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AN INVESTIGATION  
OF  
OPTICAL MEMORY TECHNIQUES

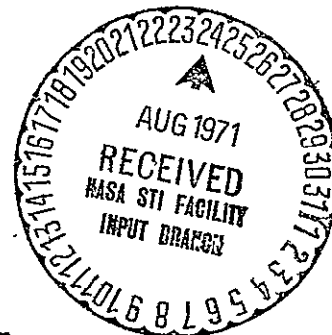
by

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FINAL TECHNICAL REPORT

July 1, 1969 - June 30, 1970

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## SUMMARY

This final report on "Investigation of Optical Memory Techniques", NASA Contract Number NAS 12-2194, covers research progress made during the one-year contract period from July 1, 1969 through June 30, 1970. This contract work was originally performed for NASA Electronics Research Center under the monitoring of Mr. N. Patt before June 1970. It was then transferred to NASA Marshall Space Center and monitored by Mr. G. A. Bailey. Significant research results obtained during this period of study are summarized in the following:

### A. Materials and Physics of MnBi Films

1. Physical properties of both the normal low-temperature phase and the quenched high-temperature phase MnBi films relevant to the optical memory applications and film improvement study were obtained. This includes the temperature dependence of magnetization, resistivity and Hall effect, the wavelength dependence of the magneto-optic Faraday effect and <sup>Optical</sup> absorption.
2. Metallurgical structure of Mn, Bi, Mn+Bi and annealed MnBi were examined under electron microscope. Detailed features relating to grain size, shape and compound formation were obtained.
3. The crystallographic transformation from the quenched high-temperature phase to normal low-temperature phase was identified to be of the nucleation and growth type. Two techniques were advanced to evaluate the activation energy associated with this transformation. The activation energy was found to be approximately 1.0 eV.

4. Experimental study for stabilizing the quenched high-temperature phase MnBi films was performed using doping or alloying techniques. <sup>conducted</sup> Doping by <sup>(or)</sup> NdAu from atomic size consideration and by Te or Ge from enhancing the covalent bonding was found to have no effect on the quenched phase lifetime. However, doping with Mn or Ni to enhance the metallic bonding was found to have a profound effect <sup>of</sup> in improving the quenched film activation energy and lifetime.

5. Uniform MnBi films of 6" diameters were prepared.

B. Optical Memory Experiments:

1. Laser writing, erasing and read-out characteristics of both the quenched and the normal MnBi film were obtained.
2. A differential balanced read-out detection technique was developed which provides the signal-to-noise ratio of greater than 20 at 1 MHz bandwidth.
3. An improved memory exerciser has been completed to accommodate <sup>of</sup> fast exercising 6" diameter films. Experimental result on film uniformity was obtained using this apparatus.
4. Repeated cycling of write-read-erase-read of film over  $10^6$  cycles was performed and no deterioration in read-out signal was detected throughout this experiment.

5. <sup>The</sup> Erasure magnetic field requirement was measured for both quenched and normal films.

6. An experimental <sup>to observe</sup> study of the Curie-point writing mechanism using one laser beam for writing and another for reading has been performed. The dynamic real-time <sup>characteristics</sup> study of spots on MnBi after <sup>a</sup> laser heat pulse indicates a slow recovery of the magnetization with a time constant approaching 10  $\mu$ sec.

7. MnBi memory characteristics were found to suffer no adverse effect under various abnormal environmental conditions including radiation.

#### C. Systems Study

1. An analytical study of the choice of detector under various operating conditions to the read-out signal-to-noise ratio has been completed.
2. An analysis of the effect of misregistration to the read-out signal has been performed.
3. A comparison of various approaches to a  $10^9$ - $10^{11}$  bit optical memory using MnBi has been undertaken. For a near future application, a rotating disc bit-to-bit approach was considered to be most promising.
4. Initial design and calculation including details of required components of a  $10^{9/10}$  bit prototype MnBi optical memory was completed. This system was considered feasible requiring no breakthroughs but only engineering development efforts.
5. Experimental investigation of <sup>and preparation</sup> magnetic holograms using Curie point writing technique on MnBi has been performed and holograms resulting from two beam interference obtained.

## I. Introduction

The objective of this contract research is to investigate the feasibility of utilizing thin films of MnBi for spaceborne optical mass memory applications. There are three major areas of study performed during this one-year research effort. The MnBi materials research has been concerned with acquiring the basic materials properties relevant to the optical memory applications and the improvement of the material. The optical memory experimental part of this investigation serves as a bridge between the materials research and the systems research. This effort was mainly concerned with the memory characteristics of MnBi in regard to the write, read and erase operations. The systems study defines a  $10^9$ - $10^{10}$  bit optical memory system using MnBi and evaluates the feasibility of such a system based on the results obtained in the MnBi materials and optical memory experimental research.

Section II of this report discusses the results on the MnBi materials research. In Section III, the results of the optical memory experiments are present. The system study is presented in Section IV. A brief conclusion of this research effort is given in Section V. Appendix A and B summarize the publications and new technology respectively.

## II. MnBi Materials Research

The objectives of this part of the contract research on optical memory techniques are to investigate materials capable of being repetitively written, erased and non-destructively read by optical means for a spaceborne  $10^{10}$ - $10^{12}$  bit memory and to determine the basic requirements on MnBi as it relates to the proposed optical memory system, with emphasis on the material parameters most affecting the storage or retention of data.

Progress made and results obtained on the materials investigation of MnBi film during the one-year investigation towards this objective are reported in this section.

### A. Physical Properties of MnBi Films

The goals for investigation of the physical properties are:

- (1) To obtain the physical properties directly related to the optical memory applications for detailed evaluation of the suitability of the storage medium;
- (2) To provide necessary material parameters as functions of operating wavelength, temperature and other variables for systems trade-off study and
- (3) To obtain basic understanding of the physics of the material to guide the material improvement effort in achieving a more suitable storage medium for the intended spaceborne optical memory application.

MnBi has two crystallographic phases. Both the normal low temperature phase and the quenched high temperature phase are found to be useful for our intended application. Therefore, physical properties were obtained for both phases.

## 1. Magnetic Properties

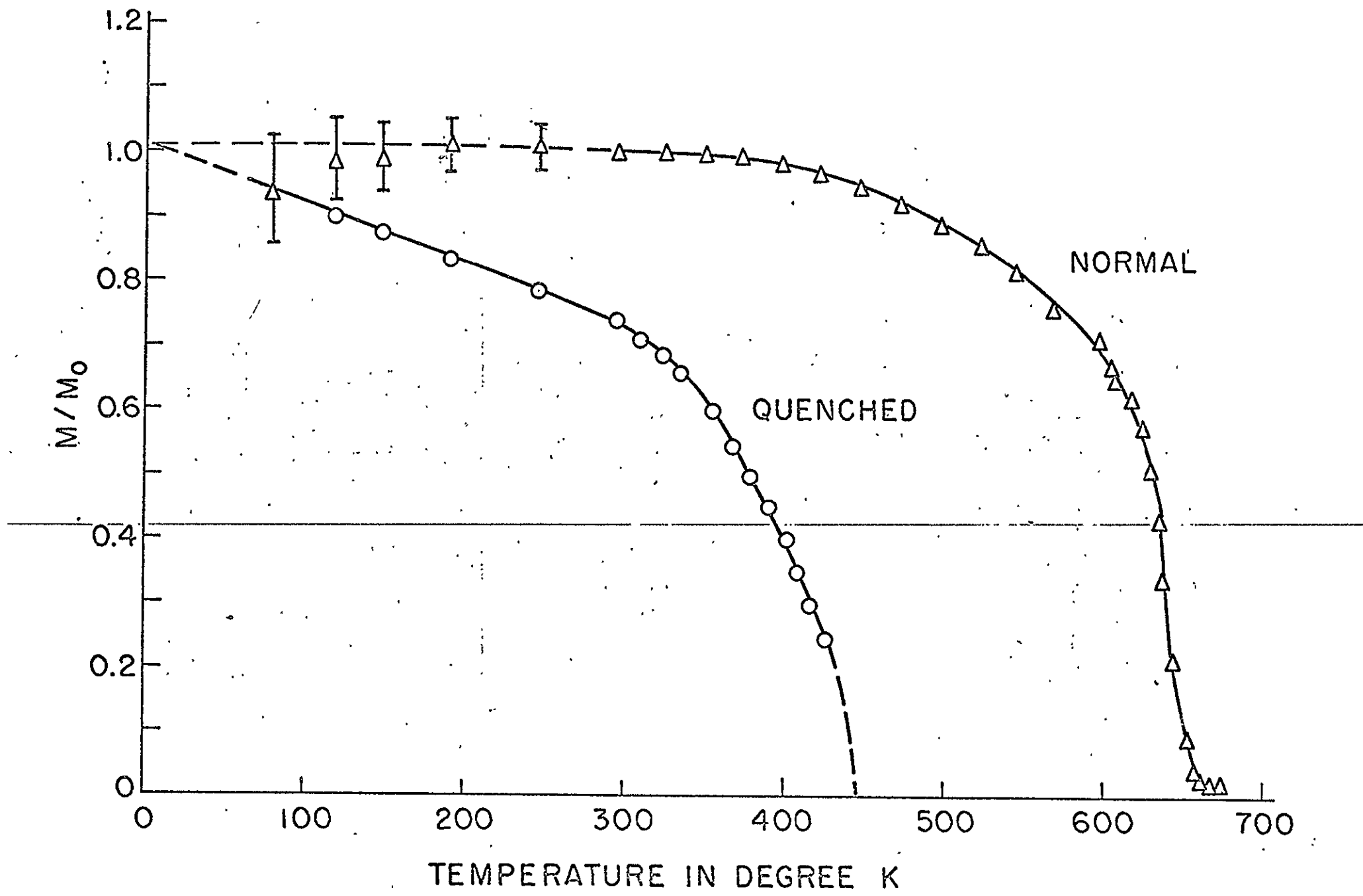
**(a) Magnetization:** The temperature dependence of the magnetization provides not only the knowledge of the required condition for Curie point writing, but also the basic knowledge of ferromagnetism in the medium. The saturation magnetization was measured from  $30^{\circ}\text{K}$  to  $680^{\circ}\text{K}$ . The measurement technique is discussed in the third quarterly report.<sup>(1)</sup> The results are shown in Fig. II-1. There are four main conclusions that we may draw from these results:

(1) The Curie temperature of the normal low temperature phase (l.t.p.) and quenched high temperature phase (h.t.p.) are  $360^{\circ}\text{C}$  and  $180^{\circ}\text{C}$  respectively.

(2) The transition near Curie temperature is <sup>a</sup>gradual rather than abrupt changes.

(3) The magnetization for both phases <sup>(extrapolated to 0 K)</sup> are about equal at  $0^{\circ}\text{K}$ , and corresponds to approximately  $4\mu_{\text{B}}$  per Mn ion in the lattice site.<sup>1</sup>

**(b) Magnetic Hysteresis:** The magnetic coercive force  $H_c$  and saturation magnetic field  $H_s$  characterizes the magnetic hysteresis of the MnBi film. In the optical memory experiment, an erasure magnetic field must be applied in coincidence with the laser beam heating to above the Curie temperature to effect an erasure. The unheated region should not be affected by the applied field. It is therefore necessary to require a coercive force higher than the erasure field. In MnBi the erasure field is about  $500\text{ Oe}$  from demagnetization field calculation as well as from the experimental result. (This will be discussed in Section III). Typical magnetic hysteresis curves of the l.t.p. and h.t.p. MnBi films are shown in Fig. (II-2).<sup>(2)</sup> The magnetic easy direction in both cases remains perpendicular to the film plane, an ideal orientation for optical memory applications.



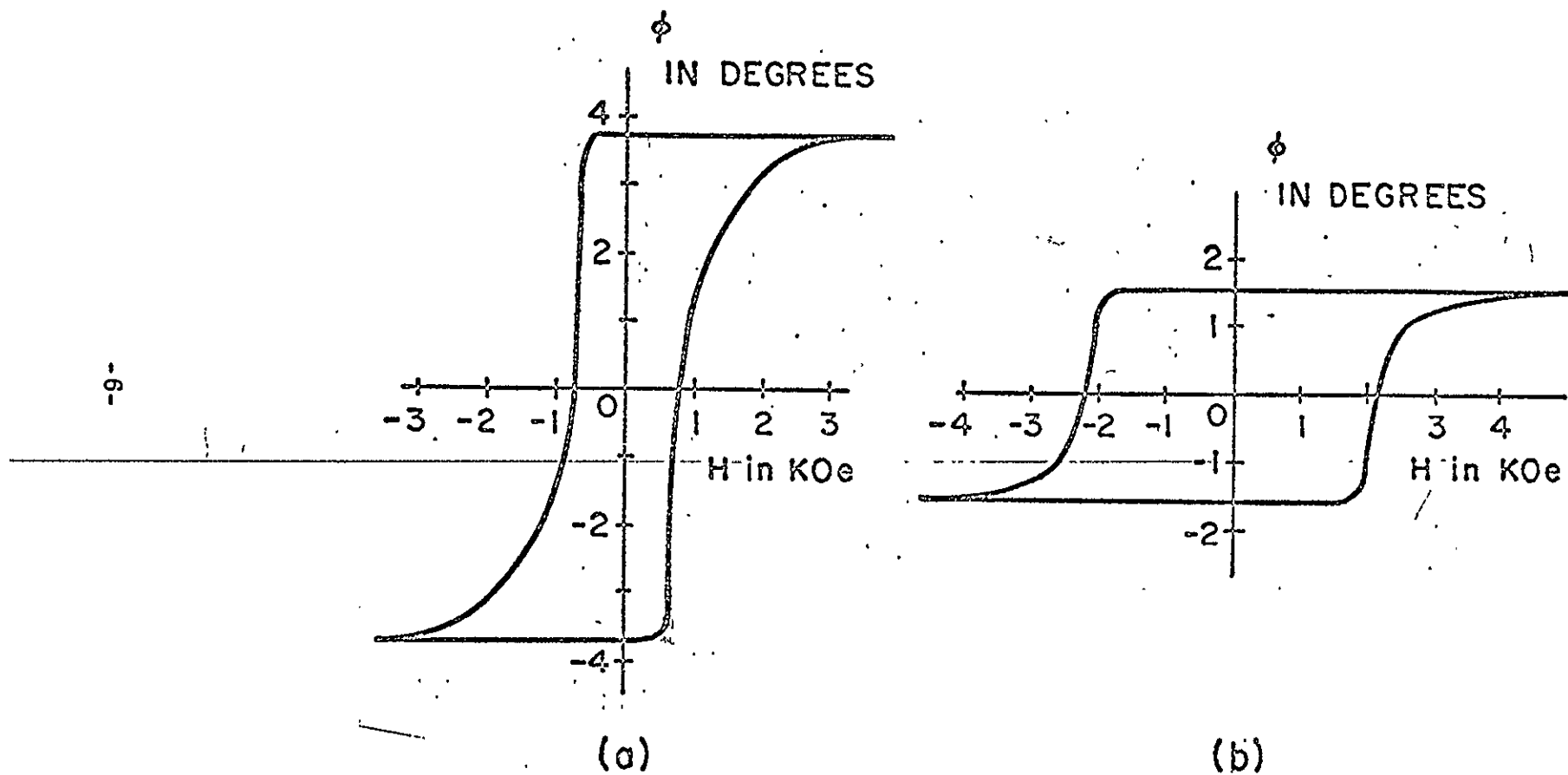


Figure II-2. Magnetic hysteresis as measured by Faraday rotation  $\phi$  for a typical MnBi film; (a) before quenching, and (b) after quenching

## 2. Optical Properties

The optical absorption and magneto-optic Faraday effect were measured over the visible wavelength region, for both the normal l.t.p. and quenched h.t.p. MnBi films. The optical absorption is characterized by the absorption coefficient  $\alpha \text{ cm}^{-1}$  as defined by the Beer-Lambert Law. The specific Faraday rotation  $F$  was measured at magnetic saturation and is given in degrees per cm.<sup>(3)</sup> The useful figure of merit  $2F/\alpha$  is then given in degrees.<sup>(4)</sup> These are plotted in Fig. (II-3). It is seen that the Figure of Merit for normal films is about a factor of two larger than the quenched film at 6328 Å HeNe wavelength. The figure of merit of 3 degrees in the visible wavelength for MnBi represents the highest value in any room temperature magneto-optic materials.

## 3. The electric conductivity and Hall effect:

The knowledge of the electronic transport mechanism in MnBi is not complete at present. However, from the temperature dependence of the resistivity and Hall effects some quantitative understanding can be obtained. These results are useful in providing the needed information to guide our study of the phase transitions in MnBi.

### (A) Resistivity:

The temperature dependence of the resistivity was measured on an MnBi film sample before and after quenching. Typical resistivity results are shown in Fig. (II-4).<sup>(1)</sup> The sample was initially prepared in its quenched phase. Upon heating to beyond 220°C the result is essentially the same as that for a normal phase. Transformation from the quenched phase to normal phase takes place gradually in the temperature region between 120°-220°, as can be seen from the figure. Some of the interesting features of this result are:

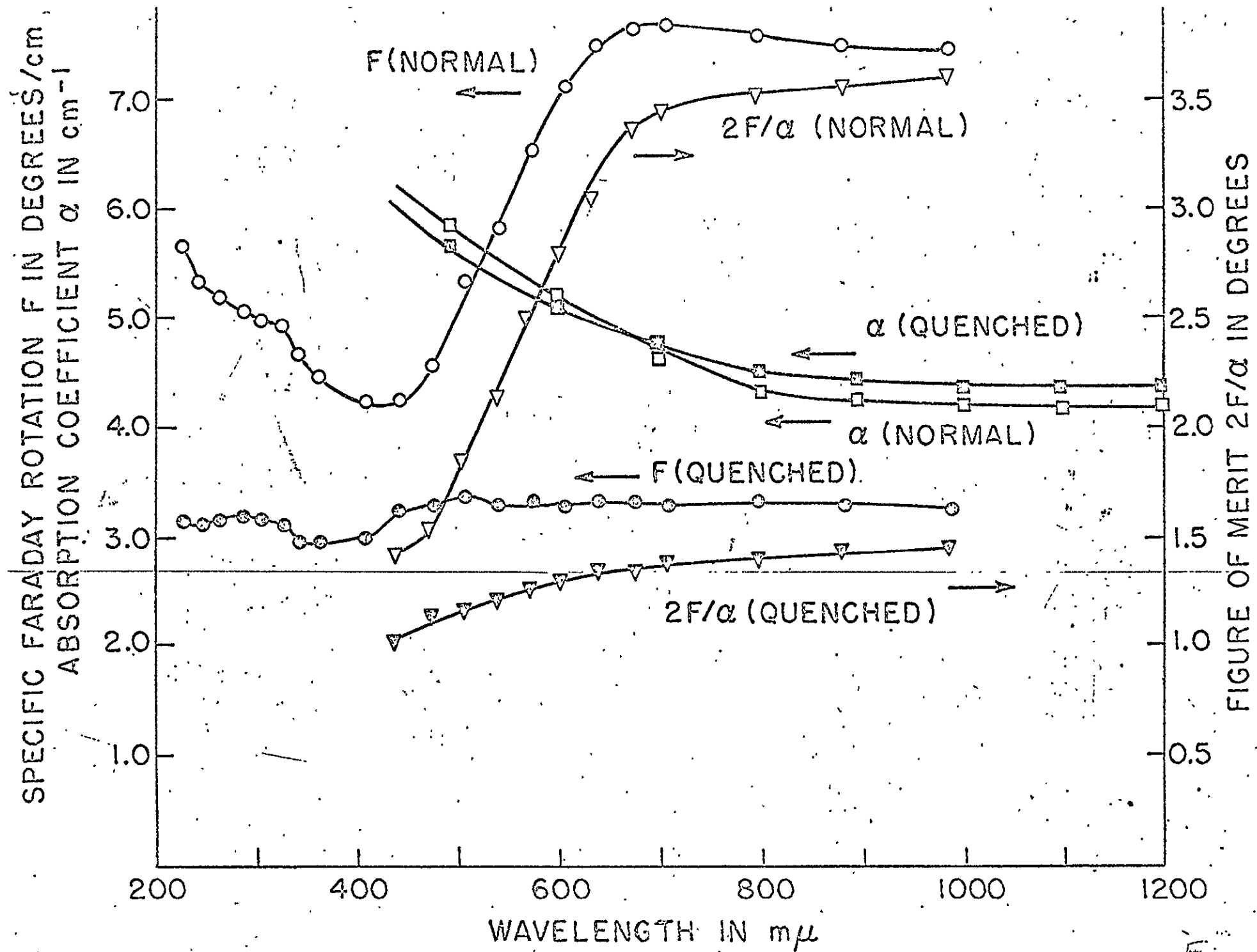
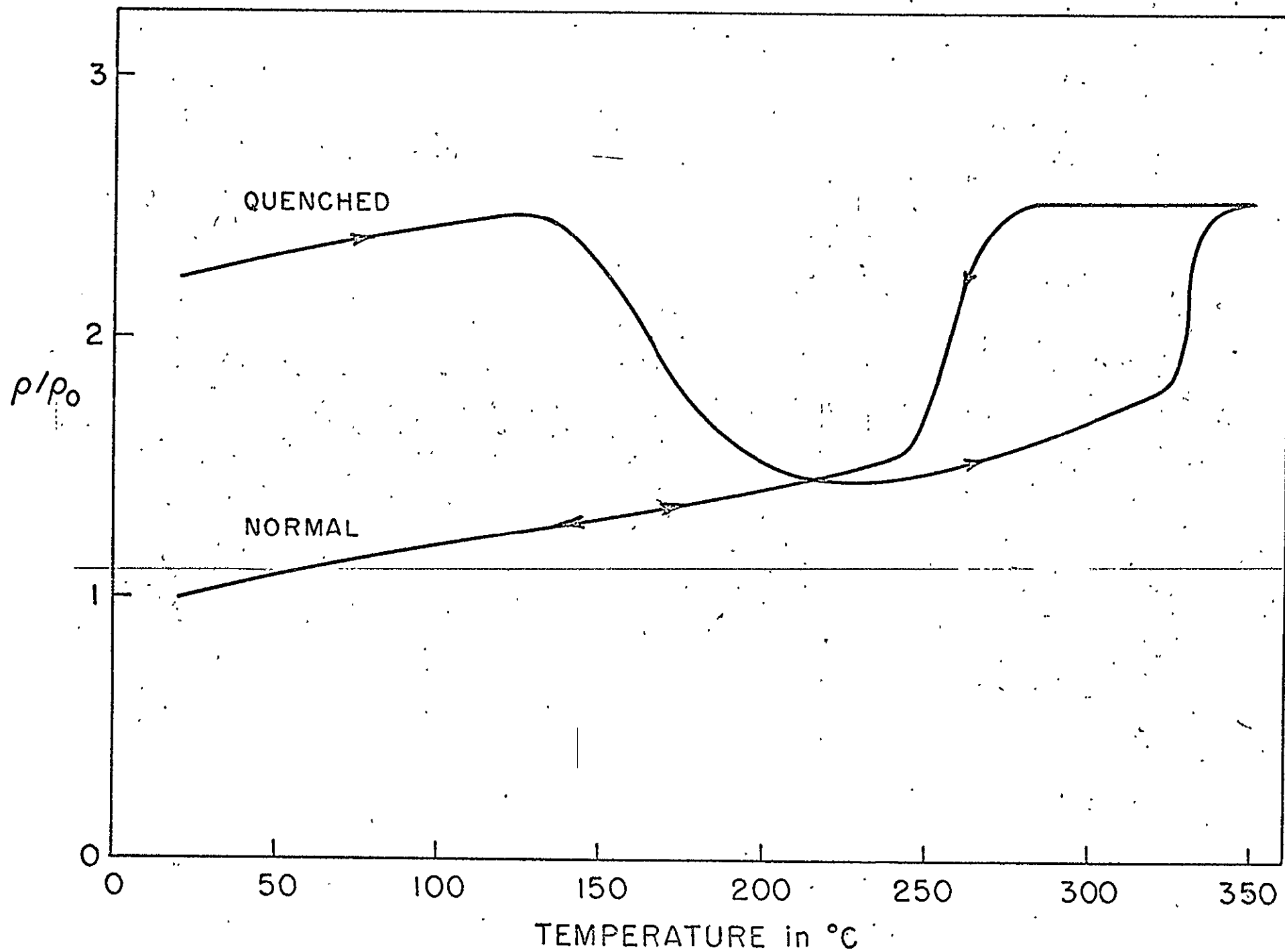


Fig. II-3



(A) ~~The~~ resistivity increases linearly with temperature for both the h.t.p. and l.t.p. below their respective transition temperatures, a characteristic of metallic resistivity. The slopes of the resistivity vs temperature curves are approximately the same for both cases.

(B) An increase in resistivity accompanies the phase transition from l.t.p. to h.t.p. by about a factor of two at room temperature. This could account for the disproportionately lower writing threshold power in the quenched phase if we assume the Wiedemann-Franz law to apply to thermal conductivity of MnBi.

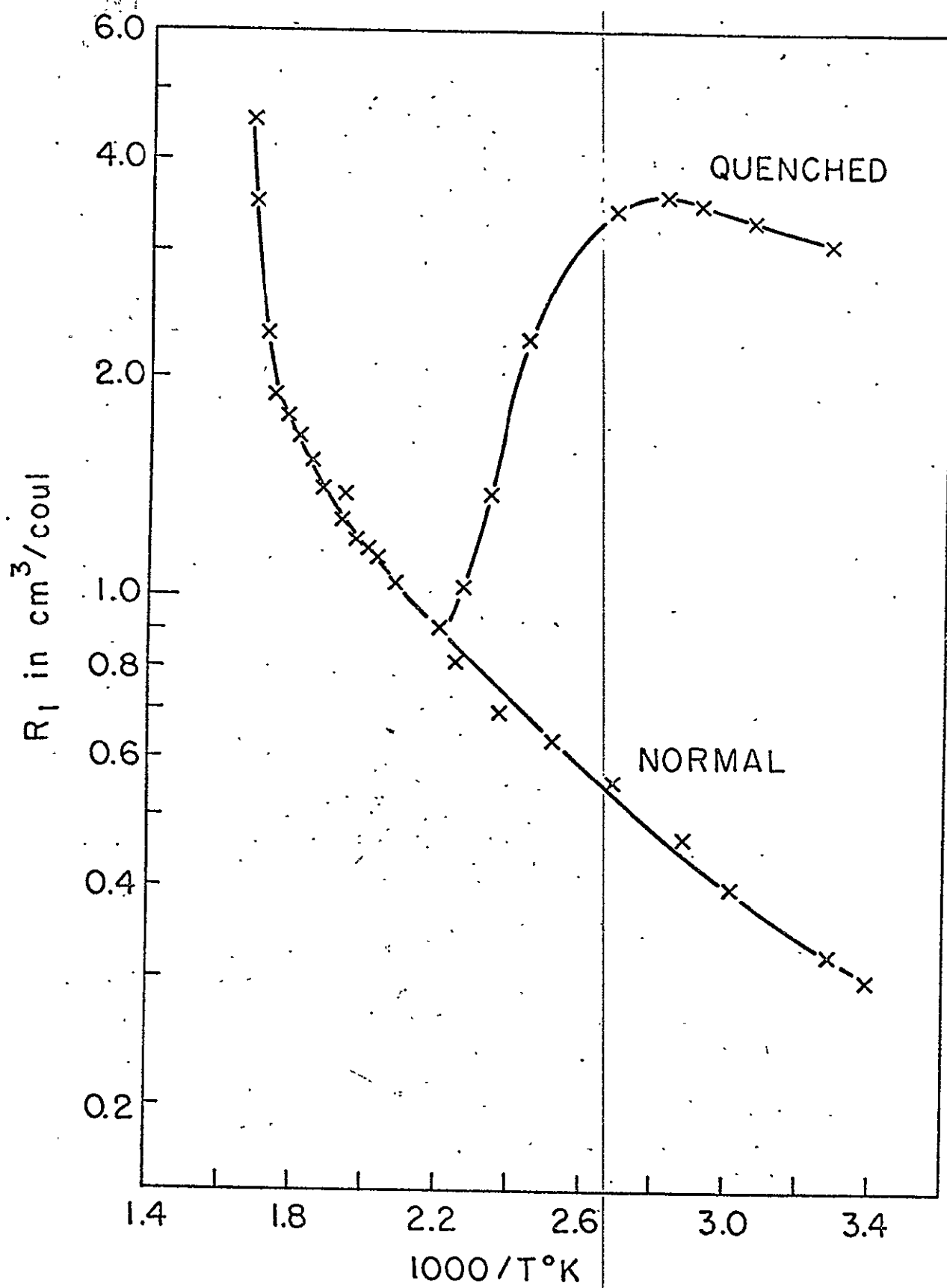
(C) The resistivity of the h.t.p. before transforming back to the l.t.p. around 300°C is approximately constant with temperature, a possible semi-conducting behavior.

These results suggest that the interstitial Mn atoms play an important role in the resistivity of the MnBi film in the phase transition. We will discuss further on this in a later subsections.

## b) Hall effect

The Hall effect of both the l.t.p. and quenched h.t.p. samples of MnBi have been measured. The Hall resistivity is given by  $\rho_H = R_0 H + R_1 M$  where  $R_0$  and  $R_1$  are the ordinary and extraordinary Hall coefficients and  $H$  and  $M$  are the applied field and magnetization respectively. At room temperature the measured value of  $R_1$  and  $R_0$  are  $0.3 \text{ cm}^3/\text{coul}$  and  $0.7 \times 10^{-3} \text{ cm}^3/\text{coul}$  respectively. This  $R_0$  value gives rise to a hole density of  $10^{22} \text{ cm}^{-3}$ , similar to the reported value obtained in MnSb and MnAs. (5) The temperature dependence of  $R_1$  is shown in Fig. II-5. Because of the extremely low values of  $R_0$ , its temperature dependence cannot be accurately obtained without extensive refinement in the measurement technique. ~~Recent theoretical analysis gives~~

The significant result can be summarized as follows:



- (1)  
(a) The positive value of Hall resistivity indicates that conduction is by positive holes.
- (2)  
(b)  $R_1$  increases with temperature. However,  $R_1/\rho^2$  is nearly a constant as predicted by Karpläs and Luttinger's theory.<sup>(6)</sup>
- (3)  
(c) The hole density corresponds to approximately one carrier per unit cell of MnBi.

#### B. Metallurgical Studies of MnBi Films

The basic materials study is an essential part of this contract research. The goals of this study are:

- (1) To obtain the metallurgical structure of MnBi films in order to provide information for improved understanding of the physical properties of the compound.
- (2) To investigate the process of the compound formation during the heat treatment. The results so obtained is essential in guiding the future material improvement study.
- (3) To obtain the basic mechanism of the phase transformation between the high temperature phase and low temperature phase, and to suggest methods for stabilizing the desired phase based on the results of this study.

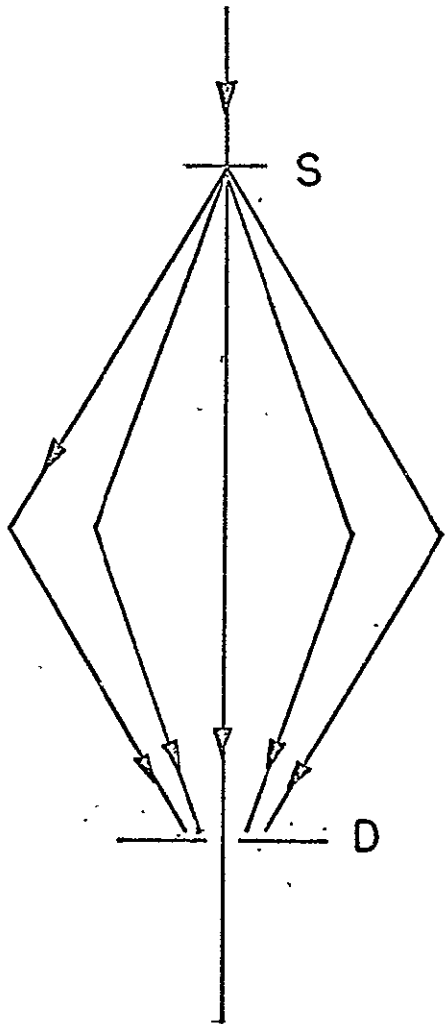
We have performed experimental investigation toward these goals during the one-year research effort. Import progress has been made in this time period. However, not all the results are considered conclusive at the present time. Since this part of the study is directly related to the future material improvement effort, it should be continued in the future.

