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An investigation of the electrooptical properties of a dipole suspension of iodoquinine sulfate

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AN INVESTIGATION OF THE ELECTROOPTICAL PROPERTIES OF A DIPOLE SUSPENSION OF IODOQUININE SULFATE

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ABSTRACT

The objective of this thesis is to investigate the electrooptical properties of a dipole suspension. A dipole suspension consists of needle-like crystals which, in the presence of an electric field, orient themselves parallel to it. If the dipoles align themselves parallel to incident light, the suspension will transmit the light. If no electric field is present, the dipoles are in a random state, and little light is transmitted. The projected area of the dipoles is smaller when they are in the aligned state.

Commercially, a dipole suspension is available from Marks Polarized Corporation as the product Varad.

This thesis will investigate the following properties of the dipole suspension Varad:

1) spectral characteristics
2) off-axis properties
3) rise and fall times
4) the dependence of optical density on the voltage and frequency of the electric field

Statistically designed experiments were used to investigate the above factors. A spectrophotometer was used to investigate the spectral characteristics, with the wavelength, frequency, voltage, and angle of incident light being varied.

For the time studies, a dual beam scope was used to

monitor the voltage to the dipole suspension and the transmittance simultaneously. Photographs made from the oscilloscope were used to determine the rise and fall times of the Varad.

All the data was analysed using statistical regression techniques, but it was not possible to find a model for all the data. The regression models that were found are shown below, along with a short discussion of each.

1) $\ln(D - 0.6) = 0.9121 - 0.0059\ E$

where E = the electric field intensity

Density changes exponentially as the voltage is increased.

2) $\ln(D - D_0) = 0.1626 - 0.0021\ f$

where f = frequency (Hz)

D_0 = minimum density obtained

A change in frequency causes the density to change exponentially also, but to a lesser degree than voltage.

3) $D = 0.4468 + 1.524/\cos(w)$

where w = angle of incidence in degrees

As the angle of incidence is increased, the density increases, but the cosine law does not fully account for the changes observed.

4) $\ln(T - T_0) = b_0 + b_1\ E$

where T = fall (milliseconds)

T_0 = minimum fall time

b_0, b_1 are constants

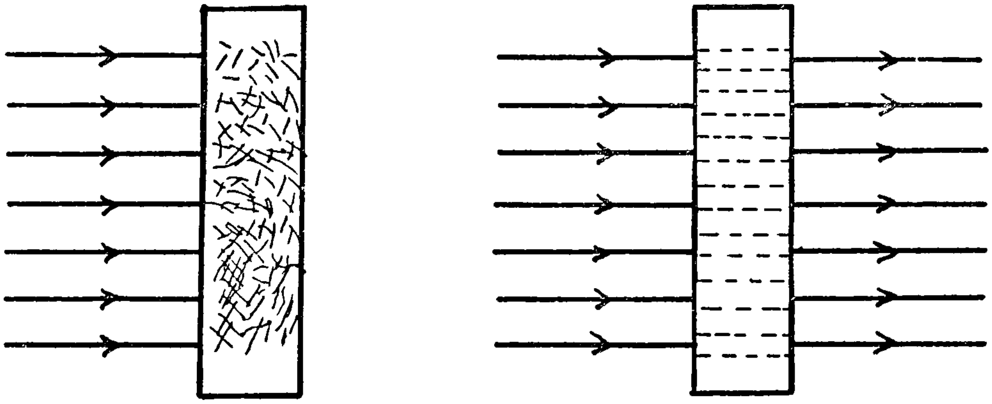
Voltage has a very significant effect on both rise and fall times. The higher the voltage the shorter the rise and fall times. Frequency has very little effect on the rise and fall times, but the effect is large enough to change the estimates of the coefficients b_0 and b_1.

The spectral characteristics could not be fit to a model because of the complicated relationships that existed. Its nonneutrality makes Varad very questionnable for use in the photographic field.

INTRODUCTION

The purpose of this project was to determine the electro-optical characteristics of a dipole suspension. A commercially available dipole suspension is the product Varad, supplied by Marks Polarized Corporation. Varad consists of hexagonal crystals of iodoquinine sulfate which are suspended in a liquid medium. When subjected to an alternating electric field, these crystals have a charge induced upon them, causing them to align in the direction of the electric field. (Figure 1).

VARAD IN RANDOM AND ALIGNED STATES



No Voltage Voltage

FIGURE 1

When the dipoles are in the aligned state, they are parallel to the incoming light, and allow it to be transmitted. When the dipoles are in a random state, they interact with the light, and cause the suspension to appear dense.

In considering the application of Varad in the photographic field, it is necessary to know the optical characteristics and how they are affected by the nature of the applied electric field. The optical factors being considered are:

1) Spectral transmittance of the suspension
2) Off-axis characteristics
3) Rise and fall times
4) Optical Density

The rise and fall times involve the time it takes the Varad to change from dense to clear. The characteristics of Varad depend greatly upon the nature of the electric field placed upon it. Voltage, frequency, and the shape of the wave all play a big role in the characteristics of the Varad. Altering the nature of the electric field applied to the Varad is the most feasible means of changing or optimizing the optical characteristics of the Varad. Two series of experiments were run on the Varad.

In the first, a four factor crossed experiment was run in an attempt to predict density as a function of:

1) Voltage of the electric field (peak-to-peak)
2) Frequency of the field
3) Angle of the incident light
4) Wavelength of the incident light

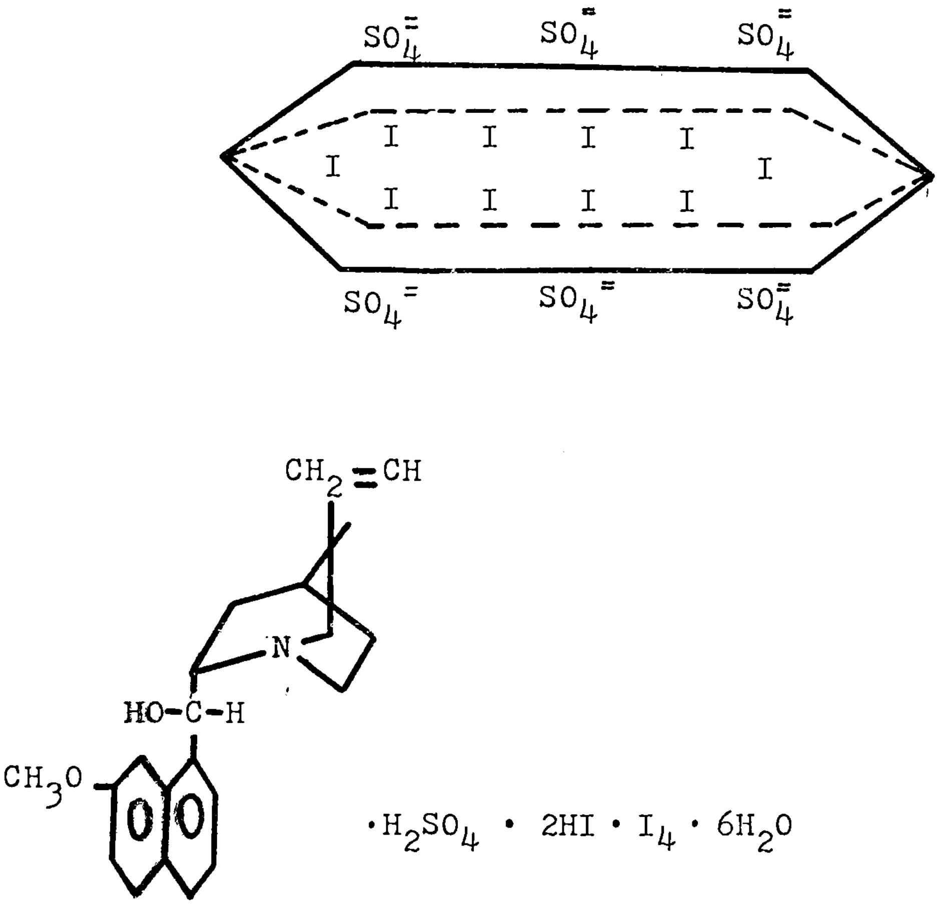
In the second experiment, the effect of the frequency and voltage of the electric field on the rise and fall times of the Varad was measured. The data was analysed by statistical techniques where possible, but graphical techniques were used for analysis when the statistical procedures failed.

EXPERIMENTAL

Theoretical Background

Marks Polarized Corporation has done intensive research in the field of dipole suspensions and polarizing materials since 1933 [1]. The interaction of the dipole crystals with light can be explained by antenna theory. Electromagnetic radiation of wavelength, λ, has a maximum interaction with particles which have a length of $\lambda/2$. The ratio of the dipole crystal length to its diameter determines the bandwidth of wavelengths which interact with the dipoles. Long, narrow dipoles interact with a narrower band of wavelengths than short, thick dipole crystals. The radiation which interacts with the dipole is converted into two forms of energy. Half of the energy is absorbed and converted into heat, and the other half is reradiated into space. The wavelength of light which interacts with the dipoles also depends upon the medium in which the dipoles are suspended. The effective length of a dipole in a suspending medium with a refractive index, n, is equal to $\lambda/2n$. For example, a dipole with length 3000 Å interacts with a wavelength of 6000 Å, in air. In a refractive medium of 1.5, the dipole will interact with a wavelength of 2000 Å.[2]

The actual composition of the dipoles is a hexagonal crystal structure of iodoquinine sulfate. The crystals' chemical structure and physical shape are shown below.



PHYSICAL AND CHEMICAL STRUCTURE OF DIPOLES

FIGURE 2

The sulfate compound forms a long needle-like crystalline structure. The dipole nature of the crystal is achieved by the transfer of electrons along the polyiodide chains which form the crystals' shape.

Mr. Marks defines the electrodichroic ratio, q_{rz}, as the ratio of the density of the randomly oriented Varad to the density of the aligned Varad.[3] The higher the q_{rz} of the material, the more effective it is as a variable attenuator. When the spectral density is used to determine the q_{rz} of the material, q_{rz} is plotted versus wavelength. This produces a curve similar to the eye visibility curve. This indicates that the wavelength of interaction of the dipoles has changed with their orientation.

In the randomized state, the dipoles present a given projected length distribution. In the aligned state, the distribution of projected lengths is shifted to a lower value. This is because the dipoles are nearly parallel to the light. This lower projected area results in more dipole interaction with blue light. This accounts for the depression in the q_{rz} values throughout the blue region of the spectrum.

The dipole size distribution is such that in the aligned state, there are few dipoles which interact with the red light. The dipoles which interacted with red radiation in the random state have shifted their interaction to the lower wavelengths due to their decrease in projected lengths. The drop in the q_{rz} above 630 nm. may be due to a factor other than the dipoles, namely, the spectral transmittance of the suspending medium. If the transmittance above 630 nm. is due to the suspending medium rather than the dipole alignment, it is independent of the electric field, and low values of q_{rz} will result.

The electrodichroic sensitivity is defined as the change in q_{rz} with respect to the electric field intensity. It is the derivative, $d(q_{rz})/dE$. Ideally, the electrodichroic sensitivity is large at low voltage; little voltage is required to produce a large change in density of the Varad.

