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* B.Sc., Ph. D. Surface Physics,
Cavendish Laboratory, University of
Cambridge, England.

STIFTELSEN
SVENSK DETONIKFORSKNING
SWEDISH DETONIC RESEARCH FOUNDATION

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J. E. Field*

and

A. Ladegaard-Pedersen⁺

* B.Sc., Ph.D. Surface Physics, Cavendish Laboratory,
University of Cambridge, England.

+ Swedish Detonic Research Foundation, Vinterviken, Stockholm,
Sweden.

SUMMARY

The fragmentation process in rock blasting is usually considered from one of two extreme viewpoints. In the first, stress waves are largely ignored and the pattern of failure is given in terms of the large gas pressures built up during the explosion process and the static stress field which would exist for the particular geometry of loading. In the second, stress wave reflection at free surfaces and 'spall' processes are considered as dominant. Though 'spall' fractures become increasingly important for large charges producing intense shocks the situation considered in this paper is for charges which cause fracture growth from the region of the bore-hole alone. In earlier work little importance has been given to the effect which the stress waves might have on the developing fractures. It is suggested here that the reflected waves play a major role in determining which fractures develop from the region of the bore-hole and in which directions they propagate. The new interpretation does not in any way minimise the influence of the gas pressures as the main driving forces for opening the fractures and throwing the rock forward. The interaction between the reflected dilatational stress wave and the fractures from the bore-hole is first analysed and 'break-out' angles predicted for both the point charge and extended charge situations: the values agree well with practically observed ones. P.M.M.A. models were used to simulate rock blasting situations; the results give strong evidence for the importance of the reflected waves. A method which gives greater control over fracture growth during rock blasting is discussed. Finally a Beckman & Whitley (model 189) framing camera was used to study the fragmentation processes in P.M.M.A. models at microsecond framing intervals.

INTRODUCTION

The basic situation in rock blasting is the explosively loaded bore-hole situated near a free surface. In 'quarry' or 'bench' blasting the bore-holes run approximately parallel to the free surface and the main fractures run towards this surface fragmenting the rock. In quarry blasting the ideal situation is for the blasting operation to leave the rock in suitable sized pieces for transport to the mill for the second-stage of break-up. This ideal is rarely achieved in practice and large boulders have to be individually drilled, the bore-holes loaded and a second blasting operation performed. In terms of time, expense and safety this double process is undesirable. A second application involving rock removal by explosives is when, for example, highways or tunnels are constructed. An important objective here is to leave a smooth rock face after the blasting process; hence the name 'smooth' blasting. The spacing, charging of the bore-holes and detailed pattern of firing are all critical factors in determining the desired result (as also in quarry blasting). Frequently the blasting operation is near a built-up area and the operation has to be even more critically controlled so as to minimise ground vibrations.

However, some aspects of rock blasting are not yet fully understood. Of particular interest is the way fractures develop from an explosively loaded bore-hole and the factors which are likely to affect their growth. In the literature on rock blasting the fragmentation process is usually considered from one of two extreme viewpoints. In the first of these as developed by Langefors, Kihlström and their co-workers [1] the main driving force for disruption of the rock and throwing the boulders forward is thought to be the large gas pressures built up during the explosion process. The reason for the major fractures growing towards free surfaces is usually given in terms of the static stress field which would be set up for the particular geometry of loading. In other words little importance is given to the influence of stress waves which reflect at the free surfaces and pass back over the developing fractures. The assumption inherent in this approach is that crack velocities are very much less than stress wave velocities. Other workers,

for example, Hino [2] , Duvall and Atchison [3] put great emphasis on break-up of the rock by 'spall' processes in which the fractures are caused by reflected stress waves from the free surfaces. However, although this type of process occurs when large charges are used producing intense stress pulses it would be wrong to apply it for most bench blasting situations. In granite with a relatively high tensile strength it is only of some importance when the charge considerably exceeds 1 Kg/m^3 ; in ordinary bench blasting the consumption of explosive is much lower, $0.15 - 0.60 \text{ Kg/m}^3$ [1]. The evidence provided by Langefors and Kihlström [1] and more recently by Persson, Lundborg and Johansson [4] , clearly shows that the main fractures start at the bore-hole. In fact these workers would regard excessive spalling as a clear indication that the bore-holes had been over-charged. In crater blasting in which the bore-hole is usually perpendicular to the free surface, there is a much greater possibility of spall processes. This is basically a geometric reason [4] , since in this situation fractures growing from the borehole travel initially in directions parallel to the free surface, rather than towards a free surface as in bench blasting. Crater blasting usually requires larger charges and for this reason the reflected stress waves and spall processes are more important.

The work described in this paper is primarily concerned with the case of a single bore-hole near a free surface. The charge and the 'burden' were such that fractures developed from the region of the bore-hole with some reaching the surface: the stress waves reflected at the free surface were insufficiently intense to cause fracture by spalling. However, it is suggested here that these reflected waves play an important role in determining both which fractures develop and the directions in which they propagate. However, although it is argued that the stress waves assist the growth of certain cracks preferentially the main driving force for fragmenting the rock and throwing it forward is still thought to be the gas pressures.

There is considerable evidence that stress waves, even when they are insufficiently intense to cause fracture alone, can interact with the stress field at the tip of a crack and affect crack motion. Line markings on the

fracture surfaces of glasses have been explained by Wallner [5] as the loci of the interaction between distortional (transverse) waves set up as the fracture front cuts through defects and the fracture front itself. Field [6] has found other markings on glass surfaces which are caused by the stress waves sent out at the onset of fracture which return from the specimen boundaries and locally alter the crack motion. Kerkhof and his co-workers (see a review by Schardin [7]) have developed an elegant method for fracture studies in which stress waves of high frequency (typically 5 Hz) are passed through a specimen at the time of fracture. If the imposed waves are of sufficient intensity they can modulate the main tensions opening up the fracture causing a rippled fracture face; the spacing of the ripples gives a very accurate measure of crack velocity. The effect of individual stress pulses on crack growth has been considered by Kerkhof [8, 9] who shows that for brittle crack motion the propagation direction is always orthogonal to the instantaneous direction of the maximum principal stress. He was also able to infer the nature and strength of stress pulses from the shape of the modulated fracture surface. Field and Heyes [10], (and with Bowden and Brunton [11]) show photographic sequences of stress waves causing crack branching in glasses and single crystals such as magnesium oxide. The fracture in these experiments were initiated by impulsive loading; the stress wave effects occurred when the reflected dilatational waves, now waves of tension, passed over the fractures. Carlsson [12, 13] in his experiments on steel has also observed changes in crack motion caused by reflected dilatational and distortional waves.

The energy which passes into the stress wave* in rock blasting has been estimated as about 5 - 15% with the remaining energy going into the explosive products [1]. There is evidence that the gases from the explosion

* The phrase 'stress wave' is used throughout this paper. Near the bore-hole the wave would travel at a shock velocity appropriate to the type of rock and the pressures involved. However, for the major part of its transit to the free surface and back to the fractures it will propagate at the elastic stress wave velocity.

enter the cracks and thus act between the crack faces as well as at the crack ends near the bore-hole. The energy density of the stress wave would, of course, diminish as the wave diverged from the hole, and there would also be losses by attenuation. Since it is unusual for the waves to produce scabbing fractures unless the burden is very small and/or the charge very intense it is clear that any mechanism which involves these waves will have to accept the fact that they are relatively weak. Conversely if it can be demonstrated that weak stress waves can cause major effects when they interact with the stress field at a crack tip then this will help explain why similar rock blasting results can be achieved with explosives of widely differing detonation characteristics.

