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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE FUNDAMENTALS OF THERMOPLASTIC RECORDING

BYRON B. NEWELL, JR.

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Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

IN

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United States Naval Postgraduate School

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ABSTRACT

The process of recording information by deforming the surface of a thin plastic film in accordance with the information content of an electron beam is described including some of the military applications. The advantages of this relatively new process, called Thermoplastic Recording (TPR), over the magnetic recording process and the recording of information using a Flying Spot Scanner (FSS)-cathode ray tube-photographic film system are described.

The packing density, capacity, and bandwidth of TPR and the FSS-film system are compared indicating analytically the advantages of the new recording technique. A formula for computing the bandwidth of a TPR system in terms of the system parameters is derived.

The many problem areas in the TPR process are pin-pointed by comparing the fundamental parameters of the FSS-film system and those of the TPR process. Particular emphasis is placed on beam and medium characteristics. An appendix detailing experimental work in the medium characteristics of thermoplastic recordings and the parameters affecting these characteristics is presented.

The writer wishes to express his appreciation for the assistance and encouragement given him by Professor George M. Hahn of the U. S. Naval Postgraduate School and by the Advanced Research Group under the direction of Mr. Reginald T. Lamb at Ampex Corporation, Redwood City, California.

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I. Introduction

A. Outline and Purpose

1. The work presented here is the result of a ten week industrial tour at Ampex Corporation in Redwood City, California. The original intent was to investigate the application of thermoplastic recording to the correlation process. It became apparent early in the tour that the state of the thermoplastic recording art would not permit such a study. The tour was devoted to theoretical and experimental attempts to develop fundamentals. This is not to be interpreted to mean that thermoplastic recording techniques cannot be applied to the correlation process. They undoubtedly can. Until repeatability is assured, until medium characteristics are firmly in hand, and until the interplay between parameters in the thermoplastic process is known, application will remain an exercise in "cut and try" engineering.

2. Thermoplastic recording is a relatively unknown process due mainly to its proprietary nature. To offer insight into the mechanism of the process including its advantages and disadvantages, a comparison will be made, where applicable, between the technique of thermoplastic recording and the process of recording on photographic film using a flying spot scanner (FSS)-cathode ray tube combination. There are many similarities between the two processes. Thermoplastic recording (called TPR hereafter) will certainly develop its own markets.[1] However, its most obvious immediate application is as a replacement in the late 1960's for the FSS-film technique now used in aerial photography electronic readout and in line scan side looking radar record and readout.[2]

[1] H. A. Strickland, Jr. "Potential Applications of Thermoplastic Recording", TPR press conference release (GE), pg 2, 12 Jan 1960

[2] G. H. Coddington, et al, "Reconaissance Tape Data Conversion" General Electric Technical Information Series No. R60ELS-103, ASTIA No. 248050, pg 16, 15 Dec 1960

The first section of this paper will present in general terms a discussion of the two processes including a general discussion of applications. A fairly complete outline form of description of the thermoplastic process will be presented with little explanation. The system parameters will be compared in general. If the reader will retain a general concept of the process without attempting to recall such details as various methods of developing recordings or scan control techniques etc., he will find that the reading goes smoothly.

The second section presents an original formulation of a constant used as an aid in defining the bandwidth of thermoplastic recording readout in terms of the parameters involved. In general this section represents the application, in a limited sense, of Information Theory to the TPR process.

The final section offers a comparison of the parameters of the FSS-film process and the electron beam thermoplastic process with emphasis on the media, ie: photographic film and thermoplastic tape. An appendix describing the experimental evaluation of twenty-two thermoplastic recordings is included to substantiate some of the data presented in this section.

B. Acknowledgements

1. Mr. Reginald T. Lamb, the Director of the Applied Research Branch of the Research Department at Ampex Corporation in conjunction with Professor George M. Hahn of the U. S. Naval Postgraduate School provided the interest, impetus, and guidance for this thesis. Their encouragement and assistance was invaluable.

Bob V. Markevitch, a senior engineer at Ampex, provided the inspiration for the majority of the original theory presented and for the

experiment conducted. The contribution through his time, talent and patience are deeply appreciated.

Senior engineers, Kurt F. Wallace, Erwin Roth and Emil V. Bobblett offered many helpful suggestions. The contributions to the overall industrial experience through association with engineers at Ampex including, William A. Eddy, Kenneth J. Pitts, William J. Martin, Jorgen Voss, Samual F. Debney, Eraldo Chiechi, Reno Chen, and John F. Herbert, Jr. is gratefully acknowledged.

The author is also indebted to Donna Messer, Lorraine Niehuis, and Barbara Hare who typed the rough and final drafts.

II. The Processes

A. Thermoplastic Recording (TPR)

1. General

The TPR process considered here involves the direct deposit of electrons onto a plastic substance such as polystyrene. It includes direct readout using an electron beam. There are processes like TPR wherein a charged photo-conducter is used to deposit electrons onto a thermoplastic medium (called ELINT or Electrostatic Latent Image Photography) or electrons are deposited through an electron beam onto an oil film. The first is bandlimited and the second is non-permanent.

There are some obvious advantages to direct electron beam recording. First, it is the most direct means of coupling from an electron beam to a recording medium. It will be shown that in an indirect FSS-photographic film system, cathode ray tube phosphors, optical system characteristics, and light sensitivity-resolution characteristics of the film can limit the resolution achievable to less than that of the electron beam used. There is also the fact that, because of the system inefficiencies, the electron beam current in the FSS cathode ray tube may have to be several times that used in a direct electron beam recording technique. Also, the dynamic range of the direct process is potentially much higher than the indirect process.

2. The process

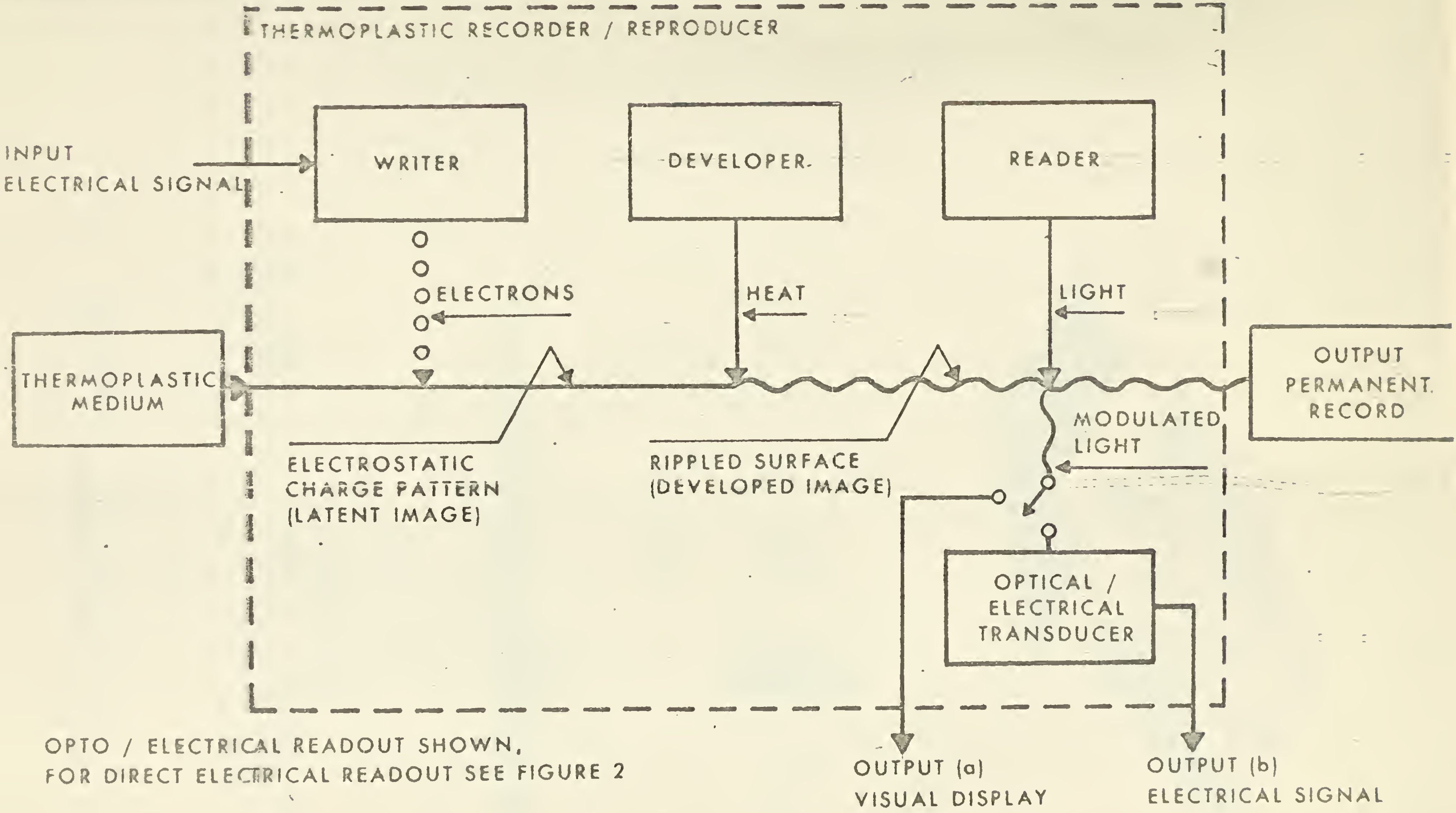
Thermoplastic recording is accomplished by deformation or modulation of the surface of a layer of a thin plastic film in accordance with the information to be recorded. The tape or film used in the process is three layered. The base may be similar to motion picture film. The surface deformation is accomplished by depositing a layer of electric charge whose density is distributed as a function of the input information. The application of heat decreases the surface forces and causes the surface to deform in accordance with the charge density. The attractive force is provided through the induced mirror image charge in the conductive layer. Upon cooling the written information is permanently stored in the material. Figure II-1. is a block diagram of a simple TPR system using an optical readout method.

The intelligence of the written information is physically stored in the relative dimension of the ripple. Figure II-2. is a picture of how the deformed plastic surface might appear.

The intelligence may be determined optically by measuring the degree of diffraction or refraction of light passing through the line gratings. This readout technique was used in the experiment discussed in Appendix A. The intelligence may be determined electrically by scanning the groove with an electron beam and sensing, for instance, the pattern of the secondary emission electrons. There are a multitude of items to be considered in a thermoplastic recording system. Some of these are outlined in Figure II-3. Many of the more important parameters of TPR are considered in later sections.

The important ideas at this point lie in recognizing the advantages of a thermoplastic recording process, perhaps not individually unique, but certainly unique collectively.

High resolutions are possible in lines/mm, information density, or bandwidth. The best wideband magnetic recording resolutions are about 1.5 square mils. A FSS-film combination is about the same. Current electron beam recording techniques are producing spot sizes on the order



OPTO / ELECTRICAL READOUT SHOWN,
FOR DIRECT ELECTRICAL READOUT SEE FIGURE 2

THERMOPLASTIC RECORDING SYSTEM, BLOCK DIAGRAM

FIG. II - I

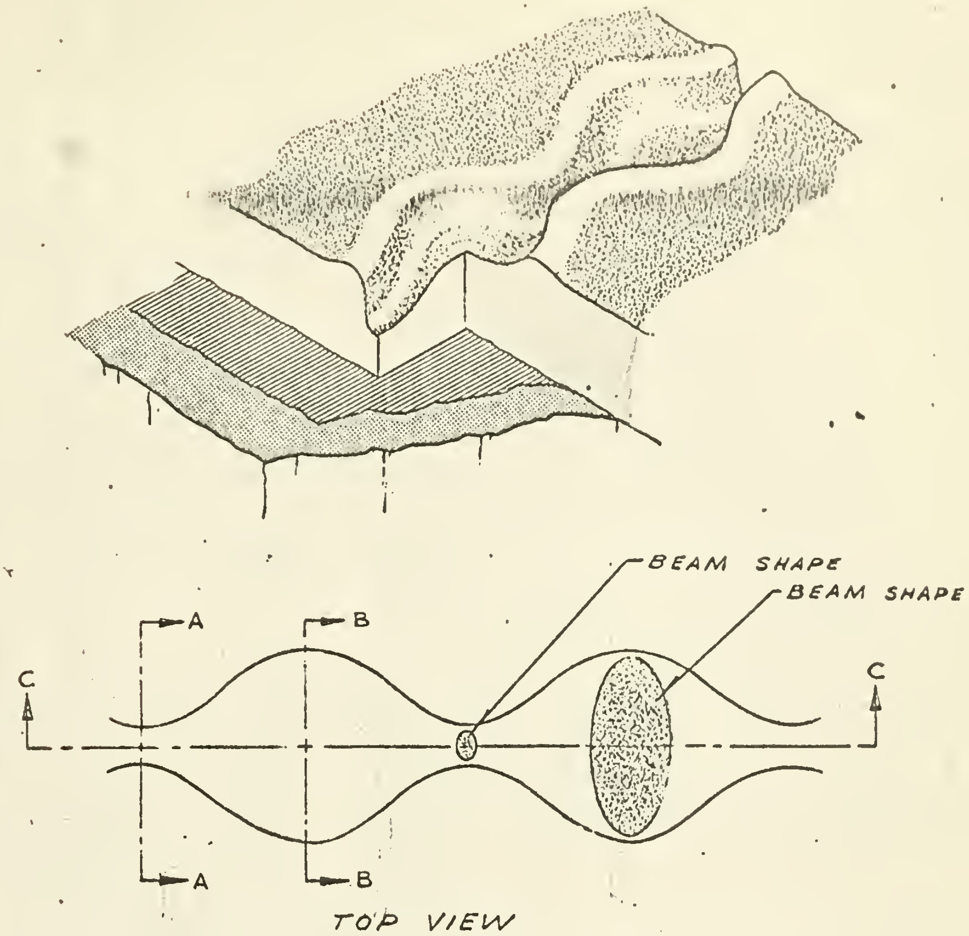


FIG. II-2 DEFORMED SURFACE OF A THERMOPLASTIC RECORDING

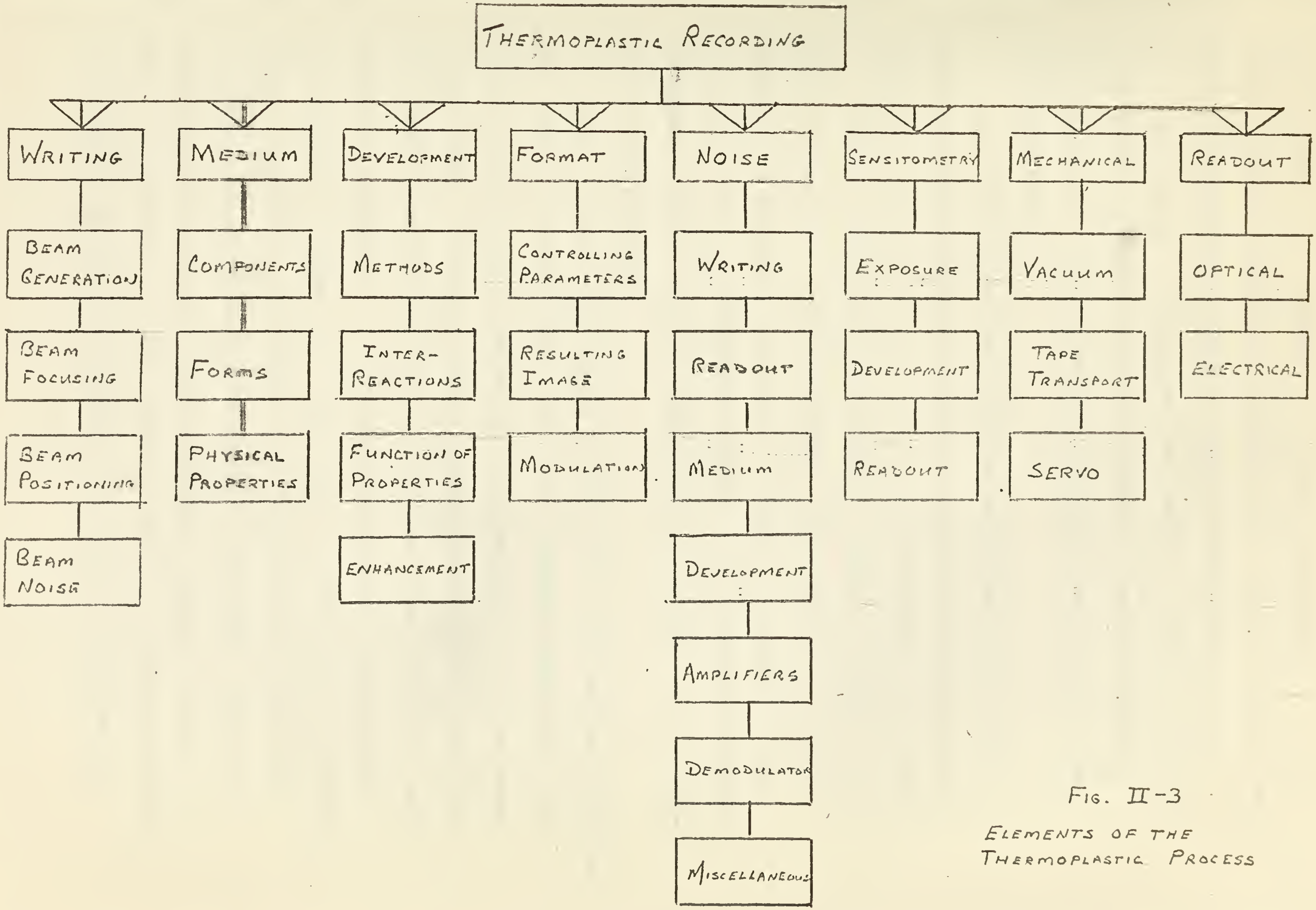


FIG. II-3

ELEMENTS OF THE THERMOPLASTIC PROCESS

of .16 square mils. Magnetic tape recording bandwidths are in the 4-7 mc region. FSS-film bandwidths are in the 10-20 mc. region. TPR recording bandwidths of 50-100 mc have been achieved in the lab.

Rapid exposure to view times are possible in TPR (for example the experimental recordings evaluated in Appendix A. were developed in 30-80 milisec.). The best wet film developing techniques are in the 2-3 minute range.

As in magnetic tape recording, the thermoplastic tape may be erased and reused. Also the medium is essentially unaffected by high electric and magnetic fields, and for practical purposes by radiation.

Finally, either optical or electronic readout is possible. This is in a sense true in FSS-film readout, but the limitations in this process will be pointed out. One of the obvious advantages is the fact that TPR offers a readymade solution to the information tracking problem in that the beam can be servoed to a null based on the physical groove characteristics.

There are some disadvantages in a TPR system. The problems associated with the use of an electron beam are sometimes overwhelming. The medium is quite fragile and subject to contamination. A system vacuum on the order of 10^{-5} mm of mercury is required. And, as in any system, there are accuracy and repeatability problems. Some of these are made obvious in appendix A. It is perhaps easiest to say that with every box indicated in Figure II-3. there exist problems which in themselves do not constitute a disadvantage of the TPR system, but which taken together place the TPR system in a somewhat unfavorable light when it is compared with the more developed systems. However, the interest in TPR is fostered by the obvious return in the form of advantages for the cost required to solve the problems and overcome the disadvantages.

B. Flying Spot Scanner (FSS) - film system

The primary purpose of this paper is to present and evaluate TPR as a function of the electron beam and the medium. This section will describe the system to be used in comparison as an explanation vehicle.

The majority of the high data rate scan systems in service today, including side looking radar systems, infrared sensing systems, and multi-transducer sonar systems, use the FSS-film system for data processing. In the record mode an intensity modulated cathode ray tube is photographed (this puts a camera with its lens in the system). The electron beam is controlled in position by a suitable scan mechanism tied electronically to the sensor. The framed image type of output, if such is used,is created by a TV type raster scan. If a line scan output is desired, the beam moves in one line back and forth across the face of the CRT, and the film is transported continuously.

The film is then processed. The final product is usually in density modulated negative form. Readout is then affected by projection using light-optic systems, or by a second FSS system wherein the CRT spot is focused through a lens system onto the film and allowed to scan the film as the scanning mechanism moves the spot on the CRT face. The light beam is modulated by the varying density of the film. The modulated light is transformed to the electronics domain through a photomultiplier In most systems this retransformation to an electronic signal is required to permit modification of the signal to remove the various distortions inherent in the recording process. For instance, for an air-ground mapping system, these distortions are a function of aircraft attitude and sensor platform position. The correction of these distortions is referred to as rectification. The rectification problem is a study in itself and is not considered in this paper.

In Section III some of the limitations of the FSS-Film system, including phosphor efficiency and characteristics and camera and film transfer characteristics, are considered.

The advantages of the FSS-film system are usually presented as compared to a magnetic recording system. For instance, the rapid tape and head wear problem associated with magnetic recording is not a consideration in FSS-film systems. There are also some advantages offered by an FSS-film system over a TPR system. For instance, it is not necessary to move the photographic film in a vacuum while recording and reading electronically. Photographic film is less subject to contamination than thermoplastic tape Probably the fact that FSS-film systems are in service should be mentioned as an advantage It is easy to "shoot down" an in service system using the theoretical advantages of a drawing board-laboratory system. It is not as easy to carry out some aspects of the theory.

This thought perhaps lies behind some of the caution demonstrated in articles[3] indicating that TPR methods may only partly supplant FSS-film systems in the 1965-1970 area. This has naturally led to the following section which discusses in general some of the applications of these two processes.

