

CONVERSION YIELDS OF SOME PHOTOGRAPHIC EMULSIONS AND RELATED FACTORS

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ABSTRACT

A method is presented for the determination of the effective average projected grain diameter ($d_{\bar{A}}$) using visual analysis of enlargements of Kodak Tri-X Pan and Kodak Royal-X Pan emulsions. Each was exposed to three light sources of color temperatures 6100°K, 2850°K, and 2040°K, and was developed in Kodak developers HC-110, DK-50, and D-19 for 5, 8, 12, and 20 minutes at 68°F. For 5- to 20-minute developing times, $d_{\bar{A}}$ was determined, from a total of over 12,000 counts, to be from ≈ 2.1 to $\approx 2.4 \mu$ for both films. A method for calculating the conversion yield η (number of grains to total number of quanta focused on the emulsion) is derived. The value η is a function of film density (D); it was found that η first increases and then decreases, and a theory which explains this behavior in connection with grain formation is proposed; that is, η is the result of a superposition of an increasing and a decreasing function. The first is caused by the fact that a photographic nucleus made up of three silver atoms has a lesser probability for development than a four-atom nucleus, where with the increased exposure (number of quanta per unit area), the ratio increases in favor of the latter, resulting in an increasing function. However, the photographic plate, unlike the photoemitter, is a "non-specie-replacing" device; as a result, the percentage of nonactivated silver halides decreases with exposure, making the latter a decreasing function. Typical values for η showing this behavior are: Tri-X Pan; 6100°K, spectral region 375 to 700 m μ ; HC-110, 8 min, 68°F; $\eta \approx 0.1\%$ at D=0.10, $\eta \approx 0.3\%$ at D=0.30, $\eta \approx 0.1\%$ at D=1.00, and $\eta \approx 0.009\%$ at D=2.00. For $\lambda=466 \text{ m}\mu$ (peak of P-11 phosphor), η increases from $\approx 0.09\%$ at D=0.10 to $\approx 0.4\%$ at D=0.40, then decreases to $\approx 0.2\%$ at D=1.00 and $\approx 0.01\%$ at D=2.00.

INTRODUCTION

The purpose of the investigation reported here was to determine the number of useful photographic grains obtained from a given number of quanta incident to some commercial photographic emulsions, which are obtained in addition to the grains that constitute the fog. The influence of the exposure, as well as the spectral distribution as determined by the color temperature of the incident quanta flux, was investigated. The investigation involved a tedious visual analysis of super-enlarged photographic negatives, in order to determine the grain-size distribution and "useful grain" density. Because several grains lying in the same vertical plane do not yield a higher projectable density in the emulsion than the largest of these grains, they must be considered as only one "useful" grain. For this reason, this paper uses the term "projectable grain," and the ratio of the number of these "projectable grains" to the number of incident quanta will be called the "conversion yield" of the emulsion. This term has an analogous meaning to the term "conversion yield" used in reference to a photoemitter, where it represents the ratio of the number of electrons, in addition to the dark-current electrons, to a known number of quanta incident to the photoemitter. Once both the conversion yield of the emulsion and the spectral distribution of the incident quanta flux are known, the grain-size distribution, the fog density and its variation, the threshold of detection, and other figures of merit, etc. (Jones 1958), may be calculated.

Some of the results reported by other workers in this field concerning grain-size calculation and other performance parameters were obtained from investigations of specially prepared emulsions. Because of the large number of variables involved, however, these do not necessarily represent the performance data of commercial emulsions, which are the real interest when, for example, one wishes to

¹Manuscript received October 4, 1966.

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compare the performance of photoelectronic devices to that of photographic emulsions.

Failure of reciprocity does not enter into this evaluation since exposure times were deliberately selected to eliminate this factor.