An analysis of the stress wave crack interaction has already been published together with experimental evidence supporting the ideas (Field and Ladegaard-Pedersen [14]). This paper summarises this earlier work and gives results from a high-speed photographic study in which rock blasting situations were 'modelled' using polymethylmethacrylate (P.M.M.A.) and glass specimens. Ideas on how better fragmentation and 'smooth' blasting could be achieved in practice are also discussed.

Crack lengths and orientation at interaction

When a bore-hole is explosively loaded many short cracks develop from near the bore-hole surface and grow outwards. After a short distance the number of radial cracks decreases and only a few symmetrically positioned cracks (usually between 4 and 8) propagate. If it is assumed that the cracks grow outwards at a velocity V and the stress waves at a faster velocity C then the reflected waves will return to reach the cracks part way to the boundary. Using the notation shown in figure 1 which is for a plane normal to the bore-hole it is possible to obtain an expression for the length of crack at the point of interaction y in terms of the burden x and the angle α . In the diagram the bore-hole is at O and the free surface is denoted by the line AB. The reflected wave can be considered as travelling from the image point O' so that the wave travels a distance $\cdot r$ before it reaches the fracture.

Simple geometry and the relation of equation (1) give the required expression for y (equation (2)),

$$\frac{y}{r} = \frac{V}{C} \quad (1)$$

$$y = \frac{2x}{\cos \alpha + \sqrt{\frac{C^2}{V^2} - \sin^2 \alpha}} \quad (2)$$

The velocities C and V are, of course, really mean velocities up to the point of interaction. In figure 2 the ratio y is plotted against the angle α for various values of the ratio C/V . Realistic values for C/V are likely to lie between the limits 3 and 10 for both homogeneous rock and P.M.M.A.

[6, 11]. Recent results by Bieniawski [15] on norite rock have supported this view.

Figure 2 shows that the distance the cracks reach before meeting the reflected wave does not depend greatly on angle. However, it is clear that the fractures have travelled quite large distances before this first interaction with a reflected wave occurs. Also relatively few complete transits of the shock waves will occur before the fractures reach the boundary (between 3 and 10 for $\alpha = 60^\circ$ and the velocities considered). This is one reason why the transient nature of the shock wave should be treated rather than the static stress field.

The question which has to be considered now is which cracks are most affected by the reflected tension wave. Clearly if the stress wave interaction is important some cracks will grow preferentially and it will be these cracks which give rise to the main 'boulders' in the fragmentation process. Assuming that cracks can grow from the bore-hole at all possible angles α , it seems likely that the maximum effect occurs on the crack with an α such that the angle γ in figure 1 is zero: in other words when the tensions in the wave front act normal to the crack direction and thus help open the crack. For other values of α only a component of the tension acts on the crack, and this is less. In the case of $\alpha = 0$ (i.e. when a crack propagates directly towards the free surface) the resolved tension aiding the opening of the crack is zero. This is illustrated by curve I in figure 3 where

the intensity of the tension component $\cos \gamma$ acting normal to the crack direction is plotted against α . ($\cos \gamma$ can be shown to equal $\sin (\alpha + \beta)$).

The ratio $\sin \alpha / \sin \beta$ equals r/y which in turn equals C/V . This particular curve is for $\frac{C}{V} = 3$ and $\alpha_{\max}$ occurs at 71.5° . For $\frac{C}{V} = 5$ and 10 $\alpha_{\max}$ is slightly greater having the values 79° and 84° respectively. The general expression for $\alpha_{\max}$ is given in equation (3).

$$\alpha_{\max} = \tan^{-1} \frac{C}{V} \quad (3)$$

If this simple model were correct one would expect the main boulder formed in rock blasting to have a semi-angle α of the order 70 to 80° . However, there are various factors which have been neglected and which could modify the above picture. These are that:-

- (i) the energy density of the stress wave decreases as it spreads out from the bore-hole. The actual value of the tension in the reflected wave front is therefore a function of the distance r .
- (ii) when a dilatational wave is incident on a boundary it gives rise to both a reflected dilatational wave and a distortional wave (see, for example, [16]). The relative intensity of these waves depends on both the angle of incidence (β in figure 1) and the Poisson's ratio of the material.
- (iii) in practice only relatively few cracks grow from the bore-hole, and thus not all values of α are represented.
- (iv) the situation described by figure 1 is a two-dimensional one, and will need extending if all practical cases are to be treated.

Considering first the effect of (i), it can be seen from equation (1) that the y/x curves given in figure 2 can readily be changed to r/x curves by multiplying each curve by its appropriate C/V value. This procedure tends to group the curves together with a value of r/x equal to about 1.8 , and with little dependence on angle. In fact at $\alpha = 71^\circ$ all the curves have the same value for r/x of 1.95 . In other words whatever the values for α and V the stress wave always travels approximately the same distance before it interacts with the cracks, and so the fact that the stress wave intensity is decreasing with increasing r can be largely neglected. It would, however,

tend to decrease $\alpha_{\max}$ slightly because as α decreases, r also decreases and so the wave intensity increases.

The effect mentioned under (ii) is relatively much more important than (i). Using data given by Arenberg [17] it is possible to evaluate the intensities of the reflected dilatational waves in terms of α ($\sin \alpha$ equals $\frac{r}{y} \sin \beta$), for various Poisson's ratios (σ). The curves shown in figure 3 are for Poisson's ratio 0.4 (P.M.M.A.) and 0.22 (granite, and some other rocks). The curves have a value of unity for $\alpha = \beta = 0$; this is the situation where the incident dilatational wave meets the free surface normally and reflects as a tension wave of equal intensity. No reflected distortional wave occurs in this case, but for finite values of β energy does go into a distortional wave. Figure 3 shows that the loss of energy into a distortional wave is of relatively greater importance the smaller the value for Poisson's ratio. For $\sigma = 0.22$ and $\alpha = 90^\circ$ the intensity of the reflected tension wave is now 64% of its initial strength.

Curve I in figure 3, it will be remembered, shows how the resolved tensile component varied with angle and has a maximum when the tension wave acts normal to the crack. Figure 4 illustrates how curves of type I are modified by taking into account the variation of intensity of the reflected wave with angle of incidence. These curves are the product of those in figure 3.

It will be seen that in the case of P.M.M.A. ($\sigma = 0.4$) the maximum is not greatly reduced (now about 70°) but has become broader with large values over the range (40° to 90°). For a material of Poisson's ratio 0.22 the maximum is not broadened, but now occurs at the much lower value of about 50° . The difference in the predicted behaviour between P.M.M.A. and rock is quite marked. The semi-angle α for the main 'boulder' in the case of P.M.M.A. should be on average about 70° , though a large spread in results would be expected. In the case of rock a much smaller semi-angle of about 50° is predicted with slightly less spread in the values recorded.

It has been assumed above that all values of α are equally possible. In practice although all values are possible only a few are represented in any one experiment since there are only a relatively small number of cracks

growing from the bore-hole: there could well be an angle of 45° to $\sim 90^{\circ}$ between any two adjacent cracks. It will be the cracks which lie nearest the peaks in the intensity curve of figure 4 which develop to form the main boulders. The angles of about 70° and 50° predicted for P.M.M.A. and rock are therefore the expected average values from a large number of experiments.

It is interesting that the experiments using P.M.M.A. described by Langefors [18], in which an essentially two-dimensional situation was used, gave mean semi-angles of about 67° (see, for example, figure 11 of this reference), while the data of Persson, Ladegaard-Pedersen and Kihlström [19] for point charge loading in rock gave an average semi-angle of about 45° in the plane we have considered. Agreement with the proposed model is therefore very encouraging.

The much larger (almost 90°) semi-angles found when extended charges are used is discussed in a later section. This situation is more complex and stress wave propagation in three-dimensions has to be considered.

