

Technical Report: NAVTRADEV CEN 1440-1

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SOLID STATE IMAGE INTENSIFIERS

Phase III

Annual Report

on

**A Broad Continuing Program for the Application
of Light and Image Intensification Techniques
to Military Training**

Project LIT

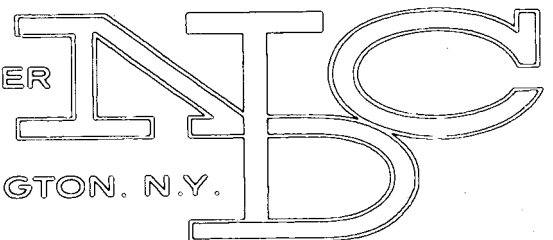


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PORT WASHINGTON, N.Y.

NAVTRADEVCEEN 1440-1
SOLID STATE IMAGE INTENSIFIERS
ABSTRACT

Technical Report NAVTRADEVCEEN 1440-1 describes the continuation of the work performed under contract [redacted] and reported in technical report NAVTRADEVCEEN 562-1. The objectives of the program were: (1) to improve the characteristics of the low resolution (40 lines/inch) photoconductive-electroluminescent (PC-EL) type image intensifier panel; (2) to construct a high resolution (1000 lines/inch) PC-EL type image intensifier (3) to build an experimental model compact optical projection system, incorporating the image intensifier panel.

During the first year of this program the work was concentrated toward the first and second objectives. Regarding the first objective, work proceeded on the following lines: (1) a parameter study of the PC-EL circuit was made with the aid of a digital computer; (2) a study schedule of fundamental semiconductor characteristics of the PC material was set up, for helping to improve the characteristics of the PC material; (3) CdSe sintered layers have been analyzed and improved; (4) an extensive program on plastic embedded CdSe PC powder has been carried out by the [redacted] during the last half year; (5) an exploratory study of new PC materials, such as ZnSe, As₂Se₃ and In₂S₃ has started; (6) improved image quality of the image intensifier panel has been obtained, although the reproducibility of the preparation method is quite low.

Panels with the best uniformity, least graininess and widest half-zone range reproducing capability had maximum standard luminous gains (measured with a 2870 K tungsten light source) of 20 foot-Lambert per foot-candle and maximum output brightnesses of 30 foot-Lamberts at 200 Volts and 2000 cps. Response times between 50 and 500 mseconds were measured.

For the development of the high resolution image intensifier panel (1) a large effort was made by the [redacted] to improve the evaporated EL films, and resulted in the preparation of EL films with longer life and better reproducibility; (2) some effort was made for obtaining useful characteristics of evaporated PC layers; (3) experiments for combining PC and EL films started and gave some sign of success.

Work is being continued toward improving the speed, spectral response, gain, and life characteristics of PC layers, developing the high resolution image intensifier panel, and building a compact optical projection system with the improved image intensifier panels.

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FOREWORD

This report describes the first year's work performed under NAVTRADEVGEN Contract [redacted] to continue the development of a solid state image intensifier. This program was initiated under NAVTRADEVGEN Contract [redacted] and reported in Technical Report NAVTRADEVGEN 562-1 dated November 1963.

The objective of this work is to produce image intensifier panels with improved characteristics. Materials are being developed to overcome the existing limitations on speed of response, gain, output brightness, and life.

Some success has been achieved as a result of the work now in progress. Improved panels have been produced with better uniformity, less graininess, increased gray scale reproducing ability, increased luminous gains and faster response times.

This report is being released prior to completion of the program to make the information available to others working in the same field as early as possible, and thereby prevent duplication of effort.



U. S. Naval Training Device Center

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SECTION I

INTRODUCTION

Work on photoconductive-electroluminescent (PC-EL) type solid state image intensifiers at the [redacted]

[redacted] was started in April 1959 with the support of the U. S. Naval Training Device Center, Port Washington, N. Y. [redacted] The results of the four years of work on this contract are described in the Final Report¹ edited in March 1963.

The above work was divided into two parts: (1) the construction of a low resolution (40 lines/inch) image intensifier and (2) the construction of a high resolution (1000 lines/inch) image intensifier. The greatest effort was placed in the development of the low resolution image intensifier and in that of the evaporated EL film, necessary for the high resolution panel.

In meeting the first objective, three new types of construction were developed. PC materials had to be prepared with different characteristics for these different constructions, and the development of these PC materials constituted the main part of the effort in this program. PC layers in three forms were developed: (1) evaporated films, (2) sintered layers, and (3) plastic embedded powders. The material, considered first, was CdS, but as the required response time could not be obtained from CdS, most of the work was concentrated in developing the necessary characteristics in sintered CdSe.

Among the construction types of the image intensifier, the sandwich construction (Figure 1) proved to be the best solution because of its simplicity and inherent highest resolution. Sandwich type image intensifiers have been built in sizes up to 6" x 6", with maximum standard luminous gains (measured with a 2870 K color temperature light source) of 100 ft-L per ft-c, with maximum output brightness of 30 ft-L and with resolution higher than 100 lines per inch.

For the high resolution image intensifier, the most important achievement was the development of evaporated thin EL films, with characteristics well suited to the construction of high resolution sandwich type image intensifiers. A high voltage variety of EL film gave about 100 ft-L brightness at around 120 Volts and 400 cps, and a low voltage variety gave the same brightness at around 25 Volts (400 cps). The film of the high voltage variety was more reproducible and its preparation method was better suited for making larger area panels uniformly. However, the efficiency of these films was lower by a factor of up to ten, and the half life was lower by a factor of ten to one hundred, than those of the corresponding powder EL layers.

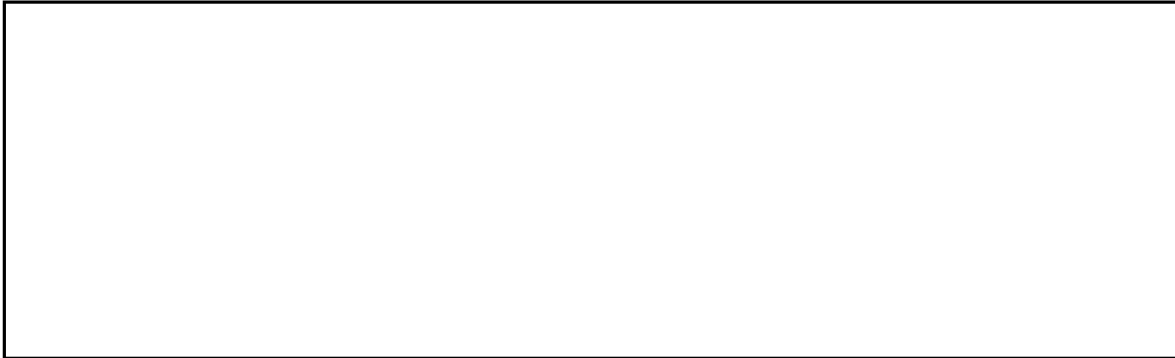
Although the development of the low resolution sandwich type image intensifier could be considered as an important achievement, there were some characteristics, such as (1) the picture quality (uniformity and contrast), (2) the speed of response, (3) the gain (primarily for shorter

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wavelengths), (4) output brightness and (5) life, which needed improvements.

The purpose of the present contract is to make an accelerated effort for improving the achieved characteristics. For the low resolution image intensifier, this necessitates the development of improved PC materials, and this has been the most important goal of the program. For the high resolution image intensifier, improvement in the efficiency and in the life of the evaporated EL film was needed along with more work toward the construction of the panel. The third requirement was to build a compact optical projection system which will incorporate the image intensifier panel. No special effort was planned for this last requirement in the first year of the program reported here.

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SECTION II

OBJECTIVES

The subject contract is the continuation of NAVTRADEVCECEN Contract [redacted] (see Reference 1). The work had to be directed principally to the same objectives as specified in the previous contract, with an accelerated program to develop solid state image intensifier panels with target characteristics shown in Table 1.

Characteristics	Type of Image Intensifier		Units
	Low resolution panel	High resolution panel	
Resolution	40	1000	TV lines/inch
Max. Brightness	50	100	foot-Lamberts
Light Amplification	100	100	ft-L/ft-c
Persistence at 0.1 ft-c illumination	20	20	milliseconds
Size	6 x 6	4 x 4	square inches

Table 1 - Target Characteristics of Image Intensifier Panels

As it was pointed out in Reference 1, the low resolution image intensifier has to be suitable for making large area observation screens. Therefore, it has to be simple to fabricate and should not be costly. It was obvious that the high resolution panel will not possess these characteristics; its construction will be considerably more delicate and more expensive than that of the low resolution panel. Consequently its use for the observation screen could not be considered.

To meet the objectives of Table 1, the program had to be directed at the development of large area polycrystalline PC layers with the characteristics listed in Table 2.

The derivations in Appendix C show that under certain conditions the theoretical maximum power gain of a low resolution image intensifier incorporating the PC layer with the characteristic values of Table 2 is higher than a thousand and that of a high resolution image intensifier is higher than a hundred, satisfying the requirements of Table 1.

The objectives for the evaporated EL film were: better than 1 lm/watt efficiency and more than one hundred hours half-life time.

Characteristics	For Type of Image Intensifier		Remarks
	Low resolution	High resolution	
Specific conductivity at 0.1 ft-c illumination	10^{-7} mhos/cm	10^{-7} mhos/cm	at 50 Volts for low resolution and 25 Volts for high resolution
Dark conductivity	10^{-8} mhos/cm	10^{-8} mhos/cm	at 200 Volts for low resolution and 100 Volts for high resolution
Breakdown field strength	10^5 Volts/cm	10^5 Volts/cm	
Speed of response at 0.1 ft-c illumination	20 msec	20 msec	
Layer thickness	100 μ	20 μ	
Type of PC layer considered	Sintered or Plastic Embedded	Evaporated or Plastic Embedded	

Table 2 - Target Characteristics of PC Layers for Sandwich Type Image Intensifiers

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SECTION III

METHOD OF APPROACH

COMPUTER STUDY OF PC-EL LIGHT INTENSIFIERS

It was thought that a computer could be a useful tool for a parameter study of the image intensifier. By feeding in the characteristics of the PC and EL layers, the computer could calculate the transfer characteristics, the luminous gain, and the voltages on the PC and EL elements under various driving conditions. This method gave a fast answer for the proper choice of the components and showed the way for the improvement of the image intensifier of a given construction.

A mathematical analysis of the basic circuit of the image intensifier (Figure 2) was given by Diemer et al² for the special case where three assumptions were made: (1) negligible dark current of the PC layer, (2) negligible conductance of the EL layer, and (3) ohmic behavior of the PC layer (i.e. linear current-voltage dependence). In Appendix A a very general mathematical analysis is described, without any of the above restrictions. The derived equations served for the computer program.

The computer program was written in FORTRAN language (see Figure 3), which is widely used for engineering problems. Appendix B describes this program. At the beginning an IBM 1620, later an IBM 1401 digital computer was used.

Data was fed to the computer on four cards. The first contained the voltage and frequency of the driving power (V_0 , f), the second contained the constants of the PC element (m , n , c_0 , c_d), the third the constants of the EL element (α , B_0 , A , C_2 , $\cos \delta$) and the fourth contained the capacitance ratio (p). Characteristics such as the conductance of the PC element (g_1), voltage on the PC element (V_1), voltage on the EL element (V_2), output brightness (B), and gain (X) were calculated for 13 input light intensities and generally all characteristics for four groups of capacitance ratios.

Having nonlinearities in the circuit elements raises the question how well the formulas of Appendix A describe the light intensifier, because these equations implicitly assumed sinusoidal voltages and currents. The problem is that the nonohmic characteristic of the PC element brings non sinusoidal voltage to the EL element. The experimental fact that the EL element is not sensitive to distorted voltages, simplifies the problem and brings the possibility of agreement between calculated and experimental characteristic despite the nonlinearities.

Because of the limited storage capability of the IBM 1401 computer, a separate program was set up for the calculation of the maximum contrast of the transfer characteristic (inflexion point). This calculation was made only for the simplified case where (1) ohmic PC element, (2) negligible dark current and (3) negligible conductance of the EL element were considered.

Figures 5 to 12 show some characteristic curves drawn from the

calculated values for specially chosen driving conditions with given PC and EL elements. The data given in these drawings are in four lines, following the scheme:

Driving power: $V_0 f$
PC element: $m n c_0 c_d$
EL element: $\alpha B_0 A C_2 \cos \delta$
Capacitance ratio: p

The meaning of the symbols is explained in Appendix A. The numerical values chosen are the practical data of average elements of 1 cm² area.

Figure 5 shows one group of transfer characteristics with the capacitance ratio as parameter. One can see the influence of this parameter on the minimum output brightness (dark output).

Figure 6 shows the transfer characteristics and the gains (ft-L per ft-c) in the case of $p=5$, with the cell sensitivity as parameter.

Figure 7 shows the voltage dependence of the PC and EL elements as a function of the input light intensity for the circuit with the elements of Figure 6 when $c_0 = 4 \times 10^{-5}$ mhos/ft-c.

Figure 8 shows the transfer characteristics and the gains for light intensifiers having PC elements with sublinear, linear and superlinear current vs. light intensity characteristics ($n = 0.5, 1$ and 2). One sees how well the gamma decreases when the exponent n is decreased. The conductivity of the PC cells was taken as equal at 1 ft-c illumination.

Figures 9 and 10 show how much effect the dark current and the power factor have on the transfer characteristics.

Figures 11 and 12 show the effect of superlinear voltage-current characteristics (non-ohmic) of the PC element. Exponents of $m = 1, 2, 3$ and 4 were chosen for these calculations. The sensitivities of the PC material were taken as equal at $V = 100$ Volts in each case, and the dark currents were supposed to be negligible ($c_d = 0$). It is surprising at first that the nonohmic PC element does not deteriorate the characteristics of the light amplifier, on the contrary improves it; makes possible a wider useful input light range, and diminishes the contrast slightly, as the exponent increases. For this reason, plastic embedded PC layers could be used advantageously, because they have an exponent $m = 4$.

Equation (23) of Appendix A gives an idea how the contrast of the image (gamma) depends on the different characteristics of the elements. γ_0 of this equation depends only on the capacitance ratio p and the conductance to capacitance ratio of the PC element. In Table 3 γ_0 values are given for different capacitance ratios with $c_0 = 4 \times 10^{-5}$ and $C_2 = 10^{-9}$ F.

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p	γ_0
3	0.44
5	0.60
10	0.86
20	1.21

Table 3 - Contrast Factor γ_0 at Different Capacitance Ratios, when $C_0 = 4 \times 10^{-5}$ and $C_2 = 10^{-9}$ F

One can see from Table 3 that lower capacitance ratio gives lower contrast. But one cannot use capacitance ratios much less than $p = 5$ because the output brightness with dark input becomes disturbing.

The formula shows that γ_{max} is proportional to the exponent n and to $\sqrt{\frac{A}{V_0}}$. With $A = 3.4 \times 10^3$ Volts and $V_0 = 200$ Volts, $\sqrt{\frac{A}{V_0}} = 4.124$, quite large factor. This factor could be diminished by using EL elements with smaller A constants and by applying higher voltages. Both have practical limitations and a sublinear PC element (in current vs. light intensity, i.e.: $n < 1$) would be required for approaching unit gamma. Table 4 gives the maximum contrasts (γ_{max}) for the transfer characteristic curves of Figure 8, showing the dependence on exponent n .

n	γ_{max}	at L-ft-c
0.5	1.772	8.88×10^{-4}
1.0	3.545	2.98×10^{-2}
2.0	7.090	1.73×10^{-1}

Table 4 - Calculated γ_{max} Values for Transfer Characteristics of Figure 7

One can see from Figure 8 that the lower n not only diminishes the contrast, but extends the useful range of light.

The frequency of the driving voltage does not influence the contrast for this simplified condition; it changes only the value of the input light intensity, where the maximum is reached.

STUDY OF PC MATERIALS

Since the limitations in the characteristics of the image intensifier panel were caused mostly by those of the PC material, the prime effort of the program was directed toward improving the characteristics of the PC materials. An improvement in sensitivity, speed, slope of current vs. light intensity characteristic, homogeneity, graininess, stability and life was necessary for meeting the requirements.

It was realized that the wanted improvement could be achieved only by a "break-through" over the present state of the art. Therefore a systematic study was planned for understanding the conduction mechanism of the PC effect in the materials selected.

The characteristics which had to be improved are interdependent, so that a variance of one processing parameter generally changed several characteristics of the PC material. Therefore, it was not planned to separate the line of approach for improving individually the different characteristics.

The work program was generally the following: a series of experiments was made by changing one parameter in the processing of the PC material and all the important characteristics of the PC cell were measured. After a theoretical analysis, according to the derivation in Appendix C, was completed the results were evaluated and the direction for the next step was considered.

Measuring equipment was set up for fast measurements and recordings of the following characteristics:

- (a) Current vs. DC voltage curves, illumination as parameter. Light source: tungsten filament lamp, with color temperature of 2870 K.
- (b) Same as (a) with AC voltage at different frequencies.
- (c) Time constant measurements at given DC voltage, illumination as parameter (2870 K color temperature light source).
- (d) Spectral response curves
- (e) Hall-effect measurements at different illuminations.
- (f) Recording of thermally stimulated currents.
- (g) Bridge for resistance and capacitance measurements.
- (h) Recording of field strength stimulated currents.

Both surface and volume conduction was analyzed, PC cells being made in coplanar (or lateral) and in sandwich construction, according to Figure 13.

From these measurements and from the geometrical data of the PC cell more fundamental characteristics of the material were calculated mostly by the equations of Figure 14, as: resistance, specific conductivity, capacitance, relaxation time, gain, M-factor, carrier

density, life time, trap density, trap distribution, mobility etc. On Figure 15 the same formulas are listed with the numerical values of the PC cell of Figure 13.

List of symbols used in equations 1 to 13 of Figures 14 and 15:

- R_L - resistance of PC cell at L ft-c illumination in ohms
- L - illumination (light intensity) of PC cell in ft-c.
- i - current of PC cell in amperes
- V - voltage on PC cell in Volts
- σ_L - conductivity of PC material at L ft-c illumination in mhos-cm
- σ_a - conductance per square of PC layer (for coplanar cells) in mhos/square
- C - capacitance of PC cell in Farads
- τ_{rel} - relaxation time constant of PC cell in seconds
- G - gain of PC cell
- M - trap-constant of PC cell
- n_L - density of electrons (cm^{-3})
- μ - mobility of electrons in $cm^2/Volt\ sec.$
- f_1 - number of photons absorbed by PC cell per second
- F - number of photons absorbed in unit volume per second ($cm^{-3}\ sec^{-1}$)
- τ - life-time of electrons in seconds
- τ_d - decay time constant of electrons in seconds
- n_{tr} - trap density per eV (cm^{-3}/eV)
- E_{tr} - trap depth below conduction band in eVolts

TECHNIQUES OF MEASUREMENT

Some details of three special circuits and instruments used for the measurement of capacitance and resistance, mobilities, and thermally stimulated currents are described below.

(1) BRIDGE. The purpose of the bridge circuit is to measure the capacitance and resistance of either a PC or an EL cell. In the case of the latter the power factor and the efficiency may be calculated from the measured data.

Figure 16 shows the bridge circuit. The resistance and capacitance values, given by were chosen so that the bridge is the most appropriate for the range of impedances to be measured in this program.

Considering the unknown cell as a resistance and capacitance in parallel and assuming R_1 and R_2 to be pure resistance and having no

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capacitive component*, the balance point of the bridge is given by

$$\frac{R_3}{R_1} = \frac{Z_x}{Z_2} \quad (1)$$

where Z_x and Z_2 are the impedances of the unknown and the second branch respectively. From equation (1),

$$\frac{1}{Z_x} = \frac{R_1}{R_3} \frac{1}{Z_2} \quad (2)$$

Expressing Z_x and Z_2 in terms of the resistances and susceptances, equation (2) becomes

$$\frac{1}{R_x} + j\omega C_x = \frac{R_1}{R_3} \left(\frac{1}{R_2} + j\omega C_2 \right) \quad (3)$$

Equating real and imaginary parts,

$$R_x = \frac{R_2}{R_1} R_3 \quad (4)$$

and

$$C_x = R_1 \frac{C_2}{R_3} \quad (5)$$

The actual values substituted, one has simply:

$$R_x = \frac{R_2}{R_1} \text{ Megohms } (10^6 \Omega) \quad (6)$$

and

$$C_x = R_1 \text{ picofarads } (10^{-12} \text{ F}) \quad (7)$$

The balance point is achieved by adjusting R_1 and R_2 for nullifying the voltage drop on the oscilloscope and eliminating the phase difference set up by the capacitances. Two different cases can occur: (1) if the components are ohmic (linear voltage-current relation), the scope pattern at the balance point will be a straight line, as shown in Figure 17a; (2) if the components are not linear, the scope pattern will be as in Figure 17b.

* See Appendix D for the more general case.

(2) HALL-EFFECT MEASUREMENTS. A very important tool in the study of conduction processes is the Hall effect. It consists of the appearance of a voltage difference (called Hall-voltage) in a semiconductive (or conductive) layer due to the effect of a magnetic field, perpendicular to the plane of the semiconductive layer. From the measurement of the Hall-voltage, the speed of the carriers (or the mobility, which is the speed in unit field), and the density of the carriers can be calculated.

Figure 18 shows the electrode structure of a sample, used for Hall-voltage and conductivity measurements. The general equation describing the Hall effect is:

$$(\vec{B} \times \vec{v}) = \frac{V_h}{c} \vec{E}_h \quad (8)$$

Where \vec{B} is the magnetic field's vector, \vec{v} is the speed-vector of the carriers, \vec{E}_h is the Hall-field vector, c is the speed of light and e is the charge of the carriers. Equation (8) applied to the case of the sample on Figure 18, gives in practical units

$$Bv = \frac{V_h}{d} \cdot 10^8 \quad (9)$$

where V_h is the measured Hall voltage. Expressing the speed of the free carriers with the mobility μ and the electric field (V is the voltage between electrodes 1 and 2):

$$v = \mu \frac{V}{l} \quad (10)$$

Substituting (10) in (9), one obtains the expression for the mobility as

$$\mu = \frac{V_h}{V} \frac{l}{d} \frac{1}{B} \cdot 10^8 \quad (11)$$

Measuring the primary current (I), the density of free carriers (n) can be calculated using the equation

$$\sigma = en\mu \quad (12)$$

to

$$n = \frac{IB}{V_h t e} \cdot 10^{-8} \quad (13)$$

where t is the thickness of the PC layer.

Considering scattering phenomena, a correction factor comes in the formulas, but this factor is generally nearly unity. Another factor has to be considered, if $\frac{l}{d}$ is smaller than 2. Therefore, Hall samples are made generally with $\frac{l}{d}$ values higher than 2.

Figure 19 shows the circuit used to measure the Hall-voltage (V_h) with S_1 switch in position 6 or 7 (depending on the polarity) and to

measure conductance in switch positions 4 (when S_3 is in position 2) or 5 (when S_3 is in position 1). The primary current can be measured with S_1 switch in position 1 or 2 (switch S_3 in position 1 or 2 respectively) and primary voltage is measured with S_1 in position 3 and S_3 in position 1. The polarity of the compensating voltage can be changed with switch S_2 .

Since the measured Hall voltages are generally low in PC layers, care has to be taken to minimize electrostatic pick-up. Therefore, the instrument was carefully shielded. And because the sample resistances were high, measurements were made generally under illumination. Even so, additional leakage between electrodes had to be carefully eliminated.

The illumination of the sample was made by guiding the light of a tungsten lamp through a flat microscope slide. The sample was placed on the far end of this slide, where the glass was etched and homogeneously scattered the light to the PC sample. In this way the light source was outside of the magnetic field, enabling the use of small magnetic pole distances, and the illumination was not changed, when the sample was moved in and out of the magnetic field. A permanent magnet was used which gave a field of about 1000 Gauss.

The noise level of the measured Hall voltage being generally high, because of high noise of the samples and some interference noises, a recorder was used to make possible the evaluation of Hall voltages when the signal to noise ratio was smaller than one.

Also, some thought has to be given to the limited value of these Hall effect measurements. Since the electrodes on the Hall sample are in coplanar structure, the calculated mobility and the carrier density (when the proper thickness is considered) relates to the surface current and can be different from those of the volume current. The construction of a Hall sample, where the volume current gives rise to the Hall voltage, was considered, but could not be made successfully.

(3) THERMALLY STIMULATED CURRENTS. Another useful tool for the study of semiconductors is the measurement of thermally stimulated currents. When the traps of a PC cell are filled up at low temperature by illuminating it at a high light intensity and then the PC cell is heated at a constant rate in dark, to free these trapped carriers, the current-temperature curve provides data on the density and energy distribution of the traps. If it is assumed that the Fermi-level E_f is located at the energy-level of the trapping center E_t , when the current vs. temperature curve has a maximum, E_t can be calculated from equations (12) and

$$n = N_c \exp(-E_f/kT) \quad (14)$$

to

$$E_t = kT \ln(N_c e \mu / \sigma) \quad (15)$$

where N_c is a constant.

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According to the process described above, PC cells were cooled in a Dewar bottle containing liquid nitrogen and the thermally stimulated current was recorded on an X-Y recorder during the heating period. An approximate constant heating rate was obtained by the proper heating of a heating element in the Dewar bottle.

SECTION IV

EXPERIMENTAL WORK

PHOTOCONDUCTIVE MATERIALS

Uniform large area PC layers, required for the image intensifier panels, can be prepared in different ways, as by (1) sintering a sprayed or settled powder layer, (2) spraying or settling in plastic embedment already sensitized PC powder, (3) vacuum evaporation, (4) vapor deposition from the elements, (5) sputtering, (6) chemical spraying or (7) chemical deposition. Methods (4), (5) and (6) are applied using heated substrates, the others, excepting (2), need a subsequent heat treatment for obtaining sensitive PC layers. Our work in this program was limited to methods (1) to (3), because they seemed to offer the most adequate, though compromised, characteristics. The other methods were not out of our interest, and the result of work accomplished by others^{3,4} was followed with the prospect of an eventual application for the construction of image intensifier panels.

Sintered PC Layers

A considerable effort was spent in the program on the development of improved sintered PC layers for the application to the low resolution sandwich type image intensifiers. Most of the work was done with cadmium selenide (CdSe), and some time was devoted to exploratory experiments with other materials, as zinc selenide (ZnSe), arsenic sulfide (As₂S₃), and indium sulfide (In₂S₃).

Cadmium Selenide

(a) An unfavorable characteristic of the low resolution image intensifier panels, made with CdSe sintered layers, was its low picture quality caused by optical graininess of a size of 10 mils diameter or smaller, and by a very high contrast. It was evident that for both of these characteristics the PC layer was responsible. Long series of experiments were carried out to find the cause of the graininess and to diminish the high contrast.

Regarding the graininess, it was thought that the sensitivities of the individual grains are different and longer baking times or higher temperature baking could improve the homogeneity. Experiments made with this idea seemed to give some improvement, but more improvement was needed. The idea that finer powder, obtained by longer ball milling, would diminish the graininess, did not result in complete satisfaction.

An other idea was that the possible cause of the inhomogeneity could be in the nonuniform bonding of the particles to each other or to the substrate or both. One of our group brought attention to the creation of cadmium oxide and cadmium oxychloride during the preparation of CdSe powders. Acetic acid was used to wash out these compounds from the powder. Similarly we tried to wash a sintered CdSe layer in 5% acetic acid. Surprisingly, the CdSe layer, which was strongly bonded to the tin-oxide coated Pyrex glass substrate, came off the glass in one piece, so that the bond among the powder grains was not disturbed.

Furthermore, a pattern was visible on the substrate, seemingly having the same distribution as the inhomogeneous light pattern on the image intensifier. On the other hand, previous water wash and boiling, which have been used to diminish the dark current of the sintered layer by dissolving the superfluous CdCl_2 , did not dissolve the bond between the CdSe layer and the substrate.

From these experiments, one could arrive at the conclusion that the binding between the glass and the sintered layer is caused neither by CdCl_2 , nor by the CdCl_2 -CdSe melt, which supposedly binds the powder particles together. Therefore, it is thought that during the prebaking and the sintering process - in the air bake - a cadmium oxychloride ($x\text{CdO} \cdot y\text{CdCl}_2$) compound is synthesized, and it is this cadmium oxychloride which is responsible for the binding of the PC layer to the glass substrate. This compound is similar to the "Sorel-cement", which is magnesium oxychloride.