~~Metallurgical Structure of MnBi Films~~  
I. Structural Study of MnBi Films

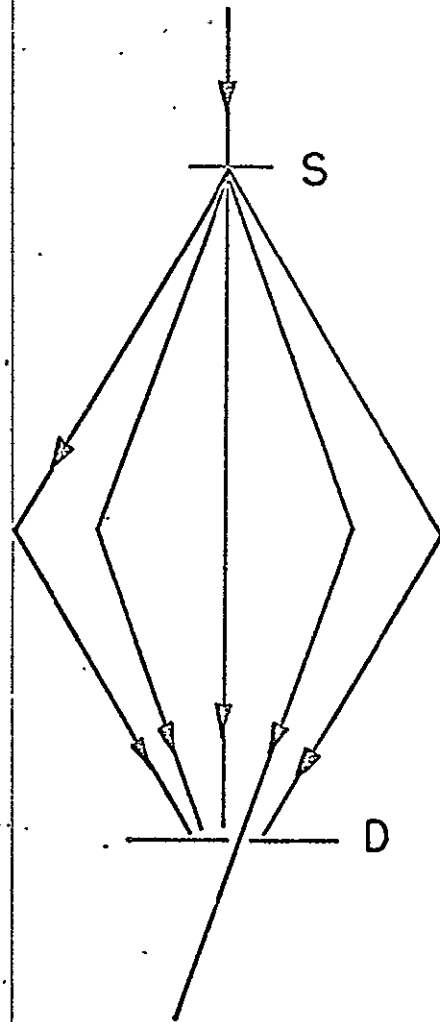
a) Experimental Procedures

A detailed ~~structure~~ <sup>the structure of</sup> observation was made on MnBi films using high resolution electron microscopy ~~technique~~. We have developed a special technique to produce MnBi film specimens which are transparent to electron beams enabling us to examine their structure by transmission electron microscopy. This technique involves the omission of the over coating SiO layer and the addition of a carbon under coating on the substrate before the evaporation of Mn and Bi components. The use of the carbon intermediate layer facilitates the stripping of unsupported MnBi films for observation using an electron beam operating at 100 KV. To assure that the introduction of carbon does not <sup>alter</sup> ~~interfere with the~~ <sup>structure and</sup> properties of MnBi, we have prepared films on <sup>a</sup> substrate which was partially covered with <sup>an</sup> amorphous carbon layer. The MnBi films thus prepared were examined under polarized light using the Faraday effect. We found that the magnetic domains to be continuous and homogeneous crossing from the region with underlying carbon film to the uncoated region. Based on this observation, we believe that the structure of the MnBi film specimens is not affected by the carbon undercoating. We have used the same technique to prepare samples of Mn films on glass for structure observation with good results.

<sup>examination</sup> The MnBi/carbon/glass samples were used extensively for structure <sup>al</sup> observation of normal phase MnBi. To obtain MnBi films with mixed quenched and normal phases, a single crystal NaCl substrate was used. Specimens after quenching can be stripped without a great deal of difficulty. The MnBi/carbon/glass samples are not suitable for this purpose because of <sup>Carbon</sup> oxidation of carbon during the heat treatment to achieve the quenched phase. Selected area electron diffraction patterns were taken on regions under investigation. Information can thus be obtained on the identification and crystallographic orientation of the phases present. The use of electron diffraction spots in conjunction with dark field imaging was especially useful in identifying specific phases. In this imaging technique a diffracted beam was selected for imaging instead of the direct beam. Ordinarily, this can be effected by tilting the electron gun slightly to avoid <sup>or</sup> deformed image. The RCA <sup>electron microscope</sup> instrument used in our experiments does not have this capability. Dark field imaging was effected by using a selector diaphragm, as shown in Fig. II-5. In dark field, the contrast producing beam is known unambiguously. This provides positive identification of the phases. On the other hand, in bright field imaging where several beams may contribute, positive identification would be more difficult.



(a)



(b)

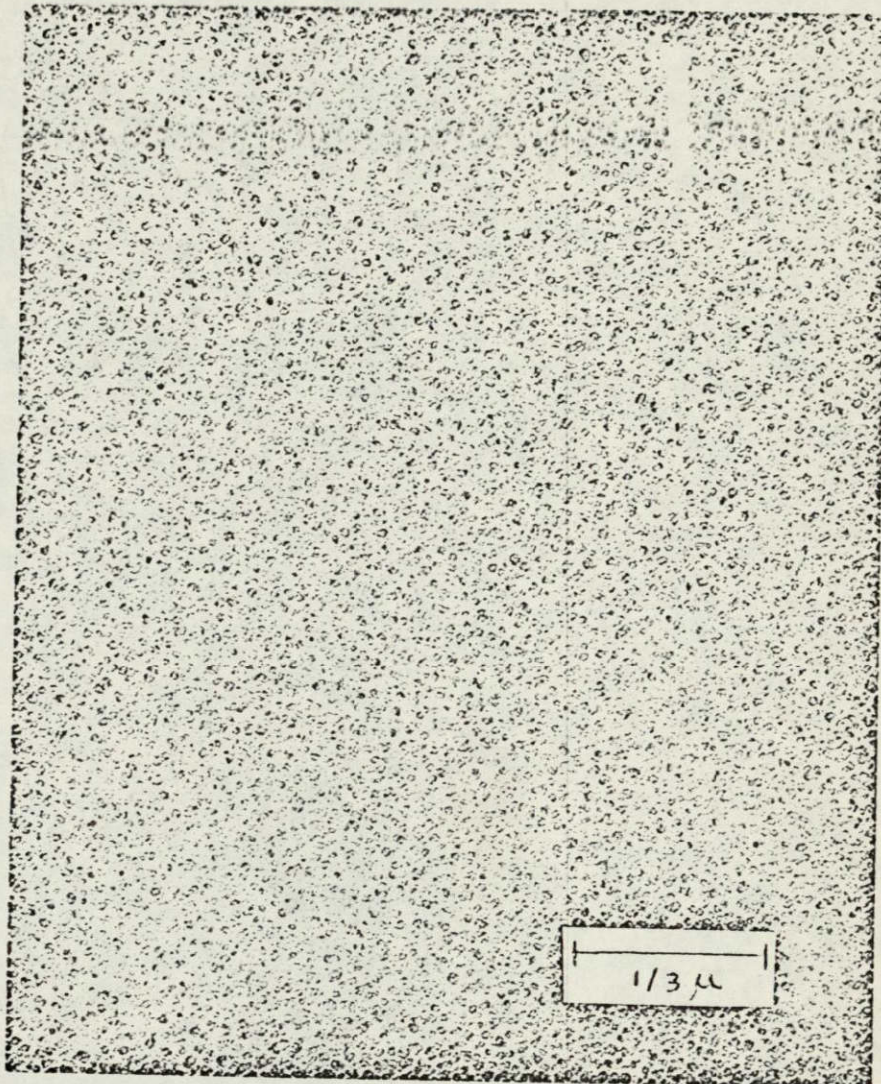
b) Experimental Results

MnBi films were prepared by annealing layers of Mn and Bi films to effect a solid state reaction. Structure of the resultant MnBi film can be profoundly influenced by the structural and crystallographic orientation of the original Mn and Bi films. It is therefore necessary to examine films of Mn, Bi, ~~Mn+Bi~~ and unannealed Mn+Bi in addition to annealed MnBi thin films. Fig. ~~II-7~~<sup>II-9</sup> depicts Mn film deposited on a carbon substrate. The average grain diameter is found to be 260Å. For bismuth deposited on glass under similar conditions as used for Mn deposition, the average grain size was found to be approximately 1300Å, as shown in Fig. ~~II-8~~<sup>II-9</sup>. ~~After vapor deposition and before MnBi film on glass substrate is shown in Fig. II-8.~~ <sup>A film observed but</sup> Here the large Bi grains overshadow the nearly amorphous Mn film. Electron diffraction of this film showed no evidence of any MnBi at this stage.

The as-annealed MnBi film is shown in Fig. ~~II-9~~<sup>II-10</sup>. This should be compared with Fig. ~~II-8~~<sup>II-10</sup>, which depicts a replica on etched MnBi film prepared under identical conditions. Grains are more apparent in Fig. ~~II-9~~<sup>II-10</sup>. This is due to the fact that the etchant used selectively attacks the MnBi grain boundaries. Grain size ranges from below 1000Å to 3000Å. This is evident also in Fig. ~~II-10~~<sup>II-11</sup>. Fig. ~~II-11~~<sup>II-12</sup> shows a typical electron diffraction pattern for this MnBi film. From this, it is observed that while the film is primarily MnBi, the presence of both manganese and bismuth are still evident. The extensive Moire pattern in Fig. ~~II-10~~<sup>II-12</sup> is noteworthy. This indicates either a small difference in crystallographic plane spacing or a difference in orientation between layers. Due to the similarity of crystal structure between bismuth (rhombohedral, which can be considered hexagonal) and MnBi (nickel arsenide type, also hexagonal) the Moire pattern could be due to the epitaxy of these crystals on glass. On the other hand, slight misorientation in MnBi crystals over one another could also produce this type of Moire pattern.

Quenching MnBi films deposited on single crystal NaCl substrates resulted in mixed quenched and normal MnBi phases. Fig. ~~II-12~~<sup>II-13</sup> depicts a specimen thus obtained. In general, a characteristic boundary well defined on one side and diffused on the other side is noticed. Since this boundary is not found in normal MnBi phase specimens, we believe it separates the quenched from the normal phase MnBi. Due to the small difference in crystal structure between these two phases, it is not possible at present to positively distinguish between the two phases using electron diffraction patterns.

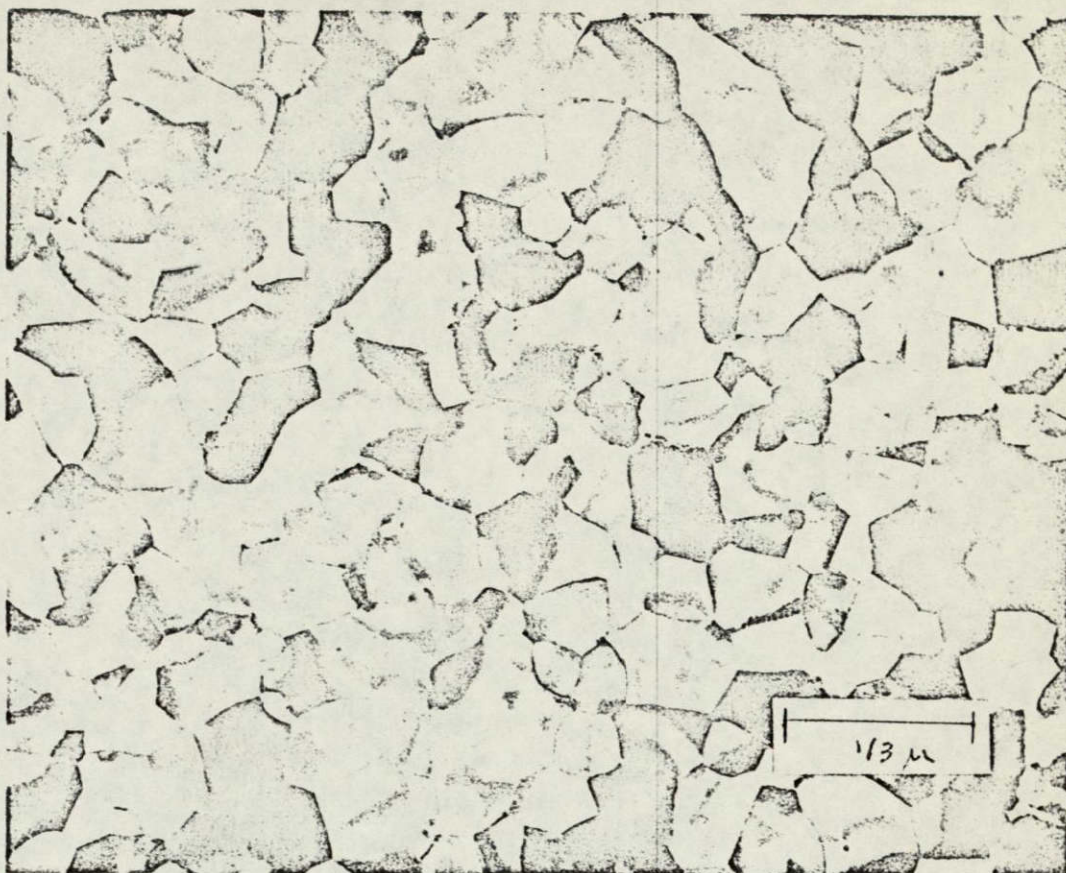
Laser damage in MnBi films was studied by purposely heating a 1 to 2μ diameter spot of MnBi to above its decomposition temperature with a focused laser beam. Fig. ~~II-13~~<sup>II-14</sup> displays an array of four of these spots at 18,150X.



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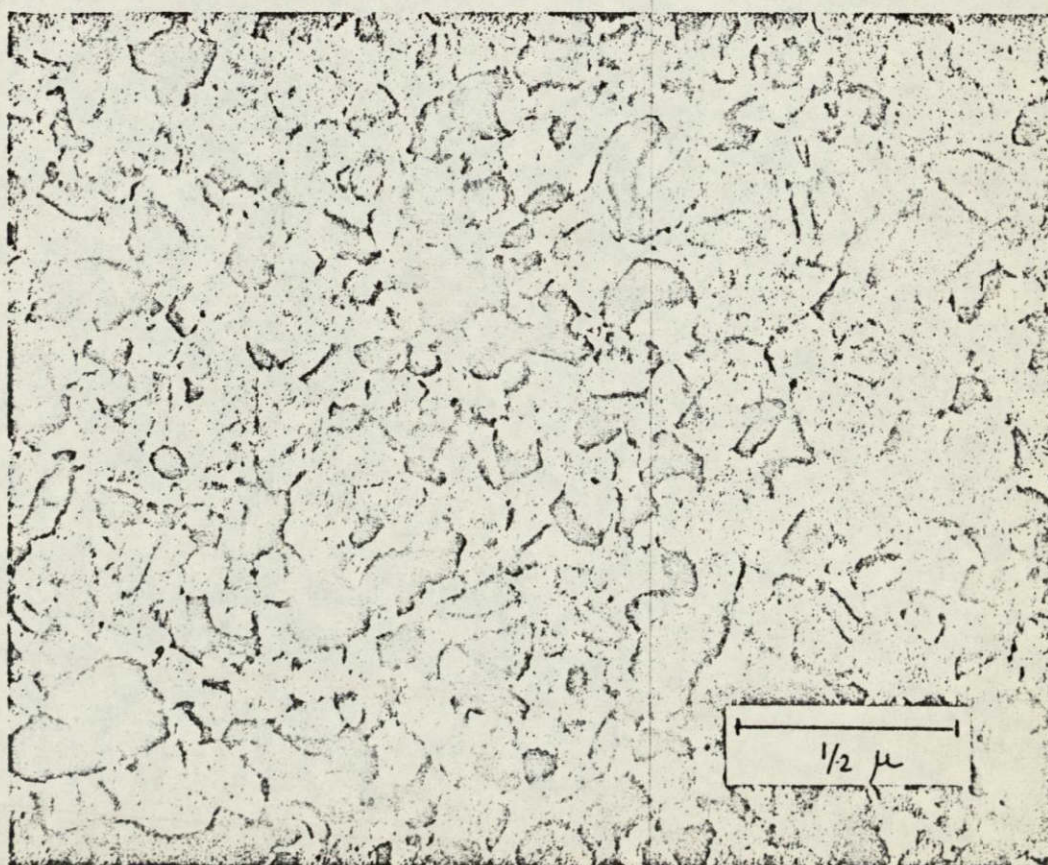
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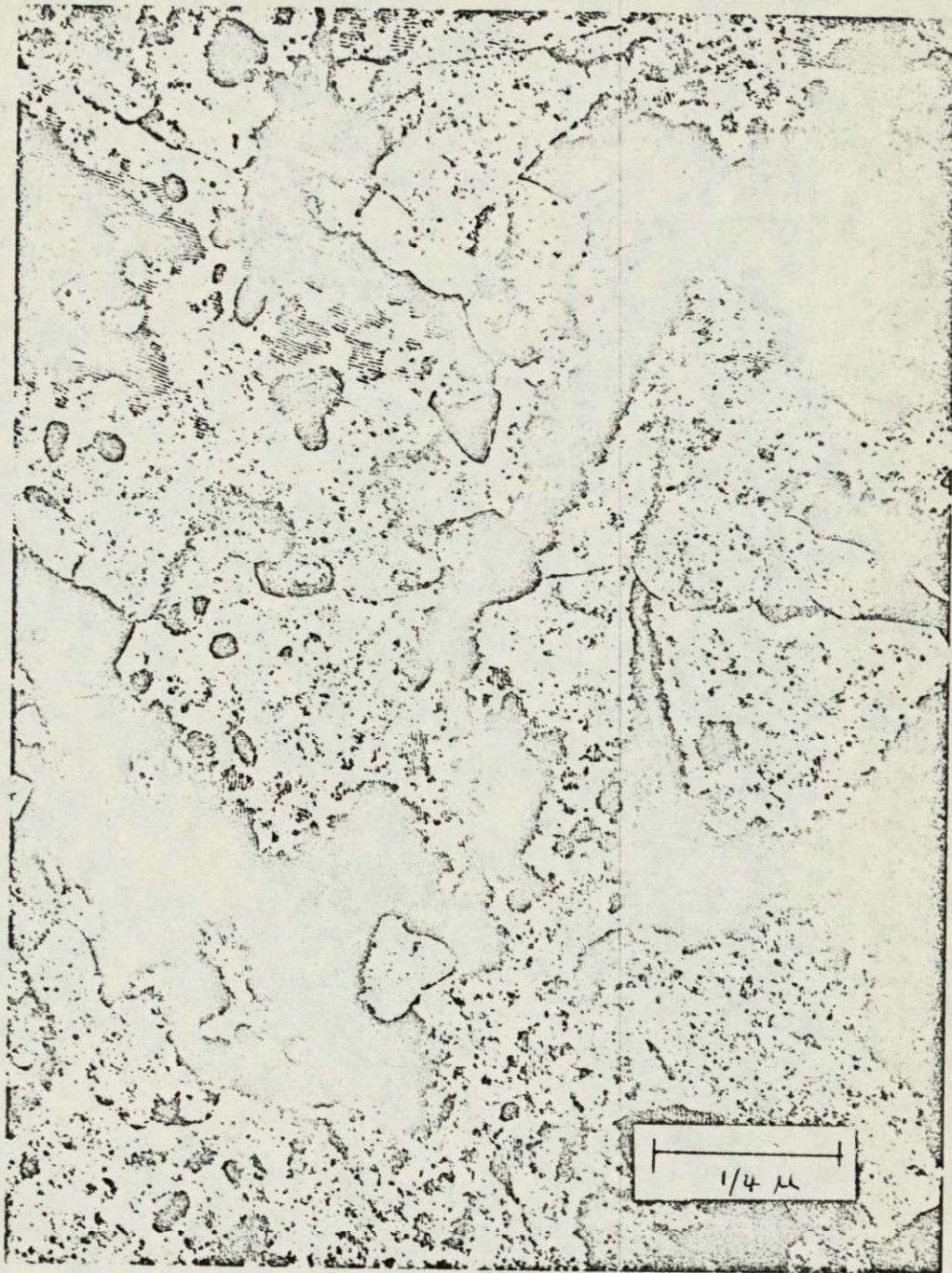
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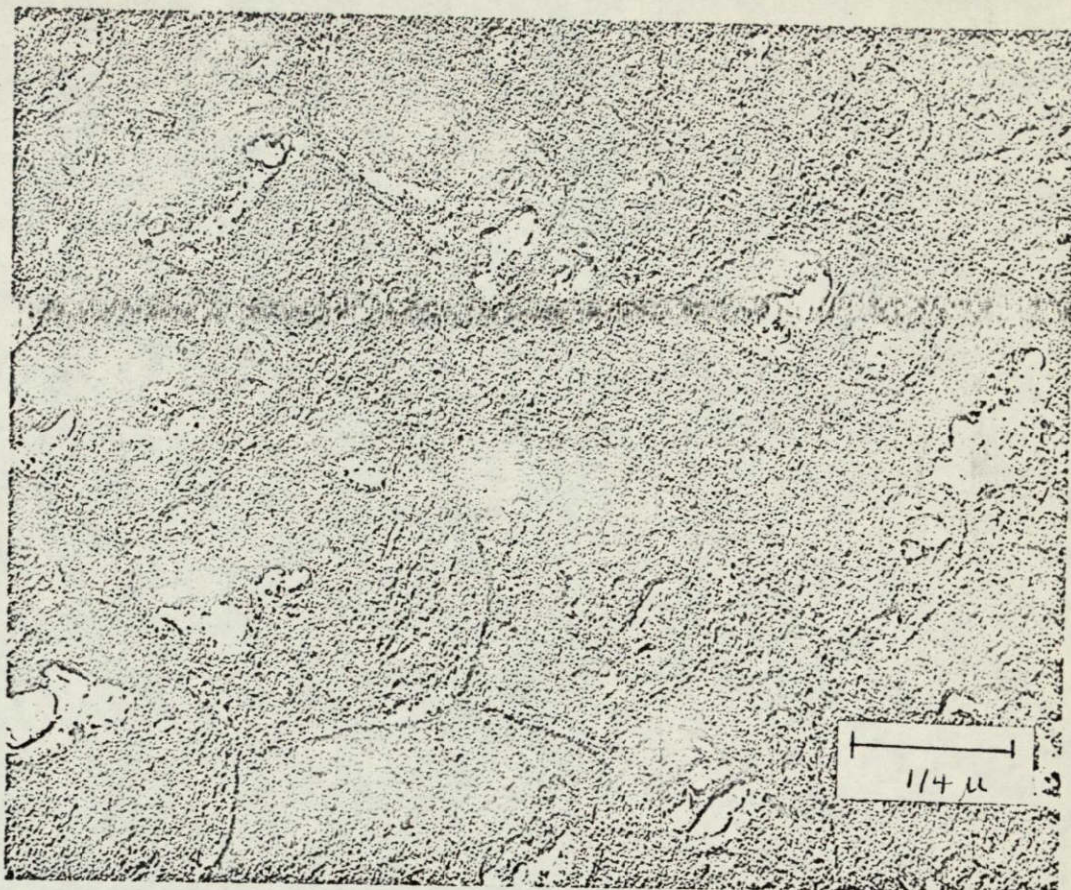
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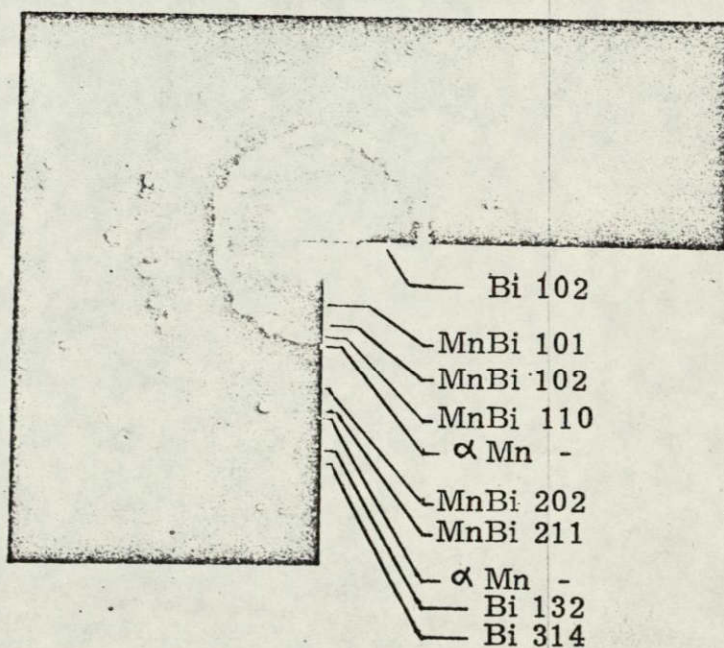
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Fig II-11



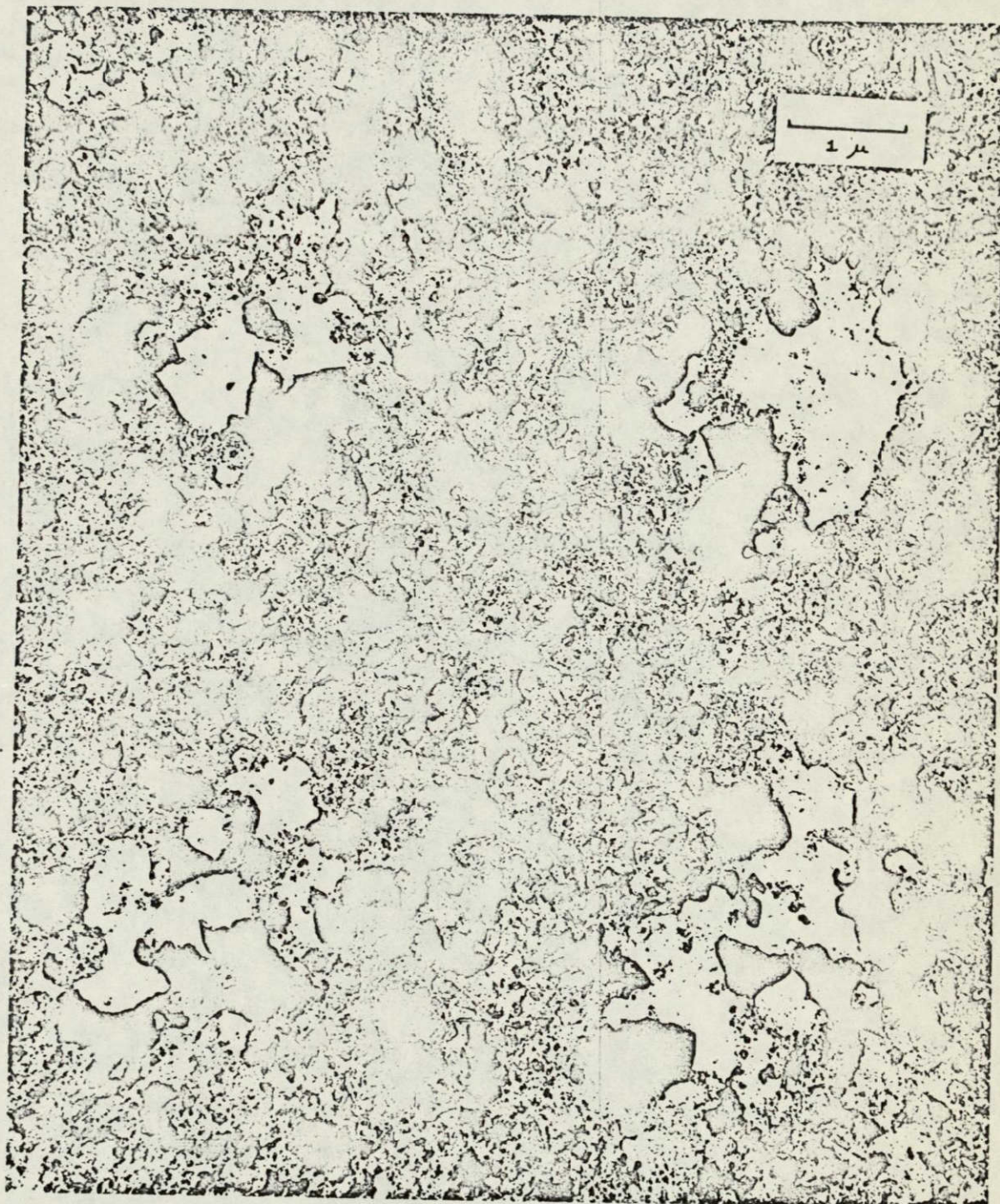
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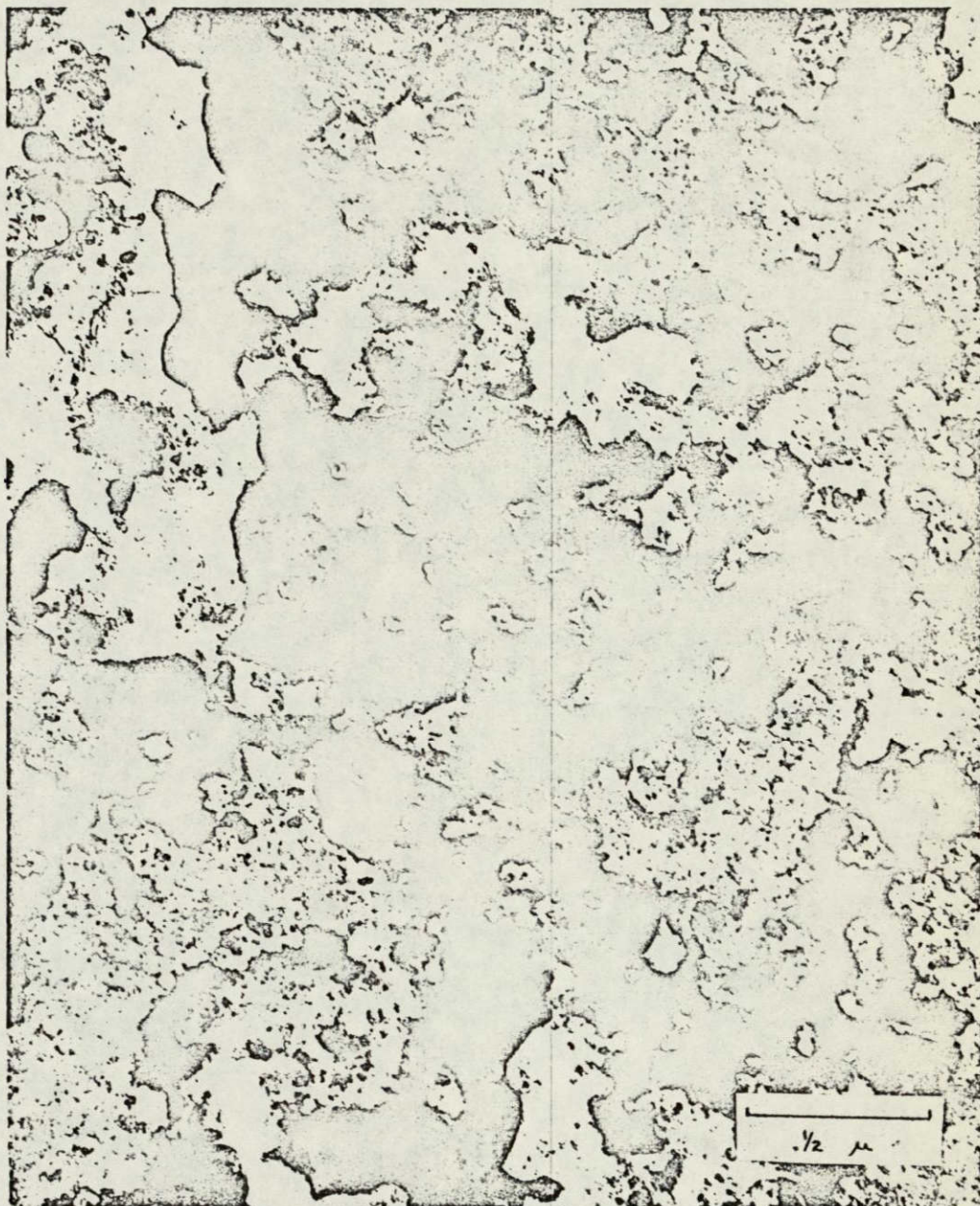
II-20

For a close examination in the vicinity of a damaged spot, dark field imaging is especially useful. In Fig. II-15, a high magnification bright field image picture was taken in an area of interest. At this magnification, the outline of <sup>the</sup> damaged spot is barely recognizable. <sup>An</sup> Electron diffraction pattern was then taken in this region, Fig. II-16. Here the most intense 6-fold diffraction spots are due to manganese crystallographic planes with an interplanes spacing of  $2.09\text{\AA}$  (these are the planes in  $\alpha$ -Mn producing <sup>the</sup> strongest diffraction intensity), five of these spots were marked on the pattern as 1, 2, 3, 6 and 7 and examined individually <sup>by</sup> the dark field imaging. A typical dark field image is shown in Fig. II-17 with areas responsible for diffraction spot "2" appearing bright. Close comparison between Figs. II-15 and II-17 reveals elemental manganese scattered along the rim of the damaged spot, probably resulting from MnBi decomposition.

