Kittel[4] for the case of a uniform motion by using the particular phenomenological damping torque introduced by Landau and Lifshitz. By taking this torque into account in the oscillatory case also, the wall velocity would be limited without having to use the approximations[17] (9) and (10). However, the effect of damping on m_w is quite small, and in the case studied experimentally[2] this correction is well within the accuracy of the approximations used in the theories of inertia. Since not even the mathematical form of the Landau-Lifshitz damping torque has been verified by existing experimental results, it seems preferable not to consider the damping effects at present. If unexpected developments in the study of the damping mechanism are excluded, one may therefore conclude that the inertia of a wall is independent of the state of motion, and dependent solely on characteristics of the wall at rest, provided the distortion of the moving wall is sufficiently small to ensure the linearity of the dynamic wall problem.

[17] It is interesting to consider some numerical values in connection with these approximations. For $\gamma_0 H_0$ one may use 2.8×10^5 cycles/sec, corresponding to the representative value of $H_0=0.1$ oersted; $\gamma_0(2K/M_s)$, on the other hand, is about 1.5×10^9 cycles/sec for iron, and about 2.5×10^9 cycles/sec for the particular ferrite which showed an experimental wall resonance (reference 2) at about 5×10^7 cycles/sec.

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On the Sensitivity of Photographic Grains to Electrons*†

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Three single-grain-layer photographic emulsions have been exposed to a measured quantity of monoenergetic electrons, varying in energy from 7 to 112 kev. Two of the coatings (both chlorobromides) had high background fog, which introduced considerable error in the counting procedure. Also, neither of these films was especially sensitive to electrons. Nevertheless, it could be ascertained that the sensitivity of these coatings was fairly constant up to 50 to 70 kev, after which it dropped off slowly. These two coatings were prepared in almost identical fashion and showed a similar response to white light, yet their sensitivity to electrons differed by a factor of 8 or 9.

The third coating was a fine-grained bromoiodide, similar to the emulsions used in nuclear track plates. This coating was essentially fog-free, and reproducible results were obtained. The sensitivity was highest at low electron energies (approaching unity), dropping rapidly at first, then leveling off for higher energies. The curve of developability probability as a function of electron energy bears a close resemblance to the curve of space rate of energy loss for the electron. It also is in fairly good agreement with curves based on grain count data for electron tracks reported by Ross and Zajac.

It was estimated that at 112 kev the electron forms about 62 ion pairs in passing through the center of a grain in this third coating. Since the sensitivity is still appreciable at this energy, this number of ion pairs should roughly represent a quantity which is approaching the lower limit of the number required to render the average grain in this coating developable. This is to be compared with the data that Webb has published, namely, that about 40 quanta of light are needed on the average to render a photographic grain developable.

I. INTRODUCTION

WHEN light of the proper wavelength is incident on a photographic emulsion, some of the silver halide grains (the number depending on the amount of exposure) are altered in such a way that they react differently toward certain reducing agents known as developers. That is to say, those grains which have been affected sufficiently by the light are reduced to metallic silver by the developer, while the other grains are not reduced at all. This developable state is called the latent image and is not susceptible to direct observation.

The latent image consists of a submicroscopic speck of silver, sufficiently large and properly located to produce developability. According to the Gurney-Mott[1] theory of latent image formation, the absorption of a light quantum by the photographic grain raises a bound electron into the conduction band or into an exciton level, the exciton being subsequently dissociated by thermal motion. Freed electrons will migrate and be trapped at imperfections in the crystal, whereupon positive silver ions will diffuse to the trapped electrons and be neutralized. Sufficient repetition of this process at a suitably located point will result in the formation of a latent image.

A high velocity charged particle striking a photographic grain should have a similar action. Coulomb

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† This work was supported in part by the AEC, the ONR, and the American Cancer Society.
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[1] R. W. Gurney and N. F. Mott, Proc. Roy. Soc. (London) **A164**, 151 (1938).

forces will free bound electrons along the path of the particle in the grain, and if the number released is sufficient, a latent image will be formed. If a single particle does not give up sufficient energy to the grain, several hits on an individual grain may be required.

For particle energies below that producing minimal ionization in the surrounding medium, the space rate of energy loss for the various charged particles will vary almost inversely with the energy of the particle. The greater the energy of the incident particle, the smaller is the space rate of energy loss. Webb[2] has given theoretical curves of the space rate of energy loss in air for alpha-particles, deuterons, mesons, and electrons, based on calculations for the proton by Smith.[3]

For alpha-particles of polonium the space rate of energy loss is so high that the number of electrons freed in a transpierced photographic grain is well above the minimum required for latent image formation. Thus, Webb[4] has measured the developability probability[4a] to be unity in this case. Indeed, for alpha-particles of 380 Mev, the probability is still so high that a recognizable track is left in nuclear track plates. Of course, the grain spacing is much greater at the high energy end of the track, since here not every transpierced grain will have sufficient electrons released to form a latent image.

