MICHIGAN STATE UNIVERSITY
PHYSICS DEPARTMENT
ULTRASONICS LABORATORY

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# OPTICAL METHODS FOR ABSOLUTE MEASUREMENT OF SOUND PRESSURE IN LIQUIDS.

Technical Report No. 8.

E. A. Hiedemann
Project Director

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# FORTRAN Computer Programs for Energy Ratios of Ultrasonic Waves Reflected and Refracted at Solid-Liquid and Liquid-Solid Boundaries

by

Walter G. Mayer

The equations governing the energy partition at solid-liquid and liquid-solid boundaries used in the two FORTRAN programs described here are as follows:

a) Incident wave in the solid:

The energy ratio of reflected longitudinal to incident longitudinal wave is

$$(L/I)^2 = [(A - B + C)/(A + B + C)]^2. \quad (1)$$

The energy ratio of reflected shear wave to incident wave is

$$(S/I)^2 = 4\,A\,B/(A + B + C)^2. \quad (2)$$

The energy ratio of refracted longitudinal to incident wave is

$$(R/I)^2 = 1 - (L/I)^2 - (S/I)^2, \quad (3)$$

where $A = \sin 2\beta \sin 2\gamma\,(V_{S2}/V_{L2})^2$,

$B = (\cos 2\gamma)^2$,

$C = V_{L1}\rho_1 \cos\beta / V_{L2}\rho_2 \cos\alpha$.

b) Incident wave in the liquid:

The energy ratio of reflected to incident wave is

$$(R/I)^2 = \{[\cos\beta - A\cos\alpha(1 - B)]/[\cos\beta + A\cos\alpha(1 - B)]\}^2. \quad (4)$$

The energy ratio of refracted longitudinal wave to incident wave is

$$(L/I)^2 = \{2\cos 2\gamma(A\cos\alpha\cos\gamma)^{\frac{1}{2}}/[\cos\beta + A\cos\alpha(1 - B)]\}^2. \quad (5)$$

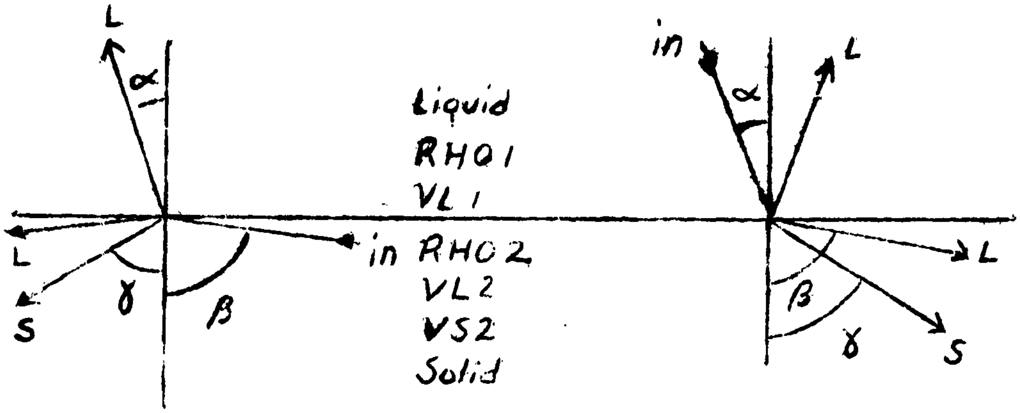
The energy ratio of refracted shear wave to incident wave is

$$(S/I)^2 = 1 - (R/I)^2 - (L/I)^2, \quad (6)$$

where $A = V_{L2}\rho_2/V_{L1}\rho_1$,

$B = 2\sin\gamma \sin 2\gamma\,[\cos\gamma - (V_{S2}/V_{L2})\cos\beta]$.

**The symbols used in both programs are given below:**




The headings in Program 1 mean:

(RL/I)SQ = Energy ratio of reflected longitud. wave to incid. wave
(RS/I)SQ = " " " " shear " " " "
(T/I)SQ = " " " refracted longitud. " " " "
BETA = Angle of incidence

For Program 2:

(R/I)SQ = Energy ratio of reflected longitud. wave to incid. wave
(TL/I)SQ = " " " refracted " " " " "
(TS/I)SQ = " " " " shear " " " "
ALPHA = Angle of incidence

The case solid-liquid is comparatively simple because all angles are real for any angle of incidence; Program 1 describes this situation. Program 2, incidence in the liquid, is more involved since the refracted longitudinal wave becomes imaginary beyond a certain angle of incidence, i.e. the sine of its angle of refraction $>1$.

Program 1 calculates these ratios for 30 different BETA. The BETA in the program proper is in radians which is transformed to BETAG in degrees. The printout in column BETA is actually the value of BETAG. The program is written so that the angle of incidence increases from 0 to $90^\circ$ in steps of $3^\circ$.

Program 2 operates with GAMMA in the loop (statement 21). The reason for selecting this angle rather than the angle of incidence ALPHA as the variable is the following: For each combination solid-liquid there is a different angle of incidence for which either the longitudinal or the shear wave become imaginary. Thus, after a certain ALPHA, there is no use calculating. Rather than finding this critical angle for each combination and programming the computer accordingly, it is much easier to do the calculations in terms of GAMMA because this angle will run from $0^\circ$ to $90^\circ$ in any event, regardless of the particular situation.

This program is written so that GAMMA decreases from $90^\circ$ to $0^\circ$ in steps of $2^\circ$, and this covers the entire range of interest as far as ALPHA and BETA are concerned. The program does, however, print out the corresponding ALPHA rather than the GAMMA. The ALPHA is calculated from Snell's law.

Obviously, the cutoff angle for the shear wave (GAMMA = $90^\circ$) in terms of ALPHA is the first entry in the ALPHA column. The cutoff angle for the longitudinal wave is calculated and printed out at the end of each set of results.

Program 1 prints out the appropriate RHO2, VL2, RHO1, VL1 at the end of the results.

Program 2 prints out the applicable RHO1, VL1, RHO2, VL2, VS2 at the top of the results.

In either case subscripts 1 refer to liquid, subscripts 2 to solid.

For both programs data tape or deck must list values in following order: RHO1, VL1, RHO2, VL2, VS2.

PROGRAM 1

**Solid-Liquid Boundary, Incidence in Solid, Incident Wave Longitudinal**
**Angle of Incidence = BETA.**

```
11 FORMAT(5HRHO1=,E10.4/4HVL1=,E10.4)
12 FORMAT(5HRHO2=,E10.4/4HVL2=,E10.4)
13 FORMAT(E6.4)
14 FORMAT(1X,8H(RL/I)SQ,7X,8H(RS/I)SQ,7X,7H(T/I)SQ,8X,4HBETA)
15 FORMAT(4(E11.5,4X))
16 FORMAT(I2)
   READ16,N
   DO22I=1,N
   READ13,RHO1
   READ13,VL1
   READ13,RHO2
   READ13,VL2
   READ13,VS2
   PUNCH14
   BETA=0
   DO23K=1,30
   SIB=SINF(BETA)
   COB=COSF(BETA)
   SIZB=SINF(2*BETA)
   WL=VL1/VL2
   WS=VS2/VL2
   COA=SQRTF(1.0-(WL*SIB)**2)
   SIG=WS*SIB
   COG=SQRTF(1.0-SIG**2)
   GAM=ATANF(SIG/COG)
   SIZG=SINF(2*GAM)
   COZG=COSF(2*GAM)
   COZGS=COZG**2
   UNTEN=WS**2*SIZB*SIZG+COZGS+(WL*RHO1*COB)/(RHO2*COA)
   RELO=(UNTEN-2*COZGS)/UNTEN
   RELOQ=RELO**2
   RETRQ=(WS*2*COZG/UNTEN)**2*SIZB*SIZG
   DURCHQ=1.0-RETRQ-RELOQ
   BETAG=BETA*57.29578
```

```
      PUNCH15,RELOQ,RETRQ,DURCHQ,BETAG
   23 BETA =BETA+0.0523598
      PUNCH12,RHO2,VL2
   22 PUNCH11,RHO1,VL1
      STOP
      END
      END
```

Sample Data Tape or Cards

```
02
1.0000
1490.0
2.7000
6330.0
3130.0
1.0000
1490.0
7.8000
5850.0
3230.0
```

Top number, (=N), indicates how many sets of data are to be calculated, 02 in this case, namely aluminum-water and steel-water. Values of densities and velocities must be in order as sequence of READ13 statements indicate.

