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A Mathematical model of halftone reproduction including the effects of optical and chemical spreading

Cort Demmert

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A MATHEMATICAL MODEL OF HALFTONE REPRODUCTION INCLUDING THE EFFECTS OF OPTICAL AND CHEMICAL SPREADING

by

Cort B. Demmert

A thesis submitted in partial fulfillment
of the requirements for the degree of
Bachelor of Science in the School of
Photographic Arts and Sciences in the
College of Graphic Arts and Photography
of the Rochester Institute of Technology

April, 1983

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Accepted by... Ronald Francis ...
Supervisor, Undergraduate Research

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A MATHEMATICAL MODEL OF HALFTONE REPRODUCTION INCLUDING THE EFFECTS OF OPTICAL AND CHEMICAL SPREADING

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Submitted to the
Photographic Science and Instrumentation Division
in partial fulfillment of the requirements
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ABSTRACT

A system which predicts halftone reproduction curves for film-developer combinations, based on the combined optical and chemical modulation transfer function for that combination, has been tested using a 100 cycle/inch contact line screen. Density in fine detail is predicted and used to determine fractional area data. Predicted fractional area data was found to lie within 95 percent confidence intervals of experimental fractional area data.

ACKNOWLEDGEMENTS

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Theoretical and experimental fractional area as a function of log exposure.

I. INTRODUCTION

The choice of film and developer are known to produce significant variations in the halftone-reproduction curve of any particular graphic arts contact screen. The objective of this project was to determine if the halftone-reproduction curve can be accurately predicted from measurable parameters of the screen and film-developer combinations. This section is devoted to a description of the process and factors contributing to the final image.

Halftone reproduction is used to print continuous tone copy using a single density ink. The process works by converting a continuous tone image into an image made up of virtually opaque or virtually transparent areas. The printed image is made up of small areas of the same density, varying only in size. When viewed at a large enough distance, the human eye integrates the small areas and produces the sensation of continuous tone. In this process, a high-contrast lith film is exposed to a continuous tone scene through a halftone screen. The halftone screen has a two-dimensional sinusoidal density distribution which attenuates the exposure from the scene. The combination of sinusoidal exposure produced by the screen, along with the high contrast of lith film and development, produce the varying density to varying area conversion.

Lithographic development produces very high contrast and a very short toe on a characteristic curve (see Figure 1). In halftone and line photography, it is required that the reproduction consist only of completely opaque and fully transparent areas, seperated from one another by sharp

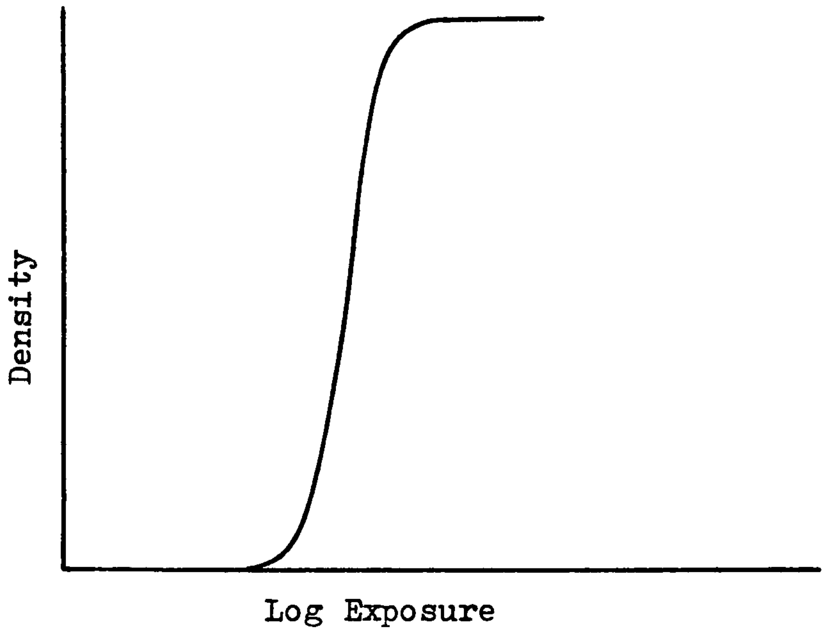

Figure 1. Lithographic characteristic curve.

bounderies.[1] The high contrast and short toe are required for a useful density to area conversion. A normal contrast for lith development is a gamma value of approximately 10.[2] The high contrast of lith films is due in large part to the development kinetics of the film-developer combination. The induction period, which is the initial development period before rapid density formation is observed, is relatively long for lith development. After the induction period, lith development rapidly accelerates essentially until the maximum density is reached. This period of rapid acceleration is commonly refered to as "lith effect" development.[3] Induction time has been shown to be exposure dependent, less well exposed grains having longer induction times.[4] This effect is desirable since it produces a very low fog level and an enhanced contrast for small images.

The developing agent used most predominantly in lith development is hydroquinone. Many studies of hydroquinone development kinetics have been made to determine the chemical mechanism causing the lith effect.[5,6,7] The mechanism which is widely accepted is a development autocatalyzation caused by oxidation products of hydroquinone.[8] Hydroquinone reacts with exposed silver halide to form silver metal, halide ions, and the oxidation product of hydroquinone, quinone. Quinone then reacts with hydroquinone to form a very highly unstable intermediate semiquinone ion, which is a highly active developing agent. The concentration of semiquinone autocatalytically grows and causes a phenomena known as infectious development. Infectious is the complete development of all silver halide crystals in the area of exposed crystals as a result of hydroquinone's oxidation products building up and migrating laterally.[9]

It is still not clear what mechanism triggers the lith effect, and when development becomes controlled by semiquinone rather than hydroquinone. An obvious possibility is a critical level of semiquinone which must be reached during the induction period.

Many other mechanisms may also contribute to the lith effect. It has been suggested that oxidation products of the developing agent bleach small-fragile latent images, and in doing so, contribute to the lith effect.[10] As the concentration of oxidized developer (quinone) grows in localized areas, the development reaction reaches equilibrium. When equilibrium is reached, an excess of oxidized developing agent can reverse the reaction and thus bleach latent images. James[5] showed that quinone, to a small extent, does bleach latent images. It has also been suggested that bromide ion present in the developer, and produced by development, inhibits development of smaller latent images and produces a longer induction period in the toe portion of the characteristic curve.[10] This is known as differential induction and reduces density produced in low exposure areas. James[5] has also suggested that a moderate increase in development of some grains, and the suppression of others, would suffice to give the lith effect. Whatever the mechanisms are that produce the lith effect, it is again critical that the high contrast be optimized for a useful density to area conversion in halftone reproduction.

A very great number of factors effect lith development, and in turn, the formation of halftone dots. Investigations of halftone images has shown that infectious development operates over very short distances which causes small halftone dots to have different properties than those of large areas.[2] The relationship between dot size, dot quality, and development time is complex.[2] Development temperature and agitation have also been shown to effect halftone dot formation.[1]

To predict the tone reproduction characteristics of a halftone screening process, densities in fine detail must be predicted. Predicting densities in fine detail is much more complex than large-area tone reproduction.[11,12,13] To predict densities in small details, the light spread function for the film layers, and the developer spread function for the film-developer combination must be known. From optical and chemical spread functions, the optical modulation transfer function, and chemical modulation transfer function can be determined. For halftone reproduction, the density distribution and spatial frequency of the screen, along with the optical and chemical modulation transfer functions, can be used to determine the effective exposure distribution on the film. From the effective exposure, the density of the detail can then be determined.

As an alternate method to determining seperate optical and chemical modulation transfer functions, Kriss[14], investigated using an output modulation transfer function which represents the combined effects of light scatter and development spread. This combined transfer function describes the combined effect of optical and chemical spreading through a single transfer function. The combined modulation transfer function can be determined from the edge response function of a particular film-developer combination using a method derived by Tatian.[15] Tatian's method works by differentiating the edge response to yield the spread function. Fourier series is then applied to determine the transfer function.

