UNPUBLISHED PRELIMINARY DATA

# FINAL REPORT

on the

# STUDY AND EVALUATION OF ELECTRONOGRAPHY

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# SOME MEASUREMENTS OF DETECTIVE QUANTUM EFFICIENCIES FOR CLASSICAL PHOTOGRAPHY AND ELECTRONOGRAPHY

## Introduction.

During the last ten years or so considerable effort has been expended in the development of photoelectronic image devices suitable for use in astronomy, in the expectation that they can provide a far more efficient means of detecting radiation than direct photography. The basis for these expectations lay in estimates[1] that, in a full exposure to blue light, the best photographic emulsions effectively record only about one thousandth of the number of incident photons; whereas it was known that photocathodes could be made which emit, on average, one photoelectron for every ten or fewer incident blue photons.[2] Hence it was argued that, if by some means all these electrons could be registered in an image preserving manner, the resulting detector would be two orders of magnitude more efficient than photographic emulsions.

In fact, a detector of this kind had already been envisaged many years before by Lallemand.[3] In his now celebrated electronic camera the photoelectrons are accelerated and focused on to an electron sensitive emulsion, where each makes a short track of developable grains. Considerable technical obstacles lay between the conception of this arrangement and its development into a useable tool of observation, but when they had been overcome it was found[4] that the camera was indeed fifty to a hundred times more sensitive than photographic emulsions. This result was encouraging confirmation of earlier predictions, and it was taken to be the target performance which might be approached by other, and more convenient, forms of photoemissive device, still in course of development.

Recently, however, it has begun to appear doubtful whether the superiority of photoelectronography over classical photography is as great as was at first supposed. In a comparison of the times required to record threshold images at 4000° A with a Lallemand camera and with Kodak 103a-o emulsion, Walker[5] has found a factor of 40 in favour of electronography when the exposure time for the emulsion was 7 hours, but only a factor of 10 when the exposure time was 15 seconds. The difference between these values is consistent with the known reciprocity failure of the 103a-o emulsion, and in subsequent experiments in which the comparison was made with baked Kodak 11a-o emulsion, the speed gain was found to remain constant at a value about 10 over a wide range of exposure times.[6] A value of about 10 in favour of electronography has also been obtained by Baum and McGee[7] from a comparison of baked 11a-o emulsion with Lenard window tubes of the type described by McGee and Wheeler[8].

Superficially these results might be accounted for if it were supposed that the original estimates of the efficiency of classical photography were too low by an order of magnitude. This is a view expressed by Fellgett,[9] who has given reasons for supposing that the fraction of incident photons recorded by the best photographic emulsions is nearer $10^{-2}$ than $10^{-3}$. If this were the case, the high relative efficiency claimed earlier for the Lallemand camera would have to be explained as being obtained under conditions which were not optimum for photography. Needless to say such an interpretation would carry important implications for photoemissive devices in general, indicating that when perfected for astronomical use they can be expected to yield a worthwhile, but not a spectacular, improvement in detection efficiency, at least in the blue region of the spectrum. However, it seems at present premature to draw this conclusion

It is not certain that the figures given by Walker, and by Baum and McGee, represent measurements of the same quantity, nor that either is a measure of the ratio of the quantum efficiency of the photocathode and the equivalent quantum efficiency of the photographic emulsion, which was the subject of the original estimates. It seems at least possible that the assessments of signal-to-noise ratio were biassed in favour of direct photography, and it is further possible that the signal from the photocathode was degraded to an unsuspected extent by the electronographic recording.

It is clear that measurements of the relative efficiency of photography and photoelectronography will not in themselves serve to distinguish between these possibilities. What is required is reliable information about the absolute efficiencies of both processes. The measurements described in this report were intended as a first step towards acquiring such information. Because of the well-known uncertainties of absolute photometry they should be treated with some reserve. For the same reason and also because the present measurements relate to a very restricted set of the relevant parameters, it is to be hoped that they may be repeated and extended elsewhere.

Detective Quantum Efficiency.

The concept of detective quantum efficiency, and its application to photographic plates, has been treated at length by Jones, [10] but for the sake of completeness a brief account is given here.