C. Applications

1. General

Thermoplastic recording promises to combine the processing speed and versatility of magnetic recording with the storage capacity of

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[3] R. Baske, et al, "Correlated Airborne displays" Seventh Annual Radar Symposium, Univ. of Michigan, pg. 199-220, 1961

photographic film and offer some additional advantages over both. It is the applications in the field of data and information handling which will make use of the unique properties of speed, packing density, erasure, rewriting, and direct optical or electronic readout that will be mentioned here. There are industrial applications such as library storage, automation control, and television recording. The military applications will be described in general terms in this paper.

It should be emphasized that as of 1 January, 1962, no operational military TPR system existed. General Electric was preparing to deliver a Thermoplastic PPI (Plan Position Indicator) to the Naval Research Laboratory for evaluation.[4] Ampex Corporation delivered a system for evaluating thermoplastic storage media to the Aerial Reconaissance Laboratory of the Wright Air Development Division (WADD) of the U. S. Air Force in February, 1962. These two items will represent the extent of the "out of laboratory" TPR equipment for 1962 at least.

2. Brief synopsis of applications

a. Radar applications.

(1). The majority of the applications of TPR in the area of radar are simply an extention of the in service optical processors. They in general involve high storage requirements. Such requirements exist in the high resolution sidelooking ground mapping radars and in coherent radar detection systems using target velocity and acceleration as a means of detection. In the former correlation techniques are used, and in the latter many simultaneous integrations are required.

Optical images have the inherent property that they possess two

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[4] Personal communication with Mr. E. F. Scully, Sales Engineer, Radar Products, Navy Programs, General Electric Co. dated 28 Feb 62

degrees of freedom as represented by the two independent variables which define a point on a surface. In this respect, optical systems differ basically from electronic systems which possess only time as the independent variable. The details of the unique properties of optical processing systems are contained in a classic article[5] by Cutrona of the University of Michigan.

(2). Since it is possible to use optical techniques in processing thermoplastic tapes, the extension of some of the ideas applicable to film techniques seems logical. But the extension is not a simple one. Photographic film techniques involve a simple density or amplitude modulation. Optical TPR techniques involve a phase modulation due to the variable index of refraction of the grooves. This phase modulation must be converted to some sort of amplitude variation to obtain an optical readout. This problem has been treated in detail by R. V. Pole of General Electric.[6] His work details the problem and the difficulties and offers some solutions. The phase problem is not the only one.

In optical-film correlation techniques, for instance, the result of correlating signals recorded on two films is recorded on a third film directly using a chain of lenses and a single light source. The result of correlating signals on two thermoplastic tapes, assuming some unique optical system (Schlieren) is available, would need to be converted to electrical information prior to recording on the final thermoplastic material. The alternative involves the use of an all electronic system using two or more guns. The physical problems associated with such a

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[5] L. J. Cutrona et al, Optical Data Processing and Filtering Systems, PGIT of IRE Volume IT-6, No. 3, pg 386-400, June, 1960 (with numerous references)

[6] R. V. Pole, "An Optical Analysis of Surface Deformation Recording" General Electric Technical Inf. Series DF 59 ELS-82, 15 Sep 59

scheme appear too great at present to merit consideration. The author is pessimistic about the near term possibilities of using an all thermoplastic system for processing requiring correlation.

However, this does not rule out the use of TPR in display systems or in initial storage systems. The display function will be discussed below. It is quite possible that the initial recording of sensor data could be on thermoplastic film. The electronic readout of the initial sensor information could be rectified and the resultant information could be recorded on photographic film for processing using optical-film correlation techniques.[7]

A great deal of library research was done prior to the industrial tour at Ampex in order to become familiar with the method of obtaining high resolution using synthetic apertures in conjunction with the side looking radar technique. This technique is explained in a series of articles in the Symposia on radar conducted by the University of Michigan, and published by ASTIA. Two articles, one unclassified, are referenced here as offering a quick general picture of the process.[8,9] Coddington,[10] gives some idea of the specifications for TPR systems applied to the processing of data from a quite fundamental side looking radar system.

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[7] L. J. Cutrona, et al, loc. cit. pg 397

[8] L. J. Cutrona, et al, "A High Resolution Radar Combat Surveillance System" IRE Transactions on Military Electronics, pg 127-131, April, 1961

[9] L. J. Cutrona, "Fine Resolution Radar: Its Status and Its Future", Fourth Annual Radar Symposium, University of Michigan, pg 133-139, June 1958

[10] Coddington, et al, op. cit. pg 62

His conclusions point to the need to continue developing the fundamentals of electron beam recording. For instance, the output recorder he specifies requires a 35mm tape, 10,300 resolvable lines per scan (277 lines per mm), and a spot size of .14 mils. It will be noted in section III and IV that: (1) nobody is projecting a scan of over 6000 lines and, (2) at present a spot size of .1 mil is in the class of a projected goal.

(3). Radar systems that measure range, velocity and acceleration require formidable signal processing capability. A feel for the scope of the problem can be obtained by noting some statistics reported in a recent General Electric Newsletter.[11] For instance, if an 8 meter range resolution over a 4000 meter range interval and a 5 meter per second velocity resolution over a 3000 meter per second velocity interval are to be realized using a 20 megacycle system bandwidth and coherent integration and filtering of many successive echoes (30 milisecond integration time assumed) the requirements are. 500 range cells each containing 600 velocity cells for a total of 300,000 resolvable targets which can be displayed. To accomplish this it is required to store 600,000 individual radar returns and to perform 300,000 integrations simultaneously. An equivalent electronic system would require 500 range gates feeding 300,000 doppler filters, each having a bandwidth of 33 cycles per second. The measurement of acceleration requires equally staggering processing facility.

The G. E. system to process this data uses an optical processor with a thin film of oil as a storage device. The process is exactly like thermoplastic recording with the exception that the oil film is never

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[11] General Electric Electronics Laboratory Newsletter No. 10 dated August 1961

allowed to solidify. Their system sacrifices permanency for the ability to maintain an exactly uniform oil film thickness. They are able to produce a real time display of information using a maser as a light source, for instance, or a photo-cathode arrangement.

Optical processing in this fashion is expected to be useful in solving the problems of nose cone detection and trajectory prediction where high resolution velocity and acceleration measurements must be made rapidly.

Goodyear Aircraft Corporation[12] has been conducting a study of data correlation techniques using multiple sensor (radar, infrared and photographic) as an aid to accurate missile navigation (this is sometimes called mapmatching). They are using the digital computer for a correlation device. This technique offers another application for the high data rate,high storage capability of TPR.

Before leaving the radar section it is emphasized that this application is probably in the distant (5 - 10 years) future. There remain a multitude of fundamental problems to be solved first.

b. Display

While this might be classed as part of radar applications, it is considered separately in this report due to its importance as an immediate application of TPR. The short exposure to view time, the permanency, and reuseability make TPR a natural display vehicle. A recent authorative article points to TPR display systems as early as 1965[13] The PPI developed by General Electric is, in a sense, a display system. The intent here is to suggest that the final stage of a sensor system be a thermoplastic

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[12] Goodyear Aircraft Corporation, "Advanced Data Correlator Study and Development"(DACOR), Annual and Quarterly Reports 15 June 1959, to 20 October 1961

[13] R. Baske, et al, loc. cit. pg 210

recording. All other stages could be kept as they are at present. The ELINT process (see page 4) is a possible final stage for an optical-film side looking radar correlated output.

The use of real time in-cockpit mapmatching displays is an obvious asset. For one thing errors in coverage on reconnaissance missions could be sensed immediately and corrections made without costly mission reruns.

TPR opens up new possibilities in large-screen display of radar and sonar images. This type of display is used in radar control centers where large numbers of people must simultaneously view information as it is received. In the past, the data has been plotted by hand on large display boards, or photographically copied from the radar screen and presented in the form of a motion picture sometime later. Both methods inherently involve delays. With TPR, the radar signal could be written on tape, developed, and projected on a large screen without a significant loss of quality or detail within a fraction of a second.

TPR will also permit a new technique, similar to that used in time lapse photography to extend the range of radar and help distinguish targets from random signals that appear as noise on the radar screen. This principle, called time compression involves speeding up the motion action on the radar screen by storing the images for a period of time, then playing them back in rapid sequence. The same procedure in time lapse photography has produced pictures of flowers bursting into bloom.

By speeding up the sequence of events taking place, slowly moving and therefore almost indistinct targets would begin to move rapidly. This rapid and purposeful motion would be enough to enable the observer to make positive identification. Experiments have shown that objects apparently hidden from view can be identified by observing some orderly motion.

In the development of integrated displays, TPR offers a means of correlating information from a variety of sensing devices, and reading it out on a single display. This would allow an operator to compare radar, infrared and optical data simultaneously, or to select whichever gives the best results at a given moment. An airborne ASW display of all submarine detection sensor information would be extremely useful, for instance.

c. Sonar Applications

These in general correspond to radar applications. Columbia University has done a considerable amount of work in high resolution, fixed transducer, doppler detection of underwater contacts using an optical processing system much like the University of Michigan system.[14] There is a need in this system for some 10,000 processing channels and a real time data output rate of $1.2x10^{9}$ samples per second.

d. Electronic Countermeasures

Through correlation processes, TPR will in effect perform a counter-counter measures function by enabling high data rate signal recovery methods. However, TPR will probably find wider use in Ferret type reconnaissance missions wherein all electromagnetic radiation from the area under surveillance is recorded. Systems today[15] employ a magnetic tape recorder to obtain a record of ECM intercepts made by a passive ECM system. Although only a limited amount of information is available using this form of reconaissance, the value of the system will increase as TPR opens the bandwidth from the video bandwidths of 4-10 mc. to electron beam

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[14] L. Gregory, "Signal Processing Equipment" Project Artemis Status Report Number 3, 15 January 1961

[15] D. A. Stentz, "The Status of the Electonics Countermeasures Problem", USNPGS Master's Thesis, pg 121, 1958

recording bandwidths of 50-100 mc.

e. Miscellaneous

The use of thermoplastic tape records in a satellite as a wideband, high packing density storage medium may become quite important. The ability to readout electronically as is done in the videotape system is an important asset of TPR in this application.

As mentioned under display and radar, the use of TPR in missile nosecones for guidance and navigation is a possibility.

The applications mentioned above cover a wide span. It is significant that the span covers areas to which both optical and magnetic recording techniques apply today.

At this point now that the reader has been led to accept TPR as a system of the future with great potential, some of the parameters of the process and some of the problems facing the engineers doing research in this field will be presented. As will become apparent the art is still in the embryo state.

III. Packing Density, Capacity and Bandwidth

A. Introduction

This section serves as the connecting link between the description of the processes in Section I and the discussion of some of the parameters in Section IV to follow.

The FSS-photographic film system capabilities are briefly described followed by the capabilities of a TPR system. The packing density and capacity of the two systems are considered first followed by the bandwidth considerations. The graph, Figure III-2, is the key point of this section. It is a graphical demonstration of the interdependence of the key parameters in a TPR system.

B. Packing Density and Storage Capacity

1. FSS - Film System

a. Packing Density

A rough figure for the resolving power of a state of the art FSS-film system used in state of the art techniques is 50 lines/milimeter.

In normal electron-optical techniques using film the signal is placed in the optical system from the electronic medium by photographing an intensity-modulated cathode-ray-tube (CRT) presentation. Assuming that care has been taken in the design of a camera and film transport mechanism, multi-channel processes are essentially straightforward.

The position of the line to be photographed is controlled in the deflection mechanism of the CRT.

For standard commercially-available 5 inch film, a figure of 50 lines/mm represents:

$$\frac{50 \text{ lines}}{10^{-3}\text{m}} \times \frac{1 \text{ m}}{39.4 \text{ in.}} \times 5 \text{ in.} = 6350 \text{ lines}$$

where a 2 mm edge on each side for handling has been neglected.

Thus, if the lines represented the resolution of a 40 nautical mile area in range:

$$\frac{40 \text{ n. mi}}{6350} \times \frac{6000 \text{ ft.}}{1 \text{ n. mi.}} = 38 \text{ ft resolution}$$

Also, 50 lines/mm is equivalent to 1270 tracks/inch.

Actually a figure of 5400 processing channels is quoted for 5 inch film with a system resolution of 50 lines/mm.

There is one point concerning film resolution that cannot be overlooked. It will be covered in more detail in the section on bandwidth. A resolution-sensitivity product relationship exists in film. While the product is not necessarily a constant, it is true that resolution must be traded for sensitivity. Bandwidth is a function of sensitivity. Therefore, if it is necessary to use fast film to provide frequency response, it may be necessary to sacrifice resolution.

b. Capacity

Shannon[16] described the capacity of a communication channel in bits/second:

$$C = W \operatorname{Log}_2 \left(\frac{S + N}{N} \right)$$

where W is the bandwidth; S the signal; and N, the noise.

Eldridge[17] modified this for recording to show that capacity per unit width could be described:

$$C_t = mC = \frac{1}{w} W \operatorname{Log}_2 \left(1 + \sqrt{\frac{w}{wo}} \right)$$

where w is the track width, w_o is the track width which will provide a s/n ratio of 1, and m is $^{1}/_{w}$, or the number of tracks per unit width. This, then, gives bits/second/inch.

Since this section deals with the spatial packing density of the medium, a spatial capacity in bits/sq. in. would be:

$$C_s = A \operatorname{Log}_2 \left(1 + {}^{S}/_{N} \right)$$

where A is the area packing density.

[16] C. E. Shannon, "A Mathematical Theory of Communication", Bell Systems Technical Journal, Vol. 27, July and October, 1958

[17] D. F. Eldridge, "The Application of Information Theory to Recording Systems", Research Bulletin No. 7, Research Division, Ampex Corporation, pg 1, September, 1960

For the optical film system discussed, the ' A ' factor for 50 lines per millimeter would be approximately 1.6 megabits/sq. in.

This yields C = 3.31 megabits/sq. in. for a 10db signal-to-noise ratio and 5.54 megabits/sq. in. for a 20db s/n ratio.

The two figures of 10db and 20db are used advisedly. For the optical film system a bandwidth limitation at roughly 10 mc will be theorized. At this frequency, the 20 db s/n ratio will probably represent a figure close to fact.*

2. Thermoplastic Systems

a. Packing Density

The packing density for electron beam recording is a function of the spot diameter of the electron gun that lays down the charge on the thermoplastic material. It is also a function of the type of modulation used. The assumption will be made that the spot diameter determines the size of the track or line.

Theoretically, the limitation on spot diameter in electron beam recording is the size of the electron. A long-term goal is a spot size of 1 micron (10^{-6} meters). A near-term goal is a spot diameter of .1 mil. This goal is close enough at hand to compare TPR and optical-film systems as far as packing density is concerned using this figure.

Thermoplastic recording has one unique disadvantage that is not present in film systems. The deformations representing the information force the plastic material into ridges alongside the groove. To avoid what might be called "spillover" it is necessary to leave a guard band of approximately two line widths between lines of information.

*NOTE: This figure and other figures used in this section have been obtained in conversation with experienced engineers at AMPEX Corporation knowledgeable in the field of recording systems.

With this in mind, the packing density of thermoplastic tape may be derived in the same manner as for film. A .1 mil spot would permit 10^4 lines per inch. This would then need to be divided by three to correct for spillover tolerance. Thus, a prospective figure for thermoplastic tape is 3333 lines per inch. This is roughly three times that for a film system.

The word "system" is emphasized in this case since it is generally conceded that film has a greater packing density than a thermoplastic tape. That is, for a given square of film, the number of lines/mm that could be laid down is greater for film than for thermoplastic tape. But the context here includes a system. Under this condition, the system limitations force a stricter interpretation of the packing density capability of film.

At present the film size that could be used for a thermoplastic system is conjecture. The 5 inch figure used here is not meant to be fact, but simply a comparison figure. The 2 mm of film nominally allotted on each edge for handling is ignored in the calculations.

For 5 inch film, then, the number of lines that could be written across the film is:

$$3333 \times 5 = 16,666 \cong 17,000 \text{ lines}$$

If the lines represented the resolution of a 40 nautical mile area in range:

$$\frac{40}{17,000} \times \frac{6000 \text{ ft.}}{\text{n. mile}} \cong 14.1 \text{ ft.}$$

At present due to other limitations 6000 lines is predicted for TPR. Thus a two inch film would suffice.

b. Contrast Ratio

Again, it is stressed that this is a system comparison. Resolution is a function of contrast ratio. Noise is generally considered to be Gaussian distributed:

$$y = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \qquad \text{in units of } \sigma$$

Assuming this distribution, there is a probability of 0.32 that the noise will exceed the average; a probability of .0014 that it will exceed 3.2 (10 db) times the average; and a probability of approximately 2×10^{-22} that it will exceed ten times the average. In any particular recording scheme the fact that the noise does exceed the difference between levels does not necessarily indicate it will cause an error. Whether it will cause an error or not is determined: (1) by the length of time the noise is larger than this level relative to the length of time allotted to the signal at a particular level (the pulse width), and (2) by the particular recording and detection technique used.[18] The point is that a 2-1 contrast ratio is just about a minimum classification for resolution. A 10-1 ratio, or 20 db, is more nearly correct.

The discussion of the optical system was based on an analog intensity-modulated track photographed as it appeared on the face of a CRT. The figure given assumes a contrast ratio of at least 2-1.

c. Capacity

The Shannon formula modified as in the previous section on film is:

$$C_s = A \log_2 (1 + S/N)$$

For thermoplastic using the .1 mil spot with the factor of three reduction,

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[18] D. F. Eldridge, op. cit., pg 2

allowing the spillover guard bond, the 3333 lines/in. represent an A of 10 megabits/sq. in.

The s/n ratio in thermoplastic recording is a function of current density (usually amps/cm^2). A current density of 10 amps/cm^2 is a realistic goal. (See Note on page 23).

Using Figure 1, the theoretical optimum s/n ratio can be found for a given current density and bandwidth.

For instance, if a current density of 10 amps/cm^2 is chosen, and if the spot size of .1 mil is used, the beam current is found:

$$I = \frac{10 \text{ amps}}{\text{cm}^2} \times \pi/4 \times \frac{10^{-2} \text{ mil}^2 \text{ cm}^2}{1.55 \text{ mil}^2 \times 10^5} = 5.06 \times 10^{-7} \text{ amps}$$

The beam modulation factor, m^2, is an indication of the effective area of the beam. Using a realistic factor of $m^2 =$ [illegible] an effective current of .00506 microamps is derived.

Entering Figure 1 with .005 microamps, it is seen that at 10mc a s/n ratio of roughly 32 db is theoretically realizable. Cutting this figure to allow for almost any system degredation of s/n ratio, the Shannon formula, using a 20 db s/n ratio, yields:

$$C_s = 10 \text{ megabits/in}^2 \times \text{Log}_2 11 = 35 \text{ megabits/in}^2$$

The 10 mc figure was chosen to afford a comparison with the optical-film system at this frequency. The packing density of that system was 5.54 megabits/sq. in. using the s/n ratio of 20 db.

C. Bandwidth

1. Optical-Film Systems

To attempt a detailed description of how the bandwidth of an optical film system is computed, optimized, or otherwise handled, is beyond the

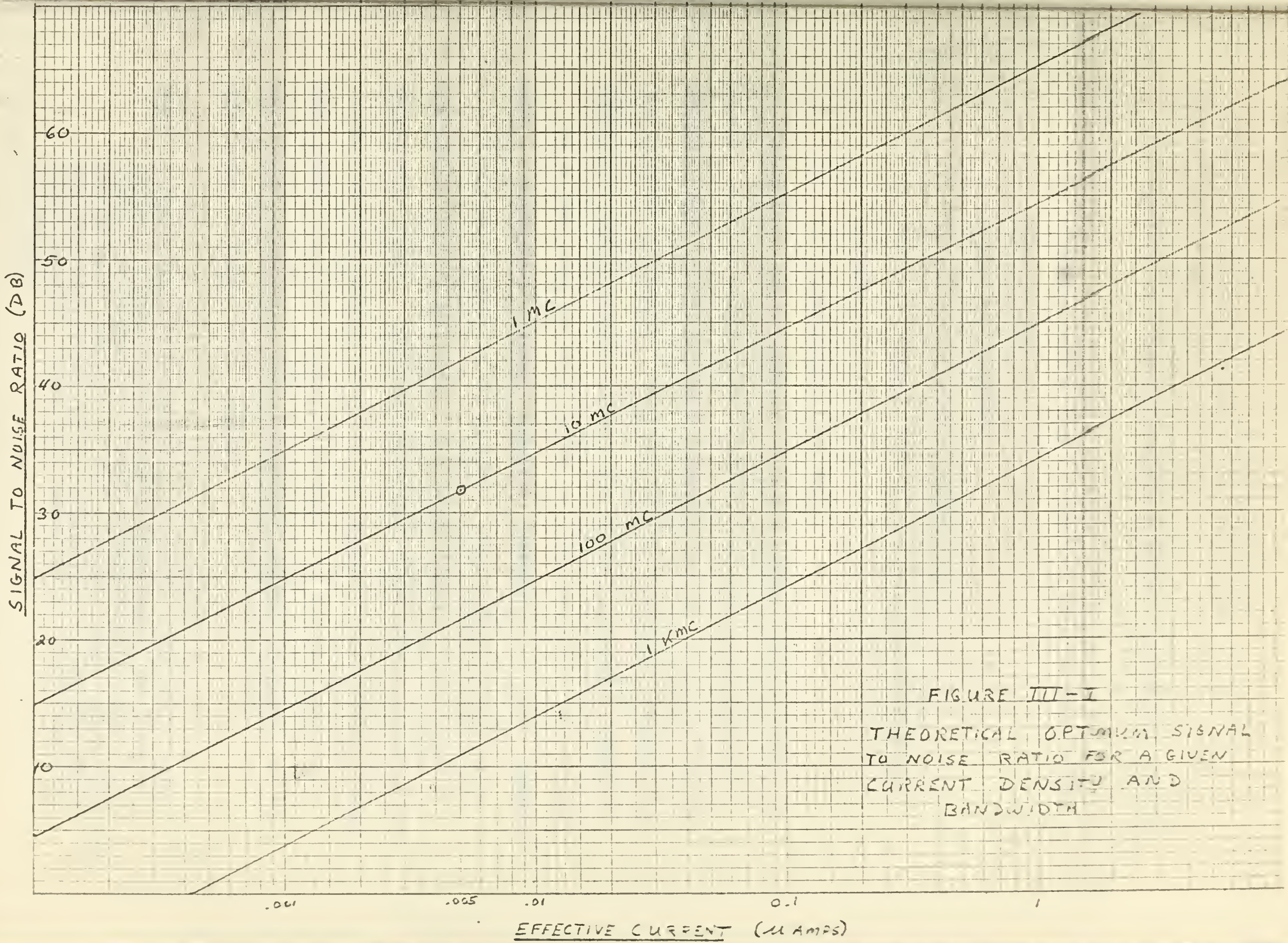

FIGURE III-I

THEORETICAL OPTIMUM SIGNAL TO NOISE RATIO FOR A GIVEN CURRENT DENSITY AND BANDWIDTH scope of this paper.