## 2. Formation of and Transformation in MnBi Films

MnBi films were prepared with a compound formation anneal at elevated temperature. The process of compound formation is an important subject of study since the material improvement hinges on a clear understanding of this process. High resolution optical metallography ~~technique~~ was used in this study utilizing the magneto-optic effect in the medium.

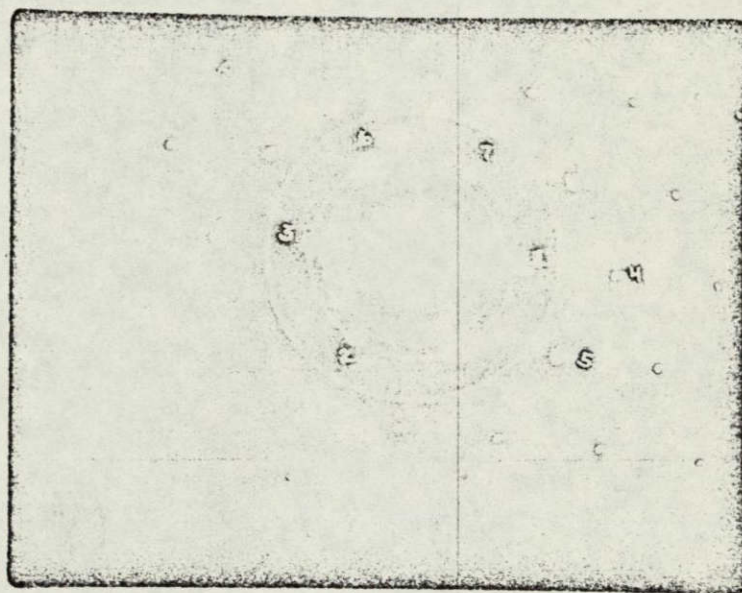
The existence of two crystallographic phases in MnBi, both appearing above ~~the~~ room temperature, makes it necessary for us to study the nature of ~~the~~ phase transition. In the Curie point writing experiment, we have found that using a normal MnBi film, bits repeatedly written will transform into <sup>the</sup> quenched high temperature phase. This is due to the rapid cooling following the termination of the laser writing pulse. On the other hand, films prepared in the quenched high temperature phase will transform back to <sup>the</sup> normal phase through a process believed to be nucleation and growth. We will now discuss the compound formation and the phase transformation in more detail.



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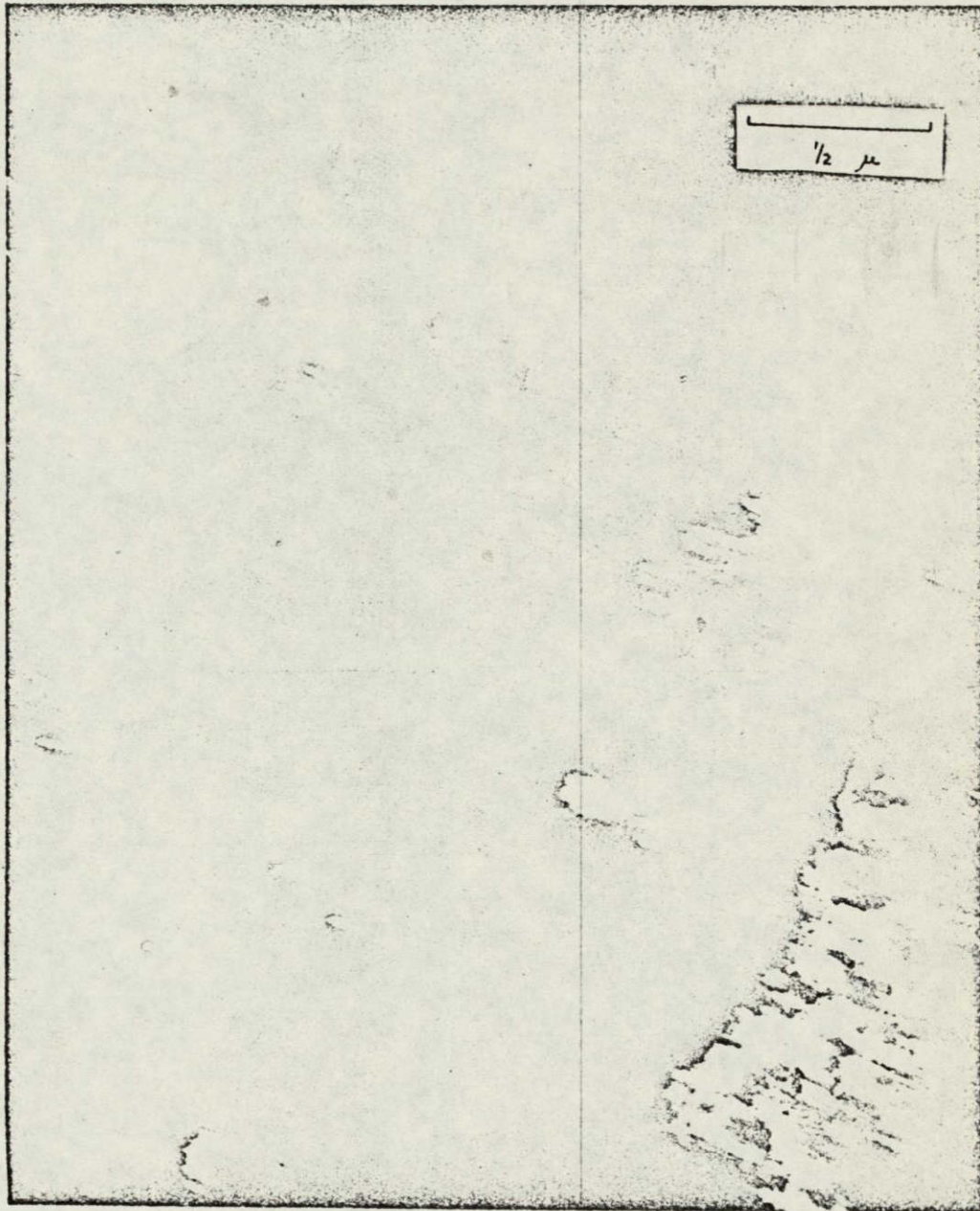
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Fig 7-16



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II-17

## a) Experimental Procedures

Optical metallography using polarized light in conjunction with cinematography were used to study the formation of MnBi and the low temperature phase (l. t. p.) to high temperature phase (h.t.p.) transformation in MnBi flat films. The films under investigation were heated from behind the substrate, thus leaving a clear optical path for observing the film surface with reflected light. <sup>The</sup> Magneto optic Kerr effect was utilized in both instances to observe the result<sup>ing</sup> magnetic domains.

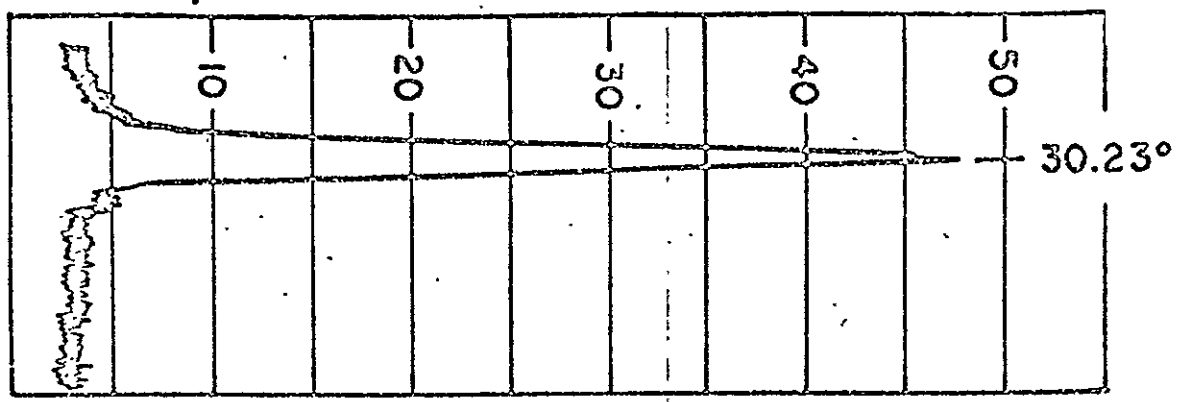
Due to the preferred orientation in MnBi films, the normally weak X-ray diffractions from the basal planes exhibit very high intensity. This property can be utilized for investigating the phase transformation in MnBi films quantitatively. This is based on the fact that the total integrated intensity of a given diffraction line is linearly proportional to the amount of the particular phase present. This diffraction line must be produced solely by the particular phase being investigated.

When MnBi is quenched from above  $360^{\circ}\text{C}$ , the retained high-temperature phase changes its lattice parameters with a 3% decrease in  $c_0$  and 1.5% increase in  $a_0$ . (7-10) Due to the highly textured nature of vapor deposited MnBi films, the basal planes of the MnBi are within  $5^{\circ}$  of the film plane. The angular positions of the intense basal plane reflections can thus be used to identify the quenched high temperature and the annealed low temperature phases. Based on  $\text{CuK}\alpha$  radiation, a 3% decrease of  $c_0$  causes a shift of  $0.425^{\circ}$  in the Bragg angle  $\theta$  for the basal plane reflections. When a diffractometer is used, this corresponds to a  $2\theta$  shift of  $0.85^{\circ}$ . One can therefore readily identify the mixed quenched and annealed phases in <sup>a</sup> partially transformed MnBi films.

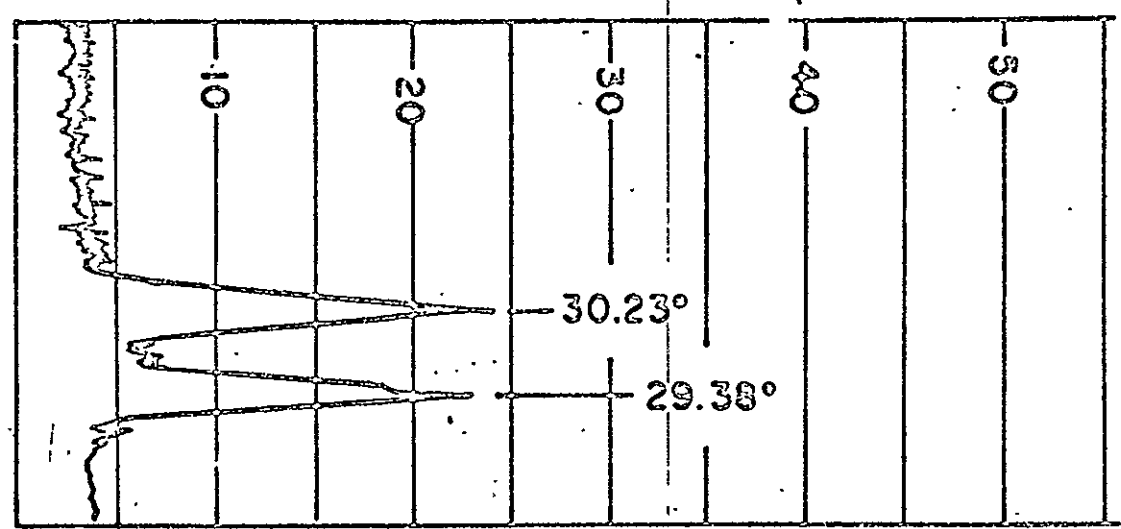
A special furnace which fits into a diffractometer specimen holder was constructed to maintain the MnBi film specimen at pre-determined temperatures while the basal plane diffraction tracings are being taken. The isothermal transformation from quenched high temperature phase to low temperature phase MnBi can be monitored in this manner. Figure II-18 shows the basal plane diffractometer tracings from the same MnBi film in the following three conditions:

- (a) Fully quenched high-temperature phase.
- (b) Partially transformed, mixed high and low-temperature phases.
- (c) Fully annealed low-temperature phase.

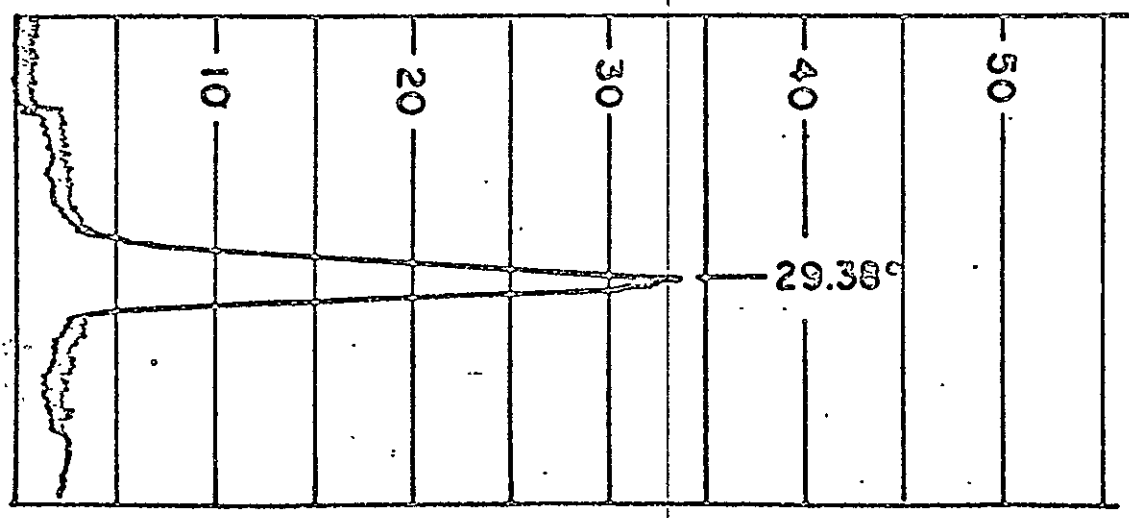
Quantitative analysis by X-ray diffraction is based on the fact that the intensity of the diffraction pattern of a particular phase in a mixture of phases depends on the concentration of that phase in the mixture. The relation between intensity and concentration is not linear, since the diffracted intensity depends markedly on the absorption coefficient of the mixture and this itself varies with the concentration. We have shown (2)



a



b



c

II-418  
13

Figure 4-11 X-ray diffractometer tracings of S1-G-16-37D in three conditions, (a) 100% quenched high temperature phase, (b) mixed quenched and normal phase, and (c) 100% normal low temperature phase.

that the product of peak intensity and half line width  $\Delta$  is proportional to the integrated intensity which in turn is linearly proportional to the amount of the particular phase of MnBi present.

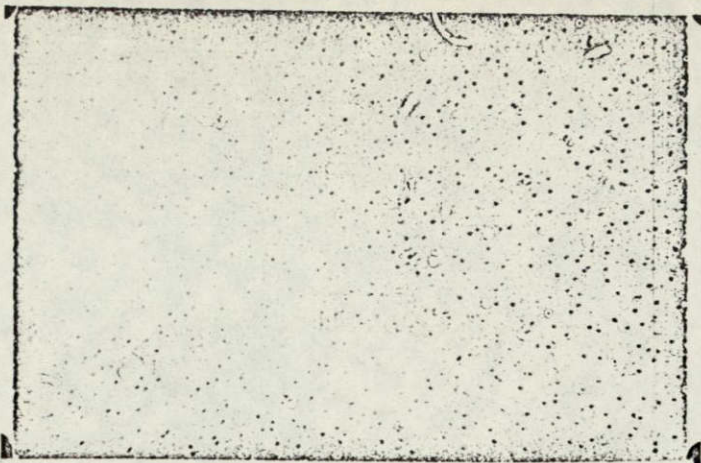
Another method of measuring the relative amount of the quenched and normal phase in a mixed multiphase compound is by monitoring the magneto-optic Faraday rotation of the specimen. The difference in the total Faraday rotation at magnetic saturation in the quenched and normal phase MnBi provides a convenient measure of the relative concentration. This method is discussed in detail in a previous quarterly report. (2)

## b) Results and Discussion

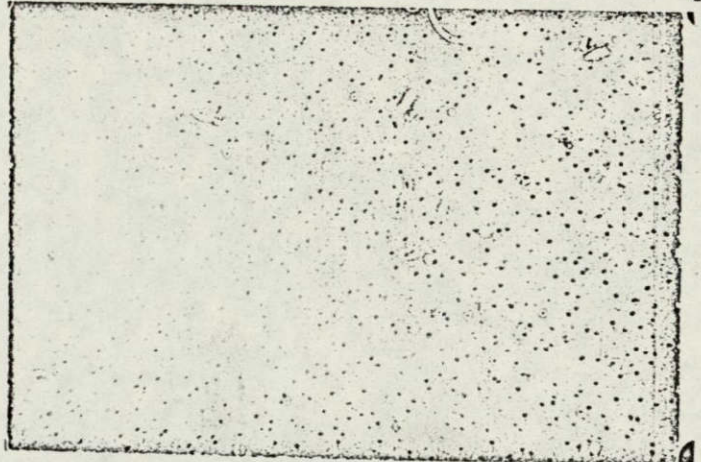
The formation of MnBi films from layers of elemental manganese and bismuth was studied by optical metallography utilizing <sup>the</sup> magneto-optic Kerr effect. The formation of MnBi as revealed by magnetic domain formation suggests a nucleation and growth process. The coalescence of domains during formation anneal results in the type of domain configuration observed. Fig. II-19 shows selected frames from a movie sequence taken during MnBi formation anneal. It is difficult to perform quantitative measurements. Cinematographic study does, however, provide a qualitative description of the magnetic domain formation.

In a similar fashion, when a magnetically saturated normal phase MnBi film is heated to its Curie point, the film becomes demagnetized. This coincides with its transformation to the high temperature phase. This enables one to observe the l.t.p.  $\rightarrow$  h.t.p. transformation in MnBi. Fig. II-20 shows selected frames from a movie sequence depicting this transformation. The scratch was introduced purposely to help focusing the film surface, since it is absolutely featureless in a magnetically saturated MnBi film. The l.t.p.  $\rightarrow$  h.t.p. transformation as observed by <sup>the</sup> Kerr effect suggests a nucleation and growth phenomenon.

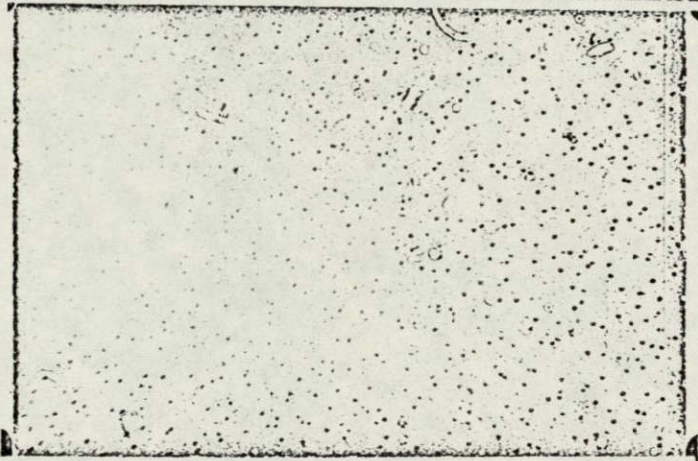
The transformation from <sup>the</sup> quenched high temperature phase to <sup>the</sup> normal low temperature phase in MnBi films can be studied by measuring the integrated x-ray diffraction intensity from the basal planes of the two phases, or by the magneto-optic method. By measuring the equilibrium quantities of the two phases during <sup>an</sup> isothermal transformation and <sup>by</sup> performing <sup>the</sup> isothermal transformation at various temperatures, the transformation path at different temperatures can be obtained. These results are then fed into a Honeywell HCN time sharing computer. A multifunction least square curve fitting program was used to evaluate the measured data. In most instances an exponential function fits



(a)

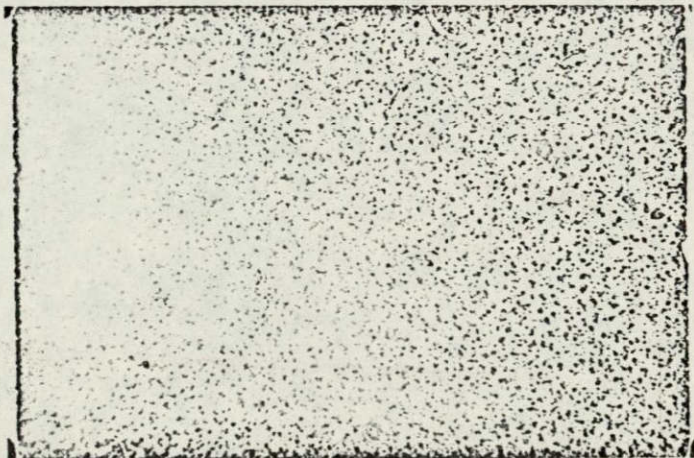


(b)



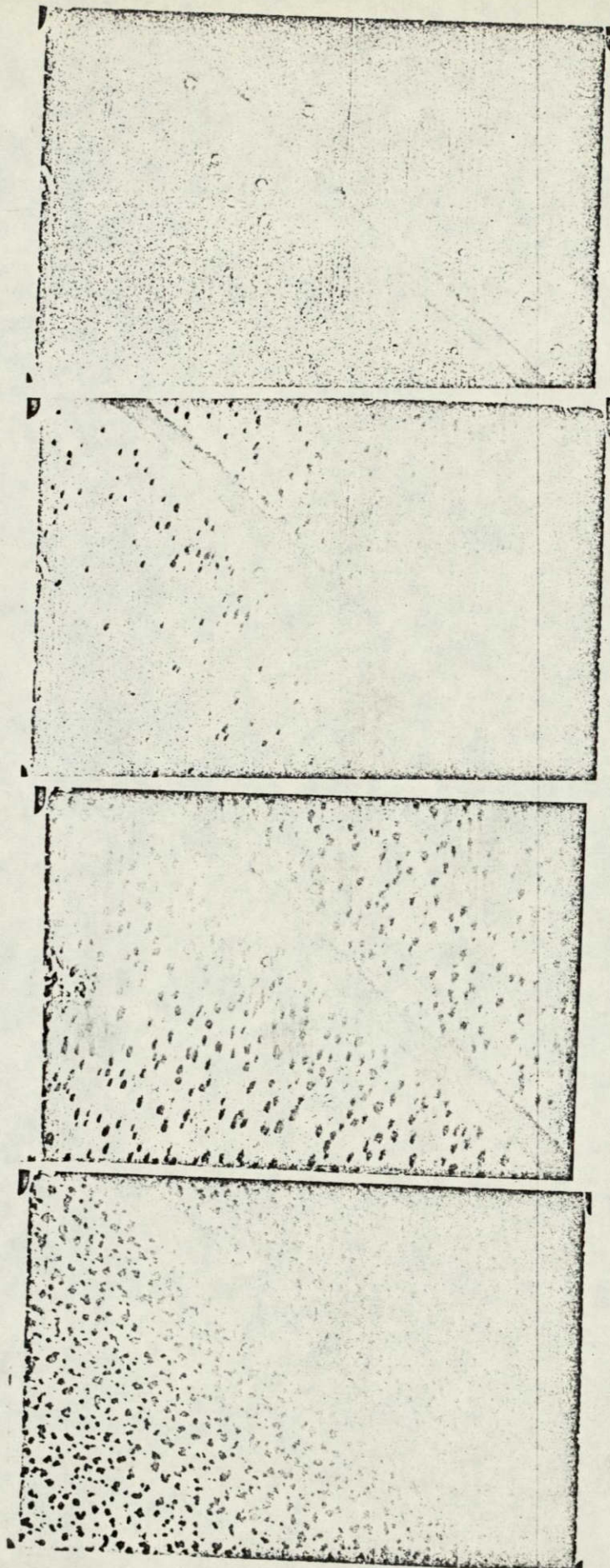
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(c)



(d)

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(c)

(c)

(c)

(d)

Q

the data with an index of determination close to unity. If we assume the concentration of quenched phase =  $N_q$ , that of normal phase =  $N_n$ , then at any time  $t$  the volume fraction of the quenched phase can be expressed as follows:

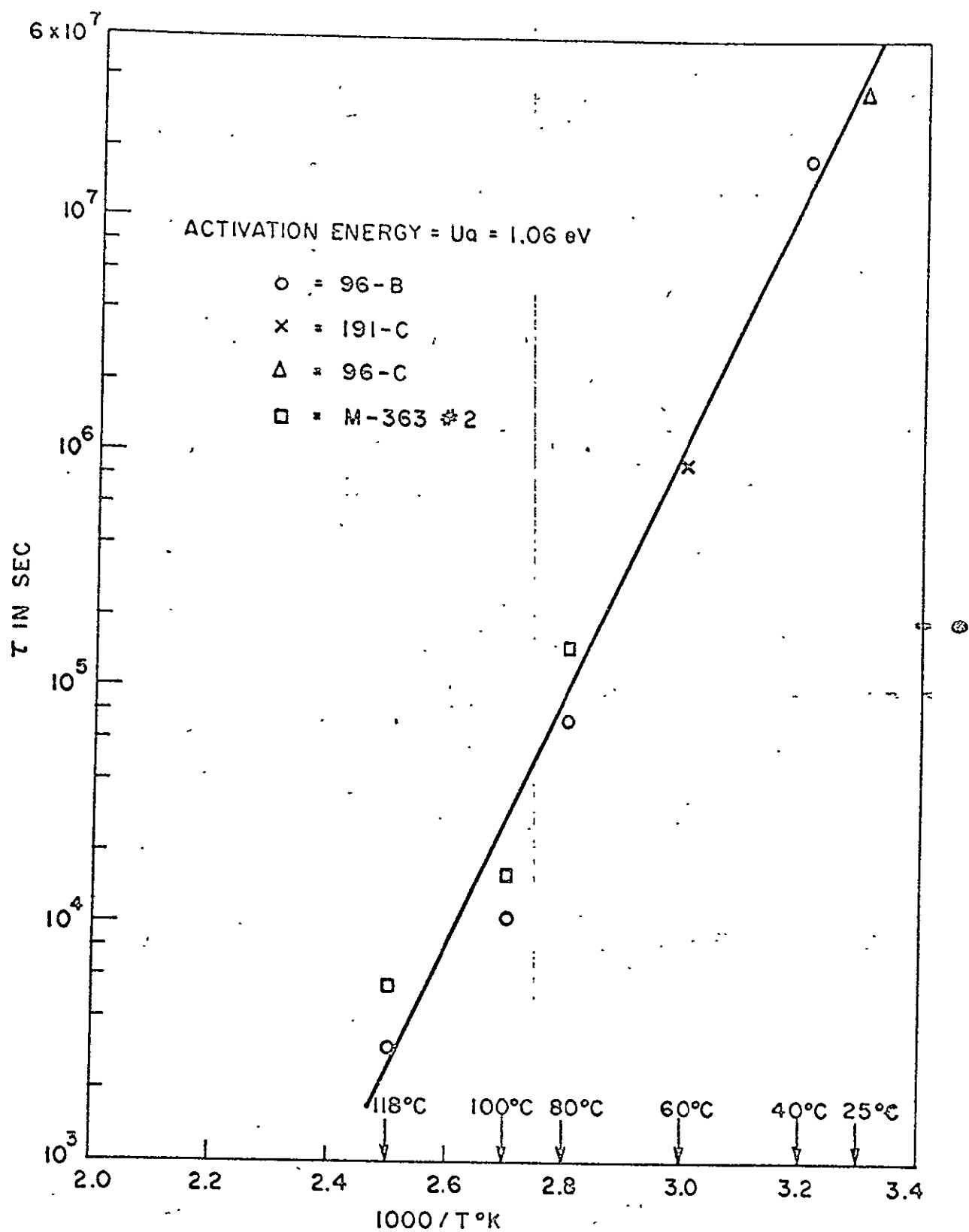
$$N_q = (N_q + N_n) \exp(-t/\tau(T))$$

where  $\tau$  is a characteristic time constant which depends on the temperature of transformation  $T$ . By least square curve fitting, one can obtain the characteristic time constant at different temperatures. The temperature dependence of  $\tau$  can be expressed by:

$$\tau(T) = \tau_0 \exp(E/kT)$$

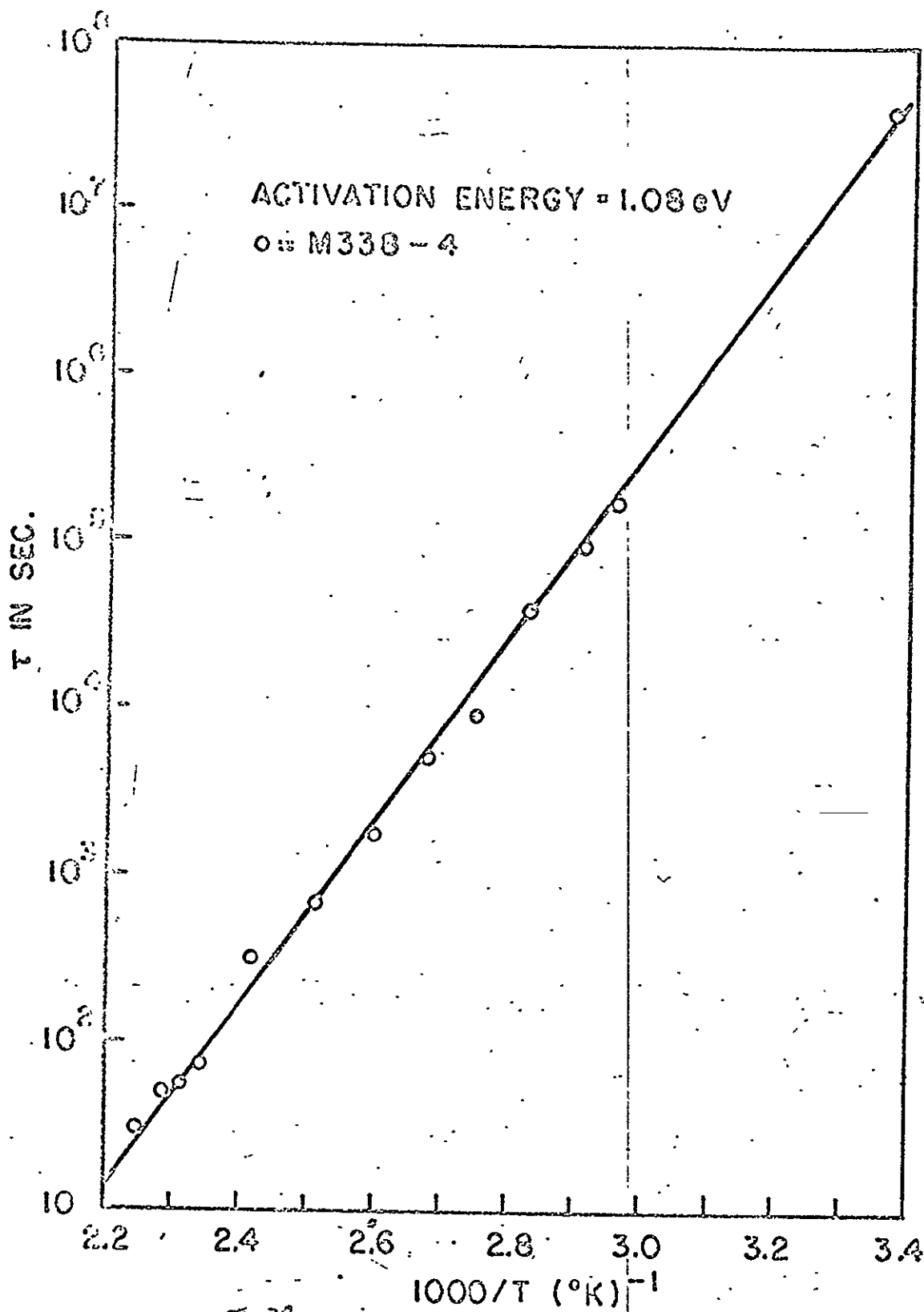
where  $E$  is the activation energy,  $T$  the temperature in  $^{\circ}\text{K}$  and  $k$  the Boltzmann constant. The activation energy can be calculated from the slope of the  $\log \tau$  vs  $\frac{1}{T}$  curve. The <sup>time constant</sup> results from X-ray diffraction method are plotted in Fig. II-21. Using the magneto-optic technique, the measured annealing time constant  $\tau$  vs  $\frac{1}{T}$  is given in Fig. II-22. There is a difference in the absolute value of  $\tau$  in these two measurements, but the resultant activation energy <sup>is</sup> are 1.06 and 1.08 eV respectively, well within the range of experimental accuracy.