For lighter particles, the space rate of energy loss, and hence the probability of developability, becomes proportionately less for the same particle energy.

Many measurements have been made on the sensitivity of photographic emulsions to electrons, including those reported by Baker, Ramberg, and Hillier,[5] Borries,[6] Charlesby,[7] Cranberg and Halpern,[8] and Ellis and Aston.[9] These papers all present Hurter-Driffield curves of density as a function of exposure for various emulsions and conditions, where the density is defined as the logarithm to the base 10 of the ratio of the intensity of the original beam of light to the intensity of the beam which is transmitted through the silver deposit in the emulsion. All measurements were made with relatively thick, multi-grain-layer emulsions in which the incident particles lost a considerable part, if not all, of their energy in their passage through the emulsion. These measurements were not intended to supply information on the response of individual photographic grains, but rather to obtain data on the gross sensitivity of the emulsion. This paper, on the other hand, reports on some direct measurements of the developability probability for individual photographic grains exposed to monoenergetic electrons in the energy range 7 to 115 kev. Special single-grain-layer emulsions were used to avoid an averaging process on the effect of the electron over its energy range while in the emulsion. The single-grain-layer emulsion also made it feasible to count individual grains visually with the aid of a microscope.

The films were exposed to measured quantities of uniformly distributed, monoenergetic electrons for

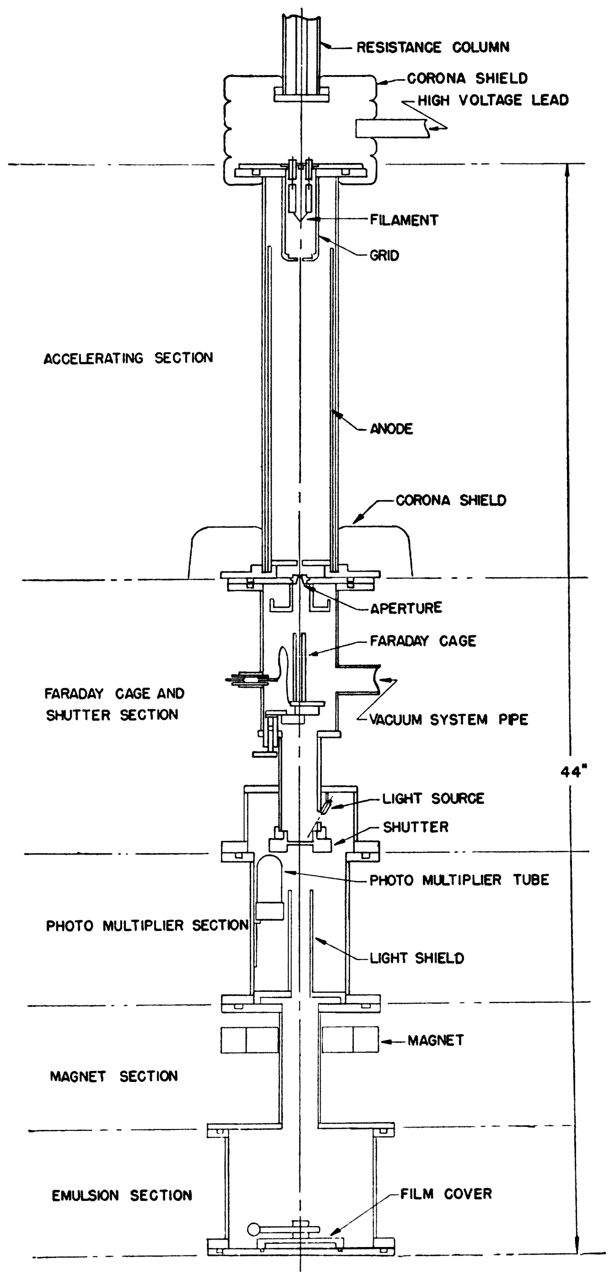

FIG. 1. Schematic, scale diagram of electron gun used to expose single-grain-layer film to monoenergetic electron beam.

[2] J. H. Webb, Phys. Rev. **74**, 511 (1948).
[3] J. H. Smith, Phys. Rev. **71**, 32 (1947).
[4] J. H. Webb, J. Opt. Soc. Am. **38**, 312 (1948).
[4a] The developability probability is defined as the probability that a photographic grain will form a latent image and be rendered developable if it is transpierced by an incident particle.
[5] Baker, Ramberg, and Hillier, J. Appl. Phys. **13**, 450 (1942).
[6] B. v. Borries, Physik. Z. **43**, 190 (1942).
[7] A. Charlesby, Proc. Phys. Soc. (London) **52**, 657 (1940).
[8] L. Cranberg and J. Halpern, Rev. Sci. Instr. **20**, 641 (1949).
[9] C. D. Ellis and G. H. Aston, Proc. Roy. Soc. (London) **A119**, 645 (1928).

various points in the energy range covered. After chemical processing of the emulsion, the developed grains were counted directly, while the original number of undeveloped grains before exposure was determined in a way appropriate to the emulsion. The developability probability was then determined from a statistical study, based on the above data and the average grain size.