Up to this point, the characteristics of the Varad have been described when the Varad has been in a state of equilibrium. The crystals do not align or randomize instantaneously. There are two forces operating on the crystals. When the crystals are in the aligned state and the electric field is abruptly turned off, the crystals randomize due to the force exerted by Brownian motion only. The relaxation time is therefore dependent on the viscosity of the suspending medium, the temperature of the medium, and the size of the dipoles. Mr. Marks states that:[4]

$$\tau_B = (1.26 \times 10^{-6})\eta L^3/Ta_0$$

where; τ_B = randomization time constant

η = viscosity of the medium

T = temperature (degrees Kelvin)

L = dipole length (Angstroms)

$a_0 = \ln(2L/d) - 0.80$

d = dipole diameter (Angstroms)

The alignment time is dependent on the electric field strength. The electric field imparts an aligning force on the dipoles. This aligning force must overcome the randomizing force due to the Brownian movement. When the force exerted by the electric field is just enough to balance the force due to Brownian motion, the dipoles are in a stable state. This

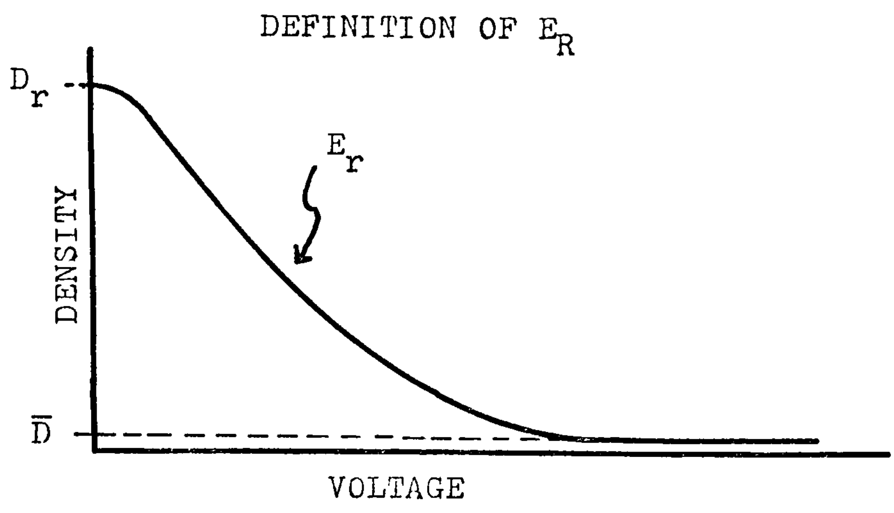


FIGURE 3

corresponds to the inflection point in Figure 3. This point is defined as E_r. At E_r, the second derivative, $d^2(D)/dE^2$ equals zero in the below equation.

$$D = \bar{D} + (D_r - \bar{D})\ \exp(-(E - E_r)/E_r)$$

where;

$\bar{D}$ = minimum optical density possible

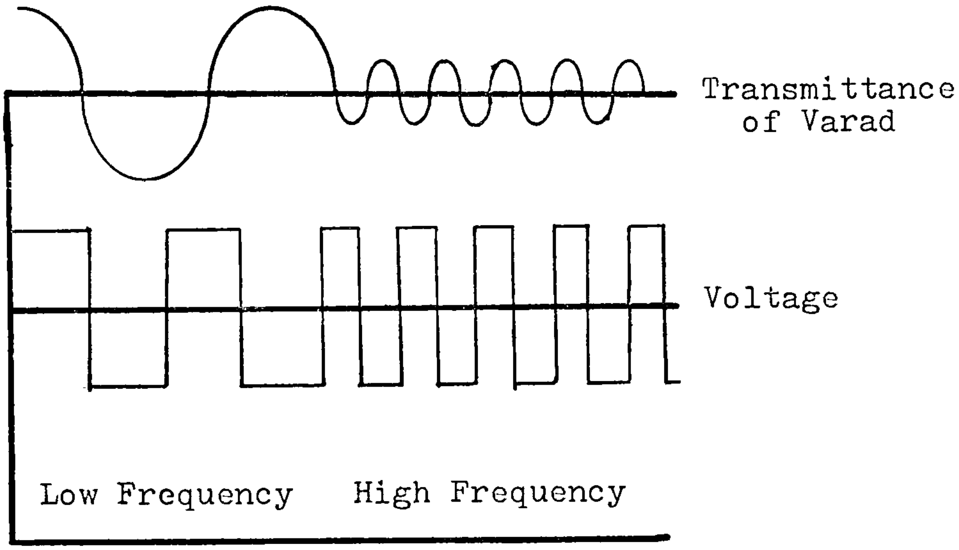
D_r = maximum optical density (random density)

E = electric field intensity

E_r = the electric field intensity which just balances the force due to Brownian motion

For Varad to be used effectively, the voltage applied to it must be at least as great as E_r. However, if the voltage applied is too large, the dipoles will produce a static charge and coagulate. If the voltage is too small, the dipoles will never leave their randomized state.

The frequency of the electric field is important in determining the characteristics of the Varad. The importance of the frequency is interrelated with the stability of the density of the Varad. It is also related with the alignment and relaxation times of the dipoles. For very low frequency electric fields, where the period is much greater than the alignment and relaxation times, the dipoles fully align and randomize between cycles of the electric field. When the period of the field is much smaller than the relaxation time of the Varad, a stable density will result, because the dipoles do not have time to fully randomize between electric pulses, (see Figure 4).



OSCILLATION OF VARAD DUE TO FREQUENCY OF FIELD

FIGURE 4

The critical frequency[6] , f_c, which produces a constant density is:

$$f_c = \frac{1}{2}\tau_B$$

Frequencies above 3 kHz create a density which is as stable as possible.

Experimental Design

The dipole suspension used was Varad series V-100. The manufacturer's specifications [7] stated that a 25 micrometer thickness of Varad V-100 would have a random density of 1.0. It was desired to investigate as dense a material as possible without having a density which was beyond the range of standard density measuring techniques. It was decided to use a 50 micrometer thick, 3 cm., by 3 cm. piece of Varad for all experimental work. This would yield a random density of about 2.0.

According to the manufacturer [8], a 25 micrometer thickness of the suspension requires a voltage of 35 volts peak-to-peak at 3 kHz. The capacitance of the suspension is 4.373×10^{-11} farads/cm. The resistivity is 10^{10} ohm-cm. The power consumption is about 1 microwatt per cm^2. For a thickness of 50 micrometers and an area 3 cm. x 3 cm. ($9\ cm^2$):

$$C = \frac{(4.737 \times 10^{-11}\ \text{farads/cm})(9\ \text{cm}^2)}{(50 \times 10^{-4}\ \text{cm})}$$

$C = 540$ picofarads

$$R = \frac{(10^{10}\ \text{ohm-cm})(50 \times 10^{-4}\ \text{cm})}{(9\ \text{cm}^2)}$$

$R = 5.56$ megaohms

$V = 70$ volts peak-to-peak

Power consumed = 9 microwatts

Time constant = RC = 3.00 milliseconds

For experimental purposes, it was necessary to be able to provide about twice the normal voltage and frequency stated in the manufacturer's specifications. This would require a variable frequency, variable amplitude power supply capable of 0-140 volts peak-to-peak at 500-6000 Hz. This was obtained by amplifying the output of a frequency generator. The schematic and design of the power supply are discussed in Appendix A.

The thesis was intended to answer the questions:

1) What are the spectral characteristics of the Varad?
2) How well does the Varad transmit off-axis light?
3) How does the density of the Varad change when the strength and frequency of the electric field is varied?
4) How is the response (rise and fall) time of the Varad affected by changes in voltage and frequency of the electric field?

The first three questions were to be answered using a designed experiment. The spectral density (measured on the Beckman Model B Spectrophotometer) was measured as wavelength, λ, angle of incident light, ω, voltage, E, and frequency, f, of the electric field were varied. The experiment was fully crossed and partially replicated. The levels run for each factor are shown at the top of the next page.

λ (nm): 450, 600, 750

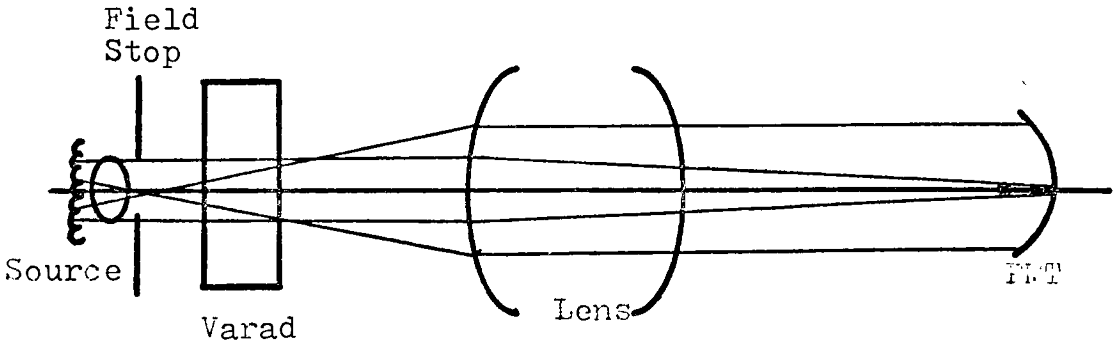
θ (degrees): 0, 15, 30, 45

E (volts): 100, 200, 400

f (hertz): 1000, 2000, 3000

Statistical methods were to be used to analyze the experiment. Problems arose in data analysis. Using purely statistical techniques, models that fit the data could not be found, due to the number of factors in the experiment. It was necessary to split the experiment into separate one factor experiments, and analyze the data by graphical means. From visual inspection of the graphs, followed by statistical regression analysis, models were fit to the data where possible.

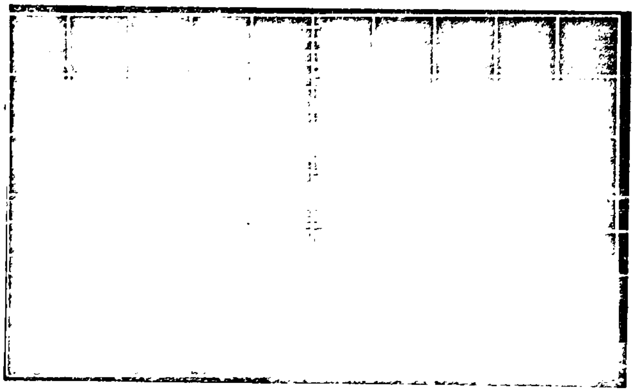
To determine how the response time of the Varad was dependent on the voltage and frequency of the applied electric field, an oscilloscope-photomultiplier tube system was utilized, (see Figure 5). The Varad was illuminated by a $1\frac{1}{2}$ cm. diameter beam of collimated light. The beam of light was then focused onto the RCA-931A photomultiplier tube. The output of the



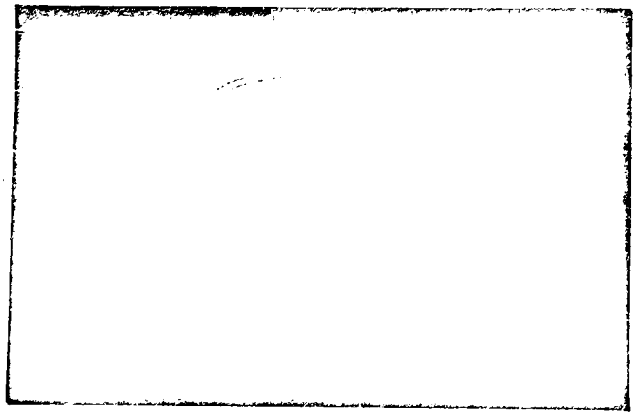
TIME STUDY OPTICAL APPARATUS

FIGURE 5

PMT was connected to one channel of a Tektronix dual beam oscilloscope. The other channel monitored the power to the Varad. A triggering system was designed to begin the trace at the exact instant that the voltage was applied to the Varad. The trace was photographed and measurements were taken from the projected images. The rise time was defined as the time between the instant when the voltage was applied to the Varad (as determined from the trace on channel two) and the time when the Varad was 95% open. An example trace is shown below.



Rise Time

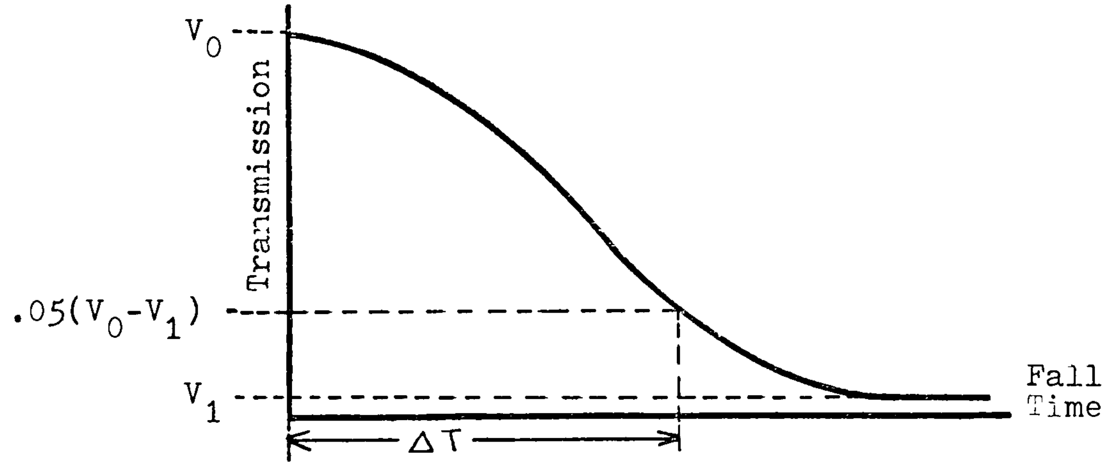


Fall Time

EXAMPLE OF RISE AND FALL TIME OSCILLOSCOPE TRACES

FIGURE 6

The fall time was defined as the time between the instant that the field was turned off and the time when the Varad was 95% closed. The cut-off points were determined by measuring the maximum vertical deflection, $V_0 - V_1$, multiplying by 0.05, and subtracting the value from V_0. Care had to be taken to make sure that the trace had really reached a minimum. This method is illustrated in Figure 7. The schematic and design of the photomultiplier tube and optical arrangements are discussed in Appendix B and Appendix C.



