THE MEASUREMENT AND REDUCTION OF DISTORTION IN THICK EMULSIONS

By V. D. HOPPER,* Y. K. LIM,* and MADELINE C. WALTERS*

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Summary

A study has been made of some of the factors influencing the distortion of developed images of tracks in Ilford G5 400 μ emulsions. It has been found that the effect of distortion on scattering measurements can be reduced to a negligible amount by developing the emulsions at 15 °C and drying with an alcohol-water solution of increasing concentration. A simple quantitative description of the distortion can be obtained by fitting a sinusoidal series to the curve of a high energy track traversing the emulsion.

I. INTRODUCTION

The use of thick emulsions is of considerable advantage in cosmic radiation studies, since the possibility that an event will be completely contained within a single layer is thereby greatly increased. Emulsions having a thickness of several millimetres have been employed but these are seriously distorted during processing. Also, in order to study an event in detail, a high power objective of 95 × is used and, as this has an effective working distance of about 250 μ, emulsions which in their final developed state have thicknesses greater than this cannot be conveniently studied. When an Ilford G5 nuclear emulsion plate of thickness 400 μ is developed and dried, the final thickness of emulsion is about 150 μ, and a 600 μ plate is reduced to 225 μ. Thus emulsions of thickness 600 or 400 μ are generally employed in cosmic ray studies and layers of such emulsions are used if greater effective thickness of emulsion is required.

When a nuclear emulsion plate of, say, 400 μ thickness on glass backing is developed, it also suffers a small general contraction in the planes parallel to the plate. The contractions are not perfectly uniform with the result that a straight track in the undeveloped emulsion shows curvature in the developed emulsion, the curvature becoming more pronounced as the inclination of the track to the plane of the emulsion-glass surface increases. With the nuclear emulsion technique the energy of a charged particle can be determined from a measurement of scattering, but, in order to accurately determine scattering effects, the distortion must be reduced to a small amount. In the measurement of scattering, additional sources of error enter due to the mechanical irregularities of the microscope stage, and observational errors. The object of this work has been to investigate factors which influence distortion and to find a method of development which produces clearly visible minimum ionizing tracks and also reduces the error due to distortion below other errors.

* Physics Department, University of Melbourne.

II. Measurement of Emulsion Distortion

It may be assumed that over a few millimetres of a plate needed to measure the scattering of a track, the curvature distortion is due to lateral displacement of parallel layers at different depths relative to the glass backing. The lateral displacement Δ of a point at a height Z in a distorted emulsion of thickness d, may be expressed as a function of Z/d by the power series

$$\Delta = K_1(Z/d) + K_2(Z/d)^2 + \ldots \quad \ldots\ldots\ldots (1)$$

proposed by Cosyns and Vanderhaeghe (1950). The first term in the series represents a change in the orientation of the tracks in the emulsion and this does not affect scattering measurements while second and higher order terms give rise to a curvature. A rapid method of measuring the second coefficient K_2 in the series has been proposed by Major (1952) who showed that this coefficient is four times the distance δ between the mid point of the chord joining the ends of the track and the point of intersection of the track with the plane $Z = d/2$. In practice the centre of the eyepiece scale is placed at the centre of the chord and the scale is then rotated until it is directed at the point of the track in focus at half-depth, when δ may be read off. The assumption is made that third and higher order terms in Z/d are zero, or may be neglected. This assumption is not always justified, S-shaped distortion being frequently observed and in these cases K_3 is greater than $0 \cdot 5\ K_2$. Even for tracks which appear C-shaped the value of K_3 may be appreciable.

The lateral displacement Δ, resulting from distortion, of a point in an originally straight track is more conveniently expressed by the series of angular functions.

$$\Delta = K_1(Z/d) + a \sin \pi(Z/d) + b \sin 2\pi(Z/d) + \ldots \quad \ldots\ldots (2)$$

The number of terms involved in a particular distortion is then apparent from the number of points of inflection along the track. The advantage in this method of expression is that the coefficients a and b are readily determined from two simple measurements on a single track, while higher order distortions are seldom observed. The parameter δ, whose measurement is described above, is equal to the coefficient a. If S-distortion is appreciable compared with C-distortion (i.e. $b > a/2$), b may be determined by an observation of the height Z in the emulsion at which the track intersects the chord joining its ends, since at this point

$$a \sin \pi(Z_1/d) = -b \sin 2\pi(Z_1/d). \ldots \quad \ldots\ldots\ldots (3)$$

Neither of these measurements is affected by the inclination of the plane containing the track with the direction of δ. Any high energy track in the region investigated may therefore be selected for measurement.

