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THE MOTION OF EARTH THROWN FROM SMALL CRATERS BY EXPLOSIVE CHARGES

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ABSTRACT

This report is a summary to date of the results of some experiments regarding the space-time distribution of earth expelled from a crater by a small elevated charge. Crater dimensions were measured in tests at P-Site and at Trinity; dimensions of craters obtained at Trinity, when extrapolated to 100 tons of explosive, give 104 feet diameter and 6.3 feet depth. X-ray flash photographs taken at P-Site showed material thrown from craters at an average angle of 40° and with a velocity of about 110 meters per second. Likewise terminal observations of the distribution of earth adhering to a verticle plane surface placed normal to a diameter of the crater showed a deposit between 13° and 45° elevation as measured from the center of the crater. It was also found by X-ray flash photography that the velocity of shock in Trinity earth was 2000 meters per second if the earth were dry powder, 1000 meters per second if it were wet mud, and that the shock was rapidly slowed down in adobe.

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THE MOTION OF EARTH THROWN FROM SMALL CRATERS BY EXPLOSIVE CHARGES

1. INTRODUCTION

The work to be described in the following report was undertaken at the suggestion of Penney and was primarily intended to yield information regarding the space-time distribution of material ejected from a crater by an elevated charge. The experiments were to be carried out using charges of the order of a half-pound and the results extrapolated to charges of the size used in the Trinity tests. The scaling law used throughout the work is that all linear dimensions and times relevant to the blast vary as the cube-root of the explosive charge weight. This law involves the following assumptions:

a) The earth is isotropic.

b) The blast is isotropic.

c) The acceleration of gravity is negligible.

c) Air resistance is negligible.

e) The material strength is not scaled.

2. EARTH FLIGHT OBSERVATIONS

2.1 X-ray Flash Photographs. The optical photographic method is unsuitable as a means of obtaining information about the motion of material ejected from an explosion crater because flame, smoke and dust obscure the entire scene. The X-ray flash photographic technique does not suffer from these drawbacks, and the P-Site installation offers the requisite X-ray equipment in conjunction with a firing site; hence the X-ray method was chosen as a means of obtaining the desired information. The P-Site X-ray equipment gives an accurately timed flash of about 1 μs duration and about 50 to 70 XU effective wavelength, and the construction of the buildings and intensity of X-rays available are

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such that satisfactory pictures may be made with the film casette about five feet from the tube target. A charge weight of one-half pound is suitable since it produces a crater having a radius of about seven inches which is the masimum that can be photographed satisfactorily using the largest available shock-resisting casette (8" x 10" film).

Following a number of preliminary experiments in which the chief difficulty was the small X-ray absorption of the flying earth, the following experimental setup was adopted. A welded iron box 4 feet square and 1 foot deep was filled with screened earth, which was first wet and packed down into a compact mass. A slice of earth about 10 inches long, an inch wide, and 4 inches deep was then replaced by an X-ray opaque paste made of powdered lead oxides. The opaque lamina was placed with its long dimension radial to the crater so that the vertical axis of the blast passed through one end of the lamina. At a chosen time after detonation of the charge, a pulse of X-rays passed parallel to the surface of the earth and perpendicular to the long dimension of the lamina. In the actual setup the center of the charge was located about 5 inches to the left of the center of the photograph and 4.6 inches above the earth level before the explosion. As a result of the divergence of the X-rays, however, the pictures are magnified 1.6 times so that as measured on the picture the center of the charge is 8 inches to the left of the center and 7.4 inches above the earth level which is indicated by a horizontal line through the lower end of the large fiducial "arrow" in Figs. 1, 2 and 3. These figures were taken at 350, 450 and 575 μsec, respectively, after the detonation of the charges. The edges of the absorbing material in the air were tenuous, and the photographs are therefore fuzzy. Material from near the center of the crater is seen to move at an angle of about 45°, while at increasing distance from the center of the crater the angle of flight decreases to about 30°. The velocity of the earth as

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calculated from these photographs is about 0.11 Km/sec. If this velocity is assumed correct, the earth must have begun to move at about the time the shock wave reached the earth.

2.2 Terminal Observations of Earth Flight. Additional evidence regarding the angle at which earth leaves the crater was obtained by means of terminal observations of the distribution of earth adhering to a vertical plane surface placed normal to a diameter of the crater. A half-pound charge was suspended with its center 4.6" above the surface of the earth and 26" from the steel vertical surface. The earth was wet enough to adhere to the vertical surface and likewise to produce the maximum size crater.

Following the explosion it was observed that two separate patterns of mud had been laid down on the surface. The first pattern (underneath) consisted of small specks of dirt of diameters ranging up to 1/4", rather sparsely and uniformly distributed, and baked quite dry and hard. These specks were very thin and had the appearance of having been driven hard against the steel surface when wet and splashed out flat like drops of water. This pattern was laid down between two definite limits having the form of hyperbolas, a result which was to be expected if the earth is assumed to travel in straight lines from a common center in a zone between two covers. The upper limit hyperbola would be produced by earth leaving the crater at an angle of about 45° and the lower limit hyperbola would be produced by earth leaving the crater at an angle of about 15°. The second pattern was observed to cling to the recording surface over a small area nearest to the crater and consisted of large wet clods of mud having diameters up to about 3". A straight line drawn from the center of the crater to the upper limit of this pattern was observed to have an angle of elevation of about 28°, while a similar line drawn to the lower limit of this pattern was inclined at an angle of about 13°. A rough visual estimate of the relative quantities of wet and dry

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deposits is 10 to 1, as sketched in Fig. 4, which shows the approximate distribution of material as a function of angle.