II. APPARATUS

A specially constructed electron gun[10] was used to supply the required electron beam. The gun, shown in Fig. 1, consisted essentially of a battery-heated tungsten filament, a resistance-biased grid, and a cylindrical anode. The beam was defined by a small aperture, beyond which a faraday cage was placed to measure the current. When the cage was swung out of line, the beam was intercepted by a camera shutter lying in its path to the film below. The exposure time was measured photoelectrically. The deflecting magnet permitted several exposures on each film sample.

Large variations in beam current were obtained by varying the bias resistor and the filament-to-grid distance. Finer control was attained by adjusting the filament temperature.

The current from the electron beam ran from the faraday cage through a shielded, insulated conductor to the input of a vibrating reed electrometer, where it was allowed to bleed through a calibrated resistor, providing a steady signal. Readings were taken before and after each exposure and the average used. It is estimated that the beam current readings were accurate within 2.5 percent absolutely, 1.5 percent relatively, while the photoelectrically measured exposure time was accurate within 0.75 percent.

The accelerating voltage was supplied by a dc power supply regulated to better than 1 percent. A resistance column was used to measure the accelerating voltage with an estimated error of less than 2 percent.

The electron gun had a volume of about six liters, which was opened to the atmosphere for every change of film. A VMF-50 oil-diffusion pump with suitable backing pumps was used to provide a fast pumping system, capable of attaining the working vacuum of 10^{-4} mm of Hg within a reasonable time.

III. DEVELOPING PROCEDURE

The film was loaded, unloaded, and developed in complete darkness. Usually, three or four exposures were made on each film strip, the latter coming from one long roll for each emulsion examined. Considerable care had to be exercised in handling the film, since it did not have the thin protective layer of gelatin sometimes coated on ordinary emulsions. Thus, the film was especially sensitive to any mechanical pressure or abrasion.

[10] D. Okrent, thesis, Harvard University (1950).

All films were developed within thirty minutes after exposure to avoid effects due to latent image fading. The temperature of the developer was controlled by a large water bath to $\pm 0.5°$F; a thermometer was placed directly in the developer immediately before use to check the temperature.

Three distinct single-layer-films or coatings were used, two of which were subjected to the same developing procedure. These two coatings (designated J-4916 and J-8957) were developed in fresh D-19 developer at 68°F for 80 seconds, placed in a short stop bath, washed thoroughly, and hung up to dry. Since both developed and undeveloped grains were to be counted, these coatings were not "fixed." The background fog was considerable and increased with increased development time; hence, the development time was limited to 80 seconds.

In the third coating (designated J-10217) the grains were considerably smaller and crowded together very closely. At 2500× magnification it was extremely difficult to count the total number of grains in a reasonably large field of view. It was impossible to distinguish accurately between developed and undeveloped grains. Hence, this coating had to be fixed after development. The development time was increased to three minutes so that the developed grains would be larger and more dense. This improved the ease of counting.

All three coatings were specially prepared on an experimental basis by the Research Laboratory of the Eastman Kodak Company.[10a] The first two coatings (J-4916 and J-8957) were prepared at different times but from a similar type of base emulsion (a chlorobromide). Relatively small changes in emulsion technique were made in preparing the two. Routine tests by Eastman indicated that these two coatings had comparable sensitivities to white light, certainly within a factor of two. The third coating (J-10217) was a bromoiodide emulsion of finer grain and had quite different over-all characteristics. It was similar to the emulsions used in nuclear track plates.

IV. COUNTING PROCEDURE

Before a grain count was made, the cross-sectional area of the beam, as measured by the size of the spot on the film, had to be determined in order to calculate the electron density per unit area. Since the spots were small (0.2 cm^2), oval-shaped, weak, and not perfectly defined, this was a difficult problem. It was decided to enlarge the spot by projection, copy the image, and compare its area with that of a projected standard. The area comparison was actually made by weighing on an analytical balance the paper sections on which the areas had been outlined.

[10a] A clear gelatin layer is superposed on film support, and on the clear gelatin layer rests a very thin layer of silver halide emulsion. These were experimental films supplied for this particular experiment and are not offered for general sale by the Eastman Kodak Company.

The counting was done on a Bausch and Lomb research microscope, using an oil-immersion, apochromatic objective, and 25× binocular eyepieces. To reduce the counting field, an eyepiece disk with ruled squares was installed and only those grains falling within one square were counted.