Sample Printout Results (Program 1)

| (RL/I)SQ | (RS/I)SQ | (T/I)SQ | BETA |
|---|---|---|---|
| .70496E 00 | .00000E-32 | .29503E 00 | .00000E-32 |
| .70086E 00 | .44751E-02 | .29466E 00 | .29999E 01 |
| ⋮ | ⋮ | ⋮ | ⋮ |

```
RHO2= .2700E 01
VL2= .6330E 04
RHO1= .1000E 01
VL1= .1490E 04
```

PROGRAM 2

Liquid-Solid Boundary, Incidence in Liquid, Incident Wave Longitudinal
Angle of Incidence = ALPHA.

```
1 FORMAT(5HRHO1=,E10.4/4HVL1=,E10.4)
2 FORMAT(5HRHO2=,E10.4/4HVL2=,E10.4/4HVS2=,E10.4)
3 FORMAT(E6.4)
4 FORMAT(1X,7H(R/I)SQ,8X,8H(TL/I)SQ,7X,8H(TS/I)SQ,7X,5HALPHA)
5 FORMAT(4(E11.5,4X))
6 FORMAT(E11.5,19X,E11.5,4X,E11.5)
7 FORMAT(11HCUTOFFXLONG,E11.5)
8 FORMAT(I2)
  READ8,N
  DO35I=1,N
  READ3,RHO1
  READ3,VL1
  READ3,RHO2
  READ3,VL2
  READ3,VS2
  PUNCH1,RHO1,VL1
  PUNCH2,RHO2,VL2,VS2
  PUNCH4
  GAMMA=1.5707963
  DO21K=1,45
  SYN=SINF(GAMMA)
  SUN=2*SINF(2*GAMMA)
  PRO=SYN*SUN
  COG=COSF(GAMMA)
  QRO=PRO*COG
  QUA=SYN**2
  BOY=1.0-((VL1/VS2)**2)*QUA
  GAL=SQRTF(BOY)
  ARM=(1.0-QRO)*VL2*RHO2*GAL/(VL1*RHO1)
  PAA=GAL*PRO*VS2*RHO2/(VL1*RHO1)
  DIV=1.0-PAA
  ROT=1.0+PAA
  UA=((VL2/VS2)**2)*QUA
  BOAC=1.0-UA
  BEAR=SQRTF(BOAC)
```

```
      IF(BOAC)31,32,32
C     THIS IS FOR COSINE BETA REAL
   32 TOPS=(BEAR*DIV-ARM)**2
      BOTS=(BEAR*ROT+ARM)**2
      RAS=TOPS/BOTS
      CS=COSF(2*GAMMA)
      CSS=CS**2
      TOPTLA=4*CSS*ARM*BEAR/(1.0-QRO)
      TLAS=TOPTLA/BOTS
      TSAS=1.0-RAS-TLAS
      SNALFA=(VL1/VS2)*SYN
      ALPHAR=ATANF(SNALFA/GAL)
      ALPHA=ALPHAR*57.29578
      PUNCH5,RAS,TLAS,TSAS,ALPHA
      GO TO 21
C     THIS IS FOR COSINE BETA IMAGINARY
   31 BUT=ARM**2
      UP=(1.0-PAA**2)*(-BOAC)-BUT
      TOPIMS=UP**2-4*BOAC*BUT
      BELO=(ROT**2)*(-BOAC)+BUT
      BOTIMS=BELO**2
      RACOS=TOPIMS/BOTIMS
      TSACOS=1.0-RACOS
      SNALFA=(VL1/VS2)*SYN
      ALPHAR=ATANF(SNALFA/GAL)
      ALPHA=ALPHAR*57.29578
      PUNCH6,RACOS,TSACOS,ALPHA
      GO TO 21
   21 GAMMA=GAMMA-0.0349065
C     THIS IS THE LONGITUDINAL WAVE CUTOFF ANGLE
      SNCUTL=VL1/VL2
      BANG=SNCUTL**2
      CSCUTL=SQRTF(1.0-BANG)
      CUTLR=ATANF(SNCUTL/CSCUTL)
      CUTL=CUTLR*57.29578
   35 PUNCH7,CUTL
      STOP
      END
      END
```

Sample Data Tape or Cards - Same as for Program 1

Sample Printout Results (Program 2)

RHO1 = .1000E 01
VL1 = .1490E 04
RHO2 = .2700E 01
VL2 = .6330E 04
VS2 = .3130E 04

| (R/I)SQ | (TL/I)SQ | (TS/I)SQ | ALPHA |
|---|---|---|---|
| .10000E 01 | | .00000E-32 | .28426E 02 |
| .92173E 00 | | .78263E-01 | .28408E 02 |
| ⋮ | | ⋮ | ⋮ |
| .77148E 00 | .16482E 00 | .63691E-01 | .12913E 02 |
| ⋮ | ⋮ | ⋮ | ⋮ |
| .70493E 00 | .29435E 00 | .71067E-03 | .95202E 00 |

cutoffxlong .13614E 02

Calculations using these programs were made for boundaries formed by the following substances:

Liquids: Water, Oil.

Solids: Steel, Brass, Copper, Aluminum, Magnesium.

## Ia. Erratum.

Equation (1), page 24 of Technical Report No. 7 which reads

$$(R/I)^2 = \left(\left[\cos\beta - A\cos\alpha(1 - B)\right] / \left[\cos\alpha + A\cos\alpha(1 - B)\right]\right)^2$$

should read

$$(R/I)^2 = \left(\left[\cos\beta - A\cos\alpha(1 - B)\right] / \left[\cos\beta + A\cos\alpha(1 - B)\right]\right)^2$$

# II. Reflection and Refraction of Mechanical Waves at Solid-Liquid Boundaries. II.

by

Walter G. Mayer

## ABSTRACT

The energy ratios of reflected and refracted waves at various solid-liquid boundaries are calculated as a function of the angle of incidence in the solid. The influence of density and wave velocities on the general shape of the resulting curves is discussed. The computer program outlined in Section I of this Report was used to obtain the results discussed here.

## INTRODUCTION

In a previous paper (Section V, Technical Report No. 7) the energy ratios between incident, reflected, and refracted waves at various liquid-solid boundaries were calculated as a function of angle of incidence in the liquid. The present paper deals with the problem of energy partition at boundaries formed by solids and liquids with the incident ultrasonic wave in the solid. The results can be used to arrive at some conclusions concerning the general shape of the curves for various values of density and wave velocities. Some similarities between the results for solid-liquid interfaces and solid-vacuum boundaries given by Arenberg[1] are pointed out. The formulas used for the calculations are based on the equations given by Ergin[2]. The same results can be obtained if one uses the formulas given earlier by Schaefer who investigated ultrasonic mode conversion at iron-xylene and Dekorit-xylene boundaries[3].

## RESULTS

A plane longitudinal wave incident at a boundary formed by a solid (density $\rho_2$) and a liquid (density $\rho_1$) will be partly reflected and partly refracted. If the incidence occurs in the solid the energy of the incident wave will be divided between a reflected longitudinal wave (velocity $V_{L2}$), and a refracted longitudinal wave (velocity $V_{L1}$). Assuming that the energy of the incident longitudinal wave is unity, the energy ratio of reflected longitudinal to incident wave is

$$(L/I)^2 = [(A - B + C)/(A + B + C)]^2. \quad (1)$$

The energy ratio of reflected shear to incident wave is given by

$$(S/I)^2 = 4\ A\ B/(A + B + C)^2. \quad (2)$$

Since no other waves are assumed to be present the energy ratio of the refracted longitudinal wave is

$$(R/I)^2 = 1 - (L/I)^2 - (S/I)^2. \quad (3)$$

The quantities A, B, and C are defined in Section I of this Report.

It is difficult to predict the shape of the three curves from Eqs. (1) - (3) even if only one set of densities and velocities is considered. In order to determine variations in the energy ratios for different combinations of solids and liquids the computer program given in Section I was used, and a set of curves was obtained for substances listed in Table I. The values of Poisson's ratio $\sigma$ and the acoustic impedances $\rho V_L$ are also shown in Table I.

Table I. Velocities (m/sec), Poisson's ratio $\sigma$, and acoustic impedances $\rho V_L$.

| | $V_L$ | $V_S$ | $\rho$ | $\sigma$ | $\rho V_L$ |
|---|---|---|---|---|---|
| Water | 1490 | | 1.00 | | 1.49 |
| Steel | 5850 | 3230 | 7.80 | 0.281 | 45.63 |
| Brass | 4430 | 2123 | 8.10 | 0.351 | 35.88 |
| Aluminum | 6330 | 3130 | 2.70 | 0.338 | 17.09 |
| Magnesium | 5770 | 3050 | 1.70 | 0.306 | 9.80 |

The results of calculations are plotted in Figs. 1 - 4 where the solid line denoted by R indicates the energy ratio of refracted wave to incident wave obtained from Eq. 3; the curves labeled L represent the energy ratio of the reflected longitudinal to incident wave given by Eq. (1); S refers to the reflected shear wave described by Eq. (2).

## DISCUSSION

Equations (1) - (3) are rather involved, and it becomes difficult to estimate the influence of the individual terms and parameters without making many numerical calculations. There are, however, some characteristic features concerning the curves obtained from these equations. The discussion of these features is based on the results shown in Figs. 1 - 4.