In order to find out how closely the form of the C-shape distorted tracks in an emulsion fitted a first order distortion of the type $\Delta = a \sin \pi(Z/d)$, the projection curves on a horizontal plane, of 10 steeply inclined tracks were measured to an accuracy of $\pm 1\ \mu$. The tracks chosen for measurement lay at angles between 18 and 90° with the direction of distortion. From plots of these

projections the horizontal distance between chord and track, in the direction of the distortion, δ, could be determined at various points along the track. Values of Δ/δ plotted as a function of depth may be seen from Figure 1 to approximate to a sine curve within limits of ± 5 per cent.

III. The Apparent Mean Scattering Angle of a Distorted Track

The apparent mean scattering angle which will be obtained from direct measurements on a track in a distorted emulsion will depend upon the orientation of the track, and will be a maximum for tracks lying in a plane perpendicular to the direction of distortion. The value of the mean scattering angle resulting from distortion may be estimated from measured values of the coefficients a and b of equation (**2**).

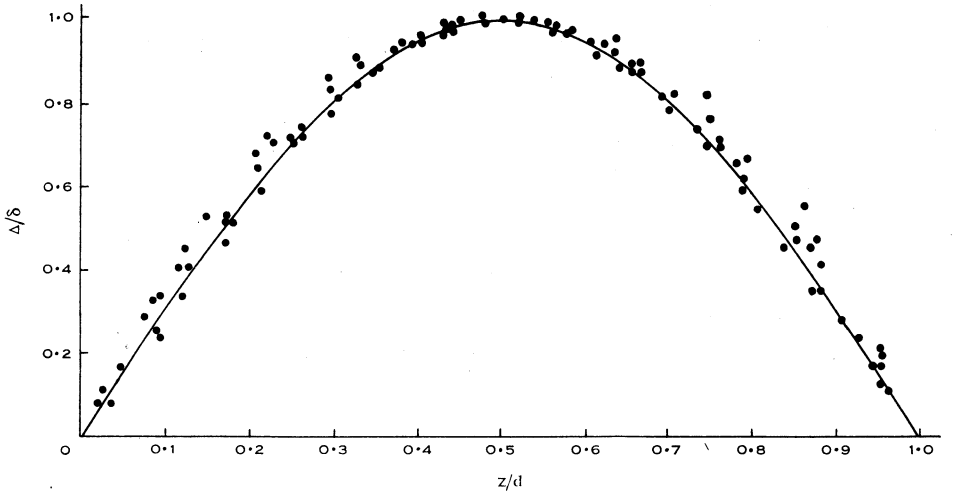

Fig. 1.—Lateral displacement in the direction of distortion as a function of depth for plate showing C-distortion.

For the case of a first order distortion, when $b=0$, the x and y coordinates of the projection on a horizontal plane of a straight track, lying at an angle θ to the direction of distortion and extending through the whole depth of the emulsion, may be approximately represented by the equation

$$y = a \sin\theta \sin \pi x/l_0, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where l_0 is the projected length of the chord joining the ends of the track. The mean scattering angle $\bar{\alpha}_d$ observed for such a track is then given by

$$\bar{\alpha}_d = \frac{a\pi c}{l^2}\left(\frac{Z_2 - Z_1}{d}\right)\left\{\cos\left(\frac{\pi Z_1}{d}\right) - \cos\left(\frac{\pi Z_2}{d}\right)\right\}\sin\theta, \quad \ldots\ldots\ldots \quad (5)$$

where l is the projected length of the track extending from a depth Z_1 to Z_2 in the emulsion, and c is the cell length measured in the direction of l.