It is thought that the cadmium oxychloride does not form a continuous uniform layer between the glass and the CdSe, and this causes the grainy structure on the image intensifier. To prove this assumption, the following experiment was made: The $\text{CdSe} \cdot \text{CdCl}_2 \cdot \text{CuCl}_2$ powder was washed in acetic acid (5%) after a prebaking at about 500°C for 60 minutes. The washed powder was deposited on a tin-oxide coated glass substrate and baked at 500°C for 35 minutes. The CdSe layer was not very strong, but it seemed that an image intensifier can be completed on it. After this was done, the panel showed a very good homogeneity. But the next day, before measurements were made, the sandwich layer separated from the glass.

After these experiments the following tests have been performed to complete the understanding of the bonding mechanism of sintered cadmium selenide layers and to prove the assumptions described above.

(i) Pure ZnCl_2 or CdCl_2 was baked on both uncoated and tin-oxide coated silica substrates at 530°C, both in air and nitrogen atmosphere. In air, on an uncoated silica substrate, three materials were present: (1) Water soluble unreacted ZnCl_2 or CdCl_2 . (2) Water insoluble, but acetic acid soluble zinc oxychloride ($x\text{ZnO} \cdot y\text{ZnCl}_2$) or cadmium oxychloride ($x\text{CdO} \cdot y\text{CdCl}_2$). These compounds were not stoichiometric. (3) Water insoluble and acetic acid insoluble zinc or cadmium silicates. These layers were highly insoluble probably because of excess silica being present; however, in the case of the zinc compound, the presence of zinc metasilicate (ZnSiO_3) was confirmed by the characteristic orange fluorescence under ultra-violet illumination. In the case of the tin-oxide coated silica substrate, only the first two materials were formed.

(ii) Pure CdO or ZnO was baked for thirty minutes on both uncoated and tin-oxide coated silica substrates at 530°C, both in air and in nitrogen atmosphere. In air or in nitrogen, on uncoated or tin-oxide coated silica, only superficial, if any attack was noted. A water wash resulted in an unetched clean substrate in any case.

(iii) A mixture of ZnO plus ZnCl_2 or CdO plus CdCl_2 was baked

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under the same conditions as (i) and (ii) above with results as in (i) above. However, similar materials were formed even in the nitrogen atmosphere. This indicates the necessity for the presence of oxygen or ZnO or CdO for the reactions to proceed.

(iv) A mixture of CdSe plus either ZnCl₂ or CdCl₂ was baked at 530°C for 30 minutes on uncoated and on tin-oxide coated silica substrates both in air or in nitrogen atmosphere. When sintered in air, strong binding was observed. A water wash removed a small quantity of CdCl₂. A dilute acetic acid rinse removed intact the sintered CdSe layer from the substrate, whether uncoated or tin-oxide coated silica. In the case of the uncoated silica substrate, a third highly insoluble layer was noted. When ZnCl₂ was used as the flux, this third layer displayed the characteristic orange fluorescence of zinc metasilicate. When the samples were baked in nitrogen, only Zn or Cd chloride was present, and no bonding was observed. This confirms the necessity of oxygen or ZnO or CdO.

Since pure cadmium selenide oxidizes very slightly, if at all, in thirty minutes of baking at 530°C, one might question how to explain the formation of quite large quantities of the cadmium oxide needed for the formation of cadmium oxychloride. It is thought that this is caused by selenium's high affinity for chlorine as compared to oxygen. Cadmium or zinc chloride, which has a high vapor pressure at 530°C, supplies the chlorine with which selenium from the cadmium selenide reacts, forming volatile selenium chlorides or oxychlorides. This leaves the elemental cadmium free to oxidize to CdO. The CdO thus formed then reacts with more of the ZnCl₂ or CdCl₂ present, to produce the zinc or cadmium oxychloride. In the case of an uncoated silica substrate, the cadmium or zinc oxychloride then attacks the substrate resulting in the formation of a quantity of the silicate. It is a well known fact in the phosphor industry that chlorides are good fluxes for the low temperature formation of metasilicates.

Although definite proof is very difficult to obtain when many simultaneous reactions take place, it is felt that the preceding tests and observations indicate the correctness of the assumptions and explanations which were made of our group.

Summarizing: In the bonding of CdSe sintered layers on glass substrates, three distinct mechanisms have to be considered.

First: Particle to particle bonding, caused by the solubility of CdSe in CdCl₂, followed by the evaporation of excess CdCl₂ at high temperature.

Second: Layer to substrate bonding, caused by oxidation of CdSe to CdO, followed by a solid state reaction between CdO and CdCl₂. This results in a hard layer of xCdO.yCdCl₂, which creates a strong bond to the substrate. This layer also is responsible for the inhomogeneity of the PC layers.

Third: A layer resulting from a reaction between CdCl₂ and SiO₂

from the substrate. This layer consists of $CdSiO_3$ which probably contains excess SiO_2 . This layer does not exist on tin-oxide coated glass, but is present, when CdSe is sintered directly on glass substrates, giving an increased bond to it.

Reisman and Berkenblit discussed the same problem in a paper published in the Journal of the Electrochemical Society⁵ and concluded that in the preparation of sintered CdSe layers on silica-based substrates two processes must be considered (the first and third mechanisms above). Our analysis gives a more complete description of this mechanism.

(b) The conduction mechanism was studied in sintered CdSe layers with coplanar and sandwich electrodes, and the fundamental semiconductor characteristics calculated, as described in Section III under "Study of PC Materials". As an example Figures 20 to 24 and Tables 5 and 6 show some of the most interesting characteristics of a PC cell, processed as described in Technical Report NAVTRADEVCEM 562-1.

Examination of Figures 20 and 21 and of the corresponding numerical data in Table 5 shows a large difference between the characteristics of coplanar and sandwich construction (surface and volume currents) of the same material. While the coplanar cell has high dark current and nearly linear current vs. voltage relation (ohmic electrodes), the sandwich cell shows linearity only below 10 volts, and becomes highly superlinear above 50 volts, when the top electrode is positive. When the top electrode is negative this superlinearity starts at lower voltages. In both cases (top - and +) the superlinearity becomes evident at lower voltages when the illumination is lower. Considering the field strengths, one calculates 1.33×10^3 volts/cm with 100 volts on the coplanar cell. The same field strength is reached with 11.6 volts on the sandwich cell. It is true that besides this difference the electrodes in the two cases are somewhat different. In the coplanar cell both electrodes are tin-oxide, while in the sandwich cell the bottom electrode is tin oxide and the top electrode is gold. The tin oxide electrodes are present during the high temperature baking of the cell, while the gold electrode is evaporated after the sintering.

For comparing the coplanar and sandwich cells, the conductivities must be considered. The data in Table 5 reveal a large difference; more than one hundred times higher conductivity of the coplanar cell, than that of the sandwich cell at 1 ft-c illumination, and higher factors at lower illuminations. This increasing conductivity ratio at decreasing illumination is caused by sublinearity in the current vs. light intensity characteristics that prevails for the coplanar cell, and the superlinearity that exists for the sandwich cell.

One tries to explain these variances by the differences between the crystal structure of a surface layer and that of the inside of the material. However, another reason for the difference is the absorption of high energy photons ($\lambda < \lambda_{max}$) in a very thin layer of the CdSe. This does not present any problems for the coplanar cell if the light enters on the electrode side. But if the light

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Voltage	Electrodes	L ft-c.	I Amperes	R Ohms	σ_L Mhos/cm	τ_d sec	τ_{rel} sec	G	M	$cm^{-3} nL$	F $cm^{-3} sec$	τ sec	ntr $cm^{-3} v^{-1}$	Etr eV		
10 Volts	Coplanar	10	6.4×10^{-4}	1.5×10^4	3.9×10^{-3}	6×10^{-3}	1.8×10^{-9}	4.2×10^2	1.3×10^{-4}	2.5×10^{15}	10^{17}	2.5×10^{-2}	2.3×10^{16}	2.1×10^{-1}		
		1	8.2×10^{-5}	1.2×10^5	4.9×10^{-4}	2.1×10^{-2}	1.4×10^{-8}	5.4×10^2	3.8×10^{-4}	3.1×10^{14}	10^{16}	3.1×10^{-2}	8.0×10^{15}	2.6×10^{-1}		
		10^{-1}	1.4×10^{-5}	7.0×10^5	8.4×10^{-5}	6.5×10^{-2}	8.4×10^{-8}	9.2×10^2	1.2×10^{-3}	5.3×10^{13}	10^{15}	5.3×10^{-2}	2.5×10^{15}	3.1×10^{-1}		
		10^{-2}	7.5×10^{-6}	1.3×10^6	4.5×10^{-5}	-	1.6×10^{-7}	-	-	2.8×10^{13}	10^{14}	-	-	-		
	0	6.5×10^{-6}	1.5×10^6	3.9×10^{-5}	-	1.8×10^{-7}	-	-	2.5×10^{13}	-	-	-	-			
	Sandwich Top +	10	1.5×10^{-3}	6.6×10^3	5.3×10^{-5}	1.5×10^{-2}	1.5×10^{-8}	3.7×10^3	3.8×10^{-3}	3.3×10^{13}	1.15×10^{16}	2.9×10^{-3}	6.5×10^{15}	3.2×10^{-1}		
		1	4.0×10^{-5}	2.5×10^5	1.4×10^{-6}	5.0×10^{-2}	5.8×10^{-7}	1.0×10^3	1.1×10^{-2}	8.8×10^{11}	1.15×10^{15}	7.5×10^{-4}	2.3×10^{15}	4.1×10^{-1}		
		10^{-1}	9.5×10^{-7}	1.1×10^7	3.2×10^{-8}	2×10^{-1}	2.5×10^{-5}	2.4×10^2	2.8×10^{-2}	2.1×10^{10}	1.15×10^{14}	1.8×10^{-4}	9.0×10^{14}	5.1×10^{-1}		
		10^{-2}	7.0×10^{-8}	1.4×10^8	2.5×10^{-9}	8×10^{-1}	3.2×10^{-4}	1.7×10^2	-	1.6×10^9	1.15×10^{13}	1.3×10^{-4}	3.6×10^{14}	5.7×10^{-1}		
	0	3.0×10^{-9}	3.3×10^9	1.1×10^{-10}	-	7.6×10^{-3}	-	-	6.6×10^7	-	-	-	-			
	Sandwich Top -	10	2.0×10^{-3}	5.0×10^3	7.0×10^{-5}	5×10^{-2}	1.1×10^{-8}	5.0×10^3	1.1×10^{-3}	4.4×10^{13}	1.15×10^{16}	3.8×10^{-3}	2.2×10^{16}	3.1×10^{-1}		
		1	7.0×10^{-5}	1.4×10^5	2.5×10^{-6}	1.4×10^{-1}	3.2×10^{-7}	1.7×10^3	4.0×10^{-3}	1.6×10^{12}	1.15×10^{15}	1.3×10^{-3}	6.3×10^{15}	3.9×10^{-1}		
10^{-1}		4.3×10^{-6}	2.3×10^6	1.5×10^{-7}	6.0×10^{-1}	5.3×10^{-6}	1.1×10^3	1.0×10^{-2}	9.2×10^{10}	1.15×10^{14}	8.0×10^{-4}	2.7×10^{15}	4.7×10^{-1}			
10^{-2}		7.0×10^{-8}	1.4×10^8	2.5×10^{-9}	2.7	3.2×10^{-4}	-	-	1.6×10^9	1.15×10^{13}	1.4×10^{-4}	1.2×10^{15}	5.7×10^{-1}			
0	5.5×10^{-8}	1.8×10^8	1.9×10^{-9}	-	4.1×10^{-4}	-	-	1.2×10^9	-	-	-	-				
50 Volts	Coplanar	1	4.6×10^{-4}	1.1×10^5	5.5×10^{-4}	Same as with 10 volts	1.3×10^{-8}	3.0×10^3	1.9×10^{-3}	3.4×10^{14}	Same as with 10 volts	3.4×10^{-2}	8.2×10^{15}	2.6×10^{-1}		
		10^{-1}	8.0×10^{-5}	6.2×10^5	9.5×10^{-5}		7.4×10^{-8}	5.3×10^3	6×10^{-3}	6.0×10^{13}		6.0×10^{-2}	2.5×10^{15}	3.0×10^{-1}		
	Sandwich Top +	1	4.6×10^{-4}	1.1×10^5	3.2×10^{-6}		2.5×10^{-7}	1.1×10^4	5.5×10^{-2}	2.0×10^{12}		Same as with 10 volts	1.7×10^{-3}	2.2×10^{15}	3.9×10^{-1}	
		10^{-1}	4.3×10^{-6}	1.2×10^7	3.0×10^{-8}		2.8×10^{-5}	1.1×10^3	1.5×10^{-1}	1.9×10^{10}			1.6×10^{-4}	9×10^{14}	5.1×10^{-1}	
	10^{-2}	4×10^{-7}	1.3×10^8	2.8×10^{-9}	3.0×10^{-4}		1.0×10^3	3.7×10^{-1}	1.7×10^9	1.5×10^{-4}			3.6×10^{14}	5.6×10^{-1}		
	0	1×10^{-7}	5.0×10^8	7.0×10^{-10}	1.1×10^{-3}		-	-	-	-			-	-		
	Sandwich Top -	1	4.0×10^{-4}	1.3×10^5	2.8×10^{-6}		3.0×10^{-7}	1.0×10^4	2.1×10^{-2}	1.7×10^{12}			Same as with 10 volts	1.5×10^{-3}	6.3×10^{15}	3.9×10^{-1}
		10^{-1}	4.6×10^{-5}	1.1×10^6	3.2×10^{-7}		2.5×10^{-6}	1.1×10^4	4.6×10^{-2}	2.0×10^{11}				1.7×10^{-4}	2.7×10^{15}	4.5×10^{-1}
		10^{-2}	7.0×10^{-6}	7.0×10^6	4.9×10^{-8}		1.6×10^{-5}	-	-	3.1×10^{10}				2.6×10^{-4}	1.2×10^{15}	4.9×10^{-1}
		0	4.5×10^{-6}	1.1×10^7	3.2×10^{-8}		2.5×10^{-5}	-	-	-				-	-	-

Table 5. Calculated Data of a Sintered CdSe PC Cell (No. B2-71XA-1-8) taking $\mu = 10 \text{ cm}^2/\text{V sec}$.

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enters on the other side, the shorter wavelengths are absorbed faster than the longer ones and the spectral response curve is transferred to longer wavelengths (see Figure 20 in Reference No. 1). In the case of sandwich construction the current carrier electrons must be transported through the layer from the negative electrode to the positive electrode. There is no complication when the light enters on the negative electrode ("top +" in the measurements), only the excited electrons have to be diffused toward the positive electrode. But when the light enters on the positive electrode ("top -" in the measurements), the other (negative) electrode has to supply the electrons. This can happen if the negative electrode has an ohmic contact to the PC material. The mechanism is similar to that of the coplanar conduction; an electron arriving to the positive electrode is replenished with a new electron emitted from the negative electrode. The shift in the spectral response curve (see Figure 22 in Reference No. 1) proves that the excited electrons are primarily responsible for the photocurrent.

The increasingly superlinear dark current at increasing field strengths is explained by the space charge limited currents. An inertia phenomena with changing field strength is connected to this mechanism.

Comparing the decay and rise time constants of the cells, one sees that the response time of the sandwich cell is slower than that of the coplanar cell by a factor of approximately five. The rise time constant is about three times higher than the decay time constant in both cases. In the calculations only the decay time constants were considered.

For the gain-calculation, it was supposed that there are about 10^{13} photons/cm² sec in 1 ft-c of light intensity, and the quantum efficiency is 1. The curves in Figure 22 show that the gain is higher with higher voltage, reaching 10^4 electrons/photons at 50 V. The positive or negative slope of these curves corresponds to superlinear or sublinear current vs. light intensity characteristics respectively.

The M-factor* is connected to the maximum gain available with a PC material. The maximum gain is limited by the field strength where space charge limited currents enter and in this case M is equal or lower than one. In some special cases M can be higher than one representing a PC material with superior characteristics. The M factor of our photocells (Figure 23) show that they are in the general category, where $M < 1$.

For calculating the electron density n_L , it was assumed that the mobility is equal 10 cm²/volt sec. It was assumed furthermore that

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the absorption and conduction mechanism in the coplanar cell takes place in a thickness of about 10 micron (t^*). In the case of the sandwich cell the current goes through the total thickness. The life time of the carrier, calculated with these assumptions, is acceptable for the sandwich cell, but are in contradiction with decay time constant measurements for coplanar cell. A larger life time value than the decay time is obtained, which indicates that some of the assumptions are not valid. It was probable that the assumed mobility of $10 \text{ cm}^2/\text{volts sec.}$ was too low for the surface conduction, but this value could be reasonable for volume currents. Indeed, when Hall effect measurements were made on similar cells, a value of $\mu = 30 \text{ cm}^2/\text{volt sec.}$ was obtained. Since this measurement relates to surface currents, data for the coplanar cell were recalculated with this mobility and are presented on Table 6.

The obtained lifetimes now are lower than the decay times, excepting at the 10 ft-c illumination. Considering the errors in the measurements and in the other assumptions, this can be regarded as an acceptable agreement. But shorter lifetimes (2.5 to 5 milliseconds) were calculated, when $\mu = 100 \text{ cm}^2/\text{volt sec.}$ was assumed.

Voltage Volts	L ft-c	σ_{\square} Mhos/square	n_L $\text{cm}^{-3}\text{sec}^{-1}$	τ sec	n_{tr} $\text{cm}^{-3}\text{V}^{-1}$	E_{tr} eV
10	10	3.9×10^{-6}	8.3×10^{14}	8.3×10^{-3}	2.34×10^{16}	0.237
	1	4.9×10^{-7}	1.1×10^{14}	1.1×10^{-2}	8.2×10^{15}	0.288
	10^{-1}	8.4×10^{-8}	1.76×10^{13}	1.76×10^{-2}	2.54×10^{15}	0.334
50	1	5.5×10^{-7}	1.13×10^{14}	1.13×10^{-2}	8.2×10^{15}	0.287
	10^{-1}	9.5×10^{-8}	2×10^{13}	2×10^{-2}	2.54×10^{15}	0.331

Table 6. Data Calculated for Coplanar CdSe Cell
with $\mu = 30 \text{ cm}^2/\text{volt sec.}$

Figure 24 shows the calculated trap distributions for both type of cells. Curves with $\mu = 10, 30$ and $100 \text{ cm}^2/\text{volt sec}$ are displayed for the coplanar cell. It is seen that the trap distribution curves for the volume (top+) and surface layer match well, when the mobility are 10 and $100 \text{ cm}^2/\text{volt sec}$ respectively for the two cases. But this matching is not necessary, since it is well possible that the surface trap structure is much different from that of the volume structure. As it was pointed out, efforts to make Hall effect measurements on volume currents were not successful.

(c) Series of experiments were made with varying prebaking and sintering temperatures and times and impurity concentrations as parameters. The objectives of these experiments were (1) to improve the

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sensitivity, (2) to increase the speed of response, (3) to obtain sublinear current-illumination dependence, (4) to approach linear current voltage dependence, and (5) to increase the response for shorter wavelengths. It was found that the highest sensitivities - higher than 10^{-7} mhos/cm specific conductivity at 0.1 ft-c illumination in sandwich construction - could be obtained with a preparation schedule as follows:

- (1) Composition of powder
 - 100 g CdSe
 - 4 g CdCl₂
 - 0.01 g CuCl₂
- (2) Prebaking at 480°C for sixty minutes
- (3) Sintering at 505°C for thirty minutes
- (4) Aging at 190°C for 16 hours

With higher baking temperatures, some improvement was obtained in objectives (3) and (5).

It was obvious that the usually measured electro-optical characteristics still do not give a full picture for the usefulness of the PC material in the image intensifier. Inhomogeneities, spottiness and graininess comes in, which could be examined by a complicated scanning device or on the finished image intensifier panel. Not having a scanning instrument available, experimental image intensifier panels were built, and the PC layer was judged by the image quality of the intensified picture. It was found that the most sensitive PC materials showed more spottiness and graininess and the search to find the cause of this graininess led to the problem of bonding, discussed in a previous part of this section. The findings of the bonding experiments resulted in the preparation of a material which showed improved characteristics in objectives (1), (3) (see Figure 25) and (4) and gave improved picture quality (less graininess) on the image intensifier panel. The starting material had the same composition, but the following schedule was used for the preparation of the sintered layer:

- (1) Prebaking at 505°C for 60 minutes
- (2) Washing the powder in 5% acetic acid
- (3) Sintering at 505°C for 30 minutes
- (4) Aging at 190°C for 16 hours

Increased prebaking temperature gave higher sublinearity in the current vs. light intensity curve (objective 3), and higher sintering temperature gave higher sensitivity (objective 1). No improvement could be obtained in the speed of response, and the spectral response curve of these layers showed higher long wavelength response.

Figure 25 shows the current-light intensity characteristics of such a PC cell in lateral and in sandwich construction measured with DC and AC voltages (100 Volts, RMS in AC case). Other characteristics, measured and calculated, are in Table 7. A mobility of $10 \text{ cm}^2/\text{V sec}$

L ft-c	σ mhos/cm	τ_d sec	τ_{rel} sec	G	M	n_L $cm^{-3}sec^{-1}$	τ sec	n $cm^{-3}y^{-1}$	E_{tr} eV
10	7×10^{-6}	3×10^{-2}	1.1×10^{-7}	3.5×10^3	1.3×10^{-2}	3.10^{12}	3.7×10^{-4}	9.4×10^{15}	0.38
1	9×10^{-7}	9×10^{-2}	8.8×10^{-7}	4.5×10^3	4.4×10^{-2}	4×10^{11}	4.8×10^{-4}	3×10^{15}	0.43
10^{-1}	1.5×10^{-7}	3×10^{-1}	5.3×10^{-6}	6.5×10^3	1.1×10^{-1}	6.6×10^{10}	8×10^{-4}	1×10^{15}	0.47
10^{-2}	4×10^{-8}	1.5	2×10^{-5}	1×10^4	1.35×10^{-1}	1.75×10^{10}	2.2×10^{-3}	4.8×10^{14}	0.51
0	2×10^{-8}	-	4×10^{-5}	-	-	-	-	-	-

TABLE 7. Measured and Calculated Characteristics of an Acetic Acid Washed Sintered CdSe Sandwich Cell (top +, V = 100 Volts)

CdSe Powder	Impurities in ppm												
	Ag	Al	B	Ca	Cr	Cu	Fe	Mg	Mn	Ni	Pb	Si	Zn
	1	1-10	1-5	1-10	1-5	1	1-5	1-10	-	-	1-5	10-100	10-100
	1	1-10	1-10	1-10	1-5	1-10	10-50	1-10	1	1-10	1-10	1-10	-

The following elements were sought, but not detected: As, Ba, Be, Bi, Co, Ge, Mo, P, Sb, Sn, Sr, Ta, Th, Ti, W. Detection limits of these elements range from 1 to 1000 ppm.

TABLE 8. Spectral Analysis of High Purity CdSe Powders

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was chosen in these calculations.

Comparing the trap distribution of this cell to that in Figure 24, one sees that the trap densities are higher in the vicinity of the conduction band, but the slope of the curve is steeper and the trap density is lower above 0.47 eV.

(d) From the spectral analysis of the CdSe powders (see Table 8), which were used in the above experiments, it was obvious that the purity of these materials was not sufficient. It seemed that there is some probability of obtaining improvements in the speed and spectral response curve by using purer CdSe. Synthesis of CdSe from the available very pure elements would be one way for obtaining better material and purification of the available CdSe is the other possibility. Work in the second direction has been started. Some preliminary experiments in zone-refining the CdSe were not successful. Therefore, another method, the purification by sublimation, has been chosen. First experiments, made according to the work of Bube et al⁶ (see also Ref. 7), yielded enough purified material for preparing PC layers from it. These layers, prepared in the usual schedule, showed lower conductivities than those made from the unpurified material. A series of experiments are being carried out to find the proper processing schedule for the purified material. A spectral analysis is also being made on the sublimed powder.

Other Materials

Other materials with a band gap between 2 and 3 eVolts were considered also for application of PC layers in the image intensifiers hoping that they could show some better characteristics than those of the CdSe. Though the state of the art offered only the CdS and CdSe, which had acceptable conductivity for the present application, some theoretical considerations and experimental results (see Ref. 8 to 11) gave a basis for further work with other materials.

An appreciable effort was made toward the preparation of ZnSe sintered PC layers. A long series of experiments to sinter the ZnSe powder brought negative results. The presence of zinc oxide in the ZnSe powder was suspected for the difficulties and a purification of the ZnSe by the sublimation method was made. It was assumed that this purification removes ZnO together with other impurities. Experiments made with the sublimed powder failed to give any perfect sintering.

Work is being continued with mixtures of ZnSe and CdSe¹⁰.

Some experiments, started with As₂S₃ and In₂S₃, are being continued.

PLASTIC EMBEDDED PC POWDERS

A series of experiments, using the prebaked CdSe powder in plastic embedment, showed promising PC characteristics. Therefore it was decided to spend a larger effort for the development of plastic embedded PC powders. The work in the last six months was carried out

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and will be continued for another six month period. The report program follows.

The experimental work may be divided into two phases, in the first of which firing was carried out in two stages - an initial firing at 400°C for 30 minutes, followed by a second firing at 650°C. In the second phase a single firing was made at around 500°C.

Much experimental work was carried out in the first phase, but the final conclusions drawn were that the conductivities of the samples were below those of samples fired at the lower temperature. However, many of the experimental techniques developed on the 650°C powders have been adapted and used in the 500°C firings.

Copper has been used as activator and halogens as coactivators. In the early work the halogens were added as ammonium halides, later cadmium chloride was used. After firing, all powders were tested by mixing them with a solution of HD27 plastic and "doctor blading" them to give dried layers about 100 μ thick. The final dried layers were found to be optimized when they contained about 1-2% plastic. Using these layers, cells were made up in both gap and sandwich configurations.

1. High Temperature Firing

The mix of raw materials was fired first at 400°C in order to reduce the rate of volatilization of the ammonium halide, then the temperature was raised to 650°C for 30 minutes. Initial firings were carried out in argon, so that oxygen might be introduced into the lattice at a later stage and in a controlled fashion.

Long series of experiments were carried out, systematically examining the effect of copper and of different halogen concentrations. Data of optimum copper, ammonium chloride, cadmium chloride, ammonium iodide, halogen to copper ratio were obtained for the special processing conditions used in these experiments where firing was made in argon atmosphere. Oxygen was then introduced into argon fired PC powders by a number of different techniques.

Several lots of powders were prepared, each of which contained 0.01% Cu and 2% chlorine. A comparison was made between oxygen built into the photoconductor by (1) air baking after argon firing, (2) including magnesium oxide in the charge, and (3) firing the charge in static air.

The inclusion of the MgO experiment in this series was of particular interest since this addition has been used to prevent excessive sintering of powder charges, thus achieving powders having fine grain sizes. In this particular experiment 5% wt/wt of MgO was added to the charge before firing, and the mixture was fired in argon.

After cooling, each of the charges in this series of experiments was washed with acetic acid to remove excess MgO, soluble chlorides, and oxychlorides. After water washing, the powders were dried.

The grain size of the MgO fired powder was very much less than that of the other powders, and no sintering at all took place during firing.

The overall conclusion of the experiments was that the air bake after argon firing produced the greatest increase in the light to dark ratio consistent with only a small decrease in overall sensitivity and that the use of MgO lead to a very fine and non-sintered powder.

Experiments were carried out to study the effect of prefiring the CdSe raw material at high temperatures in argon (1050°C) or in H₂S (900°C) in order to remove volatile impurities and fill selenium vacancies with sulphur. The conductances of the powders after this treatment were very different, and in addition, the current-voltage characteristic of the argon fired material was strongly super-linear, whereas the H₂S fired material was nearly voltage-independent. The argon fired material showed breakdown at about 200 Volts AC, whereas the H₂S fired material did not break down at 400 Volts.

If the H₂S fired material was mixed with CdCl₂ and refired in argon, it had a low conductance and low breakdown potential (100 Volts DC). If the CdCl₂ firing was again carried out in H₂S however, the conductance remained low but the breakdown potential was higher than 400 Volts DC. Finally, if the H₂S prefired material was refired in a 50-50% H₂S-HCl atmosphere, the conductance increased by four orders but the breakdown potential remained high.