For the first two coatings, the background fog was very high, being of the order of one grain in nine. Since low exposures were used to keep down the probability of multiple hits, and since the films turned out to be rather insensitive to electrons, the end result was a greater background count than induced count. Hence, the counting process became rather irreproducible, with variations of more than 20 percent in counts which were repeated.

Various methods for removing background fog in advance of exposure have been published. The possibility of non-uniform treatment, and other similar considerations, ruled out such a procedure in this experiment.

Fortunately, the third coating (J-10217) had essentially no fog, and the results were reproducible. This coating was given a wide range of exposures for each energy. When all spots were not sufficiently dark for area measurements, only the darkest were measured and the results used for all exposures. This procedure did not permit exact area measurements; a few percent variation existed between the data and a smooth curve drawn through the points when area was plotted as a function of energy.

Sampling was done at random. Since the undeveloped grains had been dissolved away, only the number of developed grains in each counting sample was noted and the average over all of the samples calculated. The total number of grains originally present in the coating for an area the size of the sample area was then determined by examining both unprocessed film and fully exposed and developed film.

It was assumed that the original number of unexposed grains per sample area did not vary significantly along the length of the film. Since data runs at the various accelerating voltages were mixed in order, a deviation from this assumption would have introduced no consistent error.

The number of grains counted per exposure varied from a few hundred to over a thousand. All grains which appeared were counted, regardless of any grain clumping. Clumping did not appear to be a significant factor, however; at low exposures practically none appeared. At very high exposures, especially at the low accelerating energies, the grains became so numerous that accurate counting was quite difficult and errors were introduced.

V. RESULTS

The results for the first coating (J-4916, a chlorobromide) are presented in Fig. 2. Two different measures of the sensitivity of this emulsion are plotted as a function of the energy of the incident electrons. The left-hand ordinate represents the ratio of the fraction of grains rendered developable to the fraction hit by one or more electron. This is really the developability probability[10b] for a single hit, so long as the likelihood of multiple hits is kept low.

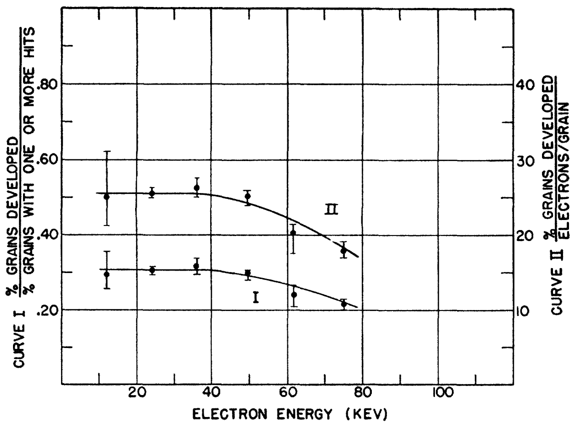

FIG. 2. Developability probability (the ratio of percent grains developed to percent grains with one or more hits) for first coating, J-4916, a chlorobromide, as a function of electron energy. Curve II gives a grosser measure of sensitivity, the ratio of percent grains developed to electrons per grain. All data is for exposures such that the probability of one or more hits per grain lies between 0.24 and 0.35.

The ordinate of the second curve plotted in Fig. 2 is the ratio of percentage of grains developed to electrons/grain. This quantity is a measure of the gross sensitivity of the coating and is particularly useful for comparing the first two coatings, which were exposed to very different intensities. The spread in data is indicated by the vertical bars through the points representing average values. This spread was considerably larger at first, but

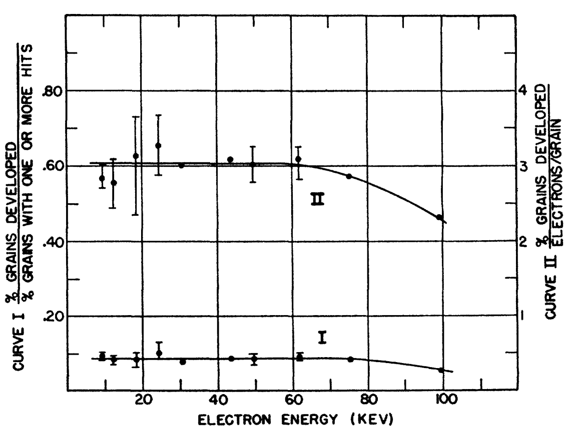

FIG. 3. Developability probability and ratio of percent grains developed to electrons per grain for second coating, J-8957, a chlorobromide, as a function of electron energy. The probability of one or more hits per grain lies between 0.87 and 0.95 for all data points. At this high level of exposure, curve II becomes a better criterion of comparison with the first coating.

[10b] The method of computing developability probability, as well as data for a sample run, are given in the Appendix.