Numerical values of $\bar{\alpha}_d$ have been estimated for tracks lying in a plane perpendicular to the direction of distortion, and are given in Figure 2. These values represent the maximum error which could result from distortion for any particular dip angle.

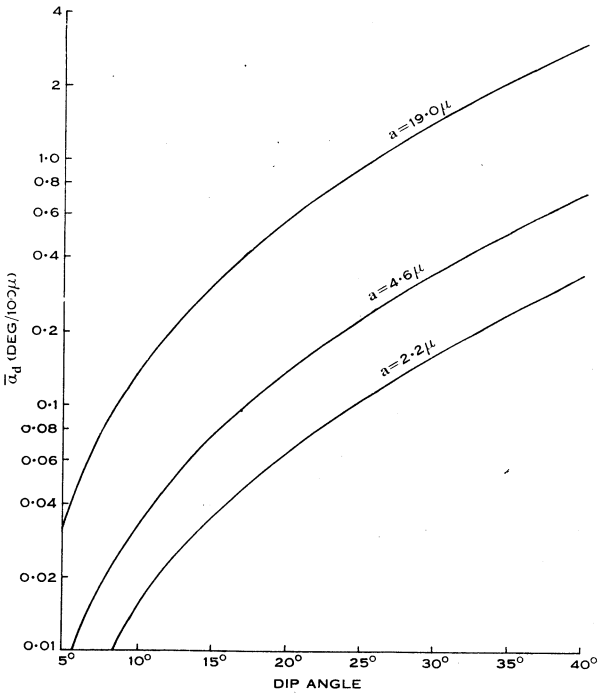

Fig. 2.—Maximum mean scattering angle due to distortion for the case of 100 μ cell length plotted against dip angle in unprocessed plate for three values of a.

IV. An Investigation of the Curves of Emulsion Distortion

In order to obtain uniform development throughout a thick emulsion layer the " temperature development method " of Dilworth, Occhialini, and Payne (1948) may be employed. During the warm stage of the process the emulsion tends to lose its elasticity and may flow slightly, and when the emulsion is later cooled such distortions become frozen in. These distortions can be reduced by lowering the temperature of the warm stage, though this tends to alter the characteristics of the development and results in an increased fog level which renders track recognition difficult (Herz 1953). In order to find the optimum warm stage temperature a series of developments has been carried out at different temperatures and the degree of distortion produced measured in each case.

The other principal cause of distortion is uneven drying of the processed emulsion. Since nuclear emulsions contain an abnormally high concentration of silver bromide, the emulsion thickness is reduced to less than half its original value during processing. The contraction occurs mainly in the drying stage,

and during washing the emulsion absorbs water and becomes swollen to a greater thickness than at any other stage in the processing. If drying should be uneven, as is the case when the plate is dried rapidly in air, large distortions occur at the edge as has been illustrated by Major (1952). Several different methods of drying have therefore been tried out and were found to have a considerable influence on the amount of distortion.

Other possible sources of distortion which have been suggested are rapid changes of temperature before and after the warm stage, and sudden changes in pH of the processing solutions. These have not been studied in the present investigation. It has also been suggested by Bonetti, Dilworth, and Occhialini (1951) that distortion produced in the manufacture of the plates may be released during development. If this is in fact the case the developed emulsion will contain some distortions whatever precautions are taken during processing.

V. Effect of Warm Stage Temperature on Distortion

Ilford G5 plates, 400 μ thick, were developed in an amidol-bisulphite developer of the type described by Dainton, Gattiker, and Lock (1951). The plates were presoaked in distilled water at 4 °C for 2 hr. After soaking in cold developer for 2 hr at 4 °C, the surface developer was removed and the plates then transferred to a hot plate at temperatures of 27, 20, and 15 °C for appropriate times. Fixation and washing were carried out at temperatures below 5 °C. The plates were immersed in a 1 per cent. solution of glycerine in water for 2 hr before being dried to prevent subsequent stripping of the emulsion from the glass backing. In order to dry the plates uniformly they were immersed for 2 hr at room temperature in each of a series of alcohol-water solutions, in which the alcohol concentration was increased in four stages up to 80 per cent. The plates were then allowed to dry in a horizontal position in a wooden box. Distortion measurements were made at 1 cm intervals over the entire area of the plates and the mean values of the distortion coefficients a and b obtained. The results are shown in Table 1.