Consider a radiation detector which integrates over a time interval T and suppose it receives a steady light signal such that the number of photons arriving in an interval T is n with mean $\bar{n}$. Let s be the corresponding output of the detector, with mean $\bar{s}$, and r. m. s. fluctuation $(\overline{\Delta^2 s})^{1/2}$. The means $\bar{n}$

and $\bar{s}$ are related by the response function $S$ of the detector:

$$\bar{s} = S(\bar{n}), \tag{1}$$

and we may write

$$(\overline{\Delta^2 s})^{1/2} = S(\bar{n} + N) - S(\bar{n}) \tag{2}$$

where N is the increment of mean input which produces an increment of mean output equal to the r. m. s. fluctuation of output. The number N is the noise equivalent input of the detector, expressed in photons; and the signal-to-noise ratio R for integration time T is

$$R = \frac{\bar{n}}{N} \tag{3}$$

With light sources of astronomical interest the incident photons obey a Poisson distribution. An imaginary detector, with which measurements were limited in accuracy only by fluctuations inherent in the signal, would therefore achieve the same signal-to-noise ratio R if it received $\nu$ photons in an interval T, where

$$\nu^{1/2} = R \tag{4}$$

The number $\bar{\nu}$ is the effective number of photons stored by the detector during an interval T, and the detective quantum efficiency q of the detector is defined as the ratio $\bar{\nu}/\bar{n}$. Thus

$$\bar{\nu} = q\bar{n} \tag{5}$$

and from (3), (4) and (5),

$$q = \frac{\bar{n}}{N^2}. \tag{6}$$

To apply these relations to the case of a photographic plate we consider the detector to be an element of the plate, of area A, and suppose that during a uniform exposure the number of photons incident on such an area is n, with mean $\bar{n}$. The mean exposure $\mathcal{E}$ in photons per unit area, then has the value E where

$$\bar{n} = AE \tag{7}$$

Suppose that, after development, the density of the plate is sampled with an aperture also of area A, and found to have mean value D with r. m. s. fluctuation

$\overline{(\Delta^2 D)}_A^{1/2}$ If the characteristic curve of the emulsion, relating mean density $\bar{D}$ and mean exposure is

$$\bar{D} = \mathcal{D}(E)$$

we have, in analogy with (1),

$$\bar{D} = \mathcal{D}(E) = \mathcal{D}\left(\frac{\bar{n}}{A}\right) \tag{8}$$

Hence, in analogy with (2), the noise equivalent input N of the detector, in photons, is given by

$$\overline{(\Delta^2 D)}_A^{1/2} = \mathcal{D}\left(\frac{\bar{n}+N}{A}\right) - \mathcal{D}\left(\frac{\bar{n}}{A}\right) = \mathcal{D}'\left(E + \frac{N}{A}\right) - \mathcal{D}'(E) \tag{9}$$

If $\mathcal{D}'$ is taken to be a linear function of $E$ over the density range $\overline{(\Delta^2 D)}^{1/2}$ about $\bar{D}$, this reduces to

$$\overline{(\Delta^2 D)}_A^{1/2} = \frac{N}{A}\left(\frac{d\mathcal{D}}{dE}\right)_{\bar{D}} \tag{10}$$

From (6), (7), and (10), the detective quantum efficiency $q_{ph}$ of the plate is therefore

$$q_{ph} = \frac{E}{A\overline{(\Delta^2 D)}_A}\left(\frac{d\mathcal{D}}{dE}\right)_{\bar{D}}^2 \tag{11}$$

Similarly from (5), (7) and (10) the effective number of photons $\bar{n}_A$ stored by area A of the plate is

$$\bar{n}_A = \frac{E^2}{\overline{(\Delta^2 D)}_A}\left(\frac{d\mathcal{D}}{dE}\right)_{\bar{D}}^2 \tag{12}$$

Similar considerations apply to photoelectronography, but in this case it is necessary to take into account the possibility of a change of image scale between the photocathode and the electron-sensitive plate. Let M be the electron-optical magnification between cathode and emulsion. The area of cathode which contributes to the blackening of area A of the emulsion is then $A/M^2$, and the corresponding mean number of incident photons for mean exposure E is

$$\bar{n} = \frac{AE}{M^2} \tag{13}$$

If the function $\bar{D} = \mathcal{D}(E)$ is now understood to be the relation between mean density of the plate and mean exposure at the cathode, we have, instead of (8)

$$\bar{D} = D(E) = A\left(\frac{M^2 N}{A}\right) \tag{14}$$

and instead of (9),

$$(\Delta^2 D)_A^{1/2} = D\left(E + \frac{M^2 N}{A}\right) - D(E) \tag{15}$$

Hence, to the same approximation as (10),

$$(\Delta^2 D)_A^{1/2} = \frac{M^2 N}{A}\left(\frac{dA}{dE}\right)_D \tag{16}$$

From (6), (13) and (16), the detective quantum efficiency of the electronographic device is therefore

$$\eta_{DQE} = \frac{M^2 E}{A(\Delta^2 D)_A}\left(\frac{dA}{dE}\right)_D^2 \tag{17}$$