Experimental procedure and results

In the experiments to study the importance of stress waves on rock fragmentation P.M.M.A. models were used. P.M.M.A. has been shown by earlier workers (see, for example, [1, 18]) to be a good material for laboratory 'model' experiments on rock blasting. The blocks of P.M.M.A. had the dimensions (in mms) shown in figure 5. The bore-hole of diameter 1.5 mm and depth 30 mm had the lower 4 mm filled with a mixture of lead azide and lead styphnate in the proportion 5 to 1. The explosive was fired by a 2 K.V. electric spark from electrodes in the bore-hole. The electrodes were made by first machining a thin-walled brass tube which was then inserted into the bore-hole until it touched the explosive. A wire with an insulating cover was then passed down through the centre of the brass tube and acted as the second electrode. It was verified that the spark alone caused no damage to the block.

Three different types of experiment were performed to investigate the influence of the reflected shock wave. These were experiments in which:-

- (i) spall plates were added to the front surface of the specimen, with the object of removing or changing the stress waves.
- (ii) the free surface was 'shaped' so as to either concentrate or disperse the reflected stress waves.
- (iii) the whole model was immersed in a liquid of acoustic impedance equal to that of P.M.M.A. This, from the stress wave viewpoint, effectively moved the free surface of the block to large distances.

A detailed discussion of the results of these experiments can be found in [14]. The main results only are summarised in figure 6, which gives a selection of results from these experiments. In (a) and (b) are shown two views of a block fired with the configuration shown in figure 5. The top view shows that there are several short cracks radiating from the region of the bore-hole, but that only two of these grow to any great length. These cracks spread out and join as they travel towards the free surface to give a roughly conical shaped 'boulder' (this can be seen standing in front of the block in the left-hand picture). The burden of 15 mm was chosen, since for greater values 'boulders' were not formed and detached from the block.

In the spall plate experiments, plates of thickness 3 mm were attached to the blocks by first smearing a thin oil film over the surfaces to be joined. When a P.M.M.A. plate is used the compression wave passes across the junction into the plate since there is perfect acoustic matching. However, when the wave reflects and becomes a tension at the outer surface of the spall plate the junction fails when the wave tries to cross it and the spall plate flies away from the specimen with the trapped momentum of the wave. Figure 6(c) shows the result of such an experiment. The fracture pattern when compared to figure 6(b) is seen to be very different with the preferential growth and boulder formation largely restricted. In figure 6(d) we see the effect of facing the block with a steel plate. The acoustic impedance of steel exceeds that of the P.M.M.A. block and so the compression wave reflects as a second, though slightly weaker, compression. The cracks radiating out from the bore-hole towards the free surface therefore tend to be closed rather than opened by the wave. The cracks which have developed are those in the

backward direction moving towards the corners of the block. These cracks would have been assisted by the tensions arriving from the other free surfaces, on which there were no steel plates.

The effect of surface shaping is illustrated in figure 6(e). With this arrangement the inner angled surfaces reflected the central parts of the wave to the sides so that they missed all the cracks; this part of the wave is therefore dispersed. The outer angled surfaces reflect their part of the waves back towards the bore-hole from effectively two angles sources. Compared with figure 6(b) there is no boulder formation, but there are relatively more radial cracks (11) with only slight preference for those growing in the forward and side directions. This is a reasonable pattern of failure if the stress wave picture is correct.

In the final experiment illustrated here a block was immersed in a large tank of salt solution, of density such that the liquid was acoustically matched to P.M.M A. In this situation all the stress waves should pass unreflected into the liquid. The result, which is shown in (f) should again be compared with (b). Except for one isolated large crack (which possibly grew from a defect in the surface of the bore-hole) the pattern is almost perfectly symmetric, and there is certainly no tendency for any of the fractures to run to the nearest surface of the block. A second noticeable feature is that there are a relatively large number of radial cracks (15); this was by far the largest number of well developed radial cracks found in any of the experiments. Since all the surfaces of the block were acoustically matched in this case, no cracks would receive help from stress waves and so all cracks which started equally would grow uniformly.

All of these results give support to the view that the reflected stress wave is instrumental in determining the pattern of failure. Control of this reflected wave helps regulate the fragmentation process.

Extended charge

It has been found in rock blasting that when an extended charge is used that the semi-angle for break-out is large. In the data published by Persson, Ladegaard-Pedersen and Kihlström [19] its value ranged from 70° to 90° . This angle compared with the $45\text{--}50^\circ$ semi-angle for a concentrated charge in rock. It will be recalled that the stress wave analysis given earlier in this paper satisfactorily predicted the angle for the concentrated charge. The larger break-out angle with the extended charge can also be explained in terms of the nature of the reflected tension waves.

A schematic representation of the situation is shown in figure 7 in which AB is an extended vertical charge of length ℓ and x is the distance to the free surface (the burden). The charge between AB may in practice be of a complex nature. Here we shall discuss briefly two extreme situations, firstly a series of well-spaced point charges distributed between A and B, and secondly, a continuous length of charge. In both cases we imagine that the charge detonates at A and propagates towards B with a velocity C' . For the series of charges a point such as O receives a succession of pulses over a long period of time. The pulse from A will appear to come from a source distance $2a_1$, that from B $2a_2$, with both greater than $2x$. Referring to figure 1 it is clear that if the wavefront interacting with the cracks is part of a larger circle then the angle α is larger. The break-out angle would be predicted to be at its largest for shots with a large burden and charge length. The data of Persson et al. [19] does in fact show this trend, where results can be compared. Table I gives four of their results where the burden is varied and all other quantities are approximately constant. The semi-angle for break-out increases, as suggested, with increasing burden. In all cases the hole diameter was 12 mm; the hole depth 1.5 m and the charge length 0.92 m. C' and C were given as 6.7 Km/s and 5 Km/s respectively. For a continuous charge the situation is a little different. We now have effectively many closely spaced point charges and the individual wavelents add (as with the optical analog) to give an expanding conical wave front (figure 7(b)). The semi-angle of the cone θ equals $\tan^{-1} \frac{C}{C'}$ and will be about 37° for rock, but for P.M.M.A. with C equal to 2.2 Km/s 18° . The duration of the pulse at

a point such as O is now only that for a single pulse. However, the wave still appears to come from an image point further than $2x$ away, in fact $2x \sec \theta$, so again the angle α should be larger than for the concentrated charge. No data is yet available for different values of $\frac{C}{C_1}$, though for $\frac{C}{C_1}$ very small the situation would revert to the two-dimensional one illustrated in figure 1.

TABLE I Showing increase of break-out angle with burden

Semi-angle for break-out	Burden m	Burden height m	Stemming length m	Total charge weight g
75°	0.35	1.65	0.58	110.4
77.5°	0.5	1.8	0.58	110.3
85°	0.6	1.6	0.58	110.6
90°	0.8	2.3	0.38	110.0

Controlled fracture growth

There are several situations in rock blasting where it would be advantageous to have more control on the growth of the cracks which develop from the region of the bore-hole. For example, in 'smooth' blasting the ideal result is to have major cracks travelling in the forward and side directions with none in the backward direction, thus leaving a strong smooth surface. In quarry blasting uniform fragmentation is required and to have a reasonably large number of cracks propagating towards the free surface is useful. In his 'model' experiments using P.M.M.A. Langfors [18] considered various factors which influence the direction of crack growth from a bore-hole, such as neighbouring holes, different arrangements of the explosive charge, and stress concentrating holes drilled or chiselled down the sides of the main bore-hole. In this latter arrangement it was pointed out that a circular hole gave an added stress concentration of 3X, irrespective of hole diameter (see, for example, [21]). The experiments showed that the largest radial cracks grew from the points of stress concentration but that many other cracks were formed (see Langfors figure 14, [18]). Some suppression of the unwanted radial cracks was obtained by having a charge diameter about half the bore-hole diameter (see Langfors figure 15 [18]). However, although preferential

crack growth had been achieved radial cracks in all directions still existed; this is not surprising since the stress concentration provided by the added holes was only by a factor of 3.