The bandwidth is a function of many elements of the system, some of which are:

- a. De-magnification; that is, the fact that the film is smaller than the CRT.
- b. Useable lens apperture.
- c. The particular batch of phosphor used.
- d. Tube life required; that is, the X-ray burn permissible.
- e. The photomultiplier used.
- f. The transmission of the film.

The maximum output bandwidth of such a system, using a flying spot scanner, is in the neighborhood of 10 mc.* An image orthicon readout technique might provide a greater bandwidth, but the resolution degradation would be intolerable. Therefore, for the resolution required, the flying spot scanner readout provides the greatest obtainable bandwidth.

It is felt that the 10 mc figure is a fair bandwidth for comparison with the thermoplastic readout bandwidth. Perhaps the ultimate limitation in a flying spot scanner is the phosphor. This element in the system operates at about 1% efficiency. Ten years of activity has failed to improve this figure. Bandwidth improvement could result in systems with a method of refrigerating or cooling the phosphor, thus allowing greater beam current without the danger of burning. The disadvantage in this improvement endeavor lies in the additional equipment involved, and the improvement is thought to be marginal.

*NOTE: A figure obtained in conversation with K. F. Wallace, a Senior Engineer at Ampex with many years experience in the field of flying spot scanners. Mr. Wallace has derived a figure for the maximum usable bandwidth of such a system, taking into account the many factors involved, in the appendices of an internal Ampex report entitled, "Flying Spot Scanner Readout of Thermoplastic Recordings".

There is no such limitation in electron beam readout. While present optical-film systems hold little promise for bandwidth improvement, the electron beam techniques are already surpassing 10 mc, and the future seems to be dependent on engineering and not media.

2. Thermoplastic Bandwidth

a. Bandwidth Constants

In thermoplastic recording, as in film systems, there are a multitude of parameters which affect the bandwidth. It is felt that the simplest way to project what may be done is to derive an empirical expression for the capacity (in a modified Shannon sense) for the system in terms of four key factors: (a) bandwidth, W, (b) beam current density, σ, (c) spot diameter, D, and (d) s/n ratio, which is in a sense a measure of sensitivity of the thermoplastic material.

The basis of the calculations is an experimental readout with the following parameters:

$B\ W = 50$ mc

$s/n = 20$ db

$D = 1$ mil

$I = 10$ microamps

$\sigma = 1.27 \times 10^{-5}$ amps per mil^2 $= 1.98$ amps/cm^2

Based on the 50 mc bandwidth which may be represented by $2 \times 50 \times 10^6 = 10^8$ bits/sec., an empirical constant is obtained as follows:

Using Shannon's capacity formula:

$$C\left(\frac{\text{bits}}{\text{sec}}\right) = W \operatorname{Log}_2\left(\frac{S+N}{N}\right) = W \operatorname{Log}_2\left(1 + {}^{s}/_{n}\right)$$

the capacity of the system based on the empirical data is:

$$C = 10^8 \operatorname{Log}_2 (1 + 10) \cong 3.5 \times 10^8 \ \frac{\text{bits}}{\text{sec.}}$$

A more suitable constant for this system would include the current. Thus, for the empirical channel where 10 microamps produced the 50 mc readout at a s/n of 20 db:

$$10\ \mu\text{amps} = 10^{-5}\ \text{coul.}/\text{sec.}$$

and:

$$K_1 = 3.5 \times 10^{8}\ \frac{\text{bits}}{\text{sec}} \times \frac{1\ \text{sec.}}{10^{-5}\ \text{coul}} = 3.5 \times 10^{13}\ \frac{\text{bits}}{\text{coul.}}$$

The question may arise as to the apparent omission of the spot diameter in the constant. Actually it is directly a part of the capacity, being the determining factor for the given current of the s/n. (See packing density)

Having now obtained the system constant, it is appropriate to expand it to a usable form for quick computation. That is, it would be desirable to have a constant in the form:

$$K = \frac{\text{Bits}}{\text{Sec}\left[\frac{\text{amps}}{\text{cm}^2}\right]\left[\text{mils}^2 \text{ or microns}^2)\ \pi/4\right]} = \frac{2.55\,W}{\sigma D^2}\left[\log_2\left(1+S/N\right)\right]$$

where W is the bandwidth in cycles/sec. and the other constants have been previously defined.

$$3.5 \times 10^{13}\ \frac{\text{bits}}{\text{coul}} = \frac{3.5 \times 10^{13}\ \text{bits}}{\text{sec}\left[\frac{\text{amps}}{\text{cm}^2}\right]\left[\text{cm}^2\right]}$$

$$K_m = \frac{3.5 \times 10^{13}\ \text{bits}}{\text{sec.}\left[\frac{\text{amps}}{\text{cm}^2}\right]\left[\frac{\text{cm}^2 \times 1\ \text{mil}^2}{2.54^2\ \text{cm}^2/\text{in}^2 \times 10^{-6}\ \text{in}^2}\right]} = \boxed{\begin{array}{l} 2.26 \times 10^{8} \\ \text{with D in mils} \end{array}}$$

$$K_{\mu} = \frac{3.5 \times 10^{13}\ \text{bits}}{\text{sec}\left[\frac{\text{amps}}{\text{cm}^2}\right]\left[\frac{\text{cm}^2 \times 1\ \text{micron}^2}{10^{-8}\ \text{cm}^2}\right]} = \boxed{\begin{array}{l} 3.5 \times 10^{5} \\ \text{with D in microns} \end{array}}$$

As a check, for a σ of 1.98 $\frac{\text{amps}}{\text{cm}^2}$ and a D = 1 mil.:

$$W = \frac{\sigma D^2 K_m}{2.55 \log_2(1 + S/N)} = \frac{1.98 \times 2.26 \times 10^8}{2.55 \times 3.5} = 50 \text{ mc}$$

This checks with the initial conditions. Using these constants, a family of curves for varying σ is plotted in Figure 2, using a s/n of 20 db.

The following hypothetical problem is offered to emphasize the utility of the constants.

Problem 1.

a. It is felt that 10 amps/cm^2 is a reasonable beam current. It is desired to reduce the spot size to .1 mil for packing density purposes while maintaining a s/n of 20 db. (10). **What will be the bandwidth under these circumstances?**

$$W = \frac{\sigma D^2 K_m}{2.55 \log_2(1 + S/N)} = \frac{10 \times .01 \times 2.26 \times 10^8}{2.55 \times 3.5} =$$

$$= 2.53 \text{ mc.}$$

This example is sufficient to illustrate the functions of the system variables. It is obvious that the bandwidth can be raised to 7.6 megacycles by obtaining a beam current density of 30 amps/cm^2. The trade off of bandwidth for s/n is also readily apparent. If, for instance, we could accept a s/n of 1, we would have a bandwidth of 8.85 mc. Conversely, if we ask for a s/n of 15 instead of 10, we must accept a bandwidth of 2.22 mc.

Another important factor readily apparent is the fact that bandwidth varies directly as the square of the spot diameter, a number in mils

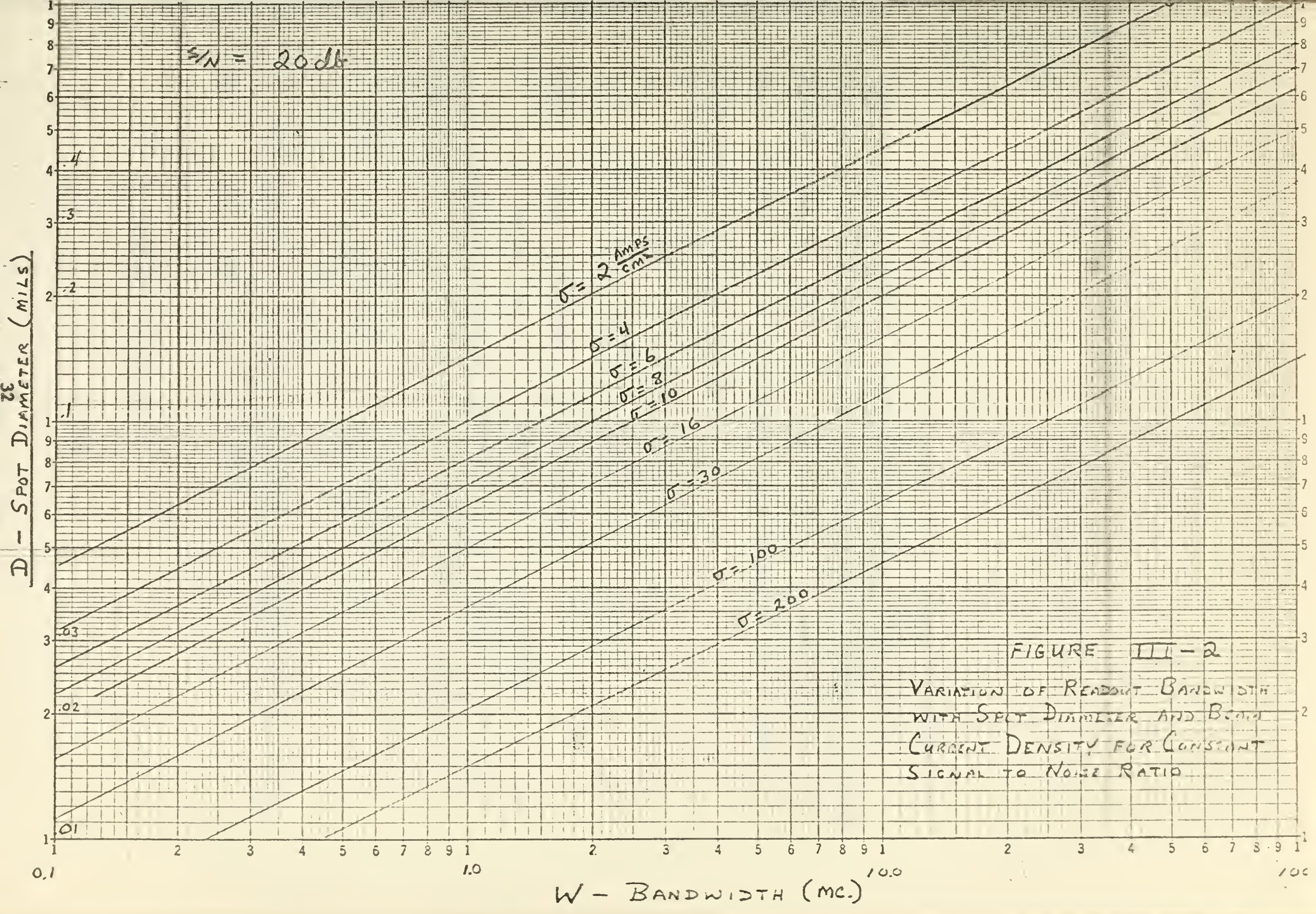

FIGURE III - 2

Variation of Readout Bandwidth with Spot Diameter and Beam Current Density for Constant Signal to Noise Ratio nominally less than 1, when seeking storage capacity. For instance, if it were desired to obtain a 1 micron (.0394 mils) spot, using K_{μ} , σ = 30 amps/cm^2, and a s/n of 10:

$$W = \frac{\sigma D^2 K_{\mu}}{2.55 \log_2 (1 + S/N)} = \frac{30 \times 3.5 \times 10^5}{2.55 \times 3.5} = 1.175 \text{ mc.}$$

b. Capacity per Unit Width

D. F. Eldridge[19] has developed equations to express the information capacity per unit width of recording media. He has shown that the information capacity per unit width of tape (or per unit area) is greatest when the tracks are made as narrow as possible. He traces this fact to the dependence of s/n on track width. This dependence can be shown for thermoplastic recording as follows:

S = signal = $k_1 I = k_2 w$

N = noise = $k_3 \sqrt{I} = k_4 \sqrt{w}$

where I is beam current and w is track width.

We will define that w, or track width, or spot diameter, as referred to in thermoplastic recording, which will yield a s/n ratio of 1 as w_0 .

Then:

$$\frac{S_1/N_1}{S/N = 1} = \frac{k_2 w / k_4 \sqrt{w}}{k_2 w_0 / k_4 \sqrt{w_0}} = \sqrt{\frac{w}{w_0}}$$

From Shannon, the capacity in bits/sec. in a communications channel is:

$$C = W \log_2 (1 + S/N)$$

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[19] D. F. Eldridge, op. cit. pg 1

So the capacity of a thermoplastic channel is:

$$C = W \log_2 \left(1 + \sqrt{w/\omega_o}\right)$$

The capacity per unit width, which is capacity determined on an area basis, is·

$$C_t = mC = \frac{1}{\omega} W \log_2 \left(1 + \sqrt{\omega/\omega_o}\right)$$

where m is the number of tracks per unit width.

C_t is obviously a maximum when w is a minimum. For instance, if w equals w_o :

$$C_t = \frac{1}{\omega_o} W \log_2 2 = \frac{W}{\omega_o}$$

as shown in Eldridge's paper.

Projecting the spot size reduction effort at Ampex, an improvement from .1 mil to a micron in diameter (1 micron = 0.0394 mils) is within reason. From the previous derivation, an example of the gain to be derived from this effort is presented.

Taking 10 mc as the fixed bandwidth, it is desired to show the improvement in efficiency (capacity per unit width) of a thermoplastic channel that will be gained by a reduction in a spot diameter from .1 mil to 0.0394 mils (1 micron). Using Figure III-2 (thus fixing s/n), at W = 10 mc and D= .1 mil, σ = 40 amps/cm^2 , and solving for D if the s/n ratio is 1:

$$D^2 = \frac{2.55 W \log_2 (1 + S/N)}{\sigma K_m} = \frac{2.55 \times 10^7}{40 \times 2.26 \times 10^8} = 2.82 \times 10^{-3} \text{mils}^2$$

$$\therefore \quad D = .053 \text{ mils}$$

Therefore, for this set of conditions at .1 mil = 1 x 10^{-4} inches.

$$C_t = \frac{1}{10^{-4}} \times 10^7 \log_2 \left(1 + \sqrt{\frac{.1}{.053}}\right)$$

$$= 10^{11} \log_2 2.37 = 1.24 \times 10^{11} \text{ bits/sec/in}$$

Using Figure III-2 again at $W = 10$ mc and $D = 1$ micron, σ = approximately 250 amps/cm^2. Solving for D if the s/n is 1:

$$D^2 = \frac{2.55\, W \log_2 \left(1 + S/N\right)}{\sigma K_u} = \frac{2.55 \times 10^7}{250 \times 3.5 \times 10^5} = .292$$

$$\therefore\ D = .54 \text{ microns}$$

Therefore, for this set of conditions at 1 micron = 39.4 x 10^{-6} inches.

$$C_t = \frac{1 \times 10^7}{39.4 \times 10^{-6}} \log_2 \left(1 + \sqrt{1/.54}\right)$$

$$= 2.54 \times 10^{11} \log_2 (2.36)$$

$$= 3.14 \times 10^{11} \text{ bits/sec/in}$$

Therefore, by affecting a reduction in line width or spot size from .1 mil to 1 micron, the efficiency of the thermoplastic media will effectively triple.

c. The application of the other points in Eldridge's paper need no specific tailoring to apply to thermoplastic recording.

He has shown that:

(1) Binary recording is more efficient than any system using higher numerical base if very narrow tracks can be utilized.

(2) Binary recording is more efficient than analog recording when high accuracies or large s/n are desired.

d. This section has put before the reader the basic system parameters With these in mind, particularly the curves of Figure III-2, the other parameters of the system involving the medium and the electron beam can now be considered.

IV. System Parameters

A. System Exclusive of Medium

1. Election Beam

a. Deflection Focus Error

The deflection focusing error in an electron gun is considered first since at the present time this error is limiting the number of lines that can be recorded in a thermoplastic recording system to less than 1000 spot diameters. This is equivalent to saying that the 5" film hypothesized in the bandwidth and packing density sections is beyond the present state of the art; allowing a two mil guard band between lines, at present only three hundred one mil lines of information can be recorded on a film one inch wide. Again this is a limitation in engineering and not medium. Active programs are in progress to engineer electron beam writers with special deflection and focusing plates to reduce this limitation.

To be sure this limitation which will be explained below is present in optical film systems using a flying spot scanner. But there is an important reason why this error is more serious in an electron beam recording system.

In recording on thermoplastic a defocus exposure causing an error deformation forces the plastic material out of the exposed area into the guard band area. Consequently excessive guard band must be reserved (2-3 line widths). The exposure of guard band area due to defocus errors not only raises the noise level, but unless sufficient guard band area is available, it may deteriorate the signal level by forcing plastic material into an exposed signal area or by decreasing sensitivity due to increased forces in the plastic. Consequently even a 5% error in spot focus may cause a forced reduction in packing density, whereas a 15% error in optical film systems may be tolerable. (See IV, B, 3, b on sensitivity)

This limitation has forced the use of reduced deflection angle in EBR on thermoplastic material. (EBR - Electron Beam Recording)

The effect mentioned above causes a loss of resolution at the edges of the recording area. There are two causes of this effect.

(1) The first cause is explained with the aid of Figure IV-1 which depicts a simple electrostatic deflection system.

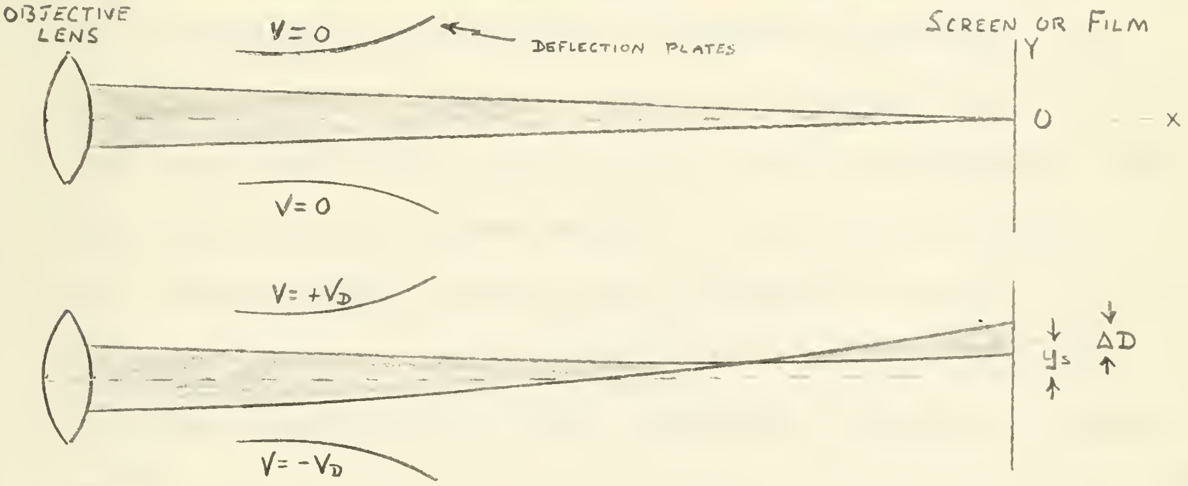

Figure IV-1

The trajectories of edge electrons, as the beam passes from the deflection system to the media, are shown for zero and maximum deflection. With no deflection, the electrons are converged to a point on the screen by the objective lens. Upon application of deflection voltages, the electrons are given additional convergence (in the direction of deflection only) by the deflecting field such that the edge electrons cross over before reaching the screen. This results in an enlarged spot in the direction of deflection. A qualitative explanation of the effect is that electrons nearest to the positive deflection plate are at a higher average potential than other electrons in the beam Consequently they pass through the deflecting field faster. Since (in the figure) the electrostatic deflection field is constant in the Y direction, the faster electrons are deflected less than are those moving more slowly. Hence, the beam is converged by the deflection system and comes to a focus in front of the screen.

ΔD indicated on the figure is the deflection for a zero spot size at zero deflection. Spot diameter is defined in many ways. The generally accepted definition is the size of a square that, when centered on the spot, will contain ninety percent of the spot intensity. The beam cross section is assumed Gaussian. The spot size increase, $\Delta\sigma$, for a Gaussian beam is the spot size enlargement of interest. Δ D is a function of a system. The relationship of Δ D and $\Delta\sigma$ is not linear. The method of calculation of these parameters is shown in the literature.[20] For instance for a σ of 3 mils and a Δ D of 5 mils, $\Delta\sigma$ is about .3 mils or 10%. For a σ of 3 mils and a Δ D of 15 mils, $\Delta\sigma$ is 1.5 mils or 50%.