Initial attempts using X-ray diffraction method to characterize the l.t.p.  $\leftrightarrow$  h.t.p. transformation in MnBi films confirmed the presence of a hysteresis of the critical temperatures. If one designates the temperature at which l.t.p. first appears on cooling as  $T_{co}$ , and that at which the h.t.p. first appears on heating as  $T_h$ , our results indicate that  $T_h$  ranges from below  $330^{\circ}\text{C}$  to  $353^{\circ}\text{C}$  while  $T_{co}$  ranges from  $324^{\circ}\text{C}$  down to  $300^{\circ}\text{C}$  depending on the rate of heating and cooling and perhaps the previous thermal history of the film specimen. To optimize our films, a series of thermal cycling experiments were made with films prepared with varying Mn:Bi ratio. These films were thermally cycled from just below  $T_{co}$  to just above  $T_h$ . The purpose of this experiment is to enhance diffusion during these solid state phase transformations thereby promoting additional MnBi formation. Based on X-ray



~~Figure 1-7~~ Annealing time constant  $\tau$  as a function of temperature. Data obtained by x-ray technique.





II-22  
Figure II-22 Annealing time constant  $\tau$  as a function of temperature. Data obtained using magneto-optic Faraday effect.

diffraction results, we could not detect additional MnBi formation even after thermal cycling some 30 times. However, upon close examination, we found that for Mn rich specimens the angular position ( $2\theta$ ) of the diffracted X-rays from the basal planes has increased about  $0.3^\circ$  for the normal l.t.p. while the angular position for h.t.p. remained unchanged. This angular shift represents a decrease of  $c_0$  by 1%. This result raises the possibility that MnBi is not a line compound, i.e. it may exhibit slight solubility of manganese. According to Hume-Rothery and Raymon<sup>(11)</sup>, if the binding of a compound with the NiAs structure becomes more metallic, the interaction of the more metallic element A (Mn in our case) extends the homogeneity range in the direction of excess A (Mn) atoms. These atoms may occupy some of the trigonal interstices. The interaction of the metal atoms leads to decreases in the axial ratio and the exothermic heat of formation.

The results from the formation and phase transformation study can be summarized in the following:

(1) The quenched h.t.p.  $\rightarrow$  normal l.t.p. transformation is identified as <sup>the</sup> nucleation and growth type. An activation energy of approximately 1 eV characterizes this transformation.

(2) The l.t.p.  $\rightarrow$  h.t.p. phase transformation near  $T_c$  is probably also of <sup>a</sup> nucleation and growth type.

(3) MnBi is probably not a line compound as was suggested by other workers previously. It may exhibit slight solubility of Mn.

### C. Material Modification

~~The goal of this study is to~~  
The main <sup>goal</sup> ~~objective~~ of this study is to obtain materials of improved characteristics for the optical memory applications. ~~ED~~

The physical properties as well as the memory experimental results indicate that the MnBi prepared in its quenched high temperature phase possesses superior optical memory properties. The main drawback of the quenched phase MnBi lies in the fact that it will slowly anneal back to normal low temperature phase under normal operating conditions. Extensive research effort <sup>was devoted to the stability</sup> ~~to~~ <sup>of</sup> stabilize the quenched phase ~~was devoted~~ during this study. Based <sup>on</sup> ~~on the~~ our understanding of the nature of h.t.p. to l.t.p. transformation discussed in the last subsection, we adapted an approach of dopir, or alloying in an attempt to retard or practically eliminate the annealing process. Alternatively, if the normal low temperature phase films can be prevented from transforming <sup>the</sup> into quenched phase, at the bit location from repeated laser writing, they will be more suitable for memory application since the read-out signal will be stable and independent of the number of repeated write or erase cycling. To this end two approaches were advanced. The first is to operate the medium at temperature higher than the phase transition temperature of the quenched phase. Therefore, the medium will always be kept at the normal phase. This method was found to be satisfactory and will be discussed in the next section.

The second approach is to modify the material. If the medium can be made such that the normal phase undergoes a second order phase transition instead of <sup>a</sup>first order transition at <sup>the</sup>Curie temperature, the high temperature phase will be eliminated. Recent research in MnAs <sup>(5)</sup> indicates that this could be achieved by <sup>a</sup>suitable choice of substrate material. We have adapted the same approach. In this subsection, we will discuss both the doping and alloying experimental results and the effect of substrate <sup>the</sup>on phase transition.

### 1. Doping and Alloying of MnBi

Experimental study of doping or alloying of MnBi falls into the following three approaches.

(1) Doping of elements of suitable atomic dimension to retard the movement of Mn ions in the quenched MnBi. Elements identified for this purpose are Au and Nd.

(2) Doping or alloying with elements to promote covalent bonding. Te and Ge are selected for this case.

(3) Doping or alloying with elements to promote the metallic bonding. Elements identified for this study are <sup>Cu, Fe,</sup>~~Co~~, Ni, <sup>A</sup>Pd and Mn. Alloying with Mn is of course equivalent to varying the Mn to Bi ratio in the compound.

Our Experimental procedure consists of introducing the dopant in the Mn and Bi elemental layers, performing the compound formation heat treatment, quenching the resultant film from above 360°C to prepare it in h.t.p., and measuring the activation energy associated with the transformation from <sup>the quenched</sup>h.t.p. to l.t.p. The technique for measuring the activation energy is by the magneto-optic Faraday effect as described earlier in this section.

(A) Doping with elements of suitable atomic dimension to retard movement of Mn ions in the quenched phase: It has been postulated that the crystallographic phase transformation in MnBi involves migration of Mn ions into the interstitial sites. On the assumption that these ions come from the ions originally at the lattice site, it is possible to prevent them from returning to normal phase by introducing foreign ions of proper valency and atomic dimensions to fill the lattice site left behind by the Mn ions. Au and Nd were used as dopants for this study. The annealing time constant or the activation energy associated with the transformation from quenched to normal phase was measured on the doped film and compared with the undoped film and the results shown in Fig. (II-22). It is seen that there is essentially no improvement in the activation energy.

Recent study <sup>of</sup> on the low temperature measurements and the investigation of the electronic transport mechanism as discussed in subsection A suggest that the Mn <sup>atoms</sup> occupying the interstitial sites in the quenched phase <sup>are</sup> ~~is~~ from the free Mn atoms in the grain boundary or dispersed throughout the film, rather than from those ions at the lattice site. The negative result from this doping experiment supports this viewpoint. This approach is therefore abandoned.

(B) Doping with elements to enhance covalent bonding. MnBi has a NiAs structure. The lattice bonding in this type of structure exhibits varying degrees of covalent and metallic bondings. Without precise knowledge of how the interstitial Mn ions in the quenched h.t.p. affects the bonding, we have to explore the methods of doping to affect either the covalent bonding or the metallic bonding. We have selected Te and Ge as dopants to examine the approach of enhancing the covalent bonding.

The results of the annealing time constant as a function of temperature <sup>also</sup> shown in Fig. (II-23). The activation energy calculated from <sup>the Ge doped sample</sup> this is found to be lower than the undoped films. Based on the limited number of experiments performed, this approach does not appear to produce the required result.

(2) <sup>C)</sup> Doping with elements to promote metallic bonding. To affect the metallic bonding in MnBi, we have selected the use of <sup>✓</sup> Mn, Pd, Cr and transition metals such as Fe and Ni for this experiment.

Doping with Fe even at a level of less than 2% by volume resulted in films of extremely low magneto-optic effect and poor uniformity. Because of this effect the resultant film cannot be accurately evaluated.

Doping with Ni was performed by two different techniques. One method was to evaporate a Ni layer with Mn and Bi layers, similar <sup>to the</sup> to doping method used with other dopants. The doping level <sup>was</sup> is less than 5%. Alternatively, we have melted Mn and Ni into an ingot as a starting material to be evaporated as one vapor source and Bi as the other. This allows us to increase the alloying level up to 20%. The results obtained from these two methods appear to vary slightly probably due to the Ni concentration difference. This is shown in Fig. (II-24). Doping with Cr requires <sup>an</sup> excessive amount of heating for vaporization in vacuum (in excess of 1200°C). It is possible that <sup>a</sup> certain amount of re-evaporation from the substrate and oxidation could have taken place. The effectiveness of this Cr doping was not certain. However, the annealing time was measured on one of the samples and results also are shown in Fig. (II-24) together with the result of doping with Pd and Ni.

<sup>the</sup> Variation of Mn to Bi ratio of the evaporated elemental layer before compound formation anneal is effectively the same as doping with Mn. We have studied <sup>the</sup> the effect of Mn to Bi ratio to the quenched phase annealing time more extensively than any other doping approach. The results are summarized in Fig. (II-25).

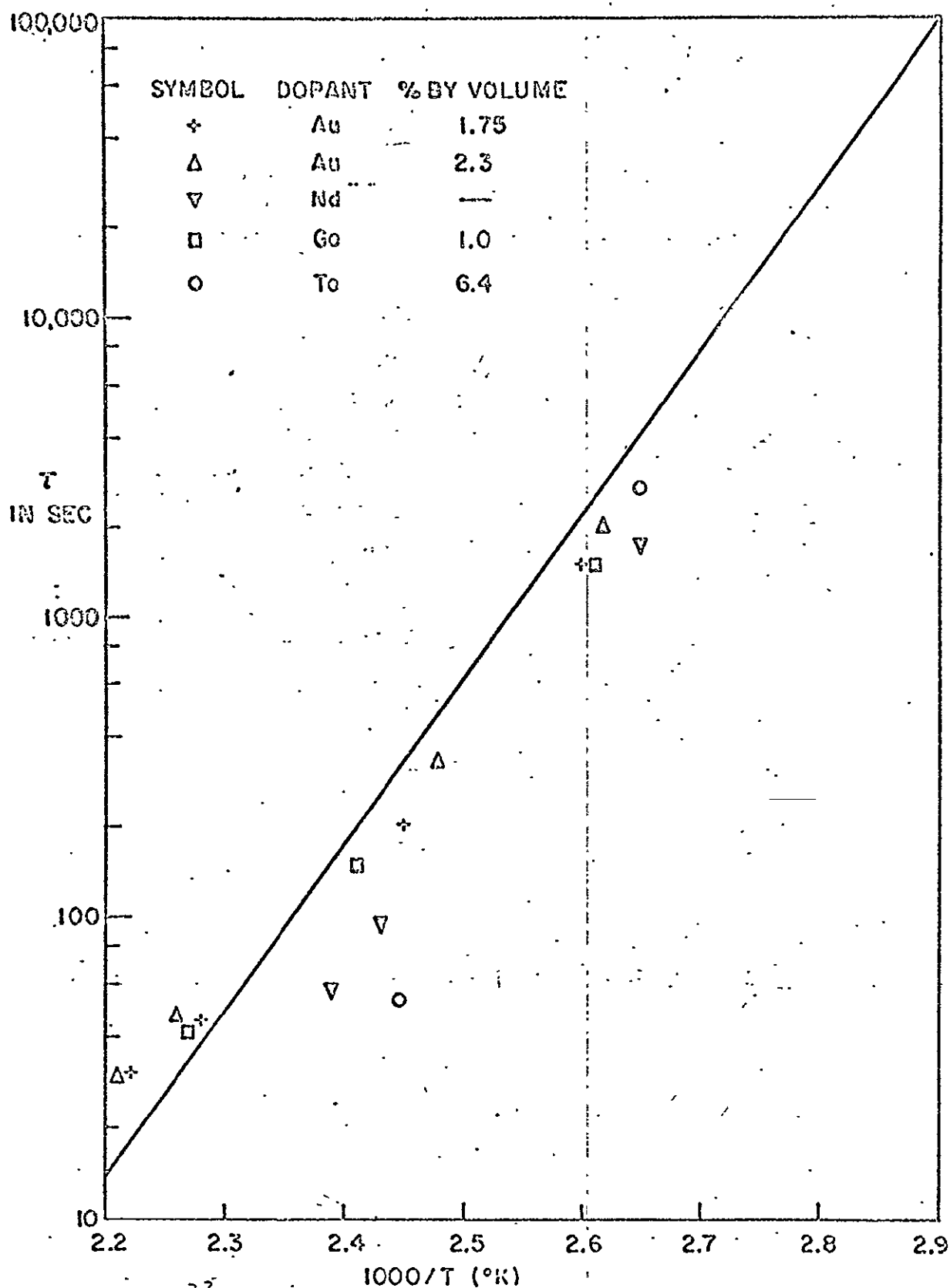
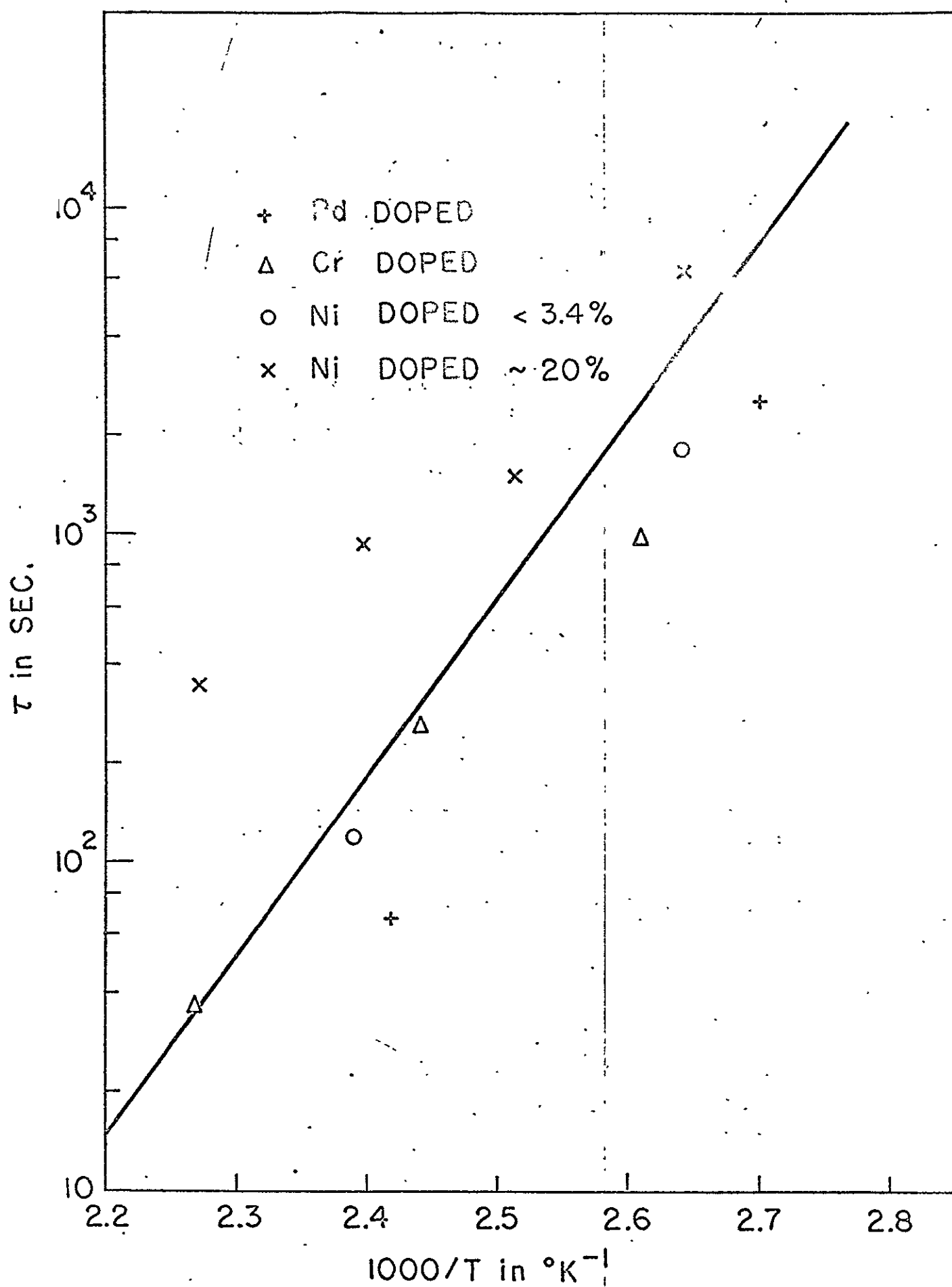
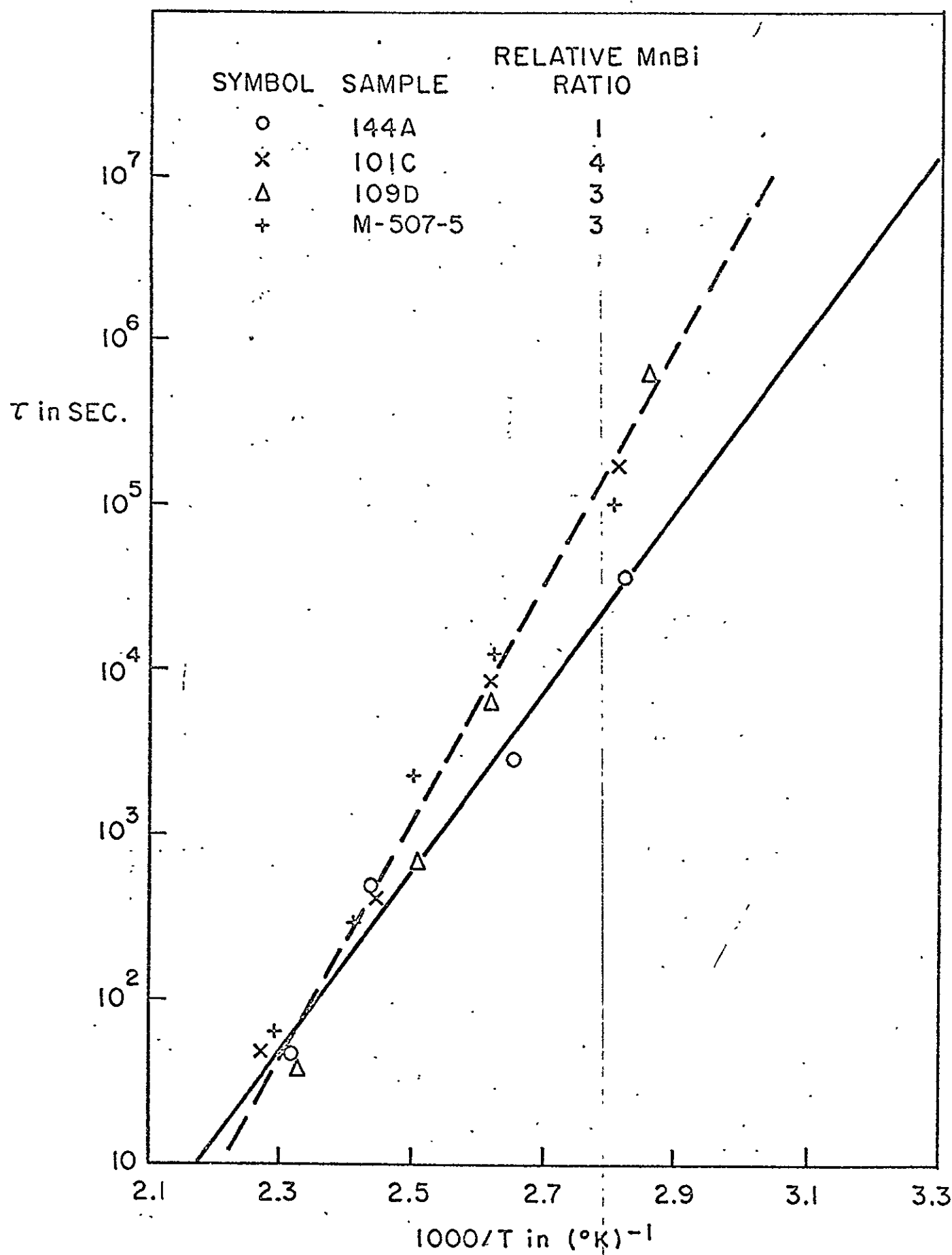


Figure II-5. Annealing Time Constant  $\tau$  as a Function of Inverse Temperature for Quenched MnBi Doped with Various Elements. Au, Nd, Ge & Te





Based on the doping experiments completed to date, we can draw the following conclusion:

(a) Of the three methods for quenched film stabilization attempted, doping to enhance the metallic bonding seems to be most effective.

(b) The activation energy associated with the quenched h.t.p. to l.t.p. can be increased from 1 eV to 1.5 eV by doping with Mn, resulting in improved room temperature lifetime, but the annealing time near <sup>the</sup> Curie temperature of 180°C does not show significant changes.

(c) Doping with Ni shows improvement in the annealing time constant near <sup>the</sup> Curie temperature but no significant change in the activation energy.

(d) Most other doping causes no significant changes in activation energy but with slight reduction in annealing time constant.

Evaluation of the annealing time constant and activation energy are based on isothermal phase transformation experiments. This static measurement is relevant to the storage lifetime of the quenched film, but does not necessarily dictate the stability of the medium during writing, which is a dynamic condition. In fact, phase transformation due to Curie point writing for both the normal and quenched phases requires a dynamic real time study during writing. We have devised an experiment using two laser beams for this dynamic study. This will be discussed in the next section.

## 2. Substrate Effect

The purpose of this study is to explore the possibility of eliminating the high temperature phase in MnBi. If the phase transition at <sup>the</sup> Curie-temperature can be changed by the use of <sup>a</sup> suitable substrate, to a second order phase transition, the medium will stay in the low temperature phase. Repeated writing or erasing will be tolerated without a phase change. The result is a stable medium with constant read-out signal operating at room temperature. The effect of substrate material on the Curie temperature and phase transition in MnAs films has been reported previously.<sup>(5)</sup> We have prepared samples on a number of substrates of various thermal expansion coefficients. The difference in thermal expansion between the substrate and film can induce a large stress in the film; this in turn will cause a change in the Curie temperature. Bean and Rodbell<sup>(12)</sup> and DeBlois and Rodbell<sup>(13)</sup> have predicted from a theoretical model that the Curie temperature can vary as

$$T_c = T_0 \left[ 1 + \beta (V - V_0) / V_0 \right]$$

where  $T_0$  is the Curie temperature for the case when the specific volume  $V$  of the medium were to be restrained to equal  $V_0$ , the specific volume at 0°K in the absence of strains, and  $\beta$  is a proportionality constant.

The linear change introduced by the substrate due to the difference in thermal expansion coefficient of the substrate  $\alpha_s$  and MnBi  $\alpha_m$  is

$$(\alpha_s - \alpha_m) (T_a - T_{op})$$

where  $T_a$  is the annealing temperature during compound formation and  $T_{op}$  is the operating temperature which is generally the room temperature.

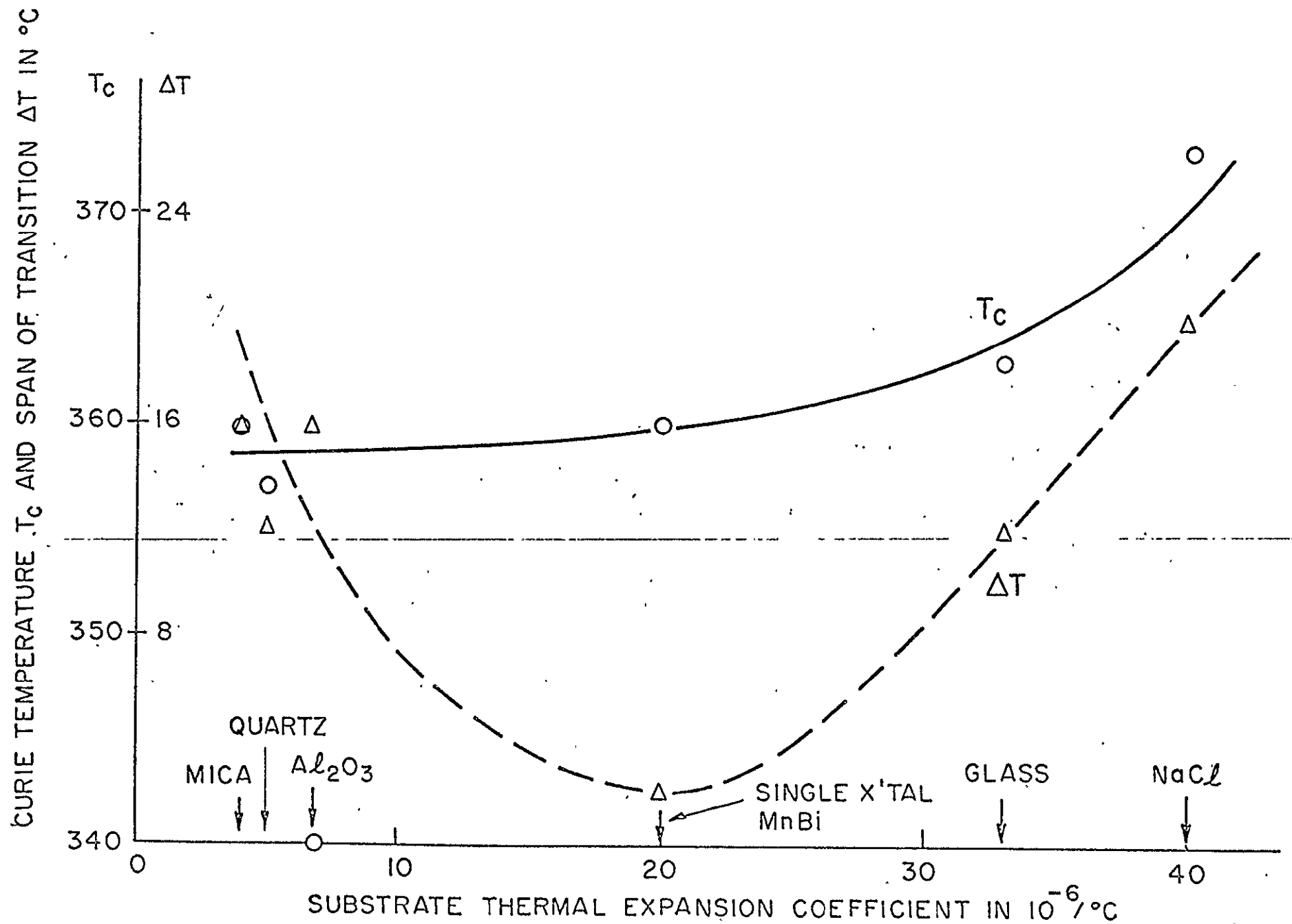
Assuming the thickness of the film is independent of the substrate, we have the change of Curie temperature

$$\begin{aligned}\Delta T_c &= T_c' \text{ (with substrate)} - T_c \text{ (no substrates)} \\ &= T_0 \beta \frac{1}{V_0} \left[ (\alpha_s^2 - \alpha_m^2) (T_a - T_{op}) \right]\end{aligned}$$

This indicates that the Curie temperature will increase if  $\alpha_s > \alpha_m$  and decrease if  $\alpha_m > \alpha_s$ .

We have prepared MnBi films on teflon, rock salt, sapphire, quartz, besides mica and glass substrates. The Curie temperature was found to vary over a range from 340°C to 375°C, depending on substrate material. Furthermore, the difference in temperature span between the start and end of the transition can vary from 8°C for films on teflon substrate to 20°C for films on rock salt substrate. The results are plotted in Fig. (II-26). The estimated thermal expansion coefficient of  $20 \times 10^{-6}$  together with the Curie temperature measured on single crystal of MnBi is also plotted on the curve. The results are in general agreement with the analysis.

The temperature span  $\Delta T$  increases with the substrate thermal expansion coefficient, a result also observed in MnAs.<sup>(5)</sup> This indicates the possibility of changing the first order transition into a second order or second order like phase transition. However, it is not clear at present that this approach can completely eliminate the high temperature phase, without resulting in a medium with a Curie temperature exceeding the damage temperature of 445°C.



## E. Film Coating

Unprotected film exposed in air will gradually decompose into a nonmagnetic layer, even at room temperature. The main source of contamination was traced to the moisture contained in air. In order to protect the film from deterioration, a protective over coating is necessary. The coating must satisfy the following requirements:

- (1) Effective as a moisture barrier.
- (2) Optically transparent and possess suitable refractive index.
- (3) Can be applied uniformly with <sup>a</sup>thickness variation no more than a fraction of one micron over the entire film surface.
- (4) The coating thickness should be controllable to achieve a maximum index match to MnBi film.
- (5) Can resist heating during laser Curie point writing.
- (6) Must be inert to MnBi under normal operating conditions.

A number of coating materials have been used in this experiment. Among the coating materials attempted we have found that SiO, SiO<sub>2</sub> and MgF<sub>2</sub> all worked well and satisfied the above requirements. Using <sup>a</sup>vacuum deposition technique it is not difficult to control the uniformity and coating thickness. Silicon monoxide coatings <sup>are</sup> was most extensively used in our films because it is easy to deposit in a vacuum system and provides the proper optical quality. The refractive index of MnBi at the visible wavelength measured earlier (1966) resulted in a ~~value range~~ from 2.4 to 2.2. To achieve index matching, the refractive index of the coating should be in the range of 1.5 - 1.6. We have found however that SiO deposited at a vacuum of 10<sup>-5</sup> mmHg which should result in an index of refraction of 1.9, serves as a good index matching medium. In order to adjust the thickness of the coating for best optical transmission

at the operating wavelength of  $6328\text{\AA}$ , a laser monitoring system was incorporated in our film deposition system. The laser beam intensity reflected from the film was recorded on a recorder as a function of time during SiO deposition. When a minimum in reflection is achieved, the coating is of proper thickness for index matching and the SiO evaporation stops. Normally, we cut off the evaporation at the second minimum to establish a better reference point for a more precise cutoff. Furthermore, a thicker coating is more desirable because it is more durable. Film coating thickness control allows a better utilization for <sup>the</sup> laser beam in the write, erase and read-out operation. The laser write power was found to be reduced by a factor of two for films with coating adjusted for minimum reflectivity as compared to those with maximum reflectivity. A detailed account of these results will be discussed in Section III.

### III. OPTICAL MEMORY EXPERIMENTS

The objective of the optical memory experimental part of this investigation is to determine the usefulness of MnBi films for the  $10^{10} - 10^{12}$  bit memory in terms of its write, read, erase capabilities. This includes ~~the~~ measurements of film memory characteristics, ~~the~~ evaluation of <sup>the</sup> uniformity in large films, ~~the~~ examination of the basic writing erasing mechanism, and the effects of environmental conditions ~~on~~ the film memory properties. The results of this study ~~will~~ serve two purposes. On the one hand, they ~~will~~ provide guidance to the materials research as to the special aspects of the material property <sup>is that</sup> needs further improvements. On the other hand the results serve as the boundary conditions for trade-offs in the systems study of the optical memory. This study is therefore <sup>a</sup> ~~the~~ bridge between the materials and systems investigation of this optical memory research effort.