A much more useful situation is to introduce a crack into the surface of the bore-hole, since this gives a very large stress concentration. The relation for calculating the stress concentrating effect of an elliptic ended crack or notch with a length of ℓ and a tip radius a is given by equation (4) [22]

$$\text{Stress concentration} = 1 + 2 \sqrt{\frac{\ell}{a}} \quad (4)$$

For a crack of length a few centimeters and tip radius of atomic dimensions the stress concentration factor is about 10,000 times. However, this is not the extra stress concentrating effect of the induced radial crack, since it must be remembered that the remaining material around the bore-hole will still have micro-defects, even though long cracks are absent. These micro-defects similarly give rise to stress concentrations but since they are only of micron length the stress concentration is about 100 times. (It is these defects which cause the 'practical' strength of brittle solids like rock to be about one-hundredth the calculated theoretical strength.) The extra effect, therefore, of having a crack of centimeter length is to give a local weakening of about 100 times (i. e. 10^4 divided by 10^2). This factor of 100 is important because it means that if a bore-hole with its added crack is loaded it is possible to choose a charge of strength such that only the initial crack extends with no further radial cracks introduced.

Experimental results

As in the earlier experiments P. M. M. A. models were used to simulate in the laboratory the likely behaviour of rock in full scale blasting.

From the point of view of 'smooth' blasting the block in figure 6 (a, b) is a poor result since several large cracks extend in the backward direction. (These cracks were partly aided by reflected waves from the side and rear surfaces, but even with a much larger block these cracks are still sizeable.) The result is also not good from the rock blasting viewpoint since the production of such a large single boulder would require further fragmentation. Clearly greater control of the failure pattern would be beneficial.

In figure 8(a) is shown a schematic representation of a bore-hole with two short radial cracks extending sideways and in (b) a bore-hole with cracks in the sideways and forward direction. Achievement of these crack patterns was the first objective. A method which proved successful in the laboratory experiments was to insert thin-walled brass tubes, with suitably shaped lower ends, into the bore-holes. The crack pattern in (a) was obtained by cutting two 4 mm length slits into the tube, and that in (b) by removing one-half of the lower 4 mm of the tube (see figure 2). As in the earlier experiments explosive filled the bore-hole to a height of 4 mm, but since the brass tubes now partly occupied this volume it reduced the charge for this first firing by about half. The brass tubes protected the holes at all points except where fractures were required, and also acted as one of the other electrodes. The second electrode, as before, was an insulated wire which passed down through the tube until it touched the charge.

In figure 9(a) and (b) are shown top and side views of a firing with the tube of figure 8(a) used. Two short radial cracks parallel to the free surface have been obtained; the side view photograph shows their development particularly well. The top view does not entirely do justice to the result since it appears that there is still damage in the backward direction. These cracks, however, are localised at the bottom of the bore-hole, as can be seen in the side view.)

→ The block was then taken and re-charged with the lower 4 mm of the bore-hole filled with explosive as for a normal firing. The result of this second shot is given in figures 9(c) and (d). It is apparent that all of the available energy has gone into the extension of the two cracks formed by shot 1, and that no unwanted radial cracks are produced. This is all very beneficial if smooth blasting is required.

Figure 10 shows the results of the second experiment with the tube of figure 8(b) in position. Many short cracks in the side and forward directions are present with a large angle of undamaged material at the rear. Again when the second charge was fired (figure 10 (c) and (d)) only the initial cracks extended. The forward running cracks gave good fragmentation while the freshly exposed surface was smooth and strong.

High-speed photography

A high-speed camera study was made of many of the situations discussed earlier using a Beckman and Whitley (model 189) framing camera capable of producing 25 pictures at microsecond time intervals. Experiments were performed using P.M.M.A., glass and a photo-sensitive plastic (allyl diglycol carbonate, CR 39) as the 'model' materials. So that the stress waves could be followed, crossed polaroids and filters were placed in the optical system.

Thin plate, essentially two-dimensional, models were made by drilling the holes through the plate thickness (thickness in the range 4 to 12 mm) and filling with explosive. Although this two-dimensional arrangement made stress wave analysis easier it had the practical difficulty that explosion products escaped from the bore-hole. These products had a velocity about that of the fractures and thus tended to obscure the stress wave/crack interactions. In blocks of sizes as in figure 5 the products were much better contained and both cracks and stress waves could be seen clearly. However, because stress wave and crack propagation was three-dimensional and the camera view only from one direction it made analysis of the phenomena more difficult. A selection of sequences is given below.

In figure 11 the view, as in all the examples given here, is from the top along the direction of the bore-hole. This specimen was a 12.7 mm thick sheet of P.M.M.A. with a 1 mm diameter hole drilled through it but with only the central 4 mm loaded with explosive. The vertical line is an electrode passing across the top surface, a similar one entered the bore-hole from the opposite side. The 'burden' was 7 mm. In frame 1 the dilatational wave, C_1 , has just reached the boundary, a distortional (transverse) wave, C_2 , travelling at about half the C_1 wave velocity and fractures developing from the region of the bore-hole can also be seen. The reflected dilatational wave C_1' can be followed from frame 2 onwards. As discussed earlier a dilatational wave on reflection produces not only a dilatational wave but also a distortional wave, C_2' . This is particularly clear in the fifth frame. The primary distortional wave, C_2 , will also reflect at a later stage producing waves of both types, but these waves are weaker and reach the cracks later. After the passage of the C_1' and C_2' waves over the cracks there is clearly preferential growth towards the

front surface for the range of angles, α , predicted (see figure 4). Over the last few frames the gas products escape, but fortunately do not completely obscure the cracks.

Figure 12 shows a 65 mm thick block with a bore-hole of 1.5 mm and a burden of 12.5 mm loaded as in figure 5. This time the gases do not escape from the bore-hole and the fractures can be followed throughout. Because of the three-dimensional nature of the block the stress pattern is more complex, and this is made worse in this particular sequence by machining stresses left in the face of the block which cause the fringes, F. (These stresses were very small, the fringes only look sharp because of the long path length (65 mm) in stressed material). It is interesting to note the very large increase in the bore-hole size, which was commonly by a factor of $\sim 4X$: (the next sequence, figure 13, shows this particularly well). However, this deformation was not permanent since measurements on the model afterwards still gave the value 1.5 mm. After the sixth frame shown here the C_1' and C_2' waves have passed over the cracks and preferential growth has started. Because of the relatively large numbers of radial cracks 'groups' of cracks rather than a single pair are assisted. In the last frame gaseous products emerge from the cracks. This and other sequences showed that these gases appeared as soon as a fracture reached the free surface and had velocities of the same order as the crack velocities (i.e. 300-500 m/s).

The effect of shaping the free-surface as for the block in figure 6(e) is illustrated in figure 13. The burden this time was 15 mm. In frame 2 the explosive charge has fired and the dilatational wave is seen propagating outwards. The object of shaping the surface in this way was discussed earlier: the inner angled surfaces reflect their part of the stress wave away from the cracks while the outer ones effectively radiate the cracks from two angled sources with the result that the stress pattern is perturbed. The last three frames, taken from later in the sequence, show wave reflections arriving from the other surfaces of the block and this helps ensure that no particular cracks are helped. If stress waves are important as suggested in this paper, the result should be that many cracks develop with no preferential growth towards the free surface: this is what is observed.

Figures 14 and 15 illustrate two loadings of the same specimen. In figure 14 is a block of thickness 54 mm with a burden of 13.5 mm loaded with a tube inserted into the bore-hole (of the type illustrated in 8(b)). The length of explosive was still 4 mm but because of the tube filling part of the hole it was only about 50% of the amount used in a normal firing. As expected, therefore, only short cracks develop and these all in the forward direction. This sequence shows particularly well how a pair of cracks is assisted by the reflected stress waves (C_1' in frame 2 and C_2' in frame 3). In the last frame wave reflections from the sides of the block arrive but by then the preferential growth is well established.