GRAIN-SIZE DETERMINATION

Using a Kodak Type 1B, Model IV Intensity Scale Sensitometer, a typical H & D curve was made for each emulsion-light source-developer combination, the two emulsions being Kodak Tri-X Pan and Kodak Royal-X Pan Extended Red Sensitivity, the three Kodak developers being D-19, DK-50 and HC-110, and the selected light sources being corrected for color temperatures 6100°K, 2850°K, and 2040°K. Next, using an American Optical Company microscope with a 43× objective and 10× eyepiece, and with a Zirconium lamp and a 433 m μ interference filter (HIB \approx 15 m μ) for illumination, and a Miranda 35 mm camera, a number of photomicrographic negatives were made and were then further enlarged. Proof of the accuracy of this procedure was established by use of an American Optical Company micrometer scale with units of 0.01 mm per division. Figures 1 and 2 show examples of such super-enlargements made from regions of very low density which are equal to or slightly above that of the fog.

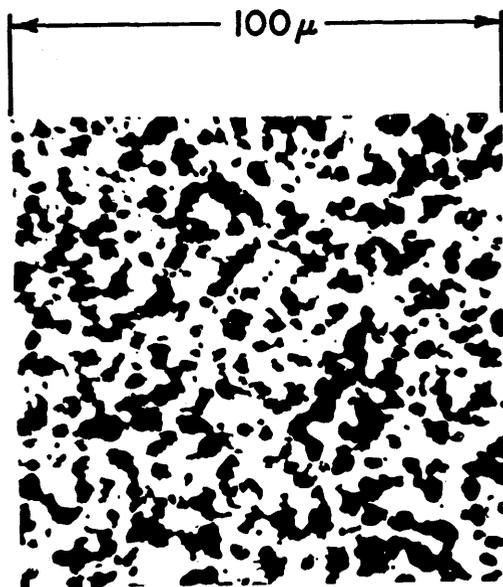


FIGURE 1. Enlargement of Kodak Tri-X Pan emulsion showing typical grain sizes and formations.

Determining the average grain size, even at these low densities, is obviously not a simple matter, since some fusing (clogging) of grains occurs even here. In addition, because the read-out of the information from a photographic layer is achieved by projecting light through it, optical fusing also occurs. Obviously, physical fusing cannot be discriminated from optical fusing. Considering these facts, we coined a more representative term, "effective average projected grain diameter" ($d_{\bar{A}}$) and devised the following method for its determination. First, all relatively round projected grain images were assumed to be caused by single

grains of various sizes, and were classed and tabulated according to their respective diameters.

Because the wave length of the illuminating light used to make the photomicrographs was about $450\text{ m}\mu$, this and the quality of the optical arrangement determined the lower limit of the grain size which could be resolved. The first class included grains up to $1.25\ \mu$, the next $1.5\ \mu \pm 0.25$, and so on by $0.5\ \mu$ intervals. Likewise, the partially fused grain images, where the outlines of the grains were rather clearly discernible, were classed and tabulated. Those "clogged grains," for which it was not possible to make a definite statement as to the number or size of the grains (that is, those for which argument was possible as to whether they were made up of a number of small grains or just a lesser number of large grains) were treated in two ways. First, assuming that they were made up of large grains, they were "fitted" with the largest grain sizes possible and were classed and tabulated in a separate table. Next, it was assumed that they were made up of grains of the same sizes and distribution as those already tabulated, or at least that their average size would not be smaller than that of the "single grains."

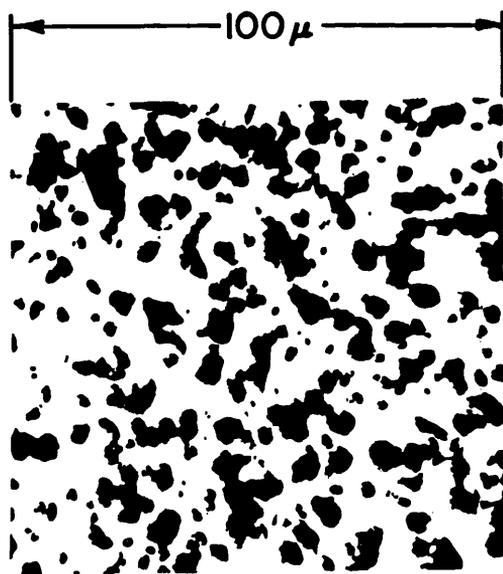


FIGURE 2. Enlargement of Kodak Royal-X Pan emulsion showing typical grains sizes and formations.