The solid-liquid combinations used were chosen not only to give numerical results for a number of substances which are of some importance in ultrasonic and material testing techniques but primarily to obtain various curves which can be compared in order that certain conclusions, which are also valid for other solid-liquid boundaries not treated here explicitly may be drawn. These general conclusions refer to initial energy partition at normal incidence, the minima of the reflected longitudinal wave, and the maxima of the reflected shear wave as a function of acoustic impedances and Poisson's ratio.

The initial values (at $\beta = 0$) of the reflected longitudinal wave and the refracted wave depend only on the magnitude of the acoustic impedances of the two media under consideration. Equation (1) reduces to the well-known reflection formula for normal incidence. The value of $(R/I)^2$ decreases gradually with increasing $\beta$. The shape of this curve is determined primarily by the quantities $V_{L1}\rho_1$ and $V_{L2}\rho_2$ while the shear wave velocity is not a significant parameter.

The shape of the curve for the reflected longitudinal wave for small angles of incidence also depends primarily on the acoustic impedances of the two media. For greater angles of incidence the energy of the reflected longitudinal wave decreases and reaches a minimum. It can be seen from Eq. (1) that in this region the terms A and B are the important parameters because C is about one order of magnitude smaller than either A or B. Since the term C does not influence the minimum of the $(L/I)^2$ curve appreciably the energy near the minimum depends mainly on the ratio $V_{S2}/V_{L2}$ or on Poisson's ratio $\sigma$. Neither the acoustic impedances nor the ratio of densities of the two media influence the minimum to a great extent.

Figures 1 - 4 illustrate the dependence on the Poisson ratio of the minimum value of the reflected longitudinal wave. It should be pointed out that for low values of $\sigma$ this curve may reach two distinct zeroes before reaching the value 1.0 at $\beta = 90^\circ$. This behavior can be predicted from curves published by Arenberg[1] pertaining to solid ultrasonic delay lines. The critical value of Poisson's ratio given there is 0.26; this value is slightly different for the present analysis since in the former case the term C = 0.

The general shape of the $(S/I)^2$ curve cannot be predicted quite as readily. Both $\sigma$ and the acoustic impedances are of importance. However, the behavior may be derived qualitatively by considering Eq. (3) and the general shapes of the curves for the reflected and refracted longitudinal waves. It is apparent from Figs. 1 - 4 that the maximm of this curve will be relatively high only if both the minimum of the $(L/I)^2$ curve and the $(R/I)^2$ curve are low.

A small change in either velocity or density of the liquid medium does not alter the shape of the curves appreciably as long as the acoustic impedance of the liquid is not changed very much. Calculations for solid-oil ($\rho_1 = 0.87$, $V_{L1} = 1740$) boundaries indicate that the energy ratios one obtains differ by no more than 1 per cent from those shown here for solid-water boundaries.

The range of values of the parameters considered here enables one to estimate the behavior of the three curves for similar combinations of solids and liquids without having to calculate the exact energy ratios.

## BIBLIOGRAPHY

1. D. L. Arenberg, J. Acoust. Soc. Am. 20, 1 (1948).
2. K. Ergin, Bull. Seism. Soc. Am. 42, 349 (1952).
3. J. Schaefer, Ph.D. thesis, University of Strassburg (1942). Quoted by E. Hiedemann in Fiat Review of German Science 1939-1946, Physics of Solids (Office of Military Government for Germany, 1947) Part I. Chap. 24, p. 169.

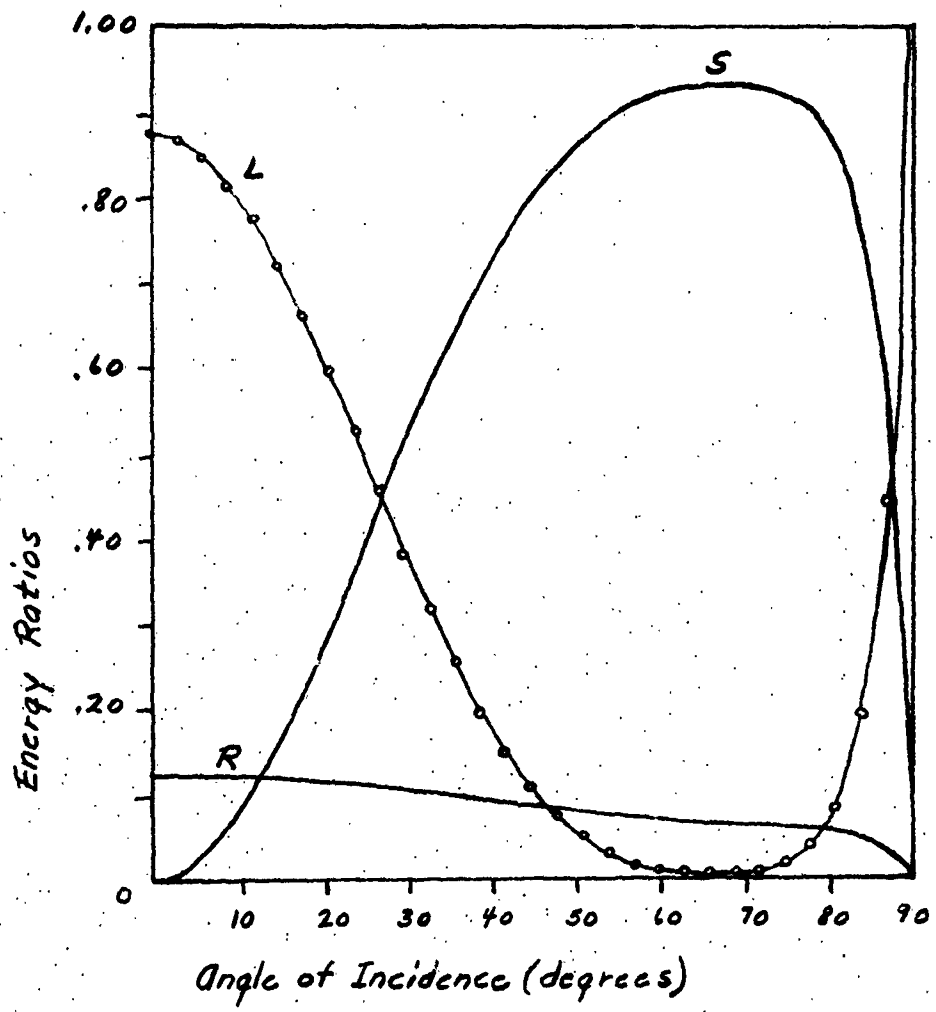



Figure 1. Energy ratios at steel-water boundary. R, refracted longitudinal wave; L, reflected longitudinal wave; S, reflected shear wave.