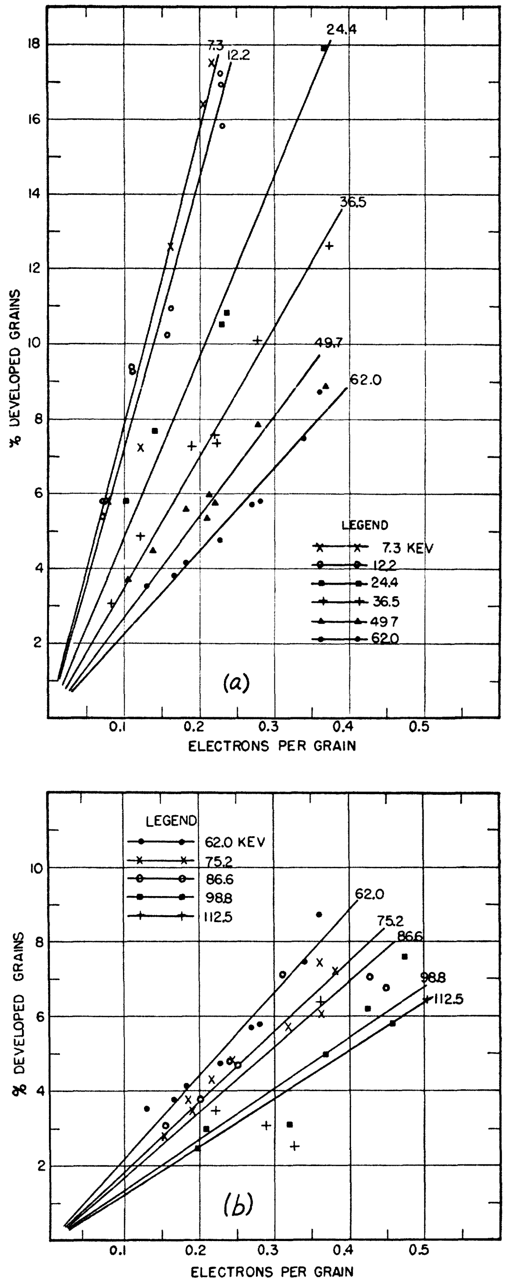

FIG. 4. (a) Curves of percent developed grains as a function of exposure in electrons per grain at electron energies between 7.3 and 62.0 kev for third coating, J-10217, a bromoiodide. This coating was prepared from an emulsion similar to those used in nuclear track plates. (b) Curves of percent developed grains as a function of exposure in electrons per grain at electron energies between 62.0 and 112.5 kev for the same coating.

by counting two or three times as many grains, the spread was reduced. The only experimental points used were those for which the probability of one or more hits lay between 0.24 and 0.35. Data points for slightly higher electron intensities did bracket the curve, however.

The data are not good enough to define the exact shape of the curve. One can state only that it is comparatively flat up to 50 kev, after which the sensitivity falls off slightly.

The results for the second coating (J-8957, also a chlorobromide) are presented in Fig. 3. The ordinates and abscissa are the same as in Fig. 2. For energies where only one experimental point was available, no spread in data was shown, but the usual wide variation in repeated measurements still existed.

The general shape of the curves, as well as the data spread, are similar to that obtained with the first coating. The sensitivity remained relatively constant up to about 60 kev, after which it dropped slowly. Curve I in Fig. 3 appears somewhat flatter because of the smaller values of the ordinate. However, the absolute sensitivity was much lower for the second coating, despite the fact that the two were intended to be very similar, when manufactured. Indeed, rough tests by Eastman showed that upon gross exposure to 100-kev x-rays, approximately the same density was produced for a given exposure; also, upon exposure to white light, a factor of 2 bracketed the variation in the density.

The results obtained in this experiment indicate a much greater difference in sensitivity to electrons for the two coatings. When the developability probabilities are compared, it appears that the first coating is about four times as sensitive. However, in order to get a visible spot with the second coating, much greater electron intensities had to be used. For the data plotted, the probability of one or more hits lies between 0.87 and 0.95. At this high probability, the Poisson law of fluctuations of small numbers dictates that additional electrons have relatively little chance of piercing an untouched grain. Hence, a comparison of the gross sensitivity, as measured by the ratio of the percentage of grains developed to electrons/grain, indicates that the first coating was 8 or 9 times as sensitive.

The results on electron sensitivity, when compared with the tests with white light by Eastman, indicate that there may be discrepancies between relative speeds to electrons as compared with white light exposures. There are other data to this effect.[11]

The apparent discrepancy in sensitivity to x-rays and electrons is unexplained. The x-rays should have produced their photographic effects by the agency of high energy photoelectrons, so that one would expect the results to be comparable. It should be noted that the accuracy of the x-ray tests was rather low because of the low total densities resulting.