Predicting densities in fine detail applied directly to halftone photography can be used to determine the system's output density distribution. From that, the reproduction characteristics of the system can be determined.

II. EXPERIMENTAL

A computer based model for determining theoretical tone reproduction data was designed based on a model designed by Engeldrum.[16] The model was tested for nine film-developer combinations and is discussed in further detail later in this section. The films and developers tested are listed in Table 1. The films tested were selected because of their design for halftone photography. Machine processes were selected to represent commercial applications and to minimize variability.

Table 1. Films and processes used for evaluation of model.

Films:
1. MPII Ortho - 2577
2. Kodalith Ortho Type 3 - 2556
3. E S Scanner Film - 2587

Processes:
1. MPII Chemistry
   1 min. 33 sec. @ 80°F
   Kodak 324 Processor
2. Kodalith Blender Concentrates
   1 min. 33 sec. @ 80°F
   Kodak 324 Processor
3. Rapid Scanner Access
   23 sec. @ 110°F
   Kodak Startech Processor

To simplify computations and avoid error introduced by scanning circular dots with a microdensitometer, a line screen was used for all tests. Specifically, the line screen used was a 100 line/inch gray contact screen manufactured by Beta Screen Co., Carlstadt, N.J.

Preliminary tests were made to determine the proper exposure required for each film with and without the contact screen. The preliminary test exposure samples were processed in Kodalith A-B developer for 2½ minutes as recommended by the datasheets. Based on the preliminary tests, eighteen sensitometric exposures were made for each film, nine with the screen, and nine without. Of the nine exposures with and without the screen, three were processed using each of the processes listed in Table 1. For exposure times and intensities see Appendix A, Table 1.

All exposures were made using a point source sensitometer. Unscreened exposures were made with a 0.05 density increment step tablet in direct contact with the emulsion using a vacuum frame to insure intimate contact. Screened exposures were made using the line screen in direct contact with the emulsion and a 0.10 density increment step tablet. Again, a vacuum frame was used to insure intimate contact between the screen and the emulsion.

All processing was done at the Photo Technology Division of Eastman Kodak. After processing three screened and three unscreened samples of each film, using each process, the result was three replicates of each film-developer combination to determine repeatability. From the unscreened samples, density vs. log exposure data was determined for each combination. Using a program to fit N^{th} order regressions to data, the computer was then used to determine 8^{th} order equations for density as a function of log exposure for each combination. 8^{th} order was chosen because it was found to fit the experimental data with the best possible accuracy. Density measurements were then made for the screened exposure samples using a 3 mm. circular aperture which averaged the density over approximately twelve cycles. Density values were converted to transmittance, which correlates to fractional area through the following expression,

Fractional Area = 1 - Transmittance.

Thus, plotting fractional area as a function of log exposure yielded experimental tone reproduction curves.

Next, the first step in determining theoretical tone reproduction curves, was to determine the density distribution of the screen. To determine the screen density distribution, microdensitometer scans of the screen were made and the distribution found to be sinusoidal.

To determine the modulation transfer function of each film-developer combination, due to the combined effects of chemical and optical spreading, microdensitometer scans of the edge response were made. The division between two adjacent steps on the unscreened samples was used as a low-contrast edge. The two steps with the highest density difference were selected and used for this purpose. Tatian's method was then used to determine the modulation transfer function of each combination. The modulation transfer function of the microdensitometer due to the efflux optics and scanning aperture were calculated and divided out of the MTF's determined using Tatian's method.

A computer based model was then written to generate theoretical tone reproduction using an Apple* computer. The program converts the sinusoidal density as a function of distance into transmittance as a function of distance. Incident exposure is then input and multiplied by transmittance as a function of distance to yield exposure as a function of distance. The modulation of the exposure as a function of distance is then decreased by the input value

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*Registered Trademark of Apple Computer Inc.

of the MTF at the spatial frequency of the screen (100 cycles/inch). The result is the effective exposure as recorded by the emulsion. Effective exposure is then converted to log exposure, and through the 8^{th} order expression for density as a function of log exposure, converted to output density as a function of distance. Output density as a function of distance is then converted to transmittance and averaged over exactly one cycle. Maximum output transmittance is determined at the point where the screen density is a minimum, and minimum output transmittance is determined at the point where the screen density is a maximum. Using the following expression, the fractional area is then determined.

$$\text{Fractional Area} = \frac{T_{max} - \bar{T}}{T_{max} - T_{min}}$$

where: T_{max} = maximum transmittance,
T_{min} = minimum transmittance and,
$\bar{T}$ = average transmittance.

The input parameters for the program and data output are summarized in Table 2. Using the log exposure values found to produce the basic density range (0.05 - 0.95 Fractional Area), theoretical fractional area data were generated. Average RMS (root-mean-square) deviation between experimental and theoretical data was calculated for each combination.

Table 2. Input parameters and data output for computer based model.

Input Parameters:

1. MTF of film-developer combination at 100 cy./in.
2. Minimum useful log exposure for combination.
3. Base + fog density.
4. Maximum density.
5. Equation for density as a function of log exposure for combination.
6. Log exposure incident on screen.

Data Output:

1. Average transmittance.
2. Maximum transmittance.
3. Minimum transmittance.
4. Fractional area.

III. RESULTS

The objective of the experimentation was to mathematically model the contact screening system. The result of scanning the screen on a microdensitometer was to find the density distribution to be sinusoidal and described by the following equation (see Figure 1).

$$D(x) = 0.53 + 0.37\sin(200\pi x)$$

where x = distance in inches.

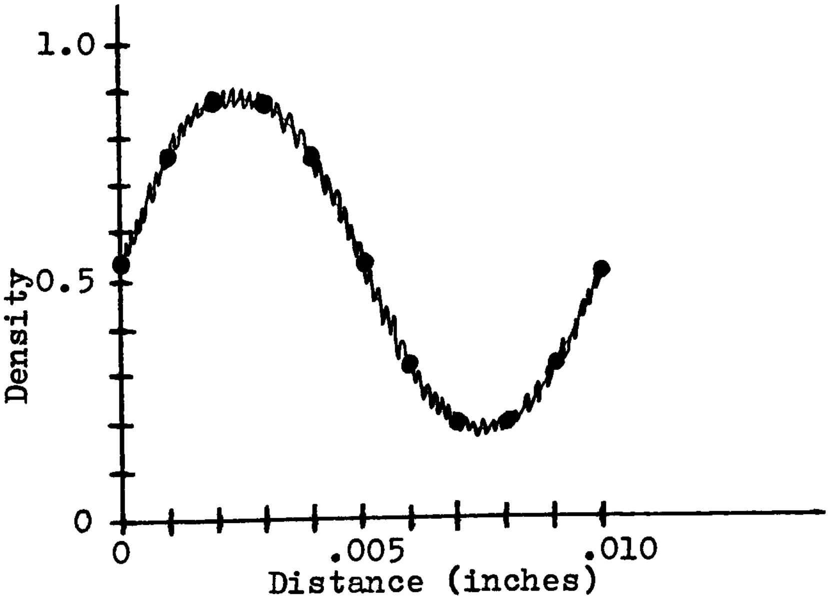

Figure 1. Microdensitometer trace of line screen compared to computed values (●).

The results of the MTF determinations illustrate that the Rapid Scanner Access process produces the largest amount of chemical spreading. This can be concluded from lower MTF values than the other processes for a given film. The amount of optical spreading due to the film layers does not change due to processing, but the decreases in MTF are due to chemical spreading. The Kodalith Blender Concentrates process produces the least amount of chemical spreading, and the MPII process produces more chemical spreading than Kodalith Blender Concentrates but less than Rapid Scanner Access. It can also be observed from the modulation transfer functions (Appendix B), that any one single process produces varying amounts of chemical spread, depending upon the film.