The second loading of the same specimen is given in figure 15, this time with the tube removed and a normal charge used. The charge fires in frame 1 and the dilatational wave can be seen in frame 2. The long cracks only develop when this stress wave passes their tips. In this example a few cracks develop in the backward direction but the main growth is of the cracks which were inserted by the first shot and there is good fragmentation in the forward direction. Although figure 14 is a good illustration of the effect of stress waves on crack motion better fragmentation would have been obtained if its effect had been 'removed', since then all the cracks in the forward direction would have been of equal length.

In the case of P.M.M.A. cracks can travel at a maximum velocity of about 700 m/s (measured in separate experiments). For the loading used in these experiments values between 300 and 500 m/s were typical. Thus when the stress wave added extra tension to the crack tip it was possible for a crack to propagate faster. However, in the experiments with glass the cracks from the bore-hole travelled at their maximum velocity of about 1500 m/s. (This is basically because the fracture surface energy of glass is much lower than with P.M.M.A.) Thus when a stress wave interacted with a crack it could not make it go faster, the result was that it made the crack branch. In figure 16 is shown an enlarged view of a crack propagating from a bore-hole. During the sequence the reflected dilatational wave passes from the lower surface upwards over the crack and the crack first bifurcates and then forks forming many cracks. As regards producing good fragmentation this is an interesting result.

Discussion

It is generally accepted that the expanding shock wave initiates the radial cracks which grow from the region of the bore-hole. However, any further influence on the developing cracks is usually either ignored or said to be of minor importance except in the case of very large charges which may produce spalling. In this paper the interaction between reflected waves and the growing cracks has been examined, and it is suggested that the reflected waves are of prime importance in determining both which fractures develop and in which directions they travel. One reason for considering a 'dynamic' situation is that the cracks from the bore-hole extend quite appreciable distances before the point of interaction with the reflected wave: further, the cracks travel a significant distance during the interaction. This distance is several millimetres in the case of the P.M.M.A. model experiments and 50 to 100 cms in the case of the extended charge in rock. Since only 5 to 15% of the explosive energy goes into the shock wave the reflected tension wave cannot be regarded as the main driving force opening up the cracks, all that is suggested here is that it is instrumental in assisting the cracks at a critical stage. When the tension wave passes over a suitably orientated crack it applies a stress over a large length of the crack surface: there is, therefore, a stress-concentration effect. This almost certainly explains why comparatively weak tensions are so effective (and why explosives which produce small shocks give similar rock blasting results to other explosives).

When a crack grows longer than its neighbours it quickly extends preferentially. This is because for equal stresses at the root of a crack a longer one always grows more easily, and accelerates more rapidly. A great many cracks are produced around the bore-hole, but relatively few (only 4-8) extend very far if the material has boundaries nearby. It will be remembered that in the experiment with the model which had all its surfaces acoustically matched (figure 6(f)), the largest number of radial cracks occurred. The only free surfaces in this case were the fracture surfaces themselves; stress waves passing to and fro between these probably explain why the cracks are equally spaced, and in fact which ones grow. In all the other experiments the cracks which propagated preferentially to their neighbours probably did so because of assistance with stress waves reflected from boundaries. There are,

for example, several cases where a crack points towards the corner of a block (assistance would be by waves reflected from the surfaces forming the corner).

The stress wave from the nearest free surface is naturally the strongest and therefore the most important, and it is this wave which determines the direction of the fractures giving the main break-out angle. When the stress wave interaction with the cracks was analysed it was possible to predict that with point charges in rock the semi-angle for break-out α should be on average about 50° , and in P.M.M.A. $65 - 70^\circ$. Further, that with extended charges larger angles approaching 90° should be found. All of these predictions are extremely close to values found in practice.

The experiments with spall plates, surface shaping and acoustic matching all gave evidence in support of the importance of the reflected wave. These results would be difficult to explain in terms of arguments using a 'static' analysis. The high-speed photographic sequences further emphasised that the stress wave picture is correct. A more sophisticated model would also need to include the effect of distortional waves, particularly the one formed when the first dilatational wave reflects. However, it is unlikely that including this wave will greatly affect the predicted break-out angles since it arrives after the dilatational wave/crack interaction and preferential growth will have started.

The experiments described in this paper on controlled fracture illustrate possible ways in which greater control in rock blasting might be achieved. Several points emerge from this investigation. The first is that preferential growth of cracks from a bore-hole can be obtained if stress concentrating cracks are first introduced. A crack, since it has atomic dimensions at its tip, gives a very large stress concentration, and is more potent than the chiselled notch or drilled hole suggested by Langefors (1959). The second point is that once cracks have been introduced preferential growth occurs from them when the second charge fires. The cracks readily restart because of the large stress concentrations at their tips. Further, since the longer a crack gets the easier it becomes for it to extend and accelerate, there is very little tendency to initiate and develop new cracks. It was found convenient to introduce the cracks in the model experiments using a small

explosive charge, and with part of the bore-hole surface protected. It is not suggested that this is the best or only way of creating the cracks, or that the process described here would necessarily translate directly to rock blasting situations. What is argued is that if suitably orientated cracks can be formed in the region around a bore-hole then there will be a controlled growth from them when the main charge is detonated.

A practical point is that the total quantity of explosive used in the two chargings need not be greater than that required in a single firing. This is because the pre-cracking allows the second charge to be reduced in size. In cases where the new procedure produced better fragmentation there would be a saving on the explosive used, and the time spent, in the break-down of over-large boulders.

The effect of a stress wave interacting with a crack already travelling at its maximum velocity and causing crack branching was illustrated in figure 1~~6~~. If good fragmentation in a material is desirable, efforts to propagate the cracks to their limiting velocity before the stress wave interaction could be of practical advantage.

Several other results discussed in this paper could have practical significance since it has been demonstrated that control of the reflected stress wave regulates the fragmentation process. The surface shape and condition of the rock face are clearly important in that they affect the reflected wave. Similarly, with multiple charge firing, the positioning, sequence of firing, pulse duration and choice of explosive would all be important factors. It seems probable that present-day rock blasting procedures could usefully be examined in terms of the stress waves produced.

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FIGURE CAPTIONS

- Fig. 1. The interaction between the reflected stress wave, which can be considered as coming from O' , and a crack growing from the bore-hole at O . AB is the free surface, y and r are the distances the crack and stress wave travel, x is the burden and α is the semi-angle for breakout.
- Fig. 2. The length the crack travels before interaction y is plotted as a fraction of the burden x against the angle α (see figure 1) for three values of the ratio stress wave velocity C to crack velocity V .
- Fig. 3. Curve I illustrates how the tensile component of the reflected wave acting normal to the crack direction (i.e. the stress which aids the opening of the crack) varies with α . The curve is for $\frac{C}{V} = 3$ and the maximum is at 71.5° . The other curves, for two different Poisson's ratios σ , show the dependence of the intensity of the reflected wave on α .
- Fig. 4. The curves are the result of taking into account both of the effects illustrated in figure 3. The maxima show where the predicted semi-angle for break-out should occur; 50° for rock ($\sigma = 0.22$), and 70° for ($\sigma = 0.4$), assuming $\frac{C}{V} = 3$.
- Fig. 5. A schematic representation of the P.M.M.A. blocks with dimensions given in mm. The 1.5 mm diameter bore-holes of length 30 mm were filled with 4 mm of explosive.
- Fig. 6. (a), (b) Angled and top views of a typical firing with the block as in figure 5. Note the preferential growth of cracks in the forward direction and the 'boulder' formation. (c) Block which had a 3 mm P.M.M.A. spall plate to remove stress wave. The fracture pattern is now much more symmetric. There was no 'boulder'. (d) Block which had a 3 mm steel spall plate. The acoustic mismatch is such that the compression wave reflects as another, though weaker, compression. Crack growth towards the front surface is restricted. Note the large cracks in the backward direction which point towards the corners; these cracks were assisted by reflected tensile waves from the surfaces forming the corner. (e) The effect of surface shaping such that the central part of the stress wave reflects away from the cracks while the outer parts reflect from effectively two angles sources. Note the large number of radial cracks (11), all of them about the same length. (f) This block was immersed in a liquid so that all its surfaces were acoustically matched. No preferential growth to the nearest surface occurs and there are a great number of radial cracks.