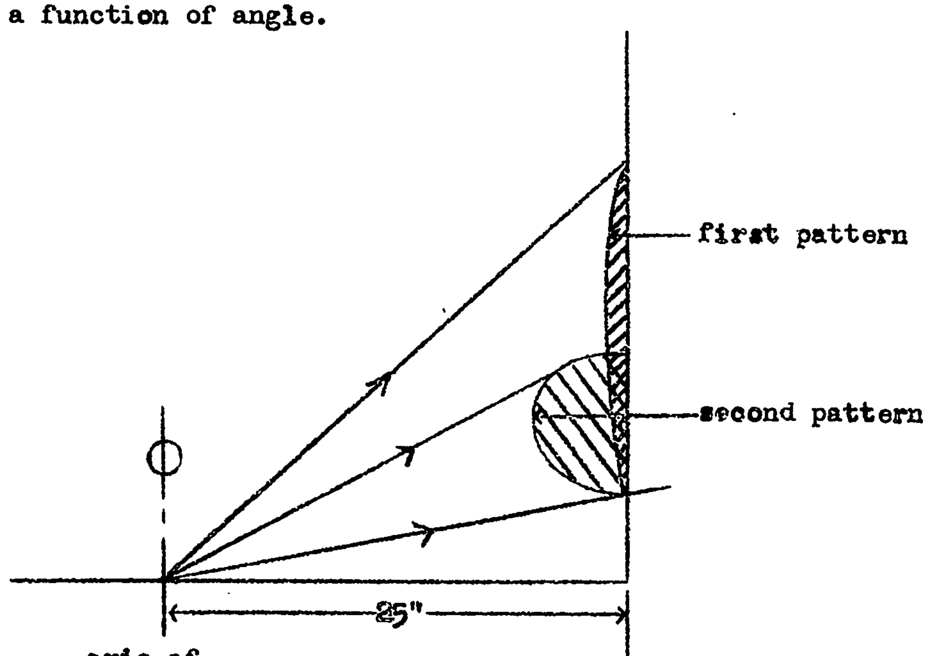

Fig. 4

The following is an hypothesis for the mechanism of crater formation by an explosion occurring above the surface of the earth. The formation of the crater may proceed in two stages. In the first stage, the blast wave strikes the earth and erodes surface material. This material moves away with a velocity of the order of 1 Km/sec, and, if located near the axis of the blast, probably leaves at an angle of about 45°; if located farther from the axis it leaves at a correspondingly smaller angle of elevation. At the same time, a compression wave starts down into the earth. It may be supposed that Figs. 1, 2 and 3 show the surface material leaving during this stage of the crater formation and that the pattern of small mud particles found adhering to a nearly vertical plane surface (as described above) is formed by material ejected during this stage. The small particle size, evidence of high velocity impact, and the angular limits of the pattern are consistent with this view and with the belief that it

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is this mud which the X-ray pictures reveal. The second stage in the formation of the crater begins when the earth is released from its compressive stresses. If the earth is elastic, as in the case of wet mud, it may be supposed that the greater part of the crater is formed by the rebound of the earth upon its release from compression. The earth is thus expelled at low velocity and in large chunks during this period of the formation of the crater. The fact that large pieces of earth, similar in appearance to the wet deposit adhering to the wall, are found lying about on the ground at distances up to about 10 feet is consistent with this view because if these pieces were moving at a velocity comparable with 110 meters per sec, as earth was shown by the X-ray pictures to be moving, they must certainly have gone farther and been more broken up. It is therefore thought likely that this massive material was ejected from the crater at a velocity of the order of 10 meters per second. No attempt is made to explain the angular distribution of material attributed to this second stage. Unfortunately the X-ray technique as used at P-Site was not adaptable to observation of material emerging from the crater at very late times because the casette seems to be blown away at some time between a half and one millisecond after the detonation.

If the earth is composed of fine powder a true crater is not formed (vide infra). It is considered likely that the energy of the compression wave is dissipated in friction and crushing between the particles and thus earth is removed only during the first phase mentioned above. In the case of very hard dry earth the compression wave produces a permanent deformation of the earth, and no earth is removed at any time. It may be supposed, in terms of the above hypothesis, that the strength of the hard, dry earth is too great for the scouring action of stage one to remove material, and, the earth being inelastically compressed, that there is insufficient rebound to tear out material in stage two.

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3. CRATER OBSERVATIONS

As a part of the experiments leading to an understanding of the space-time distribution of earth thrown out of craters, and while obtaining data from which to extrapolate the size of crater to be expected of the shots at Trinity, some observations were made of the sizes and kind of craters produced in earth by small elevated charges. The size and character of crater formed undoubtedly depend strongly upon the mechanical and hydrodynamical characteristics of the earth. Unfortunately an accurate knowledge of the magnitudes of the various important elastic moduli in various types of earth is not available. The experiments to be described were carried out on the following kinds of ground:

a) Fine powder.

b) Very wet mud.

c) Moist packed earth.

d) Dried packed earth.

e) Trinity conglomerate.

The geometry of the setup employed in these experiments was as shown in Fig. 5.

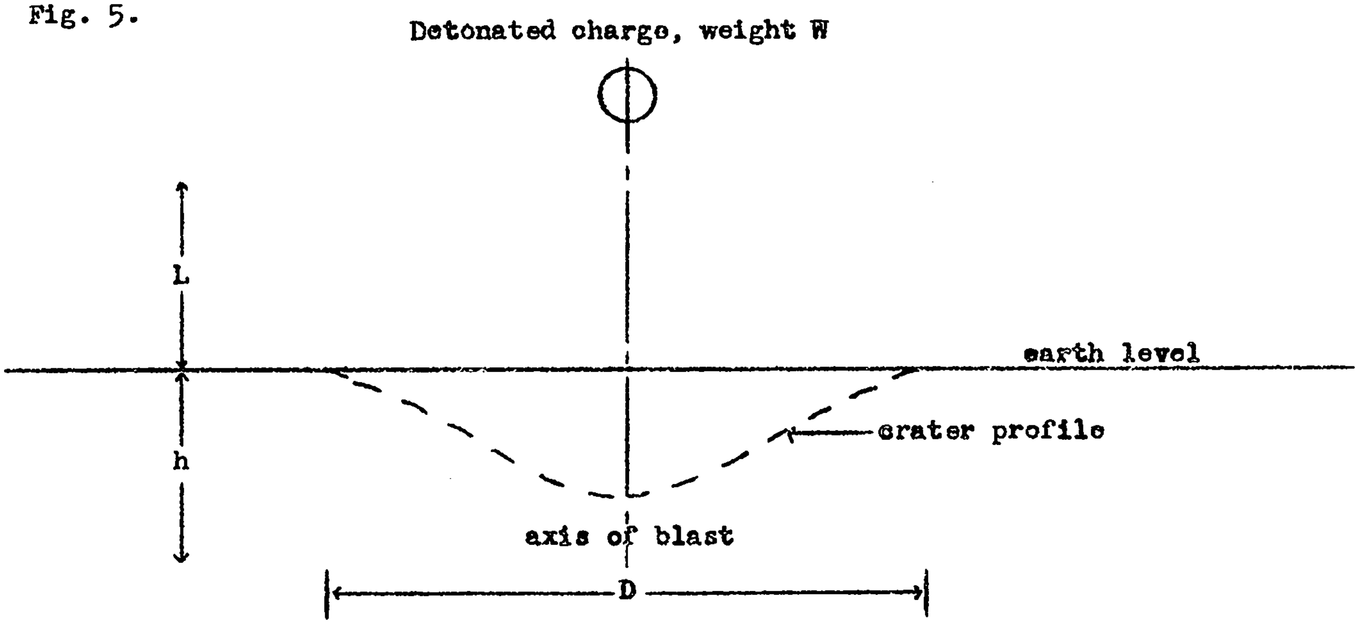

Fig. 5

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The elevation of the charge in all cases was the scaled value corresponding to 5000 tons of explosive at 100 foot elevation. The parameter $L/W^{1/3}$ therefore had the value 0.465, where L is the elevation of the charge in feet and W is the weigh of the charge in pounds.