When processed using Rapid Scanner Access, MPII Ortho, and Kodalith Ortho Type 3 yield excessive base plus fog levels and for this reason were not evaluated and compared to theoretical fractional area data. Of the seven other combinations, average RMS deviations between theoretical and experimental data ranged from 0.022 to 0.146. Input parameters used for each combination, and average RMS deviation between experimental and theoretical fractional area are summarized in Table 1. Experimental and theoretical fractional area as a function of log exposure for each combination evaluated can be found in Appendix C.

Table 1. Input parameters and average RMS deviation for film-developer combinations evaluated.

Combination	MTF*	Minimum Log E	B+F	Dmax	Average RMS Deviation
Kodalith Ortho MPII Chem.	0.916	-0.10	0.03	4.55	0.0604
MPII Ortho MPII Chem.	0.970	-0.10	0.03	4.34	0.0325
E S Scanner MPII chem.	0.947	0.20	0.03	4.23	0.1210
Kodalith Ortho K.B.C. Chem.	0.973	0.10	0.03	4.53	0.0220
MPII Ortho K.B.C. Chem.	0.974	0.10	0.03	4.05	0.0244
E S Scanner K.B.C. Chem.	0.964	0.20	0.03	4.10	0.0590
E S Scanner R.S.A. Chem.	0.925	-0.10	0.03	4.18	0.1460

*MTF at 100 cycles/inch.

IV. DISCUSSION

The model was evaluated for seven film-developer combinations and used to accurately predict fractional area for five of the combinations. From replicated data, 95 percent confidence intervals were constructed for experimental fractional area. For five of the seven combinations, predicted fractional area was within the 95 percent confidence intervals of the experimental fractional area (see Apendix C). It can only be speculated that the two combinations which did not lie within the 95 percent confidence intervals were due to eroneous data.

Accurately predicting the tone reproduction curves for five of the seven combinations illustrates that predicting densities on a microscopic level can be successfully applied directly to halftone reproduction. If expanded to two dimensions, this method could be used to design screen density distributions for specific film-developer combinations to yield optimum reproduction. By knowing the characteristics of a particular film-developer combination, such as chemical and optical spreading, and density as a function of log exposure, screen density distributions could be calculated to yield any desired reproduction curve.

An accurate mathematical model of halftone photography is a very powerful tool, and can be used to explain present results, as well as to aid in designing new processes.

V. CONCLUSIONS

The model tested is based on the following theory. From the density distribution of a contact screen, and the exposure incident on the screen, the actual exposure at the film can be calculated. The modulation of the exposure is then decreased due to optical spread in the film layers, and chemical spread of the film-developer combination. The amount of decrease in the exposure modulation can be determined from the value of the combined optical and chemical modulation transfer function at the spatial frequency of the screen. With the optical and chemical spreading taken into account in the form of a modulation decrease, the effective exposure as recorded by the emulsion can be determined. Effective exposure is then used to determine output density and transmittance, which is in turn used to determine fractional area.

From the experimentation, it can be concluded that accurate halftone reproduction curves can be mathematically predicted from the characteristics of the screen, and the characteristics of the film-developer combination. This model can then be used to determine effects of MTF on halftone reproduction, and to design density distributions for specific film developer-combinations to yield optimum reproduction.

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Appendix A

Table 1. Exposure times and intensities.

Kodalith Ortho Type 3 - 2556
Intensity: 41.98 lux
Time: without screen t=1.3 sec.
with screen t=16 sec.

MPII Ortho - 2577
Intensity: 41.98 lux
Time: without screen t=0.16 sec.
with screen t=2.0 sec.

E S Scanner - 2587
Intensity: 41.98 lux
Time: without screen t=2.9 sec.
with screen t=35 sec.