#### A. Memory Characteristics of MnBi Films

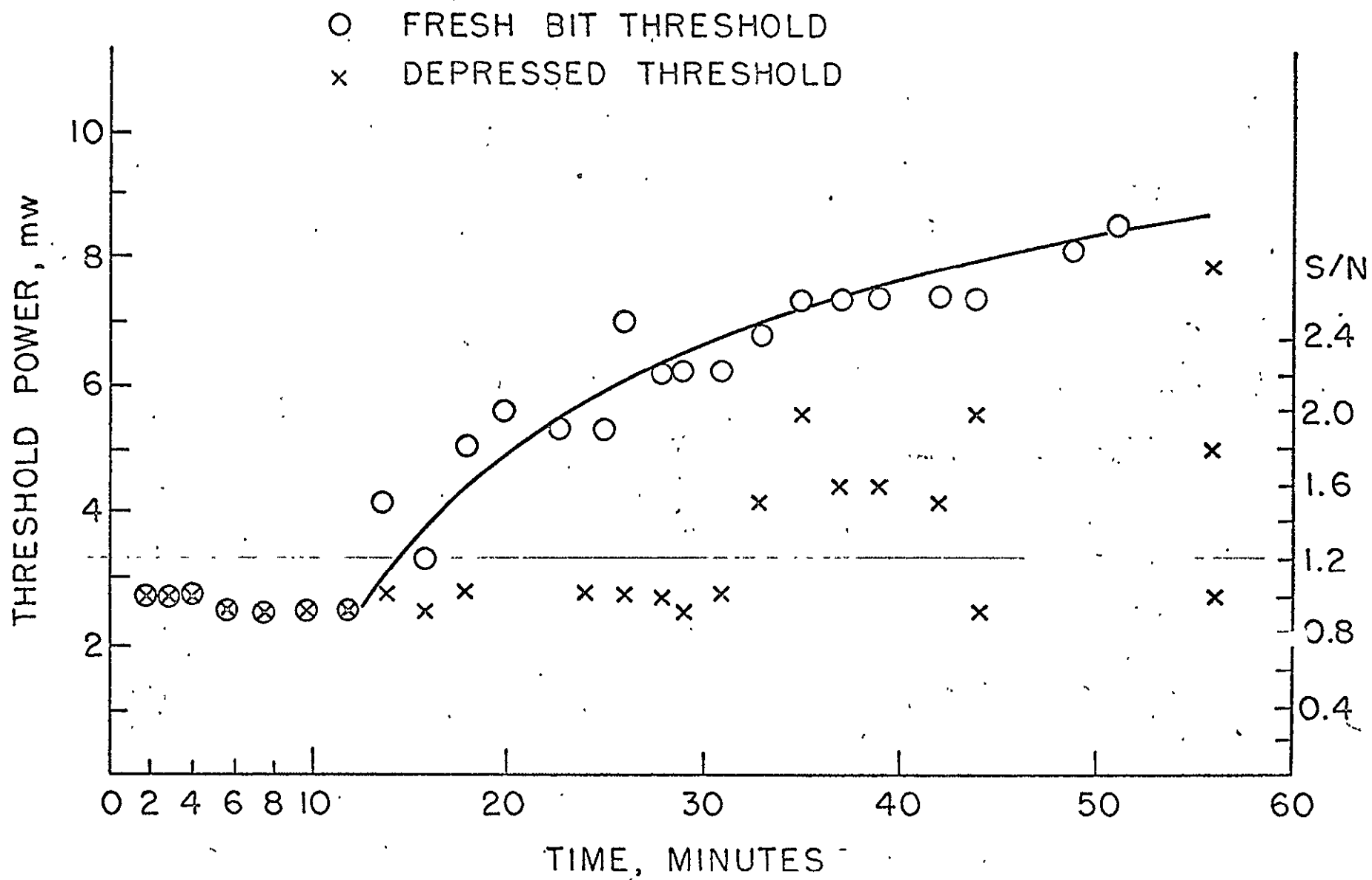
Optical memory characteristics of MnBi films involve the laser Curie point writing properties, the repeated cycling effect, the read-out signal characteristics, the erasure field requirements, the information retention characteristics, and the effect of film overcoating. These investigations were all performed <sup>with</sup> ~~in~~ the memory exerciser described in the third quarterly report.<sup>1</sup> The objective of this study is to determine the characteristics of MnBi films <sup>for</sup> ~~in the~~ optical memory applications. The results obtained in this study will provide the basis for the systems study of the intended spaceborne optical memory.

## 1. Laser writing characteristics

The properties of the material discussed in the foregoing sections have an effect on the memory characteristics of the film, particularly the two crystallographic phases. A comparison of optical memory characteristics with measurements of Curie temperature, Faraday rotation and magnetization of the normal and quenched phases is given in Table II-1 of our first quarterly report.<sup>(2)</sup> In the quenched phase the write power required is about one-fourth, the readout signal about one-half and the erasure field about one-half of that for the normal phase. Since the decomposition temperature is  $450^{\circ}\text{C}$ , the lower Curie temperature of  $180^{\circ}\text{C}$  greatly increases the margin between <sup>the</sup> write or erase <sup>power requirement</sup> and <sup>the</sup> damage level.

These are the major advantages of the quenched phase, but they are opposed by the disadvantage that the quenched phase gradually transforms back to the normal phase. A time constant for this transformation has been measured and plotted as a function of  $T^{-1}$  to obtain an activation energy for the process in the previous section. We have investigated the optical memory characteristics during this transformation also. Figure III-1 in quarterly report no. 2 shows <sup>(14)</sup> ~~of the time constant as a function of temperature~~ a plot ~~of the time constant~~ of the point at which the writing threshold power begins to increase. ~~as a function of temperature.~~ Figure III-1 of this report is a typical example of the threshold power required to effect a write as a function of time while the film operating at  $92^{\circ}\text{C}$  is transforming back to the normal phase. This relationship <sup>of the threshold as a function of time</sup> is characterized by a plateau, a sharp rise and a plateau at the normal phase level. The normal phase concentration at the beginning of the upper phase plateau is about 20 percent, well below the 63 percent point at which the transformation time constant is defined.

When the time constant for the transformation is used to extrapolate back to zero concentration, it tends to coincide with the time at which the threshold power begins to increase. Therefore, we would conclude that the first plateau



is a nucleation period during which growth of the normal phase is very slow. Apparently, the nucleation process has little or no effect upon the writing power requirements. Only when the normal phase concentration comes into the few percent range, does the writing threshold power requirement begin to increase.

## 2. Repeated Cycling Experiments *etc*

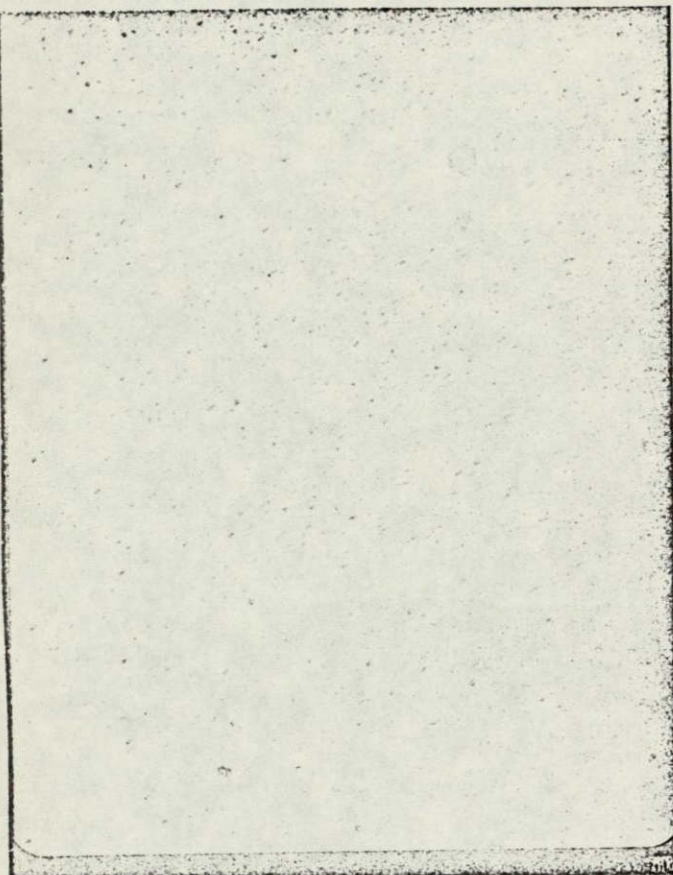
*On quenched films,* Repeated cycling experiments which require hours of time can be done without interference from the natural transformation. When spots are repeatedly heat cycled the average temperature is above room temperature. If we assume that the transformation time constant is a smoothly increasing function of temperature that can be extrapolated from the time constant measurements, we find that at  $180^{\circ}\text{C}$  the time constant is about 40 milliseconds. Assuming that the center of a spot is above  $180^{\circ}\text{C}$  for 0.5 microseconds during laser writing, we would expect to see an effect upon the optical memory characteristics after about  $10^4$ - $10^5$  pulses. Preliminary experiments of this kind performed on quenched films indicate a gradual decrease in the readout signal after about this length of time. Spots have been cycled about  $10^6$  times before the S/N becomes less than one. When these spots are examined under the microscope at high magnification, there is no evidence of physical damage. It should be noted that this kind of experiment is done with the writing power well below that required to effect a write in the normal phase. So we would expect the signal to disappear as the writing threshold power increases, <sup>due to</sup> as the quenched film gradually transforms <sup>into the</sup> into normal phase.

Similar experiments have been conducted with the film in the normal phase. When the film is at room temperature the written spot rapidly quenches into the high temperature phase after repeated cycles of writing to above  $360^{\circ}\text{C}$  with microsecond pulses of laser heating. It then exhibits a smaller readout signal due to the smaller Kerr and Faraday rotation. If the write power is then reduced repeat cycling can be continued. This has been tested for ~~around~~<sup>about</sup> a million operations with no further changes in memory properties. However, if the write power is not reduced, the center of the spot will soon burn out leaving only a ring of material that continues to switch. This ring is thought to occupy a position along the temperature profile where the "conditioned" spot on the film will not exceed the dissociation temperature. The center of the spot ~~behaves~~<sup>looks</sup> as if it had exceeded the dissociation temperature.

Spots have also been exercised greater than  $10^5$  times with the film at a nominal temperature of  $250^{\circ}\text{C}$ . High magnification photos using an oil immersion objective are shown in Figure III-1a, b. Figure III-1a shows the spots under crossed polarizers. The small patches of switched material around the test pattern are left due to misregistry during the experiment. Figure III-1b is a photograph of the same area with unpolarized light. Notice that the spots written only once cannot be seen under unpolarized light, but spots that have been switched many times show up. This can be construed as damage due to repeated cycling. The precise nature of the damage is not known.

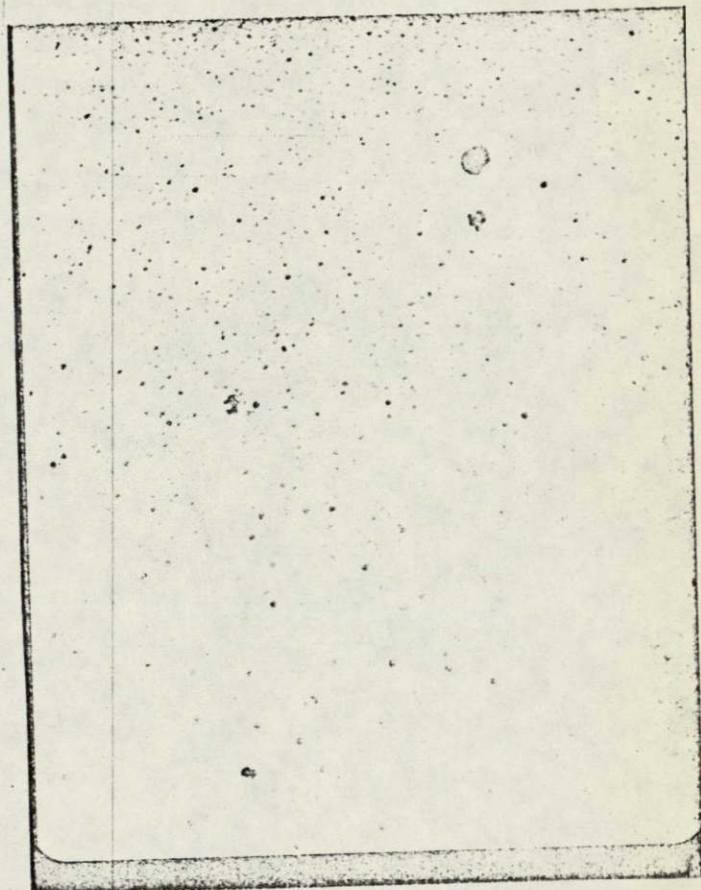
Spots tested greater than  $10^5$  times at <sup>a</sup>nominal temperature of  $340^{\circ}\text{C}$  are shown in Figures III-2a, b. The test pattern can be identified by three written spots to the left of the matrix of written spots. Note that there are no unswitched residuals evident. During this experiment the dimensional stability of the equipment was no better than it was during the foregoing experiment at  $250^{\circ}\text{C}$ . Therefore, we would conclude that a spot of slightly larger size than the written spot but no larger than a minimum domain width can be erased.

NOT REPRODUCIBLE



$1\frac{1}{2}$  min 153B  $2 \times 10^5$  @  $340^\circ\text{C}$   
10-2A-69 1250x

(a)



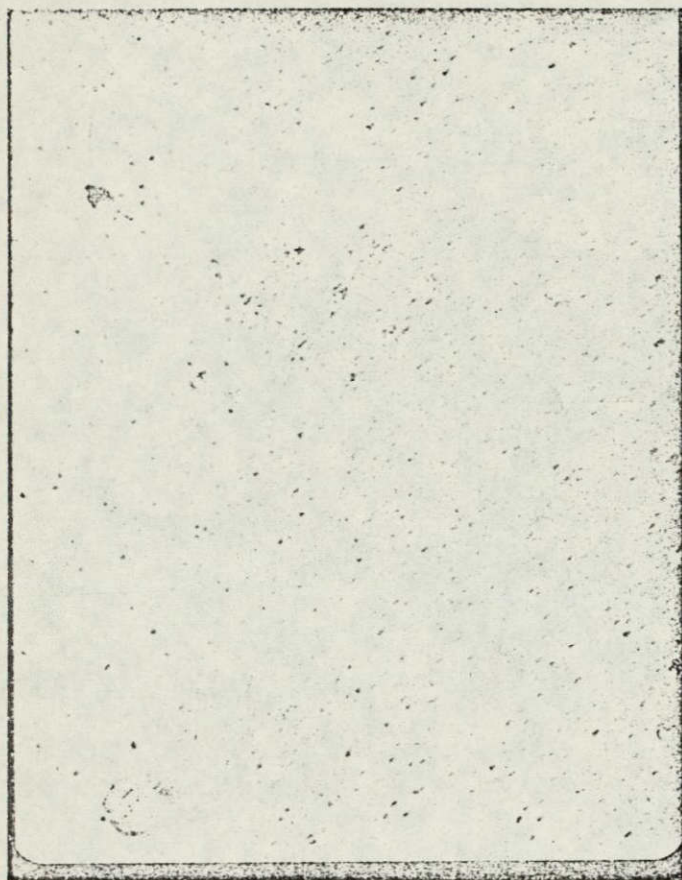
2 sec 153B  $2 \times 10^5$  @  $340^\circ\text{C}$   
un pol light 1250x  
10-1-69

(b)

Repeated Cycling Experiments at Nominal temp. of  $340^\circ\text{C}$

FIGURE III-3-

NOT REPRODUCIBLE



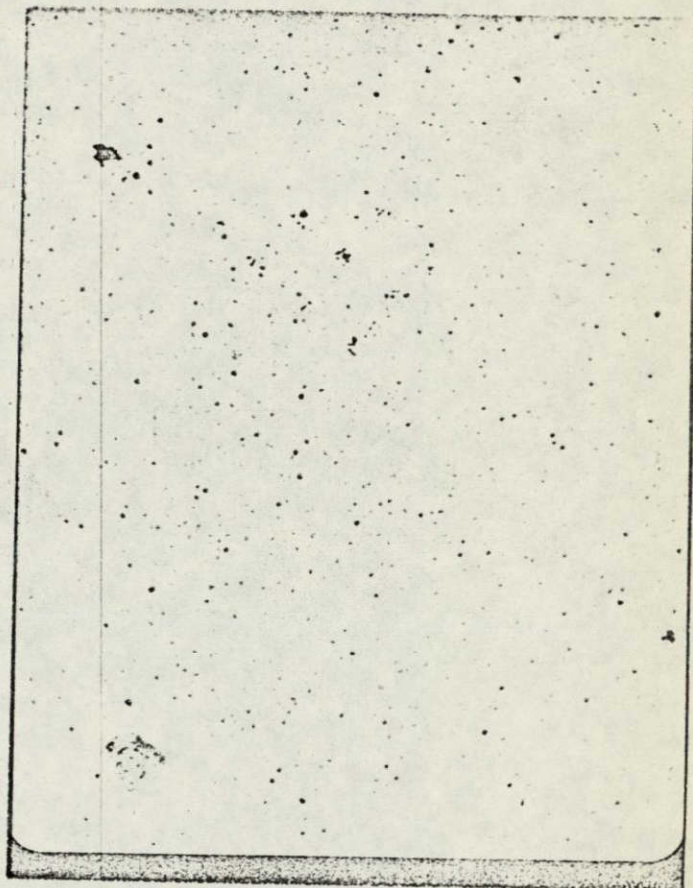
1/min

9-30-67

155B 1250x

2K05 @ 250°C

(a)



2Sec

9-30-69

Unpol.

155B 1250x

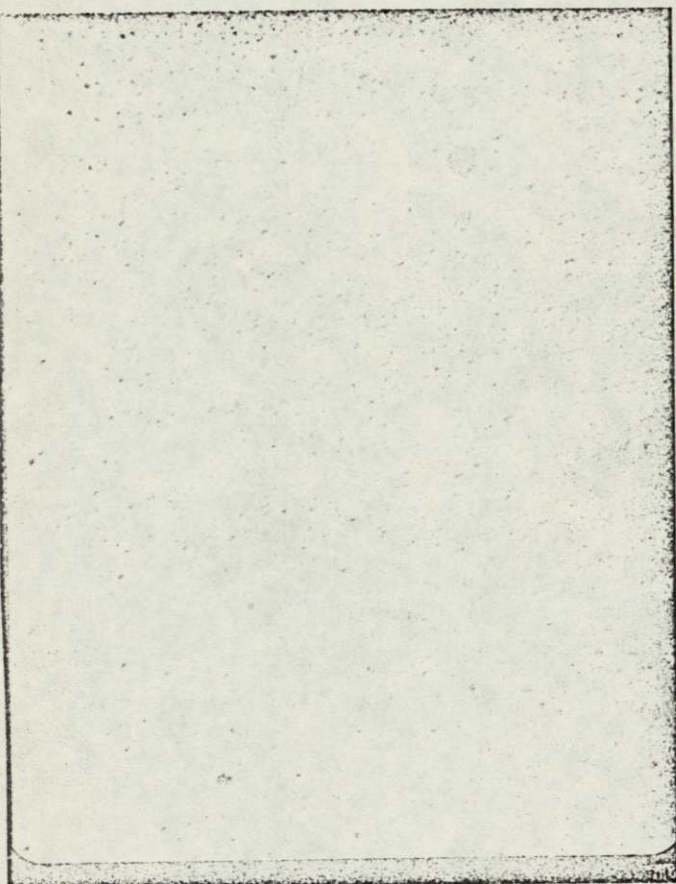
2K05 @ 250°C

(b)

Figure III-2

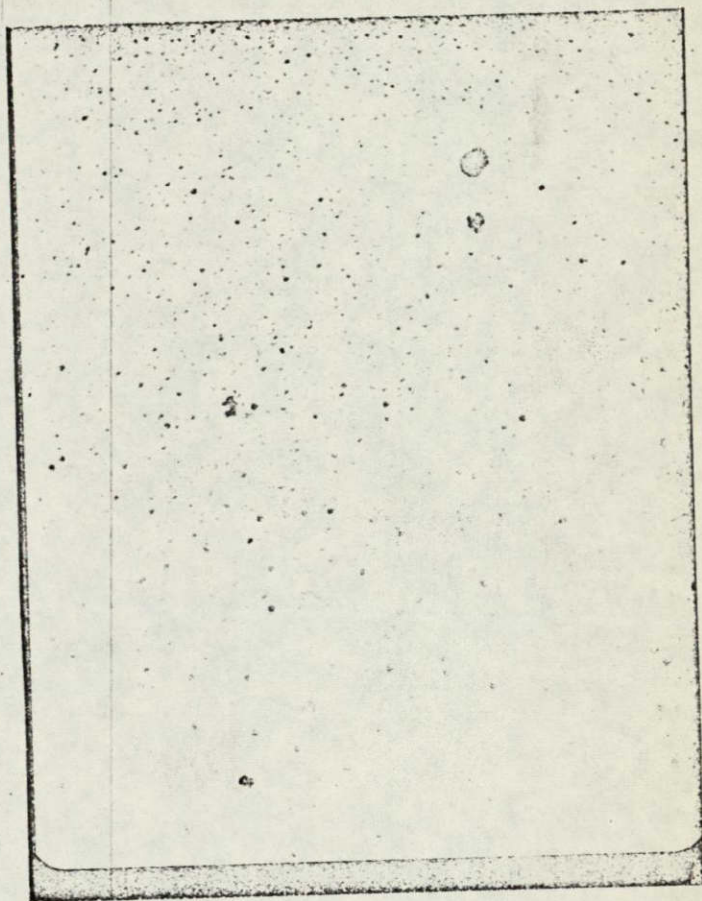
Repeated Cycling Experiments at Nominal temp. of 250°C

NOT REPRODUCIBLE



$1\frac{1}{2}$  min 153B  $2 \times 10^5$  @  $340^\circ\text{C}$   
10-24-69 1250x

(a)



2 sec 153B  $2 \times 10^5$  @  $340^\circ\text{C}$   
un pol light 1250x  
10-1-69

(b)

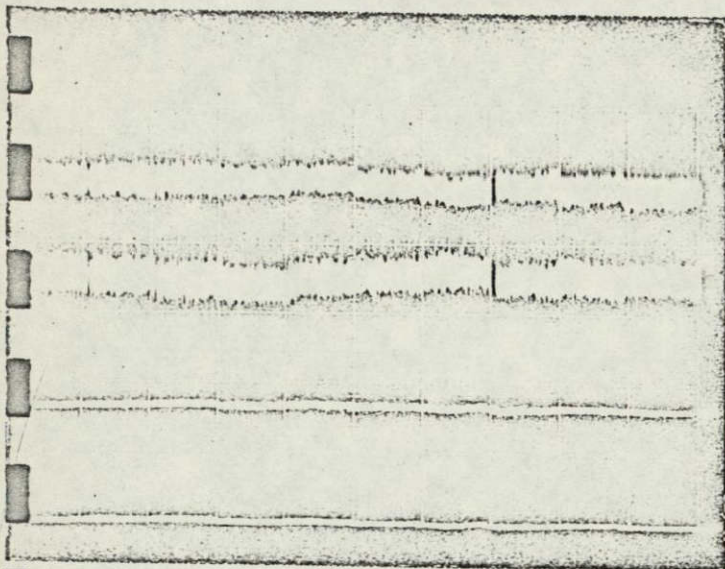
Repeated Cycling Experiments at nominal temp. of  $340^\circ\text{C}$

FIGURE III-3-

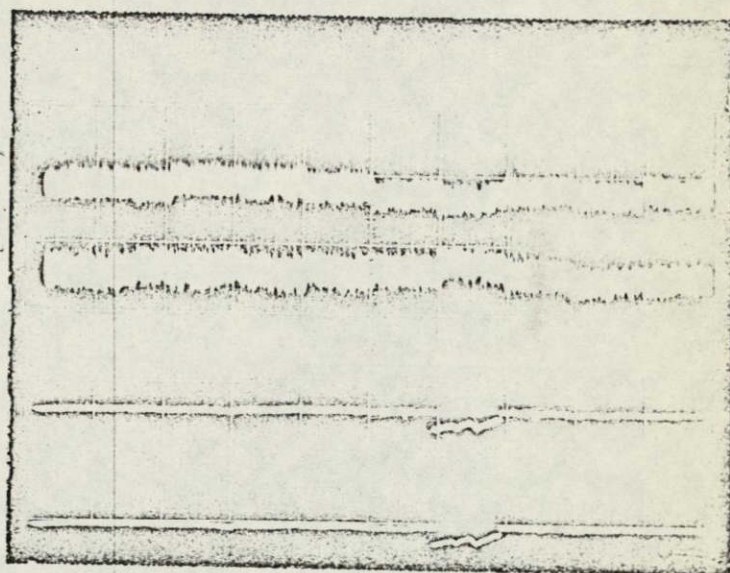
The location of the test pattern can be identified by the black spot with two protrusions to the left. Note that in this case there is no evidence of damage in photograph Figure III-2b taken under unpolarized light. The readout signal on the oscilloscope did show some evidence of degradation during the test. We would conclude from this experiment that there was no visible physical damage to the film due to repeated cycling during this experiment.

More recently, an improved test system with better rigidity and therefore much reduced misregistry problem was used to repeat the cycling experiment. Operating at  $250^{\circ}\text{C}$ , a normal phase film (film no. M-330-7) was tested through write-read-erase-read cycles at a rate of 400 cycles per second. The writing power level was 5.5 mwatt, about 10% over threshold and erasing field was 500 Oe with a spot size of approximately  $2\text{ }\mu\text{m}$  diameter. ~~In~~ <sup>shown</sup> Fig. III-4 <sup>from</sup> four photographs of the oscilloscope display of the readout ~~of~~ <sup>from</sup> signal ~~on~~ written and erased conditions on the same spot ~~was shown~~. The differential readout signal is also fed to a thresholding device which provides TTL compatible output. This output is shown in the two lower traces in each picture. The time scale was  $2 \times 10^{-3}$  cycles/cm. The photographs were taken in a sample-and-hold mode, giving 10% sampling read-out. Therefore, each photograph covers a quarter million cycles. The signal displayed at Fig. III-4 (C) shows no deterioration after  $10^6$  cycles of exercising or  $2 \times 10^6$  <sup>temperature excursions to above the Curie Temperature.</sup> Curie-point-writing.

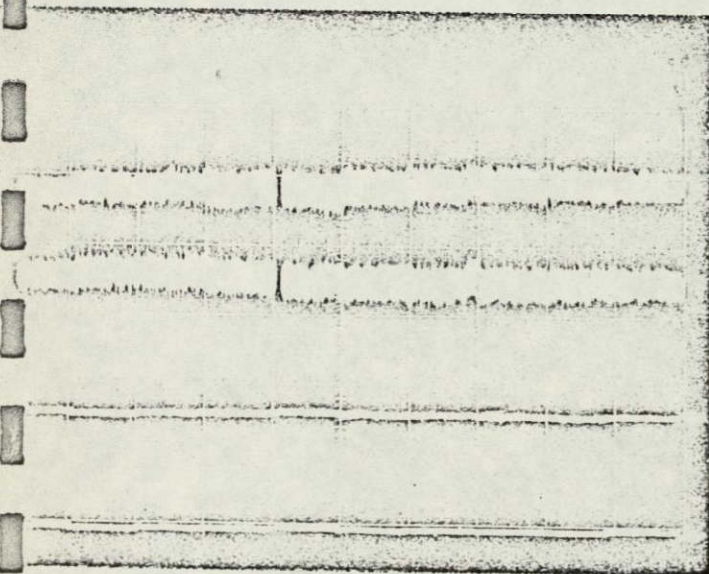
NOT REPRODUCIBLE



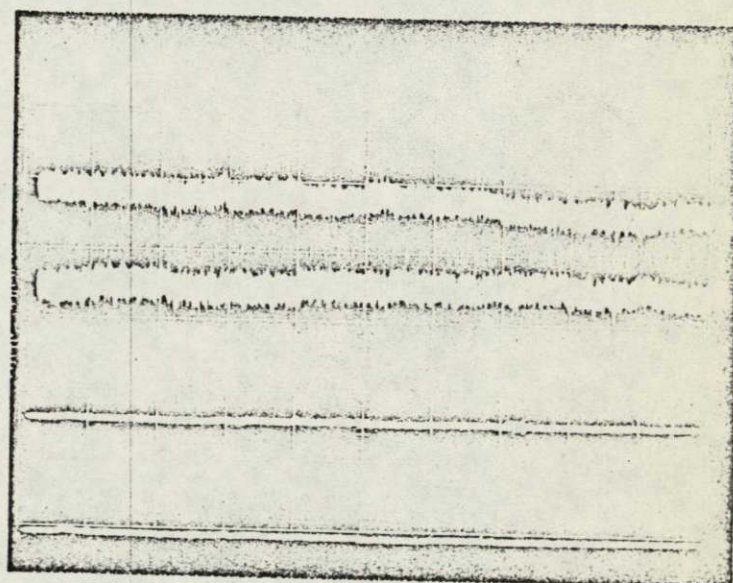
(a)



(b)



(c)



(d)

Fig III-4

### 3. Temperature Dependence of Readout Signal

Among the physical properties that affect the memory read-out characteristic is the temperature dependence of the magnetization and the resultant Kerr effect. The readout signal from a differential detector system can be analyzed as follows using the Jones calculus.<sup>15</sup>

$$\begin{pmatrix} E_x' \\ E_y' \end{pmatrix} = \begin{pmatrix} \cos^2 \alpha & \cos \alpha \sin \alpha \\ \cos \alpha \sin \alpha & \sin^2 \alpha \end{pmatrix} \begin{pmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{pmatrix} \begin{pmatrix} \cos^2 \theta & \cos \theta \sin \theta \\ \cos \theta \sin \theta & \sin^2 \theta \end{pmatrix} \begin{pmatrix} 0 \\ E_y \end{pmatrix}$$

where  $\theta$  = analyzer angle with respect to beam polarization,  $\phi$  = Kerr rotation  
 and  $\alpha$  = angle between the axis of extinction of polarizing beam splitter with  
 respect to beam polarization. Thus,

$$\begin{pmatrix} E_x' \\ E_y' \end{pmatrix} = \begin{pmatrix} E_y \sin \theta \cos \alpha \cos(\alpha - \theta - \phi) \\ E_y \sin \theta \sin \alpha \cos(\alpha - \theta - \phi) \end{pmatrix}$$

The intensity at the two detectors becomes

$$I_1 = I_0 \sin^2 \theta \cos^2 (\alpha - \theta - \phi)$$

and

$$I_2 = I_0 \sin^2 \theta \cos^2 (\alpha - \frac{\pi}{2} - \theta - \phi) \text{ for } I_0 = E_y^2.$$

where  $\phi$  is the Kerr rotation for a saturated film.  $\phi$  is a function of temperature as is magnetization. When the system is in balance,  $\alpha - \theta = 45^\circ$  so that

$$I_1 - I_2 = I_0 \sin^2 \theta (1 - 2 \cos^2 (\frac{\pi}{4} \pm \phi))$$

where "+" sign applies to a "0" bit and "-" for a "1" bit. The signal is actually contained in the last term, but the total intensity must be used for noise calculations.

So far, this analysis assumes that the film switches uniformly over the whole area illuminated by the read beam. When the same beam is used for reading and writing, the actual written spot diameter is less than the Gaussian beam diameter. Hence, the area contributing to the signal difference  $I_1 - I_2$  depends upon the area switched. We define a factor  $K(a/w_0)$  with which to multiply the readout signal difference to make the adjustment. The factor  $K$  is obtained by integrating the beam intensity distribution over the written spot giving,

$$K(a/w_0) = \frac{4}{w_0^2} \int_0^a r e^{-2r^2/w_0^2} dr = 1 - e^{-2a^2/w_0^2}$$

where  $a$  = radius of the written spot and  $w_0 = 1/e^2$  beam radius.

The power distribution is proportional to  $\exp(-2a^2/w_0^2)$  and we assume that the spot radius  $a$  is governed by the point in the distribution reaching the Curie temperature. For the normal phase, we have

$$\frac{360 - T_f}{446 - T_f} = e^{-2a^2/w_o^2}$$

where  $T_f$  is the operating temperature.