3.1 Craters in Powder. In the case of charges located over very dry powdered earth, the blast produced no true crater. Instead, a thin superficial layer of the earth was blown away.

3.2 Craters in Wet Mud. The craters formed in wet mud were the largest obtained and gave the following average values of crater parameters

$$D/W^{1/3} = 1.9 \quad \text{approximately}$$

and

$$h/W^{1/3} = 0.63 \quad \text{approximately}$$

The crater profile was usually of the form shown in Fig. 6,

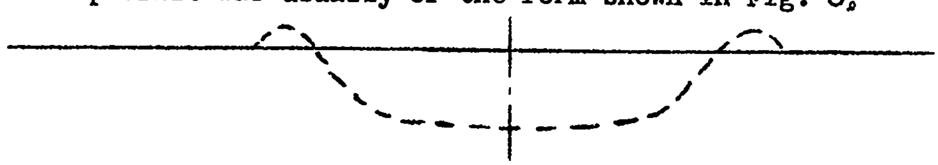

Fig. 6

although occasionally a crater was formed in which the bottom was blown out as shown in Fig. 7. In this case the surface of the inner crater was found to be much more irregular and broken than the surface of the outer crater.

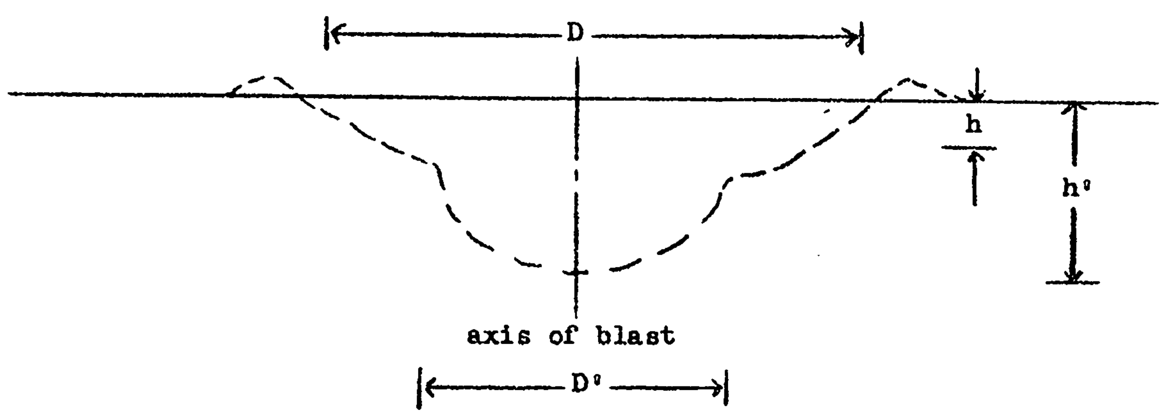

Fig. 7

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For this type of crater

$D/W^{1/3} = 1.9$ approximately

$D'/W^{1/3} = 1.3$ approximately

$h/W^{1/3} = .105$ approximately

$h'/W^{1/3} = .35$ approximately

It will be observed that Figs. 6 and 7 show craters having a slightly raised edge. Not all craters in wet mud were observed to have this raised edge; but whenever the raised edge was absent, the surface immediately surrounding the crater was noted to be freshly broken. The conclusion was drawn that the edge had been thrown up in every case, but that in some cases the air wave had torn it loose and carried it away.

3.3 <u>Craters in Moist Packed Earth.</u> In this case, the craters were roughly as shown in Fig. 8 with

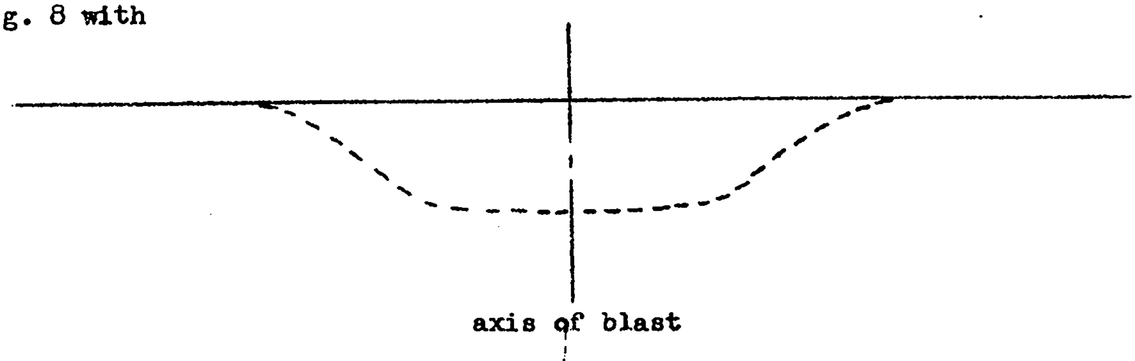

Fig. 8

$D/W^{1/3}$ 1.32 approximately

$h/W^{1/3}$ 0.341 approximately

3.4 <u>Craters in Dried Packed Earth.</u> When the earth was sufficiently packed, dry, and hard, little if any earth was thrown into the air. Instead the earth was merely compressed under the charge, and a shallow depression with gently sloping edges was formed having the profile shown in Fig. 9.

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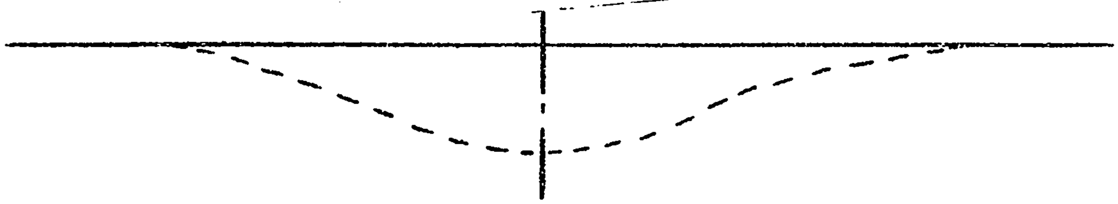

Fig. 9

The diameter of this depression was very difficult to measure because of the ill-defined character of the edge. It was estimated, however, that

$$D/W^{1/3} = 2.0 \quad \text{approximately}$$

and

$$h/W^{1/3} = 0.21 \quad \text{approximately}$$

3.5 Craters in Trinity Conglomerate. The character of the surface strata of earth at Trinity at a point near "O" (Trinity terminology) was observed in a convenient hole and was approximately as shown in Fig. 10.