Appendix B

Figure 1. Modulation transfer functions for MPII Ortho film - 2577

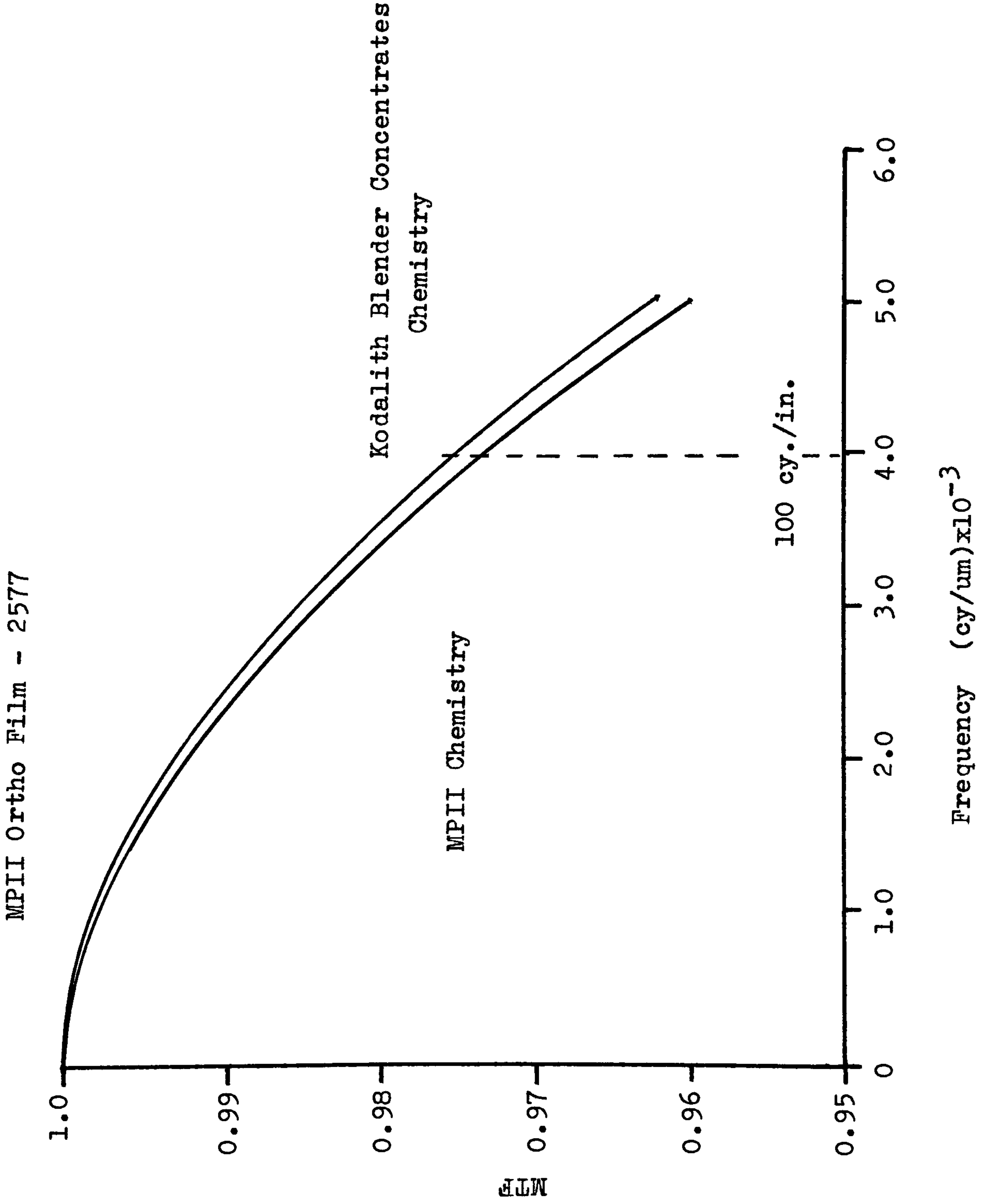


Figure 2. Modulation transfer functions for E S Scanner Film - 2587

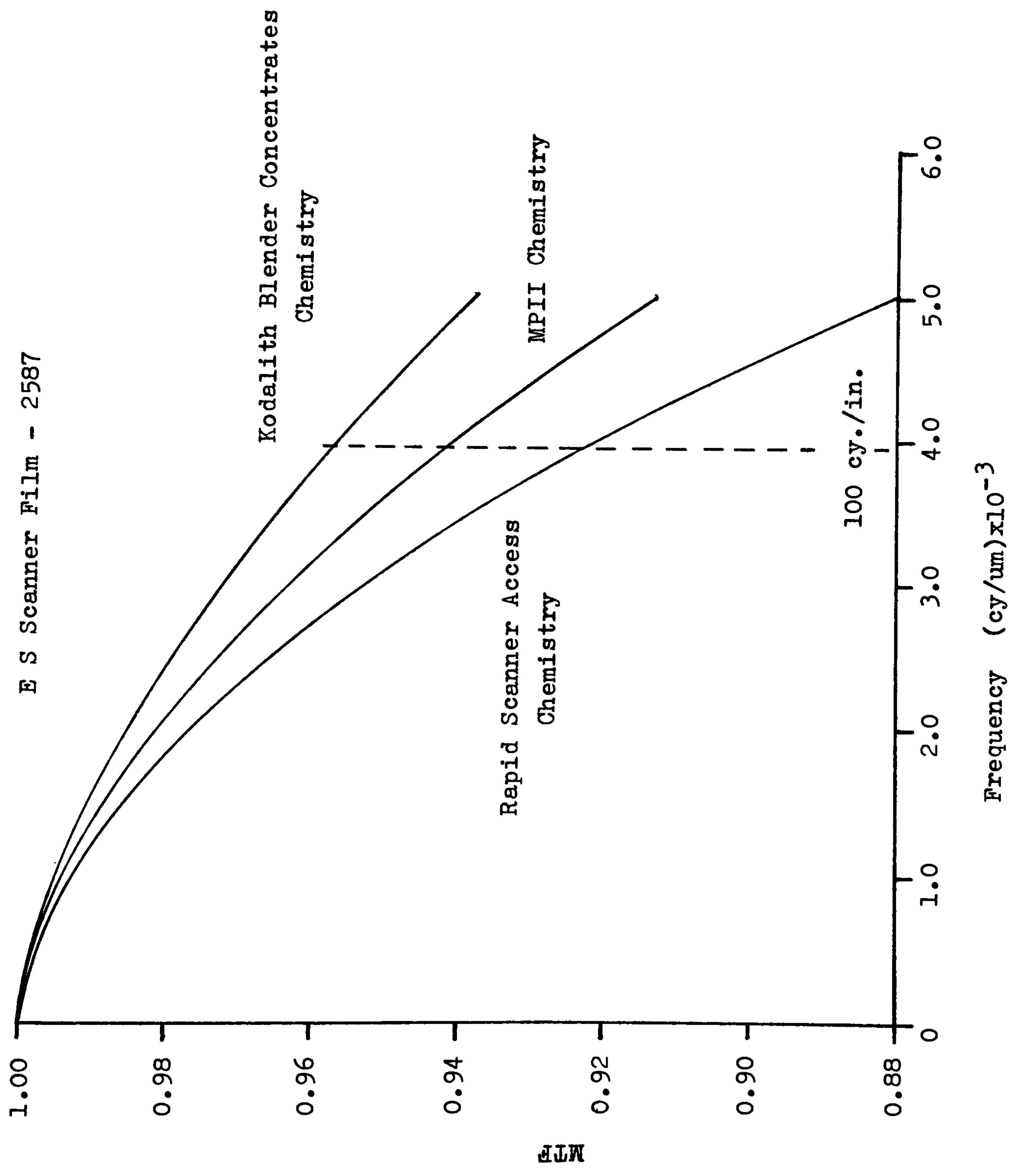
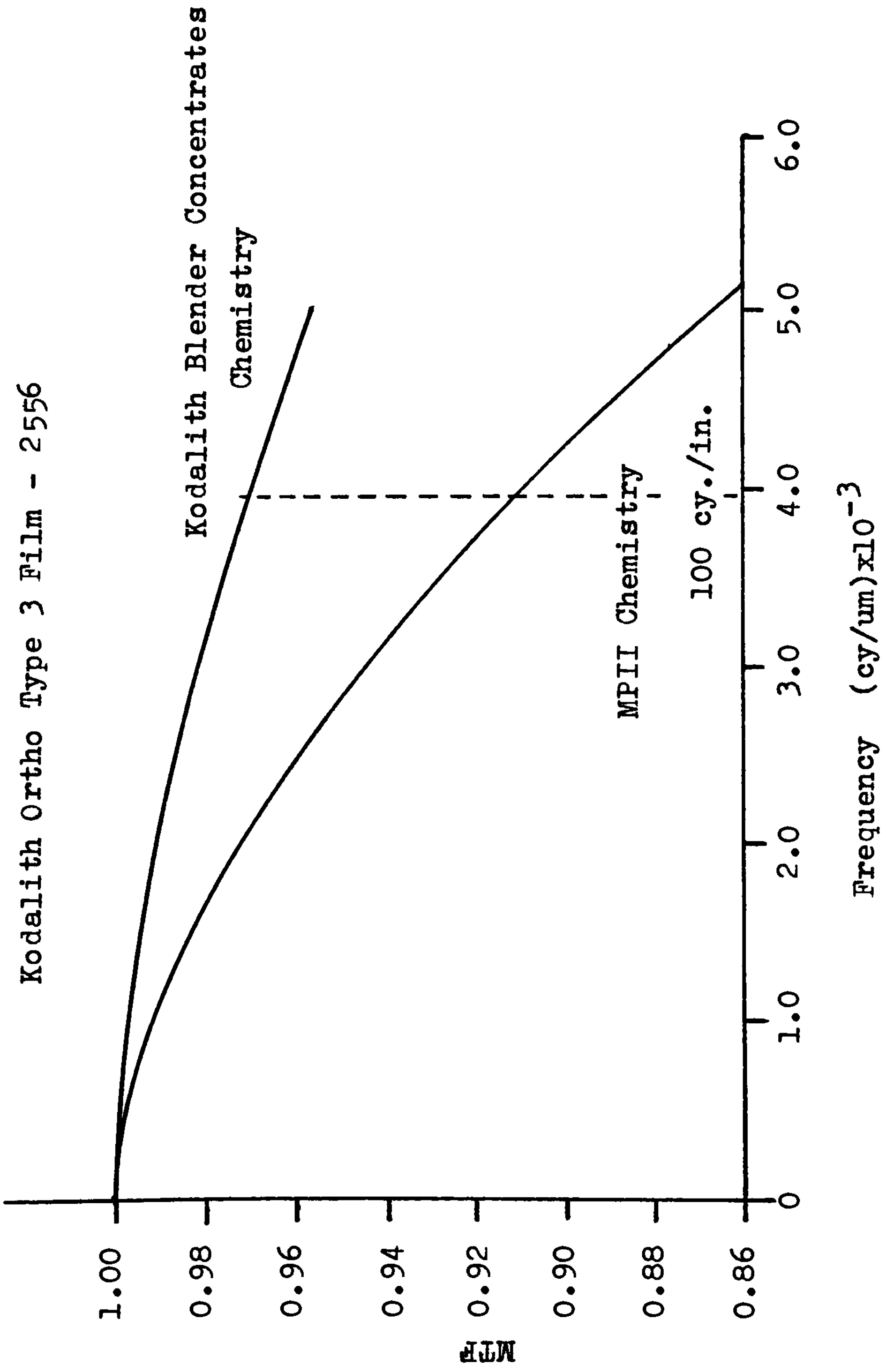