EXAMPLE OF TIME MEASUREMENT TECHNIQUE

FIGURE 7

A designed factorial experiment, (2^4), was run to determine the functional relationship between rise and fall times and the frequency and voltage applied to the Varad. The levels of the experiment are shown below.

voltage (peak-to-peak): 100, 200, 300, 400

frequency (Hz): 1000, 2000, 3000, 4000

Hypotheses

The hypothesis behind much of the experimentation was that, since the dipoles are vibrating and are not physically similar to homogeneous dye molecules, they may exhibit unusual effects. Since the degree of vibration is dependent on the properties of the electric field, these unusual effects can be determined by varying the voltage and frequency of the electric field applied to the Varad.

Literature states that the density of the Varad is related to the strength of the field by an exponential model[9]. The literature does not state any mathematical models for the dependence of density on the angle of incident light or the frequency of the field.

For the time study experiments, the main objective was to determine what minimum opening and closing times are achievable, and at what voltage and frequency these occur at. It is the shape of the curves that is important more than the estimates of any parameters involved. If the curves are exponential as expected, the minimum values should be easy to obtain.

Experimental Results-General

Visual inspection of the Varad showed that it was a very inhomogeneous, purple colored liquid between two layers of glass. The random density varied from a minimum of 2.0[illegible] to a maximum of 3.29. The standard deviation was 0.33. The suspension became more uniform after repeated use however. The manufacturer predicted that a maximum density of 2.00 would be produced with a 50 micrometer thick piece of Varad V-100 [10]. Visual density measurements made on a MacBeth TD-504 showed that an average maximum density of 2.80 was obtained. Further testing showed that the two plates of glass were not parallel. Because of this, care had to be taken to be sure all measurements were made on the same area. Density was very position dependent.

The manufacturer's specifications [11] stated that 70 volts peak-to-peak was suffiecient to power the Varad and obtain a minimum density of 0.80. Experimentation has shown that the density is still decreasing significantly at 400 volts (see Figure 10 later in text).

The crossed experiments that were run failed to give good models due to the large number of factors and possible interactions. The large esperiments were broken into single factor experiments and then analysed graphically.

The following graphs are plots of actual data. Very little smoothing of the surves was necessary. Where a functional relationship is seen, the data was transformed until a straight line resulted. Any deviation from a straight line in the plots of transformed data indicates that the transformation is not an appropriate model. When the transformed data did fit a straight line, statistical regression was used to determine the estimates of the parameters.

Results-Spectral Characteristics

The spectral density was measured while varying the voltage applied to the Varad. The results are shown in Figure 8. As one can see, the voltage seems to change the vertical position of the spectral curve, except in the infrared region. At this point (above 800 nm.), the spectral density varies greatly, with no apparent pattern. The spectral characteristics of the dipole suspension depend upon the dipole length distribution. This distribution has been stated to be nearly normal [12] which would produce a normal transmission distribution. If the spectral characteristics were to be a neutral, the density versus wavelength curve would be a straight line, and each dipole length would have an equal frequency of occurrence. This would produce a spectral efficiency, q_{rz}, which would be equal in all regions of the spectrum. As Figure 9 shows, this is not the case. The q_{rz} shows that the Varad is more efficient in the 500 to 650 nm. region. The reason for this has been discussed in the theoretical background.

Results-Density as a function of Voltage

As is seen in Figure 10, the voltage and density of the Varad have an exponential relationship. This is verified by a plot of transformed data in Figure 11. The straight line indicates that the transformation provides an adequate model. Regression analysis substantiates the graph:

$$\ln(D-.06) = 0.9121 - 0.0059\,E \qquad \text{Eq. 1}$$

$$R^2 = .9274 \qquad SE = .1340$$

FIGURE 8 DENSITY VERSUS WAVELENGTH

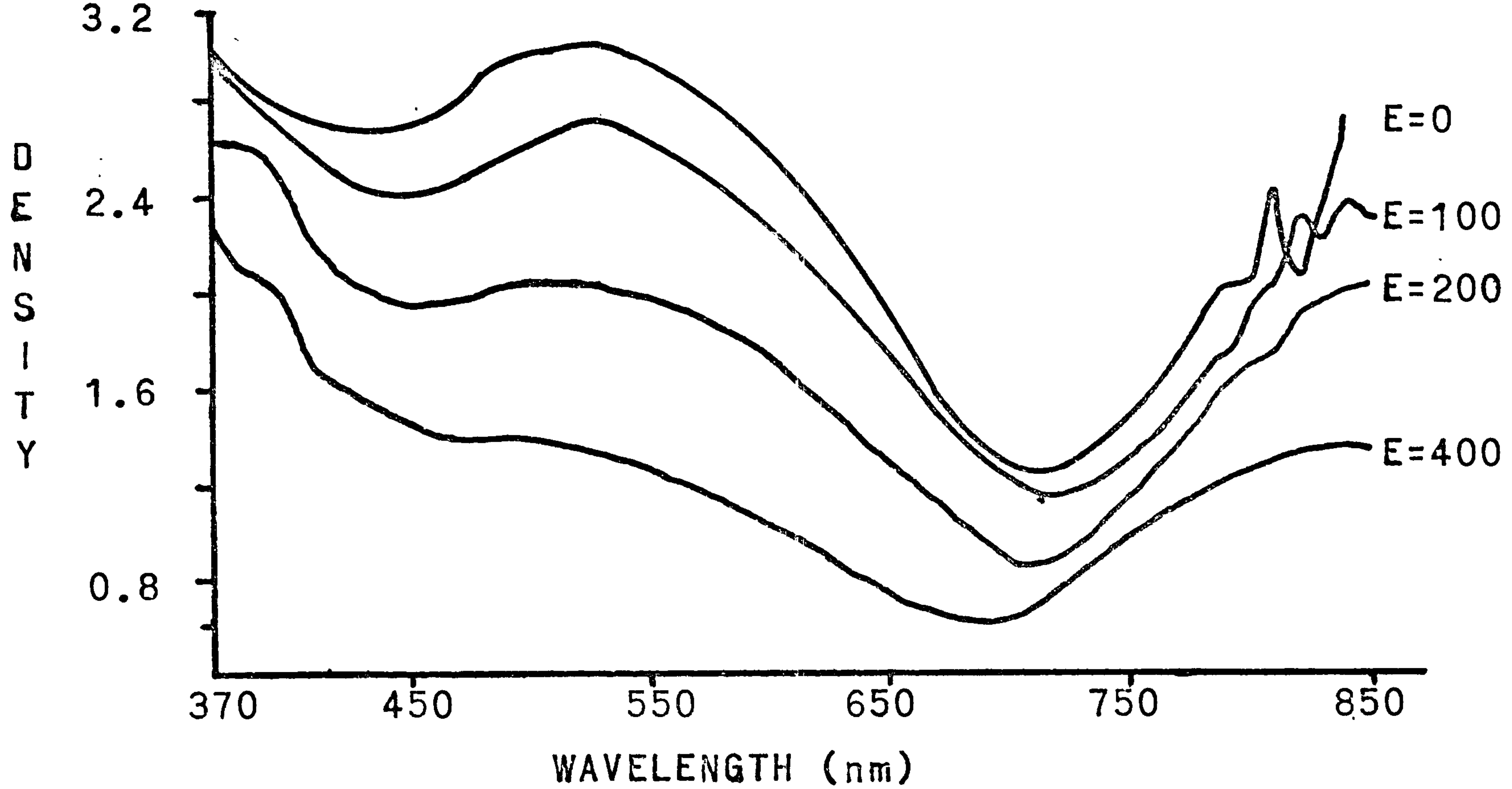
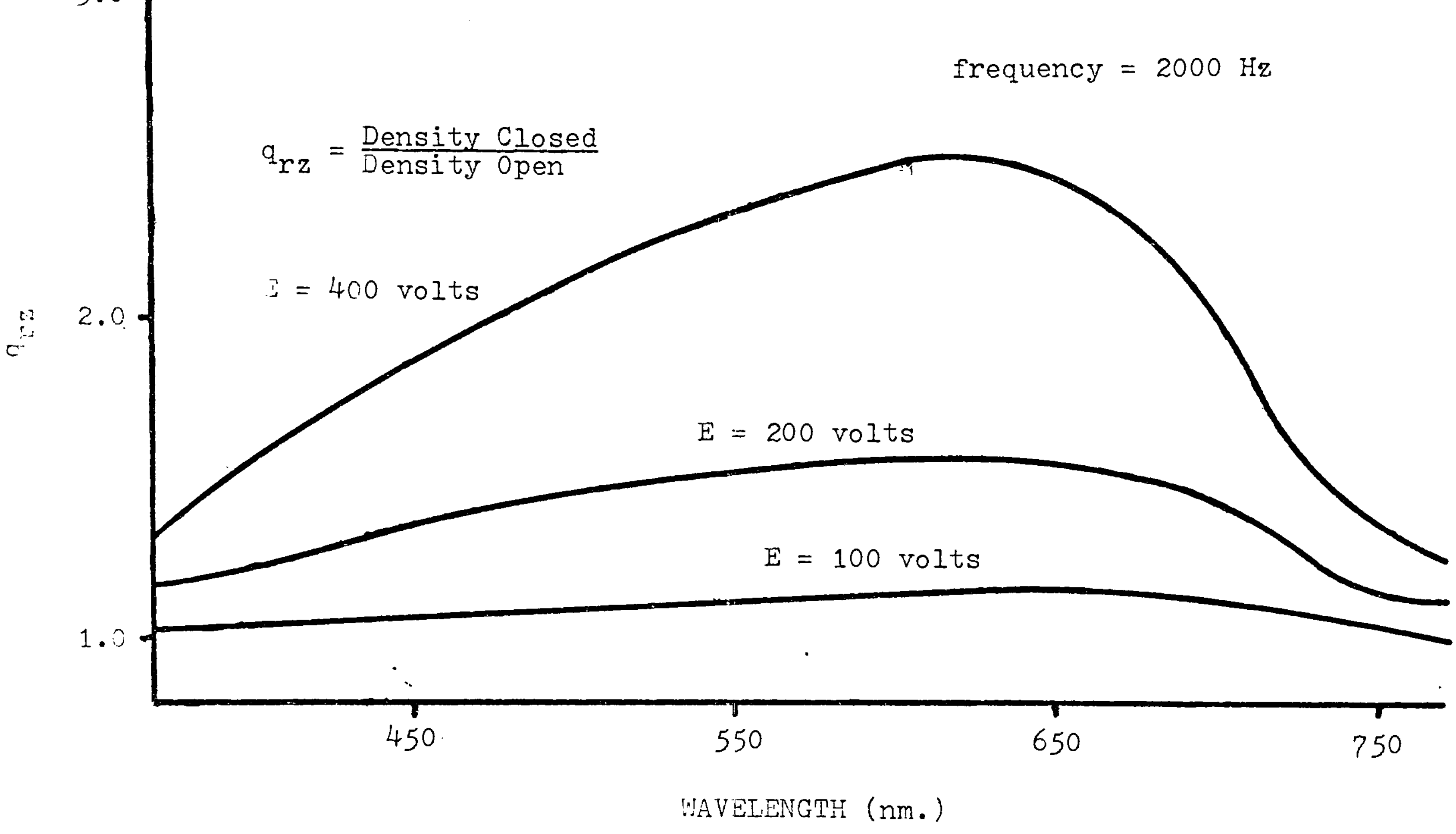