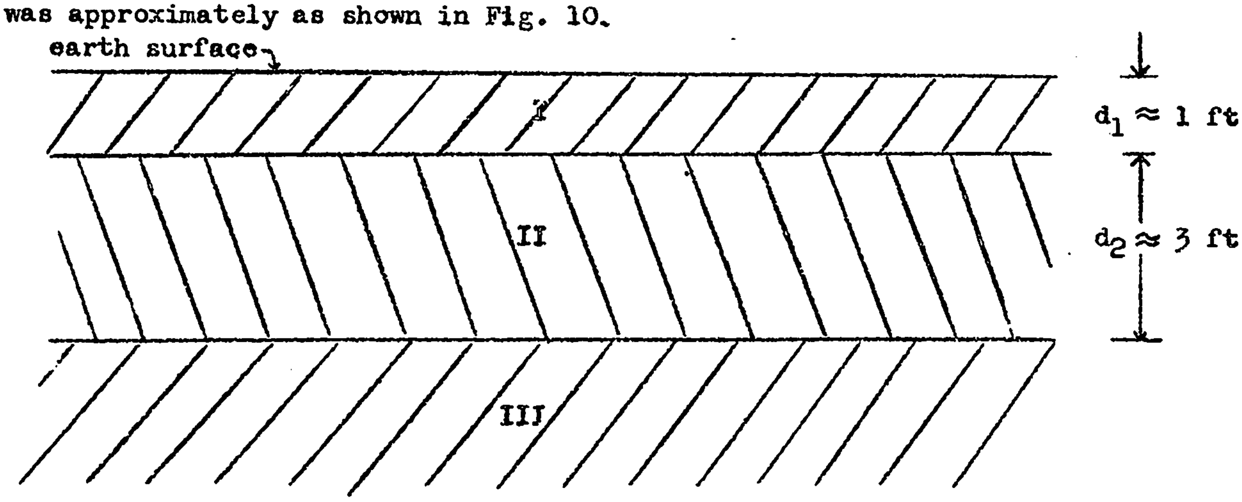

Fig. 10

Layer I is a very soft, powdered, top-soil. Layer II is a loose conglomerate, dry and friable. Layer III is a dry, hard conglomerate. Inasmuch as these observations were made on ground that had been exposed for days it is uncertain how much difference there is between layers II and III in the natural state where both layers contain a small amount of moisture.

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A charge shot above the surface of layer I produced the result typical of powdered earth. A charge detonated over earth of layer III produced no visible effect beyond a scouring of the surface to a depth of about $\frac{1}{4}$". Closer examination, however, revealed that directly under the charge there was a cone-shaped pocket filled with loose shattered earth. The profile of this cone was very similar to the crater profile shown in Fig. 9. It was found for this cone that

$$D/W^{1/3} = 1.61 \quad \text{approximately}$$

and

$$h/W^{1/3} = 0.52 \quad \text{approximately}$$

Two charges, one 0.38 lb and one 2.85 lbs, were shot above layer II and produced craters having the same general profile as those made in dried packed earth at P-Site, Fig. 9.

$$D/W^{1/3} = 1.78 \quad \text{approximately}$$

and

$$h/W^{1/3} = 0.108 \quad \text{approximately}$$

The central portion of the craters presented a baked appearance. The surface of this portion was covered with small chunks of a soft shale-like material which had apparently been produced by the compressive effect of the explosion and had then been somewhat shattered.

In the case of the 2.85 lb explosion nails, were inserted into the earth on three inch centers so that their heads formed a cross under the charge. The crater profile after the explosion was as shown in Fig. 11.

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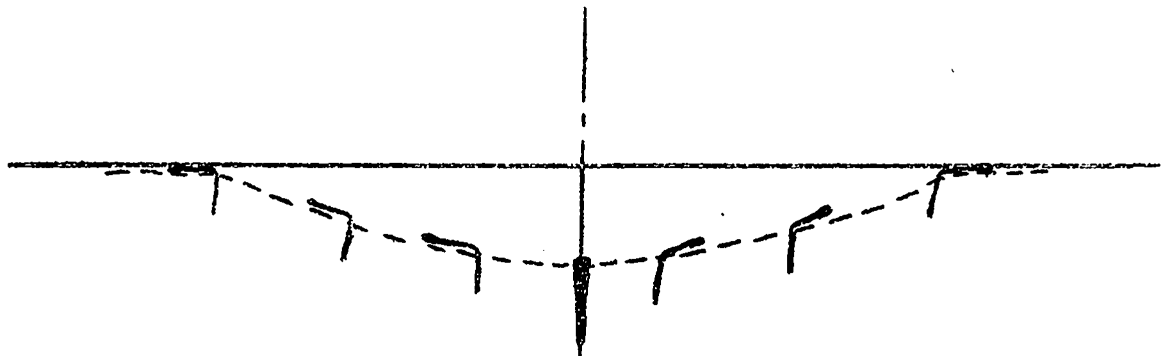

Fig. 11

The upper parts of the nails were bent away from the blast while the lower parts of the nails were found to be leaning slightly toward the axis of the blast.

It is unfortunately true that the dimensions of the crater produced by an exploding charge become increasingly difficult to predict as the charge is elevated above the surface of the earth[1]. As shown by graphs 3B1 and 3B1a of reference 1, the size of the crater diminishes rapidly as the critical elevation for zero crater size is approached. Furthermore the relation between crater dimensions and elevation seems to be increasingly dependent upon the character of the earth as the charge is elevated. Thus it is not surprising that the size and character of the craters produced in the various types of earth reported above were found to vary widely.

A 100-ton explosion at Trinity at the point where the foregoing observations of crater dimensions were made would be expected to form a crater extending somewhat into layer III and resembling in shape the craters produced in layer II, Fig. 9, by small charges. It is considered likely, however, that with large charges some material will be ejected from the crater and the profile will thus be some compromise between the craters shown in Figs. 8 and 9.

Employing the values of D and h observed at Trinity for craters in layer II, the following estimates are made for larger explosions at Trinity.

1) Weapon Data, AM-18 NDRC.

[redacted]

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a) 100 tons:

$$D = 1.78\ (2\text{x}10^5)^{1/3}$$
$$= 104\ \text{(feet)}$$
$$h = 0.108\ (2\text{x}10^5)^{1/3}$$
$$= 6.3\ \text{(feet)}$$

b) 5000 tons:

$$D = 1.78\ (10^7)^{1/3}$$
$$= 383\ \text{(feet)}$$
$$h = 0.108\ (10^7)^{1/3}$$
$$= 23.2\ \text{(feet}$$

4. MEASUREMENT OF SHOCK VELOCITY IN EARTH

In an effort to come to a better understanding of the mechanism of crater formation some measurements were made of the velocity of shock propagation in earth as shown in Fig. 12. An H.E. lens provided a plane detonation wave travelling down through the H.E. stick. The shock wave in the earth could then be observed by taking a flash photograph by means of X-rays moving perpendicular to the plane of the figure. From the measured angle between the shock wave fronts in the H.E. and in the earth, the ratio of the two shock velocities can be calculated.