(2) The second effect is caused by fringing fields. This effect is due to the aberrations introduced by fields between two sets of conventionally designed electrostatic plates.

The effects of the deflection errors are denoted by $\Delta\sigma_{V_0}$ and $\Delta\sigma_{H_0}$ in Figure IV-2. Those caused by fringe effects are indicated by $\Delta\sigma_{V_1}$ and $\Delta\sigma_{H_1}$ where V and H represent vertical and horizontal.

This fringing effect becomes more serious in systems using double

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[20] H. G. Cooper, "Design of a High Resolution Electrostatic Cathode Ray Tube for the Flying Spot Store," BSTJ, pg 723-759, May, 1961

deflection plates with a lens following the deflection plates.

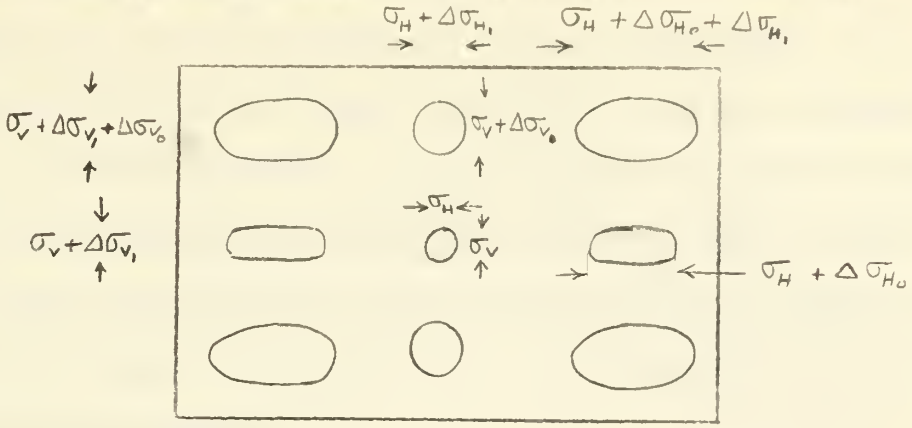

Figure IV-2

The gain in deflection distance afforded by this system, sketched in Figure IV-3, is offset somewhat by the increase in aberration due to fringing fields.

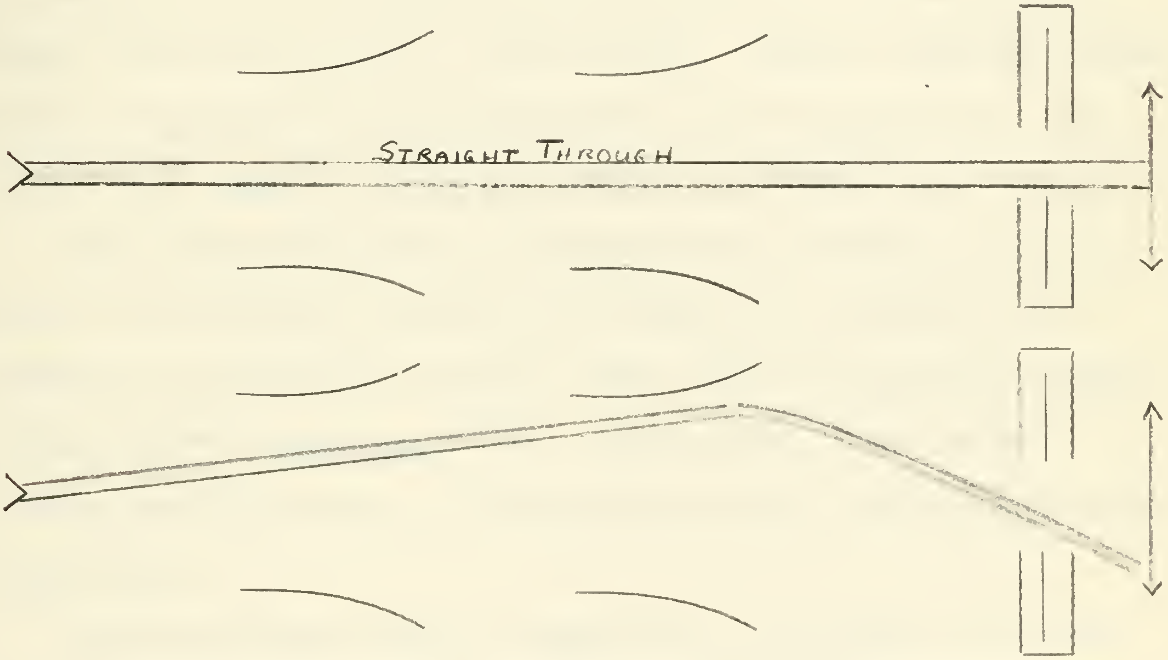

Figure IV-3

b. Other Focus Errors

The errors considered above are due to the deflection system There are errors involving the focus of the electron beam that produce the same effect as a deflection focus error, but normally to a lesser degree

It is obvious that the stability of focus can also be affected by either voltage fluctuations on the focus electrodes or current in the focus coils, either one of which in turn would depend on the stability of the driving electronics.

Aside from these errors there is a long list of aberrations that can occur in lens and gun systems. The most serious of these is spherical aberration which is defined as the inability of a lens to bring all points of an image to a sharp focus in one plane. The lens spoken of here may be considered as the focusing deflection plate in gun systems and the actual optical lens used in a readout system. Chromatic aberration which involves focus variation with wavelength is not considered here. All light sources (phosphor screen for instance) are assumed monochromatic.

Other aberrations such as astigmatism, coma, curvature of field flare, and curvilinear distortion are treated in the literature (for instance, see references 21 and 22). Their effects are generally reduced through careful engineering design. The solutions to the problem of reducing these aberrations are documented and apply to both systems under consideration.

The basic problem should be emphasized. The focusing lens system must be designed to produce a focused spot both small and well defined,

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[21] "Basic Photography," Department of the Air Force Manual Number 95-1, U. S. Government Printing Office, September, 1950

[22] E. F. Denby, "Monochromatic Aberrations of Symmetrical Optical Systems," Journal of the Optical Society of America, pg 20-31, Jan., 1962

and at the same time the lens must have an image distance long enough to make it practical for use in a deflecting system. Lenses which produce a very small spot by high power demagnification tend to have working distances so short that useful beam deflections are impractical.

c. Spot Position

The two errors noted above are errors in focus causing a change in spot diameter which affects packing density or by affecting resolution affects system capacity.

The spot position noise is manifested in wobble (random position variation) of the electron beam at the thermoplastic or screen surface. The beam deflection is given by:

$$D = \frac{E_D L}{2 E_A l}$$

where D = deflection

E_D = deflection voltage

E_A = acceleration voltage

L = length from deflection plates

l = length between deflection plates

It can be shown that if E_D is derived from E_A errors due to these sources will cancel.

Spot position is also affected by magnetic and electrostatic field pickup. Their effects can be satisfactorily eliminated by proper shielding.

Assuming, again, a Gaussian distribution for the spot energy centered about spot center, it can be shown that an error in spot position of roughly 0.3 spot diameter will cause a decrease in signal-to-noise ratio of one tenth the peak value.

Comparing the systems, the fall-off in signal-to-noise ratio is the same. Normal engineering practice should prevent spot wobble from exceeding a 1 db in 10 db error especially if the statistical averaging aspect is considered.

A question may arise (as it did with the author) whether this time base error would not cause a greater error in a thermoplastic system employing spot wobble modulation. This is a focus-defocus type modulation using a high frequency Y-axis oscillation to produce a carrier whose deflection can be amplitude modulated. Thus by varying the current per unit area modulation is achieved.

It can be shown that for correct choice of readout spot diameter, this error is negligible since the modulation is detected by effective width and not by the position.

d. Miscellaneous Beam Noise

(1) General

Beam noise is defined here as that error which results in a variation in spot intensity which for film results in variation in transmittance and for thermoplastic results in a variation in depth. Both optical film systems using a flying spot scanner and thermoplastic recording using an electron beam require currents in the microamp region due respectively to the 90% or so loss through the phosphor and to the sensitivity of the thermoplastic material.

(2) Time of arrival noise is a function of the statistical emission from a cathode. For a 10 mc bandwidth and a base current of 10 μ amps, this noise current is on the order of 10^{-9} amps and can be neglected. This effect could become important if phosphor efficiency improved or

thermoplastic sensitivity improved allowing current reduction.

(3) Partition noise is caused by the statistical randomness in the amount of the beam intersected by the various electrodes. This noise current is less than time of arrival current.

(4) Flicker is low frequency noise contributed by the cathode due to variation in surface impurities and slight non-homogeniety over the cathode emitting area The end product of flicker is time of arrival noise.

2. Special Optical-Film Parameters

a. Cathode Ray Screens

The ideal screen for the highly critical requirements of photographic film recording is one which has the proper phosphor spectral emission and decay characteristics, adequate cathode luminescent efficiency, very fine texture, extreme homogeneity, optimum screen and aluminum thickness, uniformity of that thickness, uniformity of color, and as high a contrast as is consistent with the above conditions. This general statement is factually substantiated in the literature.[23]

Each of these items is a potential error source lumped into a quantity in this treatise called screen noise. This noise source is absent in electron beam recording.

b. Camera Noise

In thermoplastic recording the film or tape replaces the cathode ray screen in FSS-film recording The camera which photographs the CRT is thus another noise source not present in electron beam recording. D. H. Kelly[24] has investigated a technique for determining loss of exposure

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[23] Meier Sedowsky, "Cathode Ray Tube and Photographic Film Characteristics Related to Film Recording for TV," Vol. 70, No. 2, Journal of the SMPTE, February, 1961

[24] D. H. Kelly, "System Analysis of the Photographic Process II, Transfer Function Measurements," Journal of the Optical Society of Americal, Vol 51, No. 3, pg 323-324, March 1961

contrast (which is in effect signal-to-noise ratio loss) due to the camera lens. He shows that it is a function of demagnification, object (CRT) distance from the lens, lens aperture (or f number since this number represents the ratio of the focal length of the lens to the aperture diameter) and the resolution required. Generally his experiments show that for the 50 lines per millimeter quoted as system resolution for optical film systems a fall off in relative contrast of about 20% must be tolerated from CRT screen to film due to the camera. This figure is derived under controlled conditions. It may certainly be agreed that the figure will vary considerably with condition; again a loss figure of 10% to 20% is offered here as a conservative order of magnitude figure. Kelly states that these losses could be referred to as lens aberration and diffraction losses, the degree of loss being a function of the parameters listed above.

3. Film or Tape Transport Errors

a. The systems discussed must include a mechanism for transporting the film or tape. This problem falls into the category of engineering design as opposed to media characteristics.

It is obvious that if a square raster (5 inches) is being recorded on the film with line spacing on the order of 2 mils an error in tape or film movement in space of:

$$\frac{2 \times 10^{-3}}{5} \times 100 = .04\%$$

will cause a 100% loss of signal.

An error in tape, film, write or read spot speed will also cause an error. This error will occur in frequency, however.

In writing or reading it is possible to move the tape at such a rate that the record or read spot need only move in one plane This is effective in reducing spot deflection errors but usually places severe burdens on the tape transport not to mention a CRT screen if one is involved. (Exotic methods have been developed to solve this latter problem). Another method is to move the film in frame steps allowing the write or read gun to scan the frame as in a TV raster pattern. Both systems require stable transports, stable film dimensions, and accurate tracking methods.

b. The stability of the transport involves several things. Variations affect tape speed. Tape speed affects time base which in effect causes errors in readout due to the time base distortions. Tension variations braking forces, sprocket deformations, guiding skew errors, capstan or pulley eccentricities, drive motor variations, and a multitude of other possible stability errors usually lumped into two words describing high and low frequency errors, flutter and wow, are reduced through careful engineering. One additional variation in a thermoplastic system (besides the requirement for a vacuum system) which may cause tension problems is the fact that pinch rollers cannot be used due to the extreme sensitivity of the plastic material. Deformations of any nature appear as erroneous information. Probably outsized film will be used with pinch rollers along the side.

c. One serious problem in all recording media is the tendency of the media under varying tension, environmental and processing conditions to change dimension both longitudinally and vertically. These shape changes obviously will produce errors between write and read cycles. In most cases their variations are tolerable only to the degree that they are measurable. That is, if measurable, corrections are possible. Longitudinal variations are normally detectable by identifying markers written along the edge of the film at accurately timed intervals. Vertical variations are not serious. Skew variations where one side of the film or both sides shift with respect to the middle are intolerable. Thermoplastic, due to its development under conditions involving heat, while under tension, may be subject to more serious variations than film. However, thermoplastic has a unique advantage in this respect over film. This advantage along with the dry processing advantage at the present (while spot diameter-scan problems remain unsolved) render thermoplastic a competitive recording media. It is discussed below.

d. It is possible to track information on a thermoplastic recording continuously. No other recording process offers this advantage. By the nature of the deformation light is refracted by, or electrons are emitted from both sides of the recorded line of information. By a continuous servoing of the readout spot to maintain equal output from both sides of the groove the spot can be made to track the information. Thus, just as in film tracking systems, the information line may be identified by a mark on the edge of the film (or both edges) to which the read head or spot may be made to flyback. The film readout must then occur based on this initiating reference marker. Thermoplastic readout needs only a start marker. It is then self-correcting In high packing density processes a small film skew may cause partial loss of film information Thermoplastic information theoretically will not be affected by skew.

B. Media

1. Granularity

a. General

The purpose of this section is to indicate that thermoplastic material offers by the nature of an effective finer grain, a less noisy recording medium than photographic film. The reader may easily dispute specific numbers which have been obtained from references which themselves admit to wide latitude. The order of magnitude is important.

It has generally been considered that the grain is the unit of photographic action and that developability is not transferred from one grain to another. This may not be true; it may be that when two or more grains form a clump, they develop as a unit. But if the "clump," theory is true, it will merely increase the granularity of film.

b. Grain

Most photographic images appear to the naked eye to be homogeneous. When magnified, however, they are seen to be inhomogeneous arrangements of grains in a matrix. The impression of non-uniformity in the image produced on the consciousness of the observer when such an image is viewed is termed graininess. The term granularity is used to designate the objective aspects of these inhomogeneities in terms of spatial variations in the transmitting or reflecting properties of the image. It is the objective granularity that is of interest in this section. It has a bearing on the real signal-to-noise ratio.

The methods of evaluating granularity are treated in the literature.[25]

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[25] C. E. K. Mees, "The Theory of the Photographic Process," The MacMillan Company, pg 981 - 1000, 1954

It is hypothesized here that the noise level of a film is proportional to the grain diameter. This seems logical. The light sensitive silver halide grains supported in a gelatin emulsion on cellulose acetate are reduced to metallic silver grains through exposure. This reduction is made visible through development. The more halide affected by light, the darker or denser that area of the negative will be. Density refers to the amount of metallic silver grains contained in the emulsion.

The more grains per given area, the less will be the inhomogeneities in terms of spatial variations in the transmitting or reflecting properties of the image and the more efficient will be the signal detection. The larger the grain diameter, the lower the density of grains and therefore, as hypothesized, the higher the noise level of the film.

Industrial fine grain films have 30 to 50 million grains per square millimeter.[26] Using the 50 x 10^6 figure and hypothesizing a square grain, the smallest grain diameter will be .14 microns. This figure will be used to compare film and thermoplastic material. The coarsest grain in photographic materials are only a few microns in diameter.[3]

c. Thermoplastic Grain

The sensitive material or thermoplastic material in thermoplastic film is a polystyrene (P. S.). It may, of course, be some other plastic material. (As a stunt a recording was made on Wildroot Cream Oil hair tonic). The polystyrene molecular weight is on the order of 30,000 - 50,000. Its density is on the order of .85 to .90 grams per cubic centimeter.

[26] C. A. Fobras and J. N. Lawrence, "Advances in Biological and Medical Physics," Academic Press, Vol VI, pg 213, 1958

[27] Mees, Op. cit., pg 974

It is hypothesized that the molecule of polystyrene is the smallest unit of thermoplastic action and that developability and deformability is not transferred from molecule to molecule. Again it is hypothesized that the noise level of thermoplastic film is proportional to the diameter of the smallest unit of action, in this case the molecules. This too is logical. Any non-uniformity in between molecules will result in non-uniform grooves upon developing the thermoplastic. This non-uniformity will result in a readout error caused in an optical readout by erroneous refraction of the light or in a secondary emission readout system by erroneous trajectories of the secondary electrons.

To calculate the diameter of polystyrene molecule, the largest molecular weight will be chosen. This will result in a comparison of the noisiest thermoplastic with the least noisy film. The procedure is chosen to allow the widest latitude in possible number errors. Again, the main objective is to demonstrate that thermoplastic film is less noisy than photographic film.

Constants: Mass of Hydrogen atom $= 1.66 \times 10^{-24}$ grams

Molecular Weight of P. S. $= 5.0 \times 10^{4}$ atoms/mol

Density of P. S. $= 0.9$ grams/cm^3

Calculation:

Weight of P.S. = $\frac{1.66 \times 10^{-24}\ \text{gms}}{\text{atom}} \times \frac{5.0 \times 10^{4}\ \text{atoms}}{\text{molecule}}$

$= 8.30 \times 10^{-20}$ gms/molecule

Volume of P.S. molecule =

$= \frac{8.3 \times 10^{-20}\ \text{gms/molecule}}{.9\ \text{gms/cm}^3} = \frac{9.22 \times 10^{-30}\ \text{cm}^3}{\text{molecule}}$

Assuming a cube as a square was assumed for film:

Diameter of a molecule = $4.53 \times 10^{-7}\ \text{cm} \times 10^{-2}\ \frac{\text{m}}{\text{cm}} = 4.53$ millimicrons

Had the figure of 20,000 been chosen for molecular weight, a diameter of 3.34 millimicrons would have resulted.

d. Comparison

The following assumptions are made based upon the stated hypotheses.

$$\text{Signal}_{\text{film}} = k_1 N_1 = k_{F_1} \frac{1}{D_G}$$

$$\text{Signal}_{\text{T.P.}} = k_T N_2 = k_{T_1} \frac{1}{D_T}$$

$$\text{Noise}_{\text{film}} = k_{F_2} \sqrt{N_1} = k_{F_3} \sqrt{\frac{1}{D_G}}$$

$$\text{Noise}_{\text{T.P.}} = k_{T_2} \sqrt{N_2} = k_{T_3} \sqrt{\frac{1}{D_T}}$$

where: All k values are constants of proportionality,

T = thermoplastic

G = grain of silver

F = film

M = molecule of polystyrene

N = noise

S = signal

The ratio of signal-to-noise ratio of thermoplastic to that of photographic film is then:

$$\frac{S/N\,(T)}{S/N\,(F)} = \frac{k_{T_1}}{k_{F_1}} \times \frac{k_{F_3}}{k_{T_3}} \sqrt{\frac{D_G}{D_T}}$$

The product of the constants is assumed equal to one for practical purposes.

This would indeed be true, if the ratios of the signal and noise constants of each system are equal.

Using the derived diameters of D_G = .14 microns and D_T = 4.53 x 10^{-3} microns, the ratio of signal-to-noise ratios is then

$$\sqrt{\frac{.14}{4.53 \times 10^{-3}}} \quad \sqrt{\text{[illegible]}} \quad \text{[illegible]}$$

This is a conservative figure. It might be stated that this indicates that thermoplastic film is roughly five times more efficient in transforming a time signal to a spatial signal than photgraphic film in regard to signal deterioration due to granular media noise.

2. Transfer Characteristics

a. General

(1) The preceding section described the effect of granularity on signal-to-noise ratio of film systems and thermoplastic recording systems. Granularity is one of the factors which has a bearing on the change in output of the system as referred to a given change in input; i.e., the transfer characteristic of the system. Transfer characteristics depend not only on the emulsion of plastic but also on the processing of the recorded signal. It is the purpose of this section to note some of the factors involved in determining the transfer characteristics. This section is included in the discussion of system parameters since in both film and thermoplastic media the transfer characteristic may be used to indicate absolute output for given input. The loss of signal as a result of transfer from input to output may be considered as a deterioration of signal-to-noise ratio due to media and/or processing.

(2) Film and thermoplastic tape are similar in general in that:

(a) Sensitivity which might be defined in transfer characteristic terms as a signal-to-noise ratio out for a given signal-to-noise ratio in falls off with increased resolution capability. For this reason military reconnaissance systems use film defined[28] by the industry as low resolution (60 lines/mm). For instance, Ansco Hyscan (50 lines/mm) is used in systems under consideration at the University of Michigan. The high signal-to-noise ratio afforded through the use of low resolution film is necessary in the analog system to provide the required number of shades of grey for target identification.

(b) Developing time in film systems is a function of sensitivity in that for a given output a shorter development time is required for a more sensitive film. This also is true for thermoplastic materials but in a different sense. Development time is important when short scan to view times are required.

(3) Gamma

By exposing film or thermoplastic in accurately graduated steps the characteristic of the media may be obtained. Photographic practice is to plot density against log exposure, where density is defined as the log to the base 10 of the reciprocal of transmission. This gives a straight line law for the major portion of the transfer characteristic. The slope of the straight line portion of the curve is usually referred to as "gamma." Gamma is normally used to define the transfer characteristic. A gamma of one would indicate that a 20% change in input to the system would give a 20% change in output.

In thermoplastic recording the practice in experiments conducted to date has been to plot log line brightness (a function of signal-to-noise ratio) versus log exposure current. The same straight line characteristic is observed and gamma is again defined as the slope of this portion.