FIGURE 9 q_{rz} of Varad



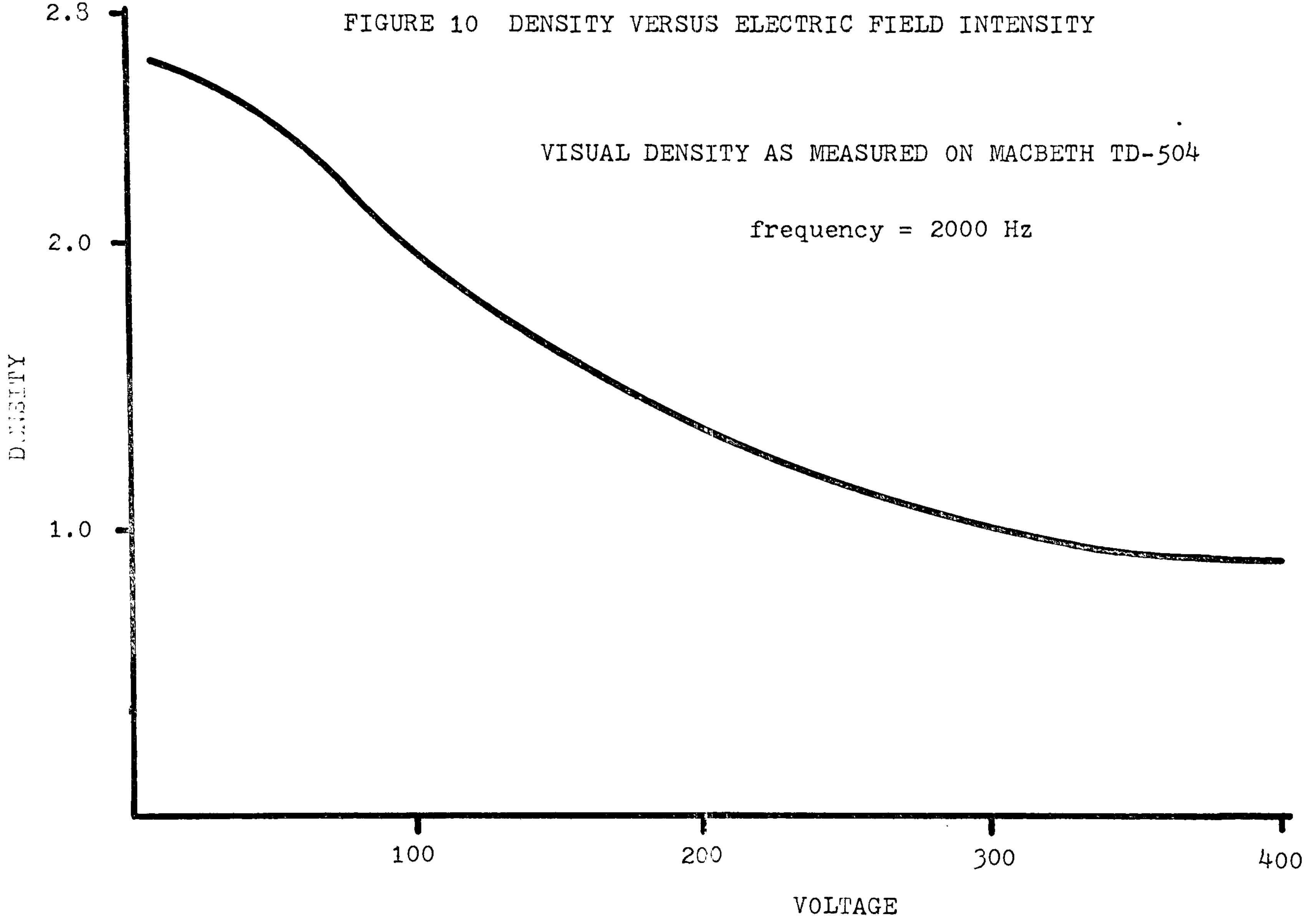
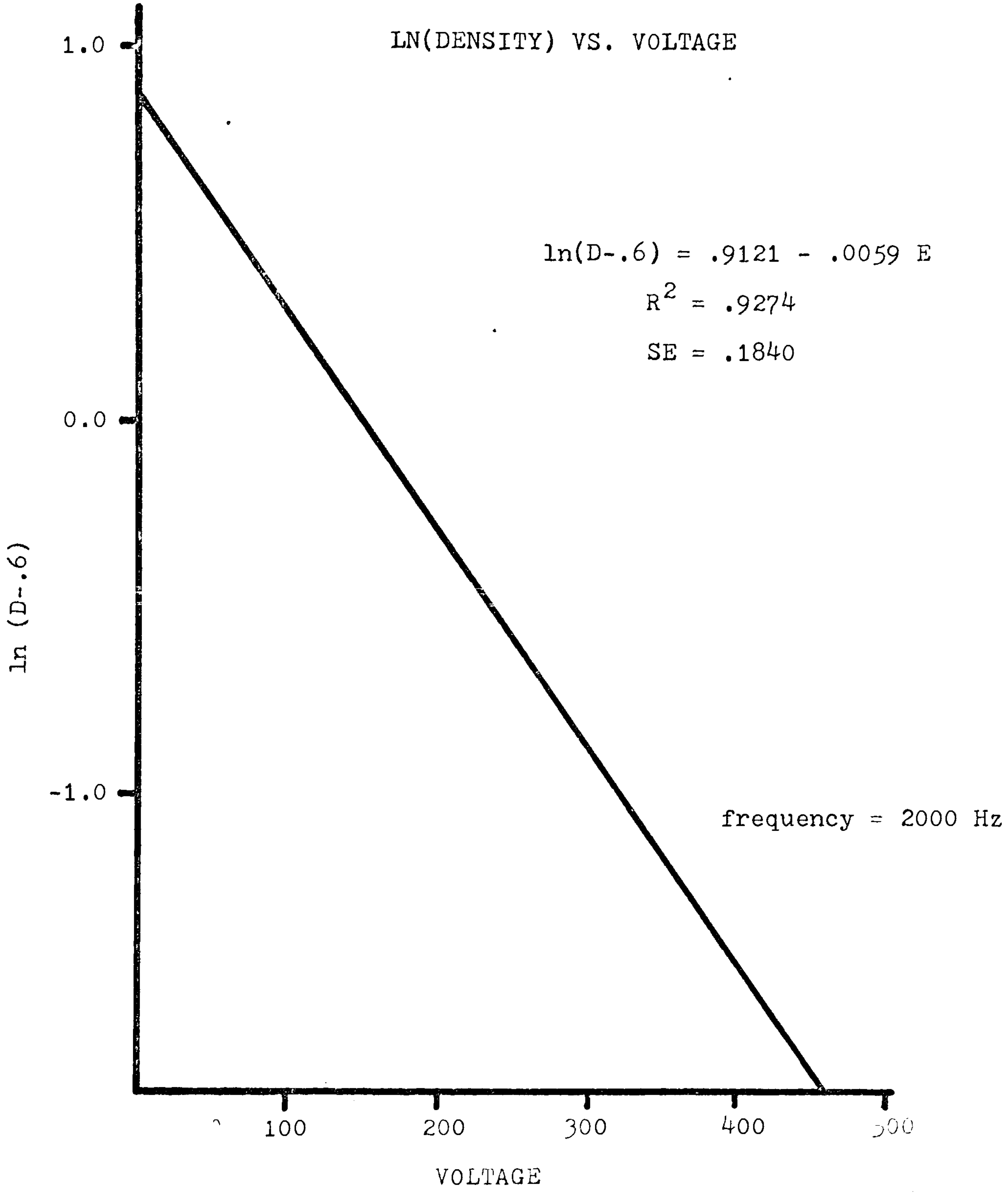


FIGURE 10 DENSITY VERSUS ELECTRIC FIELD INTENSITY

FIGURE 11


LN(DENSITY) VS. VOLTAGE
1.0
0.0
-1.0
ln (D-.6)
ln(D-.6) = .9121 - .0059 E
R^2 = .9274
SE = .1840
frequency = 2000 Hz
100
200
300
400
500
VOLTAGE

In this model, $\bar{D}$ equals 0.6. It is the minimum density possible at that frequency. Figure 10 gives an indication of the value of E_r. It is the inflection point of the curve and appears to be about 50 volts. This is the voltage needed to balance the force exerted by Brownian motion. Figure 12 is a graph of the same data that is plotted in Figure 10, but the density has been converted to transmittance. The straight line portion of the curve above 150 volts could provide an easy, useful model to determine transmittance in any application of Varad.

Results-Density as a function of Frequency

The relationship between density and frequency is depicted in Figure 13. The shape of the curves are the same, they are just displaced vertically. This means that the same model can be used for all the curves provided that a base value, D_0, is subtracted out. D_0 is the lowest density obtainable at a given voltage. The regression equation obtained was:

$$\ln(D-D_0) = 0.1626-.0021\ f \qquad \text{Eq. } 2$$

$$\text{at } E = 400 \text{ volts, } D_0 = 1.16$$

$$E = 200 \text{ volts, } D_0 = 1.86$$

The values of D_0 where obtained directly from the graphs, since they had obviously reached a minimum. In order to say that the two curves were identical, it was necessary to do a statistical t-test on the coefficients. This test uses the difference between the coefficient estimates and the reliability of the estimates, along with probability theory to determine