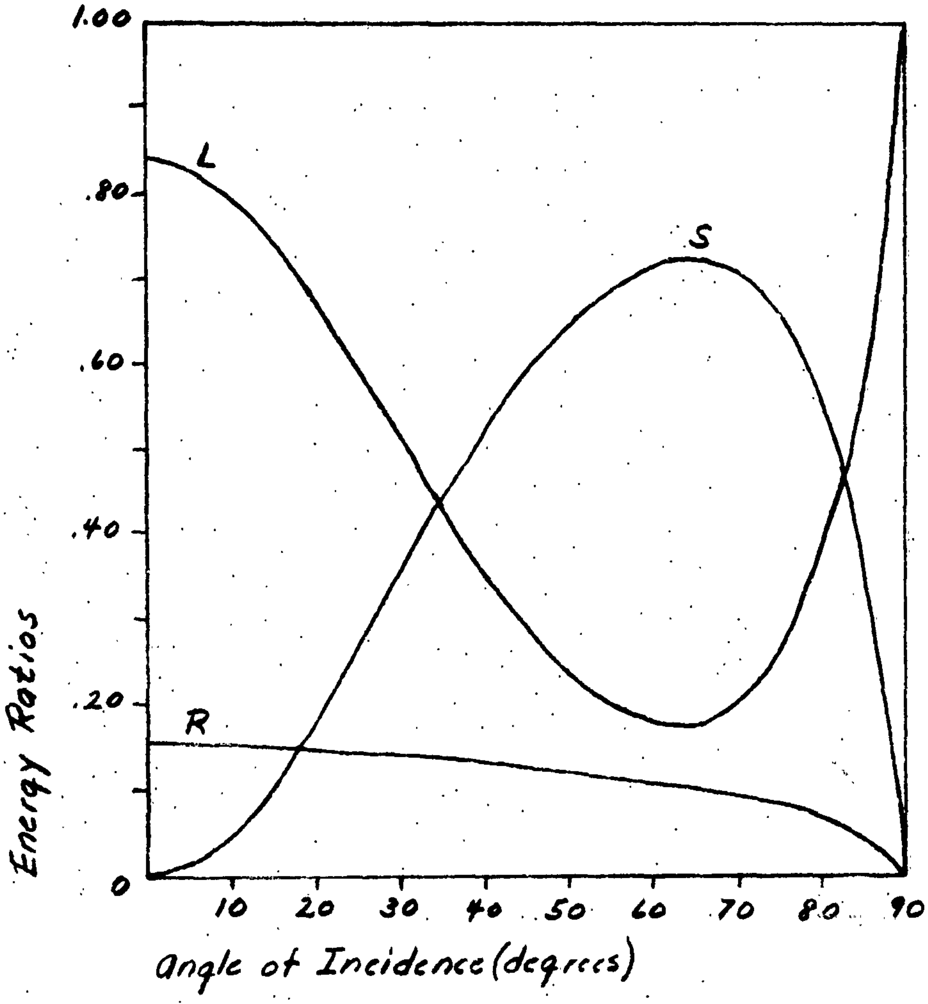



**Figure 2. Same as Figure 1 for brass-water boundary.**

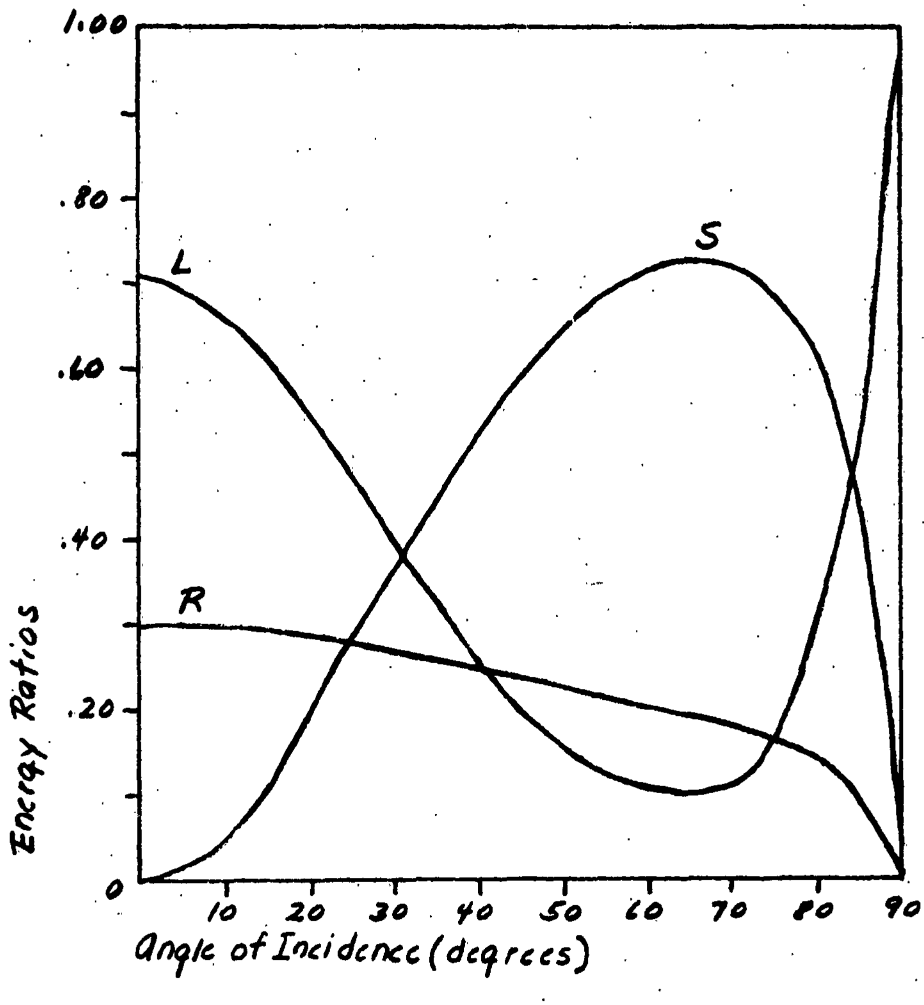



Figure 3. Same as Figure 1 for aluminum-water boundary.

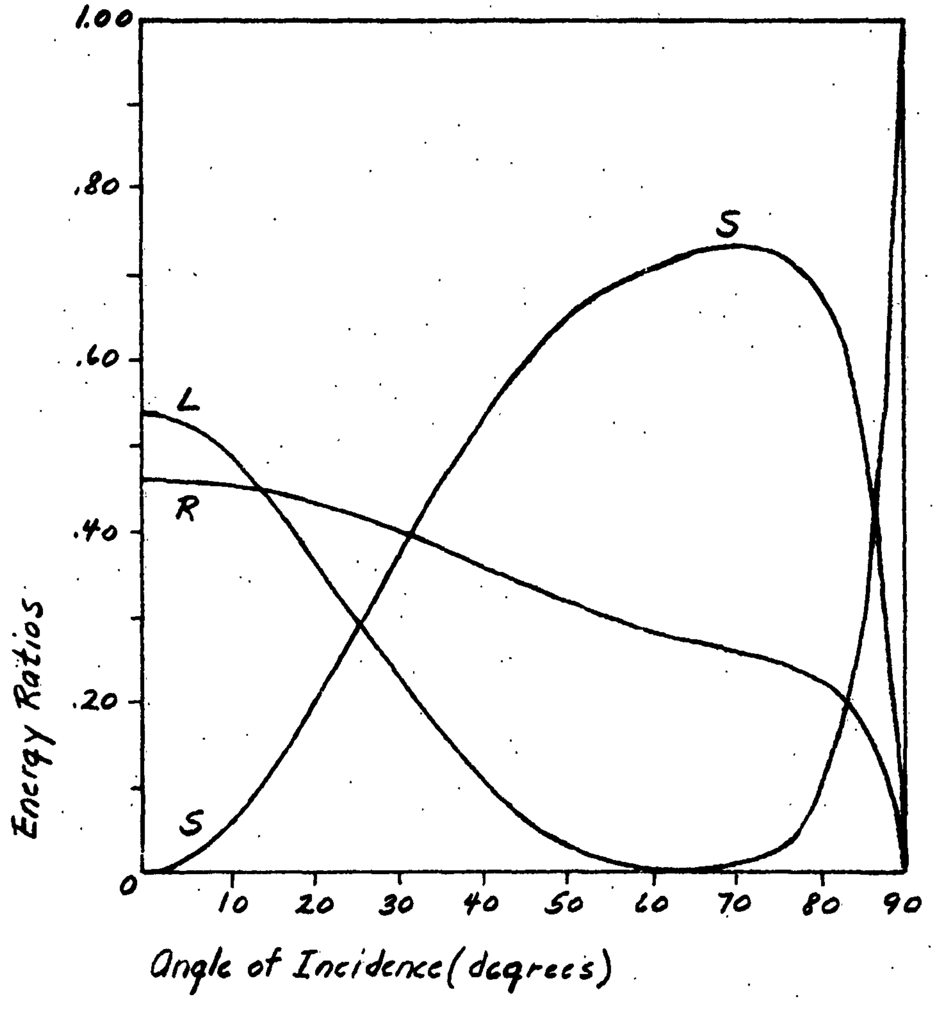



Figure 4. Same as Figure 1 for magnesium-water boundary.

## III. Light Diffraction by Ultrasonic Beams under Non-Raman and Nath Conditions

by

W. R. Klein

The Raman and Nath theory for predicting the light intensities of the various orders due to diffraction by a progressive, sinusoidal, ultrasonic beam has been very successful for cases where experimental conditions are not too extreme. For these conditions, namely where the ultrasonic frequencies are moderate, the ultrasonic beam is rather narrow, and the sound intensities rather low, one may consider the effect of the sound beam on the light beam to be that of a simple phase modulation. For these conditions the intensities of the diffraction orders have been shown to be

$$I_n = J_n^2(v)$$

where n is the order number, $J_n(v)$ is the nth order Bessel function of argument v given by

$$v = \frac{2\pi\mu L}{\lambda}$$

where $\mu$ is the variation in refractive index produced by the ultrasound, L the width of the ultrasonic beam and $\lambda$ the wavelength of the light.

Under more extreme experimental conditions, the effect of the ultrasound on the light beam is no longer a simple phase modulation, but is now a combination of phase and amplitude modulation.

A systematic study of the deviations of the measured values of the light intensities in the zeroth and first diffraction orders from those values predicted by Raman and Nath has been performed under experimental conditions more extreme than those for which the Raman and Nath theory is valid.

A paper containing a complete description of the experimental conditions as well as a comparison of the results of measurements with other theories has been submitted for publication.[1] A copy will be forwarded in a later report.

The following pages show the results of comparison of the measured values with those predicted by the theory for various beam widths. The figures show the gradual deviation from the predicted light intensity distribution as the width of the sound beam is increased. The same transducer is used for the curves shown here. The width of the beam is changed by means of a suitable aperture in front of the transducer. The smallest width of the sound beam (L) is 1.6 cm which is increased in steps of 4 mm up to an L of 4.7 cm.