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[28] Personal conversation with A. Fahrenbach, technical sales engineer for Eastman Kodak of San Francisco

b. Film

Kelly[29] has measured film loss for various films exclusive of camera and processing. He obtained a function, plotted much like the frequency response curves of an amplifier, indicating the fall off of transfer function (or relative contrast) with resolution. He also showed curves obtained for processing exclusive of film. The end result indicates a marked deterioration in contrast from input contrast at the rated resolution of the film. His curves also indicate that some of this contrast loss can be regained in processing. An over-all loss of 50% at rated resolution is indicated. This figure is the result of controlled experimentation. The value is given here merely to make a point. Resolution is apparently different things to different people. In quoting resolution figures, it is well to note the source. Electronics engineers tend to be conservative in their claims; film people tend to be liberal.

The transfer characteristic of film is usually plotted as noted in a. above. It is in actuality a determination of the character of the emulsion, such as the type of developing solution, time, temperature, the kind and rate of agitation during processing, the type of emulsion, the wavelength of light used to expose, and the exposures. These factors are not considered specifically.

Mees[30] covers the theory of processing thoroughly. The brief points made below are based primarily on this reference. The assumption is made that the desired gamma is known, thus fixing exposure, development time, developer, etc. The discussion concerns the inaccuracies possible. The

[29] Kelly, op.cit. pg. 328-330

[30] Mees, op. cit., pg. 163-344

non-uniformities that may occur in films are a function of emulsion and development. Without going into great detail, it is assumed that the noise created by non-uniform grain size (gamma decreases as grain size increases), and non-uniform emulsion thickness (gamma increases as emulsion thickness increases, but approaches a limit) can be neglected since, generally a medium gamma emulsion (and processing) would be desirable for an analog photograph of an intensity modulated CRT (say .6 - .8). Therefore, small fluctuations in gamma would not yield serious errors

The chemical processing materials[31] which may include reducers, accelerators, preservative, restrainers, rinsers, and fixers can create a major problem in military systems. In a recent article[32] comparing wet and dry development processes the author sums up the problem,

> Mechanization difficulties of wet processing and logistics problems of the expendable solutions have created the requirements for other photosensitive recording methods which utilize either dry materials or which are inherently reuseable . (i.e., thermoplastic tape.)

High speed processing requires rapid development and depending on the use, rapid fixing, washing and drying. The more complete the procedure, the more permanent the result. The limitations occur in the chemicals required in storage and the disposal of the used chemicals. Furthermore there is a fundamental limitation on the emulsion response.

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[31] Dept. of Air Force, op. cit. pg. 35-39

[32] R. L. Knehn, "A comparison of Wet and Dry Image Development for Data Displays," Conference Proceedings, National Winter Convention on Military Electonics pg. 132-133, February, 1962

The general conclusion to be drawn from the above is that through proper process control and emulsion selection the film loss in regard to signal-to-noise ratio can be reduced to tolerable levels (i.e., a 10 db signal-to-noise ratio output is possible). The important points are:

(1) The controlling factors evolve around the trade off requirements between resolution, sensitivity and developing time, and

(2) the processing materials create a major logistics problem.

c. Thermoplastic

(1) The transfer characteristics of film are determined through the use of a light source and a suitable photo-electric device. The transfer characteristics of a thermoplastic film may be determined using a Schlieren optical system. This system, by measuring the amount of light refracted around a light stop by a groove in the thermoplastic surface, effectively measures the groove depth as a function of the slope of the groove side. A very important distinction must be made between the determining of transfer characteristics of thermoplastic and the determining of film characteristics. The thermoplastic characteristic is quite dependent upon readout technique. That is, there will be a different characteristic obtained if an electronic readout is used instead of an optical readout. However, it is the purpose of this section to note some of the factors in thermoplastic which affect the characteristic. Their effects will be present regardless of readout technique. Appendix A details experimental work done at Ampex Corporation in the field of transfer characteristics determination as a function of some of the parameters involved. The results of this experimentation along with previously determined results will be presented in this section.

(2) It is always quite difficult to present numbers because they are often assumed to be gospel. As an idea of order of magnitude of the transfer loss in signal-to-noise ratio in thermoplasitc tape using a schlieren optical readout, the following one point analysis is presented.

A single line was written on a glass slide coated with thermoplastic material using a spot diameter of one mil and a current of 2 amps. The line was .224 inches long and written in 25μsec

The writing rate is therefore:

$$\frac{224 \text{ mils}}{25 \mu\text{sec}} = 9 \times 10^6 \quad \frac{\text{Spot diameters}}{\text{sec}}$$

which is equivalent to 4.5 mc writing speed assuming two diameters per cycle. Using Figure III-1, the theoretical signal-to-noise ratio based solely on beam noise (no modulation) is approximately 60 db. Using a simple schlieren readout and recording on a line chart display a contrast ratio of about 13 to 1 or about 22 db was obtained. This represented roughly a 40 db attenuation due to medium and readout. Using the same slide but an improved schlieren microscope a 50 to 1 contrast ratio was obtained. This represents 34 db. The readout factor is obvious in this example.

(3) The experimental slides were developed by measuring the resistance of the slide and computing the voltage required to pass a given current through the slide. Both the current and the duration of time for which the potential is applied may be varied.

In order to determine the transfer characteristic of thermoplastic material a firm control of parameters must be possible. For instance the thickness of coating, spot size, deflection speed and if possible, slide resistance must be held constant if the transfer characteristic as a function of beam current is desired. Even then it is found that a 5 - 10% variation will result from operator to operator in the schlieren readout system.

Also, if the reference base is to be exposure (current density) a decision must be made as to what method will be used to vary the current density. For instance, assuming a constant beam voltage, then charge per unit area is proportional to the current for a given time. Thus, one may vary the beam current or sweep speed. The experiment conducted was based on varying beam current. Future experiments will vary sweep speed.

There are several effects which in general characterized the twenty-two slides tested. For one thing a saturation level was apparent in the area of 2 μ amps. That is, further exposure would not produce greater output regardless of development.

The gamma of a film emulsion increases with development time to a level called gamma infinity. This is explained by the fact that the most active grains in the development process are those most exposed. For greater exposure, there are more active grains. Thus, when developing, more exposed grains develop to a greater extent than do less exposed areas. Thus, the peak of the characteristic is raised to a greater degree than is the toe or low exposure area, effectively raising gamma.

The experiments conducted with thermoplastic material indicate that gamma <u>decreases</u> with increased development time. The explanation offered here is the author's theory. Apparently the saturation level of thermoplastic material decreases as development time increases. This effect was noted in many of the high contrast slides. It is possible that the same grain activity theory applies to thermoplastic. However, it seems that the lowered saturation level prevents the peak of the characteristic curve from increasing to the extent that the toe portions increase, thus, lowering gamma.

In film emulsions, it was noted that gamma increased with emulsion thickness. The experiments conducted were designed to test this phenomena in thermoplastic material. It is felt that the data obtained in respect to this variation is inconclusive. The resistance of the slide varied. This is corrected in development by substituting resistance in series with the slide before developing. However, the substitution curves appear in retrospect to be slightly in error. Also local variations in slide resistance appear to have caused spot variations in development. These factors tend to obscure the variation of gamma with emulsion thickness. It is apparent that this variation must also be considered as a noise source in the thermoplastic process. The slide thickness in the experiment varied from .383 to .627 mils. It was theorized that increased thermoplastic thickness would decrease gamma. This theory is based on two ideas: (1) a greater thickness would result in a greater mass to heat which would tend to reduce line brightness for a given development. The peaks at high exposure would fall, but those at low exposure would be lost in background giving an apparent decrease in gamma. (2) The distance between the charge and its image would increase. This would reduce the attractive force thus reducing line brightness. Again background would obscure changes at the toe of the characteristic.

There did not appear to be local variation in thermoplastic thickness. Thus corrections for these variations could be made in beam current or development time for a given reel of film.

As noted above slide resistance may vary. This resistance is a function of the conductive coating applied to allow development current to heat the slide. It is apparent that future methods for developement will not include conductive coatings for development. A hot air, gas, or infrared heat source may be used. In the experiment conducted gamma, in general, decreased as resistance increased. This is apparently a function of the decrease of gamma with increased heat of development indicating a failure of the compensation curves.

There were other errors noted which may or may not affect future thermoplastic systems. The 5 - 10% error noticed between two experienced operators setting up the schlieren system and reading the same slide could be obviated in an electronic readout system, which most certainly will be the system used. The slides also were affected by random dust which tended to give different readings for different parts of the raster. This was tested and a 5% variation noted.

It is felt that in comparing film and thermoplastic transfer characteristics it is important to note that the characteristics of both systems are controlled through parameters of the system. These parameters in general are sources of inaccuracy only in the sense that they are not properly controlled.

(4) Perhaps one of the great, if not the great advantage of thermoplastic recordings is the dry processing characteristic. The chemical storage and disposal problems are absent in thermoplastic recordings. But before the reader runs out to buy the system it should be pointed out that the equipment required to pump the entire recording system down to the required 10^{-5} mm of mercury may offer more of a logistics problem than the film processing equipment. A 50 milisec processing time, however, may compensate for the logistic problem.

3. Sensitivity

a. Film

Sensitivity is sometimes called the speed of an emulsion. It refers to the sensitivity of an emulsion to light. The relative exposure required to produce a given density on two different emulsions is a measure of their relative sensitivity. The less exposure required, the more sensitive or faster the film.

The effective sensitivity of a photographic material depends upon the result required and the exact way in which it is used. The relative sensitivity of emulsions is not constant for different intensity levels.

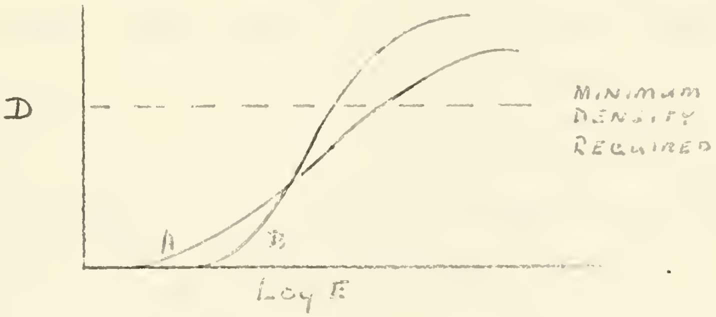

Figure IV-4

Thus, in Figure IV-4, the emulsion 'A' would be less sensitive for the requirements than 'B'. For density requirements below the intersection 'A' would be more sensitive than 'B'. In 1959, a 3,000 - ASA film was developed with a writing rate 8 - 10 times higher than any previous film. This was a product of the demand for photographic emulsions fast enough to record short duration pulses, particularly those in the sub-nanosecond regions. Advanced developments in accelerating potentials and frequency capabilities of modern cathode ray oscilloscopes often surpassed the recording capability of available films.

Today an even faster film with an ASA equivalent to 10,000 is available.

It is desirable to increase sensitivity for a number of reasons. For one thing as the characteristic moves to the left on a density - log E curve, sensitivity has increased. Development produces an effective sensitivity increase. Shorter development times for the same effective sensitivity are possible with higher speed film. Also, lower CRO beam intensities are possible with more sensitive film. This prevents interference from fuzziness (light scattering), jitter, and other undesirable effects.

Most important, higher sensitivity allows greater sweep or writing speed. For instance, by producing an emulsion with an ASA rating of 10,000 an increase in writing speed of one and one-half over the 3,000 ASA emulsion was affected.[33] Also 75% less exposure for the same density was required for the higher speed film.

The term "Maximum Writing Rate" is usually defined as, "The maximum spot speed which produces a line at a given density on a photographic negative." The ASA rating difference between two films does not necessarily reflect the true qualitative relationship in their maximum writing rates. As noted the denisty and thickness of emulsion varies from film type to film type; consequently, the maximum spot speed required to produce a discernible trace can also vary from one film to another even if both films have the same ASA rating

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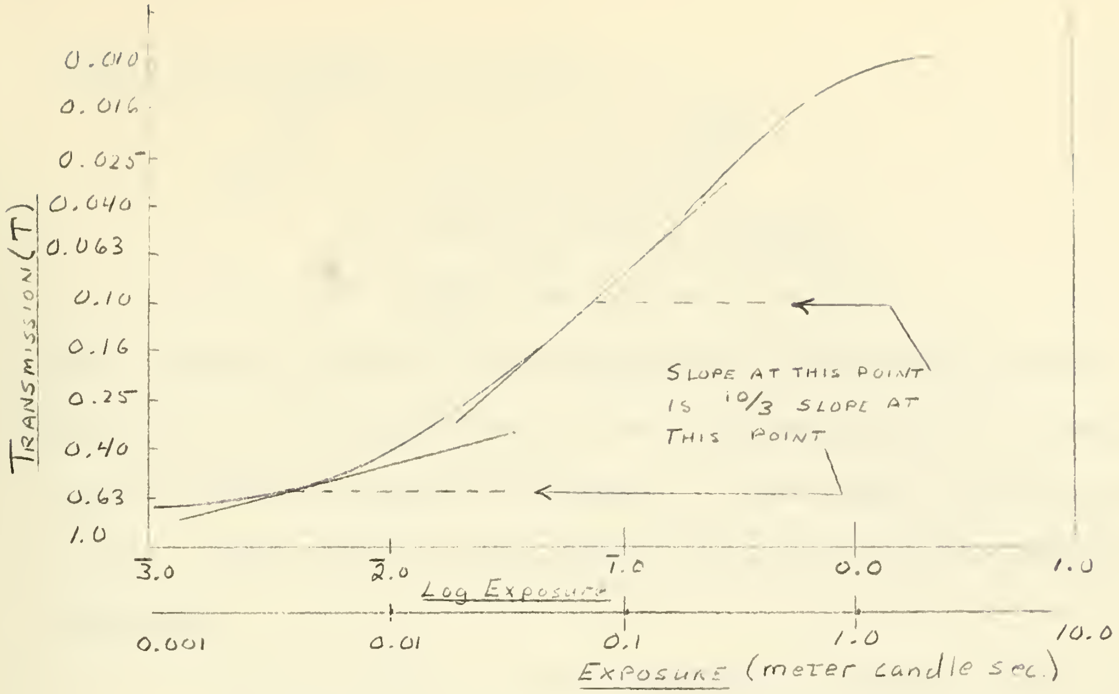
[33] R. Thomas Pierce, Jr., "High-Writing - Speed Film for CRO Recording," Electronics Products Magazine, pg 40 and 42, September, 1961



Characteristic (H & D) Curve

Figure IV - 5

The speed or sensitivity of a film is based on a calculation made from the average slope of a selected portion of the H & D curve. This slope point is taken for the ASA index as that point where the slope of the characteristic curve is 3/10 of the slope of the straight line portion of the curve. Suppose the exposure at this point was 01 meter candle seconds. 1/E = 100. The speed is usually corrected by a safety factor of 2.5 (this has been lowered recently to 1.25). Thus, the speed of this emulsion in the ASA sense would be 40. For the highly sensitive films used in aerial mapping with ratings of 10,000 the exposure would be 4X 10^{-5} meter candle seconds.

b. Thermoplastic Sensitivity

Dr. W. E. Glenn, the inventor of TPR, has derived an approximate expression for the sensitivity of thermoplastic in terms of the current density in amps/cm^2 required to produce a deformation on an insulating liquid of wavelength W and depth A:

$$L = \frac{8 \times 10^{-10}}{Wt} \left(\varepsilon T A \right)^{1/2} = \frac{\text{amps}}{\text{cm}^2}$$

where ε = dielectric constant

T = surface tension in dynes/cm

t = dwell time of spot in seconds.

This expression was derived by equating the electrostatic forces produced by the charge pattern to the restoring forces. The restoring forces consist of hydrostatic pressure in the liquid, and surface tension forces. Glenn made three simplifying assumptions in deriving the above equations:

(1) the profile of the liquid can be represented by a pair of parabolas

(2) the charge is deposited on the surface in a square of wavelength W, and

(3) The field lines are parallel.

This expression is not believed to hold when the depth of penetration of the writing electrons is an appreciable fraction of the wavelength, W (which is roughly analogous to spot diameter).

The equation is descriptive of the parameters affecting the sensitivity of thermoplastic recording processes. The dwell time t is the bandwidth function. For instance, to decrease dwell time increasing frequency the current density must increase, the surface tension must decrease, the depth of the groove (signal-to-noise ratio) must decrease, or the spot diameter must increase.

This points out nicely the trade off required between sensitivity and resolution. It is also appropriate to repeat the severe limitation in thermoplastic due to deflection defocus. As the defocus error increases with deflection angle, W increases. Assuming a constant current density, it is obvious that for a given thermoplastic and a given bandwidth or sweep speed (dwell time), there is a drop off in signal to noise ratio or depth, proportional to spot defocus. There is actually an added factor which tends to decrease sensitivity. That is, as defocus occurs the ripple or groove diameter (W) increases forcing plastic into the guard band. The next or adjacent deformation must occur against an added force. It might be said that in addition to an increase in W due to spot spread, an effective decrease in $A^{1/2}$ (the inverse to the increase in area to be moved) has occurred. Thus the effect of thermoplastic defocus errors is greater than the effect in photographic systems.

C. Section Summary

This section has brought before the reader some of the internal system parameters including the problems associated with the electron beam and those associated with the medium. The parameters associated with the FSS-film system were presented to indicate not only the advantage of the TPR system in specific areas, but also to indicate the similarity in the problems associated with the two systems.

V. Summary and Conclusions

A. Advantages of a Thermoplastic Recording System

1. Packing Density

High resolutions are possible in lines/mm, information density, or bandwidth. Readout has been achieved in the laboratory of 50mc information. A prospective figure for TPR is 3000 lines of information per inch or 130 lines per mm. This is significant in comparison to an FSS-film system where 50 lines/mm is state of the art as is a 10mc bandwidth. The capacity of a TPR system was shown to be 35 megabits per square inch as compared to 5.54 megabits per square inch for FSS-film systems at a 20db signal to noise ratio.

2. Dry processing, short exposure to view time

The dry processing advantage (30-80 miliseconds) of TPR over the 2-3 minute processing time required for film was pointed out. This will enable display of information at the same time as it is recorded, for practical purposes. Also the logistics problem of carrying processing chemicals is obviated.

3. Eraseability

Thermoplastic recordings are eraseable and may be reused. This also will enable localized editing.

4. Optical and electronic readout

Thermoplastic recordings may be read using optical or electronic techniques. The electronic readout techniques offer advantages in tracking simplicity and rectification facility.

5. Granularity

Thermoplastic recordings were shown to be roughly five times more efficient in transforming time signals to spatial signals than photographic film in regard to signal to noise ratio deterioration due to granular medium noise.

6. System loss

When compared to FSS-film systems, the direct electron beam TPR system offers the advantage of being able to eliminate the inefficient cathode ray tube phosphor as well as the lossy camera and lens. The electron beam current in the FSS-film system may have to be several times that used in direct electron beam recording. For a given current the dynamic range of the TPR system promises to be greater than an FSS-film system.

B. Problem Areas of Thermoplastic Recording Systems

1. General

This section is labeled "problem areas" rather than "disadvantages" since many of the difficulties are a function of the embryo state of the TPR art. As more effort is devoted to solving the fundamental problems associated with the art, these "disadvantages" may well disappear.

2. Vacuum requirements

The advantage in not requiring chemicals for processing may be offset by the requirement to keep the recording and readout elements under vacuum.

3. Medium sensitivity (fragility)

The thermoplastic material is quite sensitive to contamination. Any scratch, mark or dust particle will present an erroneous indication of information. Also the materials used at the present time are somewhat subject to gradual erasing over extended periods of time at room temperature.

4. Stability

As the packing density increases in any system the requirement for system stability, i.e., transport errors, beam jitter etc., becomes increasingly critical. In TPR the heating of the film to develop the information may cause stretch problems not part of normal film developing problems.

5. Guard Band

A guard band of approximately two line widths is required to provide space for the deposed plastic. This reduces packing density. It should be mentioned that when systems are considered, thermoplastic systems even with the guard band reduction, still have greater packing density than any other recording system. The deposed plastic, however, adds to the defocus problem as mentioned below.

6. Defocusing

It was pointed out that an inherent defocus error is introduced in an electron beam system as a function of scan angle from centerline. Due to the guard band requirements in TPR the defocus error is more serious in this system than in an FSS-film system. At present the maximum scan width of an electron beam system is about 1,000 lines. This is a serious problem. The general attack on this problem has been in the area of deflection system design to reduce deflection defocus.

7. Medium characteristics.

This is a problem area in that much information is lacking as to the thermoplastic film transfer characteristics. For instance, in experiments conducted using optical readout, a 34db attenuation due to medium and readout technique was observed. Work in reducing this factor is in progress. The transfer characteristic was noted to be a function of:

a. Readout technique and equipment

b. Experience of the operator doing the optical readout

c. Film thickness

d. Slide resistance

e. Development

f. Record current and current density

The various parameters above must be attacked individually and definitive information obtained about each as to its function in the system.

C. Recommendation for future field trips

1. The author feels that the particular group working on thermoplastic recording at Ampex Corporation offers the engineering student a unique opportunity to receive an enlightening industrial internship. There are several reasons for this.

a. The group is made up of people with a variety of engineering backgrounds to satisfy the process requirements for engineering "know-how" in the following areas, to name a few: mechanical engineering, chemistry, information theory, system design and engineering, electron guns and optics, material and equipment selection and procurement, salesmanship, and electronic circuitry design and fabrication.

b. The group is small (about fifteen engineers). It is possible to become acquainted with all of the elements involved to get the overall picture as well as the problems associated with a specific project.

c. The group operates in a research atmosphere with a "Try anything" attitude. The exchange of ideas is free and stimulating.