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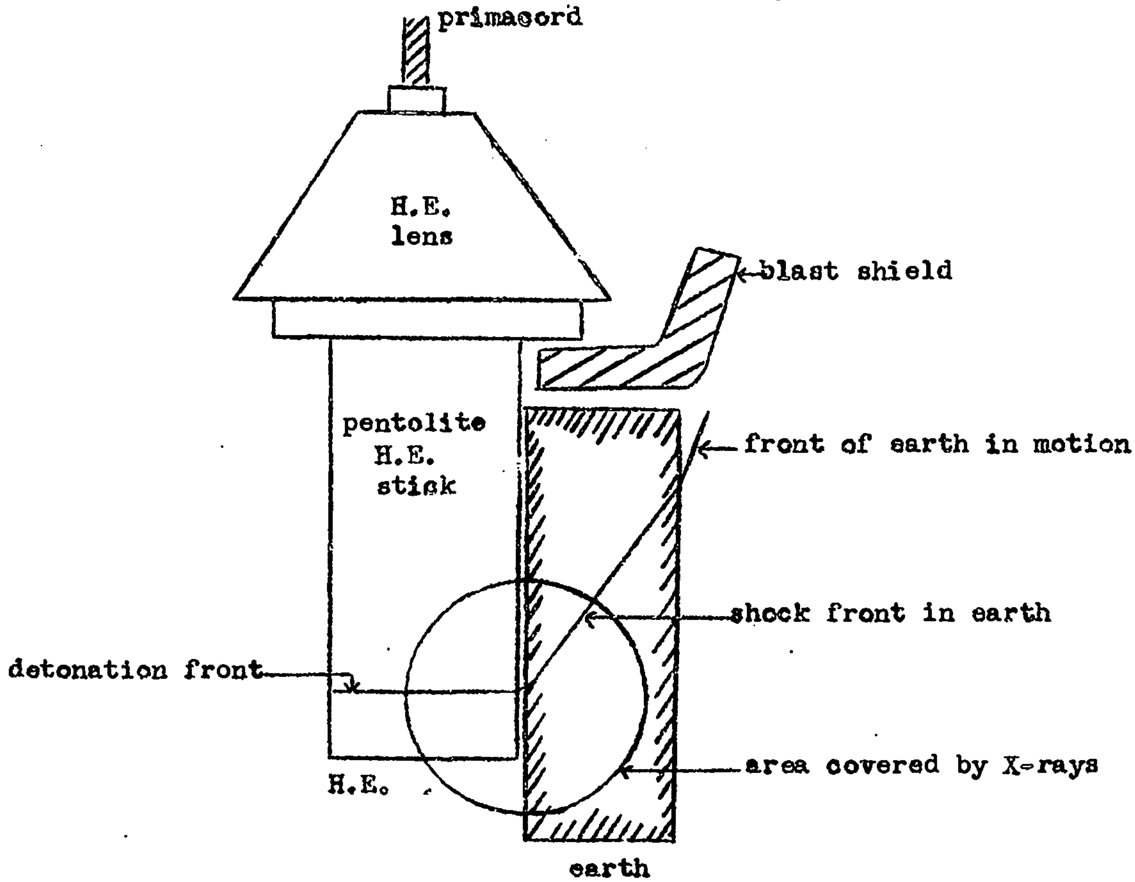

Fig. 12

The earth samples used were obtained from layer II at Trinity and measurements were made on earth in the form of dry powder, wet mud and baked adobe.

4.1 Powdered Earth. The linear dimensions of Fig. 13, obtained with a powdered earth sample, are magnified by 1.4. Line A-A indicates the demarcation between H.E. on the left and earth on the right, and line S-S-S indicates the shock wave front. If V represents the steady state shock velocity in the H.E. and if v represents the same for the earth, then

$$\sin \theta = v/V$$

[redacted]

 [redacted]

or

$$v = V \sin \Theta$$

where Θ is the angle shown in the photograph. It is found in this way that, in powdered earth, $v = 2.1$ Km/sec approximately.

4.2 Wet Mud. The symbols on Fig. 14, obtained with a wet mud sample, are similar to those on Fig. 13. In this case $v = 0.96$ Km/sec approximately.

4.3 Dry, Packed Earth. It will be observed that unlike Figs. 13 and 14, the shock front in the earth in Fig. 15 is markedly curved even after the shock has moved well into the earth. This would seem to indicate that the earth was acting like a very strong absorbent and that the shock wave velocity was, therefore, decaying quite rapidly. The evidence for this effect in earth is inconclusive, but it is plausible to expect shock absorbent properties in a material possessing a porous structure such that work is required to crush it and made of such material that, once crushed, it has no tendency to return to its original form.

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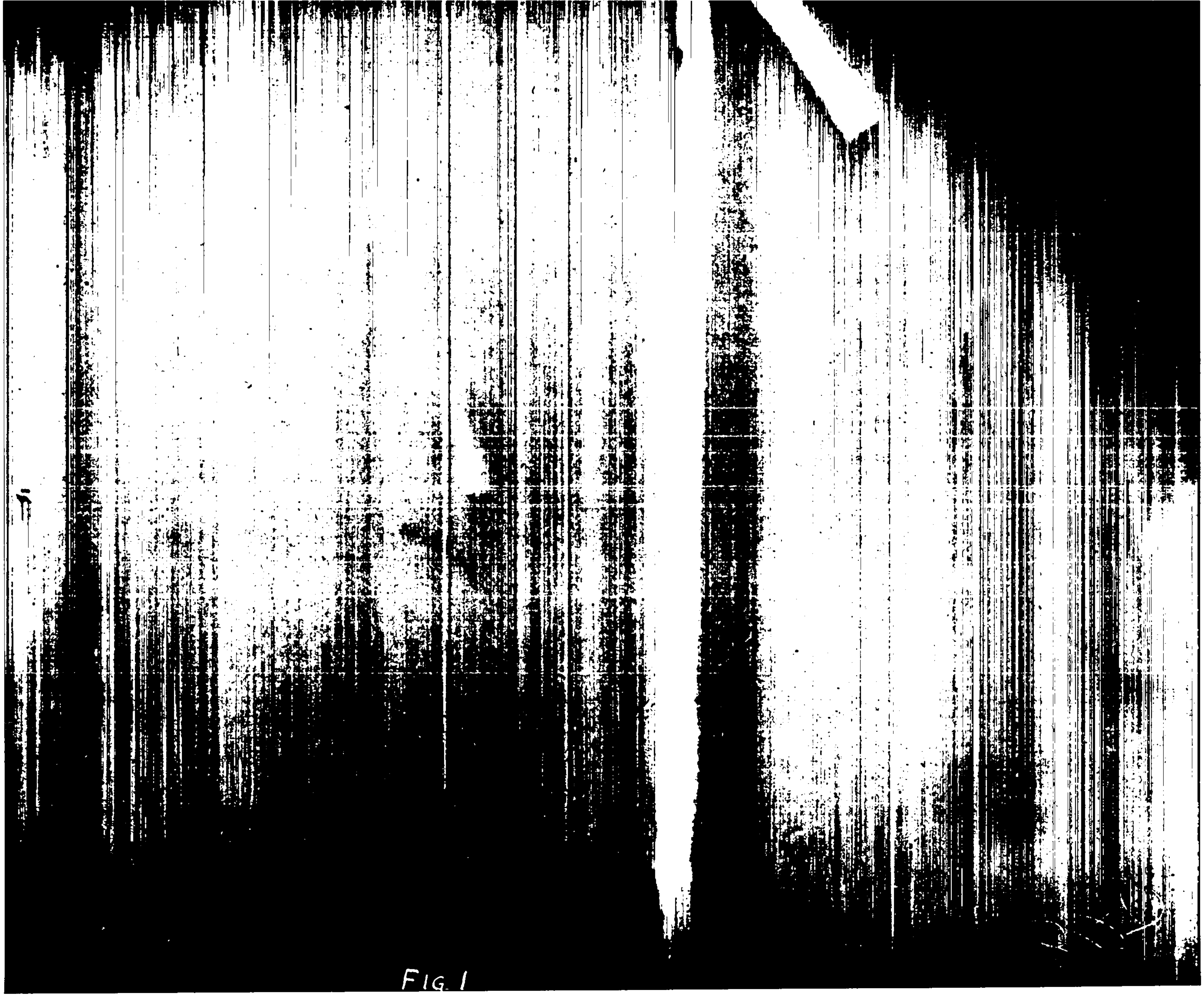