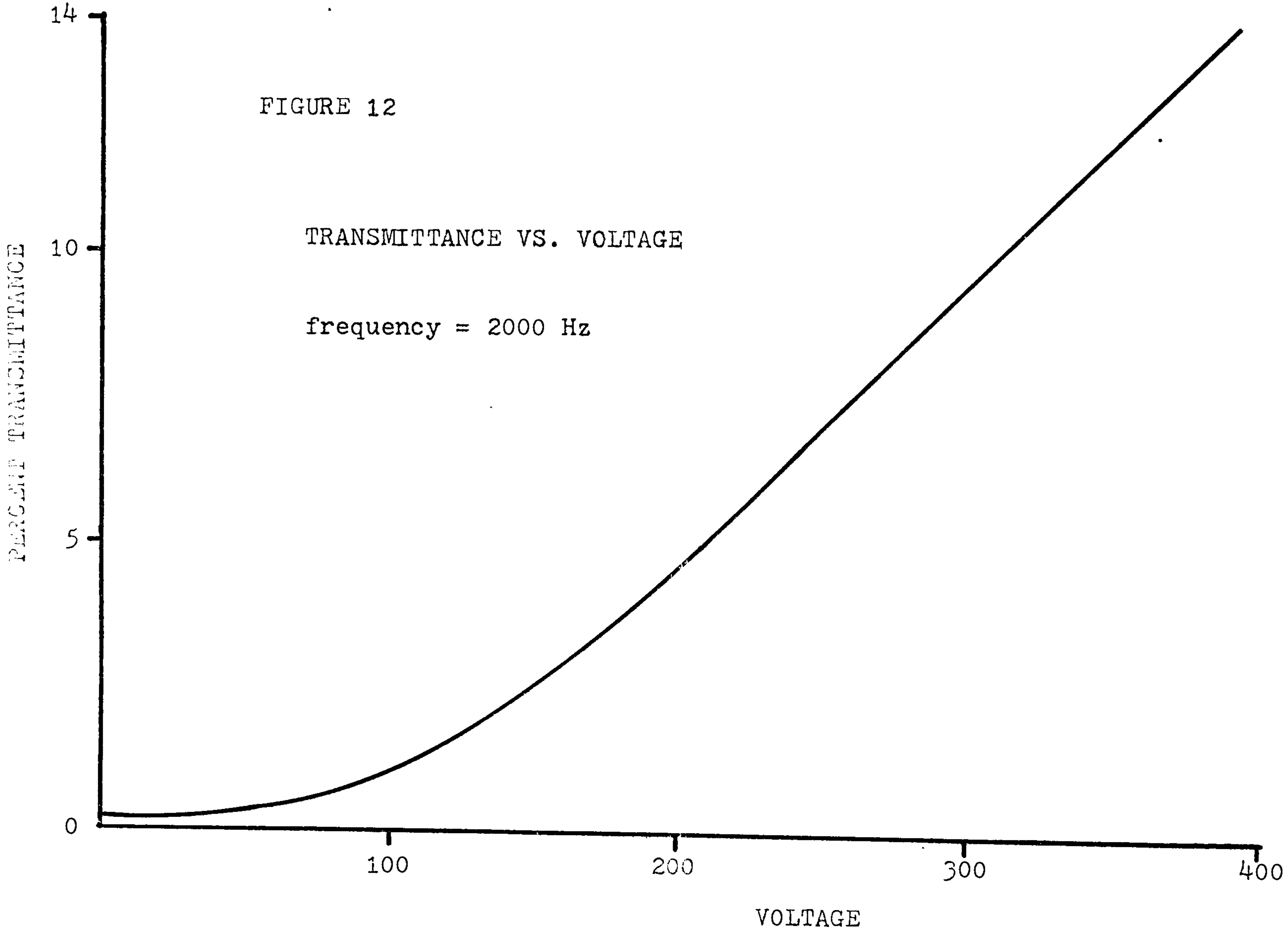


FIGURE 12

TRANSMITTANCE VS. VOLTAGE

frequency = 2000 Hz

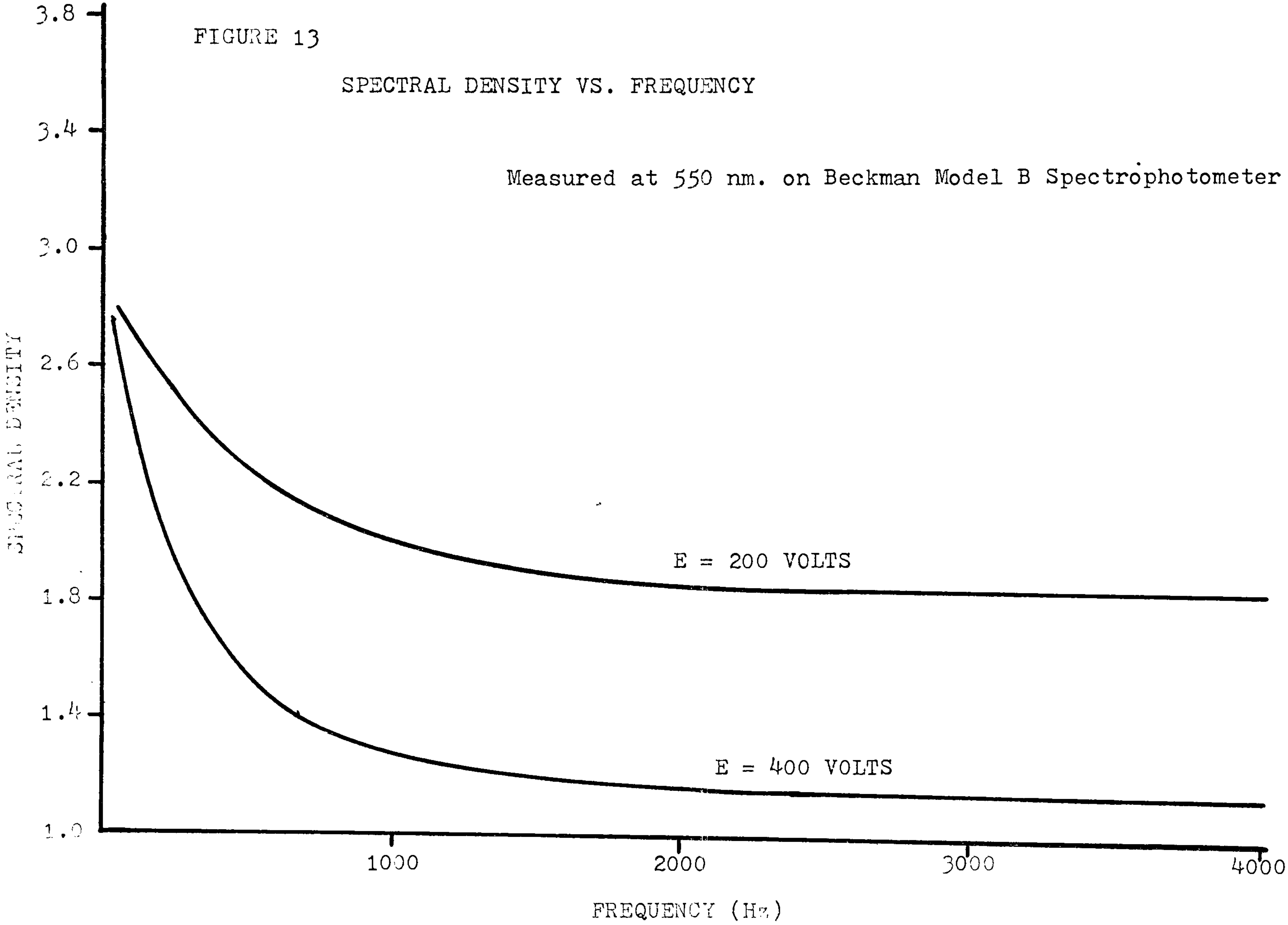
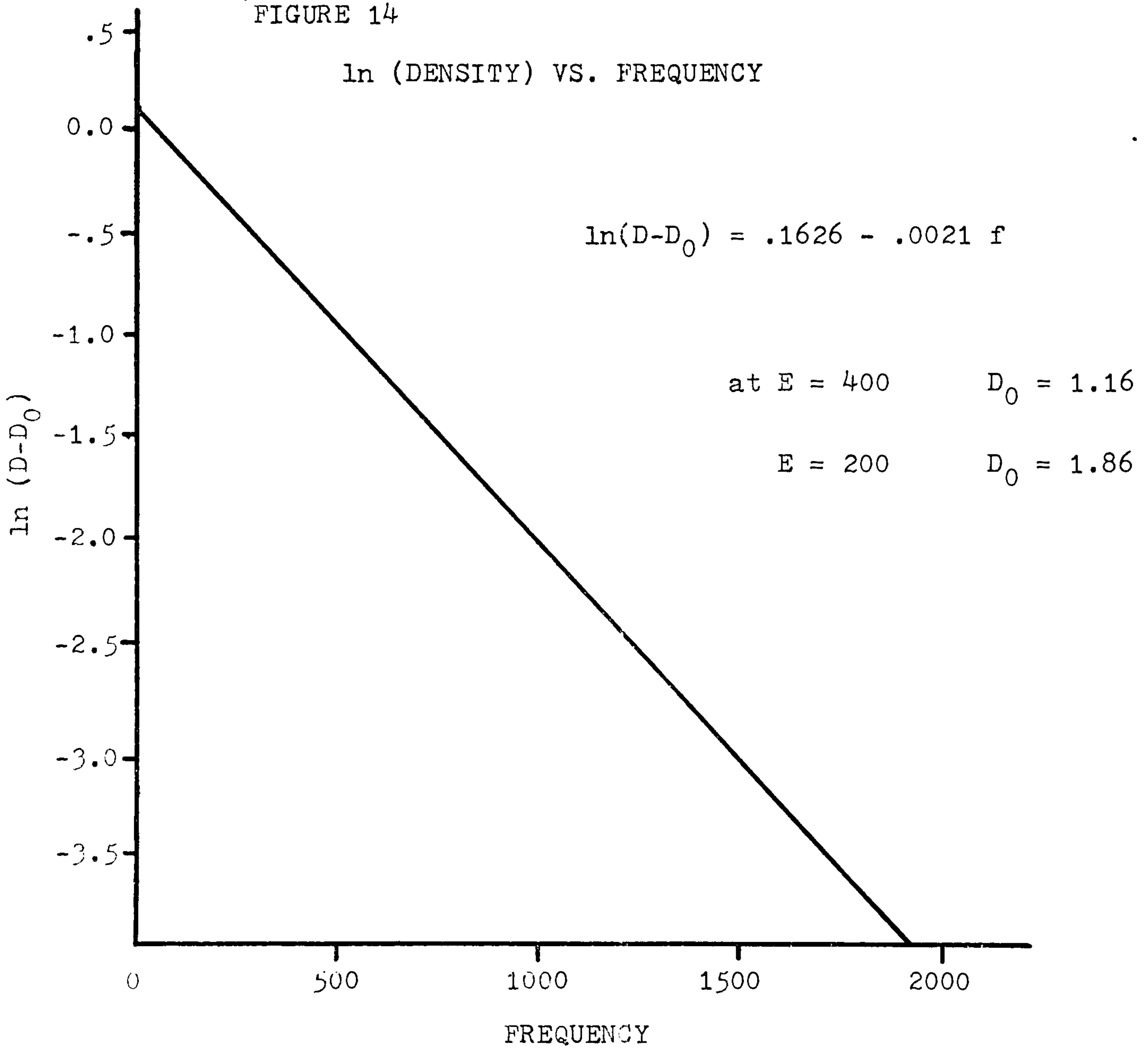


FIGURE 13

SPECTRAL DENSITY VS. FREQUENCY

Measured at 550 nm. on Beckman Model B Spectrophotometer

FIGURE 14


ln (DENSITY) VS. FREQUENCY
ln(D-D0) = .1626 - .0021 f
at E = 400 D0 = 1.16
E = 200 D0 = 1.86
ln (D-D0)
.5
0.0
-.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
500
1000
1500
2000
FREQUENCY

if the coefficient estimates are really estimates of the same number.

For E = 200 volts, $n = 27$

$$\ln(D-D_0) = b_{01} + b_{11} f$$

$b_{01} = .0801$ $s_{01} = .0341$

$b_{11} = -.00202$ $s_{11} = .0000300$

For E = 400 volts $n = 32$

$$\ln(D-D_0) = b_{02} + b_{12} f$$

$b_{02} = .244$ $s_{02} = .0448$

$b_{12} = -.00214$ $s_{12} = .0000418$

n = the number of data points

v = n - 2 (because two parameters, b_0 and b_1, were estimated)

$$t = \frac{b_{01} - b_{02}}{s_t}$$

$$s_t = \sqrt{\frac{v_1 s_{01}^2 + v_2 s_{02}^2}{v_1 + v_2}}$$

$t = 1.14$

The table value for 95% confidence and $v_1 + v_2$ degrees of freedom is compared with the calculated value of t. If the calculated value of t is less than the table value, the two b values are estimating the same number. The table value for 57 data points is 2.00. This means that b_{01} and b_{02} are estimates of the same number. The t value calculated for b_1 was 1.75, so b_{11} and b_{12} were also estimates of the same number. Hence the two curves have the same shape as shown in Figure 14.

Results-Density as a function of incident beam angle

Looking at the physical situation, one would think that the density would increase as you go off axis by the cosine law. This is because the projected area of the dipoles increases by a cosine factor. This law does not seem to be accurate except in the paraxial region. Beyond 25 degrees, the density is not predicted adequately by a simple cosine factor. To find a better model, regression analysis was used. The best model obtained was:

$$D = 0.4468 + 1.524/\cos(w) \qquad \text{Eq. 3}$$

$$R^2 = .9339$$

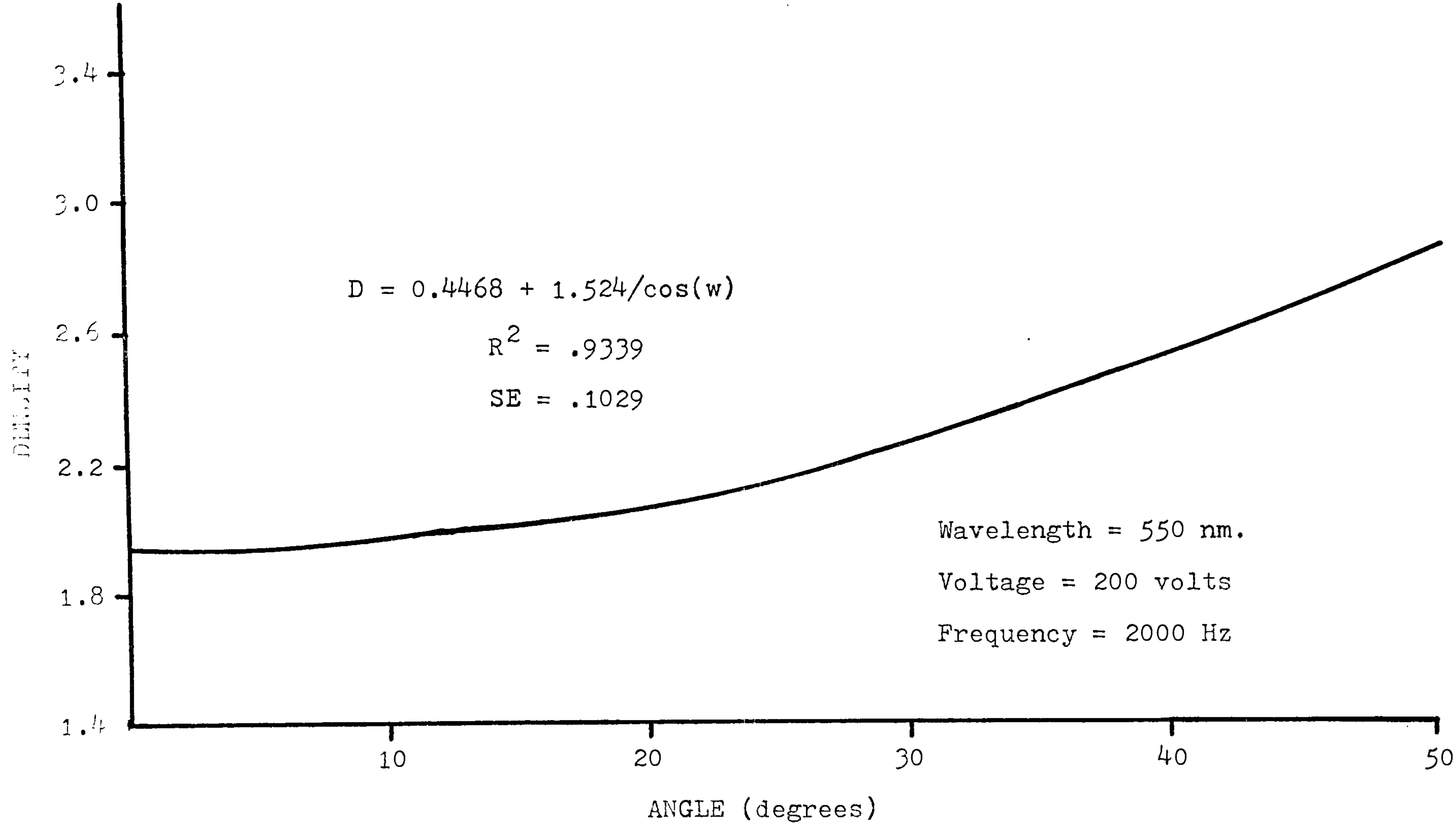
$$SE = 0.1029$$

This suggests that something other than the cosine law is causing the density to change. Perhaps the shape of the dipoles, or the nature of the suspending medium or transparent electrodes is scattering light, and causing the change in density from what was expected. The data is shown in Figure 15.