Using the equations that follow, the average size was determined first by disregarding the "clogged grains" and then by treating them and the "single grains" as a whole. As would be expected, when the "clogged grains" were included, the average grain size was larger (about 50%); however, since our intent is to treat the photographic emulsion in an optimistic way, the smaller grain size is used throughout the paper.

The total area (A) covered by all the counted "single grains" can be found thus

$$A = \sum_{i=1}^m \frac{\pi}{4} n_i d_i^2, \quad (1)$$

where m is the number of classes, n_i is the frequency for the i -th class, and d_i is the diameter associated with the i -th class (fig. 3). The total number of grains (N) is

$$N = \sum_{i=1}^m n_i, \quad (2)$$

so that the arithmetic mean average area (\bar{A}) is

$$\bar{A} = \frac{A}{N} = \frac{\sum_{i=1}^m \frac{\pi}{4} n_i d_i^2}{\sum_{i=1}^m n_i}. \quad (3)$$

Thus, the effective average projected grain diameter ($d_{\bar{A}}$) associated with the average is

$$d_{\bar{A}} = \left(\frac{\sum_{i=1}^m n_i d_i^2}{\sum_{i=1}^m n_i} \right)^{1/2}. \quad (4)$$

Obviously, $d_{\bar{A}}$, as well as the other pertinent parameters, will vary from one emulsion to another, and will also vary for different developers, developing times, and developing conditions (Reynolds, 1966).

Because it is the overall density (D_G) which is recorded by a densitometer, the density (D_B) of the substrate on which the emulsion is deposited must obviously be subtracted from D_G in order to get the density (D) caused by the grains used for calculating the grain coverage factor (F), which is the ratio of the non-transparent area to the overall area. Thus

$$F = 1 - T = 1 - \frac{1}{\phi} = 1 - \frac{1}{10^D}, \quad (5)$$

where T is the transmittance and ϕ is the opacity. Because F also includes the coverage factor (F_F), caused by the fog grains, this must also be subtracted in order to get the coverage factor (F_D) caused by the incident radiation. Thus,

$$F_D = F - F_F = \frac{1}{10^{D_F}} - \frac{1}{10^D}, \quad (6)$$

where D_F is the fog density.

From Equations (4) and (6), the number of information grains (G_D) caused by the incident radiation is

$$G_D = \frac{4}{\pi d_{\bar{A}}^2} \left(\frac{1}{10^{D_F}} - \frac{1}{10^D} \right) = G \left(\frac{1}{10^{D_F}} - \frac{1}{10^D} \right), \quad (7)$$

where $G = \frac{4}{\pi d_{\bar{A}}^2}$ and is the number of grains per unit area which is necessary for total coverage.

CONVERSION YIELD

Exposure (E) is usually given in meter candle seconds, so it is first necessary to obtain the equivalent value (Q_E) in quanta per unit area. Thus,

$$Q_E = Q_T E, \quad (8)$$

where Q_T is a conversion factor expressed in quanta per unit area per meter candle second for a given color-temperature light source (Gebel, 1964).

Because the region of spectral sensitivity of the two emulsions is $\approx 375\text{--}700\text{ m}\mu$, only the quanta in this region were considered. These are, for color temperatures of 6100°K , $Q_T = 1.17 \times 10^{10}$ quanta per mm^2 per meter candle second; for 2850°K , $Q_T = 1.21 \times 10^{10}$ quanta per mm^2 per meter candle second; and for 2040°K , $Q_T = 1.50 \times 10^{10}$ quanta per mm^2 per meter candle second (Gebel, 1964).