These curves are used[2] to determine the effective sound beam width emitted by a transducer radiating without limiting apertures placed in front of it. Since knowledge of L is essential for transducer calibrations the curves are reproduced here in detail to serve as reference curves.

## REFERENCES

1. W. R. Klein, Physica (submitted).
2. W. G. Mayer, J. Acoust. Soc. Am. (to be published).

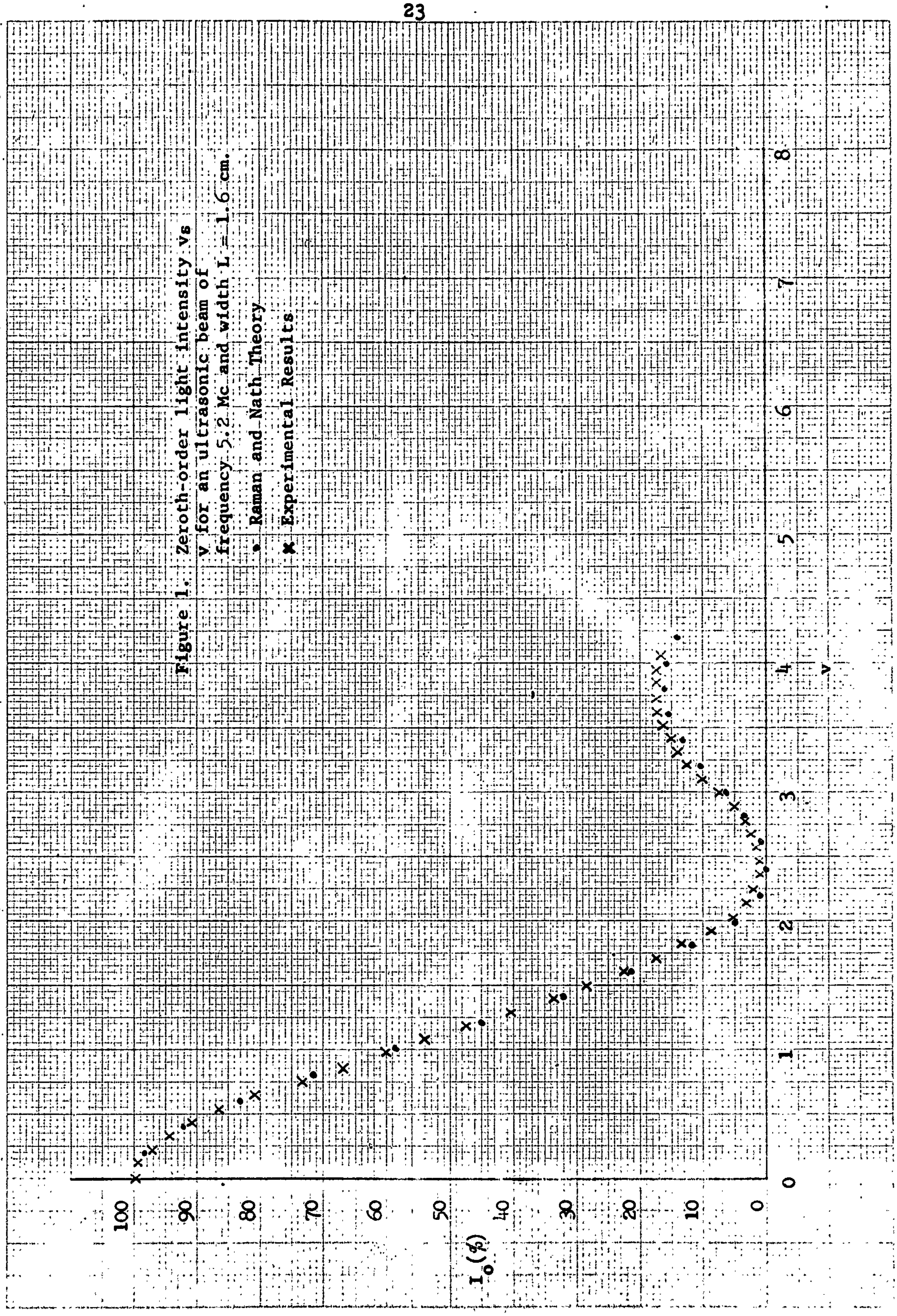



Figure 1. Zeroth-order light intensity vs v for an ultrasonic beam of frequency 5.2 Mc and width L = 1.6 cm.

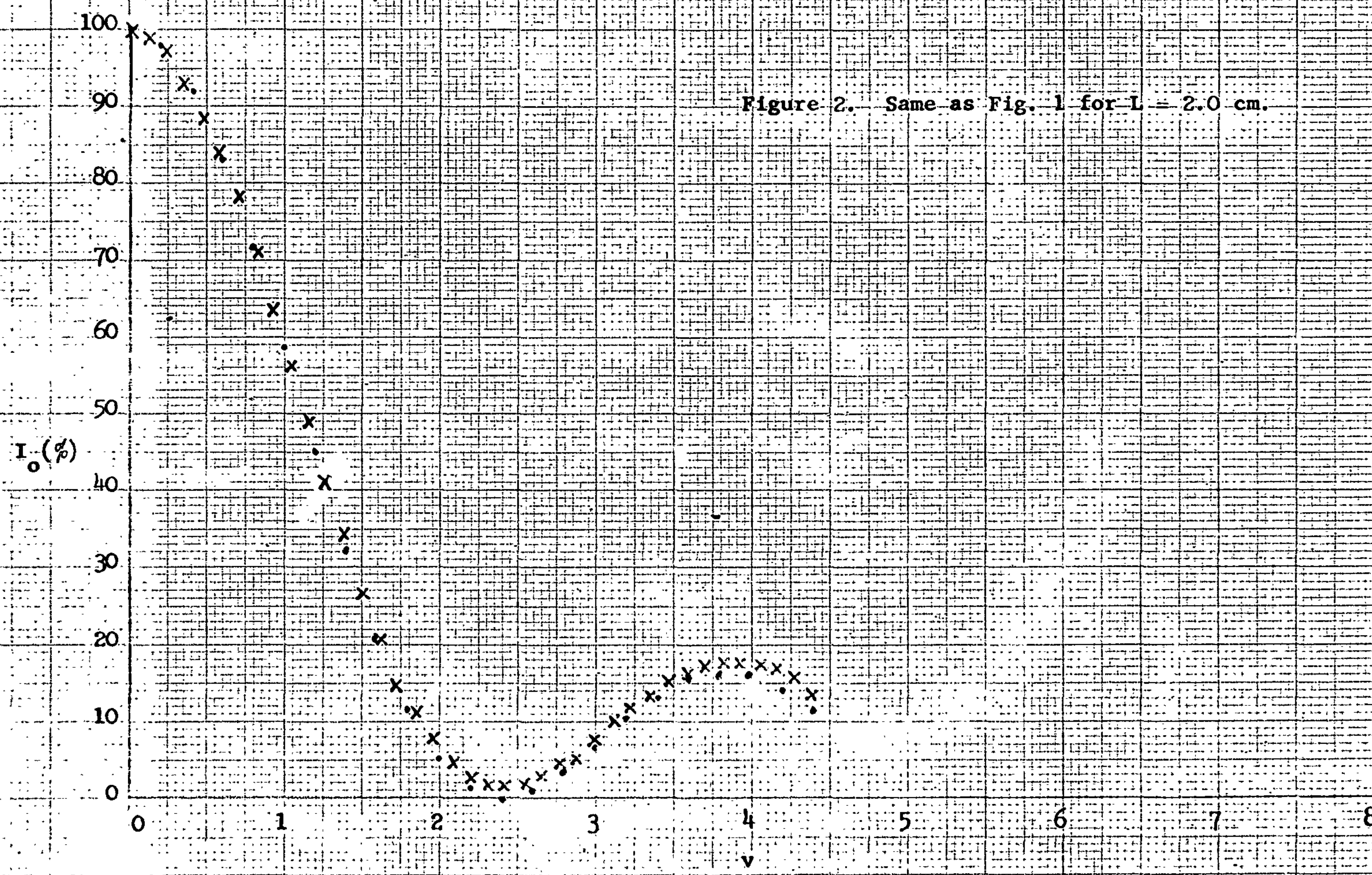



Figure 2. Same as Fig. 1 for L = 2.0 cm.