Then we can write for the readout signal,

$$\Delta I = 2I_o \sin^2 \theta' \left[ \cos^2 \left( \frac{\pi}{4} + \phi(T) \right) - \cos^2 \left( \frac{\pi}{4} - \phi(T) \right) \right] \left[ 1 - \frac{360 - T_f}{446 - T_f} \right]$$

The temperature dependent portion of this equation is plotted in Figure III-<sup>5</sup>~~4~~ assuming a maximum Kerr rotation of  $2^\circ$ . It shows a peak in the readout signal level at about  $250^\circ\text{C}$ . This has been observed experimentally on a film with a somewhat smoother decrease in the Kerr rotation with temperature, which tends to shift the peak toward lower temperatures. An increase of about a factor of two in the readout signal can be obtained by operating the film in the temperature range about  $250^\circ\text{C}$ .

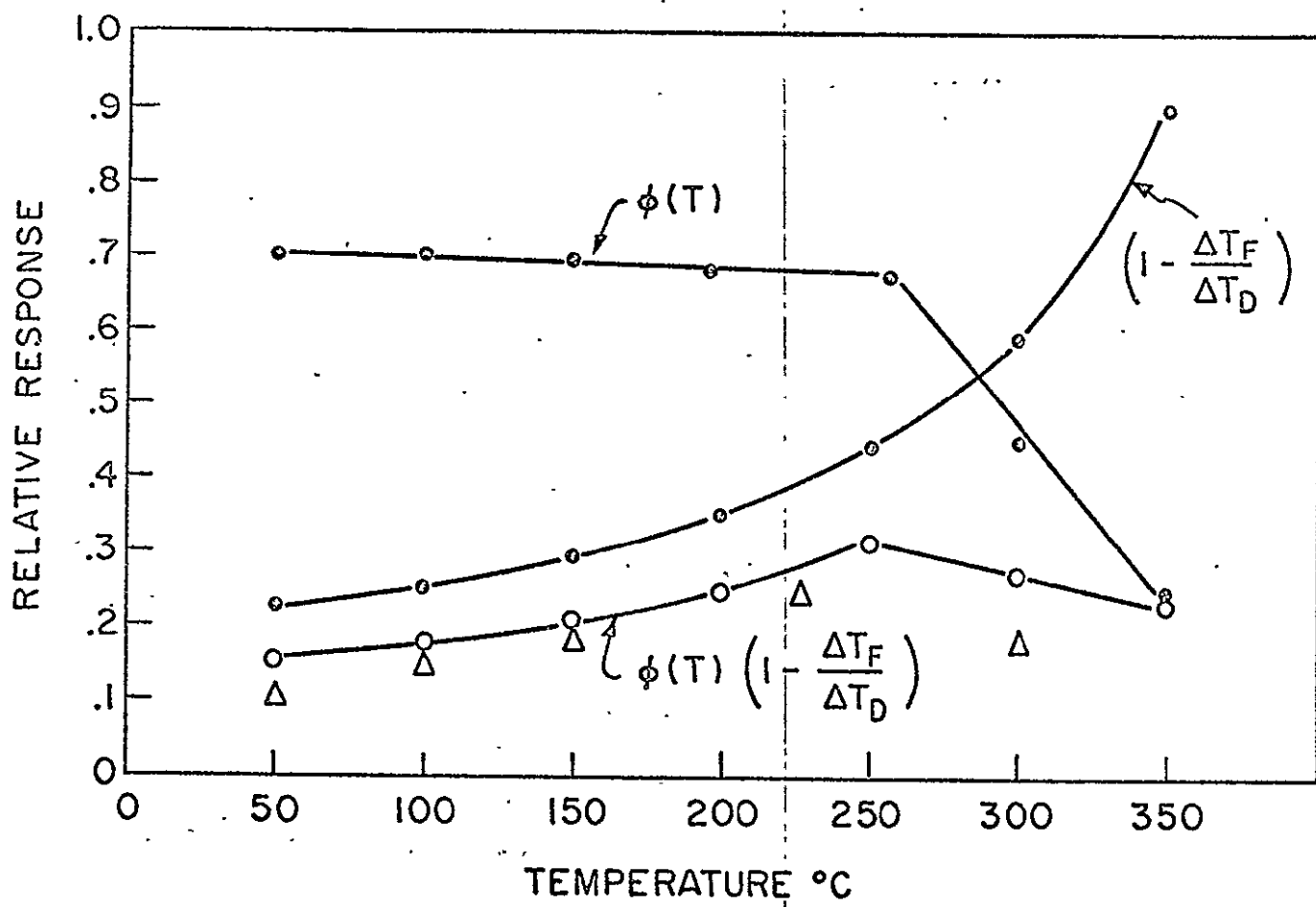


Fig. III-5

#### 4 Erasure Field and Demagnetizing Field Effect

We have measured the switching characteristics of a Curie point written spot of approximately 2  $\mu\text{m}$  diameter on MnBi films. The measurements were made by periodically heating a spot within a laser pulse and applying a magnetic field pulse on alternate cycles. The peak magneto-optic signal from the Kerr effect read-out was observed as a function of magnetic field applied during both erasure and writing. Measurements were made on the same film with the sample in the normal and quenched phases and in saturated and unsaturated conditions. The results are shown in Fig. III-6. In this figure the normalized signal which is the signal difference between a perfect write and erase normalized to the signal for a perfect write, is plotted as a function of the erasure field. The field required for a perfect erasure for <sup>the</sup>normal phase and quenched phase film is seen to be 600 and 300 Oe respectively.

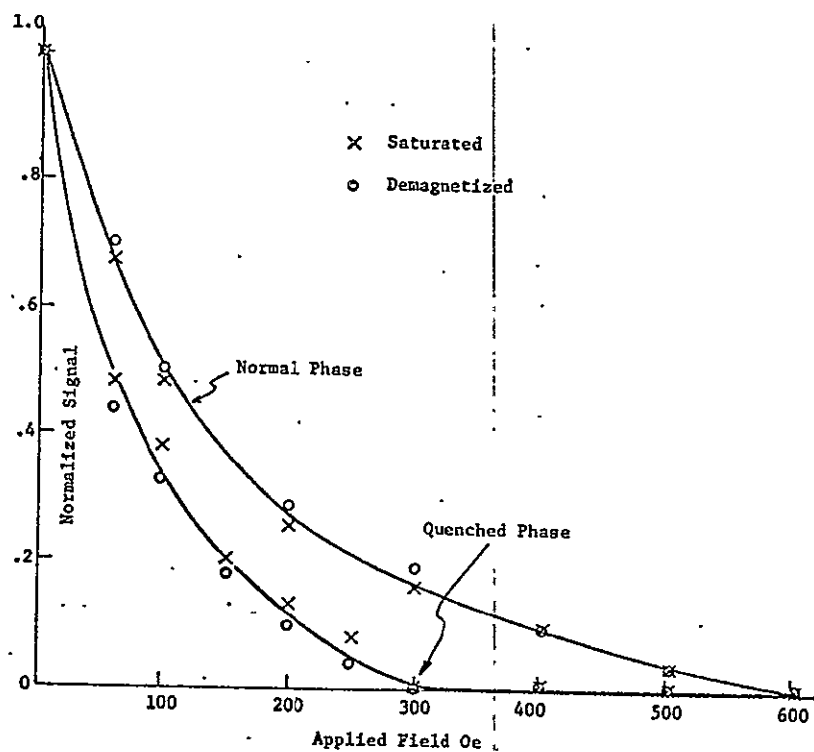


Figure III-6 The Normalized magneto-optic Kerr effect signal as a function of applied magnetic field for spots Curie-point written on MnBi films in the normal and quenched phase and in the saturated and demagnetized condition.

However, the gradual change of the signal as a function of the applied field indicates possible trade-off between read-out signal and the required erasure field.

*time dependent*

A ~~time-dependent~~ calculation of the demagnetizing field profile produced by a film of MnBi inside a spot on the film which was heated above the Curie temperature was performed by Mr. E. Bernal G. of this laboratory. The calculation was performed using two layers of poles to represent the film. The temperature profile of the heated spot at  $t = 0$  was assumed to be gaussian, which is a good approximation to the profiles produced by laser heating<sup>16</sup>; for  $t > 0$  the temperature distribution was obtained as a solution of the heat-flow equation for an unbacked film. The measured temperature dependence of the magnetization for both crystallographic phases of this material were used in the calculation. The spatial dependence of the field within the non-magnetic area was obtained as a function of time.

The calculated values of demagnetizing field maxima are in good agreement with the measured values of external magnetic field that must be applied in coincidence with a laser pulse in order to erase a written spot. The agreement is good for spot erasure in films of either crystallographic phase.

The calculated values of demagnetizing field and the measured values of external magnetic field that must be applied in coincidence with a laser pulse in order to completely erase a written spot are in good agreement. This agreement is critically dependent on the temperature dependence of the magnetization of the films.

Other features of the time-dependent results obtained also appear to explain features of the partial erasure of spots heated in the presence of external magnetic fields. The success of the calculation in predicting erasure fields and other features of Curie-point switching lead us to believe that the demagnetizing field is the dominant factor determining the magnetization direction in laser beam writing in manganese bismuth.

## 5 Retention of Information

There has been no evidence of the spontaneous loss of stored information from MnBi films in either phase of the material from room temperature to  $300^{\circ}\text{C}$ .

Although <sup>the</sup> quenched film transforms back to the normal phase, the magnetization

direction remains unchanged by the process. <sup>Therefore there is no loss of information in this phase transition.</sup> Cooling of films in liquid nitrogen

will cause them to become demagnetized, however. Also, films become demagnetized

when heated through the Curie temperature. The operation temperature of this

medium is therefore limited to between  $77^{\circ}\text{K}$  and  $633^{\circ}\text{K}$ . Observations on the

retention of information were made visually with a polarizing microscope of high

resolution. Films, with written information bits written two years ago, were

found to retain all the information. These films were stored, in air at room temperature.

## 6. Effect of Film Overcoating

The importance of the SiO coating on the MnBi films was discussed in the previous section. The primary function of the coating is protection of the MnBi. A very useful modification on this coating procedure is an optimization of the surface reflectivity (at  $6328\text{\AA}$ ). The memory exerciser is sufficiently sensitive to this change in reflectivity that it notes a change in threshold power. One test involved measuring write threshold power of a sample at minimum reflectivity; then recoating it for maximum reflectivity and evaluating it; and then recoating it back to the original minimum. Results were fairly conclusive concerning power deliverable to the film, as well as evidence indicating the maximum reflection generated excessive noise in the signal detection system. Preliminary results indicate this effect to be larger than the Mn to Bi ratio effect on threshold power. In Fig. III-7, a sample trace of recorder chart monitoring the reflectivity as a function of overcoating SiO film thickness is plotted. The cut-off point was set when the SiO coating was three quarters of a wavelength thick. The threshold laser writing power level  $P_{th}$  in mwatts is tabulated in Table III-1 for two films tested as a function of the SiO overcoating thickness.

Table III-1

| SiO<br>Thickness | $P_{th}$ in mwatts |                          |
|------------------|--------------------|--------------------------|
|                  | 6" Disc<br>G-7-292 | 5/8" diameter<br>M-512-5 |
| $1/4\lambda$     | 1.9                | 2.2                      |
| $1/2\lambda$     | 3.8                | 4.1                      |
| $3/4\lambda$     | 1.9                | 2.2                      |

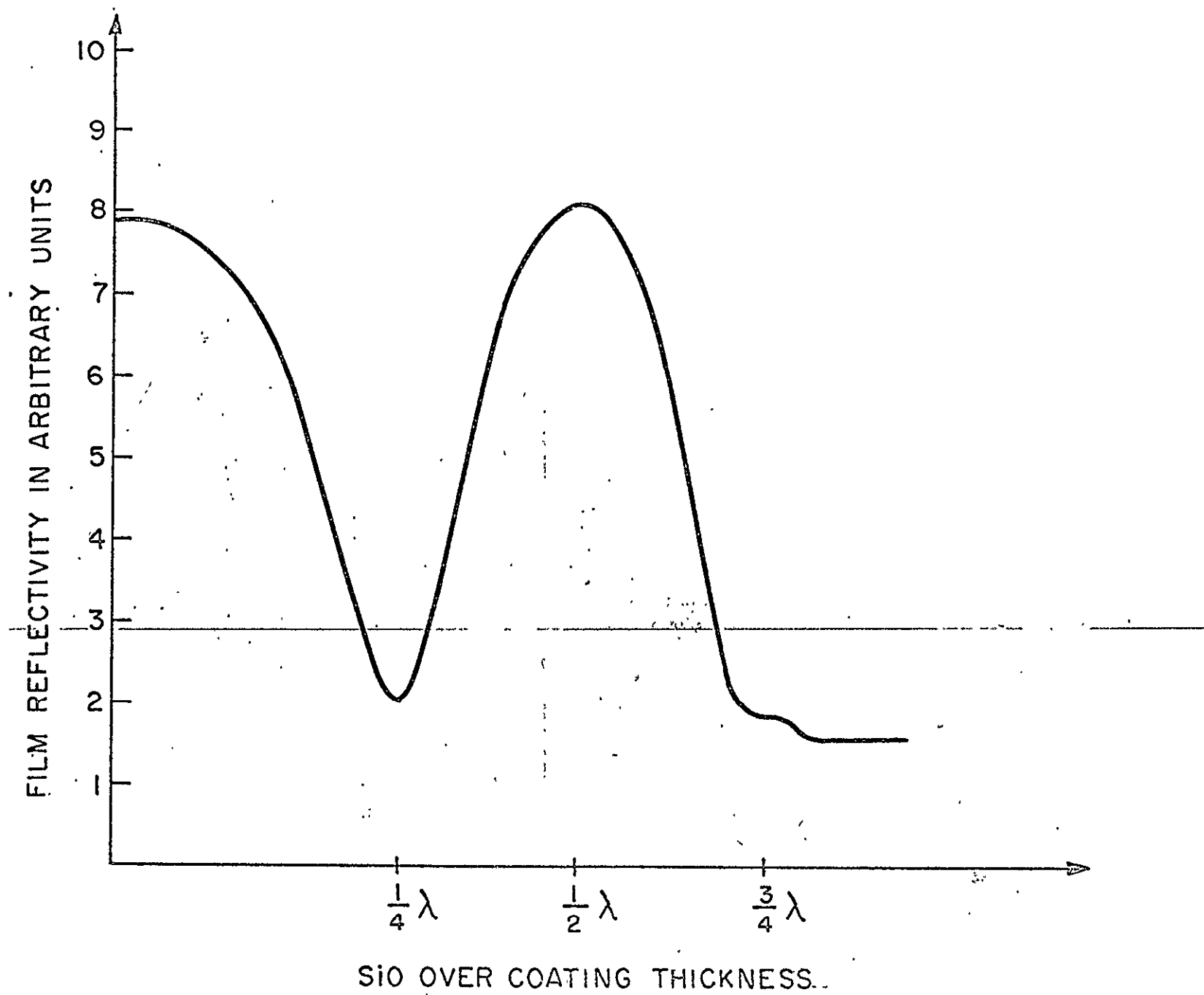


Fig III-7

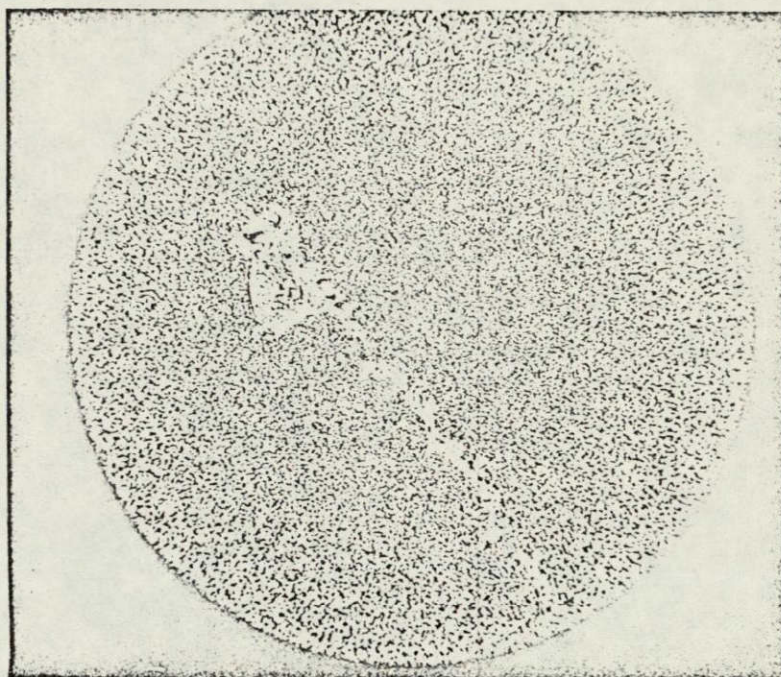
We may conclude that a laser writing threshold power can be reduced by a factor of two for films of coating for minimum reflectivity as compared to those for maximum reflectivity. The detector output signal to noise ratio is also improved for films of minimum reflectivity.

*Evolution of*  
 B. *Large MnBi Films*

1. Preparation and Optical Examination of 6" Diameter MnBi films.

Films of MnBi are prepared by vapor deposition on glass substrates. The evaporated layers of manganese and bismuth are subjected to a prolonged heat treatment during which the magnetic MnBi is formed. To insure uniform vapor distribution, a planetary motion was maintained on the substrate during vapor deposition. A protective layer of either  $MgF_2$  or  $SiO_2$  is evaporated on top of <sup>the</sup> MnBi. MnBi films thus prepared are polycrystalline but oriented with the crystallographic c-axis perpendicular to the substrate surface.

After deposition and vacuum anneal, the 6" MnBi discs are in a demagnetized state. Using the Faraday effect the magnetic domains in these films can be examined. This is an invaluable means of assessing the film's quality and of providing information for film improvement. For example, by examining magnetic domains at various defect spots, it is possible to distinguish whether the defect was inherent in the glass substrate or introduced during the cleaning operation. In general, the magnetic domain size and geometry do not change across defects of the first type (see Fig. <sup>III-8</sup> ~~17~~). On the other hand, stain marks left during substrate cleaning result in large magnetic domains in that area (See Fig. <sup>III-9(a)</sup> ~~18a~~). Fig. <sup>III-9(b)</sup> ~~18b~~ is a picture of the same area as in Fig. <sup>III-9(a)</sup> ~~18a~~ taken under ordinary transmitted light. Dust particles can be clearly seen here. Pinholes are relatively small in size and low in number. Fig. <sup>III-10</sup> ~~19~~ depicts the general appearance of the pin holes at 25X. A pinhole (at A) and a dust particle (at B) are visible in this area of the film.

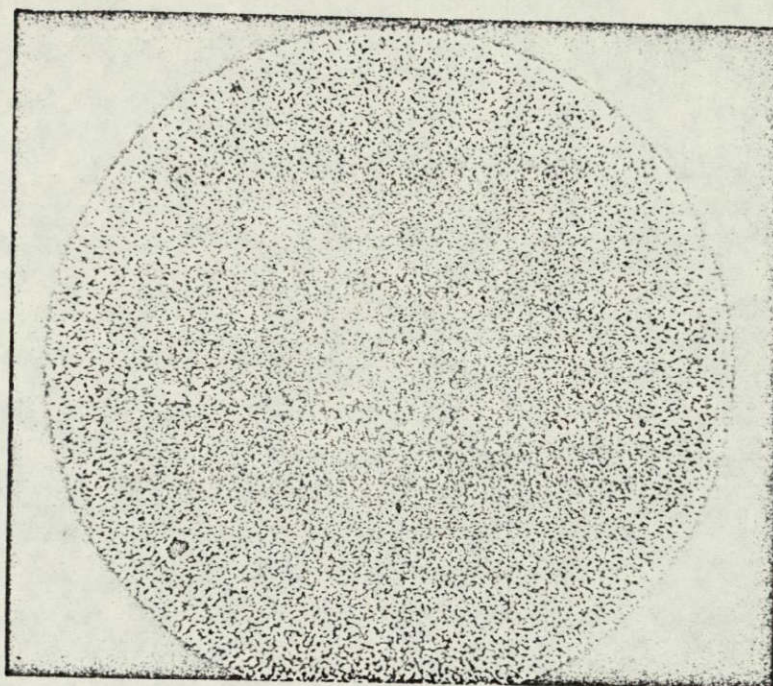


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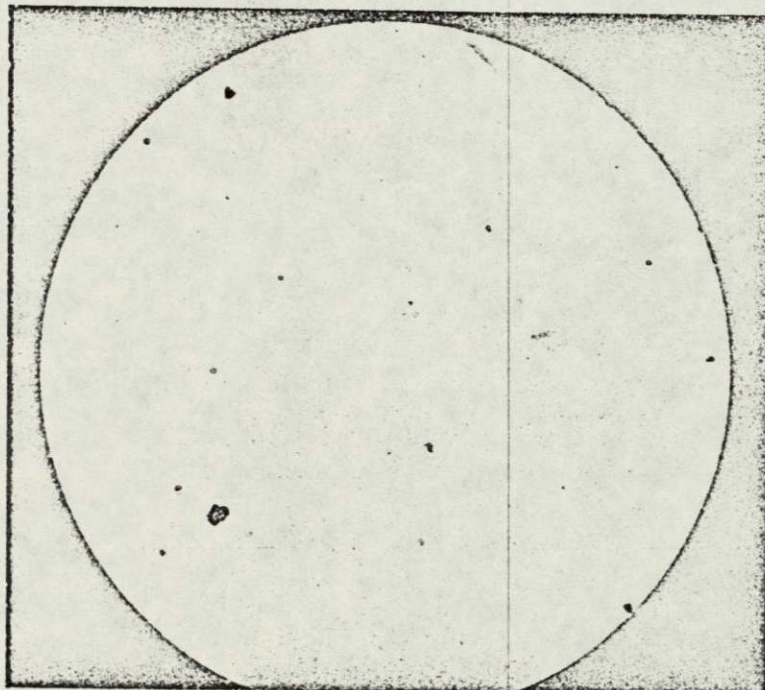
1

II-8

III-8



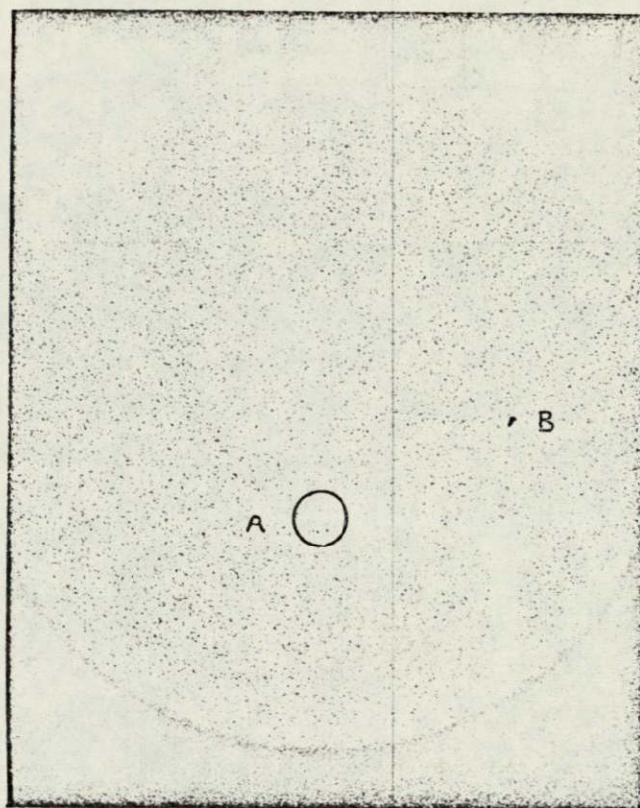
(a)



(b)

Fig. 1

III-9  
II-82



~~Fig. 47~~

III-10  
~~II-24~~

## 2 Exerciser Testing *08*

### Film Uniformity

Manganese bismuth films have been prepared on 6 inch diameter substrates in a band 1 inch wide around the outside circumference. These films are overcoated with SiO and visually they appear to be perfectly uniform.

A fixture was constructed to hold these discs in the memory exerciser and heat them to <sup>near</sup> ~~the vicinity just below~~ the Curie temperature. The fixture can be rotated and positioned such that nearly any area on the film can be in the field of the focusing lens.

Memory exercise experiments are performed over randomly selected areas of the 6" disc. A test consists of raising the write power and the erase field to a level giving a good readout signal, and then exercising a 16 x 16 bit pattern by writing and erasing 8 times. The total number of switches <sup>in</sup> ~~for~~ a test pattern is then 1448. A bi-directional counter is used to count the "0" and "1" counts for the test pattern. If the pattern is perfect the count ends at zero. If it is not perfect, a residual count remains in the counter at the end of the test.

Eight samples have been tested in this manner. The test result is summarized in Table III-2. The column  $\bar{X}$  is the mean number

TABLE III-2

| Film #     | $\bar{X}$ | $\sigma$ | $P_{\min}$ | $H_{\text{erase}}$ |
|------------|-----------|----------|------------|--------------------|
| G6 271     | 4.2       | 12.3     |            |                    |
| G7 261 (a) | 7.6       | 13       |            |                    |
| G7 261 (b) | 14.2      | 12.2     | 40         |                    |
| G7 292     | 28.2      | 102      | 50         | <1000              |
| G7 296     | 90.5      | 110      | 50         | 750                |
| G7 301     | 19.8      | 30       | 40         | 750                |
| G7 302     | 6.9       | 3.3      | 30         | 750                |

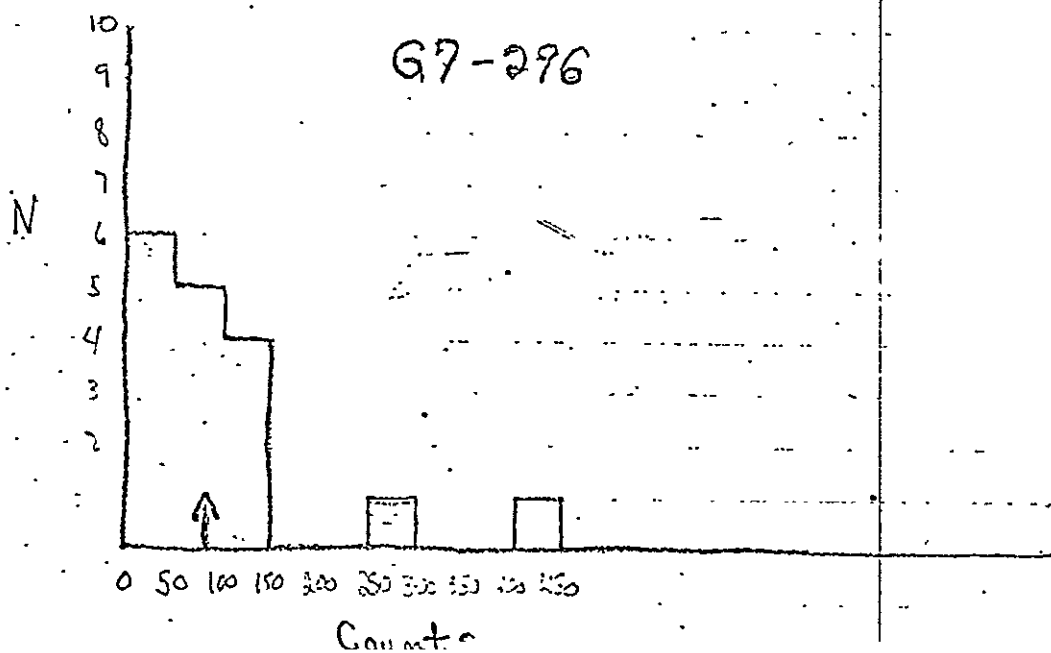
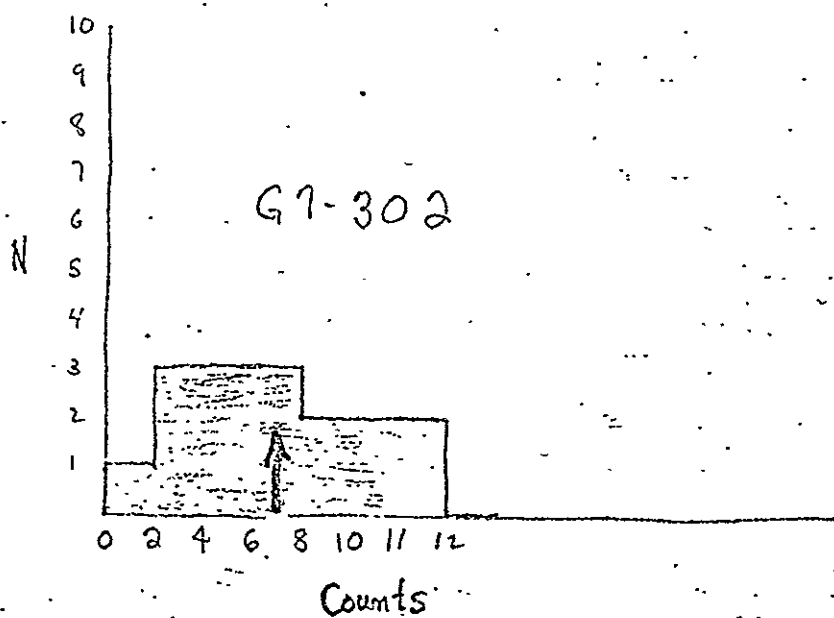
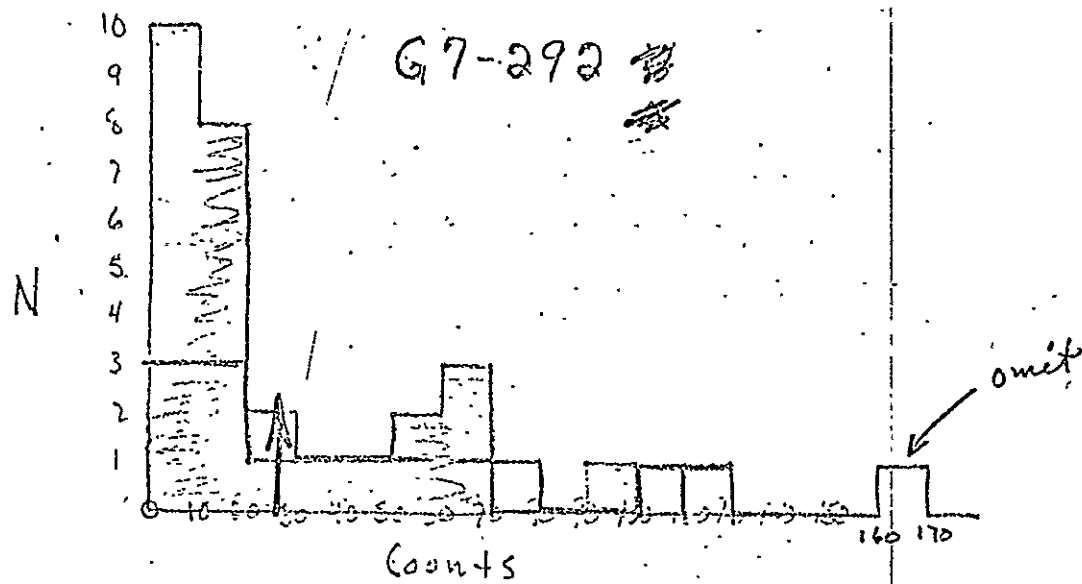
of counts missed per pattern,  $\sigma$  is the standard deviation from the mean,  $P_{\min}$  is a measure of the relative power required to write and  $H_{\text{erase}}$  is the field required to completely erase in Oe.

The first two discs yielded many patterns with no missed bits. A large standard deviation results because missed counts came in large batches rather than being distributed throughout the sample patterns. Subsequent samples were tested with a poor signal-to-noise ratio in the electronics. Disc G7 261 (b) is a duplicate run under poor signal conditions. We note that the mean is shifted but the standard deviation has remained about the same as it was for the better test conditions.