The expression for the effective number of photons stored in area A of the emulsion remains the same as (12).

The above discussion is in terms of response to uniform illumination, and makes no explicit reference to image-preserving capability of the detector. There is, however, an underlying assumption in the derivation of the noise equivalent input N from equation (8), which implies that the mean increment of density resulting from a given exposure over an element of area A is independent of A. This is nearly enough true so long as the element is large enough to include many resolution elements of the plate; but as A approaches the area of a resolution element, the density increment resulting from a given exposure falls, because some of the photons incident inside the area lead to blackening outside it. Hence as A becomes smaller, the noise equivalent input N given by (9) is increasingly smaller than the true value, and the detective quantum efficiency given by (11) is correspondingly too large.

Thus the detective quantum efficiency of (11) (and similarly of (17) ), with A understood to be large compared with the area of a resolution element, is

appropriate only to the detection of a low contrast image which is completely resolved. The present investigation is confined to measurements of this quantity, which may be called the macroscopic detective quantum efficiency for representative photographic and electronographic emulsions. For images which are not fully resolved, the detective quantum efficiency falls below the macroscopic value by an amount which depends both on the structure of the image and the resolution characteristics of the detector. This situation is conveniently dealt with by Fourier methods but it is out of place to discuss it here.

Although the expressions (11) and (17) have significance as quantum efficiencies only when A is large compared with the area of a resolution element, it is fortunately not necessary to measure the density fluctuations with such large apertures. It is known that, for a wide range of values of sampling area A, the density fluctuations in uniformly exposed photographic emulsions satisfy the Selwyn granularity law $A\overline{(\Delta\, ^2D)}_A$ = constant, which is derived theoretically on the basis of a random distribution of grain sizes and positions. There is evidence that when A is made sufficiently small, the produce $A\overline{(\Delta\, ^2D)}_A$ falls below its value for A large, either because of optical imperfections in the densitometer or because of short range density correlations. The use of measurements of mean square density fluctuation made with too small an aperture would therefore lead to calculated detective quantum efficiencies which are incorrectly high. The possibility of errors of this kind has been stressed by Shaw.[11] He interprets some data on Kodak emulsions, published by Fellgett, as showing that a circular sampling aperture should not be less than 40 microns in diameter, and suggests that this is in agreement with a recommendation of Zweig et al.[12] However, an examination of all the data available to Fellgett, which has been set out by Jones.[10]

shows that Shaw's conclusion is unjustified; there is some indication that for fast, coarse-grained emulsions an aperture 10 microns in diameter is too small, but no evidence that apertures of 20 and 40 microns diameter lead to significantly different results. A similar conclusion may be drawn from data published by Higgins and Stultz.[13] Shaw's interpretation of the paper by Zweig et al appears to be based on a mis-reading. For uniformly exposed electronographic emulsion, the relation between $A(\overline{\Delta\ ^2D})_A$ and A has been examined by Vernier.[14] In this case short-range density correlations are to be expected because of the finite length of the electron tracks, but Vernier's results show that, for Ilford G. 5 and C. 2 emulsions exposed to electrons of 25 Kev energy, $A(\overline{\Delta\ ^2D})_A$ remains constant for circular apertures down to 16 microns in diameter. It therefore appears safe to assume that a circular sampling aperture of 25 microns diameter, which was the size used for density measurements in the present work, is large enough to give reliable values of macroscopic detective quantum efficiency.

Photographic measurements.

The photographic measurements were made with Kodak IIa-O plates, some of which were used as supplied by the manufacturers, whilst others were baked in the presence of a drying agent for three days at 50°C before exposure. All exposure times were 1 minute, and development was for 4 minutes in Kodak D-19 developer at 68°F.