2. Low Temperature Firing

General results of the above work seemed to indicate that at a 650°C firing temperature the powders prepared had limiting conductances. From early experiments on materials of composition CdSe.0.005% Cu fired with 4-5% CdCl₂ at 505°C, it became apparent that fairly better conductances could be obtained, but that the charges had to be fired in static air rather than in argon, if acceptable voltage breakdown figures were to be obtained. In addition, samples fired with CdCl₂ at the low temperatures did not break up readily in acetic acid. As with most materials of this type, mechanical crushing of the hard cakes prior to washing was found to greatly reduce the conductance and increase the dark current.

However, the incorporation of 5% MgO in the charge during firing again led to much reduced sintering and to materials which broke up completely in dilute acetic acid, so avoiding the necessity for mechanical grinding.

Samples were prepared containing either 4% CdCl₂ or 2.3% NH₄Cl to maintain a constant chlorine content (1.55% Cl wt/wt), and all samples contained 0.005% Cu. Parallel specimens were prepared with and without MgO. Results, illustrated in Tables 9 and 10, show that the samples fired with CdCl₂ were much better than those fired with NH₄Cl.

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Illumination ft-c	Currents in μ A at 100 V DC			
	Lateral Cell 0.75 mmx39mm		Sandwich Cell 1cm ² 6 mil thick	
	No MgO	5% MgO	No MgO	5% MgO
33	2.1	6.4	30.0	17.0
10	0.7	2.0	3.5	5.6
1.0	0.057	0.2	0.13	0.19
0.1	0.012	0.033	0.023	0.04
0.01	0.005	0.013	0.010	0.016
0	0.003	0.0086	0.0065	0.010

Table 9. Sensitivities of CdSe Plastic Embedded Cells, Containing NH₄Cl

Illumination ft-c	Currents in μ A at 100 V DC			
	Lateral Cell .75 x 39 mm		Sandwich Cell 1cm ² 6 mil thick	
	No MgO	5% MgO	No MgO	5% MgO
33	130	160	640	300
10	48	38	250	60
1.0	7	2.5	40	3
0.1	1.5	0.28	10	0.3
0.01	0.6	0.084	5	0.05
0	0.46	0.060	4	0.03

Table 10. Sensitivities of CdSe Plastic Embedded Cells, Containing CdCl₂

3. Stability of Plastic Embedded Powders and Cells

It has previously been noticed that a P.C. powder sample had decreasing conductance when measured repeatedly, indicating that the selenide powders are not stable after preparation. To see if this was also true with the CdSe.Cu.Cl.(MgO) powders, cells were made up, tested, and the remainder of the powder samples stored for 12 days before further cells were made up. Results are shown in Table 11 and indicate that the instability is indeed present.

Illumination ft-c	Currents in μ A at 100 V DC	
	Tested June 1st	Tested June 12th
33	300	80
10	60	18
1.0	3	1.3
0.1	0.3	0.22
0.01	0.05	0.13
0	0.03	0.11

Table 11. Stability of CdSe.Cu.Cl Powder Cell in Sandwich Construction (Thickness 6 mils)

It was known that the overall sensitivities of thin film CdS photoconductors may be greatly altered by heating the layers and then

cooling them in light of different intensities. In addition, it has also been shown that postbaking or "aging" of photoconductors at temperatures lower than 200°C can improve their conductances, reduce their dark currents, and stabilize them.

Accordingly, a number of cells were made up in sandwich construction (approx. 6 mils thick) using the powder which had previously been kept for 12 days after preparation. After preparation, all the cells gave substantially the same current figures when tested at 100 V DC.

The cells were then heated to 160°C in air for 30 minutes, and then allowed to cool slowly (20-30 minutes) in light of different intensities.

Results of the experiments are shown in Table 12. It will be seen that the heating itself caused a marked increase in the conductance of the cells at high light levels and a lesser increase in dark current, whereas the intensity of light in which the cell was cooled had little effect on the high light level conductance, but high intensity illumination increased the dark current markedly.

Illumination ft-c	Currents $\mu\text{A}/\text{cm}^2$ at 100 V DC			
	12 day old sample unheated	Aged and cooled in dark	Aged and cooled in room light	Aged and cooled in bright light
33	80	2600	3000	3000
10	18	800	900	900
1	1.3	50	60	60
0.1	0.22	5.0	4.0	10
0.01	0.13	0.9	0.8	4.0
0	0.11	0.5	0.4	3.0

Table 12. Effect of Aging CdSe Powder Sandwich Cells

Work is being continued for improving sensitivity, homogeneity, speed and spectral response of the plastic embedded PC cells.

Evaporated PC Films

A small effort was devoted to the preparation of evaporated PC films, for their possible use in the construction of the high resolution image intensifier panel.

Four general problems present themselves for the evaporated film in this application:

- (1) the sandwich construction
- (2) the need for high thickness (about 20 μ)
- (3) the sensitization, without poisoning, or being poisoned by, the EL film on which the PC film is deposited
- (4) uniformity of photosensitivity

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Problem (1) i.e. the sandwich construction, in contrary to the coplanar construction, brings in the necessity of eliminating any pinholes in the film, which can cause short-circuit of the PC cell. The high thickness is necessary for two purposes: first for diminishing breakdown at the high voltages used for the panel, second for having low capacitance, necessary for the sandwich construction. Problem (3) arises because the PC film has to be evaporated on top of the EL film, and has to be heat treated for sensitizing. In this baking process there is an interdiffusion of impurities between the two layers, and the characteristics of both will be modified by it. Problem (4) is the nonuniformity of photosensitivity, found generally in evaporated polycrystalline films.

A series of experiments was carried out with evaporated CdS films for finding the lowest temperature, at which highly sensitive sandwich cells can be made. Temperatures of 300° and 350° C with different sensitizing powders (using embedment in the powder) did not result in useful sensitivity. Increasing the temperature to 430° C and using a sensitizing powder of 0.1% CuCl₂ and 4% CdCl₂, gave good conductivity and appropriate characteristics for the planned application. The film thickness was about 6 μ and the number of pinholes was not very high. The work is being continued to eliminate pinholes, make thicker layers and to improve uniformity.

EVAPORATED EL THIN FILMS

Plastic embedded EL layers were used exclusively for the construction of the low resolution image intensifiers, prepared as described in Appendix E of reference 1. Practically no development work was done with EL layers of this type, but an appreciably large effort for improving evaporated EL films for the application in the high resolution image intensifier was carried out in the [REDACTED]

This work was planned for one year period and besides the principal goals of

- (1) improving the efficiency
 - (2) improving the life
- of the EL films, the following other objectives were set up at the beginning
- (3) to produce low voltage (30 volt) films in areas large enough to be useful in a light amplifier
 - (4) to find a protective insulating coating for the EL film which would allow deposition (and firing) of the photoconductive layer onto the EL layer without harm
 - (5) to experiment with a buffer, also insulating, layer between the EL film and the conducting glass on which it is formed; this appeared to be the most likely method of significantly improving the efficiency (lumens per watt) of the EL films
 - (6) to produce films, with the best characteristics possible, in larger areas: namely, 6" x 6", 4" x 4" and 2" x 2" dimensions was the final objective.

Work was done toward all six of these objectives and is described in this section.

1. Low Voltage Yellow-Emitting Films (ZnS:Cu,Cl,Mn)

Much of the time at the beginning was spent on the problem of producing large area films of uniformly high sensitivity (100 ft-L at 30 volts, say); throughout this period, the characteristics of small areas of the films continued to improve, that is, brightness at a given voltage improved slowly, as did the luminous efficiency; but we were not successful in producing large area films with uniform characteristics across the area. Occasionally a film would be uniformly sensitive across a three inch dimension, but reproducibility was very poor.

Initially, the finished films showed pinholes which led to poor electrical strength. A new cleaning procedure, involving ultrasonic wash in detergent and treatment in isopropyl alcohol vapor, was used. Also, a shaped baffle between the heated boat carrying the ZnS powder charge to be evaporated and the glass substrate, apparently eliminated bombardment of the film during deposition by particles decrepitating from the boat, without interfering with deposition of the ZnS. These two measures apparently were responsible for alleviating the pinhole problem.

The next problem to be recognized was warping of the substrates following the tin-oxide coating step, and this was eliminated by slow cooling of each batch of glass after being coated. The warping was completely eliminated (that is, a five inch dimension of glass substrate was flat to about 0.0005"). Nevertheless, the nonreproducibility of large areas persisted. The next problem to be recognized was warping of the glass substrate during cooling of the film on the substrate after the firing step and while still embedded in the powder phosphor. Although it is hard to understand how an appreciable temperature gradient can be set up through a 1/8" thick glass plate buried in a powder which completely fills a thick-walled, covered crucible, the warping did in fact occur. It was eliminated by more gradual cooling, and better firing temperature uniformity, but this also failed to improve reproducibility of the film characteristics in large areas.

Thus the elimination of a number of successive problems, each of which was expected to be the culprit, failed to lead to successful large area high sensitivity films, even though other aspects of the films (optical uniformity, transparency, freedom from pinholes, sensitivity in small areas, and efficiency) all showed improvement. At this point, after thirty-four evaporations and complete processing of 140 films, the major effort on low voltage films was halted.

Some optimum brightness voltage data are listed in Table 13.

Some of the adjacent pairs of values were observed on the same film, and some were not.

EL Film	Brightness ft-L	Volts
a. Low voltage films, AC	10	11
	120	23
b. High voltage films, AC	200	95
	300	130
c. Low voltage films, DC	220	22
	500	47
	600	55
	960	65

Table 13. Optimum Brightness Voltage Data of Evaporated EL Films

2. Insulating Layers

The next aspect studied was the effect of an insulating film on either or both sides of the luminescent ZnS film. Two materials were used, SiO and MgF₂. These phosphor films were about 3.5 μ in thickness and the insulating films were made about 0.5 μ thick. An insulating film deposited on the tin oxide coated glass, and followed by the ZnS film, will be referred to as the "base" film. An insulating layer deposited on top of the ZnS film will be called a "cover" film.

A. Yellow Emitting Films

SiO

SiO base films (at least in thicknesses around 0.5 μ) reduce adherence of the ZnS if the sequence is SnO-SiO-ZnS-fire. Some areas adhered well enough to measure. However, if the sequence is SnO-SiO-ZnS-SiO-fire, the SiO cover largely prevents activation of the ZnS during firing. This implies that SiO is promising as a buffer between ZnS and the photoconductor during the sensitizing process of the latter in image intensifier fabrication. These layers of SiO (about 0.5 μ) were much too thick; they absorbed an excessive fraction of the applied voltage and they were light amber in color. In addition, SiO base films seem to react during firing with the SnO conducting layer and become optically more dense; this does not occur where the SiO film is on bare glass. Adherence of ZnS to glass (without SnO coating) appears to be better with an SiO base coat between them.

Results of electrical measurements are: (1) At equal light output, SiO base films under ZnS do not affect efficiency but increase voltage by a large factor (5X) for equivalent brightness. (2) Unfired SiO cover films over ZnS increase efficiency at low brightness by 15X but do not affect efficiency at high brightness; this agrees with earlier results with plastic overcoatings. (3) SiO over ZnS, then fired, reduces efficiency by 100X (prevents activation). (4) 0.5 μ SiO layers are far too thick. (5) SiO fired in ZnS phosphor

is 20X more lossy than unfired SiO₂; its resistivity is only 25X greater than the ZnS phosphor.

MgF₂

Some sequences (SnO-MgF₂-ZnS-fire) peeled and some did not, but it seemed certain that fired ZnS adheres less well to 0.5 μ MgF₂ than to tin-oxide on glass. In the sequence SnO-MgF₂-CN wash, the CN wash was effective and so either penetrated the MgF₂ cover, or removed it - probably the latter. MgF₂ cover prevents activation of ZnS and survives the firing step at least in some instances. In the sequence SnO-MgF₂-ZnS-MgF₂-fire-CN wash, the fluoride layer appears to have survived the CN wash. An MgF₂ base film caused no visible difference in the appearance or photoluminescence of the ZnS layer. The MgF₂ layers are extremely transparent. The results of electrical measurements on samples with MgF₂ layers are presented in Table 14, where the sequence of operations in making the film is symbolized by I (a 0.5 μ insulating film of MgF₂), ZnS (the evaporated layer of zinc sulfide), F (the firing or activation step), CN (the cyanide wash always used to remove excess copper).

Sample	Brightness ft-L	Near Breakdown Voltage (400 cps) rms volts	Range of Efficiency* (lumens per watt)	
			low voltage	high voltage
ZnS-F-CN (Standard)	80	90	.01	.10
I-ZnS-F-CN	8	140	.06	.06
ZnS-I-F-CN	75	25	.01	.15
ZnS-F-CN-I	50	165	.12	.15
ZnS-F-I-CN	50	80	.01	.07
I-ZnS-F-CN-I	20	200	.10	.10

Table 14. Characteristics of EL Films Combined with a MgF₂ Film in Different Constructions and Processings (I insulating layer, F firing, CN cyanide wash)

B. Green Emitting Films

Green emitting films were made from a standard green emitting powder phosphor which shows a maximum efficiency at 400 cps of 2 lumen/watt at 1-10 ft-L (200-400 V), and at 4,000 cps of 1.1 lumen/watt at 25-100 ft-L (200-500 V). Green emitting films from this phosphor show a maximum efficiency of about 1 lumen/watt at about 1 ft-L at 20 V, 400 cps, which is about half the efficiency at a tenth

* Peak efficiencies of yellow emitting films go as high as 0.25 to 0.3 lumens per watt. Since the peak efficiency of a commercial lamp made of yellow emitting EL phosphor powder was measured to be 0.4 lumens per watt, this film efficiency cannot be expected to go much higher at this time.

the voltage of the powder phosphor. The same films show: 0.3 lumen/watt at 10 ft-L, 40 V, 400 cps; 0.4 lumen/watt at 10 ft-L, 30 V, 4000 cps; 0.1 lumen/watt at 80 ft-L, 85 V, 4000 cps. All of these films were overcoated with 0.2 micron MgF_2 . The 80 ft-L at 85 V, 4000 cps figure is probably the best brightness voltage value yet obtained from a green emitting film.

There seems to be a small probability of increasing efficiency of green emitting films since an MgF_2 layer acting as a buffer between the tin-oxide and phosphor films does not improve but rather reduces the efficiency by about a factor of three. Apparently we were mistaken in assuming the tin oxide badly contaminates the phosphor film. An MgF_2 layer deposited on the evaporated ZnS film before firing also has a deleterious effect on efficiency, although with the yellow emitting films an increase in both sensitivity and efficiency resulted from the same procedure.

3. Lifetime Improvement

A. AC Operation

Improvement of lifetime of finished EL films was the next objective. Evidently we had allowed the halide content of our embedding material to become depleted, since firing the latter with additional halide improved the lifetime of the films subsequently fired in the material. Twenty new films were made by firing in embedding phosphor which had been treated by ammonium or copper halides (chloride, bromide or iodide). Six groups of films were life tested in dry air. Only ammonium chloride treatment gave much improved maintenance. The results are shown in Figure 27, in which curves A, B, C are yellow emitting ZnS:Cu, Mn, Cl films about 2.5 microns in thickness with 0.4 micron MgF_2 coating. Sample A is a standard, made similarly to all recent films; i.e., with embedding material which had not been treated with halide. Sample B was made with twice used NH_4Cl treated embedding phosphor and Sample C was the third firing in this powder. Half-lives of A, B, C increase in the ratio 1:10:50 approximately. Sample B' was identical to Sample B, but the MgF_2 coating was omitted. These lifetimes, in view of the 1000 cps operating frequency, are as good as any we have produced previously.

Efficiency was measured on films, A, B, C and found to increase slightly in that order; i.e. best lifetime associated with best efficiency. Breakdown brightness of Sample C is 100 ft-L at 105 volts rms.

Maintenance of emission of EL powders is usually increased if iodine or gallium is used for coactivation instead of chlorine. Accordingly, batches of powder phosphor were prepared according to the following recipes:

(1) Chlorine Coactivation

200 gm ZnS
3 gm Cu acetate
0.3 gm NH_4Cl
8 gm $MnCO_3$
10 gm purified sulphur

(2) Iodine Coactivation

200 gm ZnS
3 gm Cu acetate
1.8 gm NH_4I
8 gm MnCO_3
10 gm purified sulphur

(3) Gallium Coactivation

200 gm ZnS
3 gm Cu acetate
0.28 gm Ga_2O_3
8 gm MnCO_3
10 gm purified sulphur

All were fired 100 minutes at 1000°C in flowing N_2 , except the gallium lot which was fired in flowing H_2S . Films were made from each type, but no significant difference in lifetime or efficiency was found. Apparently in the case of films, only an increase in chloride content results in lifetime improvement.

B. DC Operation

Some data on direct current, constant voltage lifetime of one yellow emitting film appear in Figure 28. This behavior is perhaps least favorable since the film was operated in room air, with no protection from moisture, it was chlorine coactivated but probably was deficient in chlorine, the film had no insulating layer on either surface (such as those which markedly improve AC lifetime). Note that efficiency increases by about a factor of three; power input decreased by a factor of eight during the five hours of the run. Electrically, the major effect is an increase in impedance with operation, and this is characteristic of all EL phosphors, powder or film, AC or DC operated.

C. Other Aspects of EL Lifetime

The usual method of defining lifetime of emission of any lamp is to run the lamp at constant voltage and to measure the time required for the emission to decrease to a minimum tolerable level; this was the procedure, for example, in obtaining the data of Figures 27, 28.

These EL films are excitable by direct current and it is a simple matter, with a constant current supply, to determine the maintenance characteristics at constant current instead of constant voltage; some results are shown in Figure 29. Although this general behavior is quite typical of constant-current operation of films, the increase in brightness and efficiency with operating time is usually not so great. Although constant-current operation is not useful where the EL film is used in a conventional light amplifier, the curves of Figure 29 remind one that constant voltage operation is not the ideal, nor even a reasonable, way to realize best lifetime.

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Improvement in usable lifetime is obtained by operating the device at "constant brightness", that is, increasing voltage (or current) slightly and continuously to correct for normal decrease in output with operating time. Figure 30 is taken from old data on electroluminescent lamps, and indicates that a sizeable increase in usable lifetime is realized by "constant brightness" operation.

It is hereby suggested that provision be made for adjustment by gradually increasing the overall voltage on the completed light amplifier; a range of 10% should be sufficient. Such operation would put the useful life time on an entirely different basis, and results in many more operating hours.

4. Large Area Films

Large area EL films will, when excited over their entire area, require a highly conducting transparent electrode. For the smaller areas we have tolerated 50 ohms per square before firing and 100-200 ohms per square after firing, but spent much time on lowering this resistivity. Both substrate temperature and spraying procedure were varied, and as a result many films have been made which show about 6 ohms per square before firing and perhaps 10-30 ohms per square after firing. The coating temperature of the PPG No. 6695 glass is now held at about 815°C. The low value of about 6 ohms per square is now consistently obtained for all glass sizes from the usual 1 1/2" square to 6" x 6" pieces.

A new furnace, large enough to take the 6" x 6" plate in its crucible has been arranged. The temperature cycle at the film, during firing (activation) of the film, was measured first for a 1 1/2" x 1 1/2" film in the small furnace and then for a 6" x 6" film in the large furnace and power adjusted so both ultimate temperature and heating rate are similar.

Evaporation conditions for the large area films have apparently been successfully worked out. Both 4" x 4" and 6" x 6" sizes have been evaporated to a uniform thickness (by appearance) and fired to uniform activation (also by appearance); they are not tested and finished yet at the time of writing this report.

IMAGE INTENSIFIER CONSTRUCTION PROBLEMS

Light Amplifier Elements

It was mentioned in Section III that an agreement between the calculated characteristics and the experimental data of the image intensifier should not necessarily be found when the PC or EL elements have nonlinear voltage current characteristics. Nevertheless an agreement was expected, because of the nondiscriminatory character of the EL cell regarding the shape of the voltage curve. To see if truly an agreement exist, light amplifier units with separated PC and EL elements have been tested. In one experiment the PC cell, in another the EL element had non-ohmic characteristics. Figure 31 and 32

show the result for the first case, where a sintered PC CdSe cell and a plastic embedded EL element were combined. The current of the PC cell had a quadratic dependence on the voltage and the measured values of the transfer characteristic agree within the error of the measurements with the calculated curve. In a second case an evaporated EL film with non-ohmic characteristic was combined with an ohmic PC cell and again the calculated and measured transfer characteristic agreed within the error range.

After this proof, the theoretical considerations (see Section III - Computer Study) could serve for guiding the choice of the electro-optical characteristics of the PC and EL elements in the construction of the image intensifier.

It is true that the characteristics of the PC as well as those of the EL elements in a completed image intensifier panel were somewhat different from those of separated cells, and from measurements of separated elements one could not have a complete picture of the image quality of the intensifier panel. This was found in the case of both the low and high resolution panel.

Low Resolution Image Intensifier

Large number of image intensifier panels in sizes from 2" x 2" to 6" x 6" have been fabricated to test the changes in electrical characteristics and in the image quality, when changes in the preparation of PC layers were made.

The most effort, in improving the characteristics of the image intensifier panel, was placed in the aim to improve the image quality, i.e. eliminate the very disturbing graininess and inhomogeneity and decrease the very high contrast of the intensified image.

As a result of this effort the gamma was decreased so that image intensifier panels were built showing five to six half tones. The maximum γ of the transfer characteristic was diminished from the usual six to only about two to three, but the distribution of the γ through the useful illumination range was improved so that a less contrasty picture was obtained.

For decreasing the graininess, a study on the bonding mechanisms, described in the Photoconductive Materials part of this Section, seemed to indicate the cause of the graininess. Using the conclusion of this study some experimental panels were made, showing highly improved pictures. However, the reproducibility of the fabrication technique was not good.

It seemed at the end of the one year work period that there could exist a very critical contact inhomogeneity between the PC and EL sandwich or the PC layer is modified by the EL spraying process so that a grainy structure results from it. The study is being continued to clear up this problem and to be able to reproduce the fabrication of panels with improved picture quality.

High Resolution Image Intensifier

Evaporated EL films were connected to separate PC elements and characteristics of the light intensifiers studied. Plastic embedded, and sintered CdSe cells and evaporated CdS films were used as PC elements in these experiments. With all three variety of PC cells maximum gains between unity and ten were measured.

Building an available plastic embedded CdSe PC layer on the top of the EL film showed a gain of around unity and a highly grainy structure. Improvements in the plastic embedded PC powder program have to be achieved before continuing more experiments with this type of PC layer.

Construction with sintered or evaporated PC layers demand a high temperature baking of the EL and PC film together for sensitizing the PC layer. During this baking both layers are modified by the other and as experiments made in the previous contract¹ on image intensifiers, both layers showed highly deteriorated characteristics. The higher the baking temperature is, the worse the deterioration can be. Some experiments indicated that a thin SiO layer between the PC and EL films can diminish the interaction during the baking process.

Experiments for finding the lowest sensitizing temperature on CdS evaporated films showed that acceptable sensitivities can be obtained with a 430°C baking temperature. Consequently CdS layers were evaporated on the top of a 2 μ thick SiO coated EL film and sensitizing of the PC film was made without much deterioration of the photoluminescence of the EL film.

Problems of depositing intermediate electrodes, necessary of achieving some gain, are being worked out. After finding the appropriate electrode material (probably gold) which does not deteriorate the characteristics during the heat treatment, small samples of image intensifiers in this construction will be built.

Another problem, increasing the thickness of the PC layer, has to be solved also, because the low breakdown voltage and shorts on the 6 μ thick CdS films presents some difficulties. As the low voltage variety of EL films was not developed for larger areas than 1" x 1", the PC film has to withstand voltages as high as 130 volts. More than 13 micron thick films will be needed to keep the field strength below 10⁵ volts/cm.

Data of Best Image Intensifier Panels

Figure 33 depicts the transfer characteristics of an image intensifier panel, prepared at the end of the working period. The measurements were performed with a 2870°K color temperature tungsten light source.

Figure 34 shows a photograph of an intensified image. Comparing this figure with Figures 67 to 73 of reference 1, one sees the improved uniformity; the almost complete elimination of the dense dark and

bright spottiness and a finer grain structure. The most important constructional and electrical characteristics of the best panels are listed in Table 15.

Characteristics	Data
Construction type	Sandwich
Size	6" x 6"
PC layer	Sintered CdSe, 4 mils thick
EL layer	Plastic embedded ZnS, 2 mils
Voltage	100-200 volts
Frequency	60-2000 cps
Input light intensity range	10 ⁻² to 2 ft-c
Output brightness range	10 ⁻⁴ to 30 ft-L
Maximum standard luminous gain	30 ft-L per ft-c
Spectral response max. of PC layer	7600 Å
Spectral emission max. of EL layer	5300 Å
Decay time constant	100 msec
Rise time constant	100 to 1000 msec
Resolution	100 TV lines per inch
Brightness uniformity among elements	Better than 1 to 2 in average

Table 15. Constructional and Electrical Characteristics of Best Sandwich Type Image Intensifiers

Some explanation is needed to see the meaning of the last line in Table 15. When one illuminates the image intensifier panel with a homogeneous light intensity, one sees some kind of nonuniform graininess, which results from the unequal emission of the elements. This nonuniformity is generally the most disturbing at medium illumination levels (in the center of the transfer characteristics, where γ is maximum) and disappears at the saturation of the transfer characteristics. It is caused probably by the not well defined contacts between electrodes and PC particles. In panels made before an improved preparation method was found (see Section IV), the brightness ratio between two elements could go up to 50 for a very large number of elements. The panels prepared lately show a large improvement in this respect, and by this fact offer a less grainy structured, better image quality.

SECTION V

DISCUSSION, PLANS FOR FOLLOWING YEAR

The work in the beginning of this program was progressing at a slower pace than it was planned. The full effort was started only after the first half of the year had passed.

The work proceeded along five principal lines. The first line of work was directed toward improvements in sintered PC materials. The second line was directed toward construction problems and improvements in the low resolution image intensifier panels. The third line of work was performed during the last half year at the [REDACTED]

[REDACTED] with the goal of developing plastic embedded PC powders for the image intensifier application. The fourth line of work was performed during the last ten months at the [REDACTED]

[REDACTED] with the goal of improving the characteristics of evaporated EL films and the fifth line of work was directed toward construction problems of the high resolution image intensifier panel.

Regarding the sintered PC materials most of the effort was devoted to CdSe. Improvements in sensitivity, current light intensity characteristics and graininess have been achieved. Some problems of conduction mechanism have been examined and understood better. Based on the above study the image quality of the low resolution image intensifier panel has been improved, achieving better homogeneity, less graininess and lower contrast. A parameter study of image intensifier characteristics executed by a digital computer helped to clarify the electro-optical behavior of the image intensifier circuit. In the PC powder program the sensitivity of the CdSe plastic embedded powder has been increased to a practically useful level. In the evaporated EL film program a method was developed which gave films with reproducible life characteristics. The solution of the difficult problem of building a sensitive PC film on the EL film is progressing satisfactorily; CdS evaporated films have been sensitized on the top of EL films having an intermediary SiO layer, without seemingly deteriorating the EL film.

For the following year all the activities will continue with goals of fulfilling the requirements of the program (see Section II).

- (1) Work with new PC materials, which started already, will continue, with the main effort directed toward achieving an improvement in speed of response without loss of high conductivity.
- (2) Some construction problems of the low resolution image intensifier panel have to be cleared and the reproducibility of the fabrication will be improved.
- (3) [REDACTED] will continue the powder PC program for the next half year for developing a plastic embedded PC powder approaching the goal characteristics.

- (4) No further work for the improvements of the evaporated EL film is planned. A number of EL film panels are being delivered by [redacted] to us, and these panels probably should satisfy our needs for the construction of high resolution image intensifier panel. Nevertheless, if the need arises to resume EL film preparation, it could be scheduled in [redacted] could give some assistance.
- (5) A larger effort will be directed toward the construction of the high resolution image intensifier.
- (6) A compact optical projection system, incorporating the image intensifier panel, will be built.

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SECTION VI

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SECTION VII

APPENDIX A

MATHEMATICAL ANALYSIS OF PC-EL LIGHT AMPLIFIERS

A general formula of the transfer characteristic for the basic circuit of the PC-EL light amplifier (Figure 1) is derived here. The dark current and the nonlinear current voltage (non-ohmic) dependence of the PC element, as well as the conductance of the EL element were considered in this derivation.