From Equations (7) and (8), the conversion yield (η), which is the ratio of the average number of grains produced to the number of quanta focused onto the emulsion, is

$$\eta = \frac{G_D}{Q_E} = \frac{4 \sum_{i=1}^m n_i}{\pi Q_T E \sum_{i=1}^m n_i d_i^2} \left(\frac{1}{10^{D_F}} - \frac{1}{10^D} \right) \quad (9)$$

EXPERIMENTAL RESULTS

Using the method of tabulating the "single grains," as described in the section on conversion yields and from Equation (4), it was found from these samples that the most optimistic values for the mean value of the diameter $d_{\bar{A}}$ were: $2.1\text{ }\mu$ for a 5-minute developing time; $2.2\text{ }\mu$ for 8 min; $2.3\text{ }\mu$ for 12 min, and $2.4\text{ }\mu$ for 20 min, where the variations caused by the differences between developers and between the two emulsions were within statistical limitations.

Figure 3 shows typical histograms of measurements taken for each sample.

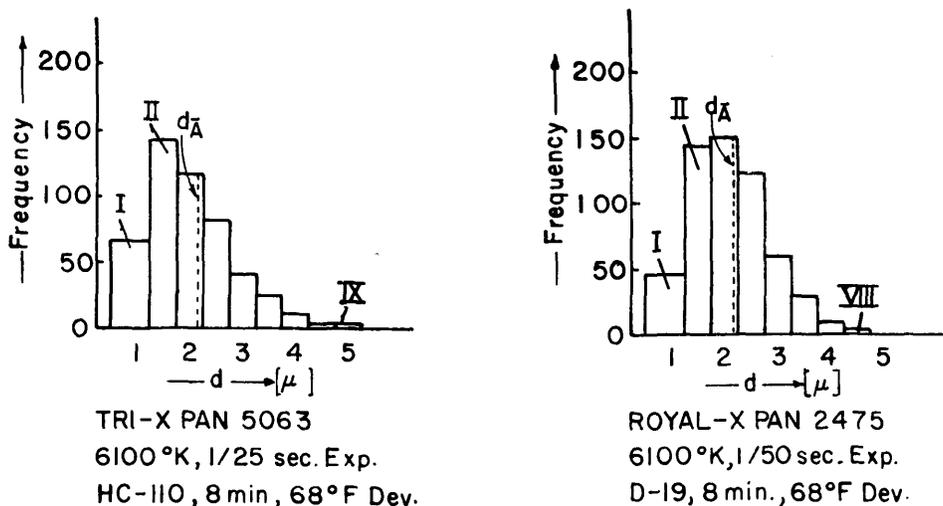


FIGURE 3. Histograms showing distribution of grain diameters. Class I: $0.5\text{ }\mu \leq d \leq 1.25\text{ }\mu$; Class II: $d = 1.5\text{ }\mu \pm 0.25\text{ }\mu$; II-IX, class center separation = $0.5\text{ }\mu$, interval = $\pm 0.25\text{ }\mu$.

Counts were made for each emulsion-developer-development time combination for the 6100°K source only (assuming no or negligible effects on grain size caused by the energy distribution of the radiation), bringing the total number of counts to over 12,000 for the 24 different histograms.

Obviously, $d_{\bar{A}}$, the efficiency values, etc. depend on the total sample size, because of statistical variations. Because of time involved in counting, counts must be limited to a reasonable number. However, the total sample size of 12,000,

as used here, should be large enough so that only insignificant deviations from other samples should occur and, thus, the data should be sufficiently accurate for use in most practical situations.