The results for the third coating (J-10217, the bromoiodide) are presented in Fig. 4, (a) and (b). At each accelerating voltage this coating was exposed to a wide range of electron intensities. The percentage of developed grains is plotted as a function of electrons/grain for each accelerating voltage. (The average measured cross-

[11] H. C. Yutzy, private communication.

sectional area for the individual grains in this coating was 0.9×10^{-9} sq cm$\pm$8 percent. The grains were essentially spherical.) Straight line curves were drawn through the data, their slopes having been computed to minimize the mean square deviation from the curve.

In Fig. 5 the developability cross section is plotted as a function of electron energy for the third coating. The data for this curve are derived from Fig. 4, (a) and (b), by reading off the percentage of developed grains corresponding to 0.2 electron per grain for all voltages, and then computing the fraction having one or more hits (a constant over all voltages, of course). If a different choice for electrons per grain were made, the absolute values for developability cross section would differ slightly, but the shape of the curve would be the same.

The results for this coating differ markedly from those of the first two coatings. Instead of having a long plateau, the sensitivity drops off sharply from a high point at the lower energies. The exact shape of the curve below 15 kev is somewhat in doubt, since the data were rather irreproducible at 7 kev.

In Fig. 4 it can be seen that for low and moderate exposures, the percentage of grains developed is a linear function of the number of electrons/grain. To investigate the shape of the curve for higher exposures, data were taken at a later date for two voltages (18.3 and 75.2 kev) over an extended exposure range. The results are presented in Fig. 6. As was anticipated, the percentage of grains developed rises linearly at first, then slows off as the electrons per grain is increased. At least part of this decrease in slope is due to electrons being wasted on grains already developable. This would account for the low energy curve deviating from a straight line earlier than the high energy curve.

It is interesting to note that when the percentage of grains developed is plotted as a function of grains hit by one or more electrons, the curve straightens out for

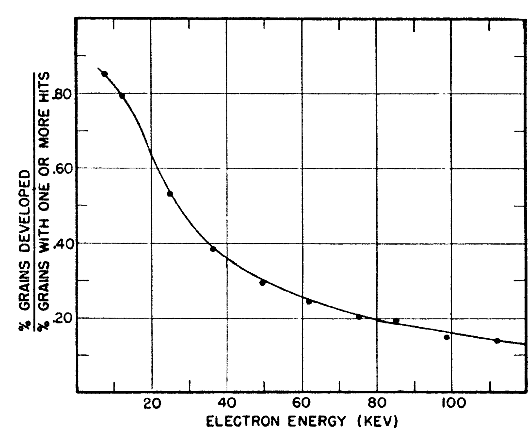

FIG. 5. Developability probability for coating J-10217 as a function of electron energy. This curve is derived from Figs. 4(a) and 4(b) by reading off the percent developed grains corresponding to 0.2 electron per grain (an arbitrary choice) for all voltages and performing the required computations.

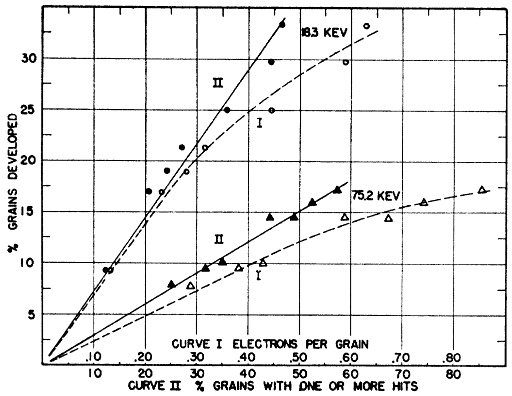

FIG. 6. Curves of percent grains developed as a function both of electrons per grain and percent grains with one or more hits at 18.3 and 75.2 kev for coating J-10217.

the exposure range used. The data for 75.2 kev fall right on a straight line; the curve for 18.3 kev is less definite.

If the developability probability remained constant for every electron-grain collision, independent of previous collisions which had not produced developability, then the curve of percent grains developed as a function of percent grains with one or more hits would be a 45° straight line for a developability probability of unity. For lower probabilities the curve should be below the 45° line initially, but rise steeply to meet it at 100 percent developed grains. This condition probably does not represent fact, since an electron which has not produced developability nevertheless would have freed some bound electrons in the silver halide grain. Thus, it might be anticipated that the task of a second electron would be simpler.

The data presented in Fig. 6 were taken at a later date than that in Fig. 4, so that there may have been some change in film characteristics. Also, the counting was done at different times, so that the sampling procedure, a rather arbitrary thing, probably differed somewhat. In any event, the sensitivity at both voltages is up to 20 percent higher in Fig. 6 than in Fig. 4. This was also true of some scattered data taken at other voltages. This variation, primarily in absolute sensitivity, is another indication of the difficulties inherent in sensitivity measurements with photographic emulsions.