The formula, giving the output brightness (B) of the EL cell is given by

$$B = B_0 f^\alpha \exp \left(- \sqrt{\frac{A}{V_2}} \right) \quad (1)$$

where B_0 , A and α are constants, f is the frequency and V_2 is the RMS value of the applied sinusoidal voltage on the EL cell (the amplitude of the voltage could be used as well, but the value of A would be $\sqrt{2}$ - times higher in this case).

For the circuit of Figure 1, V_2 can be calculated from the equation

$$V_2 = V_0 \frac{|Z_2|}{|Z_1 + Z_2|} \quad (2)$$

Where V_0 is the RMS value (or amplitude) of the applied voltage, Z_1 and Z_2 are the complex impedances of the PC and EL cells respectively.

If g_1 and g_2 are the conductances and $s_1 = \omega C_1$ and $s_2 = \omega C_2$ are the susceptances of the PC and EL elements respectively

$$Z_1 = \frac{1}{g_1 + js_1} = \frac{g_1 - js_1}{g_1^2 + s_1^2} \quad (3)$$

and

$$Z_2 = \frac{1}{g_2 + js_2} = \frac{g_2 - js_2}{g_2^2 + s_2^2} \quad (4)$$

The absolute values of these impedances are:

$$|Z_1|^2 = \frac{1}{g_1^2 + s_1^2} \quad (5)$$

$$|z_2|^2 = \frac{1}{g_2^2 + s_2^2} \quad (6)$$

and

$$|z_1 + z_2|^2 = \frac{(g_1 + g_2)^2 + (s_1 + s_2)^2}{(g_1^2 + s_1^2)(g_2^2 + s_2^2)} \quad (7)$$

Substituting equations (6) and (7) in (2), one has

$$v_2 = v_o \sqrt{\frac{g_1^2 + s_1^2}{(g_1 + g_2)^2 + (s_1 + s_2)^2}} \quad (8)$$

Introducing the capacitance ratio of the two cells as

$$p = \frac{C_2}{C_1} \quad (9)$$

and making some modifications, the voltage on the EL cell can be expressed as follows:

$$v_2 = v_o \sqrt{\frac{\left(\frac{pg_1}{\omega C_2}\right)^2 + 1}{\left[\frac{p(g_1 + g_2)}{C_2}\right]^2 + (1 + p)^2}} \quad (10)$$

Similarly, the voltage on the PC cell is given by:

$$v_1 = v_o \sqrt{\frac{\left(\frac{pg_2}{\omega C_2}\right)^2 + p^2}{\frac{p(g_1 + g_2)}{C_2}^2 + (1 + p)^2}} \quad (11)$$

and the voltage ratio

$$\frac{v_2}{v_1} = \sqrt{\frac{\left(\frac{pg_1}{\omega C_2}\right)^2 + 1}{\left(\frac{pg_2}{\omega C_2}\right)^2 + p^2}} \quad (12)$$

Equations (10) to (12) contain, besides constants of the circuit elements (p , g_2 , C_2) and data of driving condition (V_0 , ω) the conductance of the PC element, which can be expressed as:

$$g_1 = c_0 (c_d + L^n) V_1^{m-1} \quad (13)$$

where c_0 , c_d , n , and m are constants of the PC element, L is the illumination and V_1 is the voltage on the PC element. Substituting equation (11) in equation (13) one has

$$g_1 = f(g_1) \quad (14)$$

type of equation, which can be solved by the Newton iteration method, using repeatedly the formula

$$g_1^* = g_1 - \frac{g_1 - f(g_1)}{1 - f'(g_1)} \quad (15)$$

where

$$f'(g_1) = \frac{-(m-1)p(g_1) \left(\frac{pg_1}{\omega C_2} + \frac{pg_2}{\omega C_2} \right)}{\omega C_2 \left[\left(\frac{pg_1}{\omega C_2} + \frac{pg_2}{\omega C_2} \right)^2 + (1+p)^2 \right]} \quad (16)$$

Starting with an arbitrary g_1 and continuing the application of equation (15), one can generally approach the solution with any precision desired. Substituting this g_1 value in equation (10), one obtains the voltage on the EL element and through equation (1) the output brightness of the light amplifier for the given input light intensity L .

The luminous gain X is calculated to

$$X = \frac{B}{L} \quad (17)$$

The contrast γ (gamma) of the image intensifier can be calculated from

$$\gamma = \frac{d \log B}{d (\log L)} \quad (18)$$

In the case of an ohmic PC element ($m = 1$) one has:

$$\gamma = \frac{n}{2} \sqrt{\frac{A}{V_0}} \frac{a^2 c_0 L^n \left[a^2 g_1 g_2 (g_1 + g_2) + p(p+2)g_1 - g_2 \right]}{(a^2 g_1^2 + 1)^2 \varphi^{3/4}(g_1)} \quad (19)$$

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where

$$a = \frac{p}{\omega c_2}$$

and

$$\varphi(g_1) = \frac{a^2 (g_1 + g_2)^2 + (1 + p)^2}{a^2 g_1^2 + 1} \quad (20)$$

If the conductance of the EL element and the dark current of the PC element are negligible ($g_2 = c_d = 0$), one has a simpler equation for γ .

$$\gamma = \frac{np(p+2)}{2} \sqrt{\frac{A}{V_0}} \frac{a^2 g_1^2}{(a^2 g_1^2 + 1)^2} \left[\frac{a^2 g_1^2 + 1}{a^2 g_1^2 + (1+p)^2} \right] \quad (21)$$

Calculating γ_{\max} of the transfer characteristic, one must solve the equation $\frac{d\gamma}{dL} = 0$ for L. Carrying out the calculations, one has the following quadratic equation for g_1^2 :

$$4a^4 (g_1^2)^2 + p(p+2) a^2 g_1^2 - 4(p+1)^2 = 0 \quad (22)$$

By solving this equation for g_1 and substituting it in equation (21), one will have γ_{\max} .

With a given PC element γ_{\max} can be expressed in a simple form, as:

$$\gamma_{\max} = \gamma_0 n \sqrt{\frac{A}{V_0}} \quad (23)$$

where γ_0 depends only on the capacitance ratio.

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APPENDIX B

COMPUTER PROGRAM IN FORTRAN LANGUAGE FOR PC-EL LIGHT AMPLIFIERS

A computer program in FORTRAN language was written for calculating the transfer characteristic (output brightness as a function of input illumination) and other data of a light amplifier.

Equations (1), (10), (13), (15), (16) and (17) of Appendix A were used in the program for calculating the conductance of the PC element (g_1), the voltages on the PC and on the EL element (V_1 and V_2), the output brightness (B) and the luminous gain (X). The FORTRAN program for the IBM 1401 computer is shown in Figure 3.

The data of the circuit are fed to the computer on four cards. The first card contains the voltage and the frequency of the power supply (V_0, f), the second contains the constants of the PC element (m, n, c_0, c_d), the third card the constants of the EL element ($\alpha, B_0, A, C_2, \cos \delta_0$). As it is seen, the power factor ($\cos \delta$) is given here, which has more practical meaning, than the conductance. The connection between the two quantities is expressed by

$$g_2 = \frac{\omega C_2 \cos \delta}{\sqrt{1 - \cos^2 \delta}} \quad (1)$$

The fourth data card contains the capacitance ratio (p), for which the calculation has to be done. Generally four p values were used and data were calculated for 13 input light intensities for each capacitance ratio. A part of the result (half for one set of data), as it was printed by the computer, is shown in Figure 4. The calculation and printing of these data required less than two minutes.

The calculation of the contrast could not be included in the same program because of the limited storage capacity of the IBM 1401 computer. Therefore a separate program was written for the calculation of the maximum contrast (Y_{\max}) only. The program was based on equations (21) and (22) of Appendix A. As it is seen, these equations are limited for the case where the PC element has linear voltage current dependence (ohmic characteristic, $m = 1$), and the dark current of the PC element and the conductance of the EL element are negligible ($c_d = g_2 = 0$).

The work done using these programs is discussed in Section III, and some calculated data in graphical form are shown on Figures 5 to 12.

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APPENDIX C

BASIC EQUATIONS OF PC CELLS

If one supposes, as it is the case with CdS and CdSe, that the PC current is transported only by one type of carrier and the other type can be neglected, the conductivity σ is expressed by the basic formula

$$\sigma = n e \mu \quad (1)$$

where n is the density of the free carriers, e is the charge of the electron, and μ is the mobility of the carriers.

If the light creates F electrons per second per unit volume of the PC material, and the life time of the carriers is τ , the carrier density will be:

$$n = F\tau \quad (2)$$

Substituting (2) in (1), one has for σ :

$$\sigma = F\tau e \mu \quad (3)$$

Multiplying both sides with the thickness t^* in which the incident light is absorbed (t^* is generally smaller than the thickness of the layer):

$$\sigma t^* = F t^* \tau e \mu \quad (4)$$

Ft^* is the number of electrons created in a unit area and σt^* is the conductance per square (σ_{\square}) of the PC layer. If the photoconductive layer absorbs all the incident photons and the quantum efficiency of the electron creation in the PC layer is unity, Ft^* is the number of photons falling on the unit area (cm^2) of the PC per second: $N_{\text{ph/cm}^2}$ and (4) can be written as

$$\frac{\sigma_{\square}}{N_{\text{ph/cm}^2}} = e \tau \mu \quad (5)$$

Here the left side is a measure of the sensitivity of the PC layer and is related to the fundamental characteristics: life time and mobility of the material.

If one divides equation (5) by e :

$$\frac{\sigma_{\square}}{e N_{\text{ph/cm}^2}} = \tau \mu \quad (6)$$

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Here $\frac{\sigma_{\square}}{e}$ is the number of carriers per square per unit voltage, and thus equation (6) states that the number of carriers per square per unit voltage divided by the number of photons per cm^2 is equal to the product of the life time and mobility.

σ_{\square} , the conductance per square, has meaning for lateral cells only, but equation (4) still can be applied to sandwich cells as well.

Another quantity, the so called "specific sensitivity" can be derived by specifying the geometry of the photocell. For this purpose one has to discuss separately the lateral and the sandwich type PC cell.

For a lateral cell, where the direction of the light is perpendicular to the direction of the carriers, the conductance is:

$$\frac{I}{V} = \sigma \frac{l t^*}{d} \quad (7)$$

where I is the current, V is the applied voltage and l , d , t^* are the cell dimensions, as shown in Figure 13. From (7) and (3)

$$\frac{I}{V} = F t^* \frac{l}{d} e \tau \mu = F t^* \frac{l^2}{d^2} e \tau \mu \quad (8)$$

If the quantum efficiency of the photon-electron process is unity, $F t^* \frac{l}{d}$ is the number of photons absorbed in the cell per second. The power E of the incident light is

$$E = h \frac{c}{\lambda} F t^* \frac{l}{d} \quad (9)$$

where h is the Planck constant, c is the speed of light, and λ is the equivalent wavelength of the incident light. Substituting $F t^* \frac{l}{d}$ from (9) into (8) one has

$$S = \frac{I}{V} \frac{d^2}{E} = \frac{\lambda e}{h c} \tau \mu \approx 0.8 \lambda \tau \mu \quad (10)$$

where λ is measured in microns.

S is called the "specific sensitivity" of the PC material, and is obtained by multiplying the photoconductance by the square of the electrode spacing and dividing by the absorbed radiation power. The specific sensitivity is an intrinsic property of the material, being proportional to the carrier life time and mobility.

Similarly to the above, one can derive for a sandwich cell (Fig. 13) the following equation:

$$S = \frac{I}{V} \frac{t^2}{E} = \frac{\lambda e}{h c} \tau \mu \quad (11)$$

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This shows that the "specific sensitivity" is independent of any geometrical factors.

If the number of primarily created electrons per second is $F t^* l d$ in the photocell, and the number of free carriers per second is $\frac{l}{e}$, the ratio of the two quantity is called the gain of the photocell:

$$G = \frac{l}{e F t^* l d} \quad (12)$$

From equation (8), this gain is equal:

$$G = \frac{\tau_u v}{d^2} \quad (13)$$

The gain may also be expressed as the ratio of the life time of the free carriers to the transit time (T_r) of the carriers

$$G = \frac{\tau}{T_r} \quad (14)$$

As the transit time is given by

$$T_r = \frac{d^2}{\mu v} \quad (15)$$

equations (13) and (14) are identical.

The decay and rise time constants, τ_d and τ_r , of the PC cell are generally longer than the life time. This behavior is caused by the high number of traps. If the trap density is n_{tr} and the free carrier density is n , the decay time constant will be

$$\tau_d = \frac{n_{tr} + n}{n} \tau \quad (16)$$

If the trapped electrons are in thermal equilibrium with the free carriers, one can calculate the energy level of the traps as¹³:

$$E_{tr} = \frac{kT}{e} \ln \frac{N_c}{n} \text{ eV} \quad (17)$$

where k is the Boltzmann constant and N_c is the density of the states in the conduction band.

Another important equation, expressing the maximum available gain is:

$$G = \frac{\tau_d}{\tau_{rel}} M \quad (18)$$

where τ_{rel} is the relaxation time of the photocell ($\tau_{rel} = R \times C$) and M is a factor, depending on the distribution of the recombination centers.

The theoretically maximum gain of the image intensifier, according to Rose and Bube¹⁴ can be expressed by

$$G_L = \frac{2 V^2 \mu \tau}{5 t^2} \epsilon \quad (19)$$

where ϵ is the efficiency of the EL element. The gain practically cannot be increased indefinitely with increasing voltage, because of the appearance of the highly superlinear space-charge-limited currents. The maximum voltage, applicable to the PC cell is given by

$$V_{max} = \pi \frac{t^2 f \tau}{\mu \tau_d} M \quad (20)$$

where f is the frequency of the applied voltage.

APPENDIX D

MATHEMATICAL ANALYSIS OF BRIDGE CIRCUIT

Since, practically, there are some capacitances present on arms 1 and 3 of the bridge circuit (Figure 16), it was interesting to see what is the error in the measurement, introduced by their presence.

Assuming a capacitance C_1 and C_3 in parallel with R_1 and R_3 respectively, the balance condition is given by:

$$\frac{Z_x}{Z_2} = \frac{Z_3}{Z_1} \quad (1)$$

where Z represents the impedance.

From equation (1):

$$\frac{1}{Z_x} = \frac{Z_1}{Z_2 Z_3} \quad (2)$$

Expressing the admittances ($\frac{1}{Z}$) with the conductances ($g = 1/R$) and susceptances ($s = \omega C$)

$$g_x + js_x = \frac{(g_2 + js_2)(g_3 + js_3)}{(g_1 + js_1)}$$

After equating real and imaginary parts, one has:

$$R_x = \left(\frac{R_2 R_3}{R_1} + \omega^2 C_1^2 R_1 R_2 R_3 \right) / (1 - \omega^2 C_2 C_3 R_2 R_3 + \omega^2 C_1 C_3 R_1 R_3 + \omega^2 C_1 C_2 R_1 R_2) \quad (3)$$

and

$$C_x = R_1 \left(\frac{C_2}{R_3} + \frac{C_3}{R_2} - \frac{C_1 R_1}{R_2 R_3} + \omega^2 C_1 C_2 C_3 R_1 \right) / (1 + \omega^2 R_1^2 C_1^2) \quad (4)$$

Case (A)

If $C_1 = C_3 = 0$; the simple equations are obtained

$$R_x = \frac{R_2 R_3}{R_1} \quad (5)$$

$$C_x = \frac{R_1 C_2}{R_3} \quad (6)$$

Case (B)

Let us assume that C_1 and C_3 are not equal to zero but have a value of the order of a few pico-farads and other components have values shown in Figure 16. With these data, one can see the validity of the following inequalities

$$\frac{1}{R_1} \gg \omega^2 C_1^2 ; C_3 R_3 \gg C_1 R_1 ; C_2 R_2 \gg C_1 R_1 \quad (7)$$

and one has the simplified expression for R_x :

$$R_x = \frac{R_2 R_3}{R_1} / (1 - \omega^2 C_2 C_3 R_2 R_3) \quad (8)$$

In the case, where C_x is constant R_3/R_1 is a constant.

If $R_3/R_1 = K$ and $R_2 = (\omega^2 C_2 C_3 R_3)^{-1}$ equation (8) becomes:

$$1/R_x = \frac{1}{KR_2} (1 - \frac{R_2}{R_1}) \quad (9)$$

If $C_3 = 1$ pF, $R_2 = 10^3$ ohms and the frequency is 1000 c/s

$$\frac{1}{R_x} = \frac{1}{KR_2} (1 - 0.04)$$

Thus the 1 pF capacitance in the third arm causes a 4% error. A 10 pF capacitance would cause a 40% error. It can be seen that if the value of the unknown capacitance is kept constant, the percentage error in the value of the unknown resistance increases with increasing unknown resistance.

Similarly, for the expression of the unknown capacitance (equation 4) one can consider the following inequalities

$$\frac{1}{R_2} \gg \omega^2 C_1^2 ; C_2 R_3 \gg C_1 R_1 ; \frac{1}{\omega C_3 R_3} \gg \omega C_1 R_1$$

and have the simplified formula

$$C_x = R_1 \frac{C_2}{R_3} (1 + \frac{C_3 R_3}{C_2 R_2}) \quad (10)$$

or

$$C_x = R_1 \frac{C_2}{R_3} (1 + R_1/R_2) \quad (11)$$

where

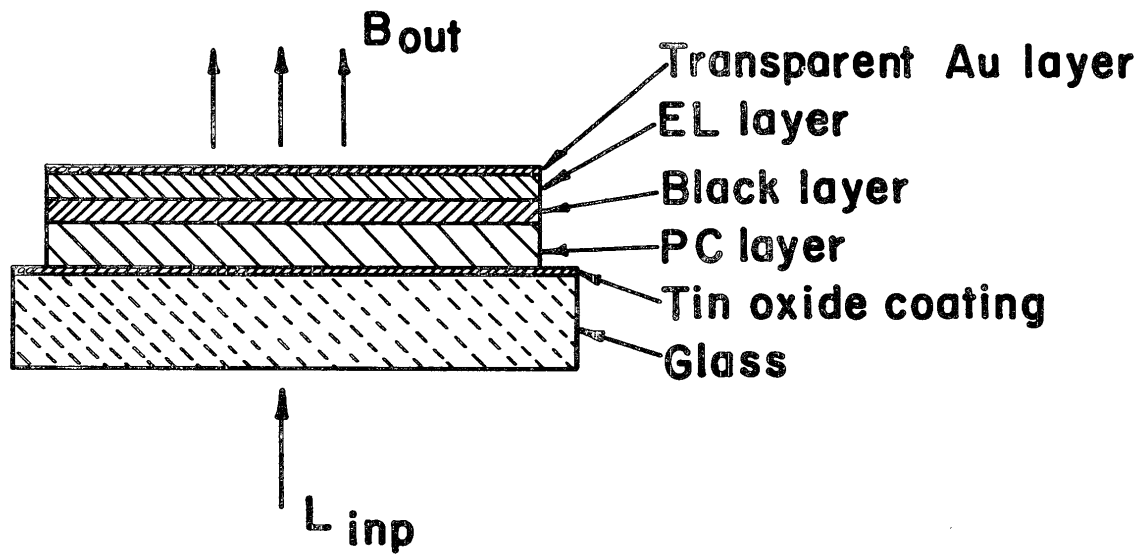
$$\frac{C_3 R_3}{C_2} = R_1$$

If $C_3 = 1 \text{ pF}$, $R_2 = 10^3 \text{ ohms}$ and the frequency is 1000 cps,

$$C_x = R_1 \frac{C_2}{R_3} (1 + 0.001)$$

Thus a 0.1% error in capacitance measurement is caused when a 1 pF capacitance is in the third arm of the bridge and a 1% error is brought in by 10 pF. It can be seen that, if the value of the unknown capacitance is kept constant, the percentage error in its value decreases with increasing unknown resistance.

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Figure 1. Image Intensifier in Sandwich Construction