Figure 3. Modulation transfer functions for Kodalith Ortho Type 3 - 2556



Appendix C

Figure 1. Theoretical and experimental fractional area as a function of log exposure.
Theoretical ●
Experimental—
(95 percent confidence intervals)

E S Scanner Film - 2587
Kodalith Blender Concentrates Chemistry

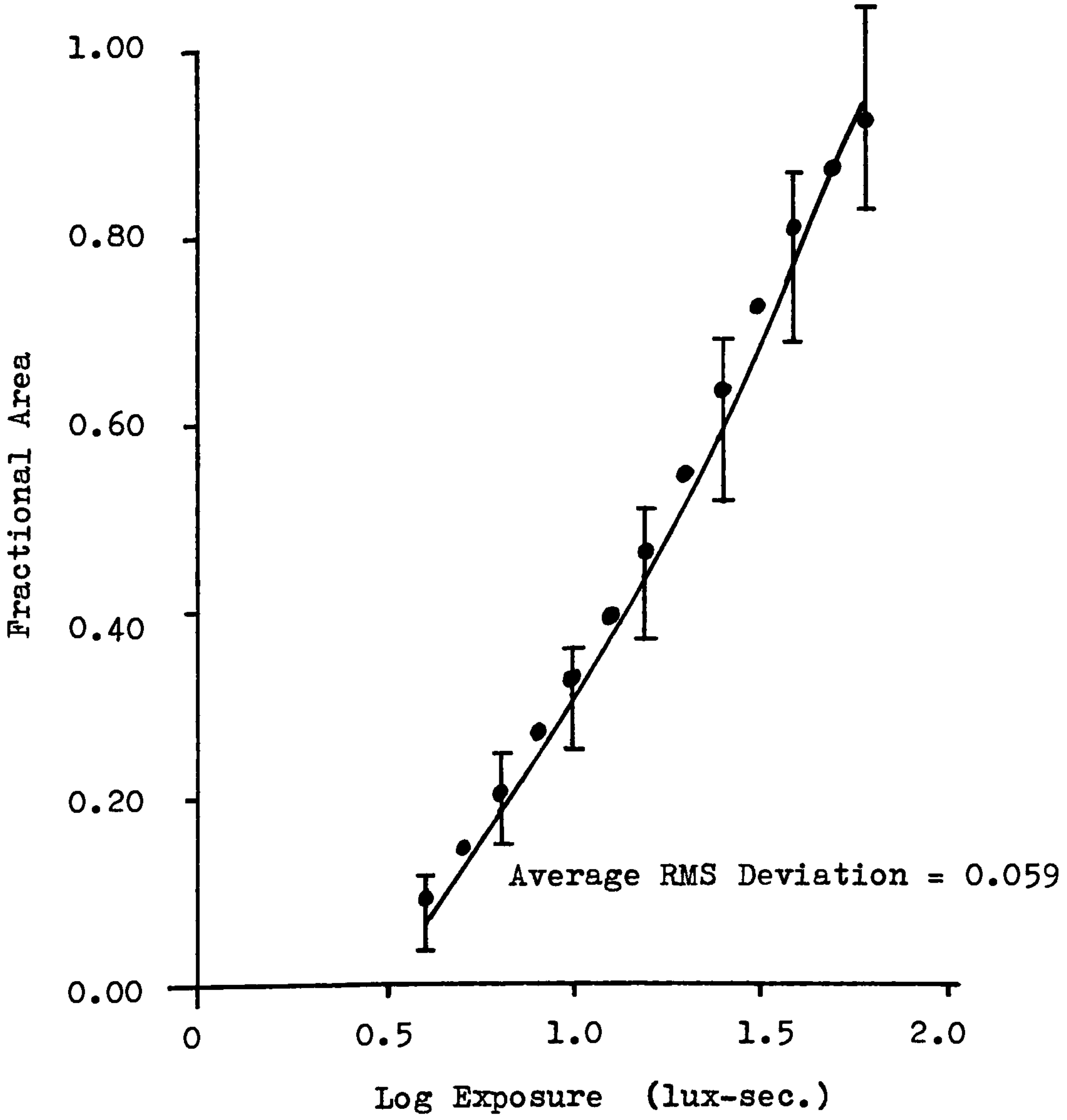


Figure 2. Theoretical and experimental fractional area as a function of log exposure.

Theoretical ●

Experimental —

(95 percent confidence intervals)