VI. SOURCES OF ERROR

As indicated in Sec. II, the error in any meter measurements is believed to have been small, i.e., of the order of 2 percent. Considerably larger errors were introduced, however, in the measurement of spot area and the correction for background fog in the first two coatings. These inaccuracies, coupled with those introduced in the counting procedure, completely overshadow any of the former errors.

It is believed that an estimate of accuracy within 20 percent, relatively and absolutely, for the data pre-

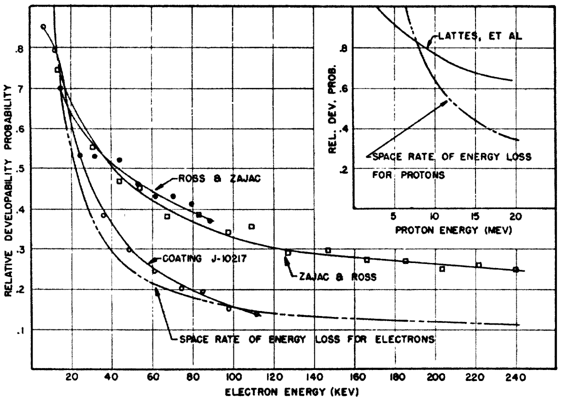

FIG. 7. Relative developability probability as a function of electron energy computed from grain counts for electron tracks in an experimental emulsion as given by Ross and Zajac (see reference 14) and in Kodak NT4 plates, as reported by Zajac and Ross (see reference 15). The results for coating J-10217, as well as an approximate curve of space rate of energy loss for the electron are presented for comparison. In the upper right-hand corner, a curve of relative developability probability computed from grain counts along proton tracks in Ilford plates as reported by Lattes *et al.* (see reference 17) is compared with an approximate curve of space rate of energy loss for the proton over the limited range available.

sented in Figs. 2 and 3 would be somewhat optimisitic. The data for the third coating were much more reproducible, thanks to the lack of background fog; and it is estimated that the data in Fig 4, (a) and (b), are correct within 10 percent relatively, and 20 percent absolutely.

No mention has been made, thus far, of a correction for backscattered electrons. Certainly, some of the incident electrons suffered collisions with nuclei or bound electrons in the gelatin layer and cellulose ester backing after penetrating the layer of silver halide grains. It turns out that this effect is small here, however. If we consider the contribution from single nuclear scattering for a scatterer of atomic number equal to 4, we find that roughly 1 percent of the incident electrons will be backscattered, using either the Mott or Rutherford formula.

Neher[12] has found experimentally that the total backscattering of monoenergetic, high speed electrons from thin and thick foils is of the same order as that predicted by the Mott theory, if we neglect backscattered electrons of very low energy. The results of Zumwalt[13] on backscattering of beta-rays indicate that less than 4 percent of the particles incident on the single-layer film should emerge in a backward direction.

Thus, in view of the considerably larger errors elsewhere, it was decided that any correction for backscattering was an unnecessary refinement at this time.

VII. DISCUSSION OF RESULTS

It is possible to obtain information on the sensitivity of photographic grains to particles as a function of particle energy by studying the variation in grain density along tracks in nuclear track plates. Measurements on grain density along tracks of β-particles have been reported by Ross and Zajac.[14,15] In the first paper the grain density in an experimental emulsion for tracks left by 100-kev electrons is given as a function of distance from the end of the track. Only unbranched tracks starting at the surface of the emulsion and having an initial direction within 40° of the central ray direction were used here. The branches, were caused by delta-rays and could not be identified with certainty if their energy was below 20 kev.

The second paper gives the mean density of grains for electron tracks in Kodak NT4 plates corresponding to an electron energy of about 250 kev. The reported counts, however, for grain number in any portion of the track, included the grains belonging to any branch produced in that portion.

With the aid of the experimental range-energy data given in the two papers, these data on grain density can be transformed into curves of relative developability probability as a function of electron energy. A rough computation has been made and the results are presented in Fig. 7. The results for the third coating (J-10217) are plotted on the same axes, as is an approximate curve of space rate of energy loss for the electron as a function of electron energy. The resemblance of the latter two is obvious; the results derived from Ross and Zajac are in good agreement with them qualitatively, fair agreement quantitatively.

Measurements on grain density for heavy particles, including alpha-particles, tritons, deuterons, protons, and mesons, have been reported by Wilkins and St. Helens,[16] Lattes, Occhialini, and Powell,[17] Brock and Gardner,[18] and Berlman,[19] among others. Lattes, Occhialini, and Powell report the variation in grain density for the longest tracks, namely, 2150 microns, corresponding to 21-Mev protons. Using the range-energy curve for protons, as given by Webb,[2] this data has been transformed into relative developability probability as a function of proton energy. The results are plotted in the upper right-hand corner of Fig. 7, along with an approximate curve of space rate of energy loss for the proton. The two curves do not match over this limited range of proton energy, although they do show a similar curvature. This is the region of high developability probability in which the developability probability curve cannot be expected to follow the rate of energy loss curve, since the former has a limit of unity.