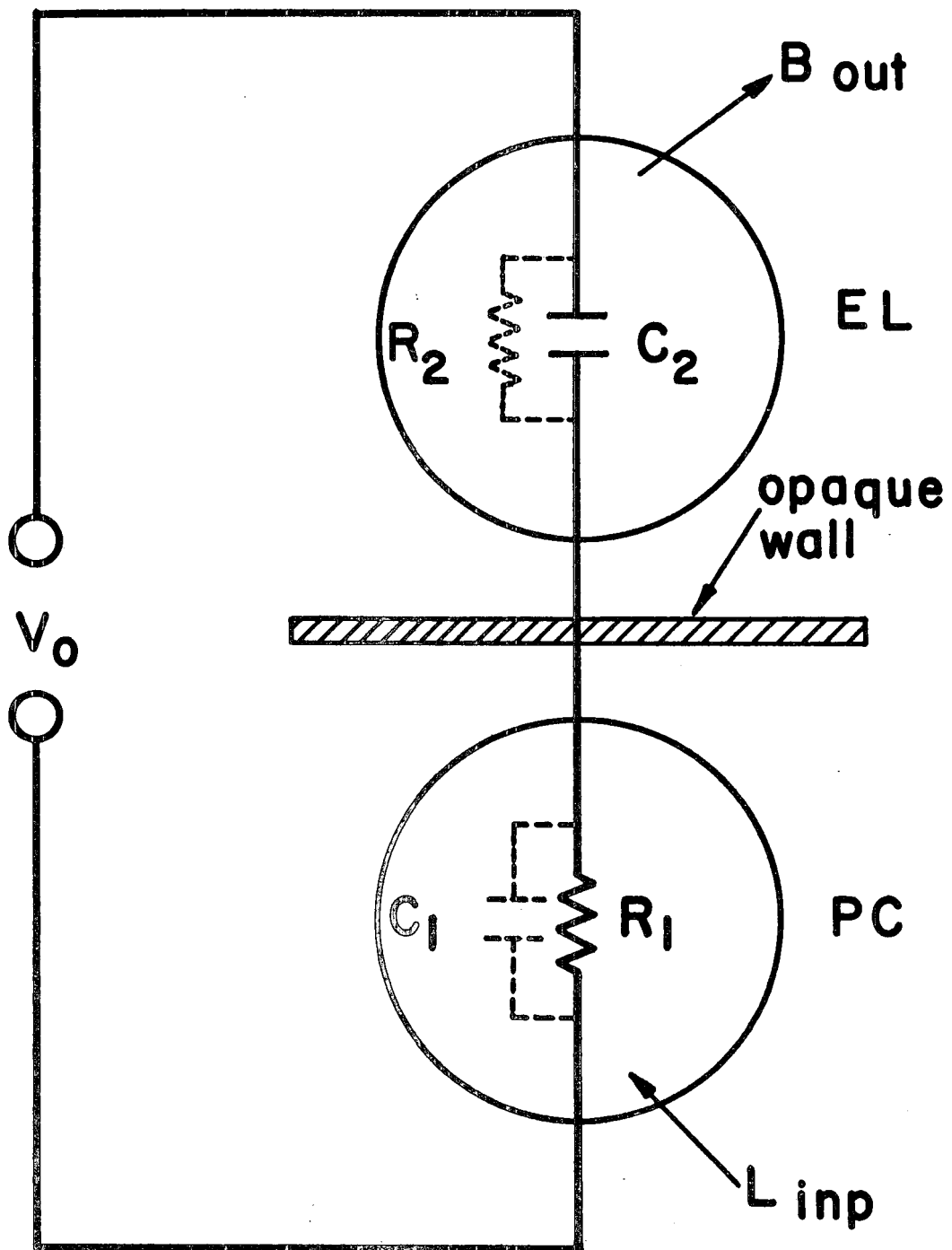


Figure 2. Basic Circuit of Light Intensifier

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C   IMAGE INTENSIFIER 8
    DIMENSION P(4)
11  READ 1,V,F,R,S,U,UD,ALF,D,A,C,PF
    READ 2, (P(I),I=1,4)
    PRINT 3, V,F,R,S,U,UD,ALF,D,A,C,PF
    DO 15 I=1,4
    PRINT 4, P(I)
    PRINT 4I
    Y2=P(I)*PF/SQRTF(1.-PF*PF)
    T=1.E-04
    DO 15 J=1,13
    G=U*(UD+T**S)*((V/4.)**(R-1.))
12  Y1=P(I)*G/(6.28*F*C)
    Y=Y1+Y2
    Z=(1.+P(I))*(1.+P(I))
    V1=V*SQRTF((Y2*Y2+P(I)*P(I))/(Y*Y+Z))
    G1=U*(UD+T**S)*(V1**(R-1.))
    DIFG=(R-1.)*P(I)*G1*Y/(6.28*F*C*(Y*Y+Z))
    G2=G-(G-G1)/(1.+DIFG)
    TEST=ABSF((G2-G)/G2)
    IF(TEST-0.01) 14,14,13
13  G=G2
    GO TO 12
14  Y3=P(I)*G2/(6.28*F*C)
    VE=V*SQRTF((Y3*Y3+1.)/((Y3+Y2)*(Y3+Y2)+Z))
    B=D*(F**ALF)/EXPF(SQRTF(A/VE))
    X=B/T
    PRINT 5,T,G2,V1,VE,B,X
15  T=T*SQRTF(10.0)
    GO TO 11
    1  FORMAT (2F7.1/2F4.1,2E10.3/F4.1,4E10.3)
    2  FORMAT (4F6.1)
    3  FORMAT (1H1//1X,2F7.1/1X,2F4.1,1P2E11.3/1X,0PF4.1,1P4E11.3)
    4  FORMAT (/6H   P=,F4.1//)
    5  FORMAT (1X,1P6E11.3)
410 FORMAT (67H   L-FT.-C.   G1-MHOS   V1-VOLTS   V2-VOLTS   B-FT.-L.
    1   GAIN //)
    END

```

Equivalence of Characters:

FORTRAN	V	F	R	S	U	UD	ALF	D	A	C	PF	P	T	G,G1,G2	V1	VE	B	X
Equations	v	f	r	s	u	c _d	α	B	A	C ₂	cos θ	p	L	g ₁	V ₁	V ₂	B	X

Figure 3. Source Program in FORTRAN Language for PC-EL Light Intensifiers.

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200.0 2000.0
 1.0 0.5 4.000E-05 0.000E-01
 1.0 3.000E 00 3.400E 03 1.000E-09 1.000E-01

P- 3.0

L-FT.-C.	G1-MHOS	V1-VOLTS	V2-VOLTS	B-FT.-L.	GAIN
1.000E-04	4.000E-07	1.500E 02	4.998E 01	1.571E 00	1.571E 04
3.162E-04	7.113E-07	1.497E 02	5.037E 01	1.622E 00	5.128E 03
1.000E-03	1.265E-06	1.491E 02	5.165E 01	1.797E 00	1.797E 03
3.162E-03	2.249E-06	1.475E 02	5.555E 01	2.402E 00	7.595E 02
1.000E-02	4.000E-06	1.438E 02	6.597E 01	4.575E 00	4.575E 02
3.162E-02	7.113E-06	1.348E 02	8.816E 01	1.205E 01	3.812E 02
1.000E-01	1.265E-05	1.160E 02	1.224E 02	3.085E 01	3.085E 02
3.162E-01	2.249E-05	8.686E 01	1.574E 02	5.753E 01	1.819E 02
1.000E 00	4.000E-05	5.669E 01	1.806E 02	7.833E 01	7.833E 01
3.162E 00	7.113E-05	3.398E 01	1.918E 02	8.904E 01	2.816E 01
1.000E 01	1.265E-04	1.959E 01	1.965E 02	9.363E 01	9.363E 00
3.162E 01	2.249E-04	1.113E 01	1.984E 02	9.554E 01	3.021E 00
1.000E 02	4.000E-04	6.286E 00	1.992E 02	9.637E 01	9.637E-01

P- 5.0

L-FT.-C.	G1-MHOS	V1-VOLTS	V2-VOLTS	B-FT.-L.	GAIN
1.000E-04	4.000E-07	1.665E 02	3.355E 01	2.548E-01	2.548E 03
3.162E-04	7.113E-07	1.661E 02	3.435E 01	2.867E-01	9.066E 02
1.000E-03	1.265E-06	1.652E 02	3.621E 01	4.019E-01	4.019E 02
3.162E-03	2.249E-06	1.631E 02	4.358E 01	8.750E-01	2.767E 02
1.000E-02	4.000E-06	1.581E 02	5.917E 01	3.063E 00	3.063E 02
3.162E-02	7.113E-06	1.464E 02	8.750E 01	1.177E 01	3.723E 02
1.000E-01	1.265E-05	1.231E 02	1.257E 02	3.311E 01	3.311E 02
3.162E-01	2.249E-05	8.974E 01	1.609E 02	6.050E 01	1.913E 02
1.000E 00	4.000E-05	5.747E 01	1.825E 02	8.007E 01	8.007E 01
3.162E 00	7.113E-05	3.414E 01	1.925E 02	8.974E 01	2.838E 01
1.000E 01	1.265E-04	1.963E 01	1.967E 02	9.387E 01	9.387E 00
3.162E 01	2.249E-04	1.114E 01	1.985E 02	9.562E 01	3.024E 00
1.000E 02	4.000E-04	6.287E 00	1.992E 02	9.640E 01	9.640E-01

P-20.0

L-FT.-C.	G1-MHOS	V1-VOLTS	V2-VOLTS	B-FT.-L.	GAIN
1.000E-04	4.000E-07	1.899E 02	1.120E 01	1.630E-04	1.630E 00
3.162E-04	7.113E-07	1.893E 02	1.423E 01	1.163E-03	3.676E 00
1.000E-03	1.265E-06	1.880E 02	2.103E 01	1.805E-02	1.805E 01
3.162E-03	2.249E-06	1.850E 02	3.422E 01	2.815E-01	8.901E 01
1.000E-02	4.000E-06	1.778E 02	5.703E 01	2.660E 00	2.660E 02
3.162E-02	7.113E-06	1.616E 02	9.142E 01	1.348E 01	4.261E 02
1.000E-01	1.265E-05	1.317E 02	1.321E 02	3.760E 01	3.760E 02
3.162E-01	2.249E-05	9.292E 01	1.656E 02	6.464E 01	2.044E 02
1.000E 00	4.000E-05	5.828E 01	1.847E 02	8.219E 01	8.219E 01
3.162E 00	7.113E-05	3.431E 01	1.933E 02	9.056E 01	2.864E 01
1.000E 01	1.265E-04	1.966E 01	1.970E 02	9.415E 01	9.415E 00
3.162E 01	2.249E-04	1.114E 01	1.985E 02	9.571E 01	3.027E 00
1.000E 02	4.000E-04	6.288E 00	1.993E 02	9.643E 01	9.643E-01

Figure 4. Computed Data as Typed by Computer

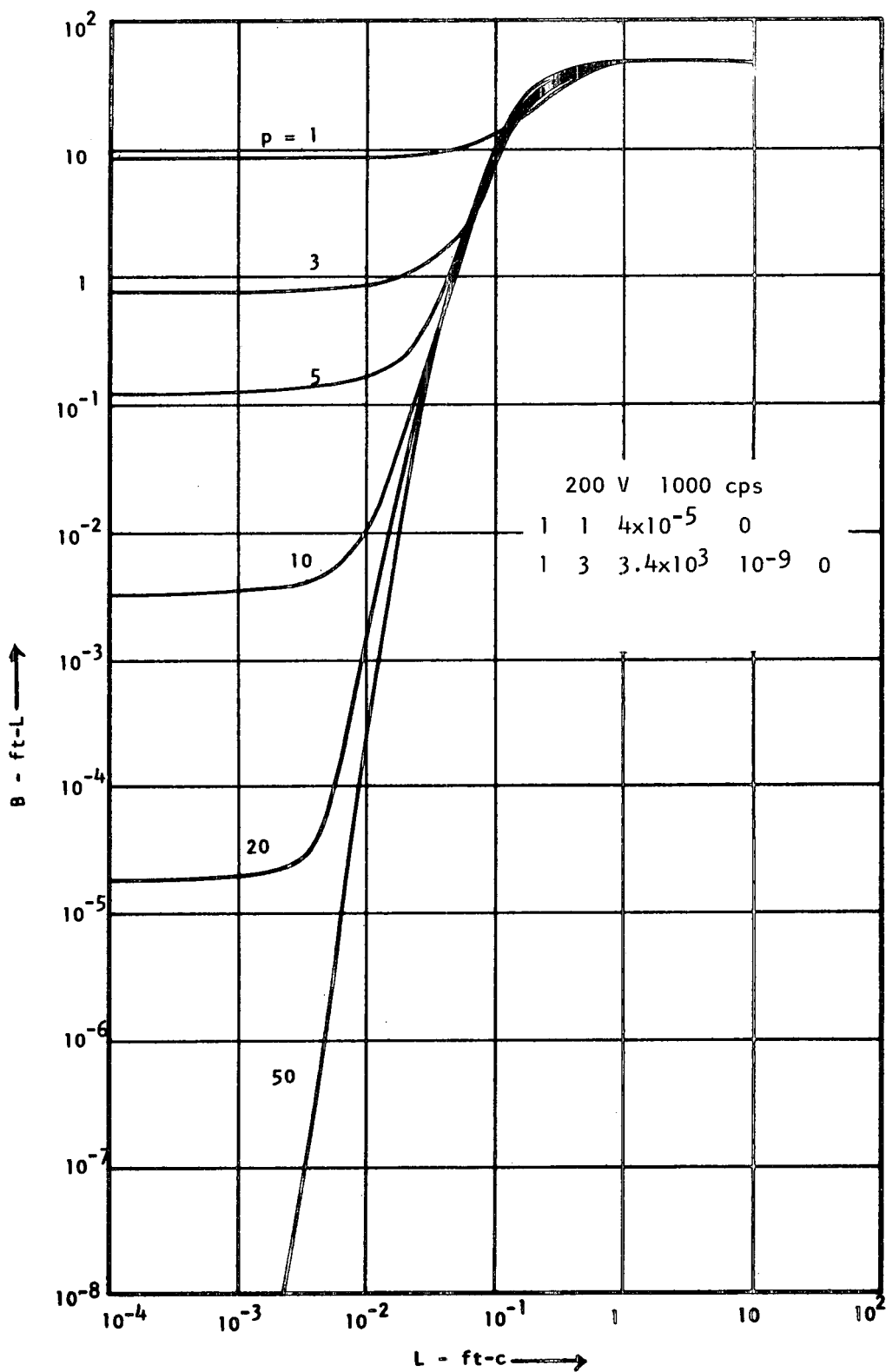


Figure 5. Calculated Transfer Characteristics of Light Intensifier

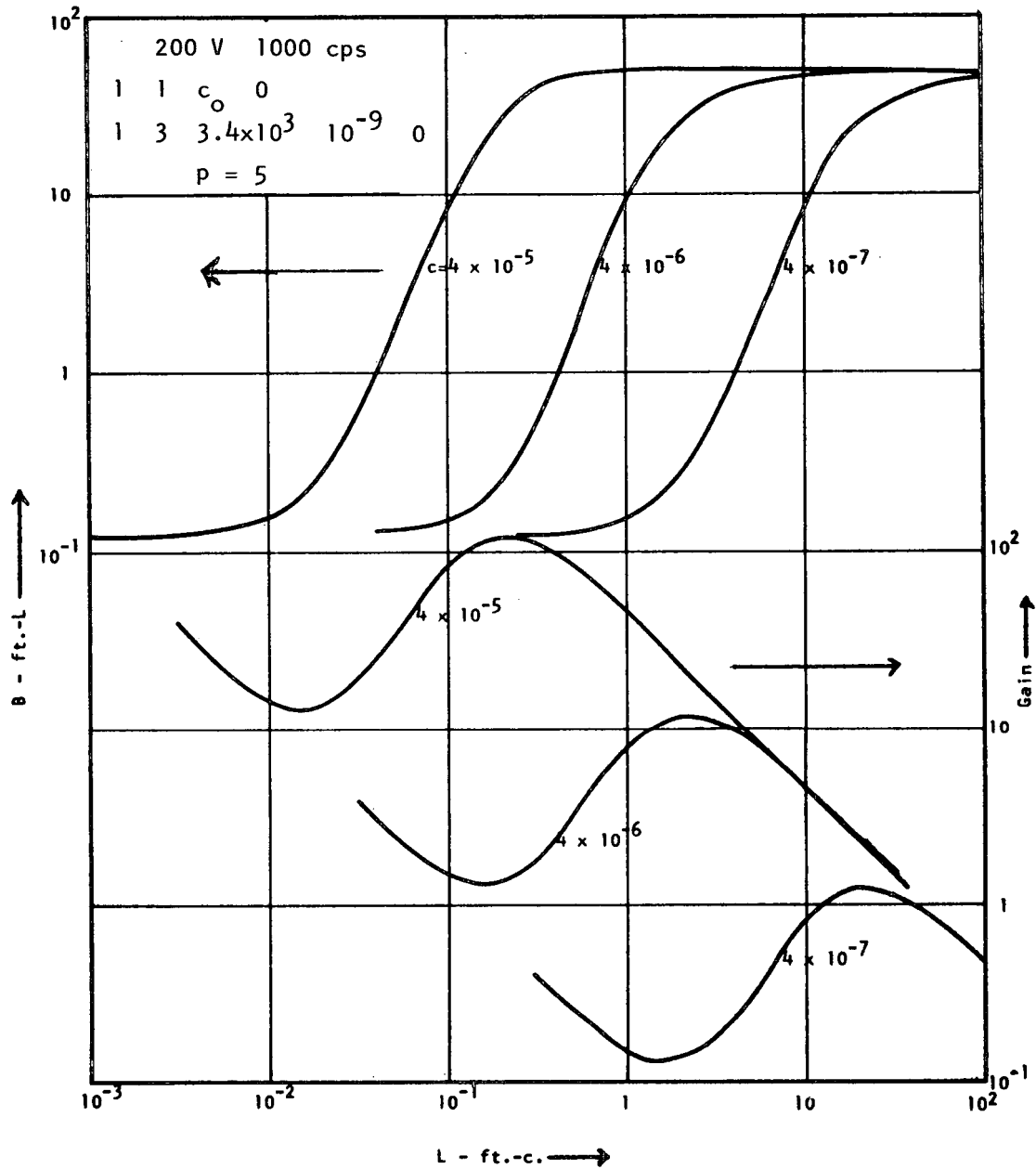


Figure 6. Calculated Transfer Characteristics and Gains of Light Intensifiers having PC Elements with 3 Different Sensitivities

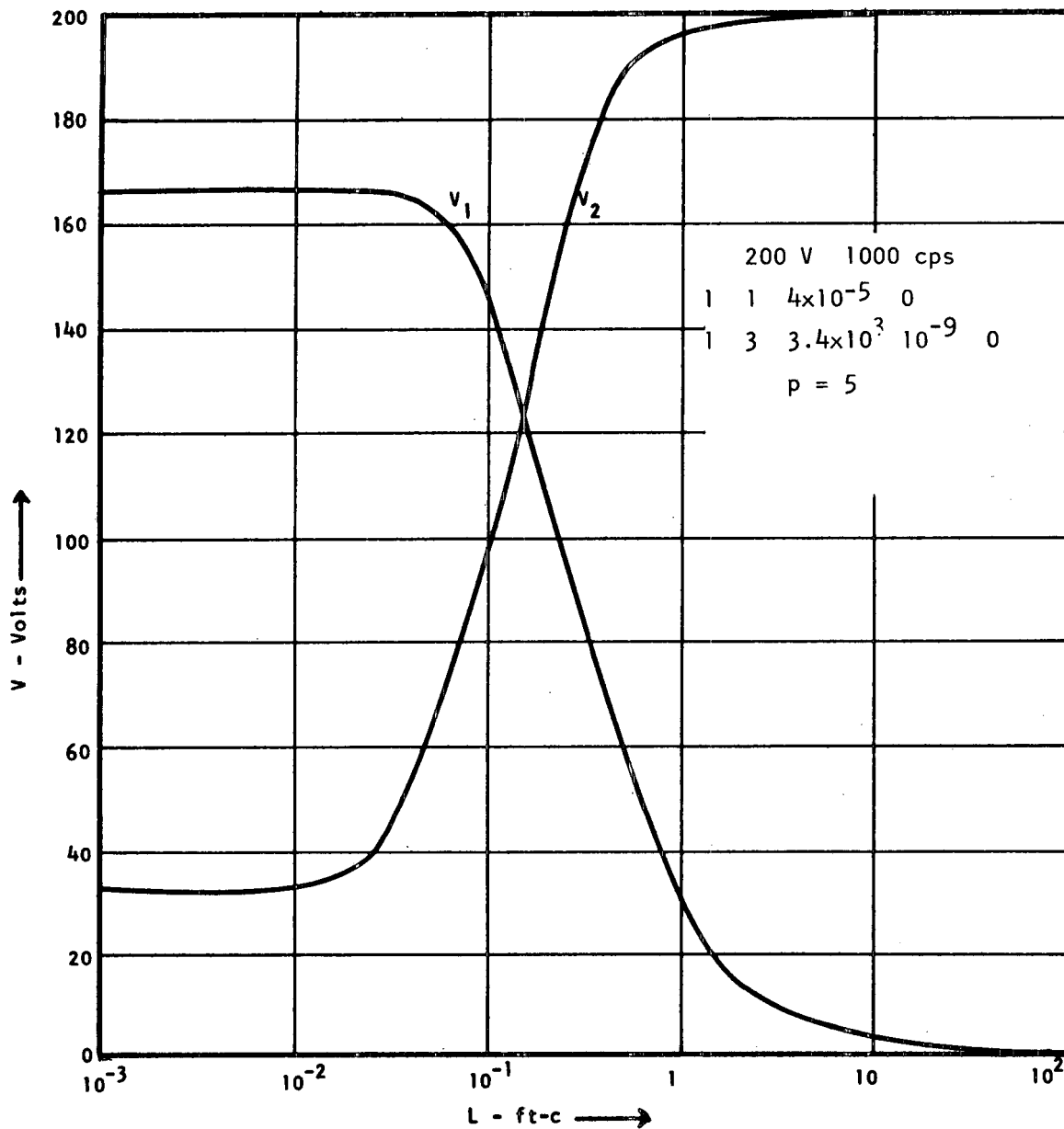


Figure 7. Voltage Dependence on PC and EL Elements of a Light Intensifier

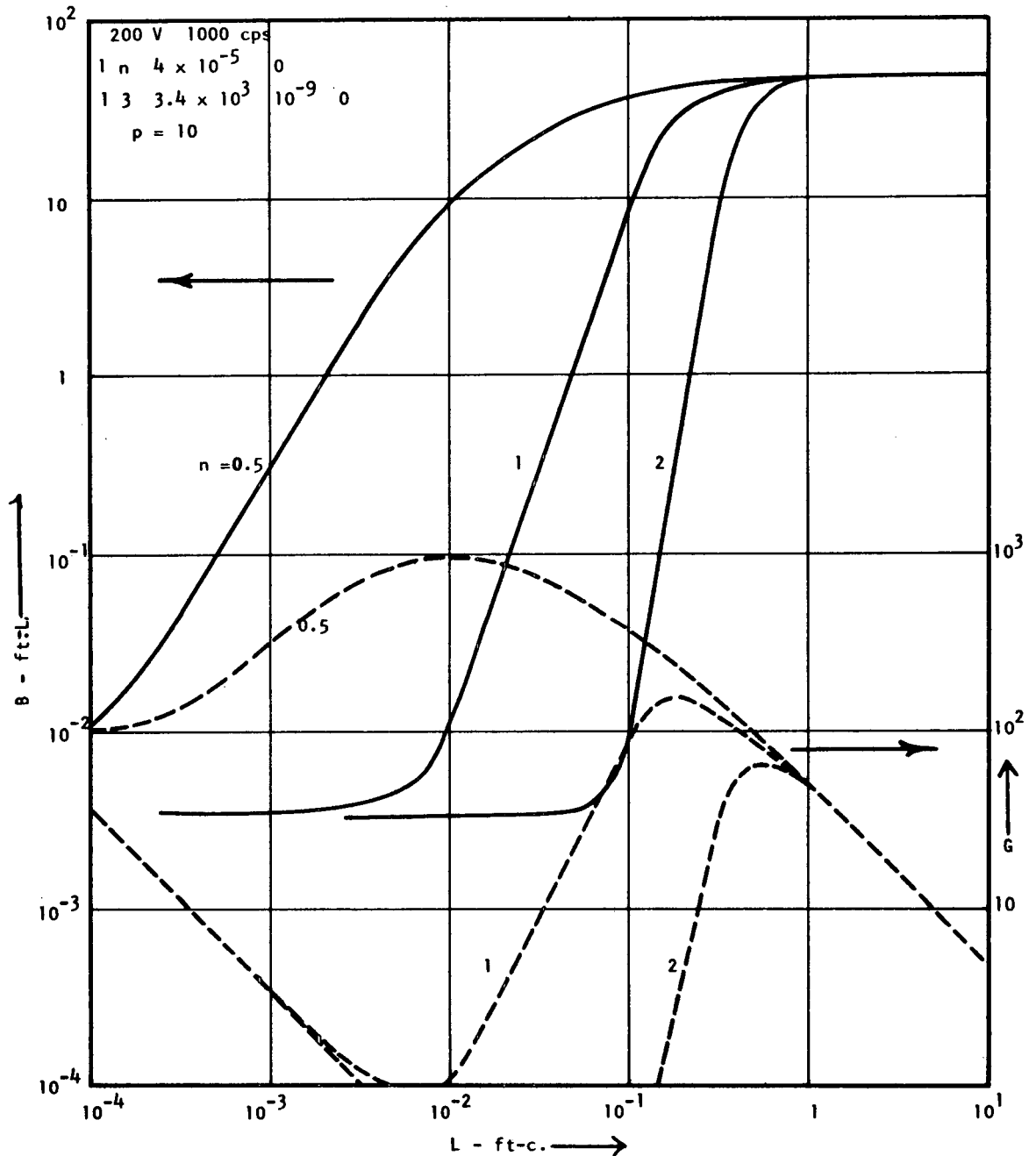


Figure 8. Transfer Characteristics and Gains of Light Intensifiers having PC Elements with Square Root, Linear and Square Current vs. Light Intensity Dependence.

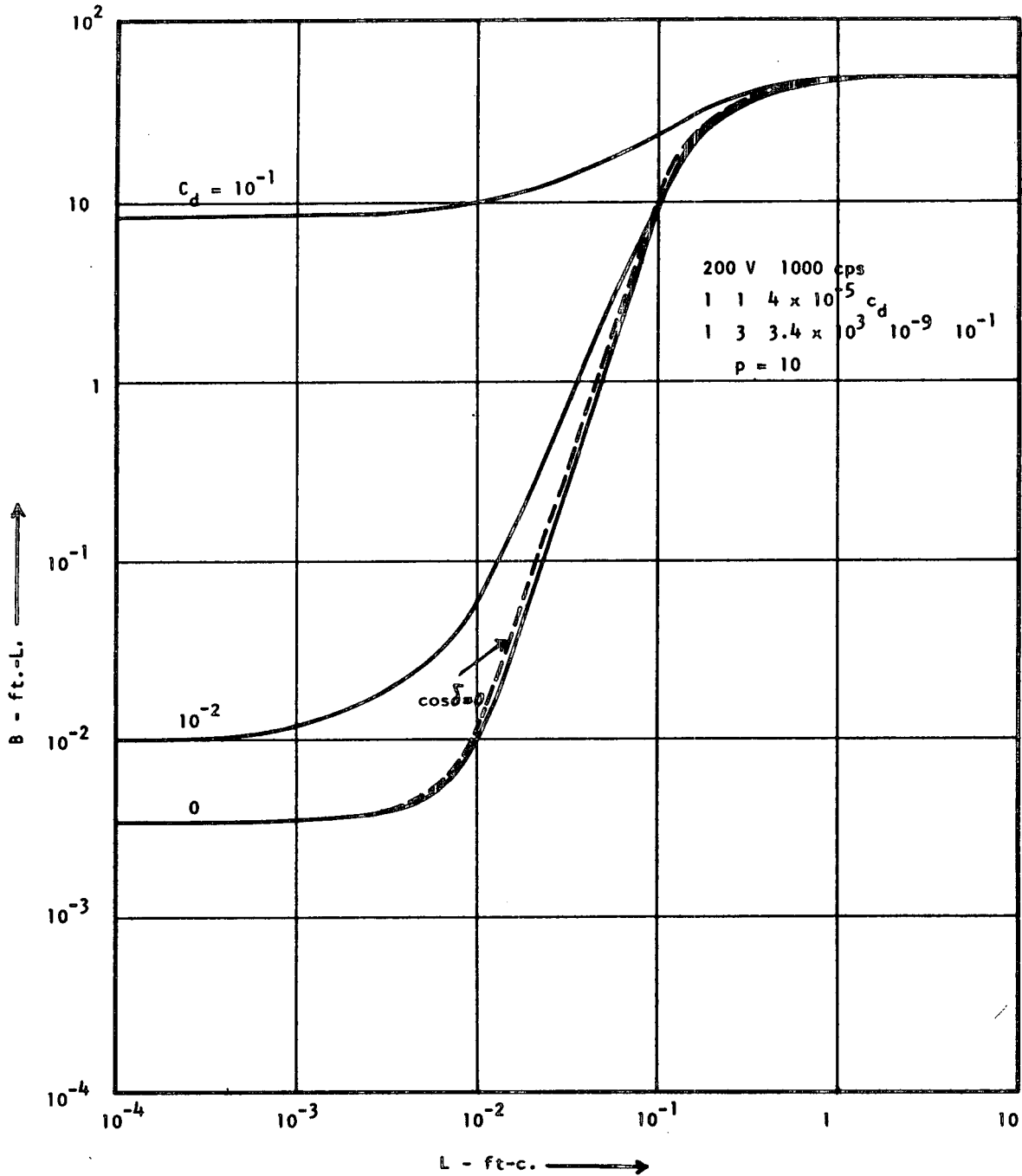


Figure 9. Effect of Dark Current of PC Element on Transfer Characteristics of Light Amplifiers.

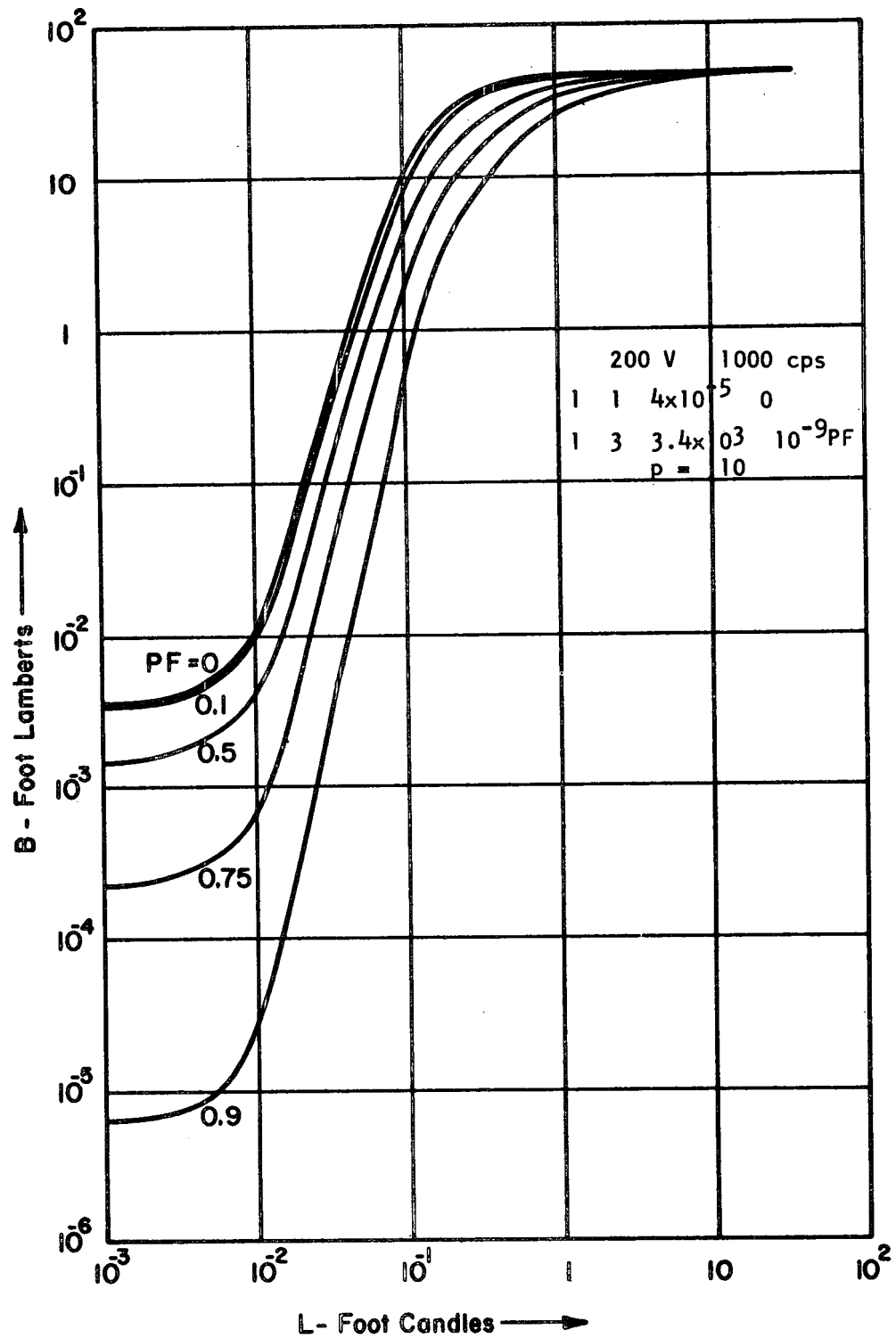


Figure 10. Effect of Power Factor of EL Element on Transfer Characteristics of Light Amplifier.

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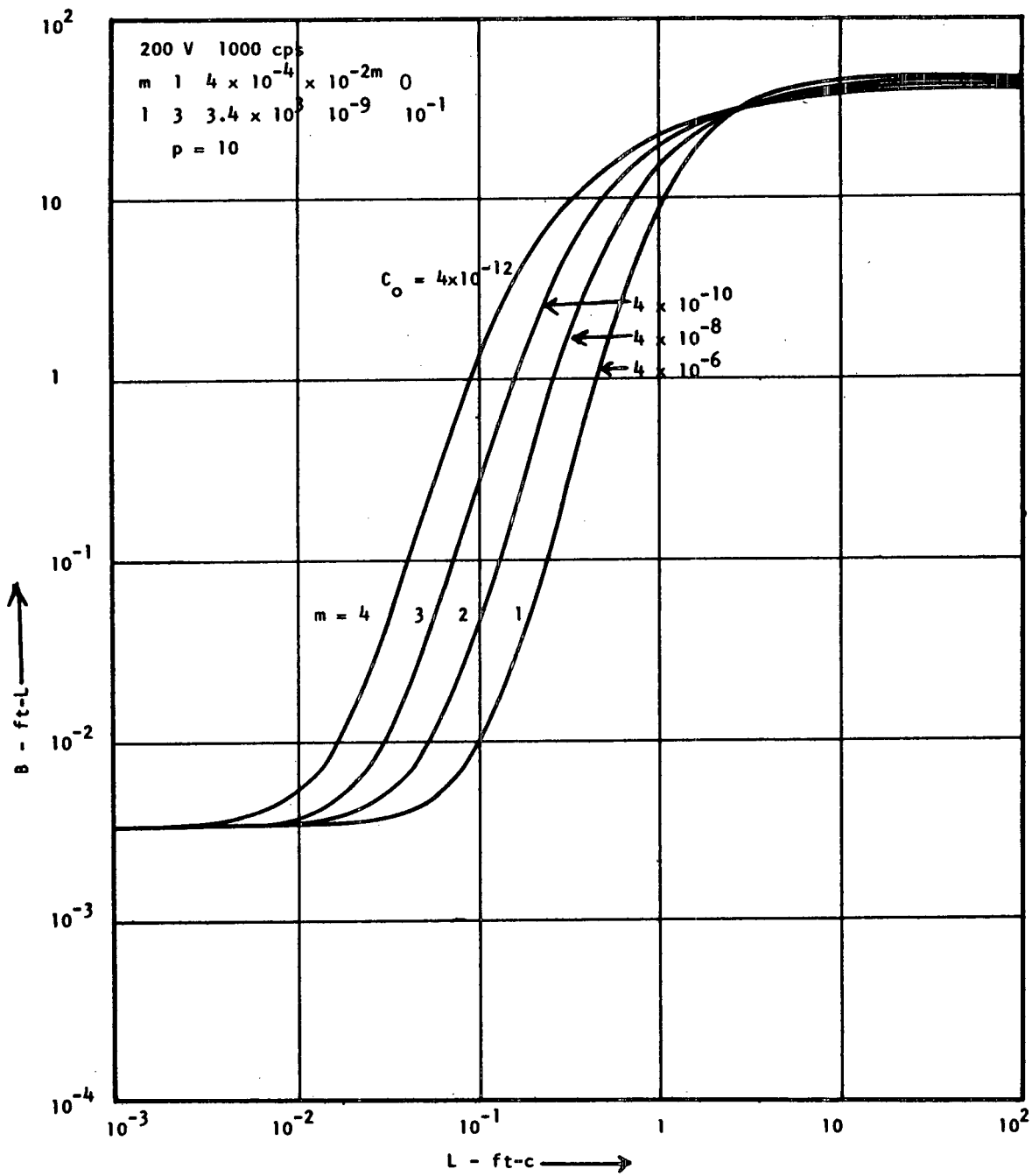
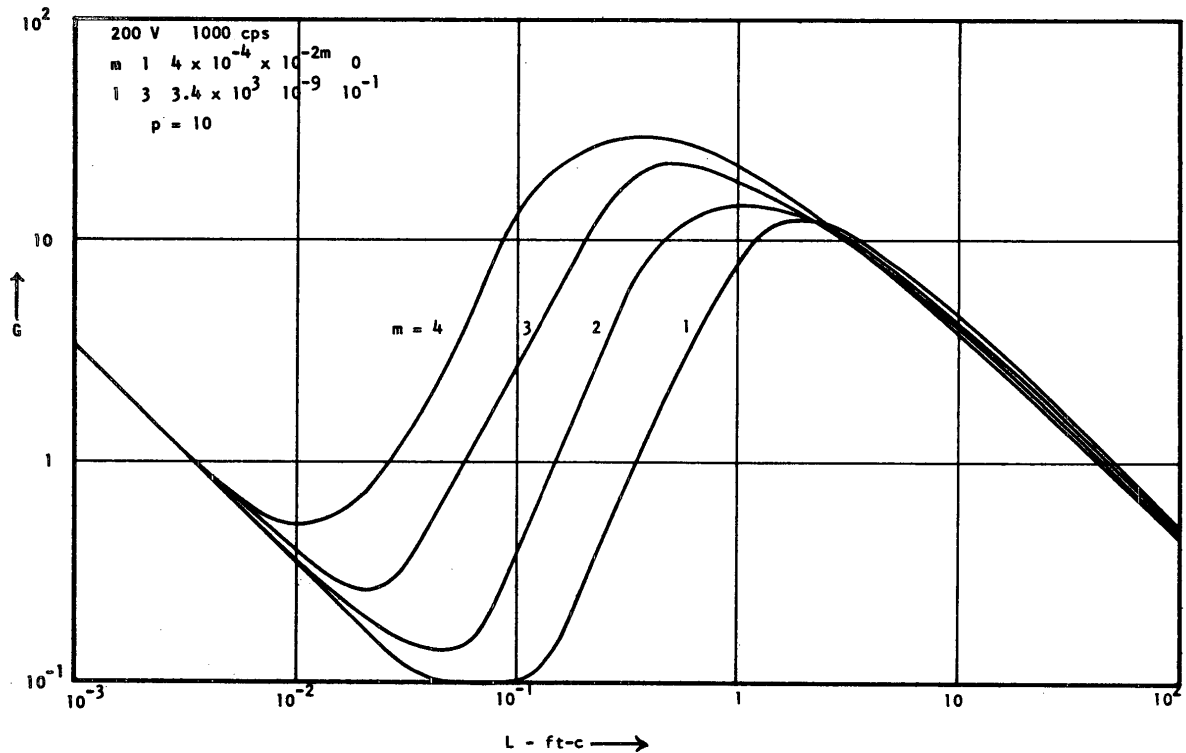


Figure 11. Transfer Characteristics of Light Amplifiers with non-ohmic PC Elements.

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Figure 12. Gains of Light Amplifiers with non-ohmic PC Elements

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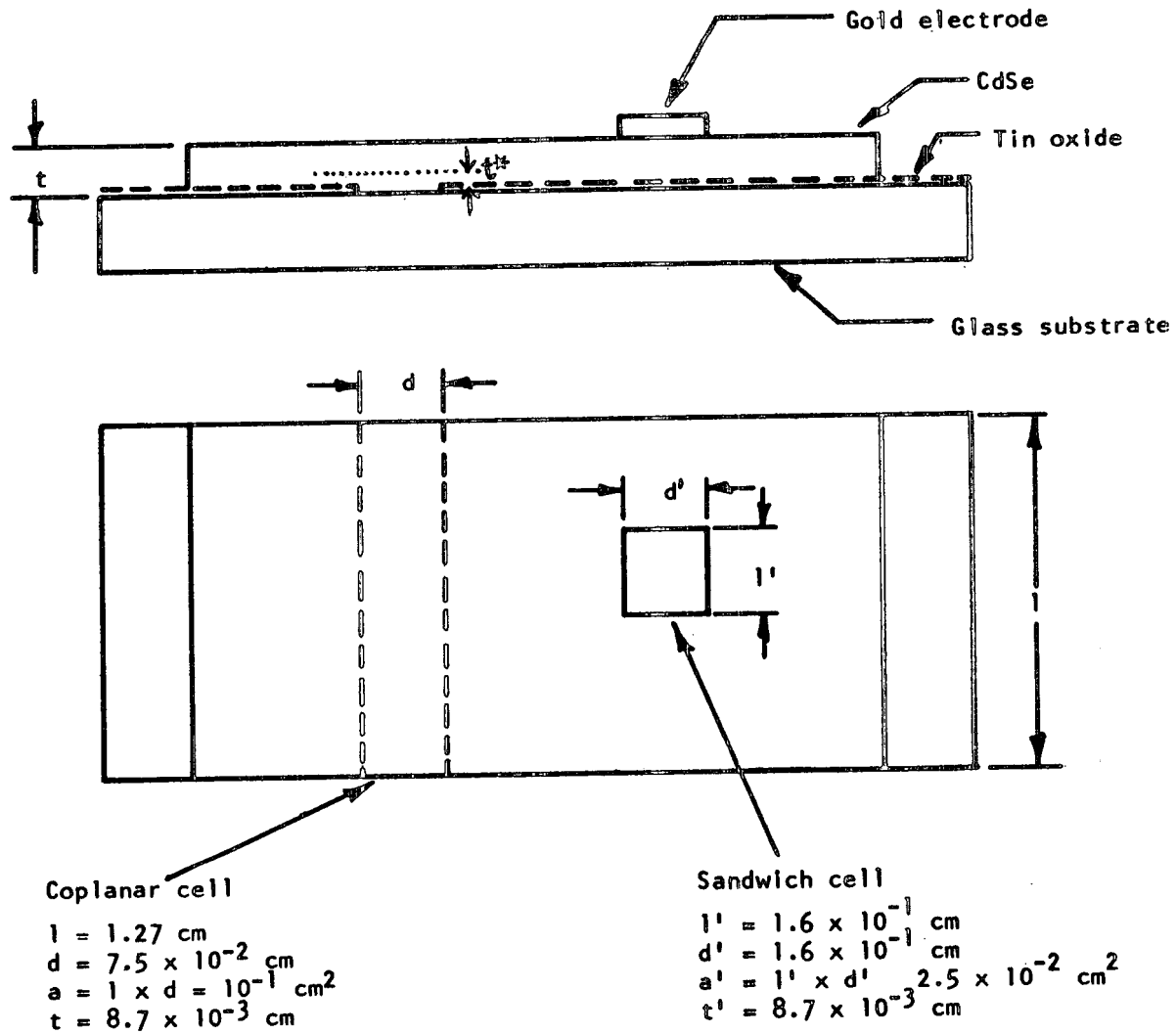


Figure 13. Structural Details and Dimensions of PC Cell B2-71XA-1-8.

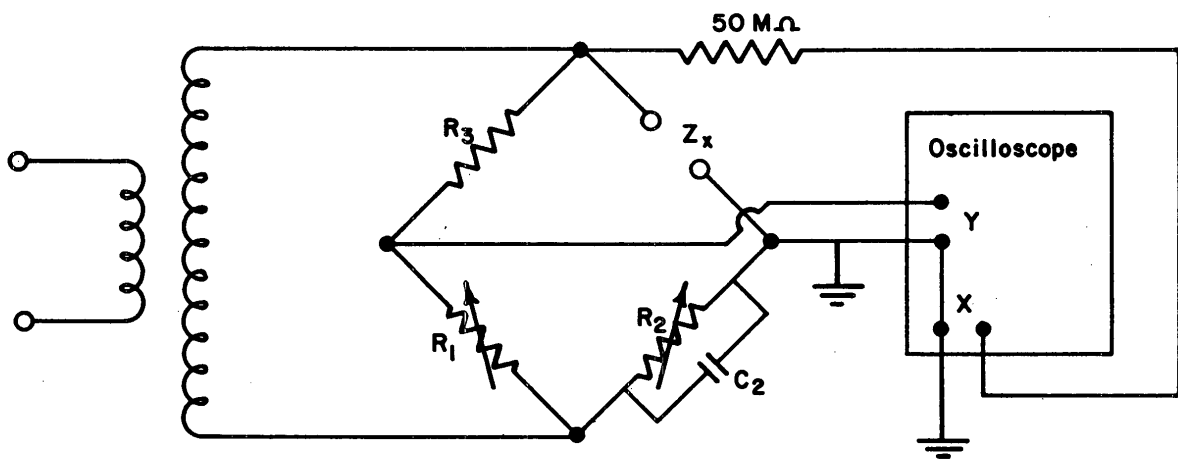
<u>Coplanar Cell</u>	<u>Sandwich Cell</u>
$R_L = \frac{V}{I}$ ohms	(1) $R_L = \frac{V}{I}$ ohms
$\sigma_L = \frac{I}{V} \frac{d}{lt^*}$ mhos/cm	(2) $\sigma_L = \frac{I}{V} \frac{t}{ld}$ mhos/cm
$\sigma_{\square} = \frac{I}{V} \frac{d}{l}$ mhos/square	(3)