- Fig. 7. Schematic representations of an extended vertical charge AB of length ℓ and burden x , (a) for a series of well-spaced point charges, (b) for a continuous charge; here the individual waves continue to give a conical (semi-angle θ) wavefront which appears to come from an image source A'B'.
- Fig. 8. Two schematic views of desirable crack patterns around bore-holes together with the thin walled brass tubes which were inserted into the bore-holes to give the patterns. The shaped ends of the tubes were at the bottom of the hole over the length of the charge.
- Fig. 9. (a) and (b) show top and side views of a block after a charge was fired with the arrangement of figure 8(a) used. In the lower part are views of the block after the second charge was fired. Only the cracks formed by the first shot are extended and no new cracks have appeared. The material in the backward direction is completely undamaged.
- Fig. 10. The results of the experiment with the arrangement of figure 8(b) used. The small charge introduces cracks in the forward and side directions, and these are extended by the main charge. Fragmentation is good, and the material in the backward direction is undamaged.
- Fig. 11. A thin plate P.M.M.A. specimen of thickness 12.7 mm and burden 7 mm. The cracks from the bore-hole show preferential growth towards the free surface after interaction with reflected waves (for details see text). 1 μ s between first 8 frames, 3 μ s intervals for remainder.
- Fig. 12. A three-dimensional P.M.M.A. block (see figure 5) with a burden of 12.5 mm. Preferential growth occurs towards the free surface. Note the gases emerging from the cracks in the last frame. Frames at 5, 11, 14, 20, 26, 29, 41, 53, 65 μ s after firing of charge.
- Fig. 13. A P.M.M.A. block with a shaped surface which perturbs the stress waves and preferential growth to the free surface does not occur. Note the large expansion of the bore-hole. Burden 15 mm. Frames at 0, 4, 6, 8, 10, 12, 22, 32, 42 μ s.
- Fig. 14. The first shot with a tube of type 8(b) inserted into the bore-hole. Only growth in the forward direction occurs; two cracks grow preferentially after the stress wave interaction. Burden 13.5 mm. In the last frame waves from the side surfaces start arriving, but by then preferential growth is established. Frames at 6, 10, 16, 20, 24, 30 μ s.
- Fig. 15. The second loading of the block shown in figure 14 (with no tube inserted) showing that the cracks extended are those introduced by the first shot. The ones in the backward direction have grown from the bottom of the bore-hole. They can be prevented by putting an inert powder beneath the charge. Frames at 0, 3, 6, 9, 12, 15, 27, 42, 57 μ s.

Fig. 16. A fracture travelling from a bore-hole in glass. A reflected stress wave passes up over the cracks from the free surface (bottom edge) causing branching. This happens because the crack is already at its maximum velocity. Frame interval 1 μ sec. Vertical extent of frames $\sim$ 12 mm.