Results-Effect of Voltage and Frequency on the Rise Time

The effects of voltage and frequency on rise time are shown graphically in Figures 16 and 17. The rise time decreases as the voltage increases from zero to about 150 volts, however, the decrease is slight. The rate of decrease is higher between 150 and 350 volts. When the voltage is increased beyond 400 volts, little change in the rise time occurs. The curve resembles an exponential decay curve, but transformation of the data did not yield a straight line. The rise time decreases

FIGURE 15 DENSITY VS. ANGLE OF INCIDENT LIGHT



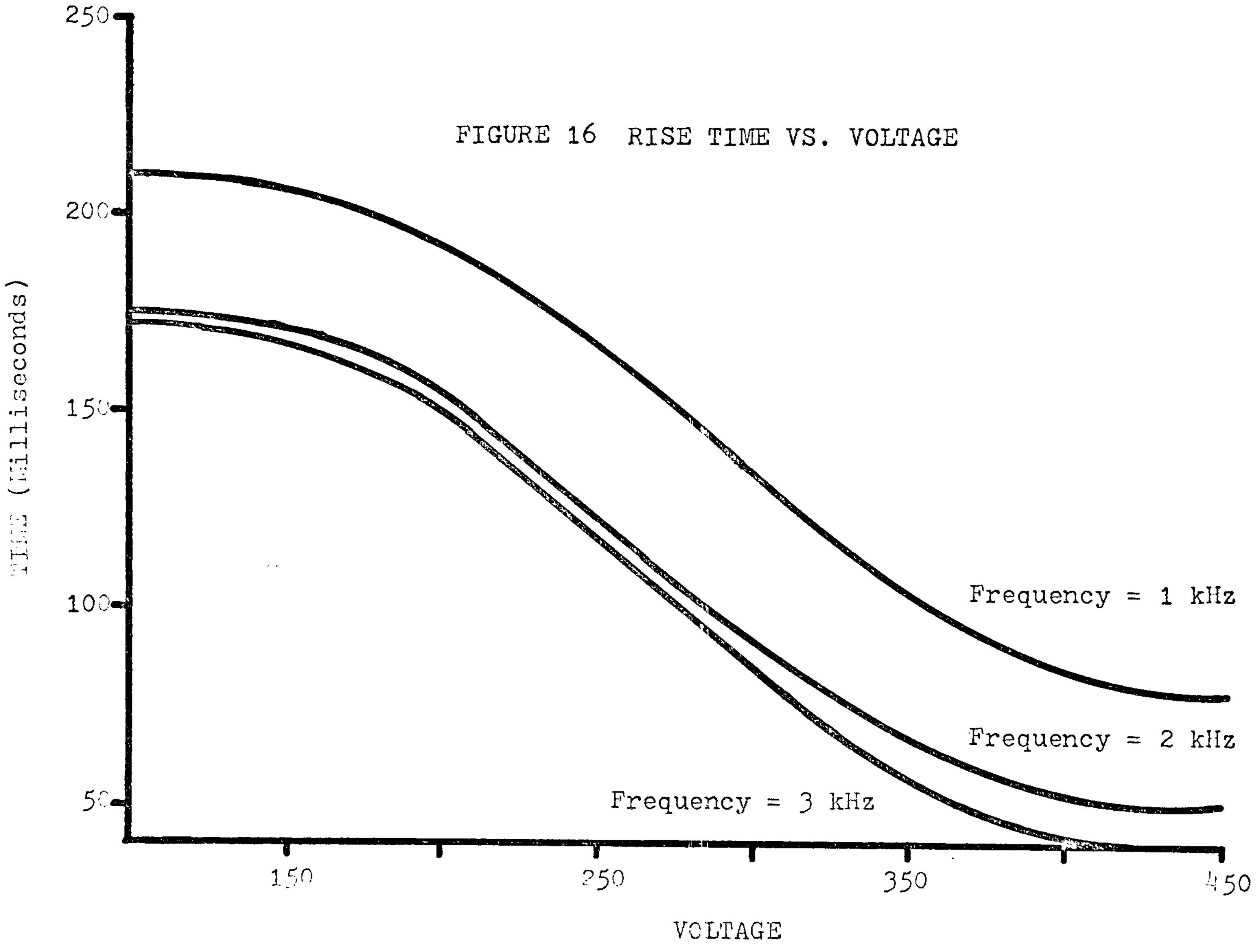
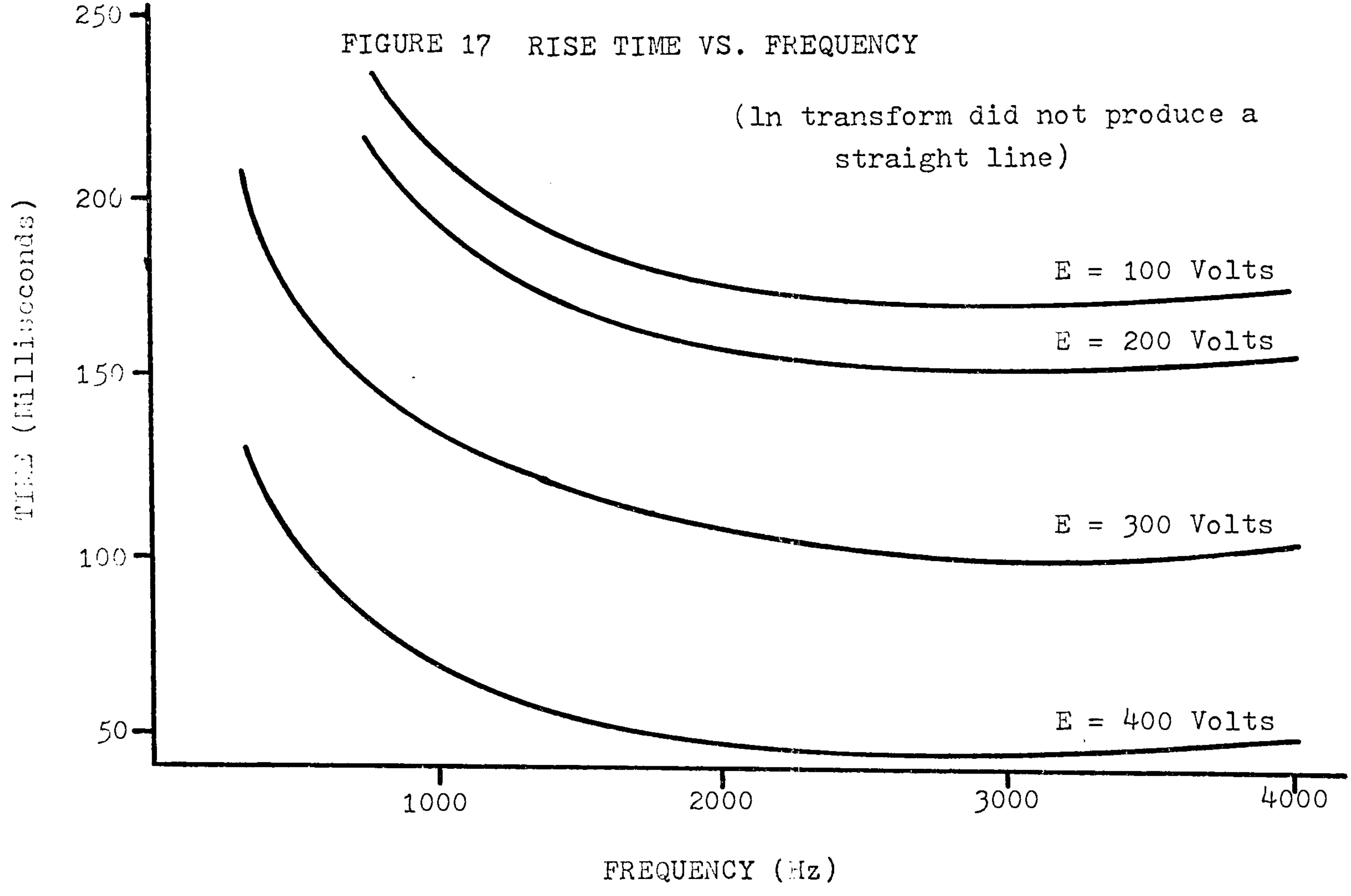


FIGURE 16 RISE TIME VS. VOLTAGE

FIGURE 17 RISE TIME VS. FREQUENCY

(ln transform did not produce a straight line)



slowly for low voltages because the force due to the electric field is only slightly greater than the force due to Brownian motion. Beyond 400 volts, the force due to the electric field is so much greater than the Brownian force that it has no further effect on the rise time.

Frequency does not have a large effect on the rise time, except when the frequency is lower than 1 kHz. At this point the dipoles are not in a stable state. Oscillation is present. The curves in Figure 17 show that the rise time increases drastically when the frequency is below 1 kHz.

A natural log transformation was fit to the time versus frequency data, but it did not provide a straight line. It accounted for some of the variability, but did not fit the data well enough for a predictive model. Some other relationship must be present.

Results-Effect of Frequency and Voltage on Fall Times

The curves of fall time versus voltage shown in Figure 18 are shaped like exponential curves. The plot of transformed data shown in Figure 19 is a straight line. The regression models fit to the curves are:

For f = 1000 Hz

$$\ln(T - 93) = 7.71 - 0.0165\,E \qquad \text{Eq. 4}$$

$$R^2 = .9792$$

$$SE = 0.3379$$

For f = 4000 Hz

$$\ln(T - 82) = 6.71 - 0.0137\,E \qquad \text{Eq. 5}$$

FIGURE 18

FALL TIME VS. VOLTAGE

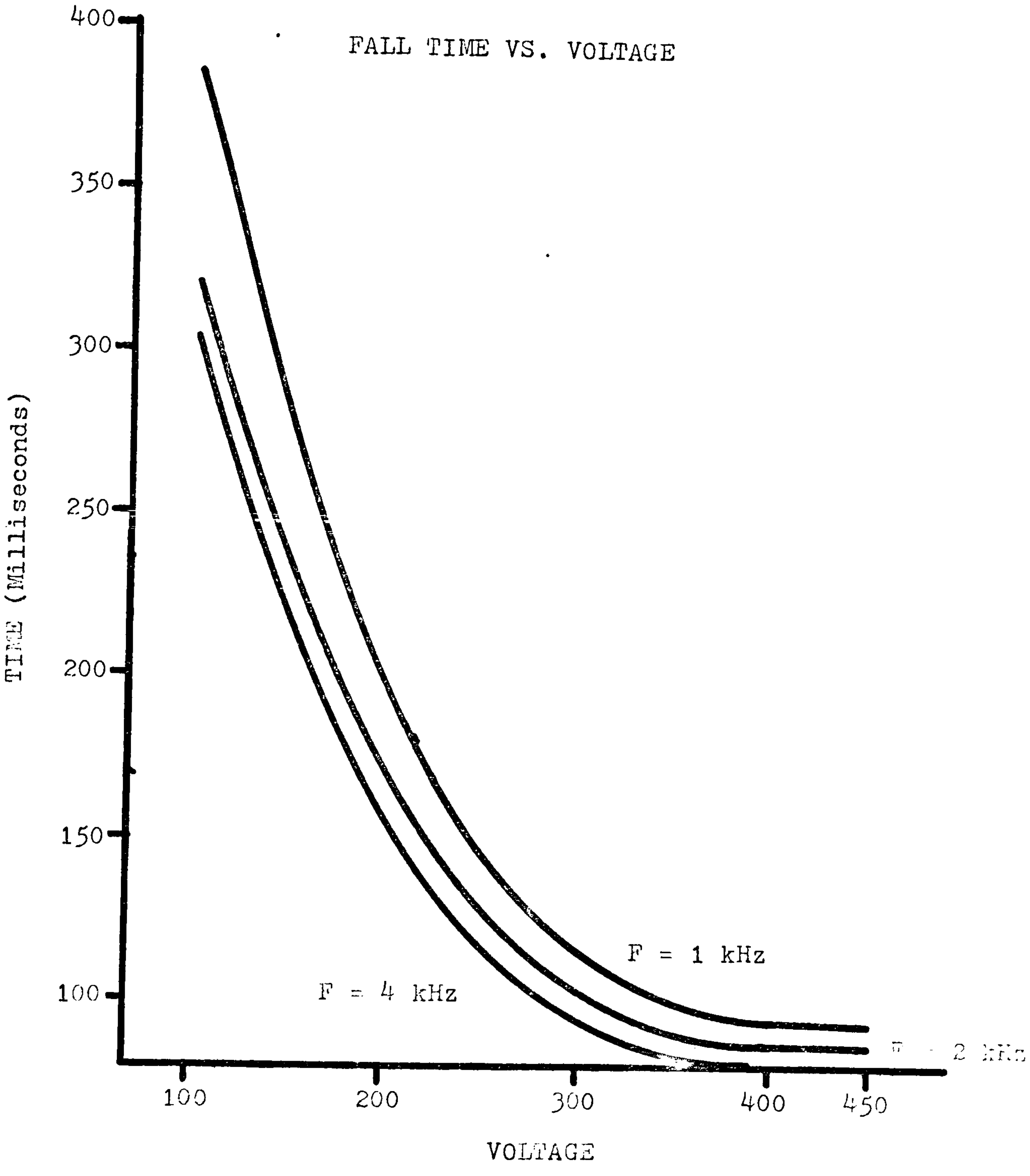


FIGURE 19

LN (FALL TIME) VS. VOLTAGE

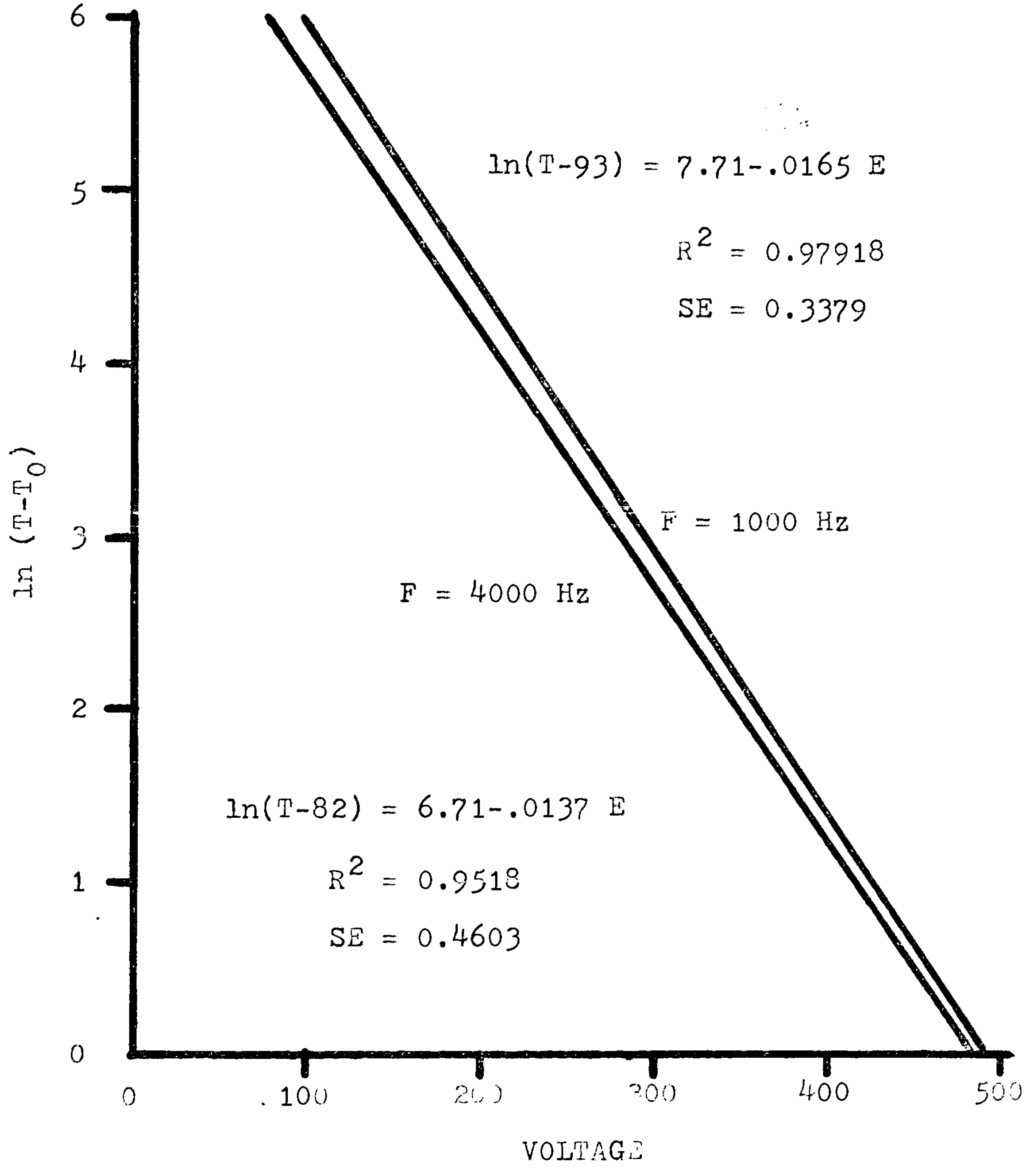
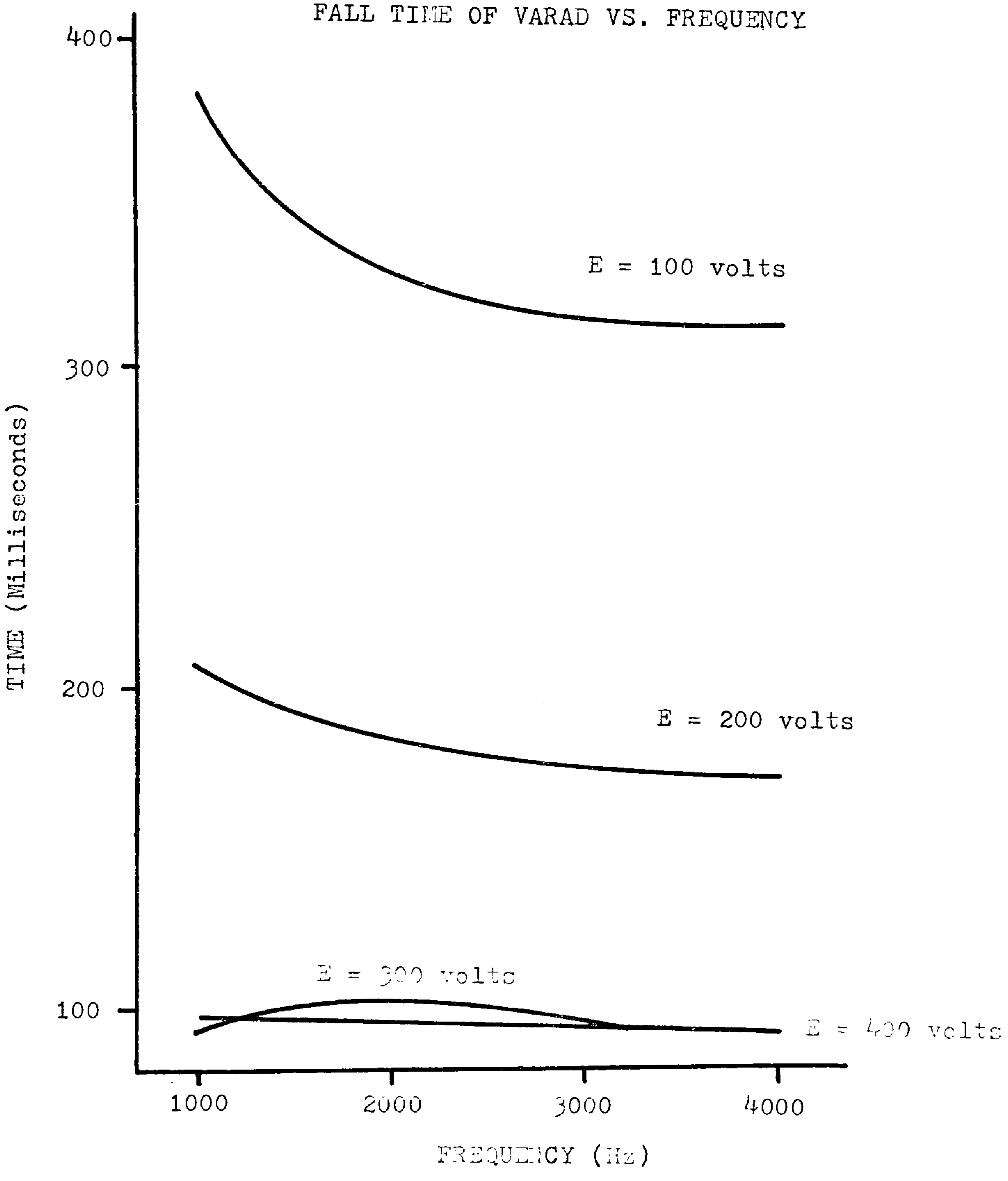


FIGURE 20

FALL TIME OF VARAD VS. FREQUENCY



$$R^2 = .9518$$

$$SE = 0.4603$$

The constants (93 and 82) subtracted from the left hand side of the equations correspond to the minimum values of T for the curves.

Frequency seemed to have little effect on the fall time. This is shown in Figure 20.

FOOTNOTES FOR CHAPTER 2

[1]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969), 7, page 1397.

[2]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969), 7, page 1399.

[3]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969), 7, page 1399.

[4]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969), 7, page 1403.

[5]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969), 7, page 1407.

[6]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969), 7, page 1404.

[7]Marks Polarized Corporation, Technical Data Sheet, "Varad Electroptical Fluids Series V-100", June 15, 1972.

[8]Marks Polarized Corporation, Technical Data Sheet, "Varad Electrooptical Fluids Series V-100", June 15, 1972.

[9]Alvin M. Marks, "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, 8 (July 1969),7, page 1407.

[10]Marks Polarized Corporation, Technical Data Sheet, "Varad Electrooptical Fluids Series V-100", June 15, 1972.

[11]Marks Polarized Corporation, Technical Data Sheet, "Varad Electrooptical Fluids Series V-100", June 15, 1972.

[12]Alvin M. Marks, Personal letter, December 16, 1975.

SUMMARY AND CONCLUSIONS

The spectral characteristics of Varad make it almost unsuitable for photographic use. This problem can be remedied by the proper choice of filters; however, this will cut down on the light transmitted. Also, the spectral characteristics change with the degree of alignment, so perfect filtration could not be achieved. This is shown in Figure 9.

Density changes exponentially as the voltage is increased. At 400 volts a minimum density of about 1.1 is reached, as can be seen in Figures 10-12. From these curves, it seems that 400 volts would be the most effective voltage with which to use the Varad.

A change in frequency causes the density to change exponentially also, as is seen in Figures 13 and 14. Frequencies above 2 kHz produce small changes in density, indicating that 2 kHz would be a good frequency to use the Varad at.

As the angle of incidence is increased, the cosine law does not fully account for the density change observed. The characteristics of the suspension or the transparent electrodes may be the cause of this.

Frequency has very little effect on the rise or fall times as long as it is above 1 kHz. Voltage has a much larger effect, as seen in Figure 16. This is because as the voltage is increased, the torque produced is larger, causing the dipoles to align quicker. Fall time is exponentially related to Voltage, as shown in Figures 18 and 19. While the data is known to be accurate, no reason has been discovered for the dipoles to randomize more quickly from a 400 volt electric field than a 100 volt field.

The Varad is not uniform. The density is dependent on position. The suspension must be more homogeneous for use in photographic applications.