Density measurements were made with the Yerkes microdensitometer, which was slightly modified for the purpose. The usual first slit was replaced by a small hole so that the condenser, of N. A. 0. 2, illuminated a circular area of the plate about 40$\mu$ in diameter. The objective, also of N. A. 0. 2, projected an image of this area on to a circular aperture about 625$\mu$ in diameter, which

was substitued for the usual second slit in front of the photomultiplier. For focusing purposes, this aperture and the image of the plate formed by the objective could be viewed with a microscope and prism assembly, which could be inserted at will between the aperture and the photomultiplier. The magnification introduced by the objective was 26.0, so that the effective sampling aperture on the plate was a circle of diameter approximately 24$\mu$. Tests of the arrangement when the object was an opaque circular disc just covering the sampling aperture showed that stray light from the region of the plate outside the aperture was negligible. The time constant of the only amplifier-recorder combination available at the time the measurements were made was several seconds, and this was long enough to damp significantly the density fluctuations recorded at the lowest motor-driven plate carriage speed. All density measurements were therefore made with the plate carriage drive disconnected; the carriage was advanced by hand at intervals of 10 seconds through a distance of about 1/30 mm, in such a way that an area of the plate $\frac{1}{2} \times \frac{1}{2}$ mm yielded about 200 independent measurements of density. From this sample the mean density, and the r. m. s. density fluctuation, were calculated.

A range of nominally uniform densities between fog level and density 0.8 was conveniently obtained by exposing plates to the blue light in a spot photometer. The exposure steps in the photometer were measured photoelectrically, and this calibration, in conjunction with the corresponding mean densities, gave the characteristic curve relating mean density and relative exposure. The conversion from relative to absolute exposure was made by finding the mean density of plates exposed to known uniform illumination from a blue light source. This source consisted of a small area of blue luminescent panel covered by an inter-

ference filter, which limited the light emitted to a band 80 Å wide centred on mean wavelength 4400 Å. To determine the illumination it produced in the plane where the plates were exposed, the light flux falling on a known area of this plane was admitted to a photoelectric photometer, and the output current of the photometer was measured. The absolute spectral response of the photometer had previously been determined by means of a standard lamp and calibrated monochromator in the Astronomy Department of the University of Wisconsin. The same monochromator was also used with the photometer to determine the spectral energy distribution of the source. With these spectral characteristics of the source and the photometer known, the absolute illumination used in the plate exposures could be calculated from the measured output current of the photometer.

Measured mean densities above mean fog density $\bar{D}_0$, for unbaked and baked plates, are shown plotted against absolute exposure in Fig. 1. It was found that these results are consistent with a relation between mean density $\bar{D}$ and exposure $E$ of the form

$$\bar{D} - \bar{D}_0 = \log_{10}(1 + aE^{\alpha}), \tag{18}$$

where a, $\alpha$ are constants. This relation, with a suitable choice of a and $\alpha$, has been used to plot the continuous curves of Fig. 1, which can be seen to fit the experimental values satisfactorily. From (13), if D is the mean density corresponding to exposure E,

i. e.

(19)

This relation has been used to give values of for the calculation of quantum efficiencies.

The measured r. m. s. density fluctuations $(\Delta^2 D)_A^{1/2}$ are shown plotted against corresponding values of D in Fig. 2. It can be seen that there is no evidence of any difference in the fluctuations associated with baked and unbaked plates, and, in view of the probable sampling error, the relation between $(\Delta^2 D)_A^{1/2}$ and $D^{1/2}$ for both emulsions has been taken as the straight line shown.

The calculated detection quantum efficiencies for unbaked and baked plates are shown as functions of exposure in Fig. 3. The efficiencies reach maxima of $5 \times 10^{-3}$ and $6 \times 10^{-2}$ respectively, at density about 0. 25 above fog. In both cases the effective number of photons stored levels off above density 0. 5 above fog at about 0. 25 photons per square micron.

Electronographic measurements.

The electronographic measurements were made with a tube of the type described by Hiltner and Niklas, [15] but without any aluminium oxide membrane, so that the electrons from the photocathode impinged directly on the electron-sensitive plate. The cathode was antimony-caesium(S-11), of sensitivity 6. 4$\mu$A/1, and the image magnification between cathode and plate was 1. 23. The tube was operated at a voltage of 20 kV, and a series of exposures on Ilford G. 5 emulsion, varying in duration from 15 seconds to 3 minutes, was made to the same uniform blue illumination as used in the photographic experiments. During the exposures, one half of the cathode was covered with opaque material, in order that a correction might subsequently be made for the plate blackening due to cathode

dark emission. The exposed plates were developed for 4 minutes in Kodak D-19 developer at 68° F, and the mean densities and density fluctuations were then measured with the equipment used for the photographic measurements.