Table 1

DISTORTION MEASUREMENTS RELATED TO TEMPERATURE OF DEVELOPMENT

Plate No.	Development at Warm Stage		Mean Distortion Coefficients		$g_{min.}$*
	Temp. (°C)	Time (min)	a (μ)	b (μ)	
1	27	23	19·0±1·2	1·54±0·15	14·8±0·4
2	20	65	17·8±0·5	0·0	12·7±0·3
3	15	120	4·6±0·3	1·90±0·20	10·9±0·3
4	26	30	12·5±0·2	—	—
5	15	120	3·3±0·6	0·31±0·03	—
6	7	180	4·0±0·6	0·31±0·03	11·0±0·3

* $g_{min.}$ represents the number of grains for 50 μ for minimum ionizing particle.

Plates 4 and 5 were developed by the same method as plates 1–3 except that the drying process was carried out at a temperature below 5 °C. They show the same general reduction in distortion with decrease in the temperature of the hot stage.

An attempt was made to reduce the distortion still further by processing a plate at a constant temperature of 7 °C throughout, as discussed by Edgar and Herz (1953), their method being modified in this case by using the alcohol-water drying method. Temperature fluctuation of $\pm 1°$ occurred about the mean temperature of 7 °C during the processing. Measurement of the distortion coefficients at about 40 evenly spaced points on one such plate yielded the comparatively low values quoted in Table 1. This method of development was not, however, considered as satisfactory as that of the plates developed at 15 °C, since the fog density in the processed emulsion particularly near the surface was abnormally high.

VI. Distortion Produced during Drying

In order to investigate the distortion which results from different methods of drying, four 400 μ thick G5 plates were developed as described in the previous section, at a warm stage temperature of 15°, and then dried by different methods. Plates 7 and 8 were dried in air immediately after washing, plate 8 being left in an enclosed space maintained at high relative humidity by the presence of water, while plate 7 was allowed to dry in air of low humidity. Plates 9 and 10 were soaked for a period of 2 hr in each of a series of alcohol-water solutions in which the alcohol concentration of successive baths was increased by steps of 15 per cent. After immersion in the 60 per cent. alcohol solution plate 9 was dried in air, while plate 10 was taken through the whole series and finally immersed in absolute alcohol for 2 hr before being allowed to dry. Measurements of the distortion coefficient a were made at regular intervals over each plate and values corresponding to points more than 1 cm from the edges are quoted in Table 2.

Table 2

Distortion measurements related to method of drying

Plate No.	Method of Drying	Distortion Coefficient a (μ)
7	Air (evaporation, low humidity)	$10{\cdot}96 \pm 0{\cdot}90$
8	Air (evaporation, high humidity)	$10{\cdot}45 \pm 0{\cdot}57$
9	Dehydration in alcohol solutions to 60%	$6{\cdot}37 \pm 0{\cdot}30$
10	Dehydration in alcohol solutions to 100%	$2{\cdot}15 \pm 0{\cdot}17$

The distribution of distortion on plates 10 and 7 is shown in Figures 3 and 4. These illustrate the difference between a plate dried in air, when drying proceeds from the edges, producing a high degree of distortion near the edges and less at the centre, and a plate from which the water has been removed uniformly

with alcohol, which shows a much more even distribution of distortion. It is interesting to note that the longer drying time necessary to remove the excess water in a humid atmosphere compared with the time required in a dry atmosphere has had little effect on the degree of distortion produced.