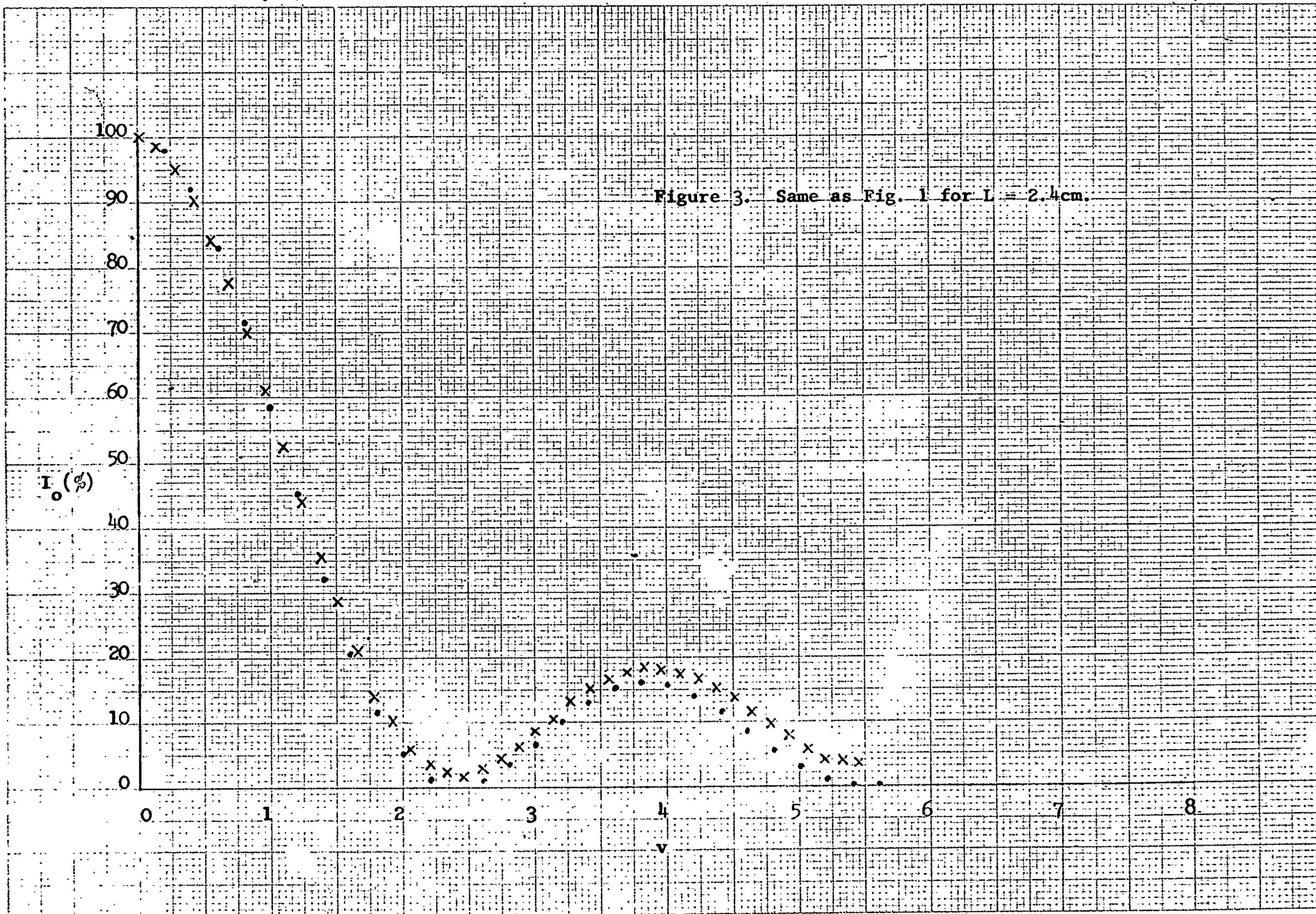



Figure 3. Same as Fig. 1 for L = 2.4cm.

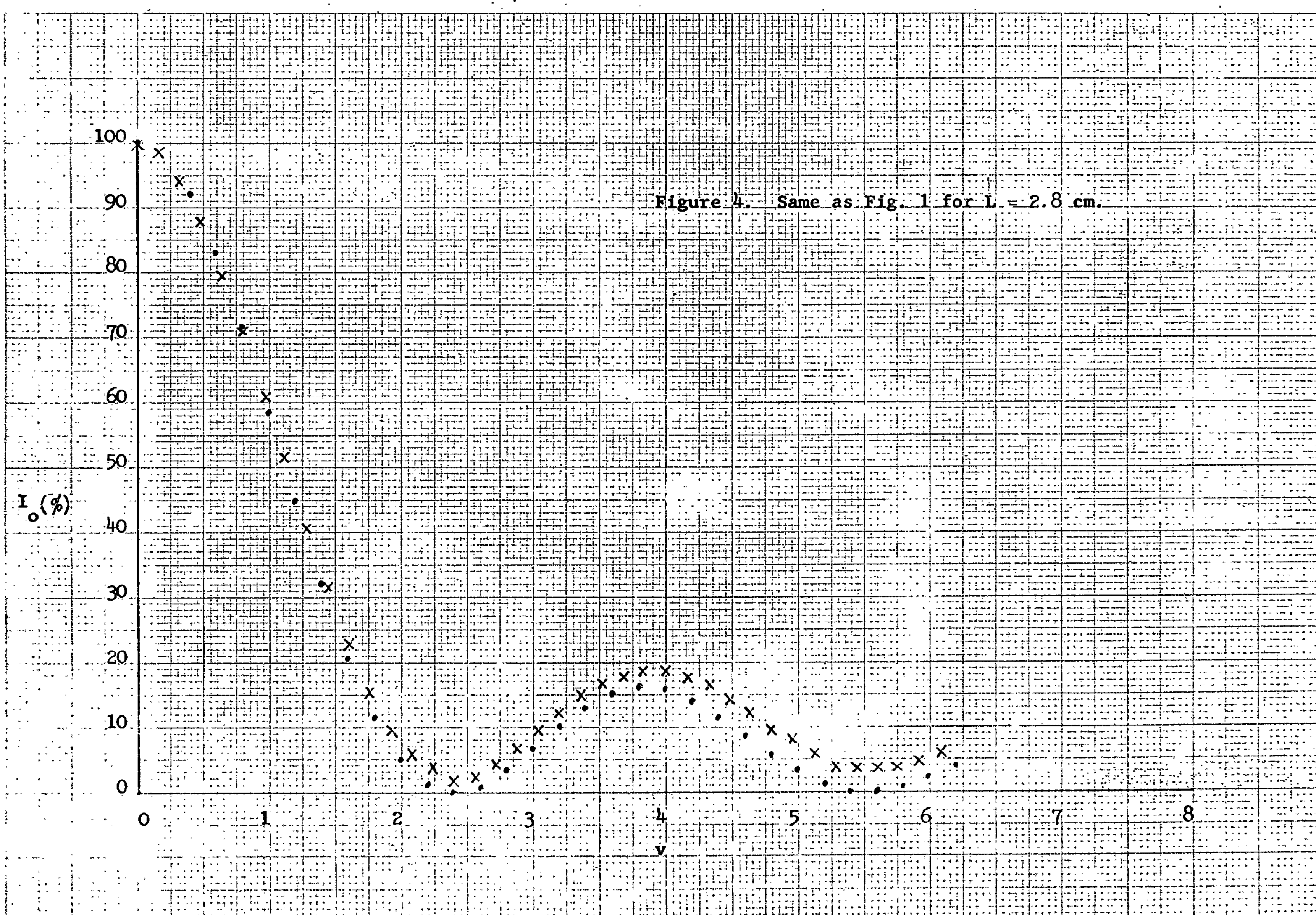



Figure 4. Same as Fig. 1 for L = 2.8 cm.