FIG. 1

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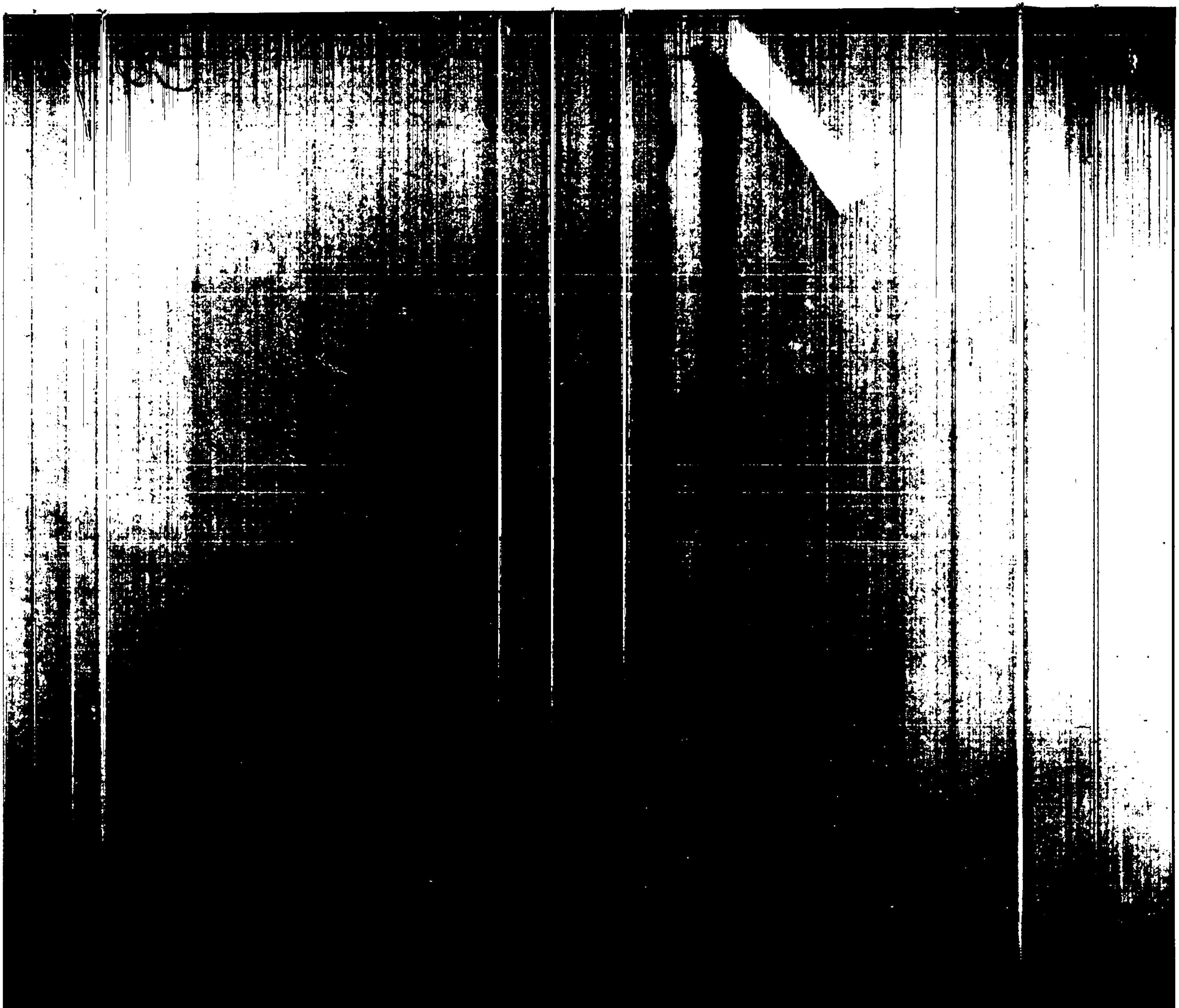