Examples of the effects of the developing time on the density, for the same developer and exposure source, are shown in figure 4. In this and each of the

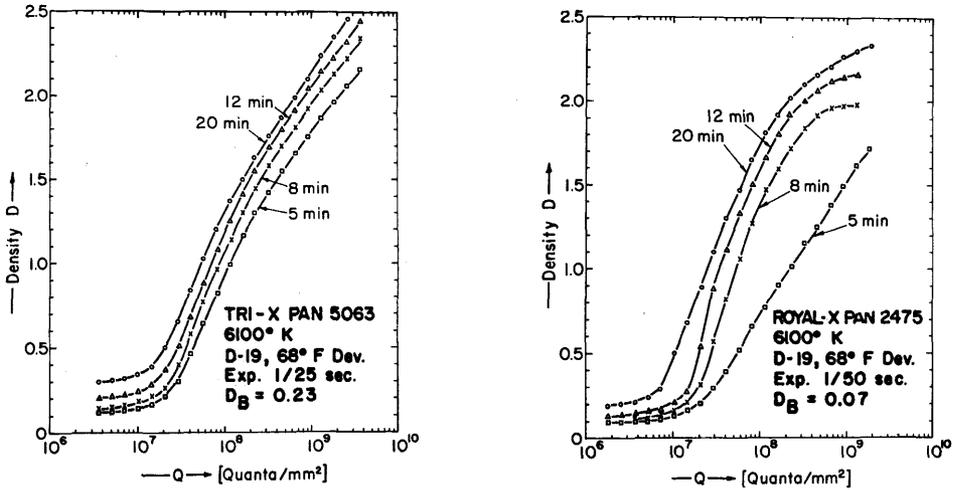


FIGURE 4. Density versus exposure for Kodak Tri-X Pan and Kodak Royal-X Pan films with the developing times as parameters.

following figures, the base density has been subtracted before plotting. The effects of the different developers are shown in figure 5 for the same light source and developing time. Figure 6 shows the effects of the different light sources for the same developer and equal developing times. The differences here are due to the relationship between the spectral sensitivity of the film and the relative spectral quanta distribution of the light source. Because the sensitivity curve

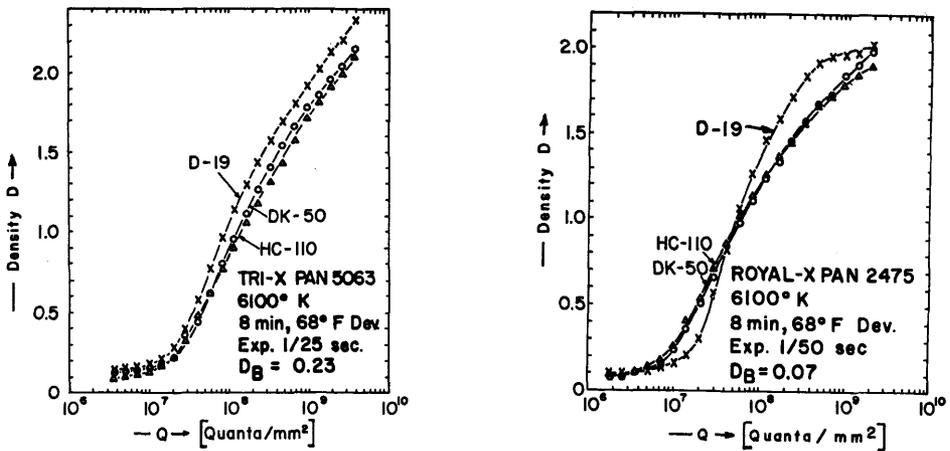


FIGURE 5. Density versus exposure for Kodak Tri-X Pan and Kodak Royal-X Pan films with the developers as parameters.