$C = \frac{lt \epsilon}{4 \pi d} 10^{-12}$ F	(4) $C = \frac{a \epsilon}{4 \pi t} 10^{-12}$ F
$\tau_{rel} = R_L C$ sec	(5) $\tau_{rel} = R_L C$ sec
$G = \frac{I}{ef_1} = 10^{-13} \frac{I}{eLa}$	(6) $G = \frac{I}{ef_1} = 10^{-13} \frac{I}{eLa}$
$M = G \frac{\tau_{rel}}{\tau_d} = 10^{-25} \frac{Vt \epsilon}{4 \pi d^2 eL \tau_d}$	(7) $M = G \frac{\tau_{rel}}{\tau_d} = 10^{-25} \frac{V \epsilon}{4 \pi t eL \tau_d}$
$n_L = \frac{\sigma}{e\mu} = \frac{I}{V} \frac{d}{lt^* e\mu}$ electrons/cm ³ sec. (8)	$n_L = \frac{\sigma}{e\mu} = \frac{I}{V} \frac{t}{ae\mu}$ electrons/cm ³ sec.
$f_1 = 10^{13}$ La photons/sec. (9)	$f_1 = 10^{13}$ La photons/sec.
$F = 10^{13} \frac{L}{t^*}$ photons/cm ³ sec. (10)	$F = 10^{13} \frac{L}{t}$ photons/cm ³ sec.
$\tau = \frac{n_L}{F} = 10^{-13} \frac{ld}{Vle\mu L}$ sec. (11)	$\tau = \frac{n_L}{F} = \frac{lt^2}{Vae\mu L}$ sec.
$n_{tr} = \frac{e}{kT} n_L \frac{\tau_d}{\tau} = 10^{13} \frac{e}{kT}$	$n_{tr} = \frac{e}{kT} n_L \frac{\tau_d}{\tau} = 10^{13} \frac{e}{kT}$
$\frac{\tau_d L}{t^*}$ traps/cm ³ V (12)	$\frac{\tau_d L}{t}$ traps/cm ³ V
$E_{tr} = \frac{kT}{e} \ln \frac{Nc}{n_L}$ e Volts (13)	$E_{tr} = \frac{kT}{e} \ln \frac{Nc}{n_L}$ e Volts

Figure 14. Formulas for Calculating Fundamental Characteristics of PC Cells from Voltage, Current, Light Intensity and Time Constant Measurements.

$R_L = \frac{V}{I}$ ohms	(1')	$R_L = \frac{V}{I}$ ohms
$\sigma_L = 5.9 \times 10 \frac{1}{V}$ mhos/cm	(2')	$\sigma_L = 3.5 \times 10^{-1} \frac{1}{V}$ mhos
$\sigma_D = 5.9 \times 10^{-2} \frac{1}{V}$ mhos/square	(3')	_____
$C = 1.2 \times 10^{-13}$ F	(4')	$C = 2.3 \times 10^{-12}$ F
$\tau_{rel} = 1.2 \times 10^{-13} \frac{V}{I}$ sec.	(5')	$\tau_{rel} = 3.2 \times 10^{-12} \frac{V}{I}$ sec.
$G = 6.6 \times 10^6 \frac{1}{L}$	(6')	$G = 2.5 \times 10^7 \frac{1}{L}$
$M = 8 \times 10^{-7} \frac{V}{L \tau_d}$	(7')	$M = 5.7 \times 10^{-5} \frac{V}{L \tau_d}$
$n_L = 3.7 \times 10^{20} \frac{1}{V \mu}$ electrons/cm ³ sec.	(8')	$n_L = 2.18 \times 10^{18} \frac{1}{V \mu}$ electrons/cm ³ sec.
$f_1 = 10^{12}$ L photons/sec.	(9')	$f_1 = 2.5 \times 10^{11}$ L photons/sec.
$F = 10^{16}$ L photons/cm ³ sec.	(10')	$F = 1.15 \times 10^{15}$ L photons/cm ³ sec.
$\tau = 3.7 \times 10^4 \frac{1}{V L \mu}$ sec.	(11')	$\tau = 1.9 \times 10^3 \frac{1}{V L \mu}$ sec.
$n_{tr} = 3.89 \times 10 n_L \frac{\tau_d}{\tau} =$		$n_{tr} = 3.89 \times 10 n_L \frac{\tau_d}{\tau} =$
3.89×10^{17} L τ_d traps/cm ³ V	(12')	4.5×10^{16} L τ_d traps/cm ³ V
$E_{tr} = 5.8 \times 10^{-2} \log \frac{10^{19}}{n_L}$ e Volts	(13')	$E_{tr} = 5.8 \times 10^{-2} \log \frac{10^{19}}{n_L}$ e Volts

Figure 15. Same Formulas as in Figure 14 with Numerical Values of PC Cell of Figure 13 Substituted.

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$R_1 = 0 - 10^3$ ohms

$R_2 = 0 - 10^4$ ohms

$R_3 = 10^6$ ohms

$C_2 = 1\mu F$

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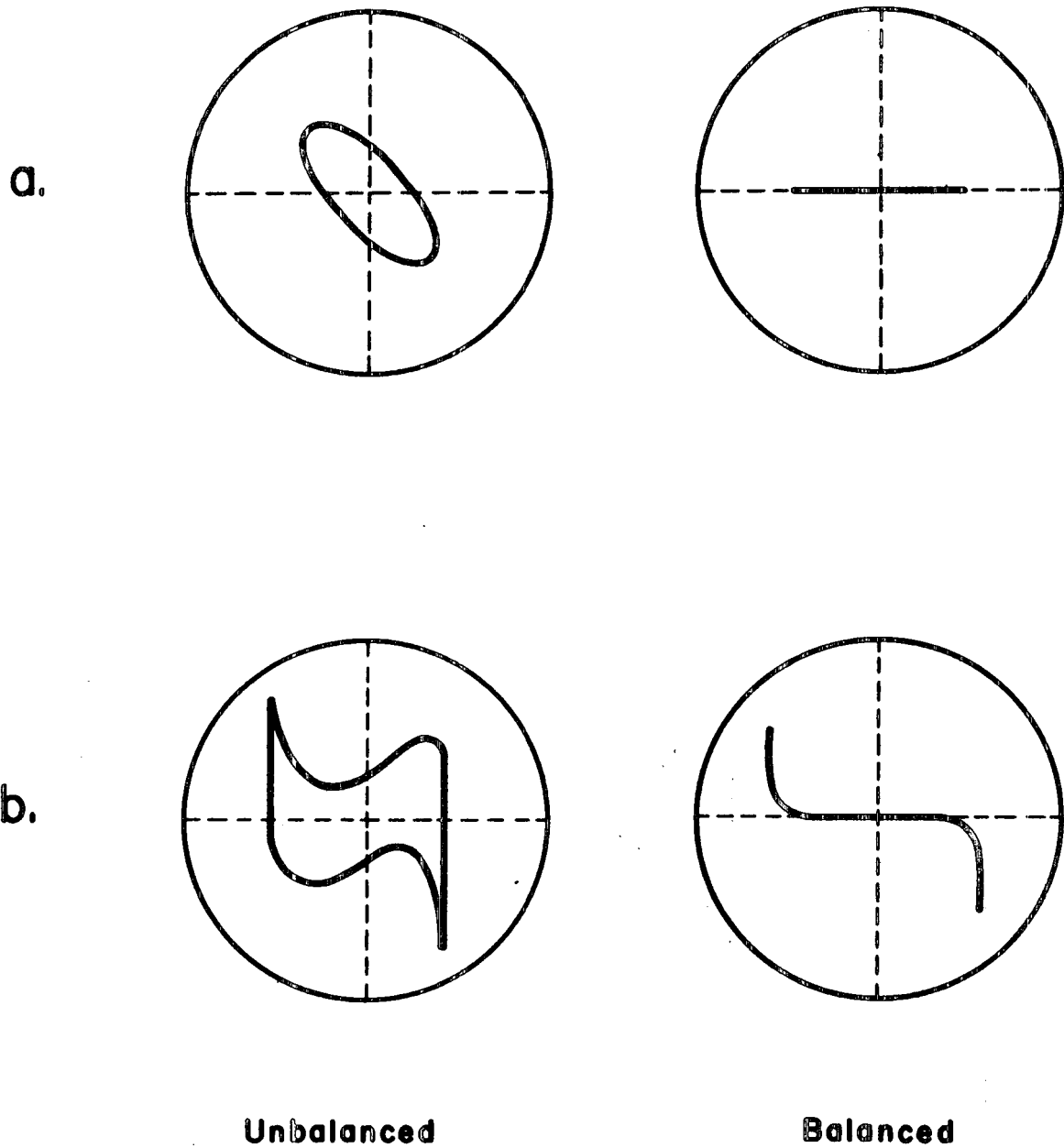
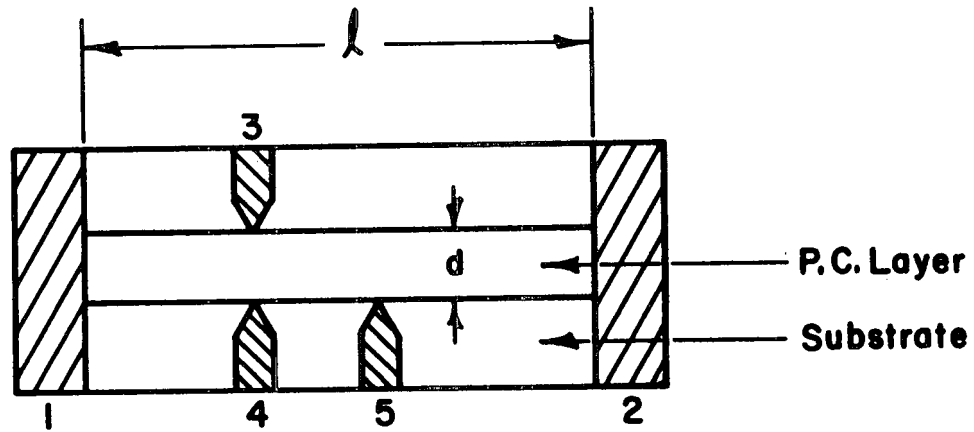


Figure 17. Scope Patterns in Bridge Measurements



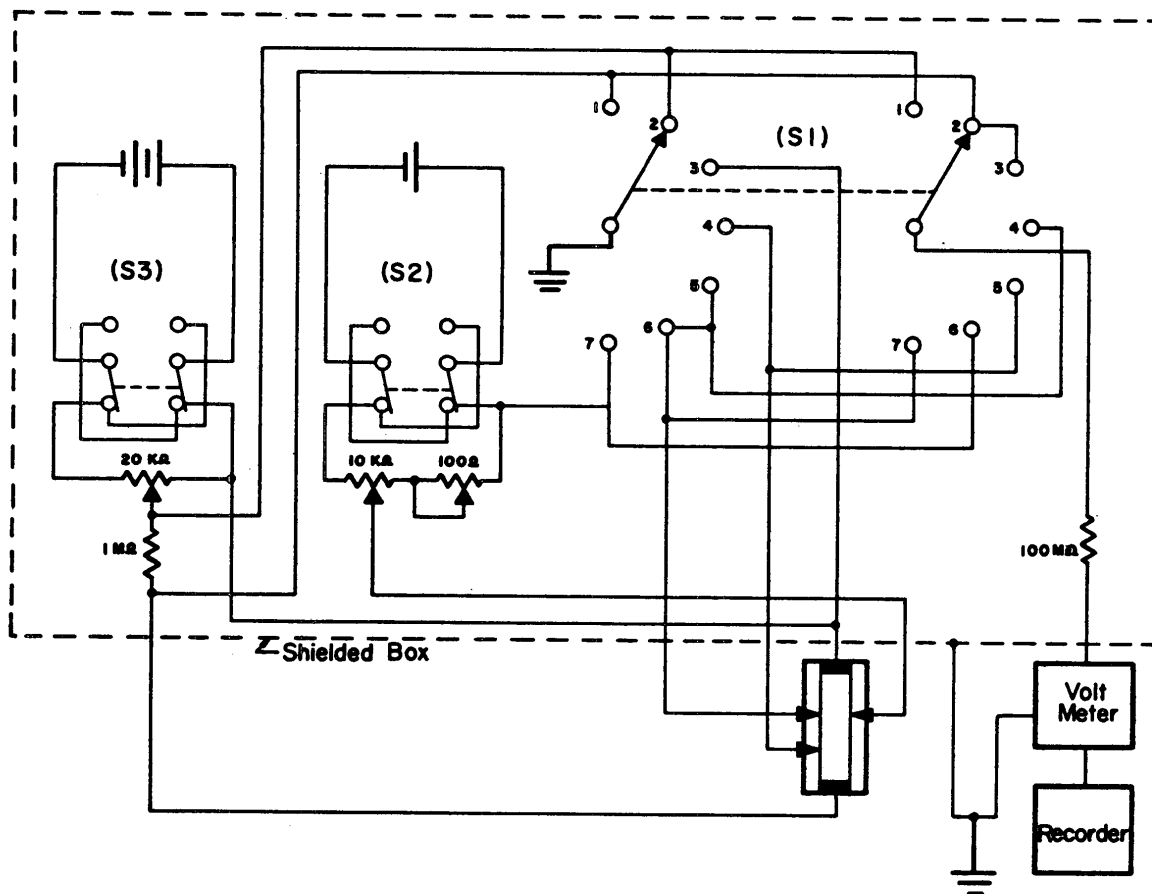
1-2 - Electrodes for Primary Current

3-4 - Electrodes for Hall Effect Measurement

4-5 - Electrodes for Conductivity Measurement

**Magnetic Field Perpendicular to the Plane
of the Layer.**

Figure 18. Electrode Structure of a Hall-Sample



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Figure 19. CIRCUIT FOR HALL EFFECT MEASUREMENTS

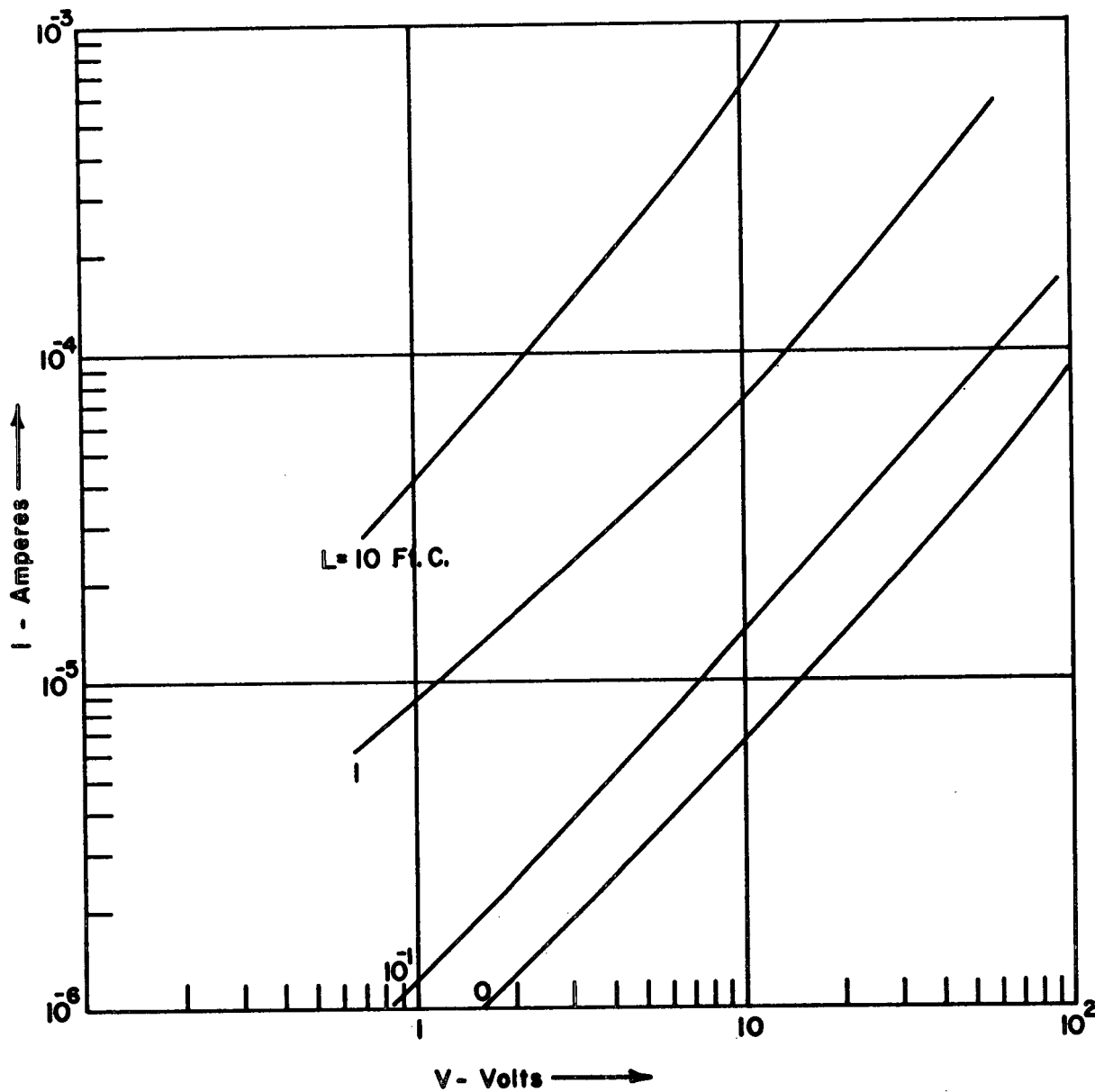


Figure 20. Current-Voltage Curves of a Sintered CdSe Cell (No. B2-71XA-1-8) with Coplanar Electrodes.

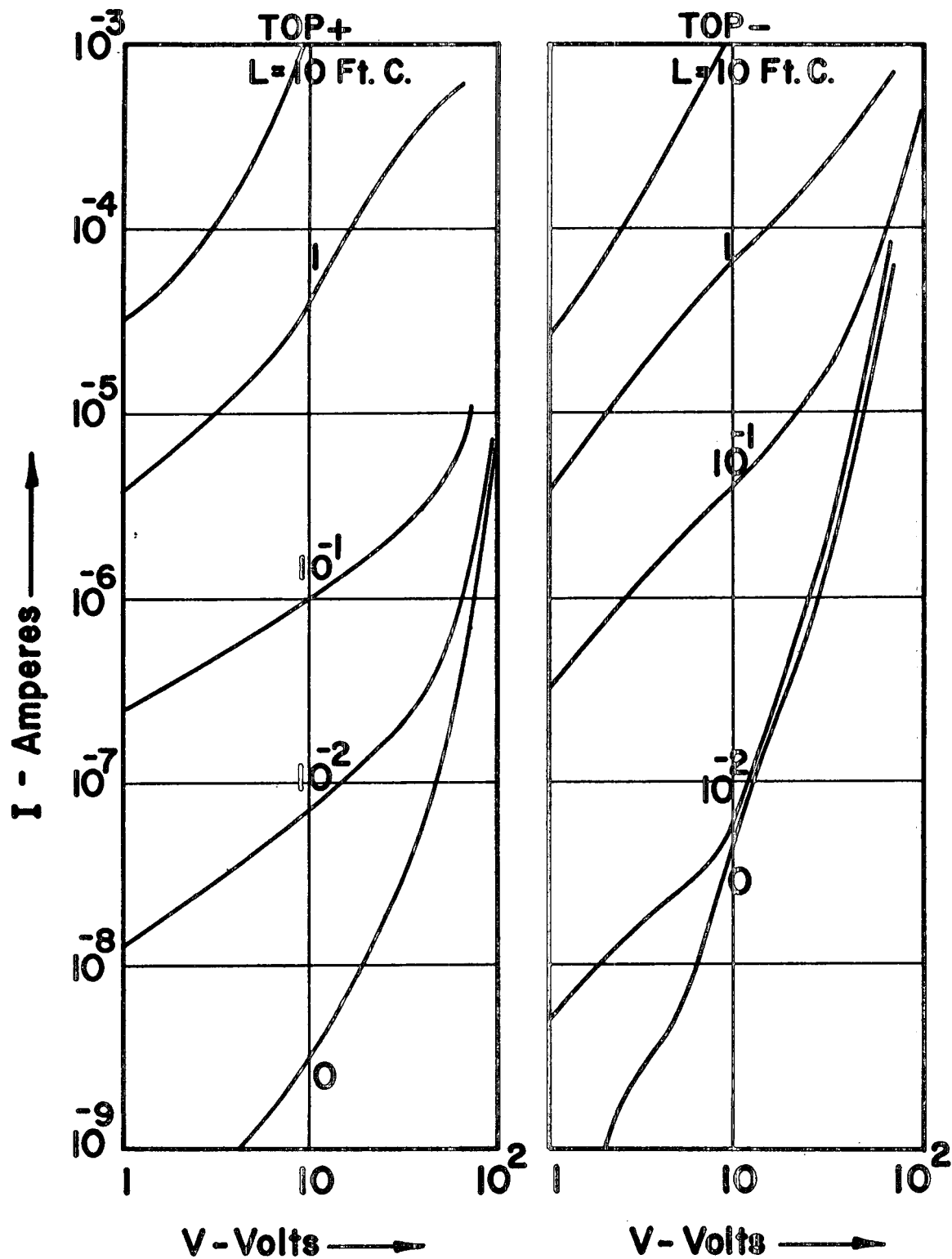


Figure 21. Current-Voltage Curves of Sintered CdSe Cell (No. B2-71XA-1-8) in Sandwich Construction.

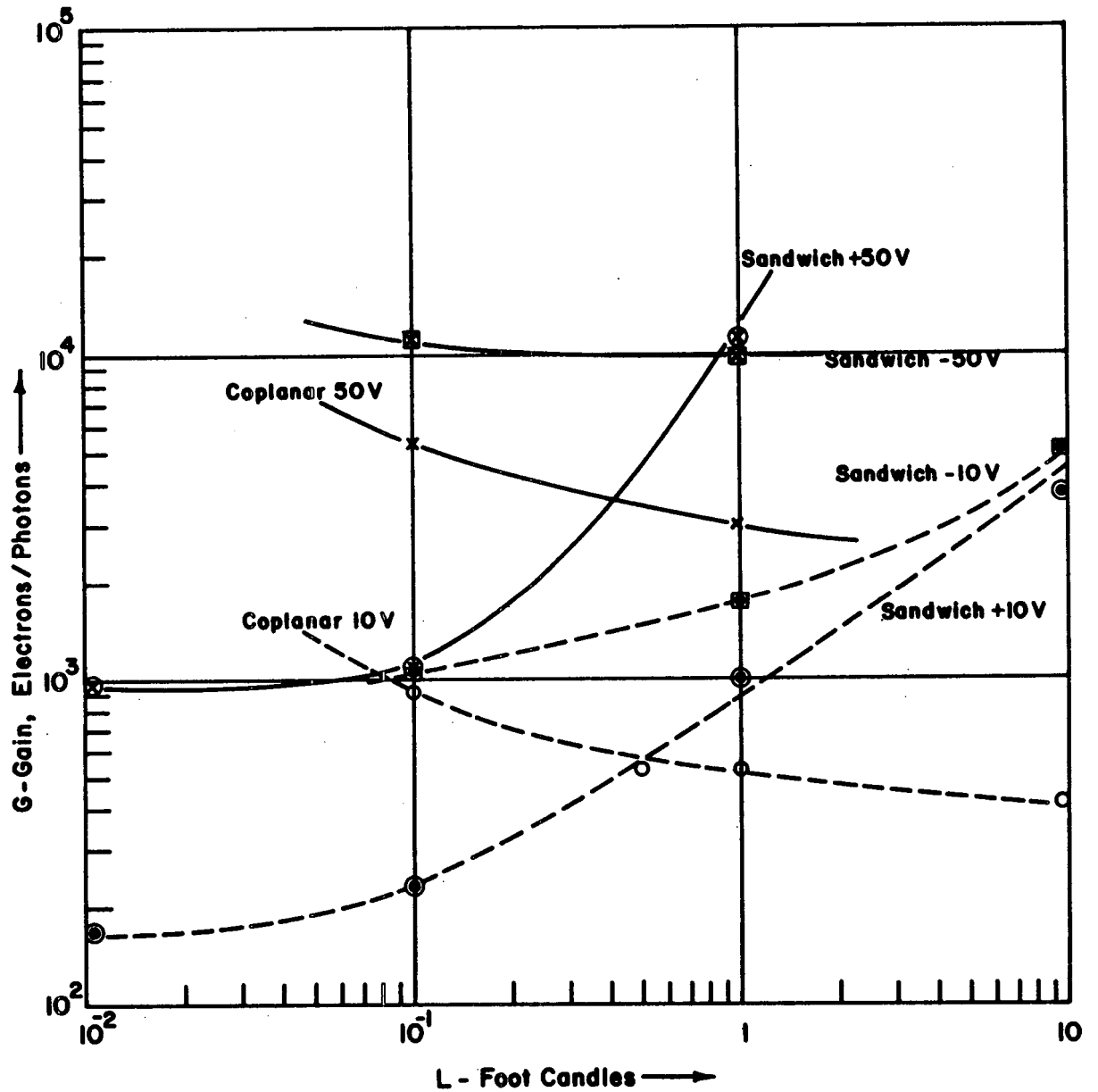


Figure 22. Gain vs. Light Intensity of a Sintered CdSe Cell (No. B2-71XA-1-8)

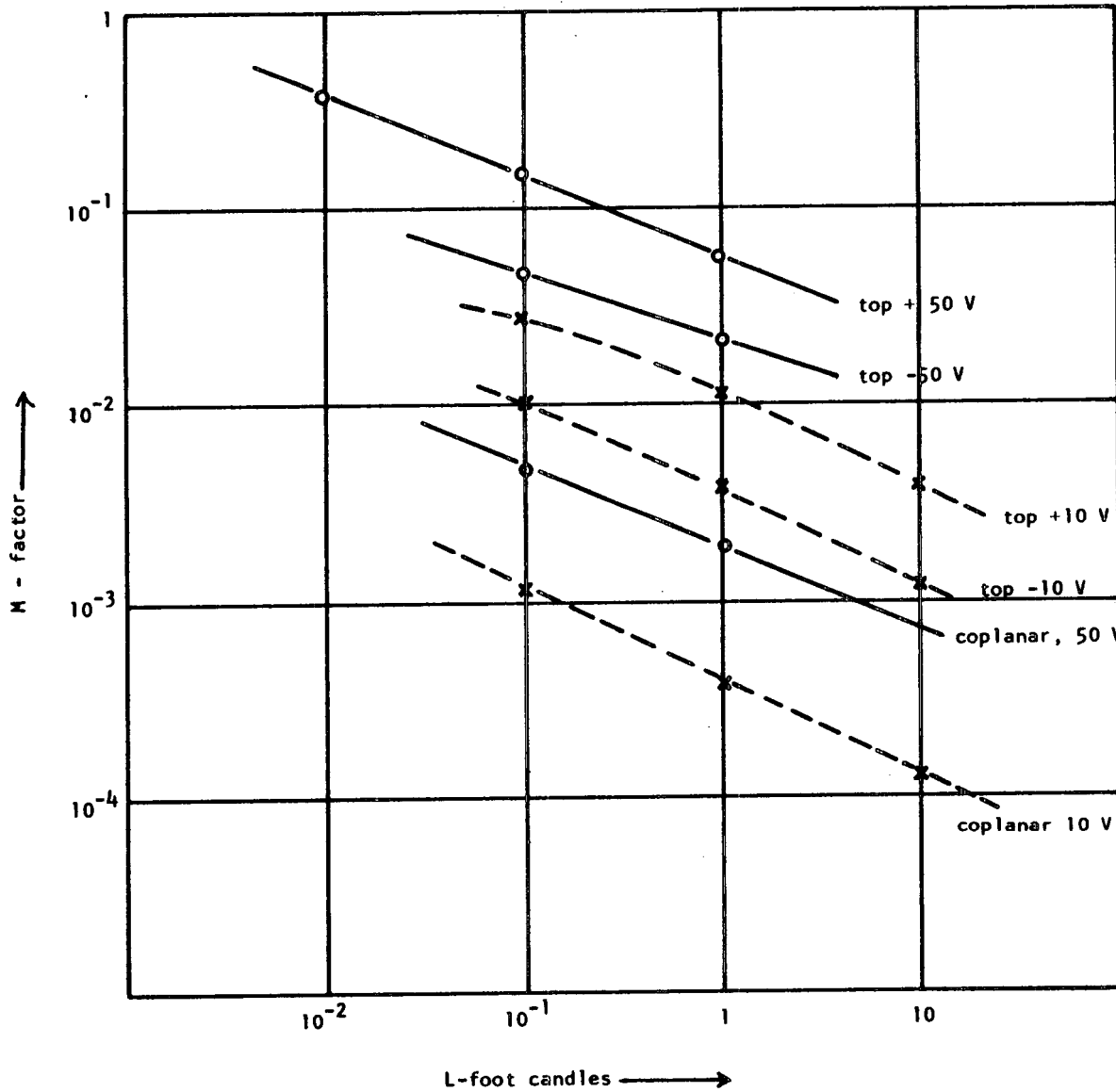


Figure 23. M-Factors of a Sintered CdSe Cell (No. B2-71XA-1-8)

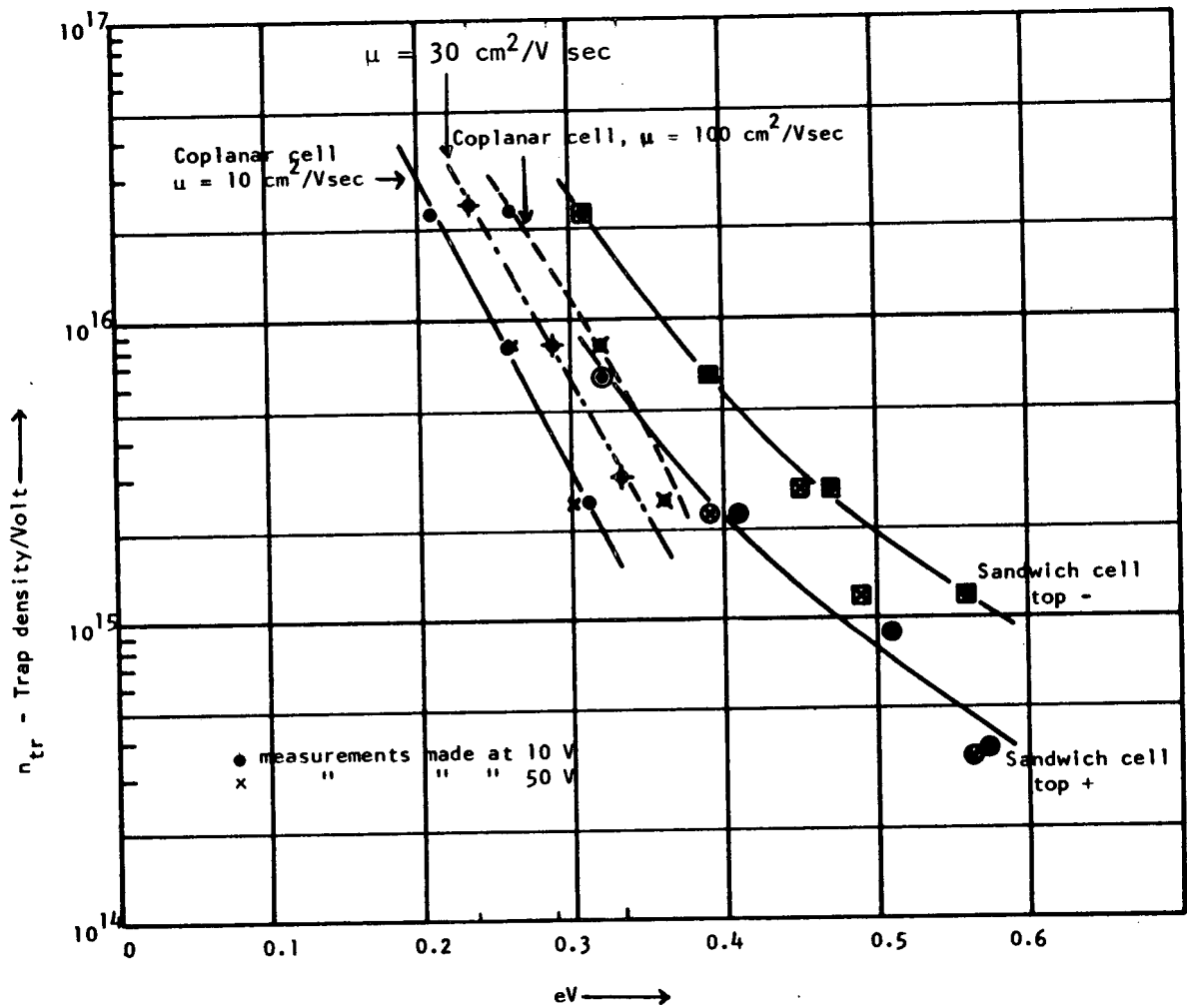


Figure 24. Trap Distribution in a Sintered CdSe Cell (No. B2-71XA-1-8)

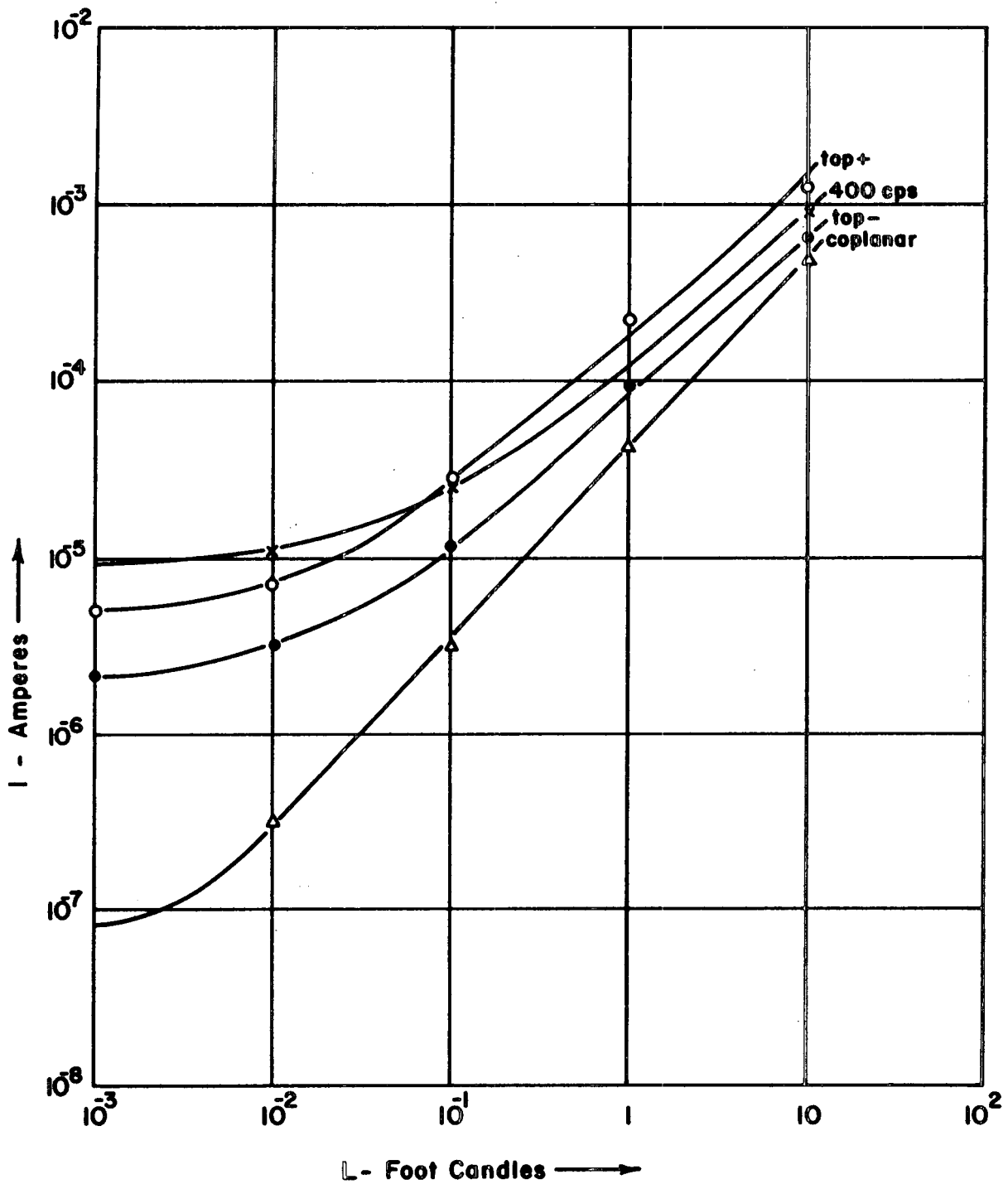


Figure 25. Characteristics of an Acetic Acid Washed Sintered CdSe Cell

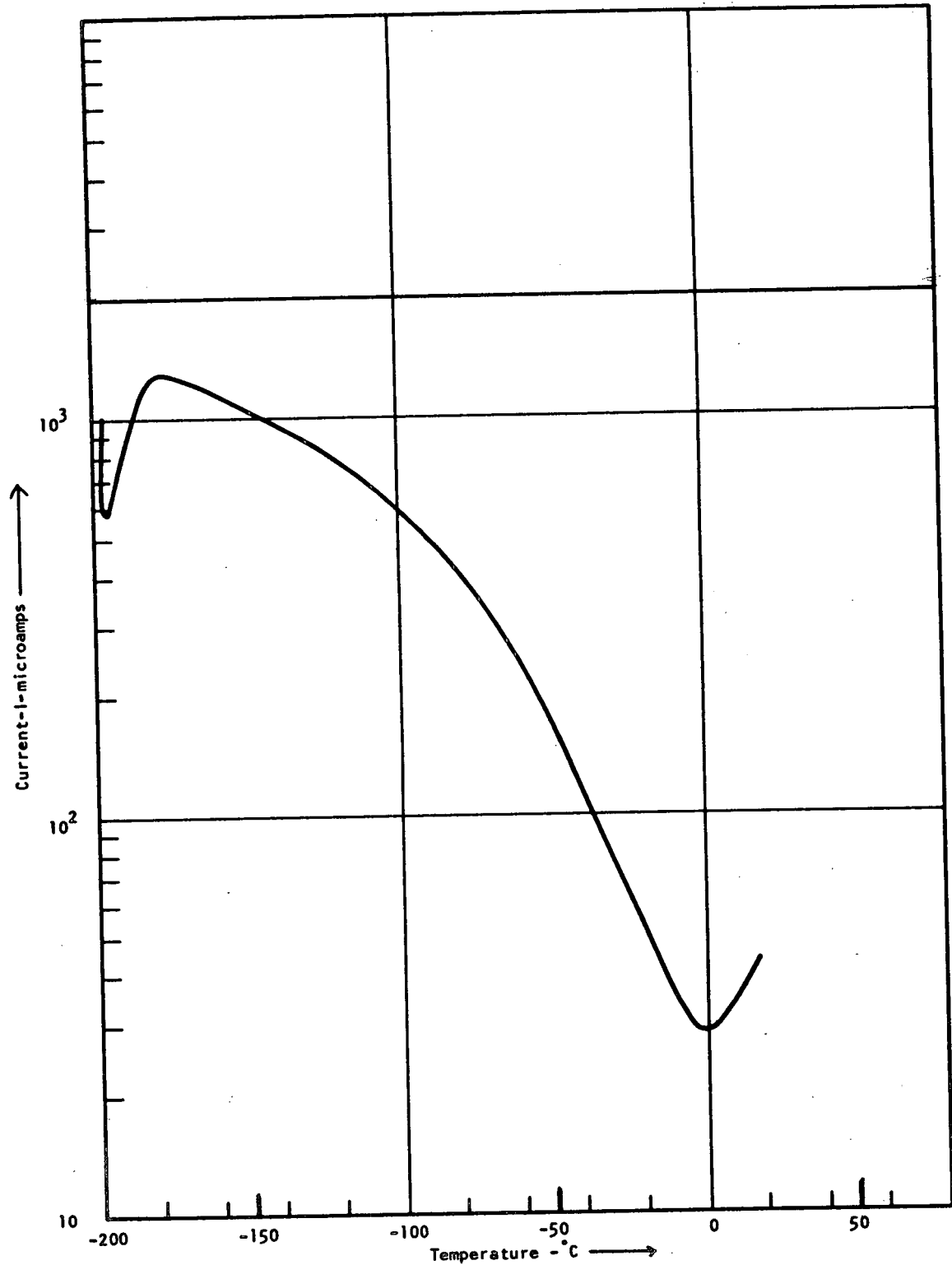


Figure 26. Thermally Stimulated Current of a Sintered CdSe Coplanar Cell. Rate of Temperature Change: 27.6°C/min.

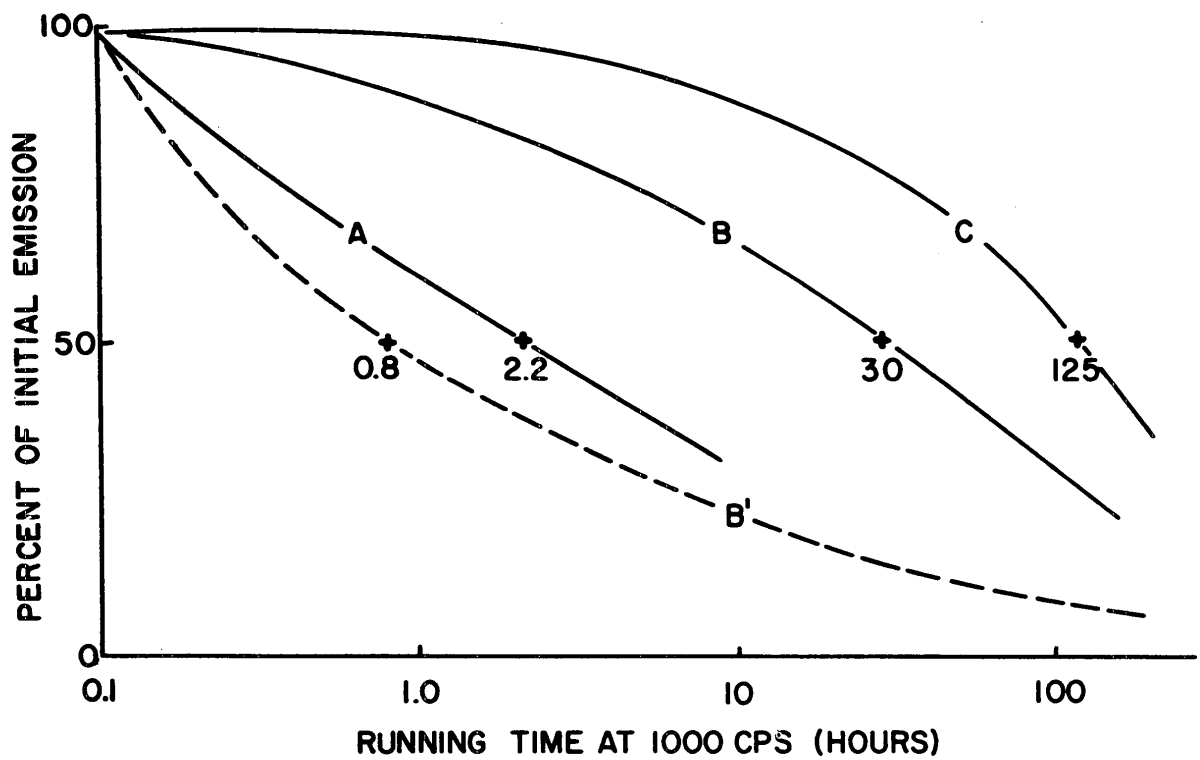
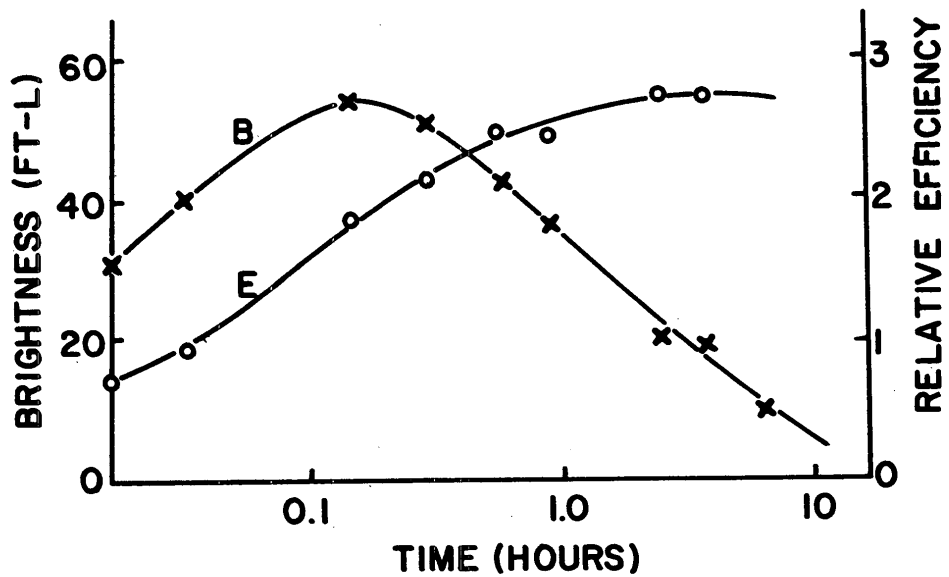


Figure 27. Life Test Measurements on EL Films at AC Voltage

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Figure 28. Life Test Measurements on EL Films at DC Voltage

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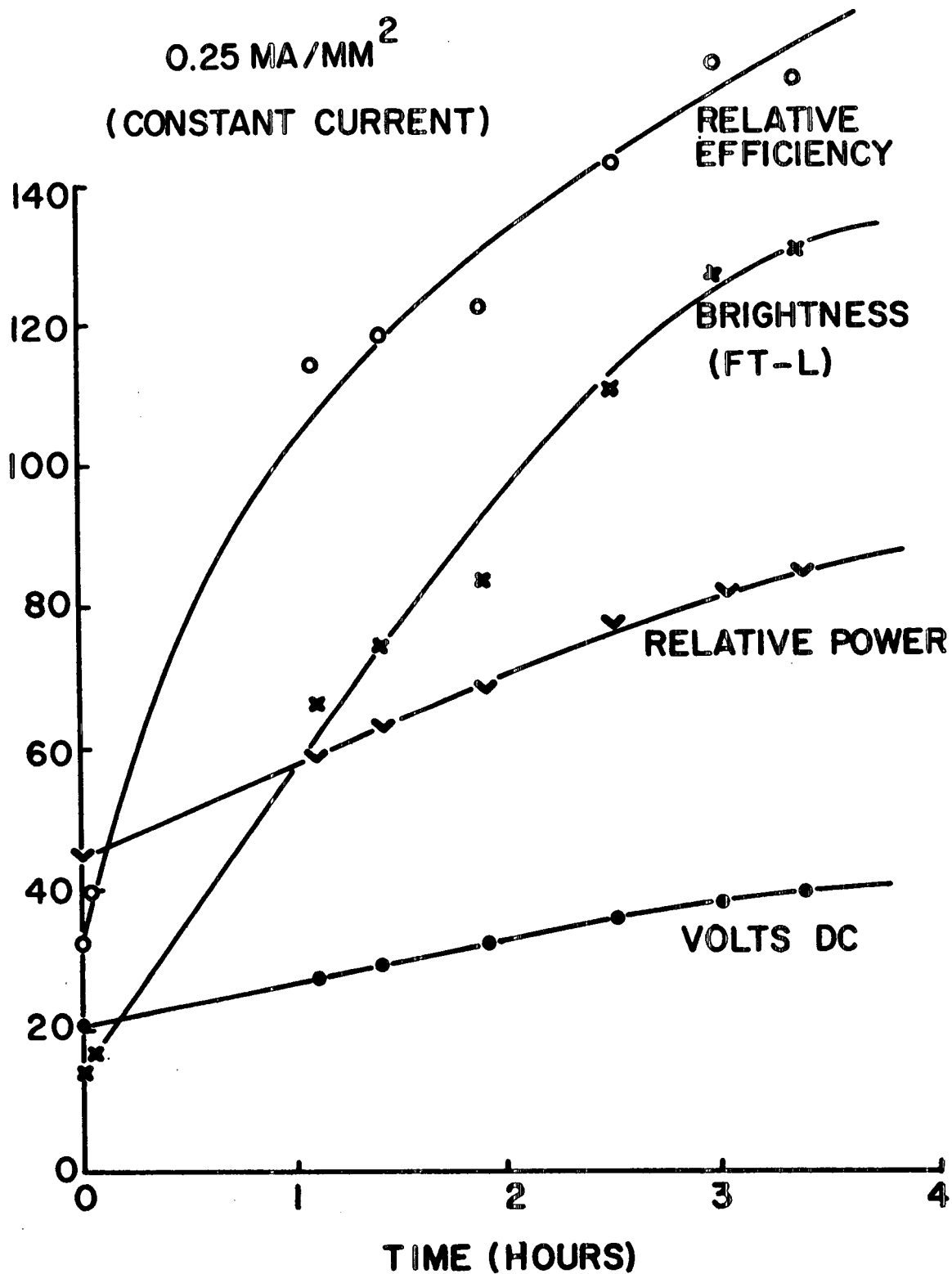


Figure 29. Life Test Measurements on EL Films at DC Voltage with Constant Current.

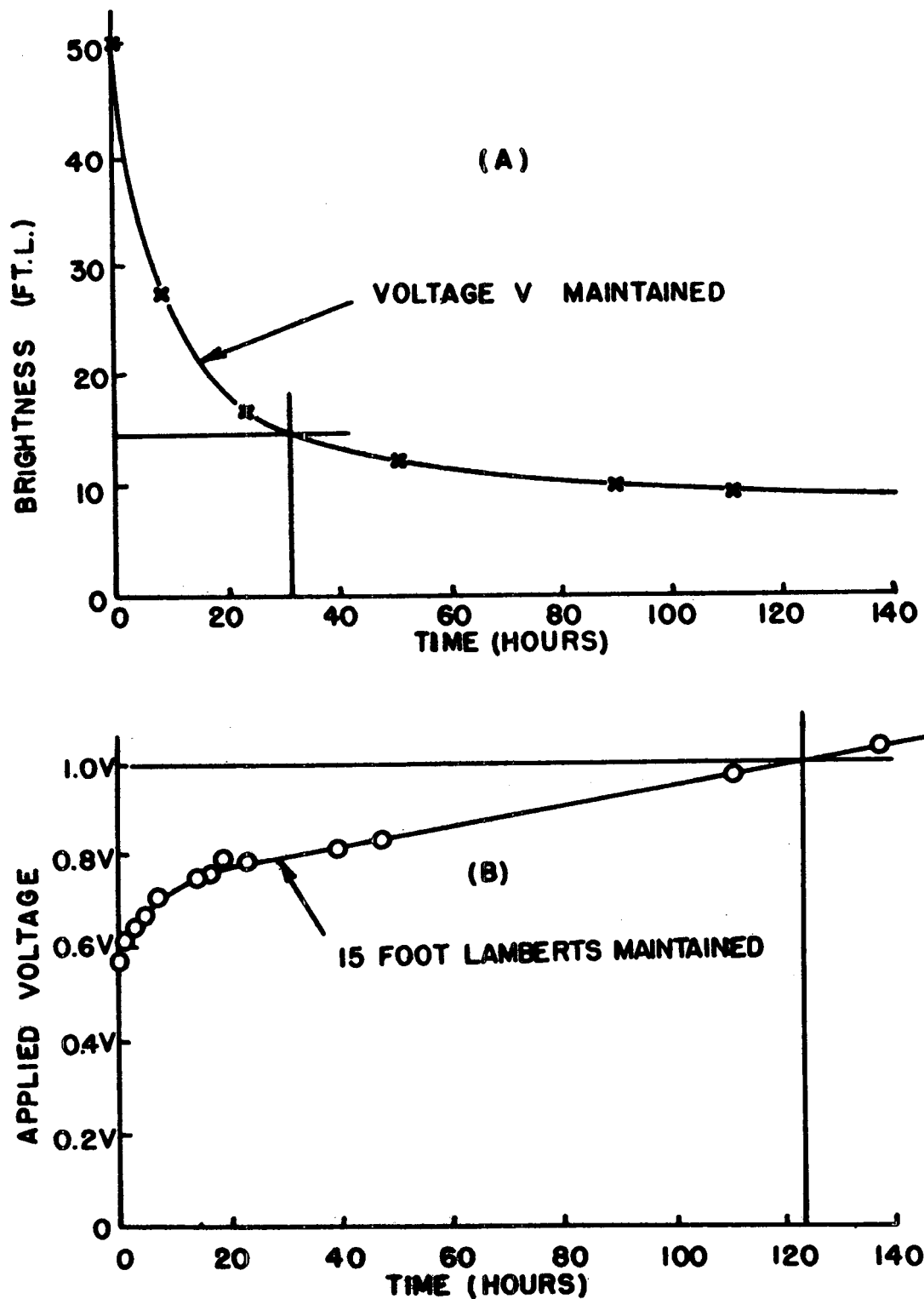


Figure 30. Life Test Measurements on EL Films with Constant Brightness

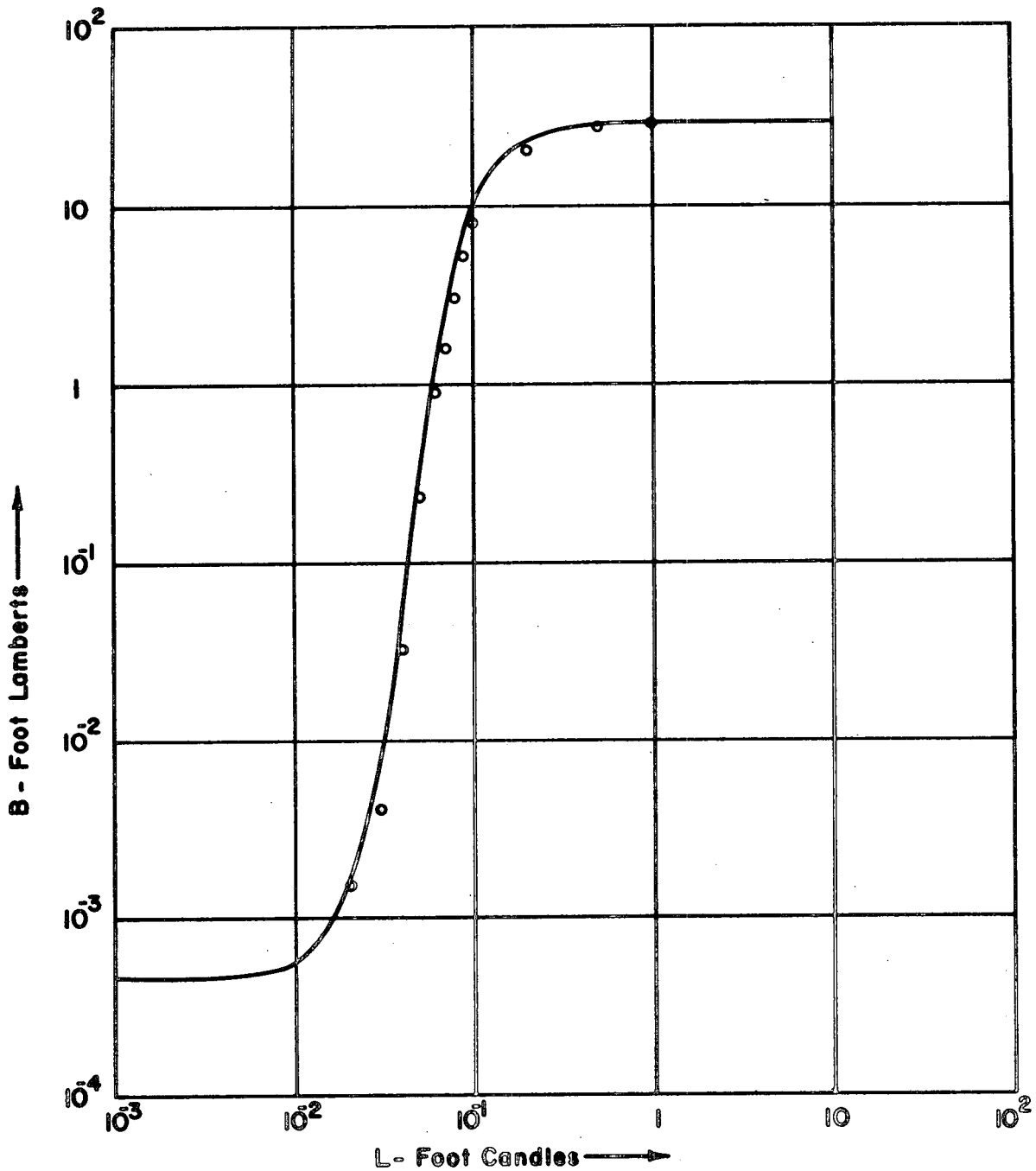


Figure 31. Calculated and Experimental Transfer Characteristic of a Light Amplifier Element.

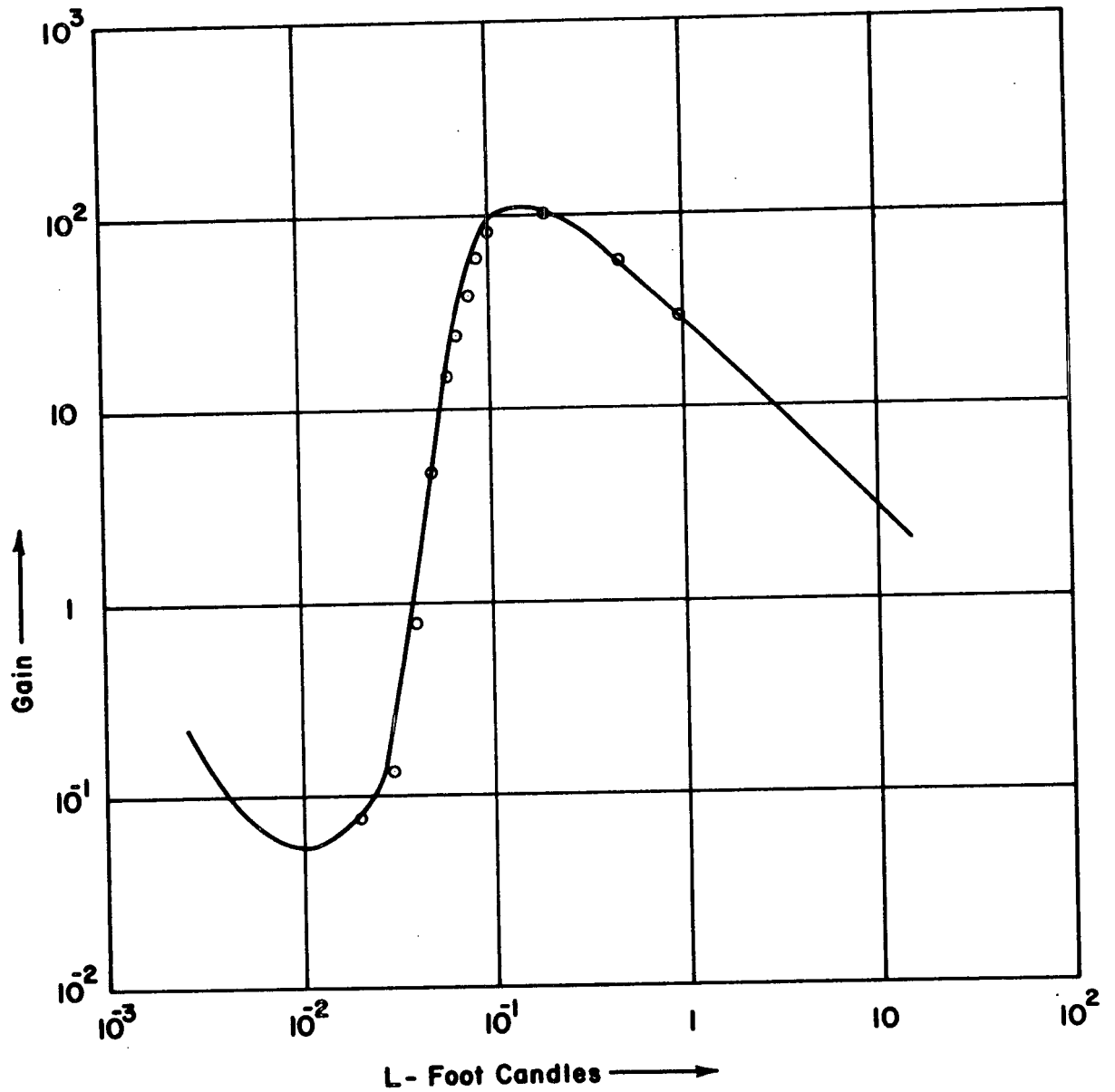


Figure 32. Calculated and Measured Gains of the Light Amplifier Element of Figure 31.

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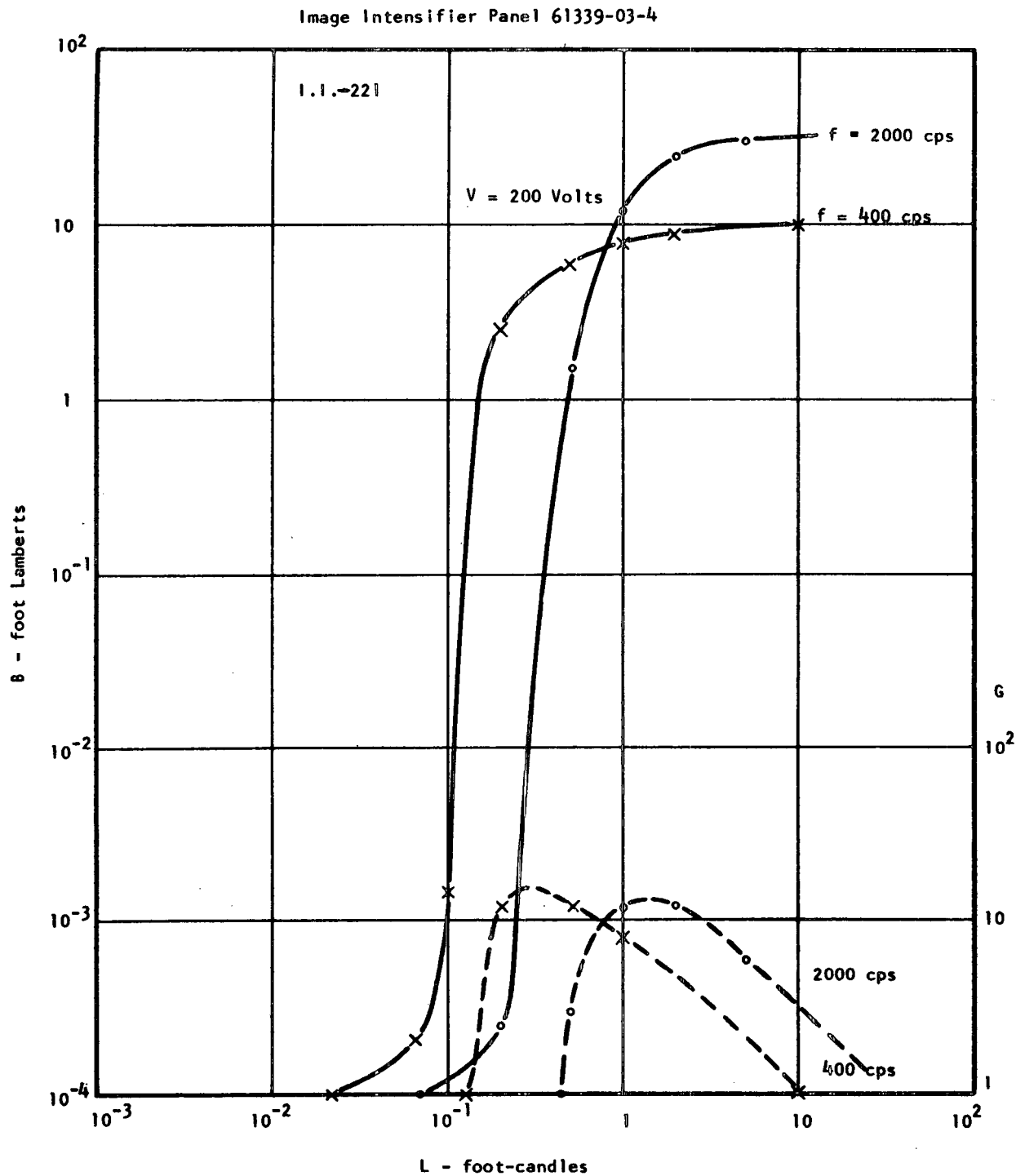


Figure 33. Transfer Characteristics of Image Intensifier No. 221

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Figure 34. Intensified Image of a Projected Slide Picture
on Image Intensifier No. 252, V = 200 Volts,
f = 2000 cps, L = 1 ft-c, B = 8 ft-L.

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SECTION VIII

GLOSSARY

Brightness - Measure of visual sensation of luminous intensity. It is often used instead of luminance or luminous emittance.