With the small contribution from tube background subtracted, the man densities above mean fog density $\bar{D}_0$ are shown plotted against absolute exposure in Fig. 1. It is apparent that, above density 0. 3 above fog, the relation between density and exposure is markedly non-linear, contrary to expectation. The cathode sensitivity was monitored when the tube was initially opened to the cryogenic pumps, and was observed to remain constant during this operation and subsequently in the period preceding the first exposure. Since from previous experience with this type of tube there was no reason to anticipate other than a slow fall in sensitivity, the sensitivity was not measured again until several hours after the calibrated exposures were completed, by which time it was measurably lower than its initial value. However, by a fortunate chance the sequence of exposures was not in order of increasing exposure duration, but in the order numbered. Since the observations lie on a smooth curve, the non-linearity cannot therefore be a result of a decline in cathode sensitivity during the short time taken to make the exposures, and the reason for it is uncertain. The most recent investigation of the relation between density and exposure for commercial electronographic emulsions exposed to 27 Kev electrons is by Duchesne and Meallet.[16] According to them, non-linearity is the rule rather than the exception, and they find a linear relationship only for Ilford G. 5 emulsion developed for 5 minutes in Kodak D-19 developer at 68° F. The conditions of the present experiment differ from those of Duchesne and Meallet, notably in respect of electron energy, current density, emulsion temperature and development time, so that the results are not

necessarily conflicting. It is, however, worth remarking the Khogali,[17] working with Lenard window tubes, claims a linear response up to density 1.0 not only for Ilford G.5 emulsion, but also for Ilford L.4 emulsion, which is contrary to the finding of Duchesne and Meallet. These apparent discrepancies can be resolved only by a more comprehensive investigation, but it is at least clear that a linear relation between density and exposure is not a property of electronographic tubes that can be taken for granted, as has been the case hitherto.

In order to determine the gradient of the curve relating mean density $\bar{D}$ and exposure $\mathcal{E}$, it was assumed that this relation was of the form

$$\bar{D} = c\,\mathcal{E}^{\beta} + d \qquad (20)$$

whence

$$\left(\frac{\alpha \bar{D}}{\alpha \mathcal{E}}\right)_{\bar{D}} = \beta c \mathcal{E}^{\beta - 1} \qquad (21)$$

where c, d and $\beta$ are constants. Values of these constants, chosen to fit the observations according to the continuous curve of Fig. 1, were used in (21) to obtain values of $\left(\alpha \bar{D}/\alpha \mathcal{E}\right)_{\bar{D}}$ for the calculation of quantum efficiencies.

The measured r.m.s. density fluctuations $(\Delta^2 D)^{\frac{1}{2}}$ are plotted against corresponding values of $\bar{D}^{\frac{1}{2}}$ in Fig. 2. For purpose of calculation the relationship between these quantities has been taken to be the straight line shown. Its slope is practically the same as the line for the photographic plates, but if extrapolated it passes through the origin.

The calculated detective quantum efficiency is shown as a function of exposure in Fig. 3. It passes through a maximum of about $1.4 \times 10^{-2}$ at density about 0.2 above fog. The reduction of efficiency at higher densities is a consequence of the non-linearity of the mean density-exposure characteristics. If

this characteristic were linear, with the observed initial slope (shown as the broken line of Fig. 1), the detective quantum efficiency would follow the broken curve of Fig. 3.

The low efficiency at low exposures is due to the density fluctuations in unexposed developed plates. The measured mean fog density for the plates used was 0.033. For plates free of fog, and having the linear characteristic assumed above, the detective quantum efficiency would have the constant value $1.7 \times 10^{-2}$. If each photoelectron makes a track in the plate, and single tracks contribute with equal weight to the observed density fluctuations, this constant should equal the responsive quantum efficiency of the tube photocathode. Taking the responsive quantum efficiency of a typical S-11 photocathode of sensitivity 60$\mu$A/L to be about 0.14 at wavelength 4400A, the responsive quantum efficiency of the tube photocathode, inferred from its luminous sensitivity, is $1.5 \times 10^{-2}$. The numerical agreement between this value, and the value deduced from the electronographic measurements, must be counted satisfactory, in view of the photometric uncertainty, and the possibility of abnormal spectral response in a photocathode of such low sensitivity.