Discs G7292 to G7301 appear to be similar to the first two discs in quality. The last disc gives<sup>a</sup> different result. We believe that it is of better quality because the standard deviation is smaller than the mean. The large mean missed counts are due to poor signal-to-noise ratio rather than defects in the film. The S/N problem must be resolved, but the data is presented to illustrate how we can differentiate between film defects and poor S/N.

Our general conclusions about the quality of the films are as follows. Faults are restricted to localized defects like pin holes or dust particles. These flaws constitute much less than 1% of the film area. Microscope observations show many of the defects to be associated with the cleanliness of the substrate on which the MnBi film was deposited. Finally, the memory characteristics (write power, erase field and S/N) appear to be uniform over the surface of the "6" diameter film to within a few percent.

A histogram of the number of locations showing a designated number of missed counts is shown in III-11 along with an arrow at the mean. The important feature is the location of the mean with respect to the most frequent number of missed counts. When the peak is to the left of the mean as G7-292 and G7-396 are the missed counts are more probably due to pinholes. Whereas, when the peak and the mean coincide<sup>or G7-302</sup> the missed are more probably due to poor signal-to-noise ratio.



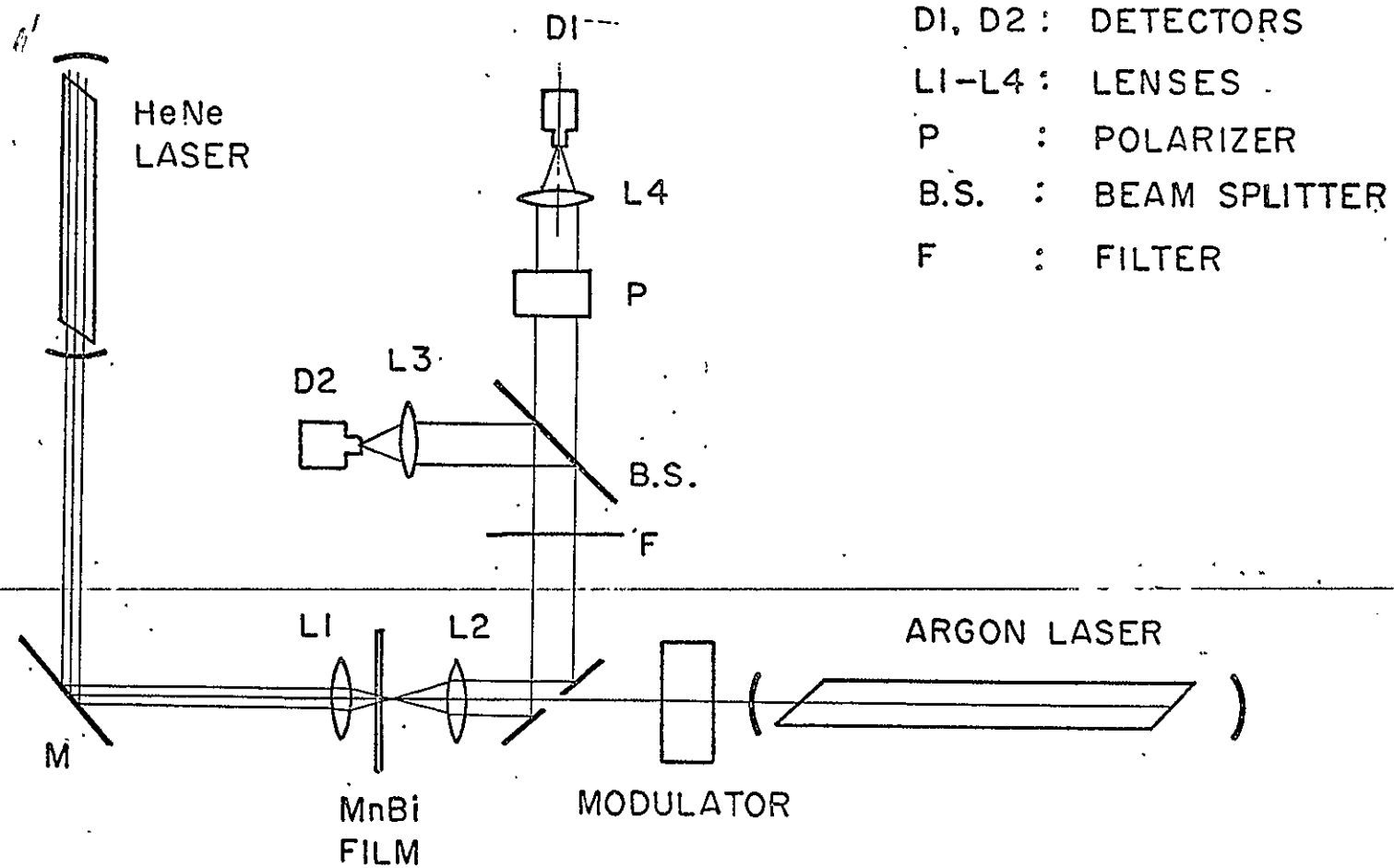
Histogram of missed  
counts  
III - 11

### C. Laser Curie Point Writing Mechanism experiments.

The time interval during laser Curie point writing and erasing operation is typically <sup>of</sup> the order of microseconds. It is evident that the writing mechanism is dynamic in nature. The static phase transformation study discussed in the previous section cannot be adequately extended for the understanding of the dynamic writing and the consequent phase transformation mechanism. However, it is essential to obtain a thorough understanding of the writing mechanism because:

- (1) A mathematically model of the writing and erasing mechanism is a necessary tool for the trade-off study in the systems design effort.
- (2) The limitation of repeated writing cycling without <sup>a</sup> phase change could be extended by suitable adjustment of the writing conditions, if the dynamic process of the phase change is known.
- (3) The knowledge of the writing mechanism can guide our materials research effort in both the doping and other material improvement studies to achieve long term stability.

With these reasons in mind, we have devised a two-beam experiment for this study. An argon laser operating at <sup>5145</sup> 4880 Å wavelength and at a power output of about 100 mwatts was used to write 7 μm spots on MnBi film. A HeNe laser <sup>>1</sup> of 1 mwatt power level focused to 2 μm spot size was used to probe into the spot being written by the argon laser. The magneto-optic Faraday effect of the film modifies the polarization direction of the probing beam, which was analyzed and detected. In this manner, the magnetization within the spot being written can be monitored on a real time basis. Fig. (III-12) shows the

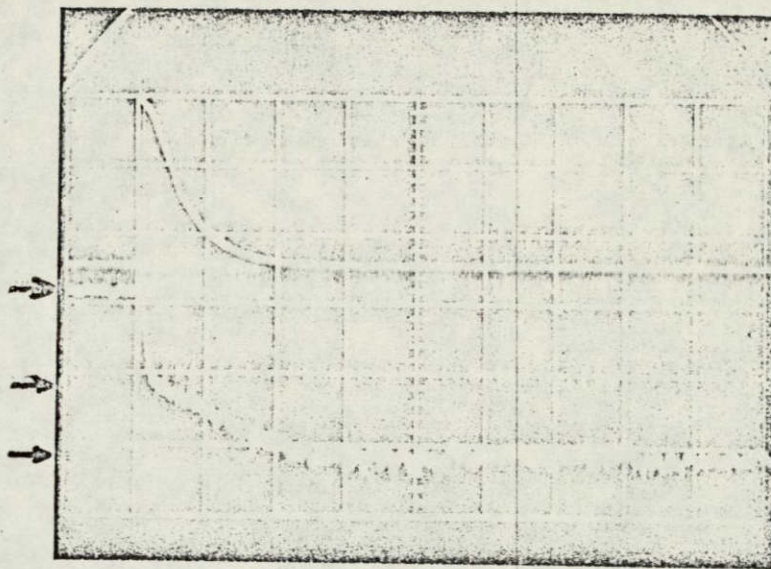


schematic of the experimental arrangement. The modulator used for switching the argon laser was a liquid Kerr cell with a rapid rise and exponential decay pulsing network. The decay time constant is approximately  $10\mu\text{sec}$ . This long decay time is used so that the details of the time dependence of magnetization switching can be more clearly monitored.

Experimental measurements are still being refined. However, a preliminary result displayed on a dual beam oscilloscope is shown in Fig. (III-43). The upper trace shows the time dependence of the writing argon laser pulse. The lower trace gives the detector output monitoring the read beam polarization direction. The time scale for both traces are  $10\mu\text{sec}/\text{cm}$ . There are three arrows marking the levels of the read beam. The top arrow indicates the level for the read beam with the spot unswitched. The center arrow is for the level when the spot loses its magnetization. The lower arrow indicates the level for a completely switched (or written) spot.

From this result, we can conclude that the spot rapidly loses its magnetization during the Curie point writing process. Magnetic switching was accomplished at that instant. However, because of the slower physical process in the recovery of magnetization, the full value of the reversed magnetization was not realized before a time lapse long beyond the end of the heating pulse. One obvious implication of this result is that a time lapse of the order of  $10\mu\text{sec}$  should be allowed between writing and reading on the same spot to allow proper recovery of <sup>the</sup> magneto-optic effect.

Detailed information in regard to the phase change during writing is now being carefully examined. This requires considerable refinement of the experimental technique.



NOT REPRODUCIBLE

Fig III-13. Dual beam display of <sup>the</sup>  $\Lambda$  laser Curie point writing process on <sup>an</sup> MnBi film. The upper trace monitors the writing <sup>Argon</sup>  $\Lambda$  laser output and <sup>The</sup> lower trace monitors the magneto-optic Faraday rotation within the spot being written using a probing HeNe laser beams. Time scale for both beams: 10  $\mu$ sec/cm

## D. ~~THE~~ Environmental Effects

### Radiation

A normal phase MnBi film on a mica substrate with 2000Å of SiO was used in a radiation test. Magneto-optic information in the form of Curie-point written bits was stored on the film. The film was then placed in a cobalt bomb at 115 mr/hr for 410 hours giving a total of 47.15 rads. Subsequent microscopic evaluation showed no change in the film or its stored information.

### Humidity

Normal phase films with SiO<sub>2</sub> overcoating stored at room temperature where the relative humidity is >50% show no degradation over a period of several weeks. Samples stored at elevated temperatures (>100°C) can survive boiling water placed on them with no obvious effect. The usefulness of the SiO coating, as mentioned above under "aging", is of prime interest here also. Preliminary results indicate that good quality coatings are a requirement. This good quality overlayer must also extend beyond the edge of the MnBi to guarantee a good seal.

### Temperature

Film temperature environment test was performed in a series of tests at 340°C on films in air and partial vacuum and with varying thicknesses of SiO coating. Obviously tests at this temperature exclude quenched films. Tests were held below the Curie temperature to avoid loss of information. This allowed running some of the retention tests and the aging tests simultaneously. Films with thin SiO (~2000Å) protective layers deteriorated in air at 340°C in less than one day. Nearly identical films were used in tests where control samples were needed. A pair of these films were run one in air and one in partial vacuum (~1 micron Hg) to test the possibility of deterioration from within MnBi

under the SiO. Results indicate that contact of film to air through imperfections in SiO coating to be the problem. Other control samples were recoated to thicker SiO ( $\sim 11000\text{\AA}$ ) and subjected to the same  $340^{\circ}\text{C}$  test in air. Exposure >1 week produced deterioration only where there were holes in the coating. Some intentional scratches thru the coating substantiated the type of film breakup caused by SiO coating imperfections, giving another verification to the source of deterioration. From this experiment, we conclude that using a SiO protective coating free from imperfections, film will not deteriorate even at an operating temperature of  $340^{\circ}\text{C}$ .

#### IV. Systems Study

The objective of this part of the optical memory investigation is to define an optical memory system in sufficient detail to allow boundary conditions to be placed on parameters of the storage materials under consideration. It must define the requirements of other portions of the memory besides the memory medium. The memory should have a capacity of  $10^{10}$ - $10^{12}$  bits.

Our initial goal was to develop a system involving no moving parts. Based on the state of the art of ~~the~~ beam deflection ( $3 \times 10^3$  spots in each dimension) and optical technology ( $10^7$ - $10^8$  resolvable spots for the focusing lens), it is now apparent that the inertialess optical memory approach can only provide  $10^7$ - $10^8$  bits of capacity. A multiplicity of  $10^2$ - $10^4$  units will be needed for a total  $10^{10}$ - $10^{12}$  bits. The complexity and cost will be prohibitive for such an approach.

Based on this discussion, we have been concentrating on a method of addressing requiring the simplest mechanical motion, namely a rotating disc or drum system. This type of mechanical motion is largely maintenance free and requires <sup>configuration</sup> very limited amount of power to drive.

The technology discussed in this section, to a large extent, will be directly applicable for an inertialess system when high performance beam deflectors and lens<sup>es</sup> with much larger flat field<sup>offering</sup> with orders of magnitude improvement over the present state of the art capabilities, become available.

In the following, we will discuss the general consideration of an optical memory system, the choice of memory medium, and geometric configuration, the specification of the proposed system which includes the design feature and required components, and some<sup>v</sup> of the MnBi holographic experimental work which was contributed by Dr. T. C. Lee of this laboratory. The holographic research is included to indicate the adaptability of MnBi films for this approach.

#### IV-A. General Considerations

A computer memory of high packing density and billion to trillion bit capacity has been a challenge for many years. An ideal embodiment of such a device would consist of no moving mechanical parts. Early concepts of a high capacity random-access mass memory employed an electron beam and a magnetic thin film storage medium.<sup>16, 27</sup> Presumably the electron beam could be deflected to a large number of discrete locations with ease. Some of the most recent work with electron beams in integrated circuit mask preparation has achieved half micron resolution over a 2 x 2mm square area.<sup>18</sup> This is only about half-way in orders of magnitude to the capacity of interest today. Furthermore, an electron beam provides a rather poor mode for reading out information from a magnetic thin film.<sup>28</sup> It therefore is reasonable to assume that the electron beam or combination of electron beam and optical readout from MnBi will not be practical in the foreseeable future.

Optical techniques as applied to the mass memory problem appear extremely promising. Considering system possibilities using MnBi as the storage medium with optical addressing, there are also formidable obstacles. The light beam now must be deflected. Deflection of a light beam to a large number of address locations electronically, i.e. without moving mechanical parts is extremely difficult. Even if the light beam could be deflected to a large number of address locations, the lenses required would limit the capacity to  $10^7$ - $10^8$  bits per focusing lens. This is because of a technological limit in lens design. As lenses become larger, the resolution decreases about in proportion to the increased field for lenses with field larger than about  $1\text{cm}^2$ .

Another possibility of current interest: the holographic storage technique is popular because no lenses are required for making a hologram.<sup>28,64</sup> The large polar Kerr and Faraday effect of MnBi<sup>72</sup> film allow a Curie point written magnetic hologram to be reconstructed with a detectable diffraction efficiency. This possibility is also attractive as a means of introducing redundancy to reduce the effects of dust, dirt and other defects in the film. Presumably, the information would be stored in pages and read out a page at a time. A page size of the order of  $10^4$ - $10^5$  would be necessary to provide a page capacity about the same as the track capacity of a rotating disc configuration. This means of course that a deflection system of  $10^6$ - $10^7$  spots is required for reading. A deflection system for the writing beam must carry all of the spatial frequencies in the raw page in a bundle reaching the storage medium occupying an area the same or greater than the minimum bit size times the number of bits in the page. Assuming that the packing density for holographic information bits on MnBi is the same as individual bits, the energy required will be about equal to the number of bits per page times the energy required for an individual bit. In the case of MnBi at room temperature, about 5 nanojoules are required in a 100 nanosecond pulse for an information bit.<sup>238</sup> That is about  $5 \times 10^{-4}$  joules or a peak power of about  $5 \times 10^3$  watts per page. Pulses of about 10 nanosecond duration are required to produce holographic storage on MnBi (to be discussed in a later section). Allowing losses in the optical system a realistic peak power is in the neighborhood of  $10^4$  to  $10^5$  watts. Only pulsed, Q-switched lasers are capable of these requirements. One of the limitations of this type of device is the flash lamp life. Anything over a million shots is good.<sup>614</sup> This means that when the memory is full, it is time to change the lamp in the main laser. Even a motor-driven Q-switch will outlast the flash lamps. ~~These are just some of the known difficulties associated with the holographic storage technique using MnBi.~~

A more important difficulty for the holographic storage is the need for a page composer in order to transfer the information to be stored into the storage medium. The page composer is in essence an alterable mask. It must have a bit capacity of a page ( $10^4$ - $10^5$ ) and must be able to accept and display the input within an acceptable time frame (about 10-100 msec). Furthermore, it must have suitable optical properties (either very reflective or very transparent) together with high contrast. The development of a suitable page composer requires considerable effort and time. This together with the requirement of a more sensitive storage medium capable of higher diffraction efficiency are the main topics of research which must be completed before the advantages of holographic storage technology can be fully realized.

The shortcomings of the foregoing concepts can, for the most part, be avoided by accepting or tolerating a moving medium as a part of the memory system. To meet the objective of a  $10^{10}$ - $10^{12}$  bit memory sufficiently light and reliable to carry aboard a spacecraft and to be constructed in the next few years, we recommend a moving medium device. The high packing density and large Kerr effect of MnBi make it basically the best storage medium available today.

The moving medium approach allows the use of a single focusing lens and a small erasure coil since the write and erase head does not have to cover a large number of bit locations. However, the main advantages of this approach is in its ability to meet the specified bit capacity requiring no breakthroughs for a high performance inertialess beam deflector.

## ~~2.2~~-B. Choice of the Memory Medium and Geometrical Configuration

Manganese bismuth has two crystallographic phases in the temperature range useful for optical memory applications. At the normal phase Curie temperature of  $360^{\circ}\text{C}$ , the material undergoes a phase transformation. This second phase can be retained by quenching the material.<sup>4,11</sup> When  $\text{MnBi}$  is used at room temperature, this quenching occurs as a result of Curie point writing.<sup>3,12</sup> The whole film can also be quenched and exhibits the same memory properties as the laser quenched spots. Quenched films have a lower Curie temperature of  $180^{\circ}\text{C}$  and therefore require less laser power for Curie point writing with the film at room temperature,<sup>4,11</sup> but the material gradually transforms back to the normal phase. This process is characterized by an activation energy of 1 eV and a conversion time constant of two years at room temperature. Optical memory experiments have shown that the memory characteristic is affected very early in the transformation process.<sup>on early</sup> For the time frame requirement the quenched phase of  $\text{MnBi}$  films would not be suitable in its unmodified form. This indicates

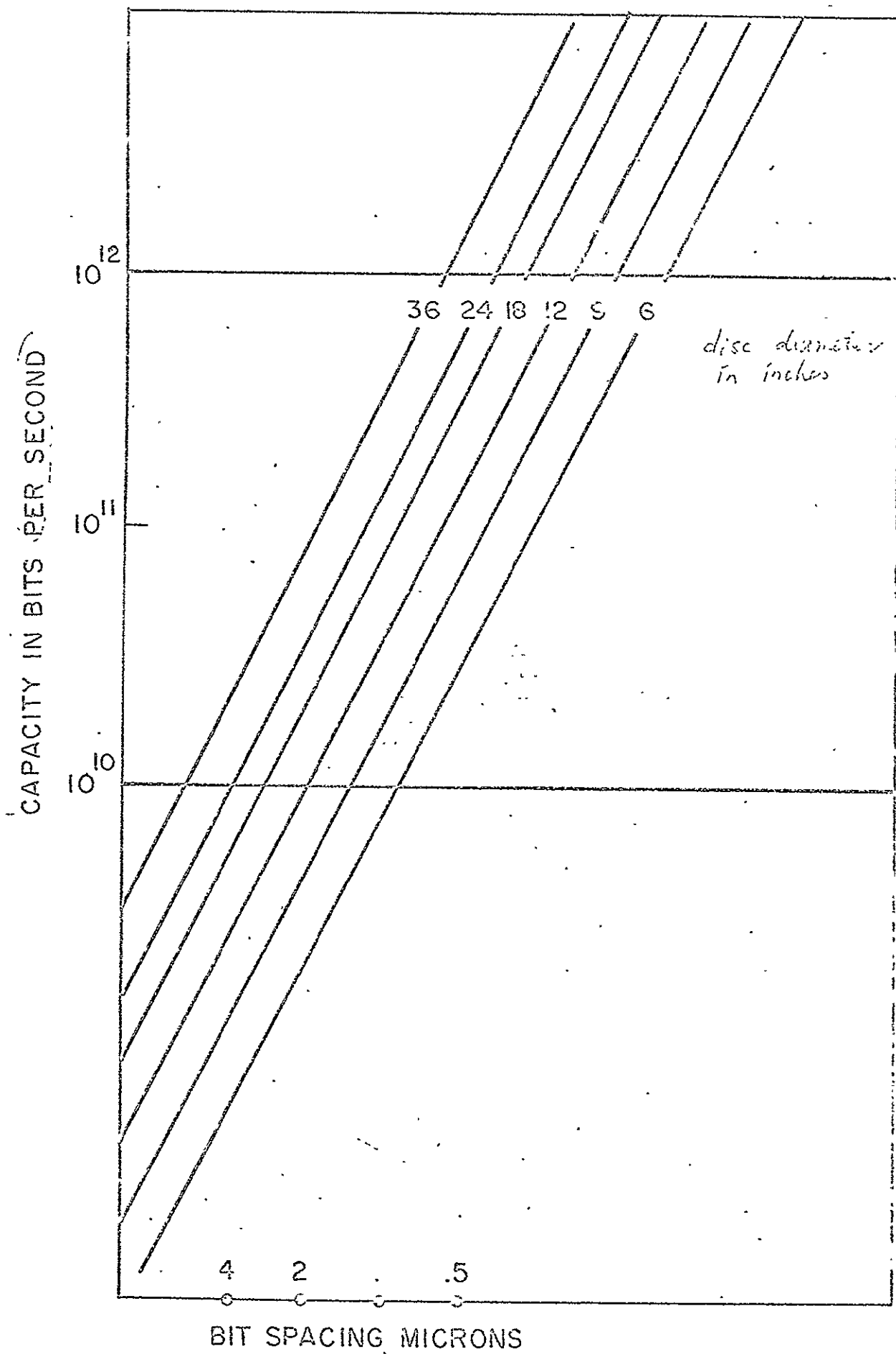
that quenched films need further research effort to improve their usefulness, but large normal phase films can be prepared and have been tested for mass memory application at elevated temperature. We would recommend as a first choice the normal MnBi film at elevated temperature and second the quenched film (at operating) low temperature to extend the shelf lifetime for the optical memory medium.

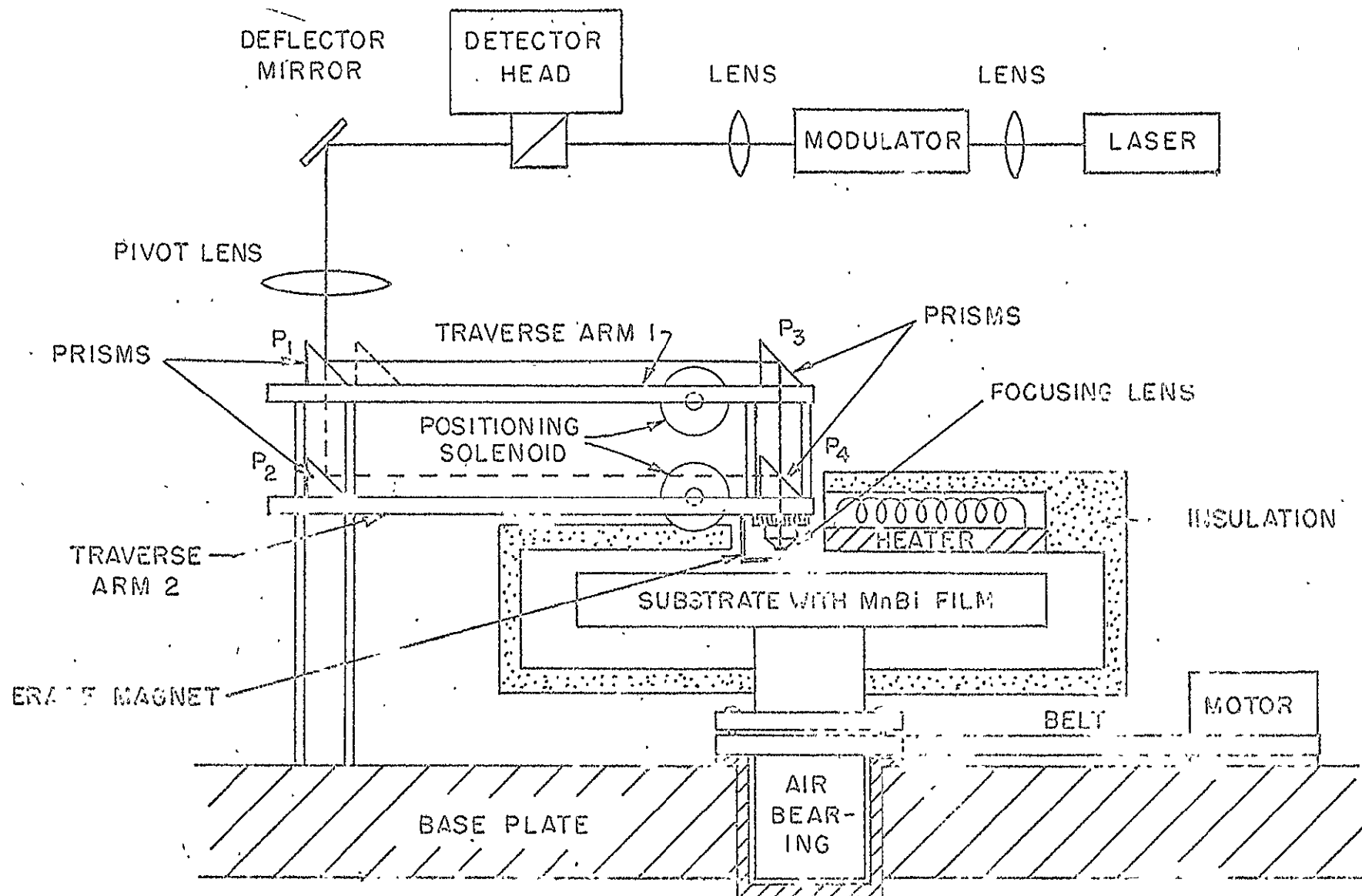
To <sup>serve</sup> carry the moving medium approach in more detail, we consider a simple rotating medium system. We choose this approach over the tape transport or card file system for the simplicity in mechanical motion and consequent reliability and maintenance free operation and compatibility with the rigid substrate requirement of the MnBi films.

The shape of the memory medium substrate should either be a disc or drum. A drum configuration has the advantages that the surface is always the same distance from the center and the packing density can be uniform over the surface.

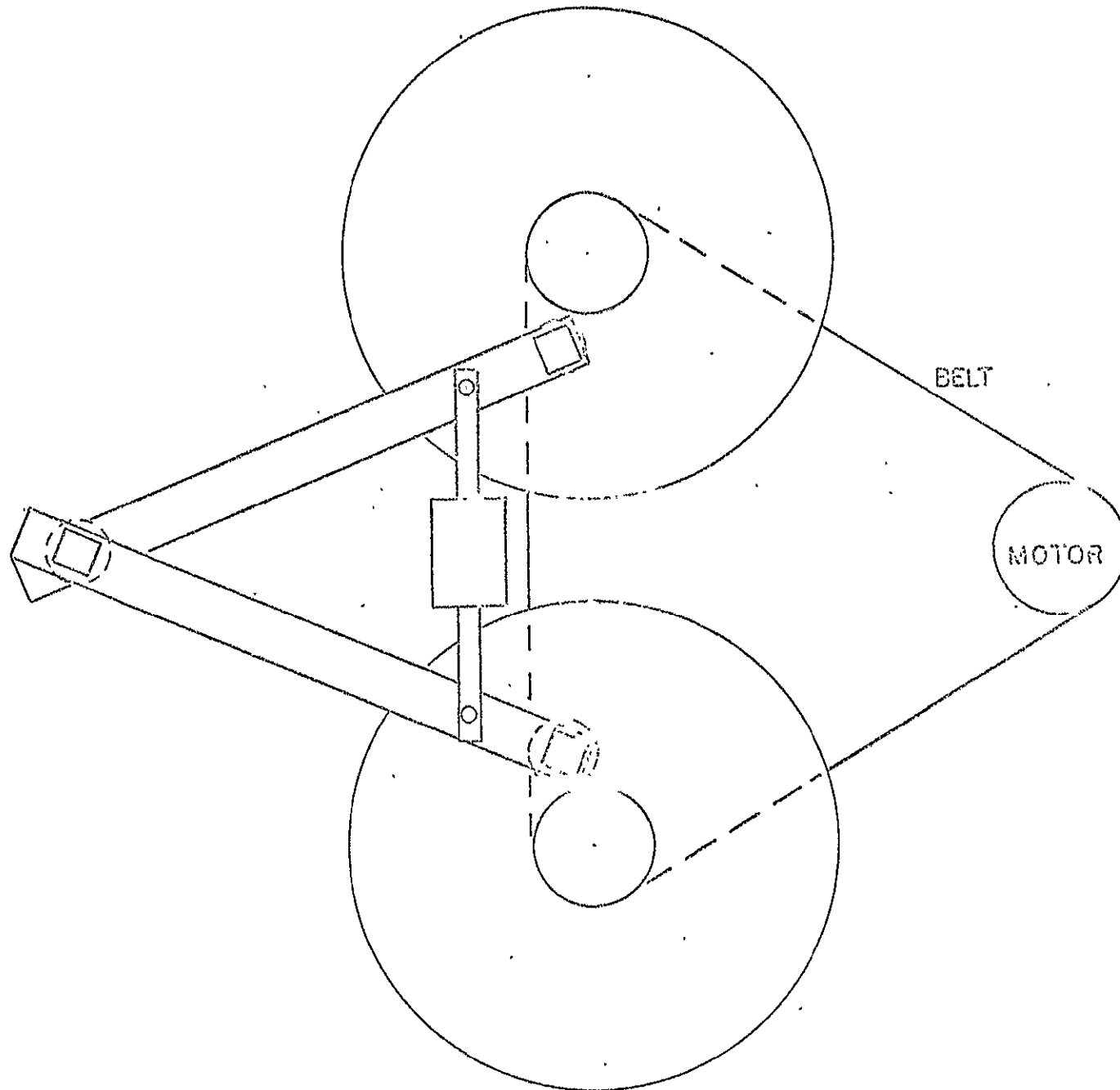
A disc provides the advantages that it is easier to fabricate for smaller areas and access to tracks is easier. A disc configuration is recommended at this stage of development. Figure IV-1 shows the disc capacity as a function of minimum bit spacing with disc diameter as a parameter.

For reasons of conservation of momentum, and elimination of gyroscopic forces, the memory equipment should have two discs rotating in opposite directions. A diagram of the components in the memory are shown in Figure IV-2. It consists basically of two discs, heated and insulated, and rotates on precision hydrostatic or gas bearings with an arm to swing over the discs carrying the read-write optics.





SIDE VIEW



TOP VIEW

A sliding prism is shown for guiding the light beam down the appropriate arm. This element rather than an electro-optic switch is shown because it will not interfere with the polarization of the read-beam. An electro-optic switch contains a polarizing element, so that when the read beam returns through it the signal would be analyzed before reaching the differential detector.

## C. ~~IV-D.~~ Memory Specifications

### 1. Speed and Capacity

Optical memory experiments on MnBi films have provided the necessary information from which many of the actual optical memory requirements can be calculated. Equations for these calculations were derived in quarterly report numbers 2 and 3. Results of these calculations and others are shown in Table IV-1.

Since the source of the figures under capacity and speed have been discussed in earlier reports, we will continue with the power requirements.

The requirement for 50mw of HeNe laser power was discussed in quarterly report no. 2. An input power of 450 watts to the power supply is typical for this size laser.<sup>26</sup> At this time a HeNe laser is recommended because of the superior lifetime and stability of these devices. For example, a commercial 5mw HeNe laser has recently been space qualified.<sup>27</sup>

### 2. Power

An amount of power from 100 to 500 watts is estimated for a moderately well-insulated enclosure around the film and substrate for maintaining the film at the required temperature. This can be contrasted with the input power to a larger laser necessary to Curie point write from room temperature at an attractive speed. A laser of 500 to 1000 mw output power would need about 6 times to 10 times more input power than the HeNe laser. Therefore, the bias heater and lower power laser is an economical trade-off.