Brightness gain - The ratio of the luminance of a selected portion of the radiating area in foot-Lamberts to the illumination of the corresponding irradiated input area measured in foot-candles. The input spectrum, the output phosphor and the input or output level must be specified.

Discrimination ratio - The brightness ratio of an EL lamp at a given voltage to the brightness at the j -th part of the voltage ($j = 2, 3, 4, \dots$) and designated by R_j . The commonly used discrimination ratio is R_2 ($j = 2$). The discrimination ratio is dependent on the brightness and frequency.

Efficiency - Measure of power conversion of a light source, given generally in units of lumens/watt. A light source converting completely the input power to light power would have an efficiency of about 680 lm/w, if radiating at a wavelength of 5550 Å.

Electroluminescence (EL) - Luminescence excited by an electric field or current.

Foot-candle (ft-c) - Unit of illumination. Equal to the luminous flux (in lumens) received on 1 square foot area of the illuminated surface.

Foot-Lambert (ft-L) - Unit of brightness (more correctly luminous emittance) of a radiating source. Equal to the luminous flux (in lumens) emitted by 1 square foot area of the light source.

FORTRAN (FOR-mula TRAN-slation) - Symbolic language for writing mathematical or engineering programs for digital computers.

Gain - Measure of amplification in (1) photocells and (2) image intensifier panels.

- (1) The gain of a photocell is equal to the ratio of the number of the free carriers per second to the number of the primarily created electrons per second.
- (2) The gain of the image intensifier is the ratio of the output to the input light intensity. Depending on the units and on the input illumination source used, one defines the following gains: luminous gain, brightness gain, radiant power gain, standard luminous gain, standard brightness gain, and

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Optical Train - A compact optical system, for the demonstration of image intensifier panels. It contains: (1) a given projection system (as simple projection of transparencies or opaque images, projection of cathode ray tube displays, superposed projection of two separate images, and two stage cascaded projections), (2) power supplies and (3) image intensifier panels.

Optical Bench - Equipment for enabling precise positioning of lenses and other optical instruments, providing great versatility for the realization of any optical system.

Peak Radiant Power Gain - The same as radiant power gain, when the input flux is essentially a monochromatic radiation at the wavelength yielding maximum radiant power gain.

Photoluminescence - Luminescence excited by electromagnetic radiation as ultraviolet or visible light, and x-rays.

Radiant Power Gain - The ratio of the total radiant output flux in absolute units (e.g. watts) to the corresponding input flux measured in the same units. The spectral distribution of the input and output flux, and the input or output level must be specified.

Resolution - Measure of the optical quality of an image, regarding the separation of close elements. Its units are: (1) optical lines per inch; (2) line-pairs per inch; (3) TV lines per inch, and (4) elements or cells per inch. Units (3) and (4) differ by a factor of two from units (1) and (2). e.g.: a resolution of 50 optical lines (or simply optical resolution of 50 lines) per inch, 50 line-pairs per inch, 100 TV lines per inch and 100 elements or cells per inch are equivalent statements.

Spectral Distribution (of emission) - The power distribution of emitted light as a function of the wavelength. Given generally in relative units, with the maximum value as 100%.

Spectral Response (of photoresponsive elements) - Dependence of photosensitivity (or photocurrent) on wavelength of illuminating light. Measured generally by recording the current of the photocell, when irradiating it with a constant power of monochromatic light of changing wavelengths. If the dark current is not negligible, its value is subtracted from the measured currents. The spectral response curve is given generally in relative units, the maximum of the curve being set to 100%.

If the slope of the current-light intensity curve is not constant, the spectral response curve depends on the intensity of the monochromatic illumination. To eliminate this variable, another measuring method can be used

peak radiant power gain (see under these headings). In the case of the PC-EL image intensifier, where the sizes of the input image and the output image are the same, the luminous and brightness gains are the same.

Gamma (γ) - Measure of the image contrast of an intensifier panel. It is equal to the slope of the transfer characteristics drawn on double logarithmic paper: $\gamma = \frac{d(\log B)}{d(\log L)}$ (where L is the input light intensity, B is the output brightness).

Illumination - Density of the luminous flux on an illuminated surface. Its units are the foot-candle (lumens per square foot), lux (lumens per m²) and phot (lumens per cm²) 1 ft-c = 10.764 lux = 1.0764 m phot (milliphot = 10⁻³ phot).

Image Intensifier or Image Amplifier - Device for increasing the brightness of an optical image. Two varieties of such image intensifiers are under development: (1) vacuum tube type, using photoelectric emission, electron optics and cathodoluminescence; (2) solid state type, using PC and EL materials. The solid state type is much simpler, more compact, and less expensive to fabricate than the vacuum tube type, but has lower speed and lower picture quality at the present state of the art.

Light Intensifier or Light Amplifier - Device for increasing light intensity. One element of an image intensifier.

Lumen (lm) - Unit of luminous flux. It is equal to the flux through a unit solid angle (steradian) from a uniform point source of 1 candle.