## Comparison of Classical Photography and Electmography

For the purpose of comparing classical photography and electmography, it is convenient to express the results above in terms of the produce $\sigma = q\mathcal{E}$. This quantity is the effective number of stored photons from unit area of the incident optical image, and may be taken as a measure of the information content of the image recorded. The relation between $\sigma$ and $\mathcal{E}$, derived from the curves of Fig. 3, is shown in Fig. 4.

The results for electmography relate to an electron-optical magnification M = 1.23. For other magnifications, the curves remain geometrically similar, but with scale proportional to $M^2$; the curve for M = 1 is shown for example. The linear relation between $\sigma$ and $\bar{\epsilon}$ for the idealised case of linear response and no fog is, of course, unaffected by a change of M; it is obvious that with this type of response the information content of the recorded image is independent of its scale.

If it is assumed that baked IIa - O emulsion is free from reciprocity failure, the ratio of abscissae in Fig. 4 for given $\bar{\epsilon}$ is the ratio of exposure times required to give comparable recorded images, i.e., it is the speed gain. Speed gains over photography with baked IIa - O emulsion are shown as functions of $\sigma$ in Fig. 5. The non-linearity observed with the tube is not significant upto values of $\sigma$ approaching saturation of the photographic emulsion, so has little effect on the speed gain. On the other hand, the presence of fog in the electron-sensitive emulsion depresses the speed gain to an appreciable extent, particularly at low values of $\sigma$. In the idealised case of a fog-free tube, the speed gain rises to very high values as $\sigma \to 0$. This is consistent with the results obtained by Lallemand et al[18] from direct counting of electron tracks, which is an effective means of discriminating against fog.

The speed gains of Fig. 5 relate to a photocathode of sensitivity only 6.4 $\mu$A/L. If they are scaled up by a factor 6, to correspond to a photocathode of responsive quantum efficiency 0.1 (about 40 $\mu$A/L), the speed gains predicted are shown in the following Table 1.

TABLE 1

Speed gains relative to baked IIa-O

| $\sigma$ (photons $\mu^{-2}$) | M=1.23 | M = 1 | M = 1 (no fog) |
|---|---|---|---|
| 0.25 | 21 | 23 | 35 |
| 0.5 | 15.5 | 18 | 24 |
| 0.75 | 14 | 15.5 | 20 |
| 1.0 | 13.5 | 15 | 18 |
| 1.25 | 13.5 | 14 | 17.5 |
| 1.5 | 13.5 | 14 | 17 |
| 1.75 | 14 | 14 | 17.5 |
| 2.0 | 15.5 | 15 | 18.5 |
| 2.25 | 18 | 15 | 21 |

From this it appears that, over a wide range of exposures to blue light, the speed gain to be hoped for with an average photocathode is somewhere between 15 and 20. The fact that this falls below earlier predictions by a factor of about five arises from the underestimate of the detective quantum efficiency of photographic plates.

Acknowledgements

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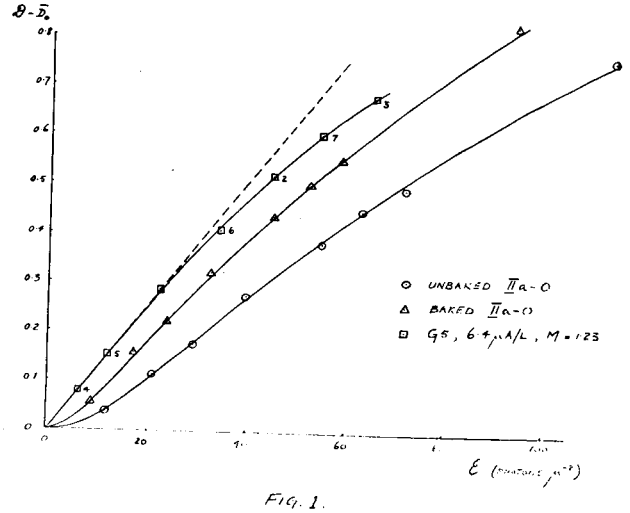


FIG. 1.