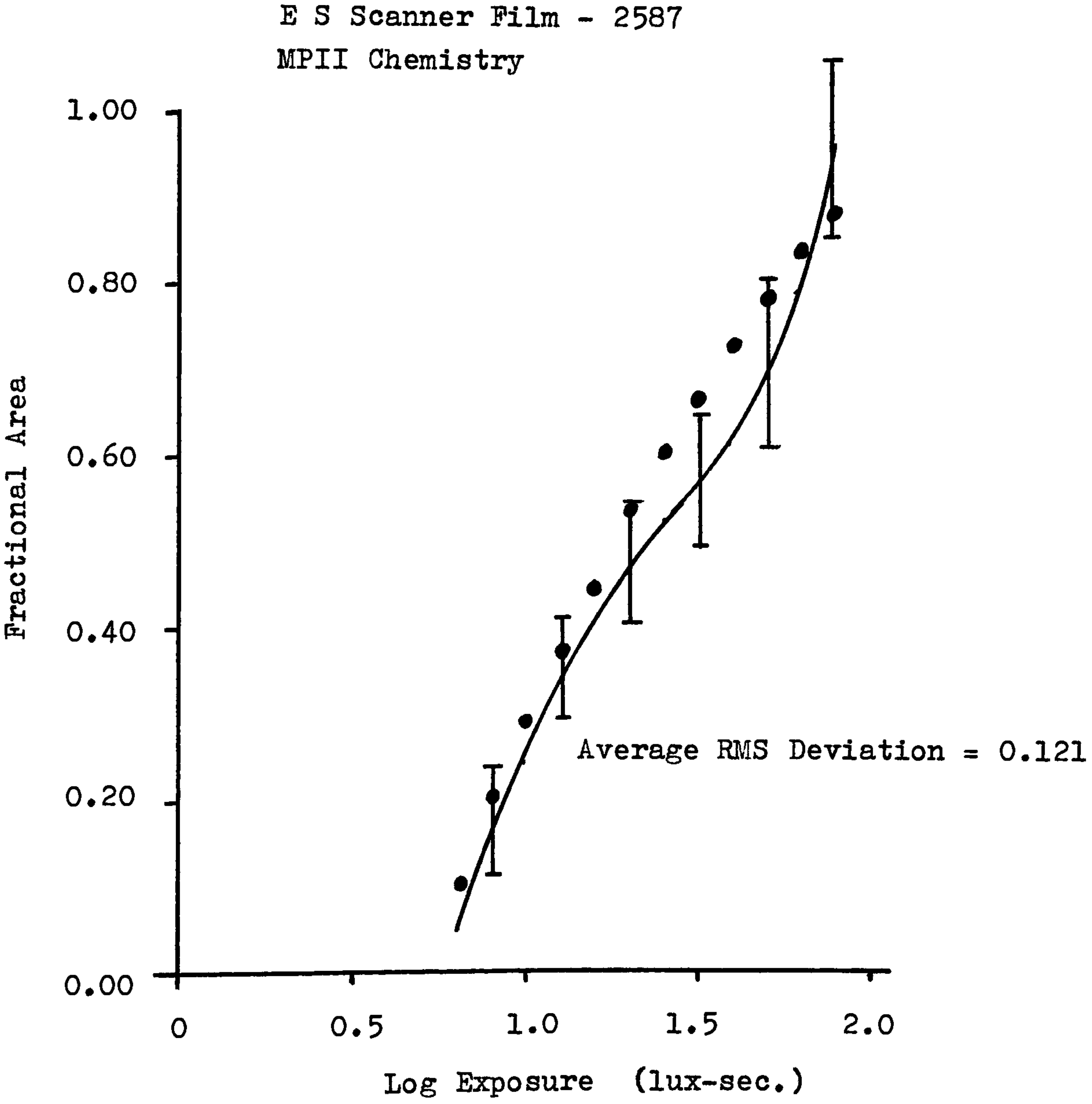
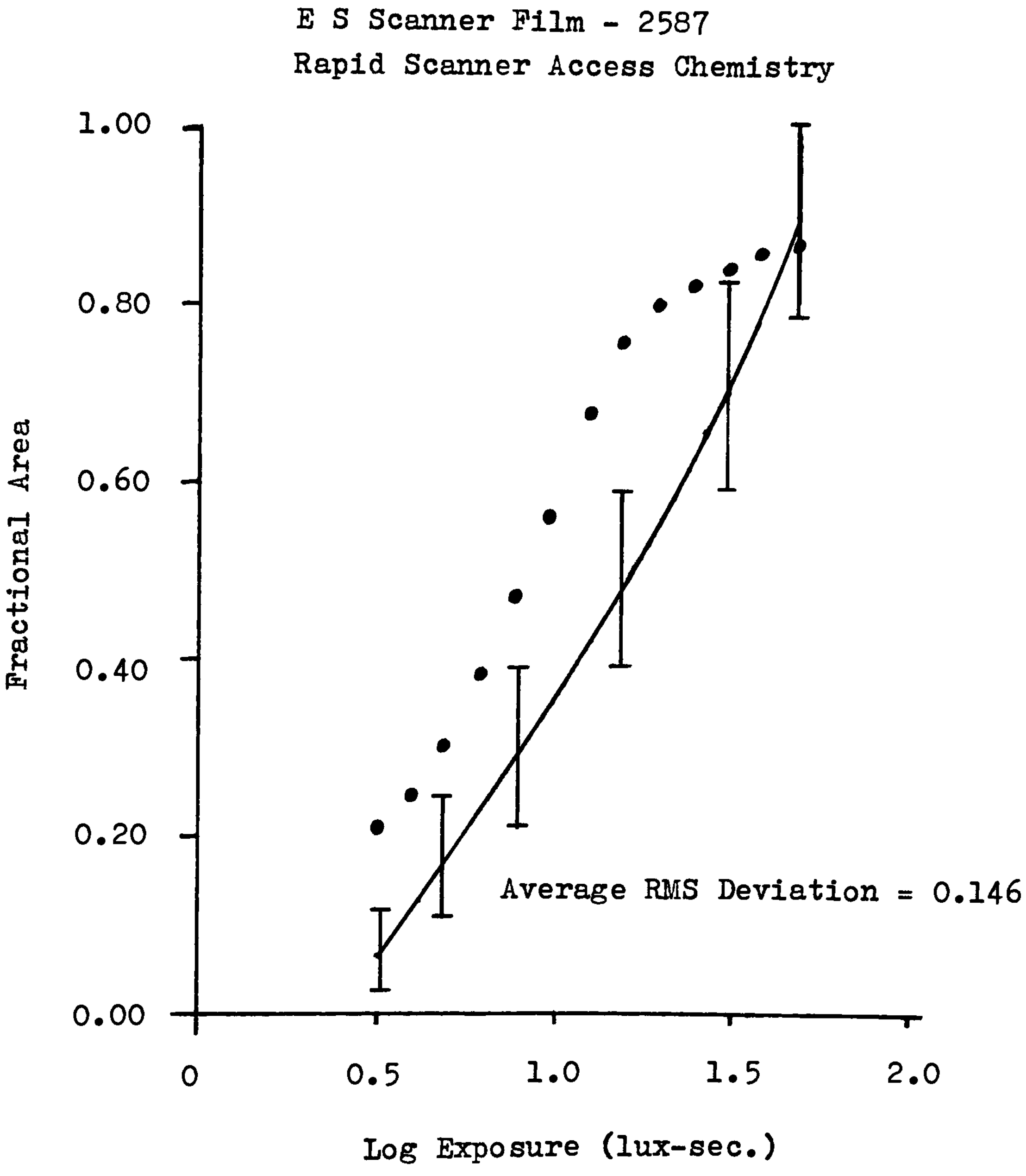


Figure 3. Theoretical and experimental fractional area as a function of log exposure.

Theoretical ●
Experimental —
(95 percent confidence intervals)



E S Scanner Film - 2587
Rapid Scanner Access Chemistry

Figure 4. Theoretical and experimental fractional area as a function of log exposure.

Theoretical ●

Experimental ——

(95 percent confidence intervals)

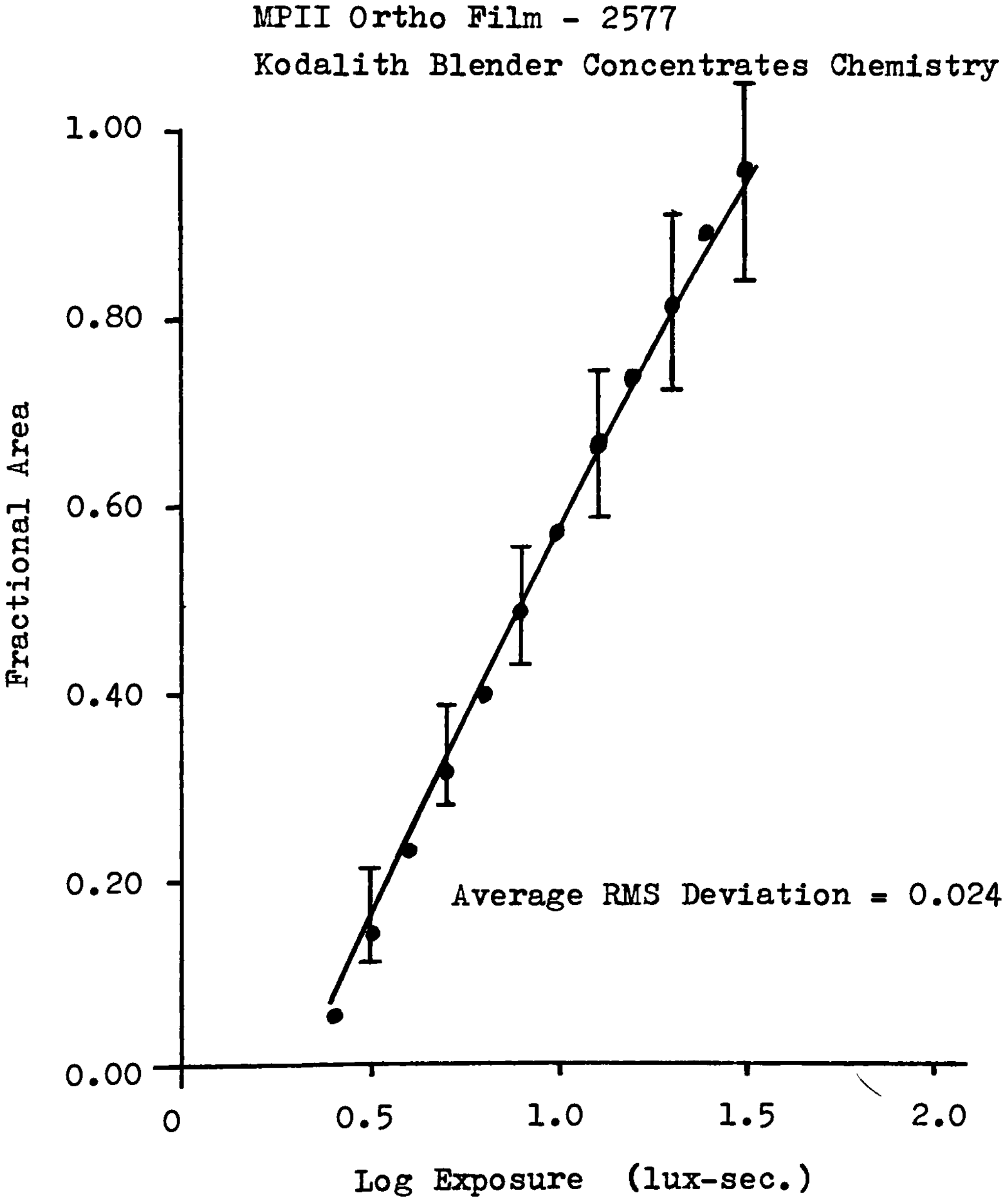


Figure 5. Theoretical and experimental fractional area as a function of log exposure.