The data presented by Brock and Gardner for the alpha-particle and the deuteron give similar results, but again only the energy range corresponding to a very high space rate of energy loss is reported herein.

[12] H. V. Neher, Phys. Rev. **38**, 1321 (1931).
[13] L. R. Zumwalt, MDDC-1346 (unpublished).

[14] M. A. S. Ross and B. Zajac, Nature **162**, 923 (1948).
[15] B. Zajac and M. A. S. Ross, Nature **164**, 311 (1949).
[16] T. R. Wilkins and H. J. St. Helens, Phys. Rev. **54**, 783 (1938).
[17] Lattes, Occhialini, and Powell, Nature **160**, 453 (1947).
[18] R. L. Brock and E. Gardner, Rev. Sci. Instr. **19**, 299 (1948).
[19] I. B. Berlman, Phys. Rev. **80**, 96 (1950).

One other bit of information can be gleaned from the results. Webb[4] has found that on the average about 40 quanta of light had to be absorbed by a photographic grain to produce developability. This information was gained by exposing single-grain-layer photographic plates, prepared from a non-color-sensitized, slow-speed, uniform-grain-size emulsion to monochromatic light of three different wavelengths. On the other hand, by considering the limiting sensitivity of nuclear track plates available in April, 1948, Webb[2] estimated that about 150 ion pairs per grain were formed by the particle as it entered this threshold.

The results for the third coating indicate that at 110 kev there is still an appreciable sensitivity present. By following Webb,[2] we can estimate the number of ion pairs formed for this electron energy and thus gain information on the number of ion pairs which will render a grain developable. Van Heerden[20] (as quoted by Webb) found that 7.6[21] ev is required to produce each ion pair for the case of high speed beta-particles passing through silver chloride. From the space rate of energy loss curve for the electron, we find that at 110 kev it loses about 0.0045 Mev/cm in air. The maximum number of ion pairs produced in a photographic grain for a particle of this energy-loss value can be found by multiplying the rate of energy loss in air by the stopping power of silver bromide relative to air (3000), multiplying by the diameter of the grain (0.35 micron), and dividing by the electron volts used per ion pair. Then we find that

$$\text{ion pairs/grain} = 0.0045\times 10^6 \times 3000 \times 3.5\times 10^{-5}/7.6 = 62 \text{ ion pairs/grain.}$$

This approximate number does not represent the average number of ion pairs produced along a straight line which are needed to render the grain developable, but rather something which approaches the lower limit. It is not surprising that this process seems less efficient than the random absorption of light quanta throughout the grain. Since all the ion pairs are produced in a very short time and along an essentially straight line, losses due to recombination should be favored. Also, there is direct evidence[2] of inefficiency in the photographic process for light exposures of duration less than 10^{-3} sec as compared with equal exposure over a longer time. Thus, the very short duration of exposure when incident particles are considered should provide further loss in efficiency.

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APPENDIX

The developability probability is computed in the following manner. The area of the exposed spot is read from the curve of spot area as a function of electron energy. The average electrometer reading in millivolts is converted to number of electrons and then combined with the shutter open time and spot area to give electrons/sq cm. Using this value and the average measured grain area, the poisson law of fluctuations of small numbers is then applied to compute the fraction of grains hit by one or more electrons.[4]

The fraction of the total number of grains present which has been rendered developable is determined from the microscopic counting data after correction for fog. This fraction, divided by the fraction of grains hit, is equal to the developability probability.

Typical data for one exposure of coating J-4916 was as follows:

1. Accelerating voltage	49.7 kv
2. Average electrometer reading	7.05 mv
3. Shutter-open time	0.150 sec
4. Fraction grains rendered developable	0.101
5. Spot area (read from curve)	0.183 sq cm
6. Average grain area	2.24×10^{-9} sq cm.

The bleed resistor on the electrometer was 1.98×10^8 ohms; hence, the total beam current was 3.56×10^{-11} ampere, corresponding to a charge density of 1.82×10^8 electrons/sq cm delivered to the coating. The number of electrons per grain, therefore, amounted to 0.407. From the poisson distribution we then find the number of grains suffering one or more hits to be 0.335, so that the developability probability is equal to 0.301.

[20] P. J. Van Heerden, *N. V. Noord-Hollandsche Uetgevers Maatschappy* (Amsterdam, 1945).

[21] W. L. Whittemore and J. C. Street [Phys. Rev. **76**, 1786 (1949)] report a value of 6.6±0.7 ev, while Hofstadter, Milton, and Ridgeway [Phys. Rev. **72**, 977 (1947)] obtained a variety of much higher values. Van Heerden's value was used to make the result directly comparable with that of Webb.