2. There are many areas for future thesis work with this group. They range in scope from broad coverage of applications to specific coverage of problem areas such as the electron gun deflection system.

APPENDIX A

A. General

The specific project on which the writer worked during the industrial tour with Ampex Corporation is described in this Appendix. It is significant to mention that the experiment conducted was in conjunction with a WADD contract with Ampex to develop techniques for the evaluation of thermoplastic storage media. One of the readout techniques involved the use of a Schlieren microscope which is referred to as a densitometer in this appendix. Figure A-1 is a sketch of the densitometer elements. Figure A-2 is a drawing of the assembly. Figure A-3 is a drawing of a typical experimental glass slide makeup, and Figure A-4 is a raster recording on such a slide. The project involved the development of techniques for operating the densitometer assembly to provide maximum repeatability. It also involved an investigation of medium variables as to their effect on line brightness (groove depth) which in a sense may be thought of as contrast ratio.

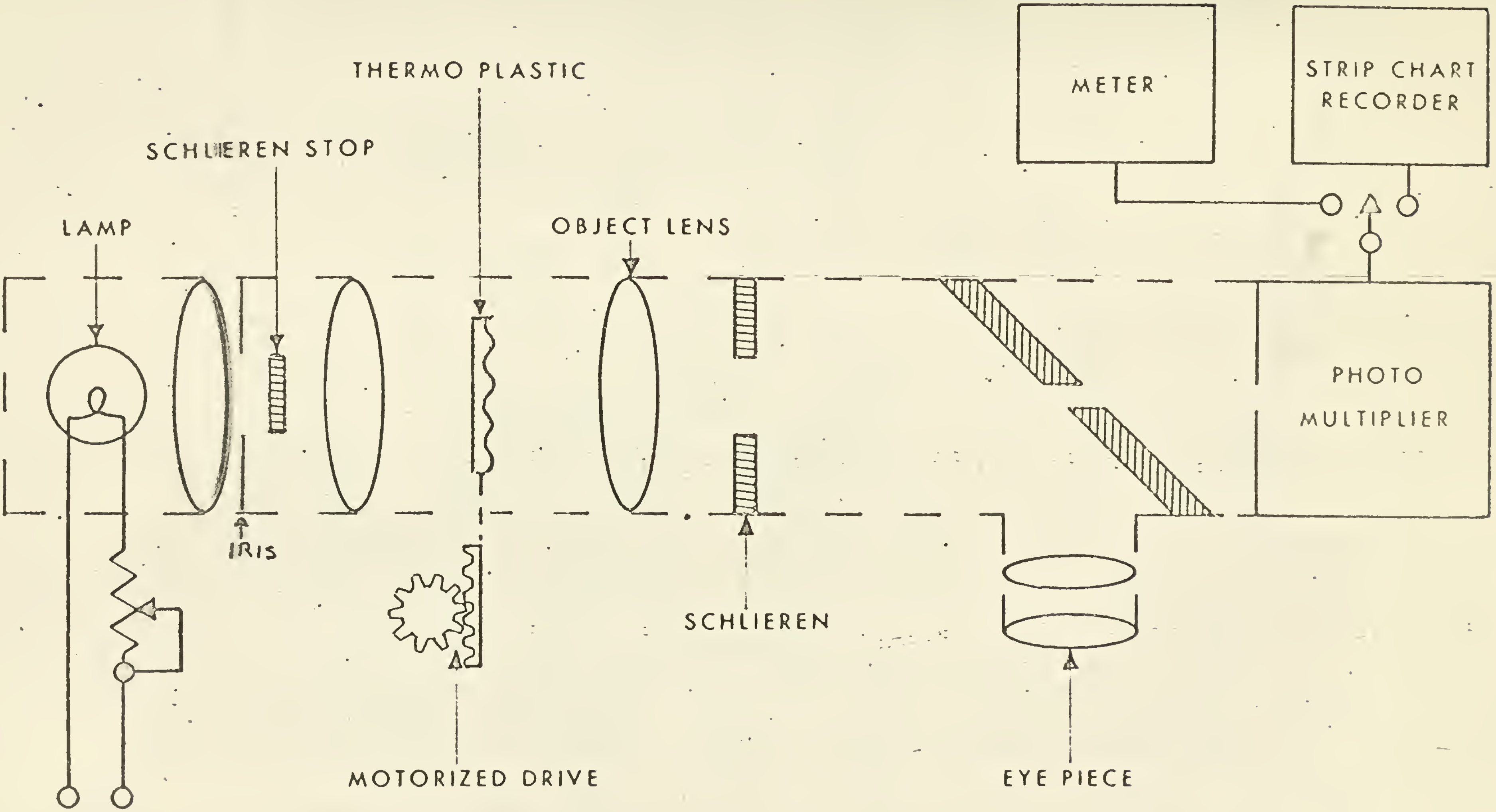
The development of the operating techniques was a long and tedious process. Without going into great detail it involved:

1. Variation of aperture (iris, see Figure A-1) to obtain optimum brightness, all other elements being fixed.

2. Standardization of focus techniques. A mechanical technique was developed to remove the human element.

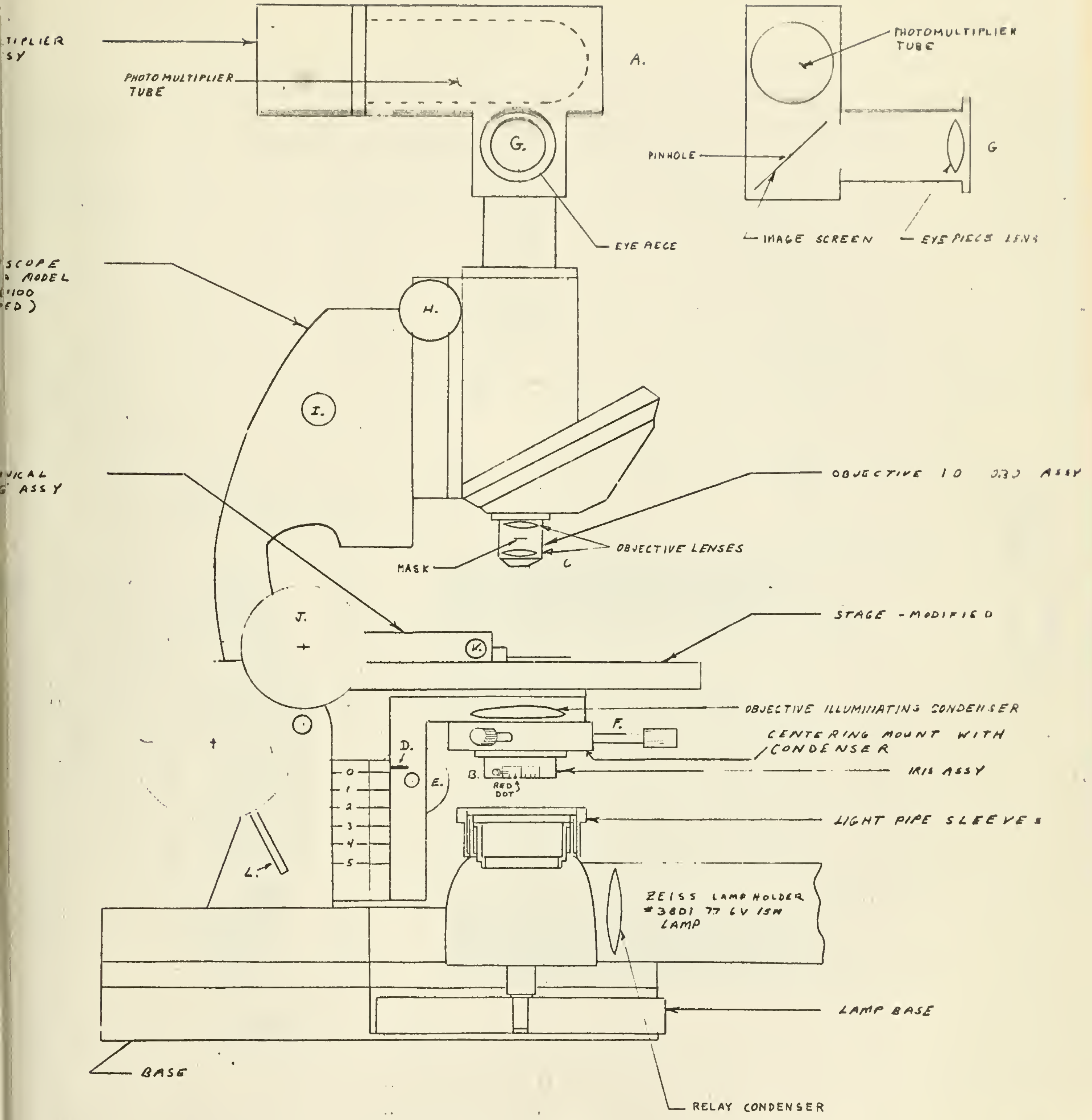
3. Determination of variability due to different starting positions on the slide.

4. Determination of Schlieren setup to achieve maximum reproduceability.



DENSITOMETER (SCHLIEREN) ELEMENTS

FIGURE A-1



DENSITOMETER
ASSEMBLY
FIGURE A-2

WAE
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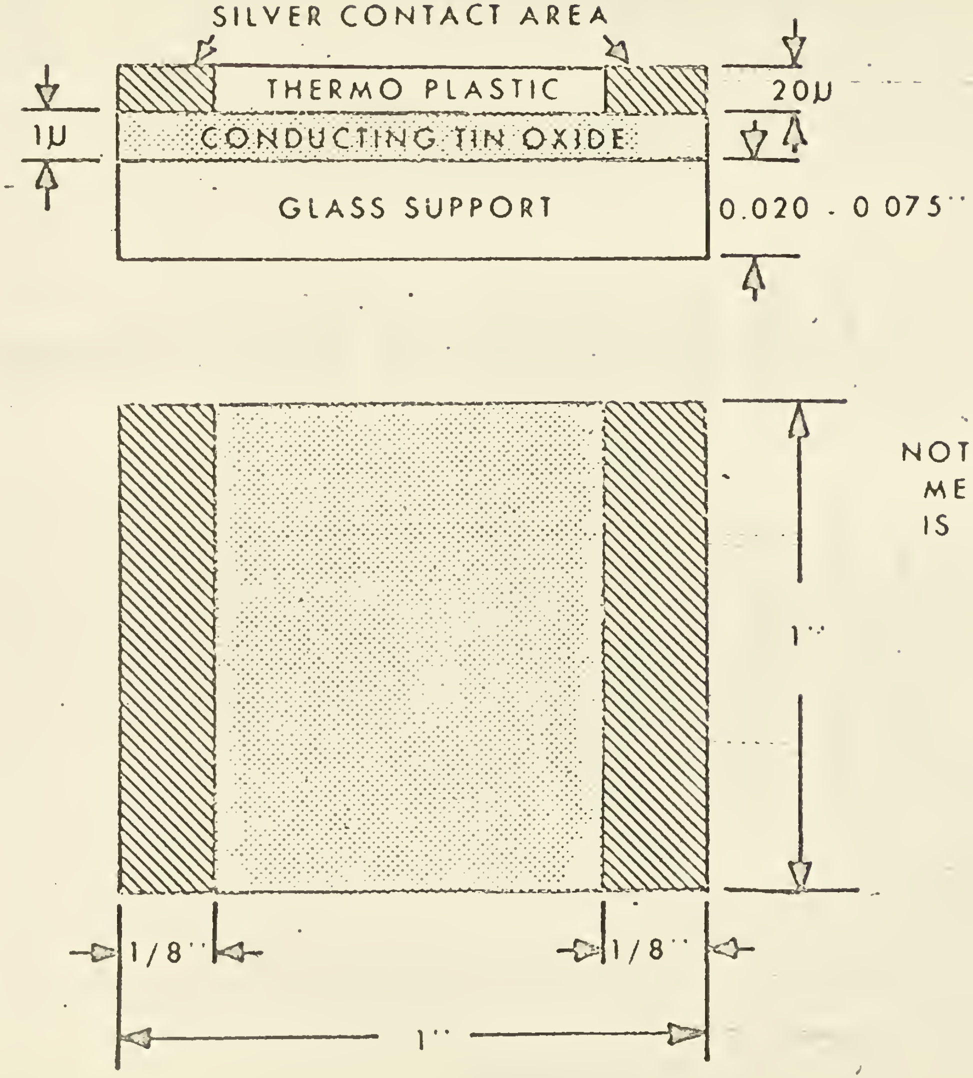


NOTE: RESISTANCE OF TIN OXIDE, MEASURED BETWEEN CONTACTS, IS 50Ω - 300Ω.

Slide Makeup
Figure A-3

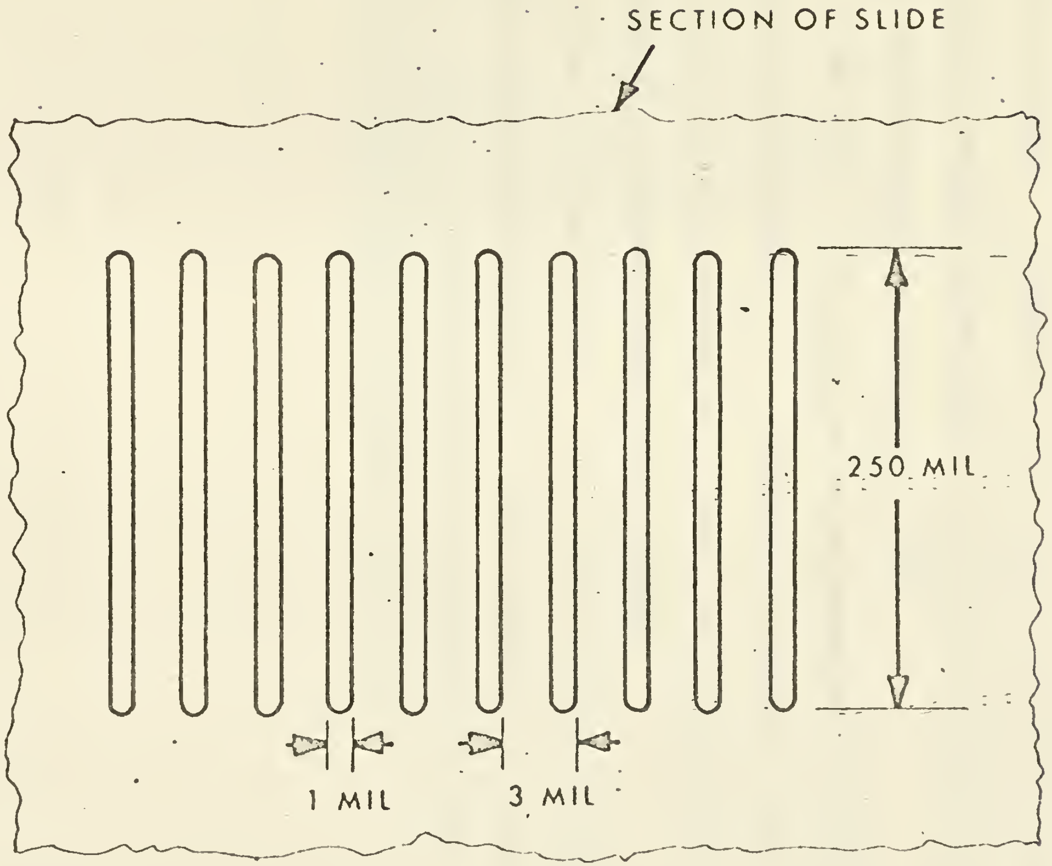


FIGURE A-4
RASTER RECORDING

5. Variation of pinhole size to optimize output.

6. Variation of light intensity to minimize fluctuations due to power supply and system drift.

7. Data taking and data plotting techniques to yield maximum reproduceability.

The following section describes the equipment and techniques that finally evolved. In general it is a copy of the operating technique instructions written by the author for inclusion in the preliminary report delivered with the equipment to WADD.

At the start of the experiments the technique and operating errors produced a 30-40% variation in repeatability using the same raster. These variations were reduced to 5% prior to delivery of the equipment providing the Schlieren setup was not changed.

In the following section a four raster slide is discussed. In general, four rasters each of four lines (instead of ten lines as shown in Figure A-4) were recorded on a single glass slide. Each raster was exposed using a different beam current.

B. Operating Technique

1. General Description

a. The densitometer assembly obtains quantative information on the line brightness of a recording. It comprises a Schleiren microscope with which the slides can be examined in a semi-automated fashion plus a recorder which produces a strip chart of the point-by-point brightness of the recording. The optical system in the microscope is analagous to the Schleiren projection systems which are normally used for projecting thermoplastic recordings. The stage of the microscope is driven by a timing motor which drives the slide through the optical probing point at a uniform rate. Various controls are provided for adjusting the level of the strip chart recording trace to an appropriate amplitude for the work being done. The slide being measured can also be observed visually on an inclined screen in the microscope barrel through an eyepiece.

b. Units comprising densitometer assembly.

(1) Densitometer microscope assembly, Tiyoda model BSZ1100. (Fig. A-2)

(2) Photometer, Universal, model 201, Eldorado.

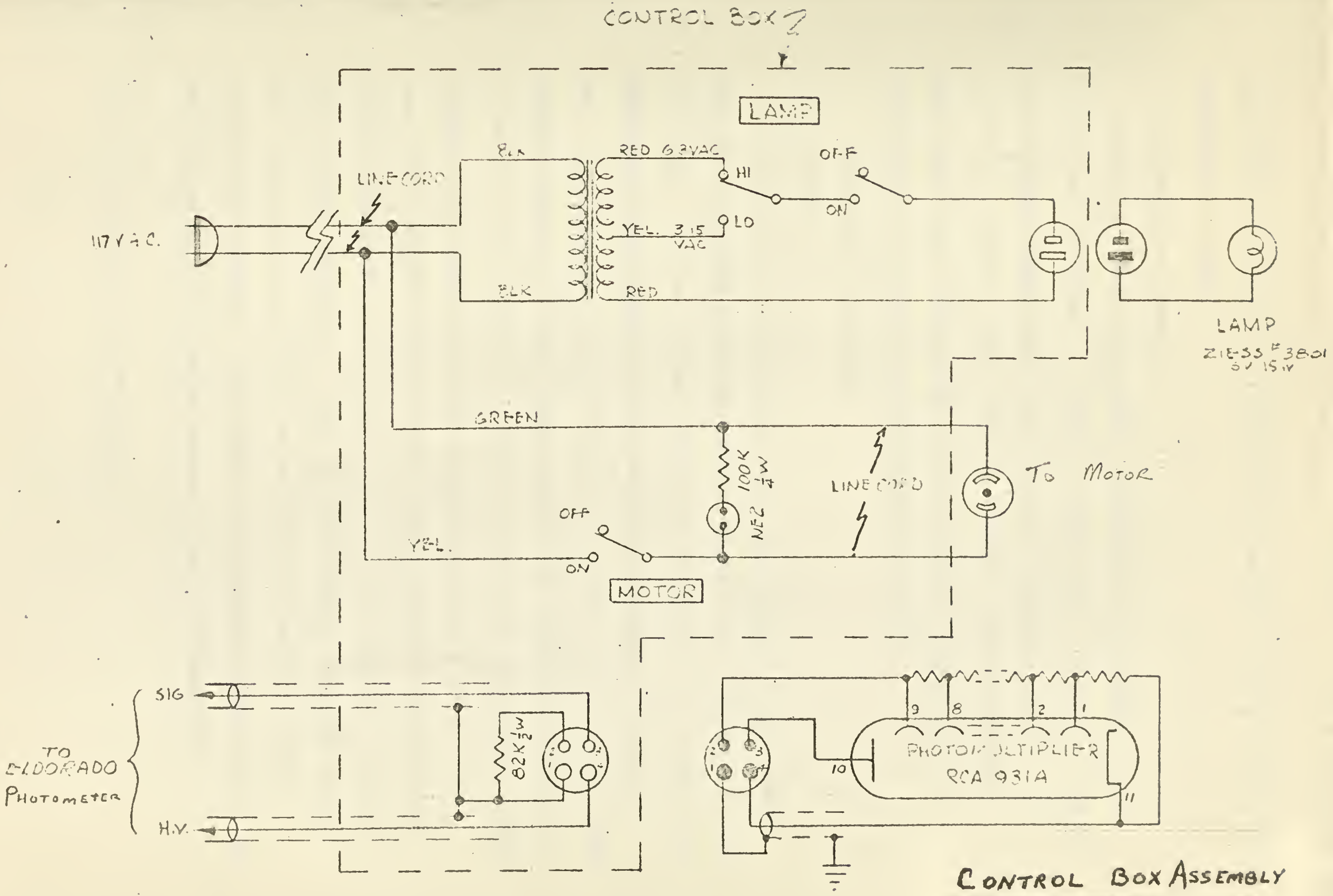
(3) Strip chart recorder, Varian model G11A.

(4) Control box assembly. (Fig. A-5)

2. Physical Description

a. Densitometer microscope assembly.

This assembly includes the photo-multiplier housing, the lamp holder assembly, the mechanical stage assembly, the aperture assembly, centering mount with condensing lens, the microscope, an image screen with a twelve mil diameter pin-hole and two objective lenses; a Schlieren mask objective



CONTROL BOX ASSEMBLY

FIGURE A-5

(with black lettering) No. 116397 and an unmodified objective (with red lettering) No. 112463.

b. Control Box Assembly

This unit houses the filament transformer for the Zeiss 6 volt 15 watt lamp providing, in addition to full power, a center tap connection through a toggle switch for half-power focusing intensity. The unit also provides an outlet, through a switch, for the mechanical stage drive motor, and provides a high voltage "in" signal "out" receptacle for the four-prong photo-multiplier plug.