Suggestions for Further Research

1) Develop a dipole distribution that would provide a neutral density.
2) Experiment with the use of ultrasonics to speed up the randomization process and decrease the fall time.[1]
3) Develop a Varad cell which can align the dipoles either parallel or normal to the incident light.
4) Connect a resistor in parallel with the Varad to dissipate the capacitive charge when the voltage is ceased, possibly shortening the fall times.[2]

FOOTNOTES FOR CHAPTER 3

[1]Conversation with Dr. G. Schumann

[2]Conversation with Professor John Carson.

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Chirlian, Paul M., Fortran IV, New York: Academic Press, 1973.

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Marks, Alvin M., "Electrooptical Characteristics of Dipole Suspensions", Applied Optics, July 1969, Vol. 8, No. 7, pp. 1397-1412.

Rickmers, Albert, and Hollis N. Todd, Statistics, New York: McGraw Hill Book Company, 1967.

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APPENDIX A

Design and Construction of the Power Supply

The Varad requires a voltage of about 140 volts peak-to-peak at 3 kilohertz. A power supply was designed to boost the output of a square wave generator to the needed voltage. A triode amplifier was used because of its stable quality, and high amplification factors. The amplifier was designed for use with a square wave generator with an output of about 10 volts peak-to-peak. This meant that an amplification factor of about 15 was needed.

The power supply circuitry is as follows:

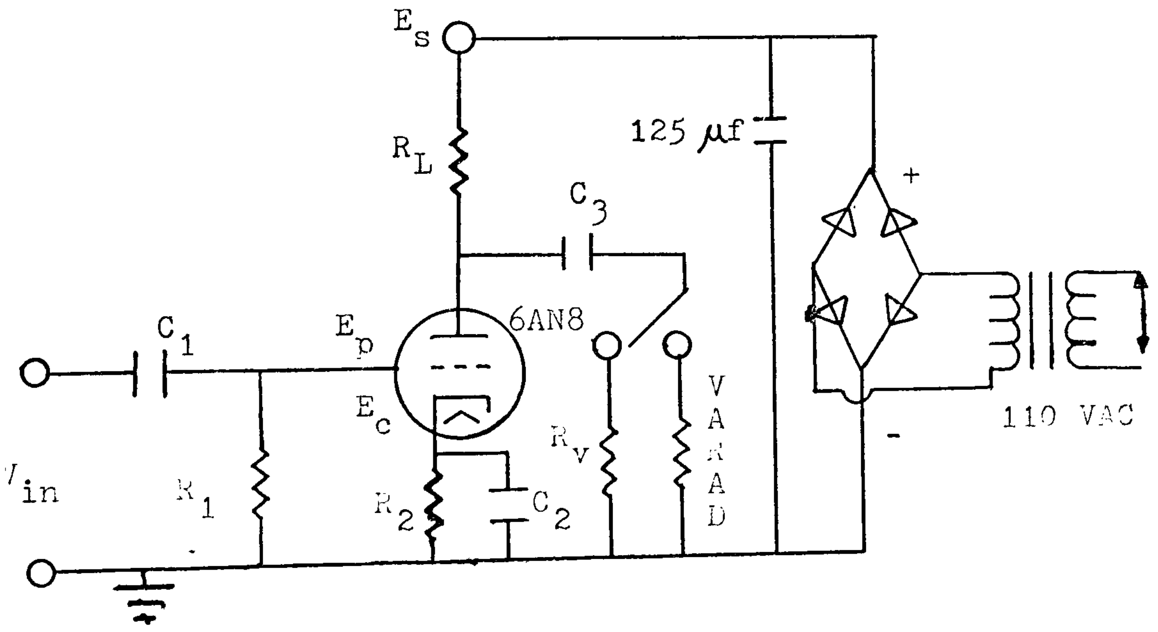

FIGURE A-1 POWER SUPPLY SCHEMATIC

In the preceding circuit diagram, E_s is the external power source, E_p is the plate voltage, and E_c is the grid voltage. R_1 is a bleeder resistor used to keep the cathode negative with respect to the grid. This was set at 1 megaohm.

Using Kirchoff's law for the loop containing the input voltage:

$$E_c = V_{in} - iR_2$$

For a given operating point on the IV curve, E_c, E_p, and i are specified. When V_{in} equals zero:

$$R_2 = -E_c/i \qquad \text{Eq. 1}$$

Therefore E_c is always negative. To find R_L, the loop through the triode is used. This yields the equation:

$$E_s = iR_L + iR_2 + E_p \qquad \text{Eq. 2}$$

Since E_s and R_L are both constant, this equation represents a straight line. This line is called the load line.

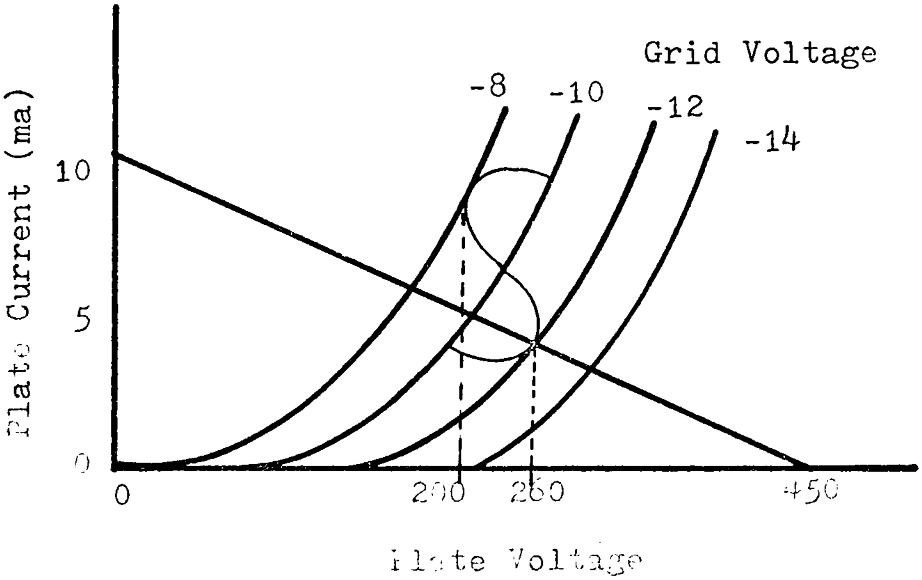

FIGURE A-2 CHARACTERISTIC CURVE OF 6AN8

Any grid voltage on the load line will produce a corresponding plate voltage, but a slight shift in grid voltage produces a large change in plate voltage.

The capacitors C_1 and C_3 are filter capacitors and act as shorts for AC current. Their values are determined by the equation:

$$C \gg 1/(2\pi fR)$$

Where R is the parallel resistor in the RC circuit and f is the frequency of the minimum frequency to be passed. C_2 is a bias capacitor used to keep the cathode bias constant. Its value is also determined by the above equation.

In order to keep the circuitry constant at all times, R_v was added to the circuit. Its resistance is 5.56 megaohms, the equivalent resistance of the Varad. By adding R_v, the circuit is under a load at all times, and the capacitors are always in a charged state. This alleviates any transient circuit problems which could affect the time study experiments.

Since the square wave generator produces a maximum of 10 volts peak-to-peak, the operating point was set at a grid voltage of -10 volts and 5 milliamps. This keeps the grid negatively charged at all times. Should the grid become positively charged, it would start to emit electrons, burning itself up.

Once the operating point is chosen, equation 1 is used to determine R_2.

$$R_2 = 2000 \text{ ohms}$$

To obtain R_L from equation 2; E_s, i, and E_p must be determined. E_s was 480 volts because a four times line transformer was used. To determine i and E_p, the characteristic curve of the tube, a 6AN8, must be consulted. At the operating point of -10 volts grid voltage, i is 5 milliamps, and E_p is 450 volts. This results in:

$$R_L = 46{,}000 \text{ ohms}$$

APPENDIX B

Design of Photomultiplier Tube Dynode Chain

The principle of the dynode chain is to cause an amplification of the light which is incident on the phototube. This is accomplished by an applied voltage driving a series resistance network. This causes a potential difference between each successive dynode, resulting in an amplification. A schematic of the situation is shown below.

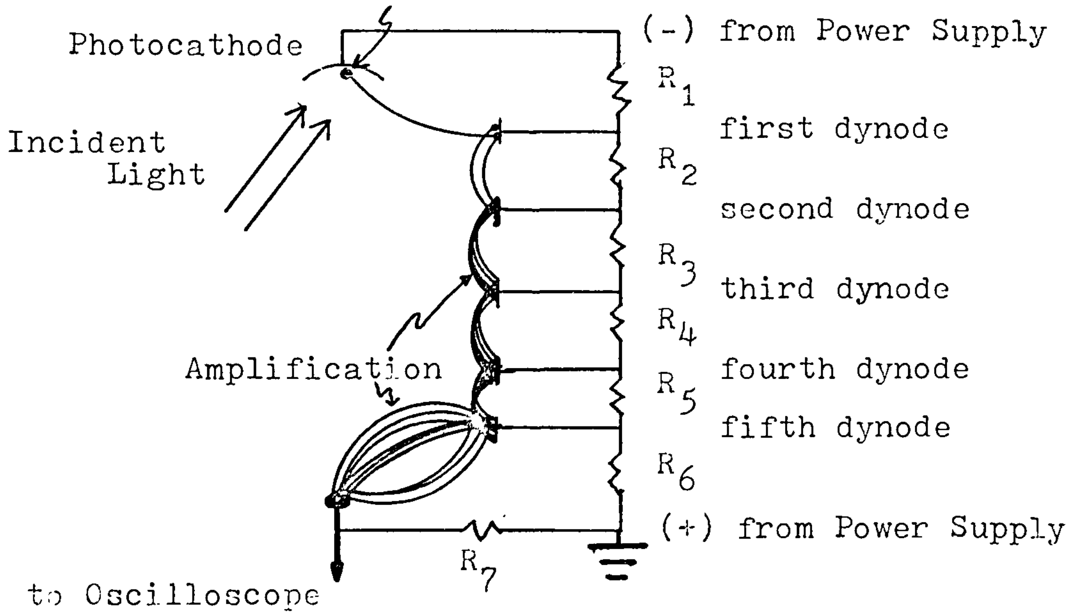

FIGURE A-3 PHOTOMULTIPLIER SCHEMATIC

The dynode chain shown above consists of five dynodes, a photocathode, and an anode. An electron is generated on the photocathode due to the incident light. This electron is attracted by the higher potential on the first dynode, and this process continues down the dynode chain, the number of electrons emitted increasing at each dynode. A 931A photomultiplier tube was used, and its pin configuration is shown below.

Pin #1 - first dynode

Pins #2-8 - dynodes

Pin #9 - ninth dynode

Pin #10 - anode

Pin #11 - photocathode

In the circuit, the resistors between the dynodes are 100,000 ohm resistors, which, with an amperage of 0.1 milliamps, cause a potential difference of:

$$V = IR$$

$$V = (0.0001 \text{ amps})(100{,}000 \text{ ohms})$$

$$V = 100 \text{ volts}$$

$$\text{Power} = IV = 0.1 \text{ watts}$$

The amount of light incident on the photomultiplier tube is inversely proportional to the potential across R_7. It is desired to read the potential difference across that resistor with an oscilloscope. The potential drop across the resistor, when R_7 is 1200 ohms. is:

$$V = IR$$

$$V = (0.0001)(1200)$$

$$V = 0.12 \text{ Volts}$$

This potential drop is well within the measureable range of the oscilloscope. A capacitor was placed across this resistor to reduce noise from the phototube. A value of

0.1 microfarad was used, and in conjunction with the coaxial cable and the oscilloscope capacitances yielded a time constant as shown below:

$$T = \text{sum of } RC = (1{,}200 \text{ ohm})(10^{-7} \text{microfarad}) + (10^{6} \text{ ohms})(20 \times 10^{-12})$$

$$T = 1.4 \times 10^{-4} \text{ seconds}$$

This time constant is sufficiently small for readings in the millisecond range to be obtained with very little error.

APPENDIX C

Optical Setup for Time Study Experiments

The design of the optical set-up is shown in Figure 5. This optical design was chosen because it provided a magnification which filled the phototube using the lenses that were available. This arrangement also provided a brighter image on the phototube than Kohler illumination. The field stop was used to minimize spherical aberration. The entire system was baffled and light tight. This was done to eliminate both flair within the system and external light from outside the system.

In the optical system, a beam of collimated light 1½ centimeters in diamter was incident on the Varad. A lens then focused this beam of light on the phototube.