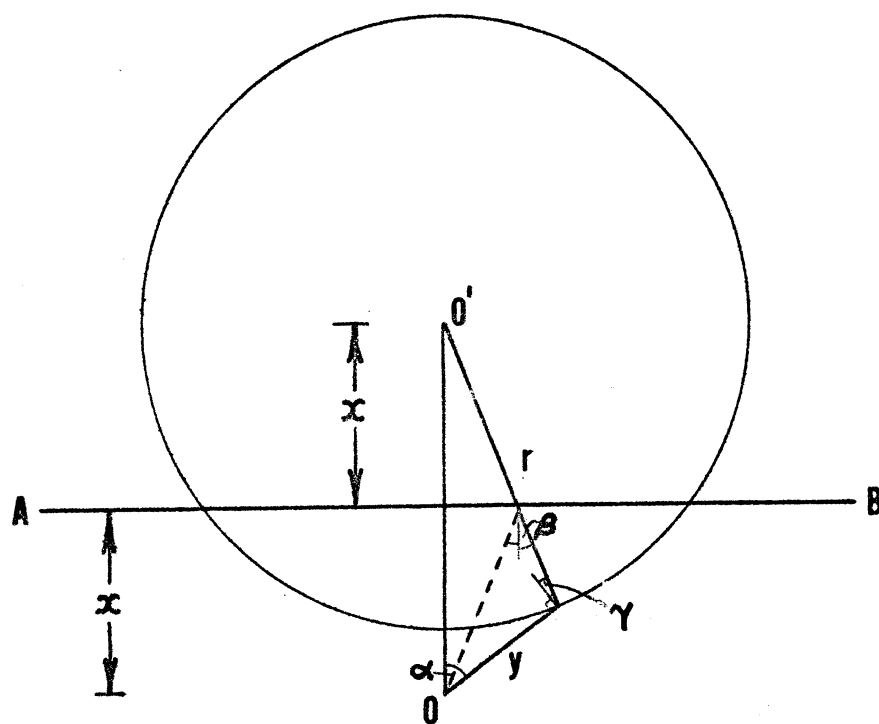


Fig. 1

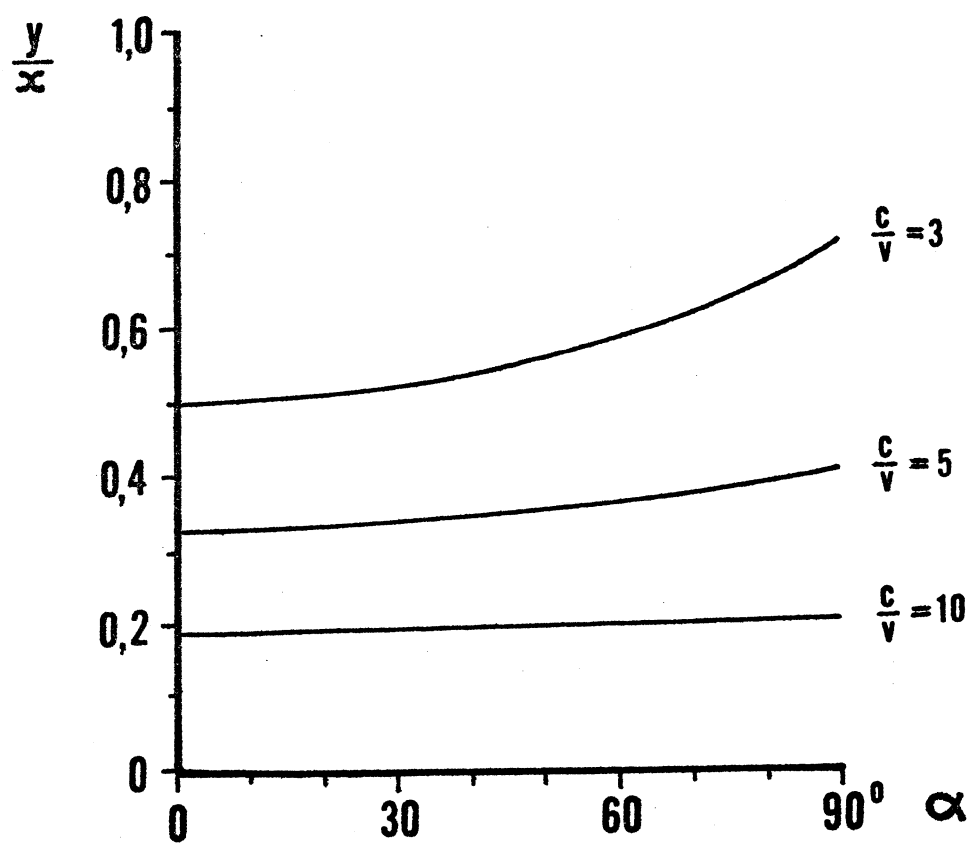


Fig. 2

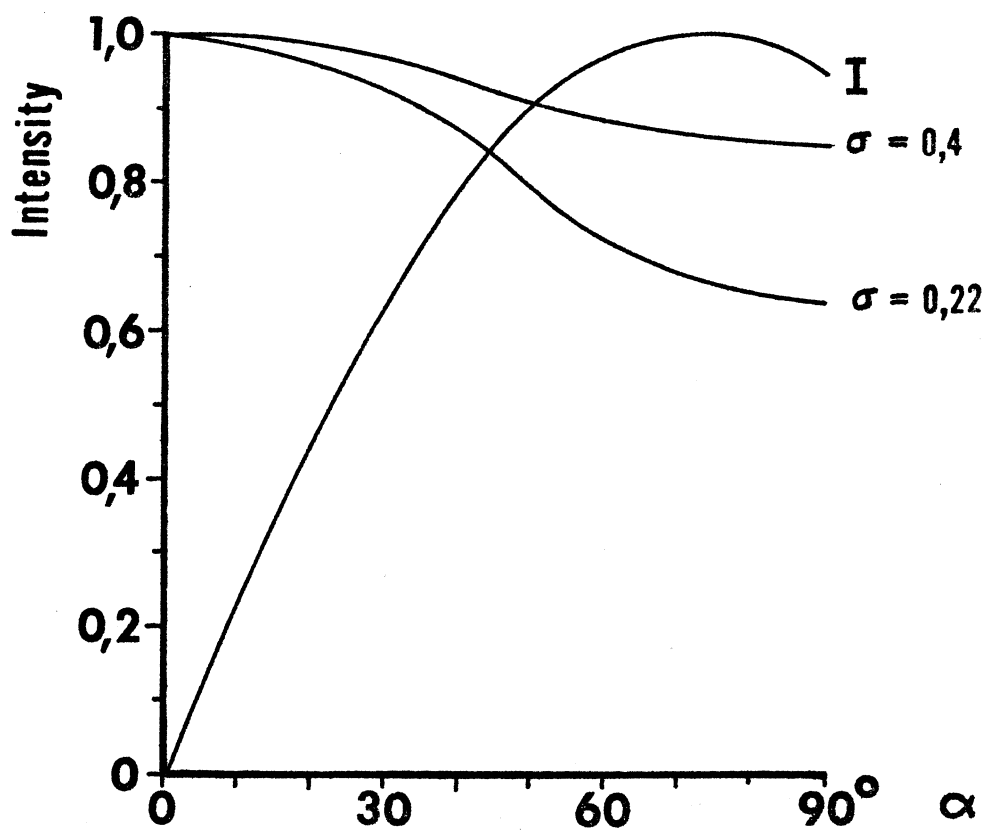


Fig. 3

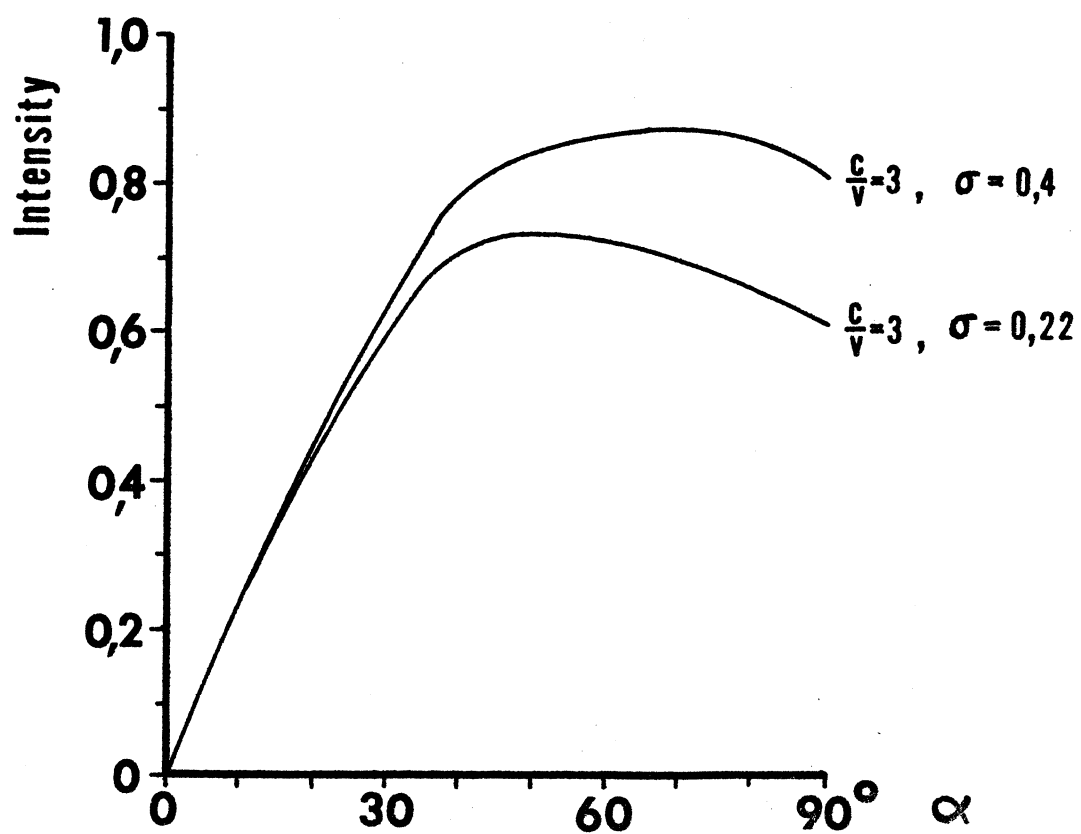
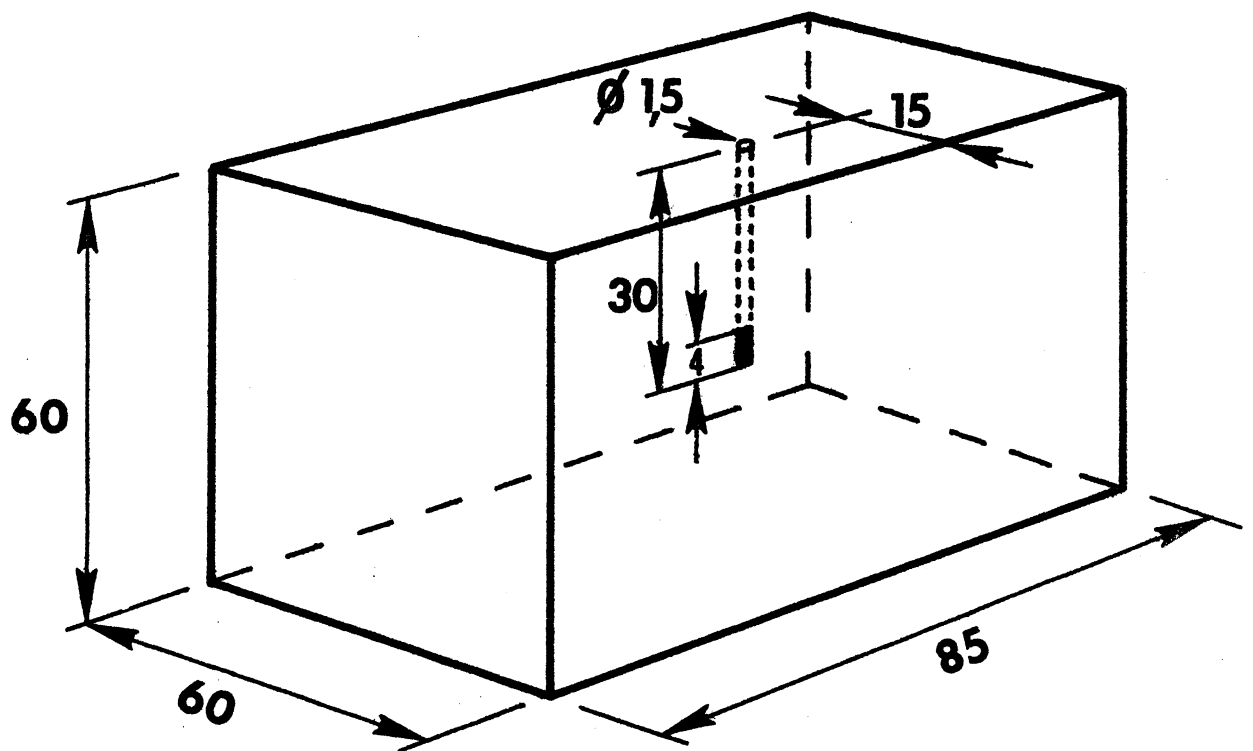