Luminance - Light intensity per unit of projected area of source. Its units are: candle/cm², candle/ft² etc.

Luminescence - Phenomenon of light emission caused by any other effect than high temperature (thermal radiation), as electroluminescence (EL), photoluminescence (PL), bioluminescence, cathodoluminescence etc.

Luminous Emittance - Luminous flux emitted per unit area. Its units are: lumen/cm² (Lambert), lumen/ft² (foot-Lambert).

Luminous Gain - The ratio of the total output flux in luminous units to the corresponding input flux in the same units. The input spectrum, the output phosphor and the input or output flux level must be specified.

Luminous Flux - The total visible energy emitted by a source per unit time. Its unit is the lumen.

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preferably: the power of the monochromatic light is adjusted so that a constant photocell current is obtained when changing the wavelength. The reciprocal value of this illuminating power as a function of wavelength will give the spectral response curve.

Standard Brightness Gain - Same as brightness gain, if the input illumination source is a 2870 K color temperature tungsten lamp.

Standard Luminous Gain - Same as luminous gain, if the input flux is a 2870 K color temperature tungsten lamp radiation.

Sublinear-Curve (or function) - Where the absolute value of the slope (first derivative) is decreasing with increasing abscissa (independent variable). If the function is of the form $y = c x^n$, it is sublinear when $n < 1$.

Superlinear or Supralinear-Curve (or function) - Where the absolute value of the slope (first derivative) is increasing with increasing abscissa (independent variable). If the function is described by the equation: $y = c x^n$, it is superlinear when $n > 1$.

Torr - Unit of pressure, equal to 1 mm Hg.

Transfer Characteristic - Curve, representing the output brightness as a function of the input light intensity of the image intensifier. Drawn generally on double logarithmic paper.

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Abbreviations and symbols used in report:

A	- constant of EL cell
Å	- Ångstrom = 10^{-8} cm
AC	- alternative current
α	- exponent in formulas
B	- brightness in foot-Lamberts
B_0	- constant of EL cells
c_0	- sensitivity constant of PC cell
c_d	- dark current constant of PC cell
C	- capacitance
C_1, C_2	- capacitances of PC and EL cells respectively
CdS	- cadmium sulfide
CdSe	- cadmium selenide
d	- width of PC cell
DC	- direct current
e	- charge of electron
EL	- electroluminescent, electroluminescence
exp a	- e^a , where $e = 2.7182$, base of natural logarithm
ϵ	- dielectric constant
f	- frequency in cps
f_1	- number of incident photons per second per unit area
F	- number of incident photons per second per unit volume
ft-c	- foot-candle
ft-L	- foot-Lambert
g	- conductance
G	- gain
γ	- measure of contrast
h	- Planck constant
I	- current
j	- $\sqrt{-1}$
l	- electrode distance
L	- light intensity in foot-candles
λ	- wavelength
m	- exponent in formulas
M	- constant of PC material
M	- megohm - 10^6 ohm
μ	- micro- = 10^{-6} or micron - 10^{-6} m or mobility of carriers
n	- exponent in formulas or density of carriers
N	- number of carriers or photons
p	- capacitance ratio
PC	- photoconductive, photoconductor
RMS	- root mean square
R	- resistance
R_1	- resistance of PC cell
ρ	- specific resistivity
σ	- susceptance
σ_0	- conductivity
σ_0	- conductance of a square of any dimension
t	- thickness of layer
t^*	- light absorption thickness
τ	- time constant or life time
τ_r, τ_d	- rise and decay time constants

- τ_{rel} - relaxation time constant
- V - Volts, voltage
- V_0, V_1, V_2 - Voltages (RMS) on image intensifier, on PC layer and on EL layer respectively
- W - Watts, power
- x_1, x_2 - reactances of PC and EL cells respectively
- X - luminous gain of image intensifier
- Z - impedance
- ω - circular frequency ($2\pi f$)
- Ω - ohm

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cadmium Sulfide						
Cadmium Selenide						
Electroluminescence						
Fortran						
Image Intensifier						
Photoconductivity						
Sandwich Construction						
Selenides						
Solid State						
Sulfides						
Thin Films						
Zinc Sulfide						

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13. ABSTRACT		
<p>Technical Report NAVTRADEVGEN 1440-1 describes the continuation of the work performed under contract N61339-562 and reported in technical report NAVTRADEVGEN 562-1. The objectives of the program were: (1) to improve the characteristics of the low resolution (40 lines/inch) photoconductive-electroluminescent (PC-EL) type image intensifier panel; (2) to construct a high resolution (1000 lines/inch) PC-EL type image intensifier; (3) to build an experimental model compact optical projection system, incorporating the image intensifier panel.</p> <p>Panels with the best uniformity, least graininess and widest half-tone range reproducing capability had maximum standard luminous gains (measured with a 2870° K tungsten light source) of 20 foot-Lambert per foot-candle and maximum output brightnesses of 30 foot-Lamberts at 200 volts and 2000 cps. Response times between 50 and 500 mseconds were measured.</p> <p>Work is being continued toward improving the speed, spectral response, gain, and life characteristics of PC layers, developing the high resolution image intensifier panel, and building a compact optical projection system with the improved image intensifier panels.</p>		

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- IV. Tech. Rept. NAVTRA-DEVCEM 1440-1
- V. [redacted]

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Vertical text consisting of a repeating pattern of the letters 'H', 'O', 'N', and 'Z' arranged in a grid-like fashion, oriented vertically.