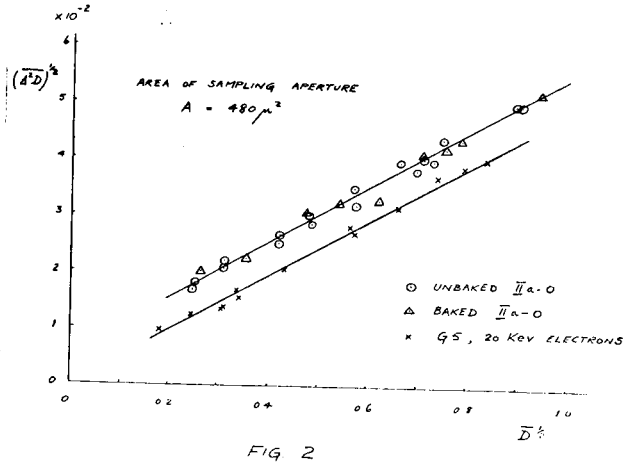


FIG. 2

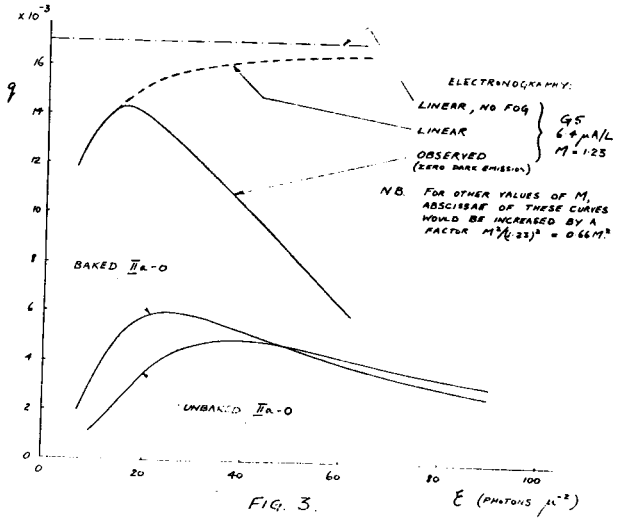


FIG. 3.

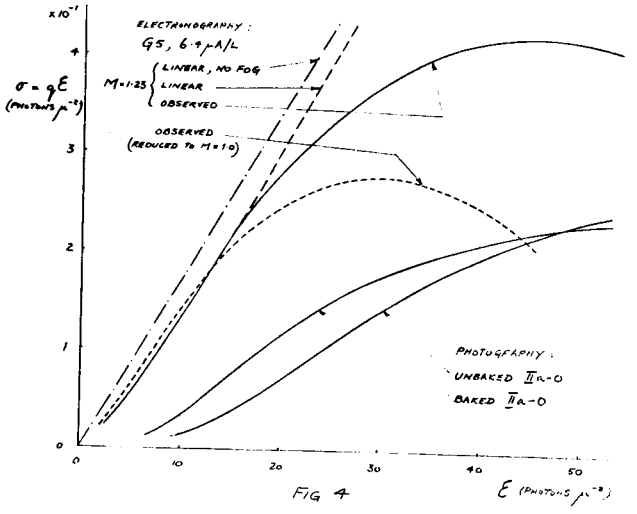


FIG 4

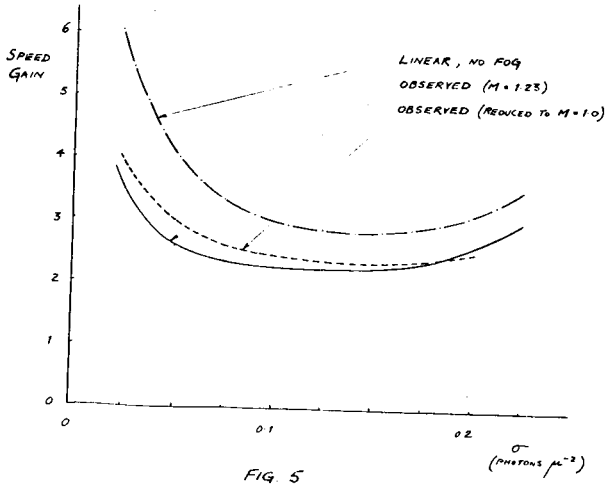


FIG 5