FIG. 2

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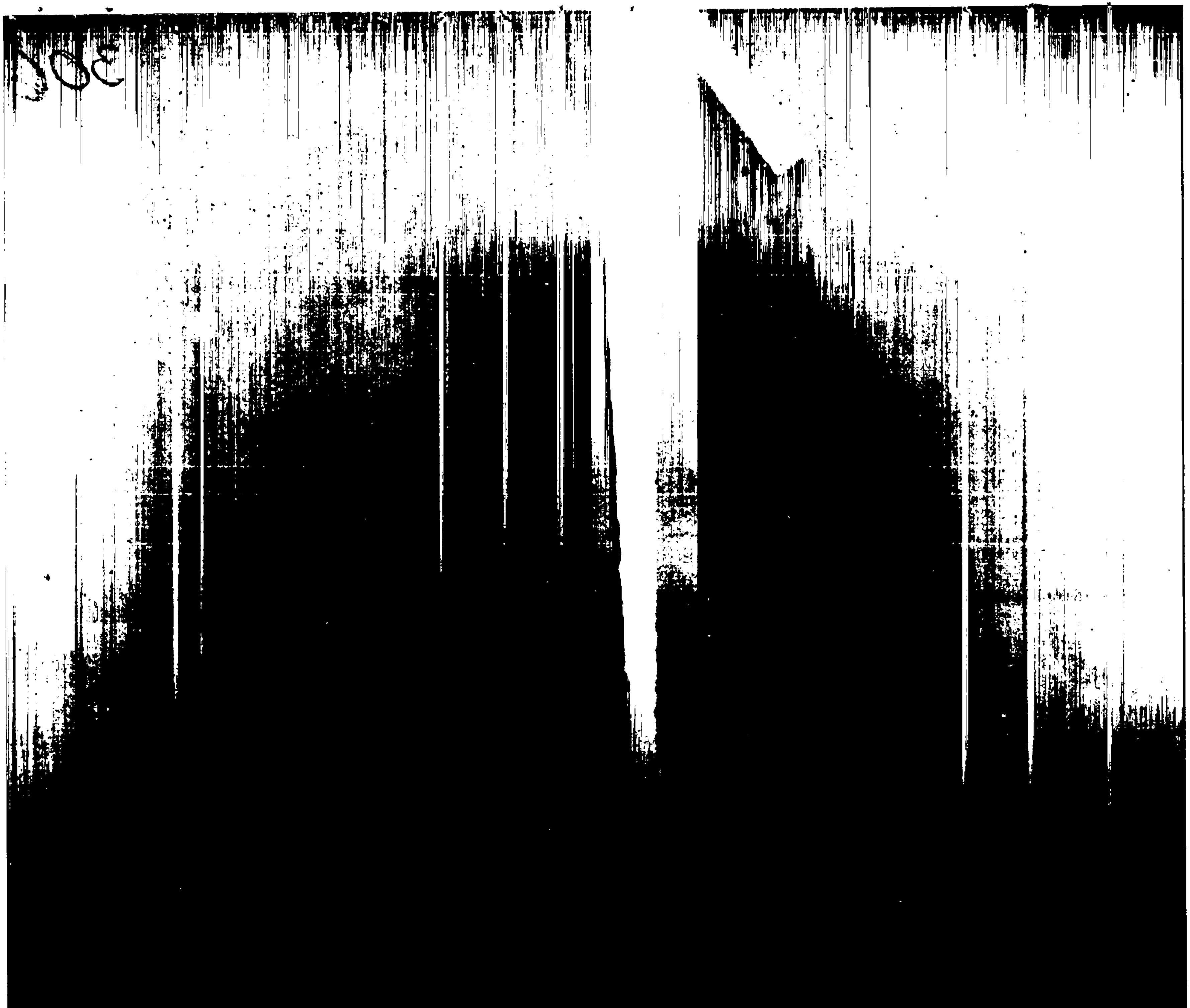

FIG. 3

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$\theta = 15.5°$ M = 1.4

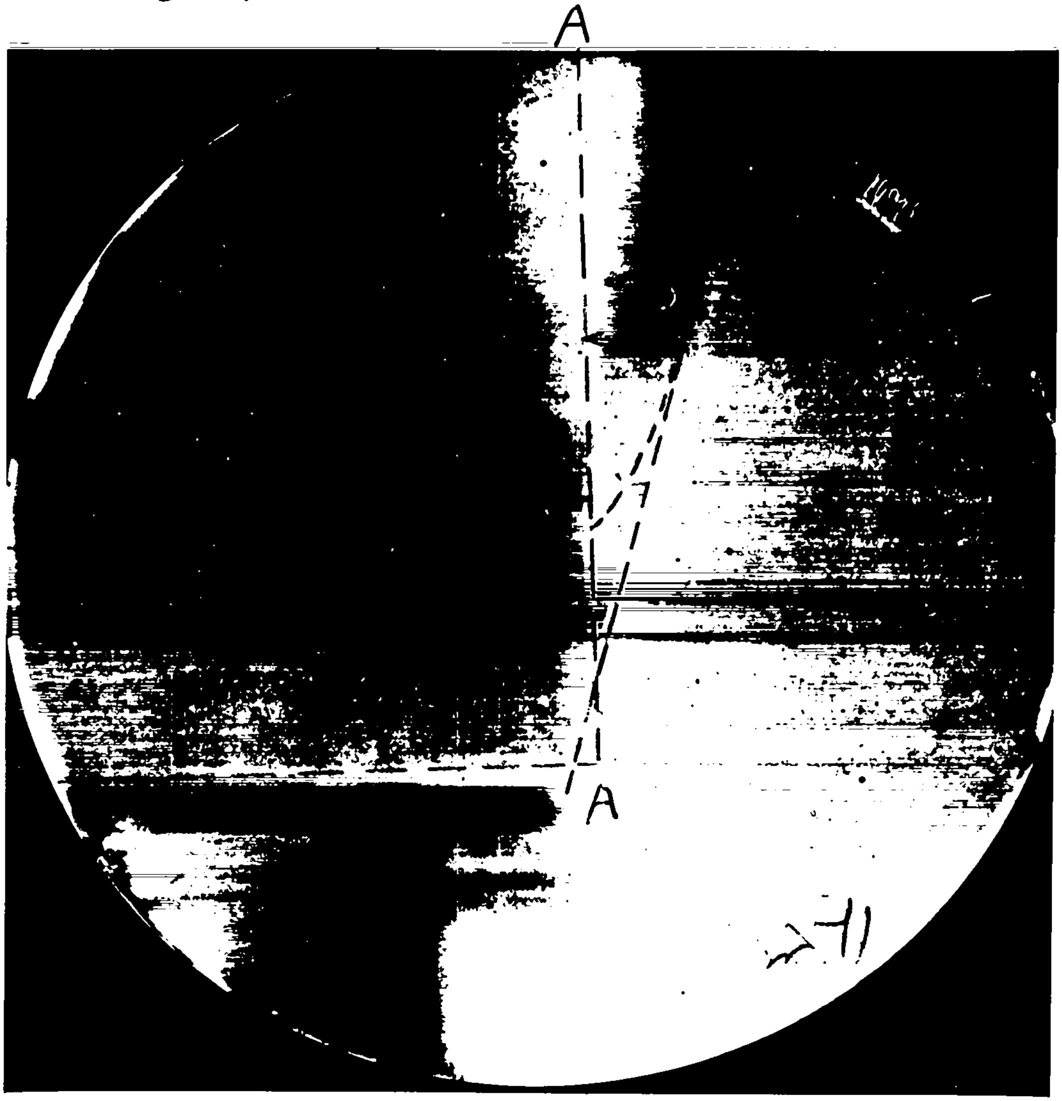
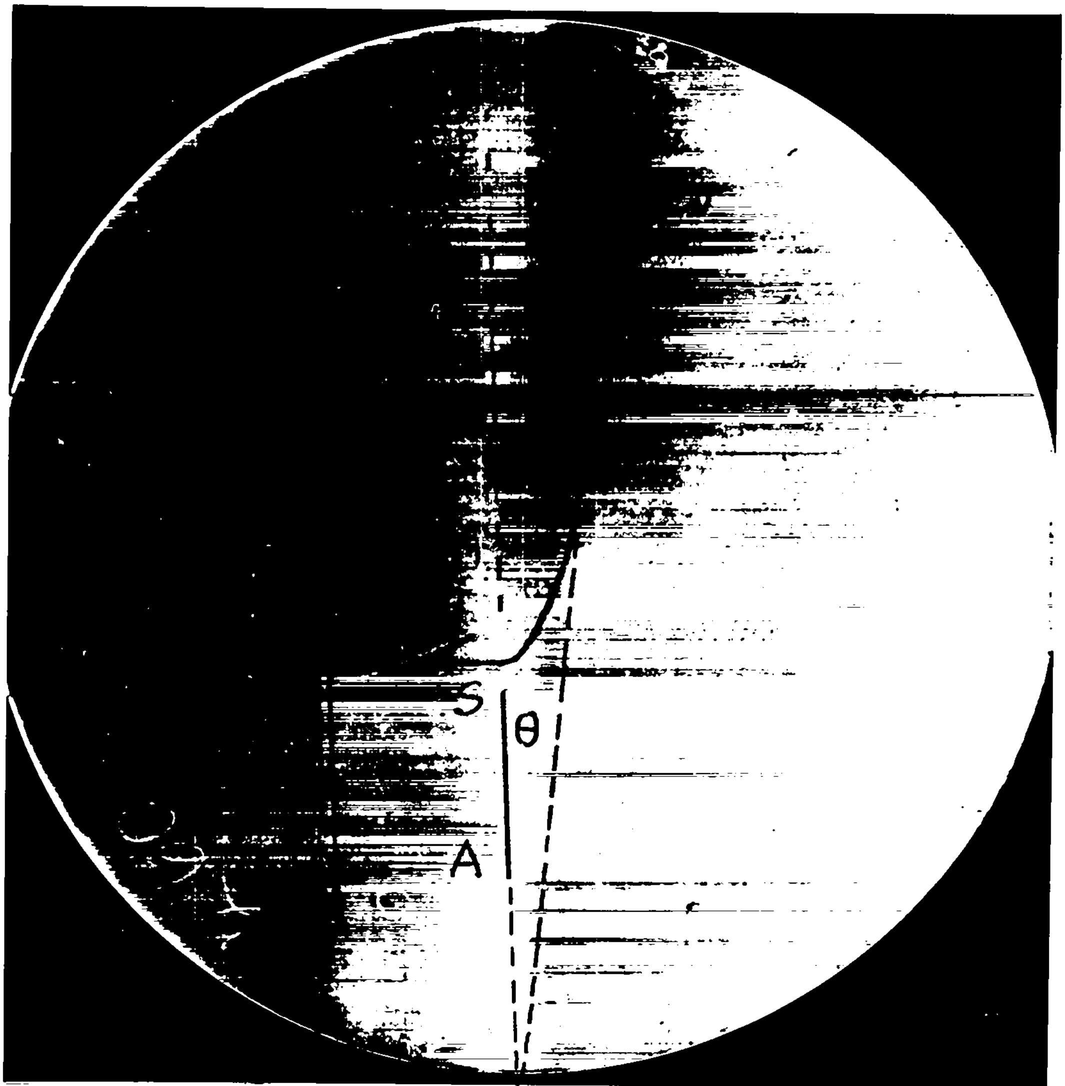