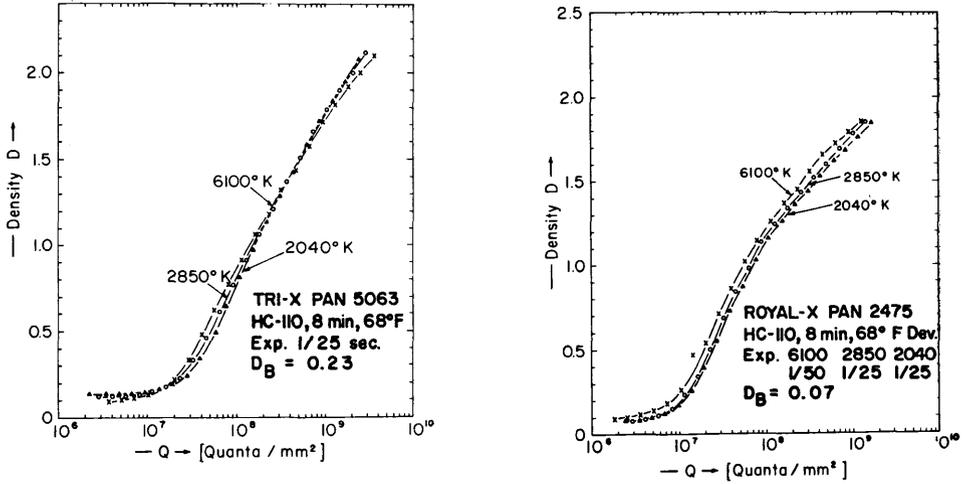


FIGURE 6. Density versus exposure for Kodak Tri-X Pan and Kodak Royal-X Pan films with the exposure sources as parameters.

of the film is not exactly rectangular, any light source which has a color temperature that peaks near the same region as the peaks of the film sensitivity curve will obviously cause a higher density than those which do not.

The characteristic curves for Tri-X Pan, which serve to demonstrate the effects of the spectral quantum distribution in relation to the spectral sensitivity of the emulsion, are shown in figure 7. The light source used for both was the same (6100°K) except that a 466 mμ interference filter (HIB ≈ 10 mμ) was used in front of the source for one exposure. Because this is one of the regions of

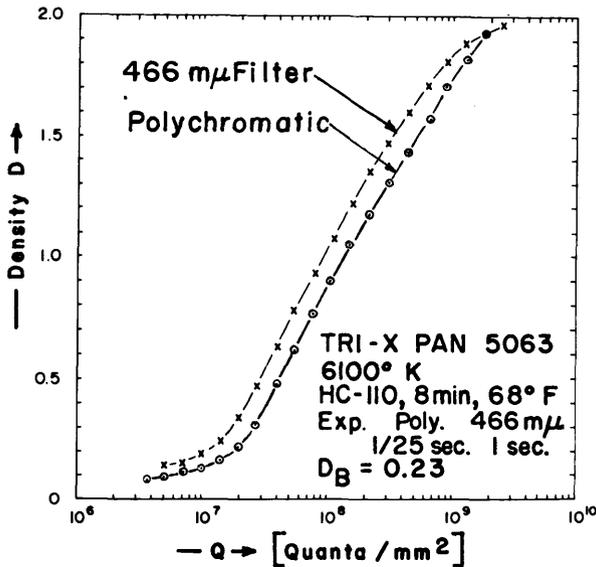


FIGURE 7. Density versus exposure for Kodak Tri-X Pan film for exposure to a light source of color temperature 6100°K with and without 466 mμ filter (HIB ≈ 10 mμ).

higher sensitivity of the emulsion, the density is somewhat higher for the same number of quanta than it was for the polychromatic radiation, because the latter is an average for the entire region of spectral sensitivity of the emulsion.

The conversion yields were calculated, using figure 5 and Equation (9), and are presented in two ways. The first (fig. 8) shows the conversion yield plotted against the exposure in quanta per mm^2 for the same light source and developing