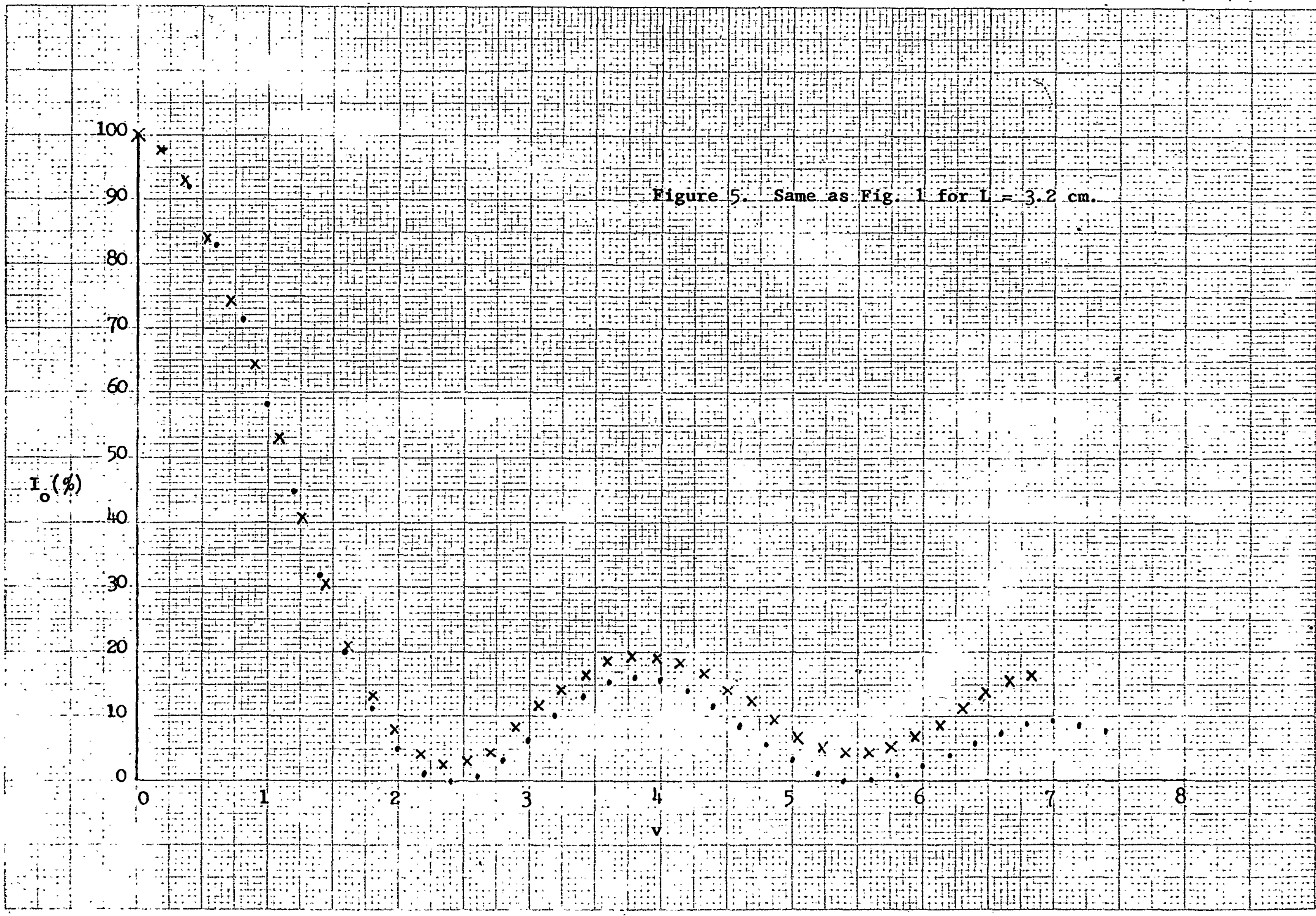



Figure 5. Same as Fig. 1 for L = 3.2 cm.

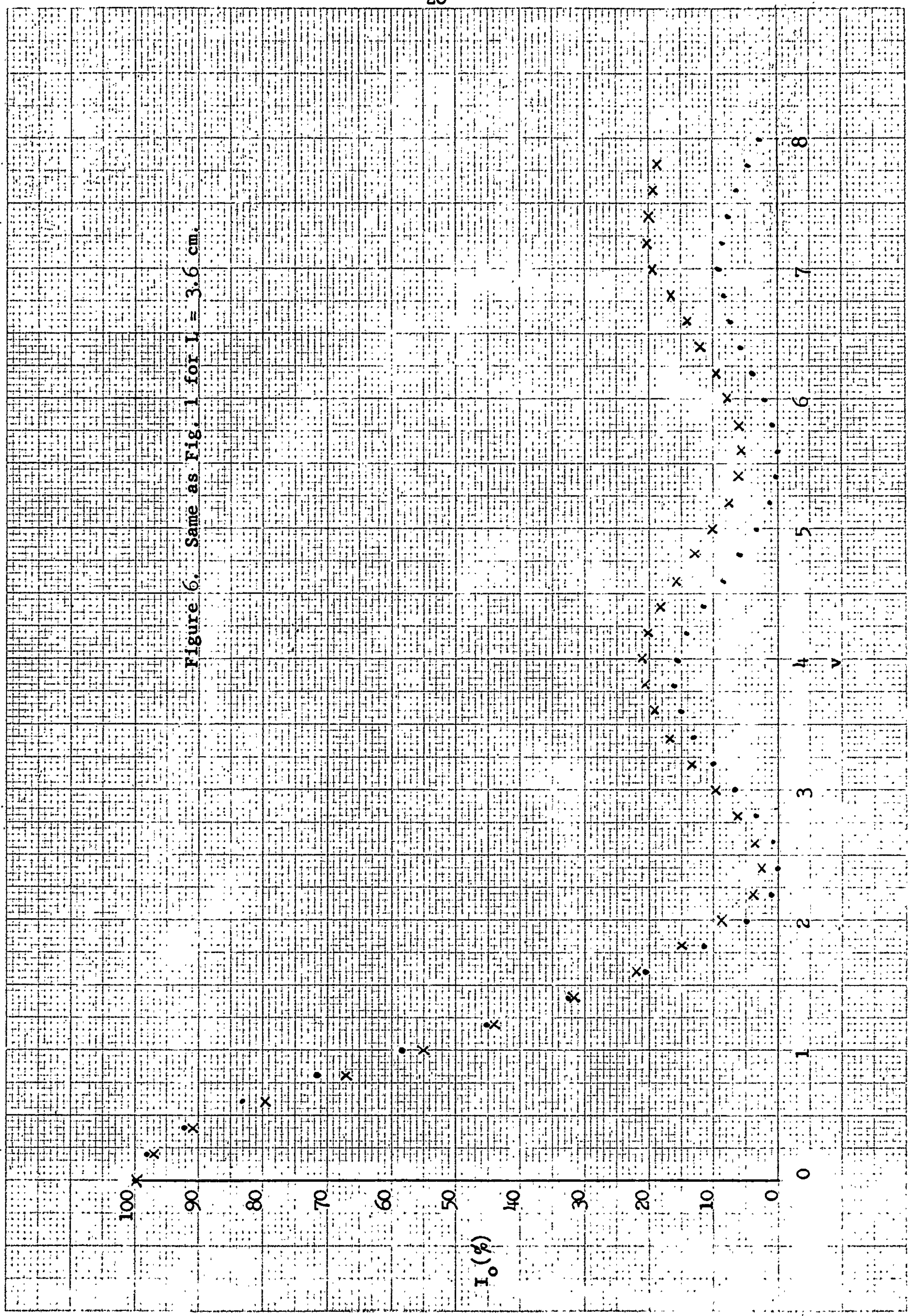



Figure 6. Same as Fig. 1 for L = 3.6 cm.

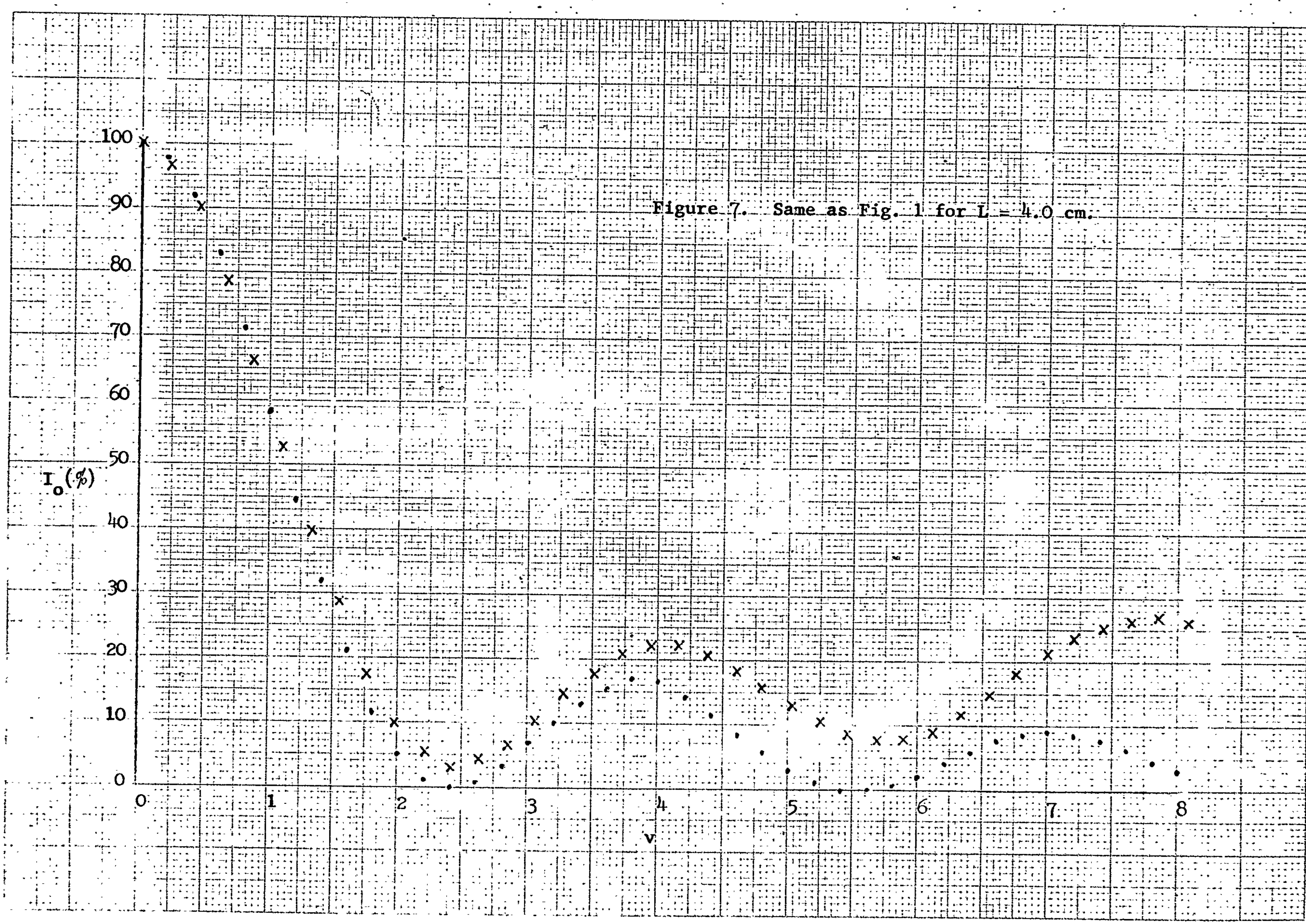



Figure 7. Same as Fig. 1 for L = 4.0 cm.