Theoretical ●

Experimental ——

(95 percent confidence intervals)

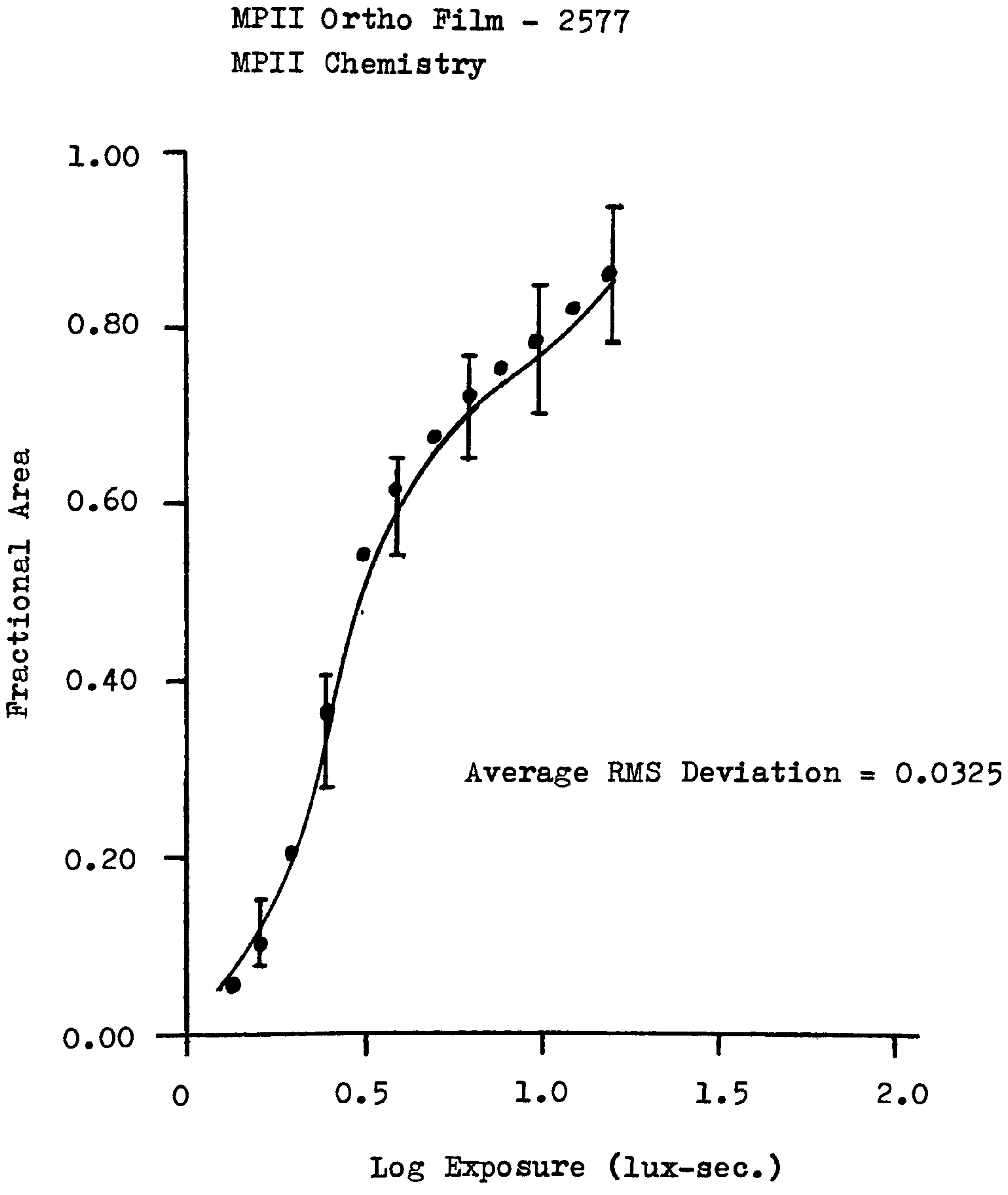


Figure 6. Theoretical and experimental fractional area as a function log exposure.

Theoretical ●

Experimental ——

(95 percent confidence intervals)