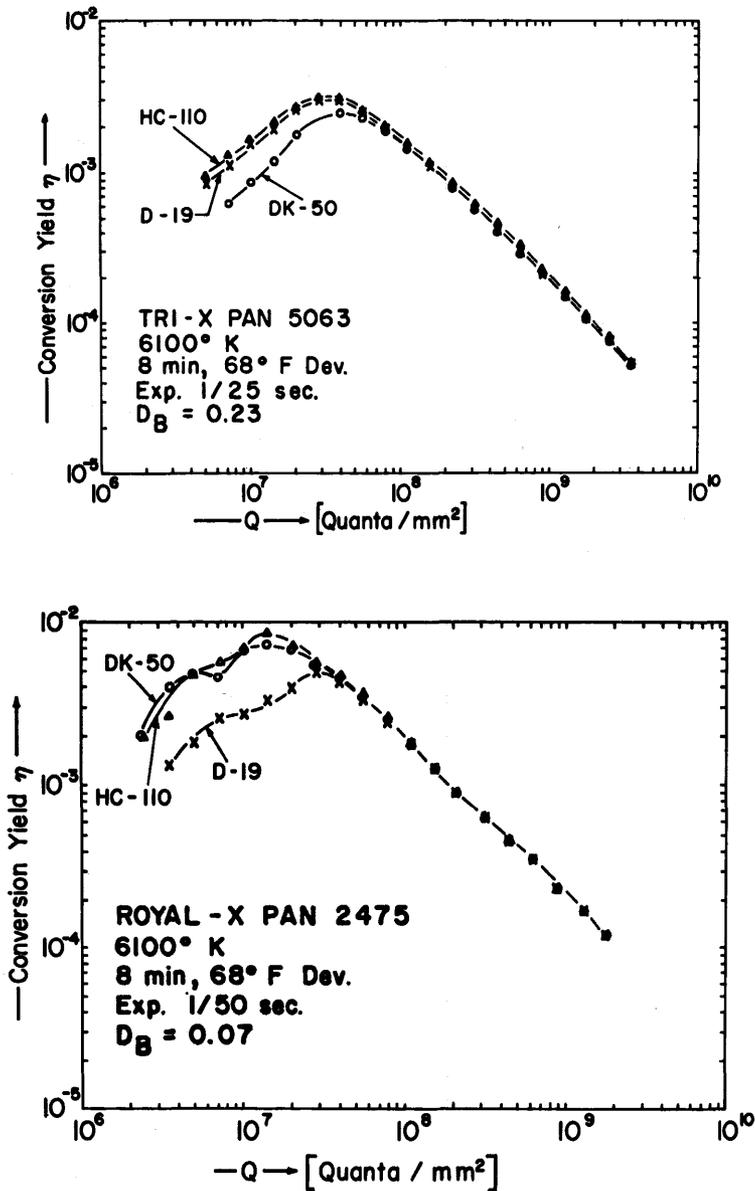


FIGURE 8. Conversion yield versus exposure for Kodak Tri-X Pan and Royal-X Pan films with the developers as parameters.

time, with the different developers as parameters. The second (fig. 9) plots the conversion yield against density.

It might have been expected that, with a constant increase in the number of quanta for each exposure, there would be a decrease in the conversion yield, because of the increasing probability of multiple hits of the same crystallite by the larger number of quanta. However, these results (figs. 8 and 9) show that

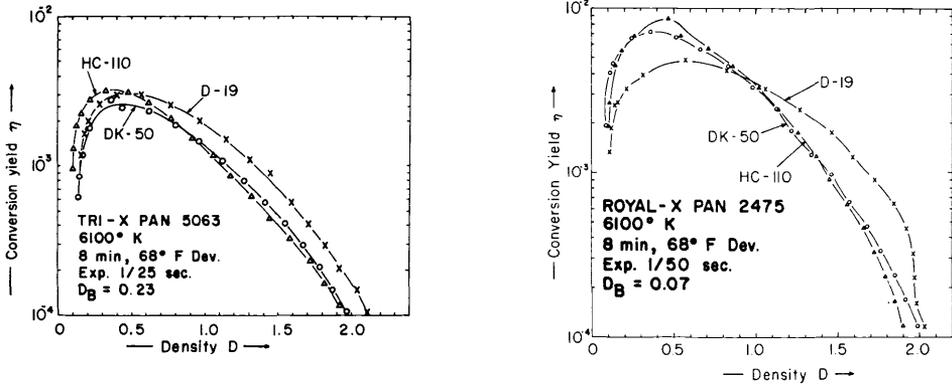


FIGURE 9. Conversion yield versus density for Kodak Tri-X Pan and Royal-X Pan films with the developers as parameters.