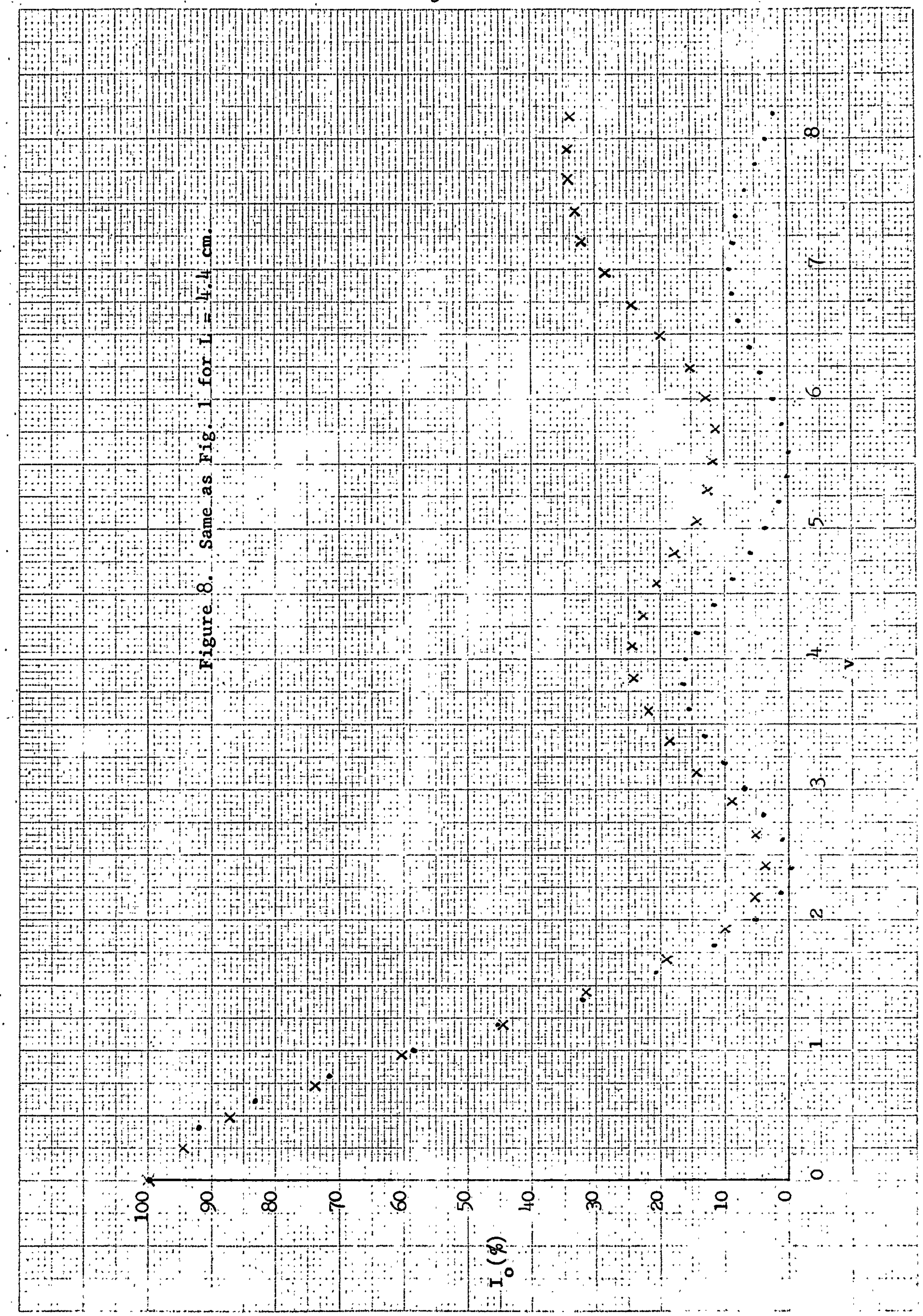



Figure 8. Same as Fig. 1 for L = 4.4 cm.

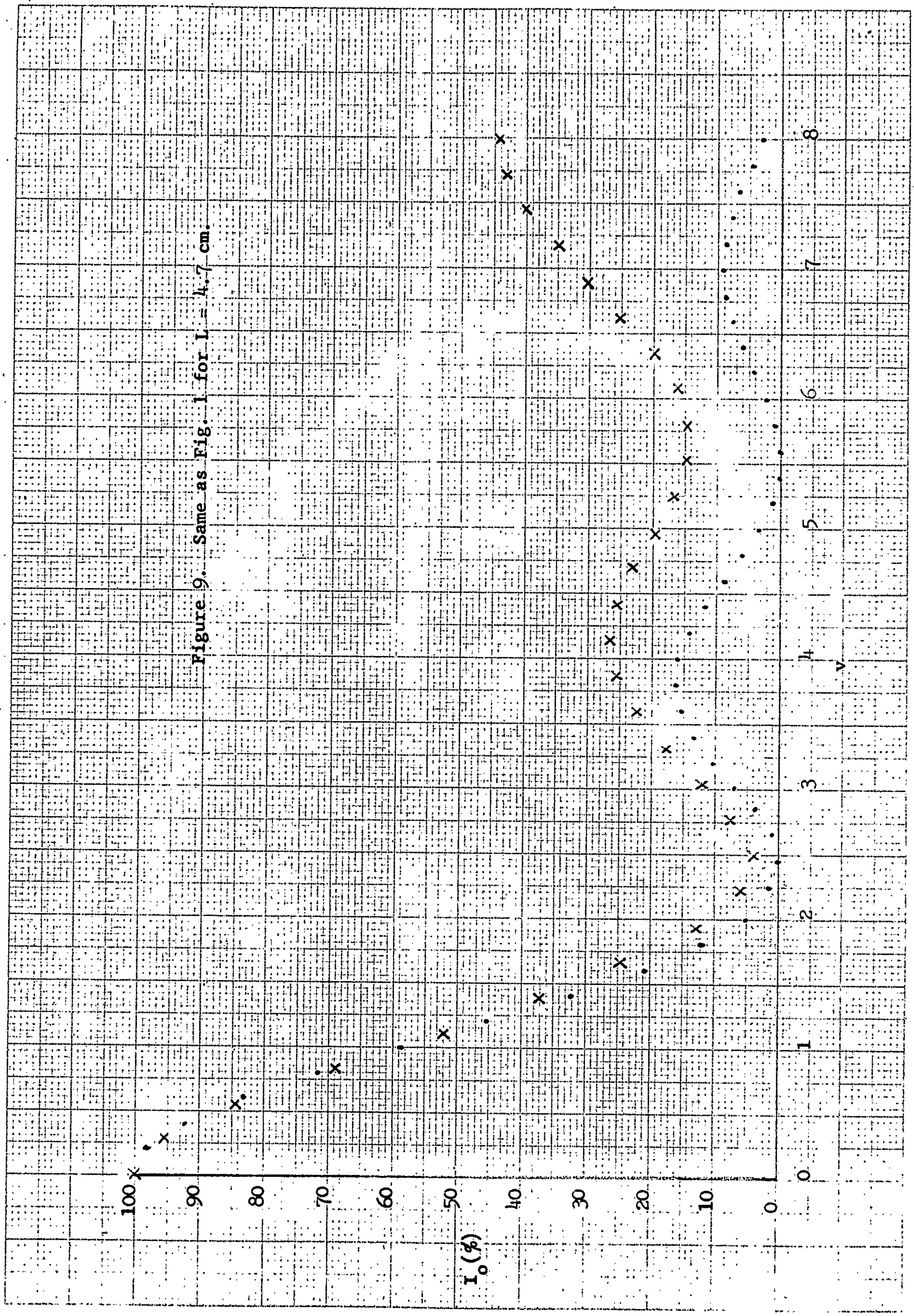



Figure 9. Same as Fig. 1 for L = 4.7 cm.

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