3. Setting Up the Assembly

a. General

Check that the carriage drive motor is disengaged (Lever L* Down). Plug the two-pronged lamp plug into the control box. Plug the carriage drive motor cord into the motor cord from the control box. Insert the four-pronged photo-multiplier plug into the receptacle in the control box. Insert the female high voltage cable connect and male signal cable connect leading out of the control box into the respective receptacles at the rear of the photometer. Connect the positive and negative monitor outputs of the photometer to the respective inputs of the recorder. Ground the photometer chassis to the recorder ground. Connect the recorder, photometer, and control box to a 117V AC source. Turn the lamp and motor switches on. Place the lamp "high-low" switch in low. (The high position should only be used for short periods of time if required for focusing.) The recorder and photometer manual give switch and dial positions for placing these equipments in operation.

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*Note: All letters refer to Figure A-2

b. The Densitometer Microscope Assembly (Refer to Figure [illegible]-2)

(1) Initial Conditions are as follows- photo-multiplier housing (A) off, image screen out, aperture knob (B) on the red dot, Schlieren mask objective (black lettering) in place (C). and carriage clear (no slide).

(2) Setting the Schlieren

(a) Rough set-up

Sight down the microscope trunk from the top. By adjusting the X-Y position of the light image using the two knobs from the centering mount (f), position the light so that the Schlieren mask (black spot) and the light roughly coincide as far as X-Y position is concerned. Now focus the light on the Schlieren mask using knob (E). The focus is correct if, when moving the head from side to side, while observing the plane of the mask, the mask and light appear to move together. Experience has shown that the focus is correct when the scribe in the black line (D) is opposite the "1" on the scale on the housing. The observer will now see a small concentric halo around the mask.

(b) Fine Set-up

Place the image screen on the 45° ledge at the top of the scope tube with the white paper side down. Put the photo-multiplier housing (A) securely in place. Place a small cap over the eye piece (G). Adjust the photometer range to achieve a suitable deflection (about mid-scale at "1" range). By using the centering knob (F) carefully adjust the XY position of the light to achieve a sharp null on the photometer. The visual positioning in (A) above should have set the visual Schlieren close to a null.

c. The Recorder and Photometer

(1) Zero and Full Scale Adjustments

(a) Turn the photometer range knob to "off". Adjust the meter to zero. Adjust the chart recorder to zero.

(b) Turn the photometer range knob to "10". Place the slide to be read in the carriage with the thermoplastic coating up. If the slide has several rasters each containing several lines, and if the raster with the heaviest exposure is at the observer's right hand, facing the densitometer microscope, as in the figure, the motor will drive the slide so as to record the lines in order of decreasing exposure. Sight through the eyepiece (G) and focus on dust on the slide using the coarse knob (H) and the fine knob (I). The slide may be positioned under the objective by knobs (J) and (K). Move the slide so that the pin-hole (seen through (G)) is not on or near a line. Midway between two lines is a good position. Place the standard objective lens (with red lettering) in the optical path (C). Using the sensitivity knob on the photometer (or, if necessary, the high voltage screw driver adjustment on the back) bring the needle to "100" or full scale. Using the "Calibrate" screw driver adjustment, adjust the chart recorder so that it reads the same as the meter needle. Now using only the sensitivity knob on the photometer, drop the scale reading (still focused on dust midway between lines) to about 95.

The assembly is now set up to read a slide. Re-setting is not necessary unless obvious changes occur. For instance, the next slide may peg the needle on the photometer when the straight objective is focused on dust. The only change required in the set up is to drop the sensitivity to 95 again.

4. Procedure for Reading a Slide

a. Focus

(1) Put the Schlieren objective in place. Through proper manipulation of knobs (J) and (K) position the first line of the first raster of the objective so that the line passes through the pin-hole, as seen through the eyepiece (G). Bring the line roughly into sharp-one-line focus using knob (H).

(2) With the photometer range knob on "10" observe that, as the line is passed back and forth under the pin hole, the meter needle moves from a background level of somewhere between three and ten on the 0-100 scale to a peak value dependent on the line being read. A contrast ratio (peak-to-background) of 10 to 15 is considered good. By moving knob (J) maximize the reading. Now, by using the fine focus (I), further maximize. Continue adjusting (I) and (J) for a sharp maximum. It may be necessary to cover the eyepiece to keep out spurious light during the fine focusing process.

b. Operating Procedure

(1) Having completed focusing move the slide back, using (J), to a position such that the first line to be read is just to the right of the pin-hole, as seen through the eye piece.

(2) Engage the motor by pushing lever (L) to the right and up. Cover the eyepiece. Start the chart recorder by throwing the chart switch to high. Be sure the chart drive lever is solidly up. The motor is slow starting. Figure A-6, a chart recording, is the result of allowing a slide to run through one raster at a time with

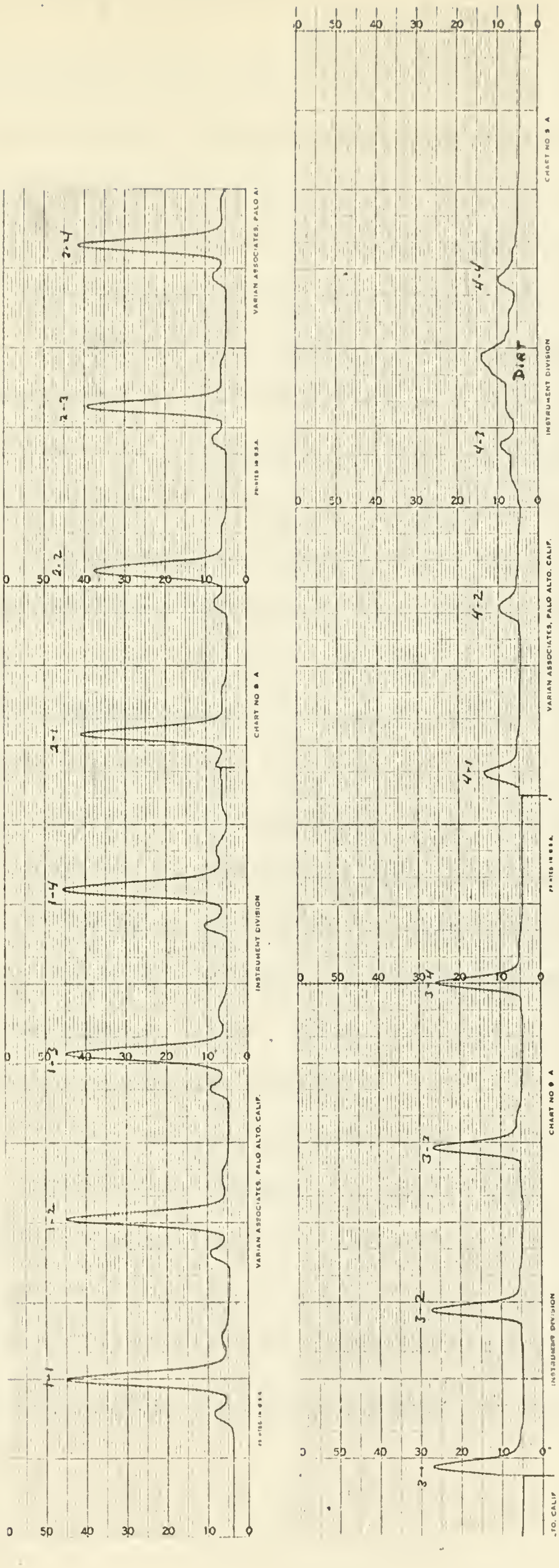

CHART RECORDING OF SLIDE RUN
FIGURE A-6

no action taken between lines. To save time, if there is a large space between rasters, the motor can be carefully disengaged and the slide quickly advanced, using knob (J), to the point where the first line of the second raster is just to the right of the pin-hole. The motor is then reengaged and the next raster read.

(3) The preferred method, and the one deemed to provide the most uniform results, involves the use of a light level calibration between lines. The procedure in (2) above is followed except that as soon as the peak of one line is recorded and the needle has returned to approximately background level, the straight objective is dropped into place (C). This is the reason for the dust calibration in the setup phase. The meter will rise to roughly the value set previously with the sensitivity control. As soon as a level reading is obtained, but before the next line is read, the Schlieren objective is dropped into place for the reading of the next line of the raster.

This procedure is followed for each line of the raster. The calibration reading is taken after the last line, the Schlieren objective is dropped into place for a background level reading, if desired (for contrast ratio), and the procedure for skipping dead spaces between rasters is carried out.

(4) When snapping the motor drive in place the slide carriage may jump. Always check through the eyepiece before starting a run to be sure that the slide is in the desired starting position. When rotating objective lenses, be sure the lens is solidly in position. An error in position will give an obviously high background. When the slide run has been completed, disengage the motor, as it will

drive against the chassis if not disengaged.

5. Plotting the Readings

a. Log/log paper was chosen as the charting medium for the following reasons:

(1) The transfer function, gamma, is directly available.

(2) The function plots as a straight line in unsaturated regions.

(3) The saturation effect is more apparent.

b. Procedure

(1) Figure A-7 is a plot of the values of Table A-1 (on the figure) obtained from a recording using the procedure 4 b (3) above

(2) Having obtained values for each line, as in Table A-1 on Figure A-7, plot the data as follows:

(a) Set a pair of dividers the measured distance between the line peak and the calibration level.

(b) Lay off the set distance along the ordinate corresponding to the raster beam current. Reference the distance to "100", in effect normalizing to one.

(3) Note that this plot will usually show a "spread" averaging 10%. This is due to a number of factors: i.e., dust, non-uniform slide coating and system fluctuations. However, the mean value plot averages the random system errors as indicated by the linearity of the non-saturated portion of Figure A-7.

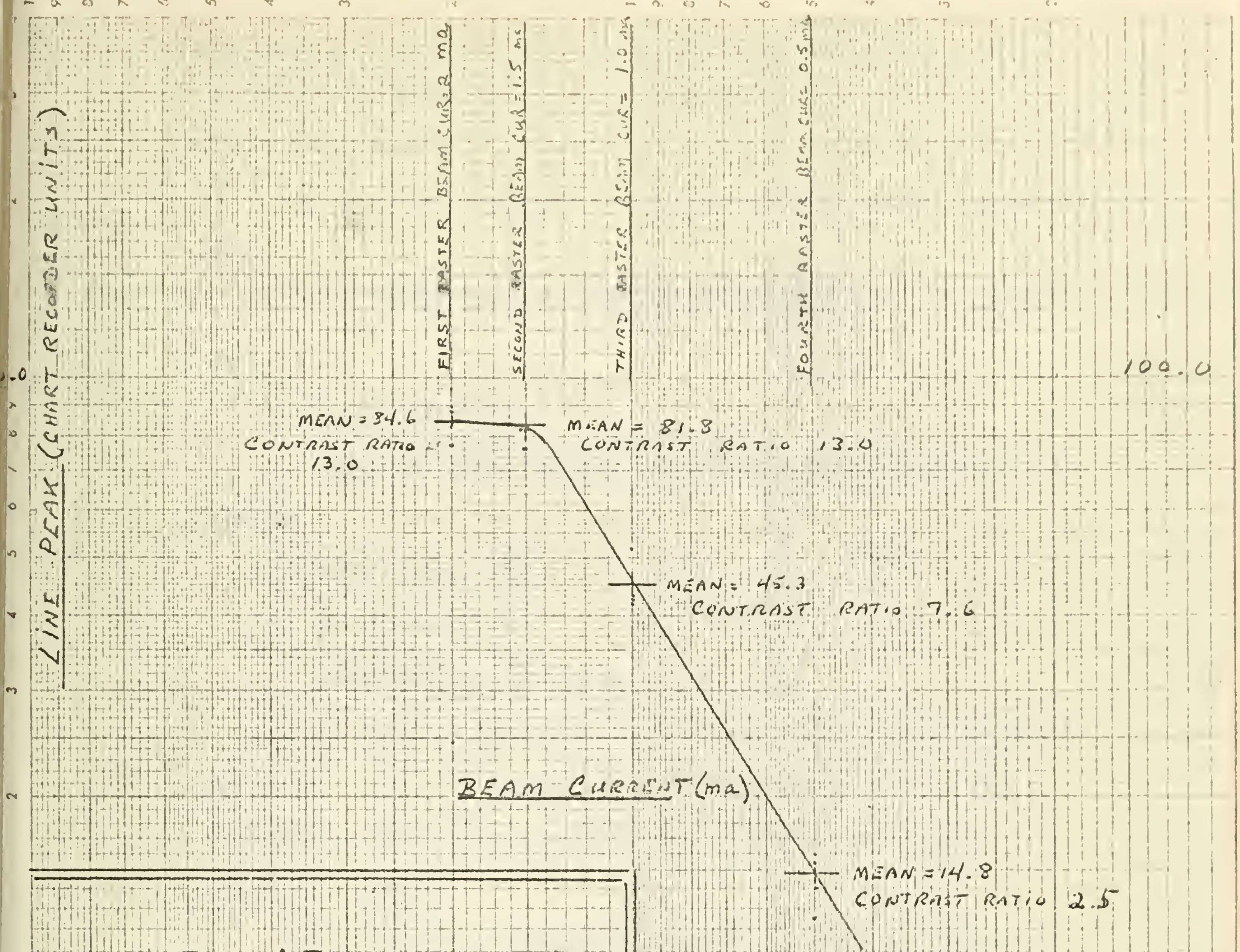

TABLE A-I

PEAK		CALIBRATION LEVEL
81.8	FIRST RASTER	93.0
83.1		95.0
79.6		96.4
74.5		96.5
77.1	SECOND RASTER	94.0
83.5		96.0
76.2		93.0
72.1		95.3
50.1	THIRD RASTER	96.5
40.2		96.0
41.0		97.0
43.0		96.6
13.5	FOURTH RASTER	97.0
15.2		92.5
13.0		93.0
12.0		96.0

FIGURE A-7

PLOT OF DENSITOMETER RECORDING OF FOUR RASTER SLIDE BV-25 SHOWING VARIATION OF LINE PEAK WITH BEAM CURRENT
5 FEBRUARY, 1962

C. Slide Variables

1. Experiments

The variables evaluated as to their effect on line brightness were:

a. Pump down (three slides can be recorded upon per vacuum pump down).

b. Slide thickness

c. Glass uniformity (three slides are cut from the same glass strip)

d. Saturation level

e. Development time.

f. Thermoplastic thickness

Table A-2 is a tabulation of the data obtained for each slide evaluated. The line brightness levels are normalized to 100 as a reference. Each value represents the arithmatic average of four lines in a raster.

The arrangement of these experiments is shown in Figure A-8. The horizontal grouping indicates a pumpdown (labeled p) and the dotted lines, the strips of glass (labeled s), from which the slides were cut. The numbers indicate the numbers assigned to the individual slides. In the first two sets of experiments the vertical rows carry no significance, whereas in the third set the first column are slides with low development, the middle column are slides with normal development, and the last column with greater than normal development. The development times used in the third experiment were 32, 50 and 80 milliseconds, with a power output of 300 watts. This was the same

SLIDE No.	RASTER MEAN PEAK				SLIDE RESISTANCE (OHMS)	GLASS THICKNESS (MILS)	GAMMA	DEVELOP TIME (MS)	BACKGROUND LEVEL
	1	2	3	4					
12	51.8	37.8	20.5	6.8	55	.383	1.60	50	6.0
13	76.0	50.8	29.8	8.6	80	.500	1.60	50	5.0
14	60.5	46.8	28.8	7.8	80	.390	1.65	50	5.0
15	112.0	66.0	36.8	13.2	86	.627	1.55	50	6.7
16				BAD	SLIDE				
17	79.0	56.5	35.5	10.0	80	.460	1.55	50	5.6
18	55.0	42.6	27.5	10.0	59	.390	1.35	50	7.2
19	28.8	21.8	12.8	6.6	56	.383	1.10	50	5.0
20	71.0	60.0	33.5	9.6	54	.418	2.00	50	6.5
21	62.0	43.5	25.5	12.1	60	.453	1.30	50	6.0
22	78.5	62.2	40.5	13.6	51	.383	1.80	50	5.5
23	53.0	54.5	38.0	12.1	55	.453	1.70	50	6.0
24	78.0	60.2	36.8	13.5	50	.418	1.70	50	6.0
25	71.2	62.0	40.0	13.0	58	.383	1.25	50	5.5
26	53.6	48.4	36.3	25.1	150	.453	0.59	80	5.0
27	56.9	56.5	43.6	21.9	100	.453	1.00	80	5.5
28	66.7	59.8	50.7	23.9	81	.453	1.15	50	5.6
29	35.7	28.9	20.6	—	195	.383	0.74	50	5.6
30	64.7	57.6	42.6	27.8	88	.453	.667	80	5.5
31	78.4	71.0	61.5	17.6	94	.418	2.00	50	5.6
32	70.5	66.6	38.5	18.2	78	.418	1.30	32	5.6
33	20.2	13.3	—	—	199	.487	1.50	32	5.5
34	59.6	47.4	27.5	13.5	94	.487	1.20	32	5.5

NOTE: SLIDES 1-11 WERE NOT INVOLVED IN THIS PARTICULAR EXPERIMENT.

TABLE A-2

TABULATION OF EXPERIMENTAL DATA

P-1	BV-13	BV-15	BV-17	S-1
P-2	BV-12	BV-14	BV-16	S-2

FIRST EXPERIMENT

	S-3	S-4	S-5
P-3	BV-19	BV-20	BV-25
P-4	X	BV-22	BV-24
P-5	BV-18	BV-21	BV-23

SECOND EXPERIMENT

P-6	BV-33	BV-29	BV-26	S-6
P-7	BV-34	BV-31	BV-27	S-7
P-8	BV-32	BV-28	BV-30	S-8
	32ms	50ms	80ms	

THIRD EXPERIMENT

KEY: p = pump down
s = glass strip

FIGURE A-8
ARRANGEMENT OF SLIDES

for all slides in this group without compensation for slide resistance. However, in the first two experiments an attempt was made to compensate for variation in slide resistance through the use of series resistors to equalize d.c. development current.

2. Results

Figure A-9 shows the superposition of curves for slides 13, 15, and 17 and demonstrates the scatter using a single strip of glass under the same pumpdown conditions. The variation is apparently caused by slight variations in the resistance of each slide. In group two, Figure A-10 shows the super-position of curves for 19, 20, and 25 and demonstrates the large scatter obtainable with the same pumpdown, but with slides from different strips of glass. Figure A-11 is the super-position of 23, 24, and 25 showing that different pumpdowns with slides from the same glass are very close together.

Figure A-12 is the super-position of 26, 27, and 32 (this set had very high resistance which exaggerated the effect) of progressively increasing development. This in particular can be called the variation of gamma as development is varied.