TABLE IV-1

| CAPACITY                       | $10^{11}$ Bits        | $10^9$ Bits           |
|--------------------------------|-----------------------|-----------------------|
| Disc                           | 2 ea.                 | 2 ea.                 |
| Bit and Track Spacing          | 2 microns             | 2 mils                |
| Disc Diameter                  | 50 inches             | 6 inches              |
| Bits Per Track                 | $5.6 \times 10^5$     | $1.1 \times 10^5$     |
| Tracks Per Disc                | $.94 \times 10^5$     | $2 \times 10^4$       |
| Operating Temperature          | $300^\circ\text{C}$   | $300^\circ\text{C}$   |
| SPEED                          | 2Mbits/sec            | 2Mbits/sec            |
| Rotation Rate                  | 4RPS                  | 20RPS                 |
| Access Time                    | 125ms                 | 25ms                  |
| Max. Lin. Vel.                 | $10\mu/\mu\text{sec}$ | $10\mu/\mu\text{sec}$ |
| Modulator Pulse Duration       | 40ns                  | 40ns                  |
| Detection Bandwidth            | 10 MHz                | 10KHz                 |
| Servo                          | 1KHz                  | 1KHz                  |
| POWER                          |                       |                       |
| Laser Output                   | 50mw                  | 50mw                  |
| Laser Input                    | 450 watts             | 450watts              |
| Film Bias Heater               | 500 watts             | 100watts              |
| Modulator Driver               | 300 watts             | 300watts              |
| Drive Motor                    | 50 watts              | 50watts               |
| Bearing Air Pressure 30-60 lbs | 50 watts              | 50watts               |
| Total System Power             | $\sim 1.5 \text{ KW}$ | $\sim 1 \text{ KW}$   |

## OPTICAL SYSTEM

F:4

Focusing Lens

16mmf1

Pivot Lens

100mmf1

100mmf1

Deflector Galvanometer

2x2cm

2KHz

Detectors-differential

Si pin diode

Si pin diode

## MECHANICAL SYSTEM

Air Bearing

 $\pm 10$  in Radial Axial

Vibration

&lt;2cps

Motor

 $\sim \frac{1}{3}$  Hp

Translation Stage

 $\pm 10$  in. Vert. Horiz.

A substantial amount of power is required for the modulator as a result of the high bandwidth of most high speed electro-optic modulators. For example, a 150 pf modulator with 200 volt half-wave retardation voltage at a bandwidth of 10 MHz would require a load resistance of about  $500\Omega$ . That is about 80 watts in the load resistor alone.

The drive motor and bearing hydrostatic supply should have an upper limit power requirement of 100 watts for both components. It may be economical in a final design to drive the discs hydrostatically also.

The total power requirement for a  $10^{11}$  bit system should be around 1.5 Kwatt.

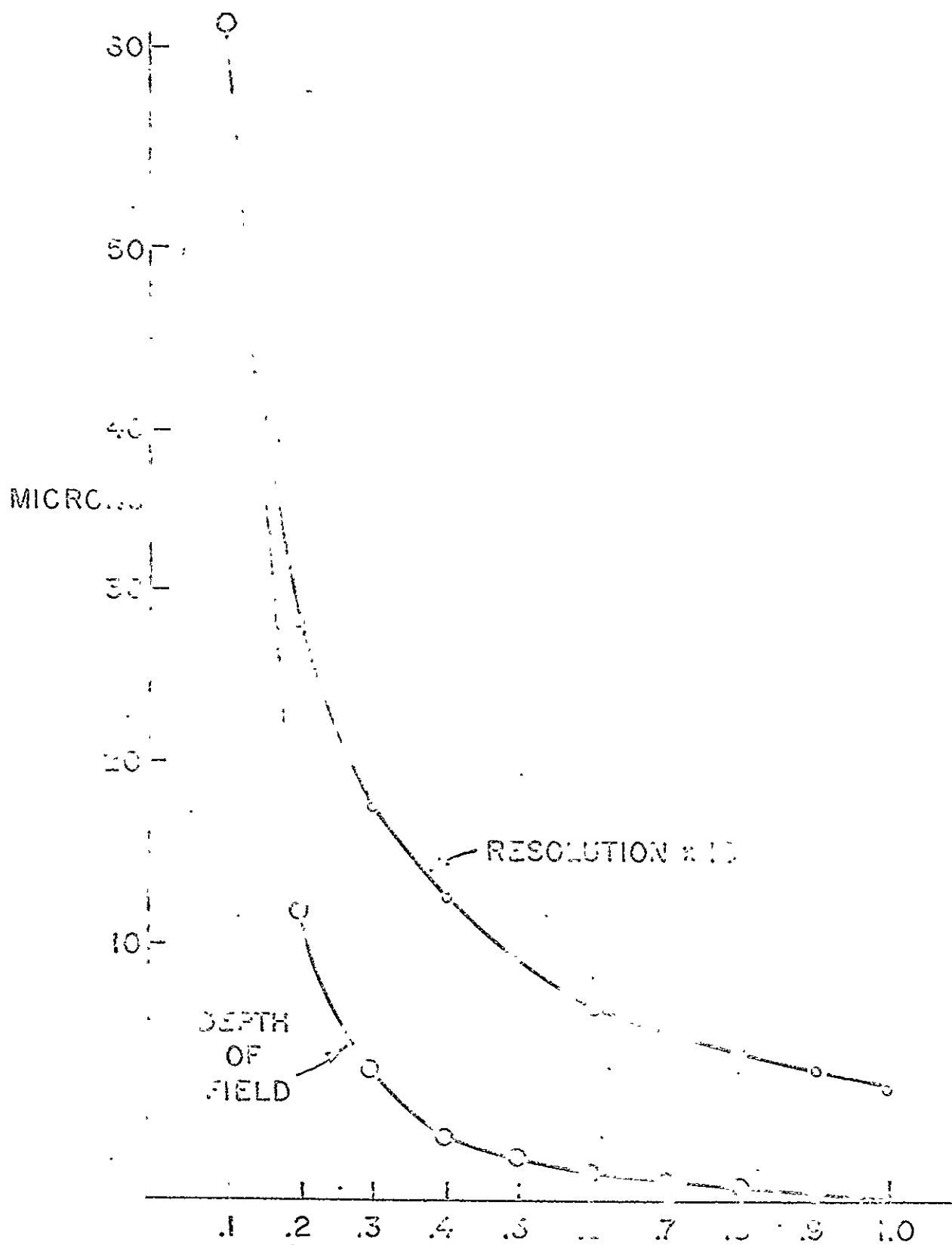
### 3. Optical System

The lenses, detectors and deflectors in a rotating disc system would follow about the same general design as that used in the memory exerciser as was described in the previous quarterly report.

An additional design consideration for a rotating disc configuration is the depth of field associated with a particular focusing lens. A graph of the resolution and depth of field as a function of numerical aperture is shown in Figure IV-3. Our table shows an F:4, which is not quite as good as an F:2 from the trade-off of depth of field and resolution. The reason for choosing an F:4 is mainly to provide the working distance needed for a magnetic field coil.

### 4. Mechanical System

Mechanical considerations were discussed briefly in the section on geometrical considerations. No further discussion will be made here other than to call attention to the bearing specification in Table IV-1 in the light of the F:4 focusing optics.



## 5. Electronics

The electronics needed can be divided into the following 5 categories:

1. Readout amplifiers
2. Modulator
3. Field Coil
4. Deflector Servo Control and Arm Motion Control
5. Timing and function control

Readout or sense amplifier requirements have been discussed in quarterly report 3 with regard to the signal-to-noise ratio analysis. These amplifiers are in use with our present memory exerciser and the output is compatible with T<sup>2</sup>L logic elements. The modulator drive power requirement was discussed earlier so we will proceed with the field coil.

## 6. Field Coil

From measurements of the erase field required for MnBi films as reported in the first quarterly report, we know that about 600 Oe is required. We apply geometrical considerations to the coil so as to keep the field uniform over the flat field of the focusing lens. The normal component of the field from a circular coil of radius  $a$  and Cartesian coordinates with  $x$  perpendicular to the plane of the coil is <sup>ES18</sup>

$$B_x = \frac{1}{2} \mu_0 I N a^2 \left[ \frac{1}{(a^2 + x^2)^{3/2}} + \frac{3(y^2 + z^2)(a^2 - 4x^2)}{r(a^2 + x^2)^{7/2}} \right]$$

where  $a$  is the coil radius, which lies in the  $y$ - $z$  plane.  $I$  is the current in amperes and  $N$  the number of turns. In this expression  $\mu_0 = 4\pi \times 10^{-7} \frac{\text{newtons}}{\text{amp}^2}$ .

Therefore, if we multiply  $B_x$  by  $10^4$  the result is in Gauss with spatial dimensions in meters. The corresponding field  $H_x$  in oersteds is equal to  $B_x$ .

Figure IV-4a,b shows  $H_x$  as a function of fractional units of  $a$  for distance away from the coil at the center and for distance away from the center at  $X = .3a$ . These calculations show that for small distances away from the plane of the coil  $dB/dx$  is small and beyond  $.3a$  it is nearly linear. Figure IV-4b shows that a reasonably flat area of about  $.3a$  exists along the radial direction. The coil radius to choose is one about 3 times the radius of the flat field of the focusing lens.

We can further analyze the field coil with regard to the power efficiency to see what the optimum number of turns is. First, the field and power for a multiple turn coil is

$$B_i = If(x_i, a) \quad P_i = I^2 R_i$$

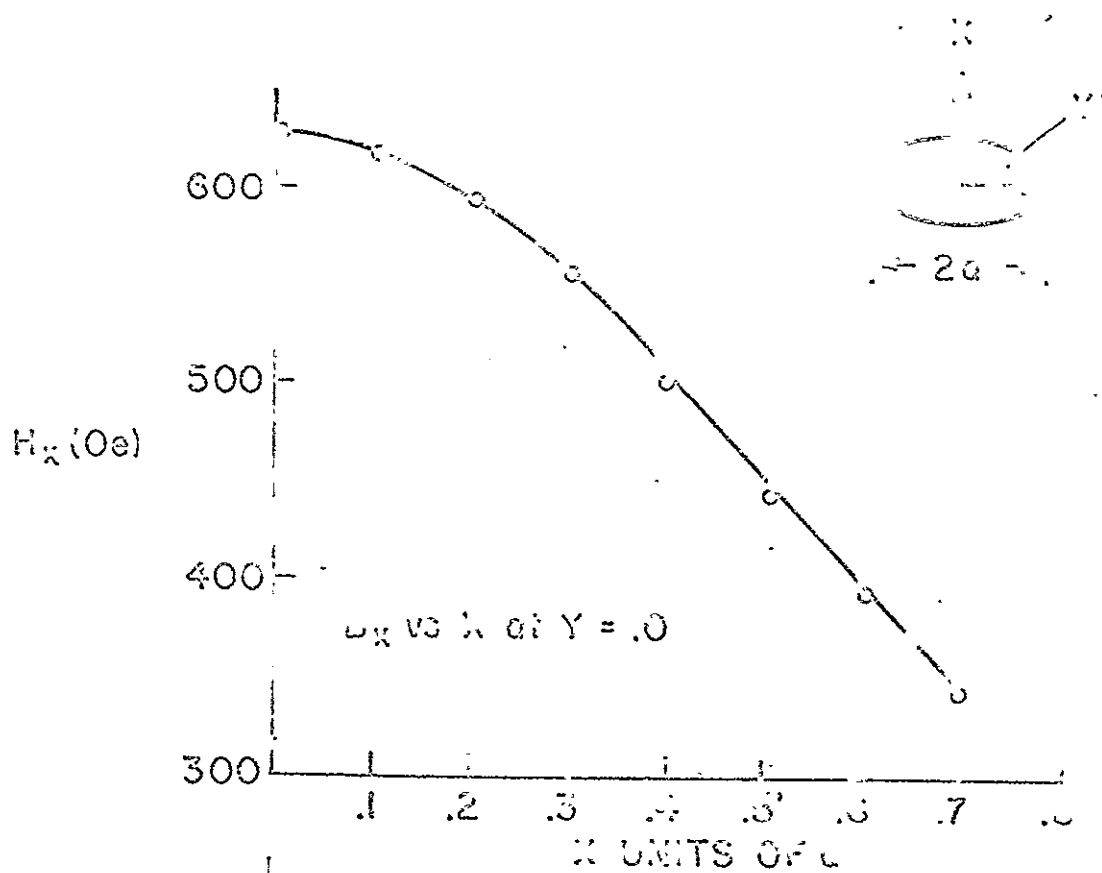
for the  $i$ th turn. Then,

$$\frac{B}{P} = \frac{I f(x_i, a)}{NRI^2} = \frac{f(x_i, a)}{NRI}$$

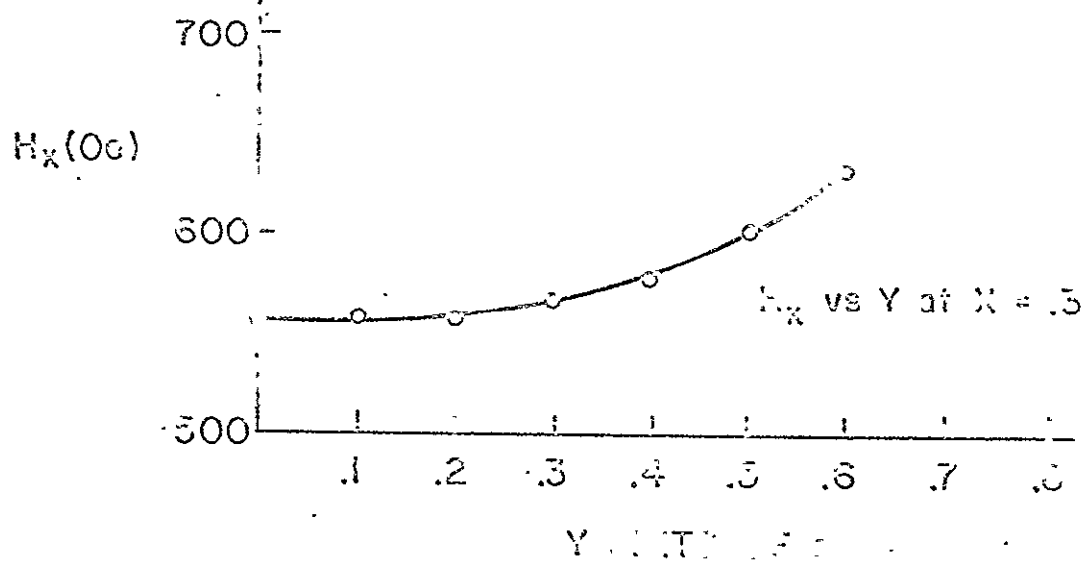
Now, for a single turn having the same dimensions as the sum of the turns in the multiple turn coil, we have

$$B_i = If(x_i, a) \quad P = I^2 R_i$$

for the  $i$ th parallel segment of a single turn coil, where  $(x_i, a)$  is the field spatial distribution and  $R$  is the resistance of the  $i$ th turn. The field to power ratio for a single turn of  $N$  parallel segments is then,



(a)



(b)

$$\frac{B}{P} = \frac{\frac{I}{N} f(x_i, a)}{\left(\frac{I}{N}\right)^2 R} = \frac{f(x_i, a)}{\frac{I}{N} R}$$

The ratio of the multiple turn case to the single turn case for the same current is then

$$\frac{\frac{B}{P} M}{\frac{B}{P} 1.} = \frac{1}{N^2},$$

where N is the number of series or parallel turns. This shows that increasing the current through a few turns is the most economical trade-off in power. This is also significant for reducing heat damage to the field coil.

For a single turn coil of 1mm radius, the maximum field is about  $2\pi I$ , implying a pulse current requirement of about 100 amps peak value for erasure.

#### 7. Deflector Servo Control

A servo amplifier is used in the proposed model. This is shown in Figure IV-5 with inputs from the detector amplifier and control electronics through a servo logic block. The storage procedure is assumed to be one in which a clock bit is periodically stored on each track. This clock bit or pattern would be used for both track positioning and timing. A gate would be opened between the amplifier and the servo amplifier to apply the raw signal for feedback control to a phase sensitive amplifier.

A block is also shown labeled step. It refers to a mechanism for positioning the focusing lens and field coil over the appropriate band of tracks. Positioning of this kind could be achieved with an accuracy of 300-500 microinches. The analog servo deflector would be required to do the final positioning.

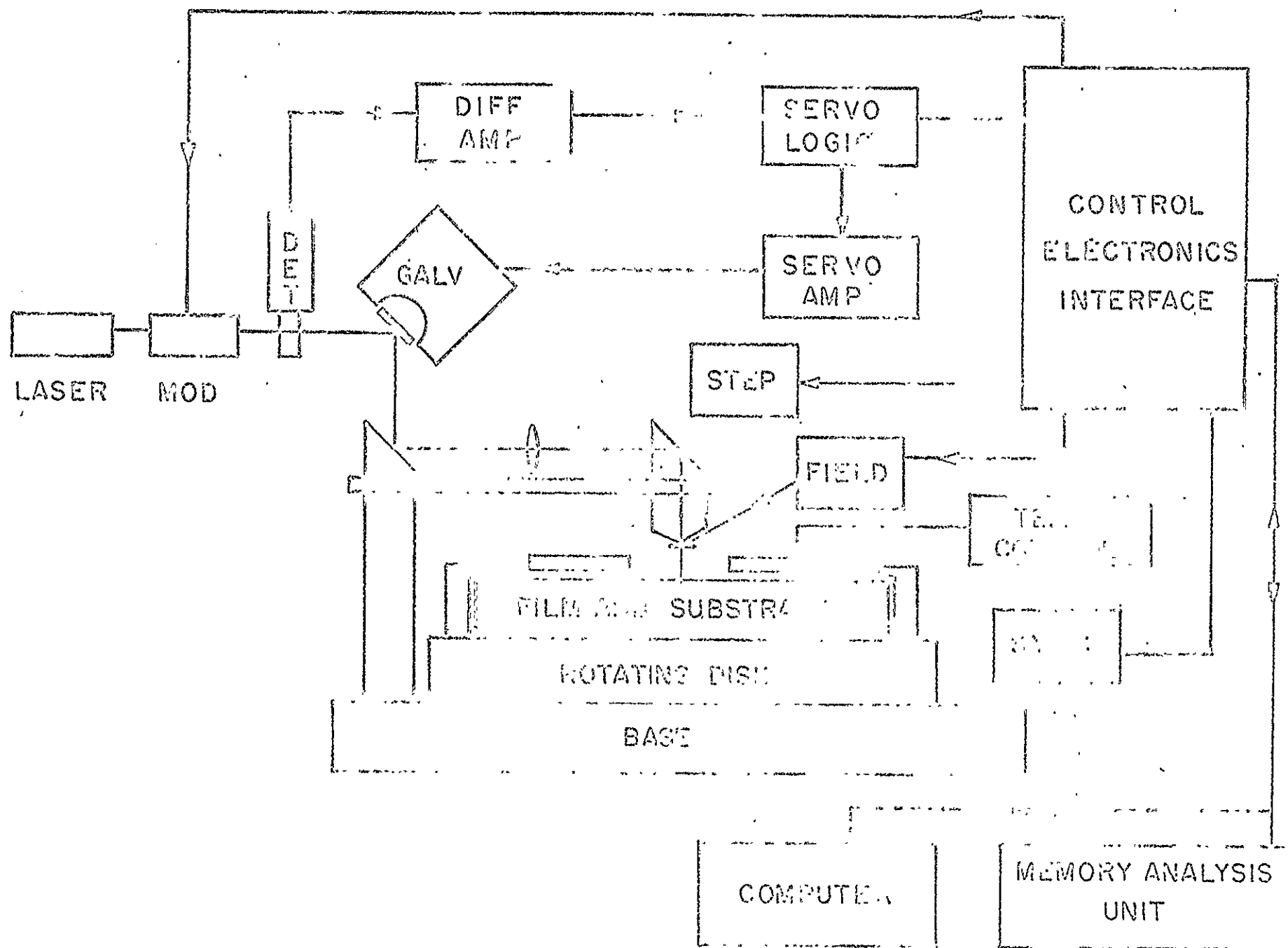


Fig 12-5

EXPERIMENTAL  $10^9$  BIT OMM MODEL

### 8. Timing and Function Control

The function of the timing and control electronics is to feed information in and draw it out of the store in the most appropriate form. This involves directing the read/write head to the proper track and maintaining servo control on the track. Also, it must control the timing of the memory clock field pulses for writing or erasing.

### 9. Temperature Control

The block labeled Temp. Control in Fig. IV-5 should maintain the temperature sufficiently constant to keep the dimensional stability within the tolerance of the optical system. Radial expansion of the memory media would be compensated by the servo control, but vertical displacements would not as presently shown. It may be easier to sense the distance from the surface and servo the focusing lens than to control the temperature precisely. This is a systems trade-off that can be made.

NOT REPRODUCIBLE

## D. MnBi Magnetic Hologram Experiments:

We have begun experimental work<sup>1</sup> of recording magnetic holograms on MnBi. The setup was described in Fig. IV-2, p. 29, in a previous report to NASA,<sup>(14)</sup> quarterly technical report no. 2. We shall first briefly describe the quality of the ruby laser used for write-in, then some preliminary results on coated MnBi films.

### Experiment Conditions

The ruby laser cavity has a near-concentric configuration; an intracavity cell filled with Vanadium Phthalocyanine in nitrobenzene serves<sup>as</sup> the passive Q-switch. We have used cryptocyanine in alcohol which gives basically the same result. The output pulse duration can be varied from 25ns to 50ns and it contains about 7 millijoules. We can control the alignment to obtain a TEM<sub>00</sub> transverse mode, which is quite reproducible from shot to shot. The divergent beam is made parallel to a diameter of about 1mm by a lens of 20cm focal length.

The output from the laser was attenuated by CuSO<sub>4</sub> solution or by microscope glass slides. In forming simple grating holograms, we have used angles between the two beams of 20°, 10° and 5°. The energy in the two beams have a ratio of about 1:1, which gives a modulation index of 100 percent, but thermalization decreases the modulation index considerably at the end of the laser pulse. We have not accurately determined the dependence of thermalization on grating angle pulse length and medium coating as yet.

## 2 Results on Coated Film

The protective coating on the glass-backed MnBi is a thin layer of SiO. The coating thickness is controlled to minimize reflection loss at 6943Å. The grating hologram work reported below was done at 5° between the two beams and with a pulse duration of 25ns to minimize thermalization of the grating. Depending on the beam power level at the MnBi film we can obtain a four-zone hologram or a two-zone hologram or a good hologram. By good hologram we mean the whole hologram consists of magnetically written grating lines. A good hologram is shown in Fig. III-6. The picture was taken by means of a polarizing, transmission microscope, with X750 magnification. Reconstruction by Ne-He laser always gives only the 0th and the  $\pm 1$  order, suggesting a grating with gray scale instead of a two level grating. As expected, the polarization of the  $\pm 1$  orders are perpendicular to that of the 0th order. Diffraction efficiency measurements will be carried out shortly.

In a two-zone hologram, the periphery of the hologram is bounded by magnetically written grating lines while the center portion is totally switched, shown in Fig. III-7. To avoid the formation of the totally switched zone, it is imperative to carefully control the laser power incident on the film. Assuming that the spatial profile of the ruby beam in the TEM<sub>00</sub> mode is Gaussian, it can be easily shown that the bias temperature produced by the d.c. term of the two-beam interference is also Gaussian. Where the bias temperature exceeds the Curie point, total flux reversal will occur although the modulation envelope may extend below the Curie temperature. The reasoning is as follows. The time constant of thermalization for the grating is, according to Mezrich (1970)

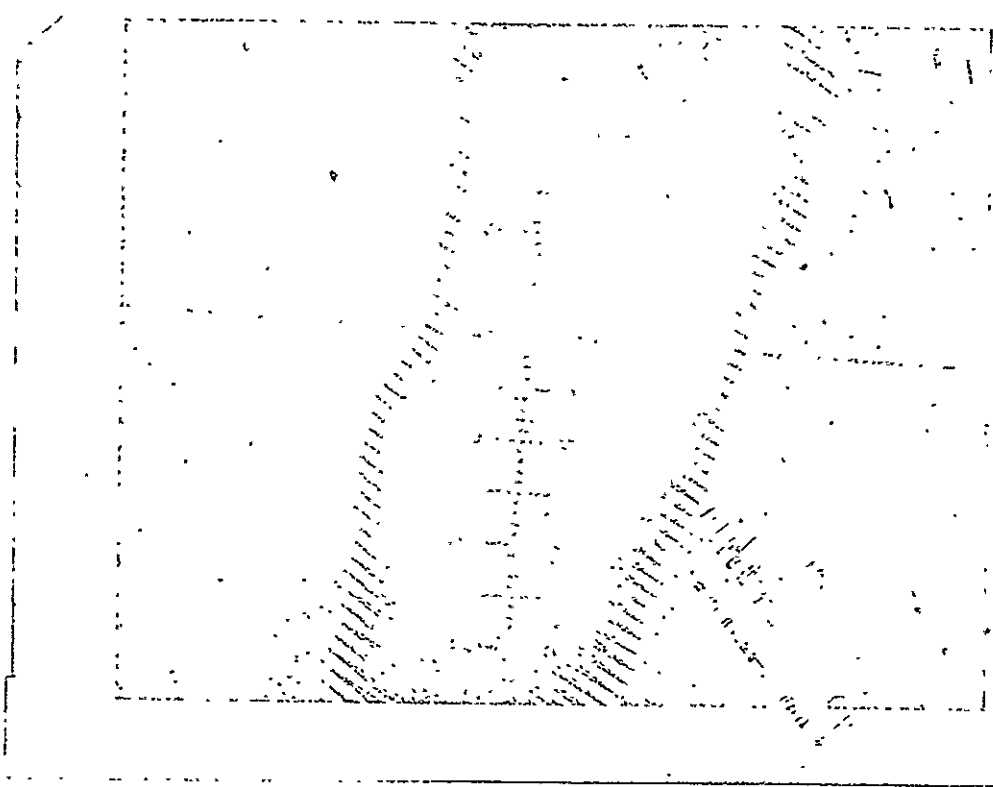
$$\tau = d^2 / 4\pi^2 K :$$

where  $d$  is grating spacing and  $K$  medium thermoconductivity. While the grating is thermalizing, the whole hologram is also decreasing in temperature but at a much lower rate. Based on (1) one expects that the thermal decay time constant for the overall hologram as compared to that of the grating is on the order of  $D^2/d^2$ , where  $D$  is hologram size. Therefore, if the bias temperature is above the Curie point, the thermal grating disappears long before the bias temperature drops below the Curie point, resulting in total flux reversal.

We have also made holograms with four distinct zones. The outermost region consists of magnetically written grating lines, the next region totally switched, the third region has burnt-in grating lines and the fourth region totally burnt. Burnt-in occurs when the local temperature reaches beyond the dissociation temperature,  $440^\circ\text{C}$  of MnBi. A hologram containing significant portions of burnt-in grating lines will produce higher orders than  $\pm 1$  orders and the diffraction efficiency is also much higher as ~~has been~~ discussed in the previous quarterly report.

NOT REPRODUCIBLE

Fig. 5.6 A grating hologram formed on  $\text{MnSi}$ .  
Magnification of photo is 75%.  
angle between the two beams forming this hologram was  $5^\circ$ , the laser energy on  $\text{MnSi}$  for hologram construction is 1 millijoule, and the laser pulse was 2.5  $\mu\text{s}$ .



NOT REPRODUCIBLE

Fig. 107 A micrograph with the outside portion slightly  
 notched due to the bias temperature there  
 rising above the curve temperature of  $\alpha$ -Be.

## V. Conclusion

A critical evaluation of the feasibility of using MnBi thin films for a spaceborne optical memory medium with capacity in the  $10^{10}$ - $10^{12}$  bit region has been performed during this one-year research effort. We have identified many important properties of this medium as it applies to such a memory. From this study we can conclude that this medium is suitable for the intended applications. From the materials study effort we have measured and obtained all of the needed physical properties of the medium relevant to the intended application. The process of the transformation from the quenched high temperature phase to low temperature phase was identified and methods for stabilizing the quenched phase deduced and experimentally evaluated. Although positive results have been achieved, further research effort is needed in order to fully realize the advantage of MnBi in this quenched phase. On the other hand, MnBi in its low temperature phase was found to be stable even under adverse environmental conditions. This is the material we considered in the systems study. From the optical memory experimental study we have obtained and evaluated the optical memory characteristics of MnBi using a specially constructed optical memory exerciser. The writing, reading and erasing boundary conditions were obtained and optimized through close coordination with the materials preparation effort. Emphasis was placed on the MnBi stability and aging characteristics. We have performed a repeated cycling experiment of write-read-erase-read for over one million cycles and found no change in the material memory properties. Further research effort on the refined understanding of the physics of the Curie point writing should be undertaken to yield a mathematical model of the writing and erasing process. This will be an indispensable tool for the system trade-offs study.

The results of the materials and optical memory study were fully applied to the systems study. We have identified that, for the near future, MnBi prepared in the normal phase, operating at a temperature above  $180^{\circ}\text{C}$  is most suited for the intended application. For a completely inertialess system the addressing system requires beam deflectors and lenses unavailable at present. We therefore suggest a rotating disc approach which uses minimum amount of mechanical motion. Such a system with a  $10^9$ - $10^{10}$  bit capacity has been defined in detail and performance specification obtained. Based on this study, we are confident that an optical memory as defined above using MnBi films can be constructed and will satisfy the requirement for a spaceborne application.

## APPENDIX A. PUBLICATIONS

During this one-year period of contract, three papers were presented at scientific meetings and one paper published on work related to this investigation. These are listed in the following.

1. D. Chen, R. L. Aagard and T. S. Liu, "Magneto-optic Properties of Quenched Thin Films of MnBi and Optical Memory Experiments"; paper presented at the Fifteenth Annual Conference on Magnetism and Magnetic Materials, Philadelphia, Nov. 18-21, 1969.
2. R. L. Aagard and F. M. Schmit, "Detection of Magneto-Optic Signals from Curie-Point Written Manganese Bismuth Films", paper presented at the Spring Meeting of Optical Society of America, April 1970.
3. E. Bernal G., R. L. Aagard and D. Chen, "The Effect of the Demagnetizing Field on Curie-Point Writing in Magneto-Optic Thin Films of MnBi", paper presented at the Intermagnetic Conference, April 21-24, 1970.
4. D. Chen and R. L. Aagard and T. S. Liu, "Magneto-Optic Properties of Quenched Thin Films of MnBi and Optical Memory Experiments", J. Appl. Phys. 41 1395 (1970).

## APPENDIX B. NEW TECHNOLOGY

There are two new technologies developed during this research work.

### 1. The use of demagnetized MnBi Film for optical memory.

In the past, MnBi films were always prepared with their magnetization saturated. A laser written "1" bit and erased "0" bit having magnetization opposite to each other, form the basis of binary information content. When the film is prepared in the demagnetized state, laser heat writing with an applied field of positive and negative orientation results in "+1" and "-1" bits, whereas laser heat writing without a field erases a bit back to "0" or the demagnetized state. This three-level writing technique increases the content from binary to ternary. This scheme is possible only when the bit dimension is much larger than the minimum domain size. In MnBi film with micron size bit dimension, this condition is satisfied, because the minimum domain size is estimated to be less than  $0.3 \mu\text{m}$ .

### 2. Partially damaged magnetic hologram

We have, in collaboration with Radiation Incorporated and the University of Michigan, performed a magnetic hologram experiment by two beam interference using a MnBi film. The Curie-point written grating consists of alternated non-magnetic (damaged) and magnetic (MnBi) stripes. This type of grating can enhance the Kerr or Faraday rotation as observed at the first order diffracted spot.

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