FIG. 13



$M = 1.42$

$\theta = 7.5°$

FIG. 14

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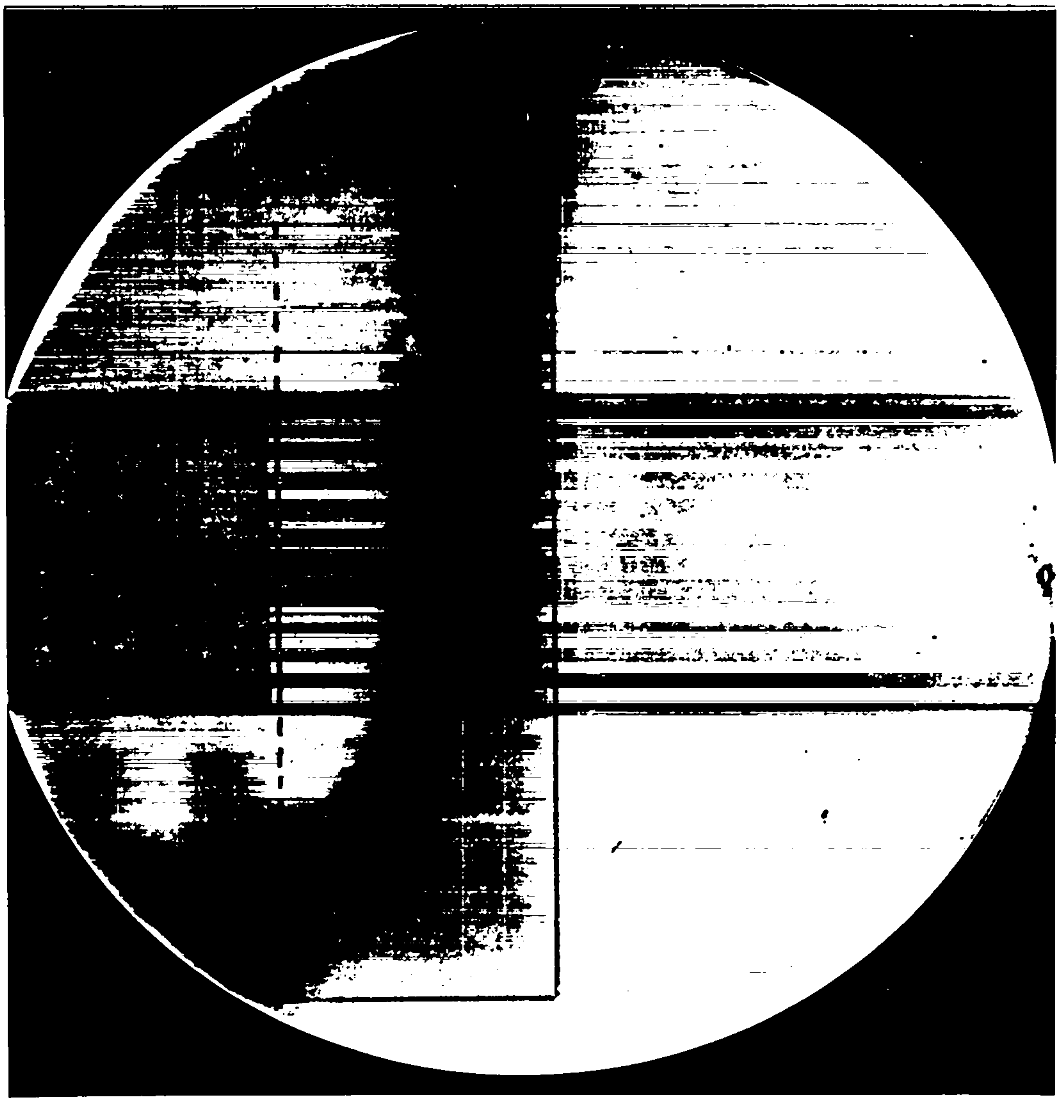

FIG. 15

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