Figure A-13 which is a super-position of slides 28, 30 and 32 shows a less exaggerated tendency toward a variation in gamma as development is varied, but more graphically shows another effect -- that of a variation in the saturation level with different development. In particular it indicates that with low development, gamma is higher and saturation is higher although the sensitivity is lower. As development is increased, the sensitivity increases raising the amplitude or the brightness of the lines with low exposure, gamma decreases

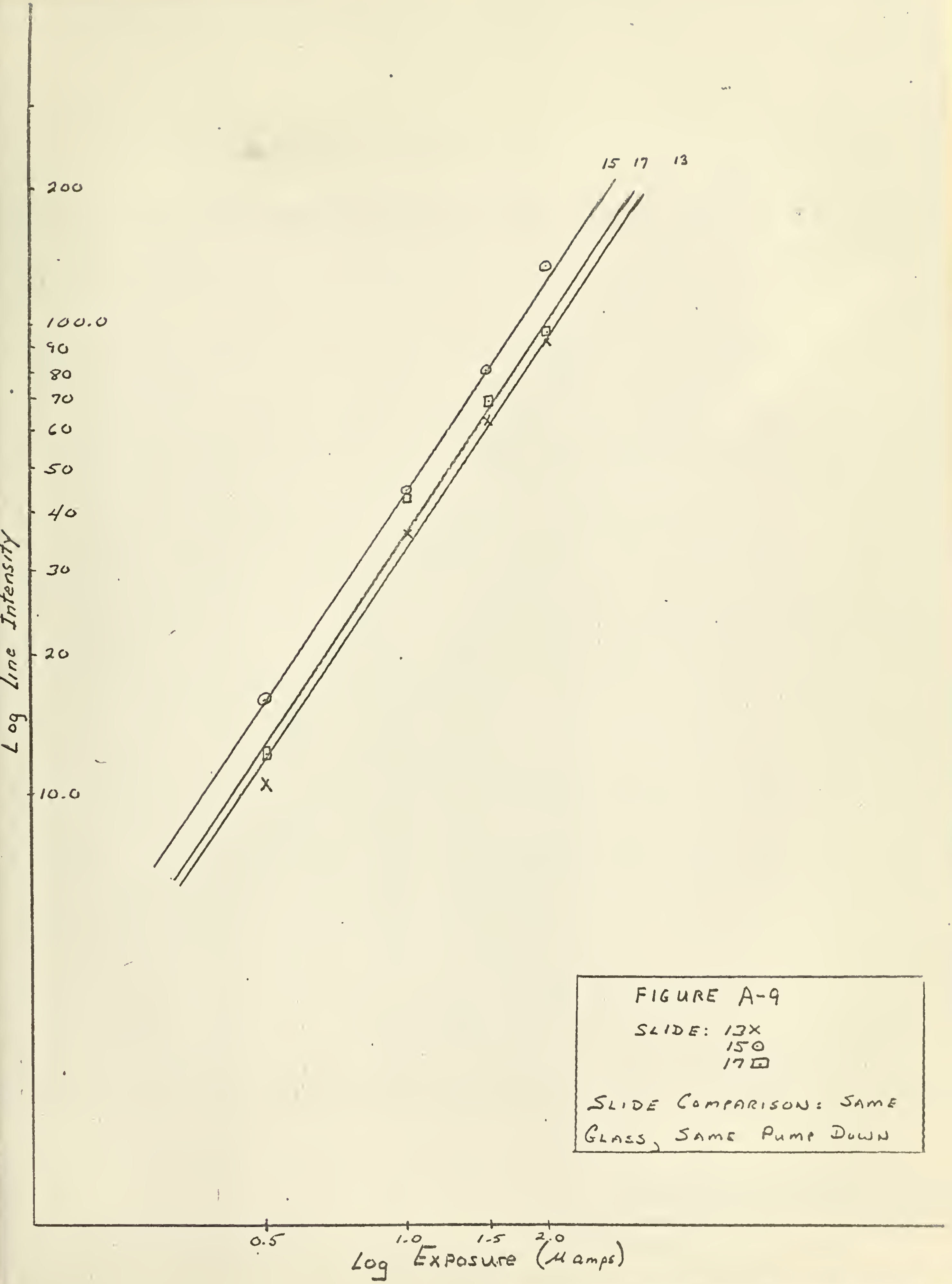

FIGURE A-9

SLIDE: 13X
15O
17▢

SLIDE COMPARISON: SAME GLASS, SAME PUMP DOWN

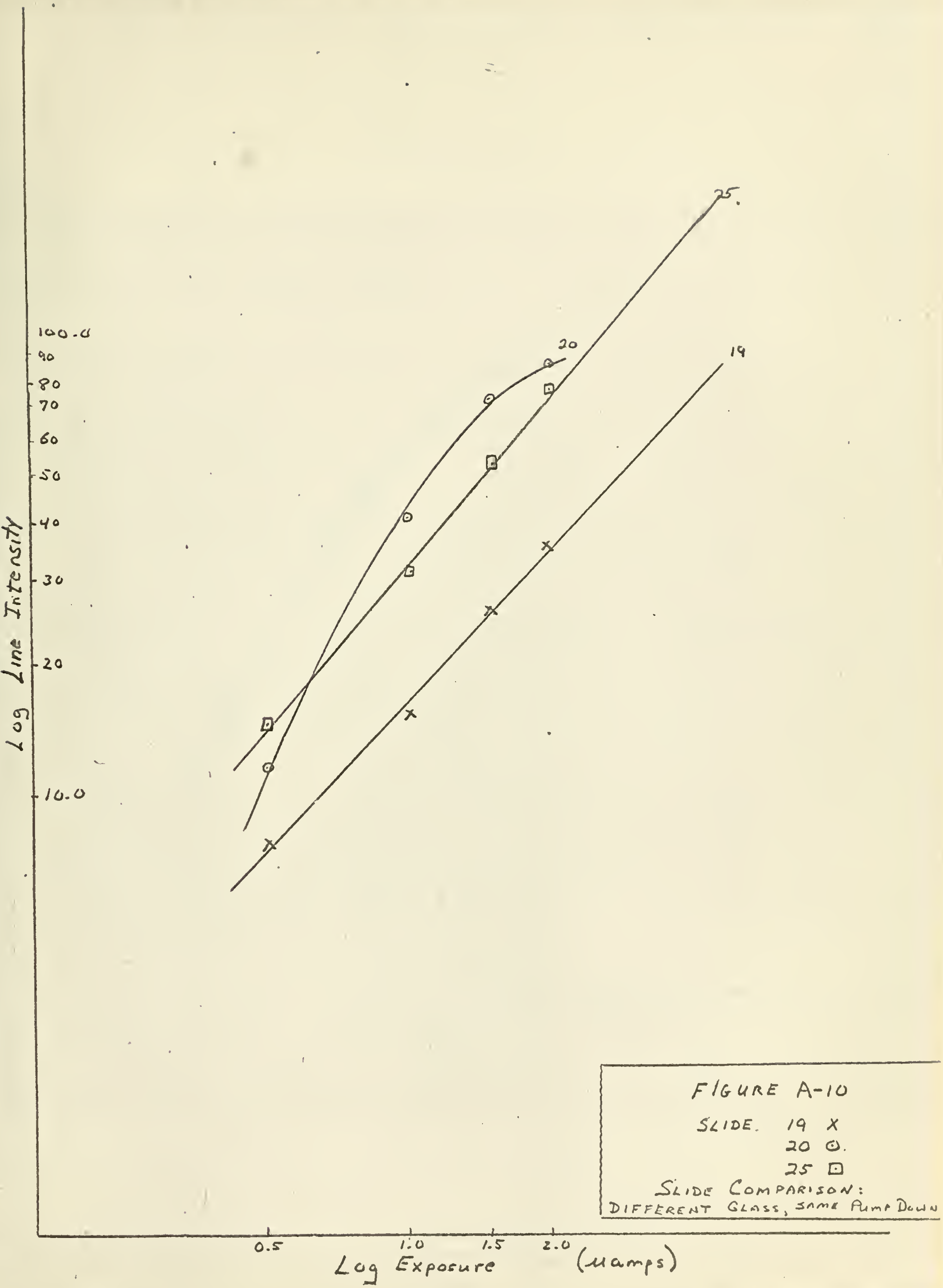

FIGURE A-10

SLIDE COMPARISON: DIFFERENT GLASS, SAME PUMP DOWN

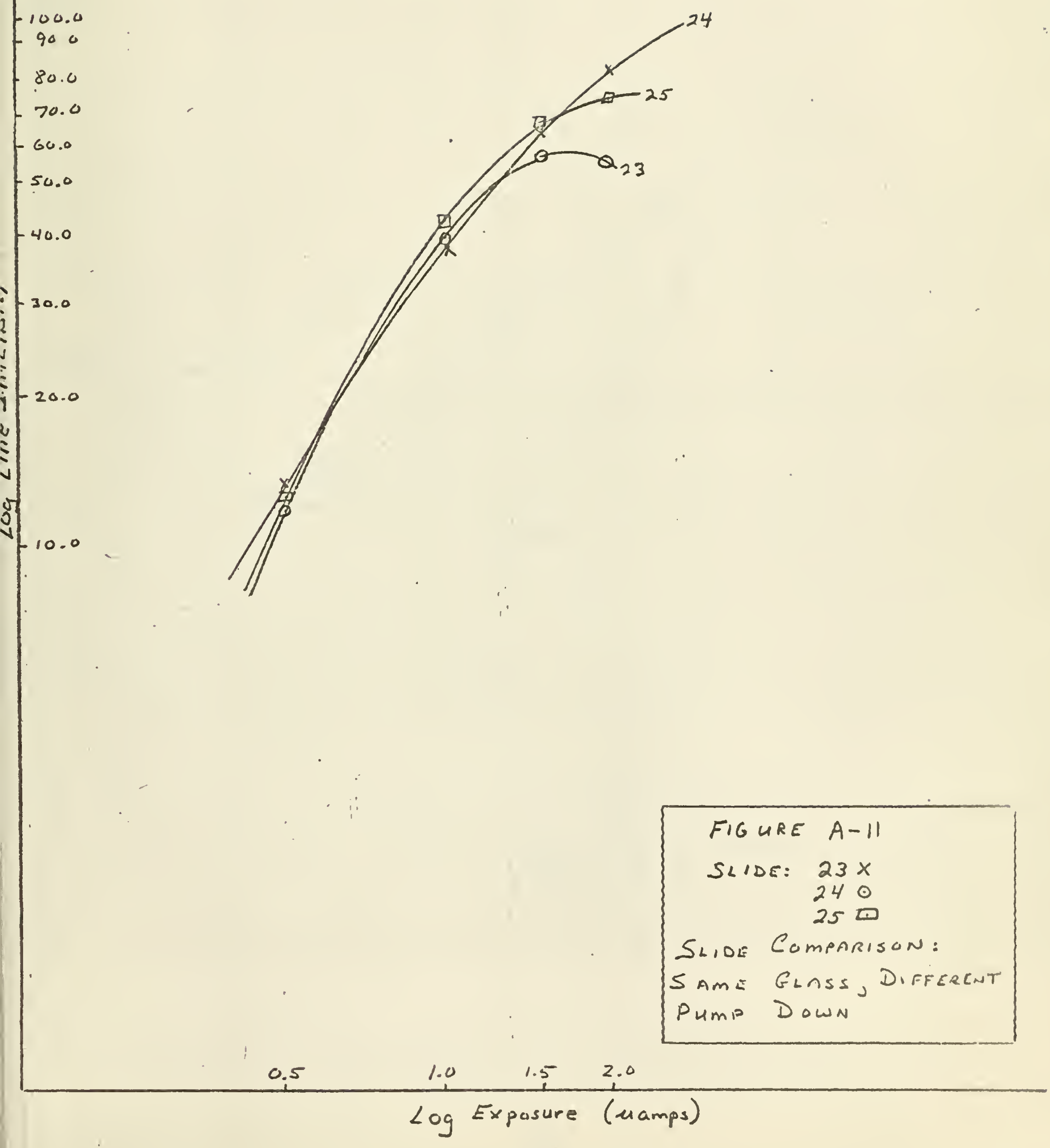

FIGURE A-11

Slide Comparison: Same Glass, Different Pump Down

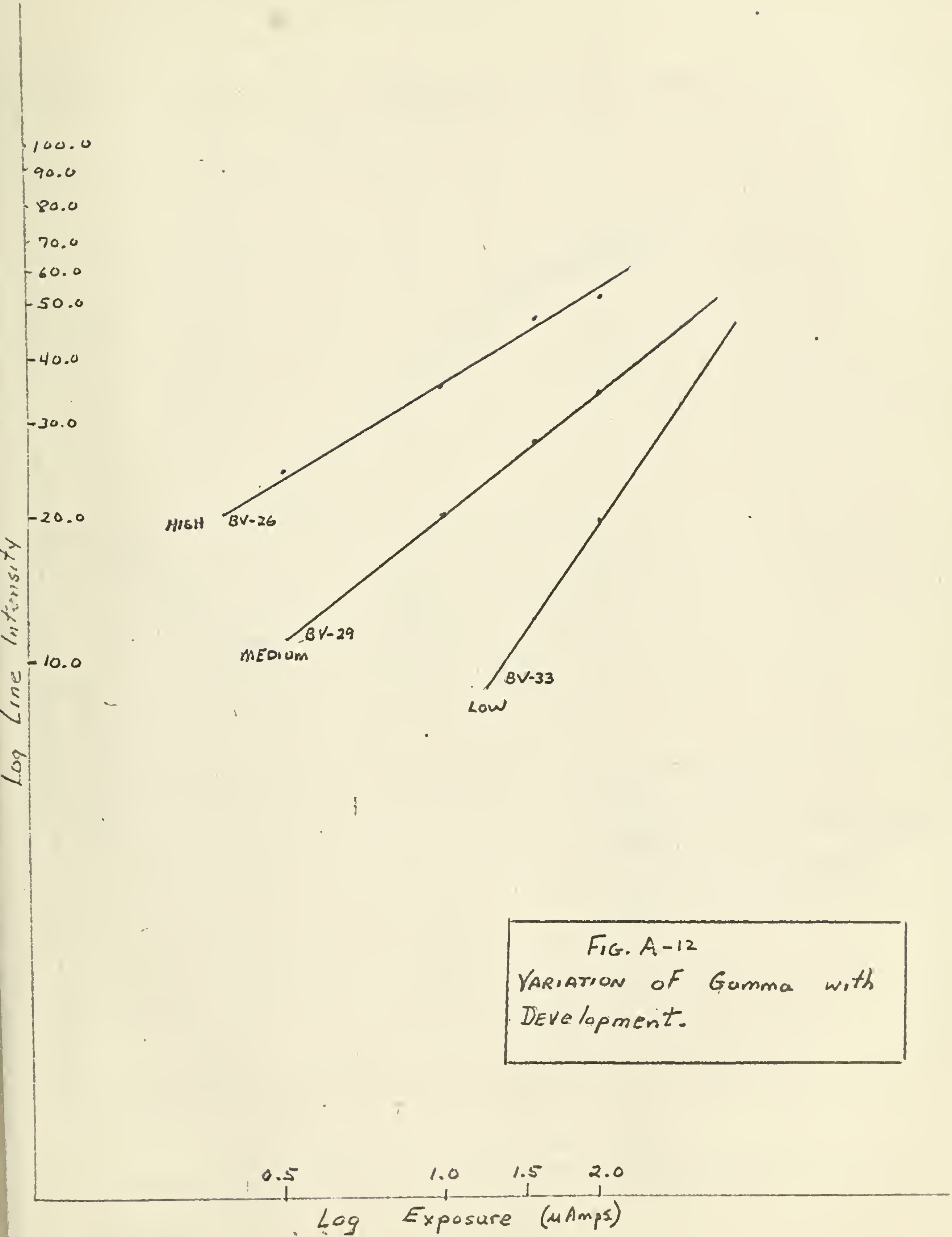

FIG. A-12
VARIATION OF Gamma with Development.

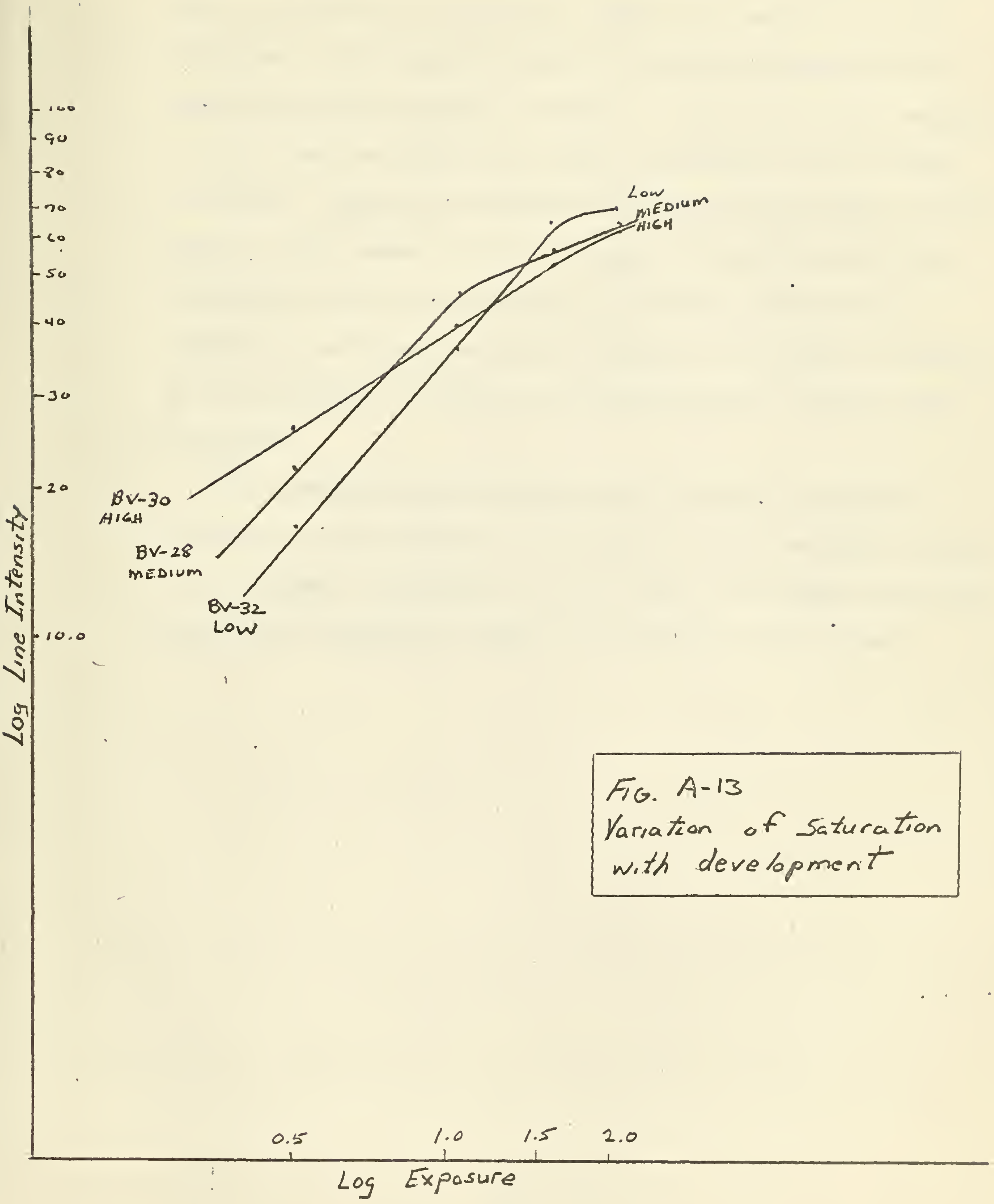

FIG. A-13
Variation of Saturation with development

and saturation occurs at a progressively lower level both in the exposure and the ultimate brightness after saturation. Curves in Figure A-14 which were exaggerated and hypothesized to give "idealized" shape more graphically explain the effects of sensitivity, or the brightness, at low exposures, and the variation of gamma and the saturation point as exposure is varied. It was not at first realized to what extent the different variables contribute to the variations in results. This set of experiments pointed out that further investigation is badly needed. They also appear to show that the initial development curves for compensation of the slide resistance are perhaps not good enough and provide different development; in effect, do not compensate or normalize the development with different slide resistances.

With sufficient experimentation and sufficient progressive improvement in the equipment and tieing down of the variables, including the possible elimination of some of them, it is expected that the sensitometric variation of data can be reduced to 5% or better.

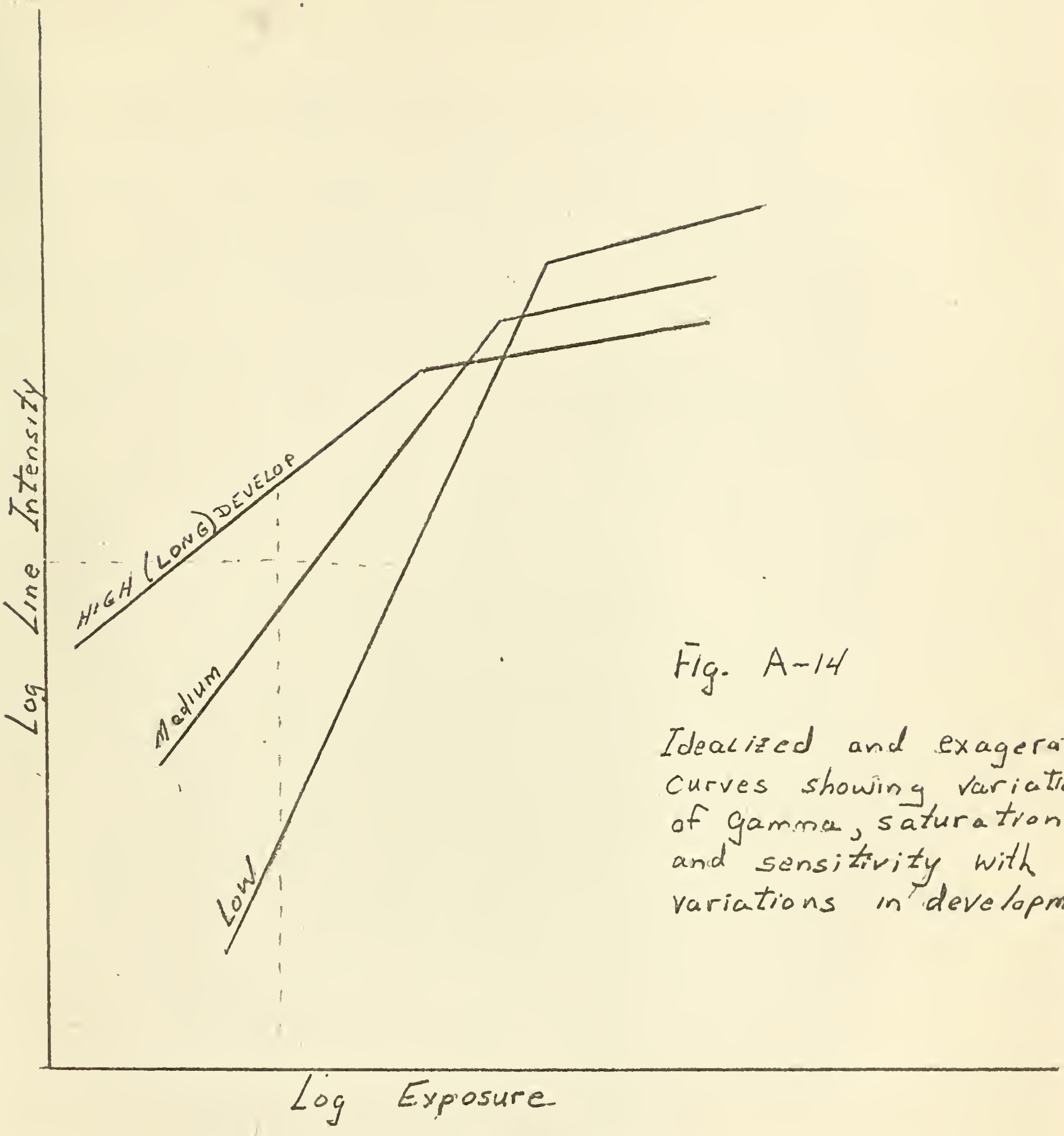

Fig. A-14

Idealized and exagerated curves showing variation of gamma, saturation and sensitivity with variations in development