the conversion yield first increases, and then decreases. Although we recognize that other explanations are possible, we would like to propose the following interpretation for this behavior. Assuming that a four-atom nucleus will give a crystallite a probability of one for development, and that a three-atom nucleus will have a lesser probability, then, since the percentage of four-atom nuclei will increase with the number of quanta, so will the probability for development of the crystallite. Also, an increase in the quanta flux means a greater probability that the silver atoms freed by the breaking of the ion bonds will be in closer proximity within the crystallite and, hence, that there is a greater probability for nucleus formation and thus for development. However, with a still further increase in

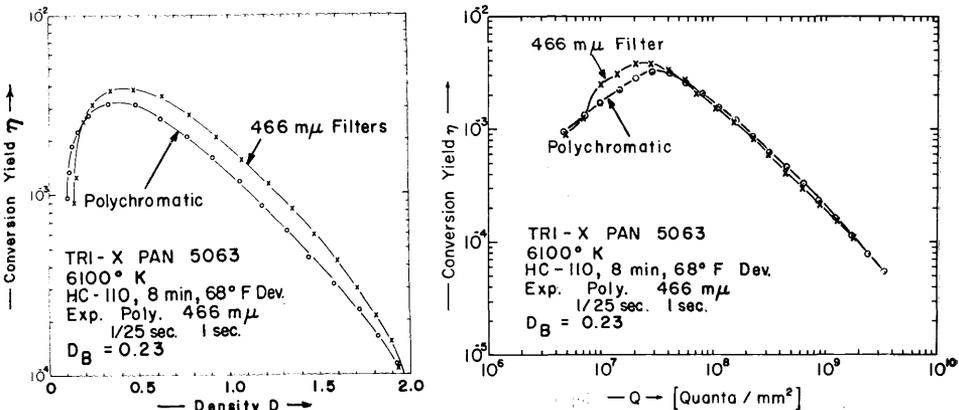


FIGURE 10. Conversion yield versus density and conversion yield versus exposure for Kodak Tri-X Pan film for exposure to a light source of color temperature 6100°K with and without 466 mμ filter ($HIB \approx 10 \mu$).

the quanta flux, the increase in the percentage of multiple nuclei in the same crystallite and the formation of nuclei in crystallites at different depths in the emulsion begin to outweigh the other factors and the conversion yield then decreases. In addition to the above factors, which we believe to be the most important, others may also be involved.

A comparison between monochromatic and polychromatic light, with the conversion yield plotted against density, is shown in figure 10a. Figure 10b shows the same comparison, where the conversion yield is plotted against the exposure in quanta per mm². Here, as in figure 7, the curves for monochromatic light are somewhat higher than for polychromatic light, because the quanta are all in a region of higher sensitivity for the monochromatic light.

ACKNOWLEDGMENT

This research was supported by the Aerospace Research Laboratories In-House Independent Laboratory Research Fund. The support of Colonel Robert E. Fontana, Commander of the Aerospace Research Laboratories, is gratefully acknowledged. We also wish to express our gratitude to Dr. G. T. Reynolds, Princeton University, for scientific review, to Dr. H. L. Harter for consultation on statistical problems, and to Dr. L. Spialter for helpful discussions. Our sincere thanks are also expressed to Mr. J. C. Lewis, Mr. A. C. Zonars, and Mr. R. B. Summers for making the sensitometric exposures on which the evaluation was based, and to Mr. H. A. Bost, Mr. R. R. Hayslett, and Mr. H. R. Mestwerdt for general assistance and support in preparation of this paper.

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