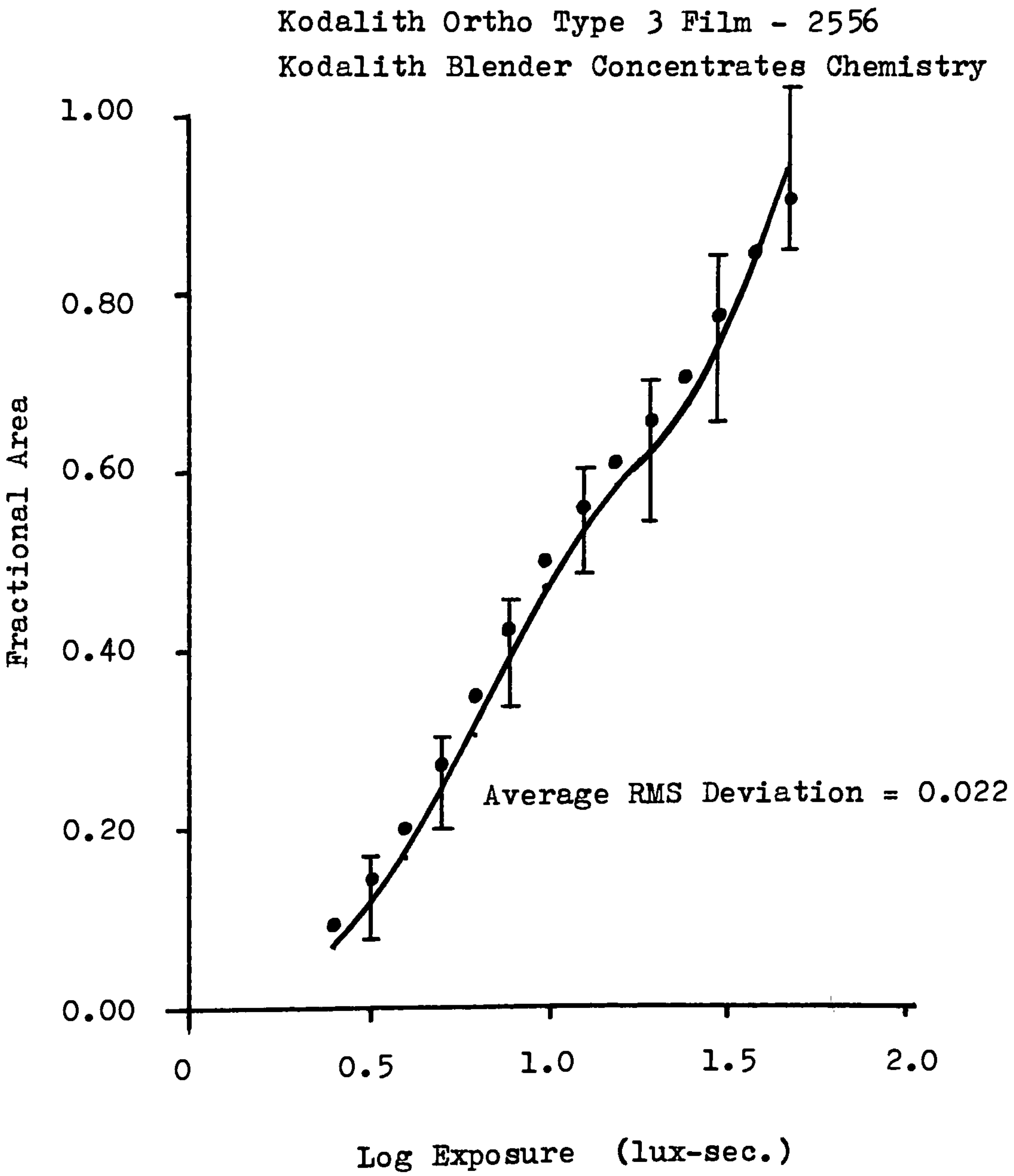
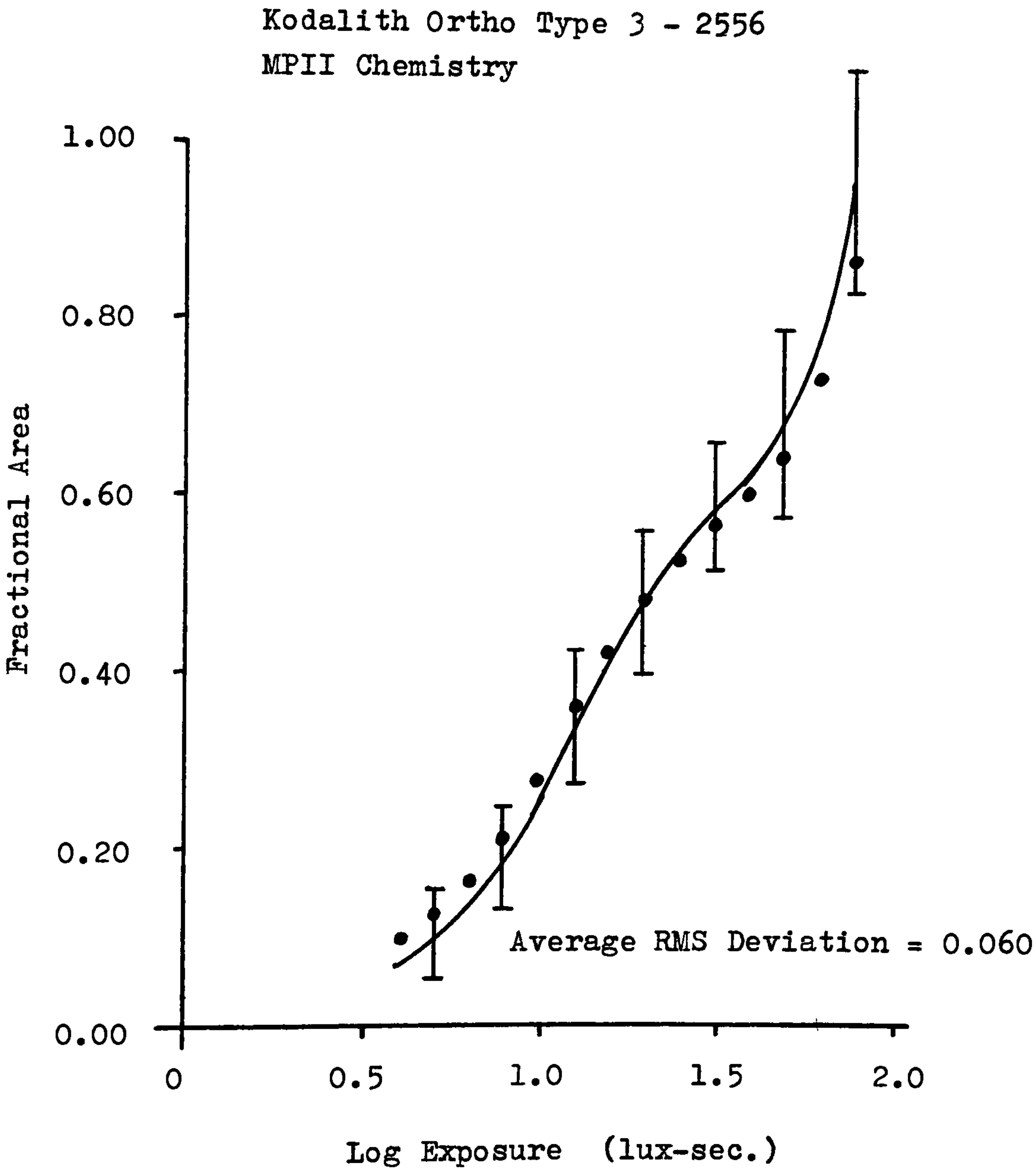


Figure 7. Theoretical and experimental fractional area as a function of log exposure.

Theoretical ●

Experimental —

(95 percent confidence intervals)



APPENDIX D

Table 1. Listing of computer based model.

```
]LIST

10  HOME
20  DIM X(50)
30  DIM LE(50)
40  DIM ID(50)
45  DIM E(50)
46  DIM OD(50)
47  DIM OT(50)
48  DIM EFF(50)
50  DIM IT(50)
60  HOME
70  PRINT "THE DENSITY DISTRIBUTION OF THE SCREEN IS GIVEN BY"
80  PRINT "THE EQUATION D(X)=0.53+0.37*SIN(200*PI*X)"
90  PRINT "WHERE X=INCHES AND PI=3.1415927"
100  INPUT "WHAT IS THE MTF AT 100 CY./INCH?";MTF
120  INPUT "WHAT IS THE MINIMUM USEFUL LOG H?";ME
130  INPUT "WHAT IS BASE + FOG?";BF
140  INPUT "WHAT IS DMAX?";DMAX
150  INPUT "WHAT IS THE INCIDENT LOG H?";LH
170 X = 0
180 AVRT = 0
190  FOR I = 1 TO 20
200 X = X + .0005:PI = 3.1415927
210 ID(X) = 0.53 + 0.37 * MTF *  SIN (200 * PI * X)
220 LE(X) = LH - ID(X)
250 EFF(X) = IT(X) * E(X)
260 LE(I) = LE(X)
270 OD(I) = .05611 - (1.233 * LE(I)) + (14.439 * LE(I) ^ 2) - (31.73 * L
    E(I) ^ 3) - (145.4 * LE(I) ^ 4) + (706.51 * LE(I) ^ 5) - (926.6 * LE
    (I) ^ 6) + (391.70 * LE(I) ^ 7)
275  IF OD(I) >  = DMAX THEN OD(I) = DMAX
276  IF LE(I) <  = ME THEN OD(I) = BF
280 OT(I) = 10 ^  - OD(I)
290 AVRT = AVRT + OT(I)
296  IF I = 5 THEN A = OT(I)
297  IF I = 15 THEN B = OT(I)
300  NEXT I
310  PRINT "THE AVERAGE TRANSMITTANCE=";AVRT / 20
320 TAVE = AVRT / 20
322 FA = (A - TAVE) / (A - B)
323  PRINT "THE MINIMUM TRANSMITTANCE=";B
324  PRINT "THE MAXIMUM TRANSMITTANCE=";A
325  PRINT "THE FRACTIONAL AREA =";FA
350  PRINT "       "
360  GOTO 150
```

VITA

The author was born on March 11, 1961 in Summit New Jersey. Upon Graduation from high school in 1979, he enrolled in the Rochester Institute of Technology. While at R.I.T. he studied Photographic Science and Instrumentation.