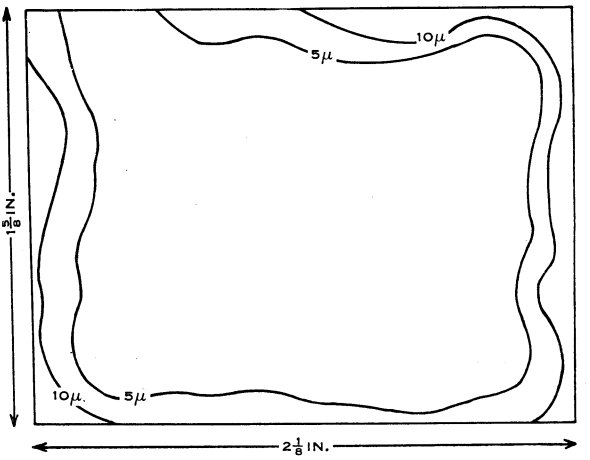

Fig. 3.—Contour map of distortion δ for plate 10. Emulsion dehydrated with alcohol.

VII. Comparison of Distortion and Noise Level Errors

The minimum distortion value of a so far produced, 2·2 μ in a 400 μ thick emulsion, is satisfactory from the point of view of scattering measurements,

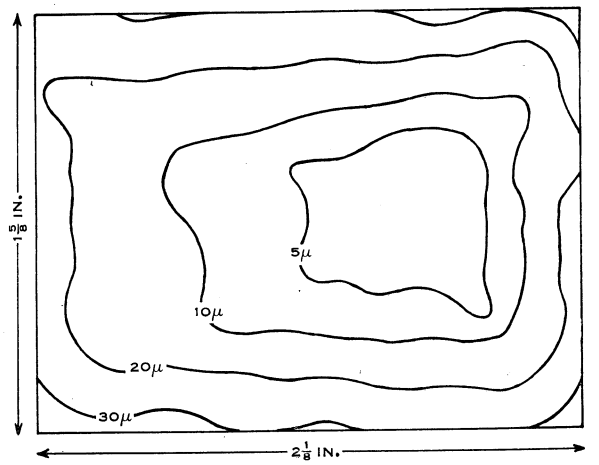

Fig. 4.—Contour map of distortion δ for plate 7. Emulsion dried in air.

since the error arising from such distortion is small in comparison with the noise level due to mechanical irregularities of the microscope stage and observational errors. If tracks which traverse an emulsion free of distortion are measured, the

accuracy of the measurement of scattering depends on the length of track in the emulsion. For steep tracks few successive cell lengths can be employed and these must be comparatively short, resulting in low statistical accuracy. The noise levels in degrees per 100 μ for varying cell lengths have been measured for the microscope employed in scattering measurements. These are compared in Table 3 with the maximum distortion errors in degrees per 100 μ, $\bar{\alpha}_{d(\max.)}$, calculated for the same cell lengths for tracks having 17 successive cell lengths in the distorted emulsion which has a value of a of 2·2 μ. It will be observed that, for the track of cell length 100 μ and 1700 μ length in the emulsion, the error in the scattering measurement is only one-fifth of the error due to the noise level and this ratio decreases with increasing cell length and corresponding length of track in the emulsion. The lower limit to the small-angle scattering which is measurable thus depends primarily on the noise level and it is not necessary to make any correction to the scattering measurement for distortion for such plates.

TABLE 3

NOISE LEVEL ERRORS COMPARED WITH DISTORTION ERRORS (PLATE 10)

Cell Length (μ)	Corresponding Track Length (μ)	Maximum Dip Angle (deg)	Maximum Distortion (deg/100 μ)	Noise Level (deg/100 μ)
100	1700	13·3	0·028	0·15
200	3400	6·7	0·0095	0·081
400	6800	3·4	0·0033	0·036

VIII. CONCLUSIONS

These investigations have shown that the two principal causes of emulsion distortion are (1) the increased plasticity and consequent flow of the emulsion during the warm stage of development, and (2) the uneven contractions produced by non-uniform drying. Distortion arising from the first of these causes may be minimized by reduction in the temperature of the warm stage, though the change in the development action which then occurs sets a lower limit to this temperature. A warm stage temperature of 15 °C appears to result in satisfactory development while reducing distortion to a low level. Distortion produced in the drying stage can be minimized by gradual and uniform dehydration of the emulsion in alcohol-water solutions of increasing concentration, and finally in absolute alcohol. For plates developed in this manner the error in scattering measurements due to distortion is very much smaller than that due to noise level.

IX. ACKNOWLEDGMENTS

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