Fig. 4

**Fig. 5**

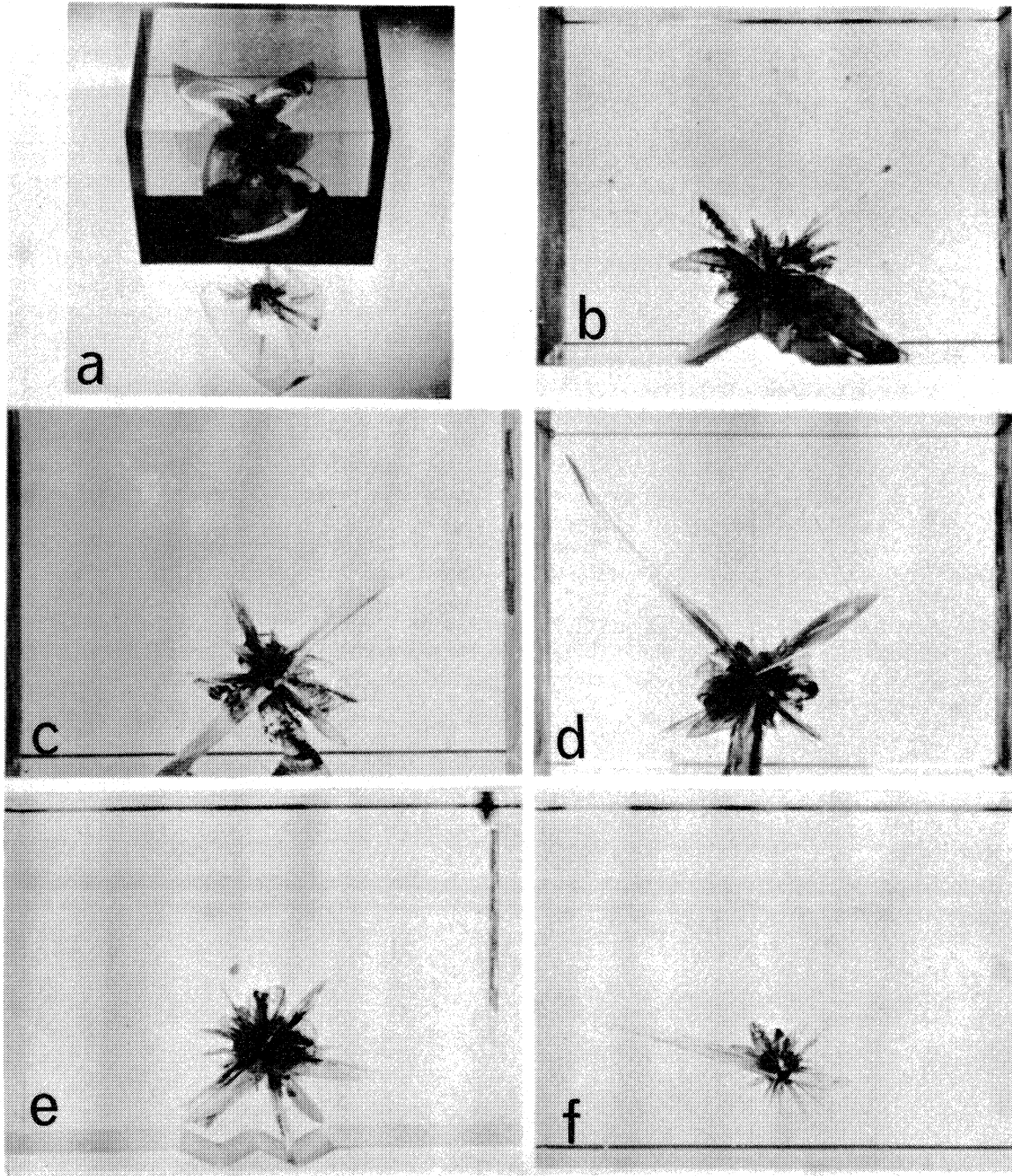


Fig.6

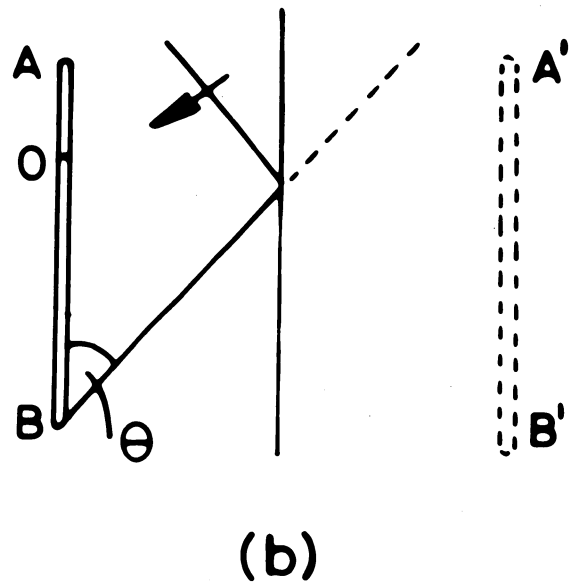
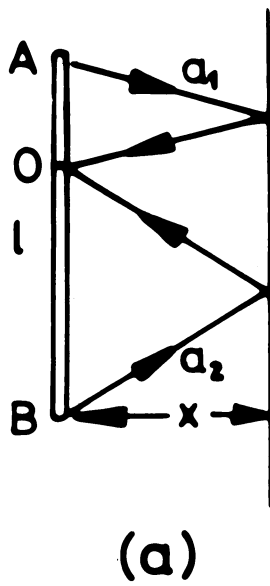
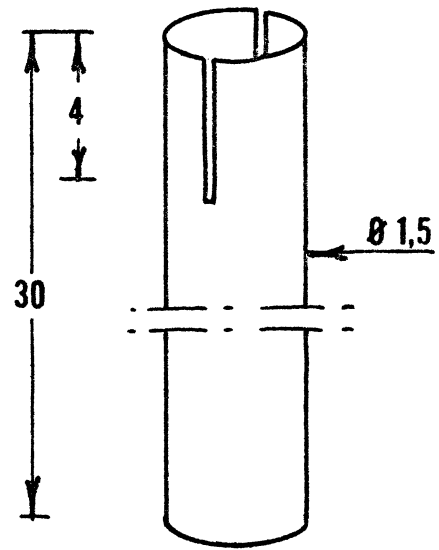


Fig.7

(a)



(b)

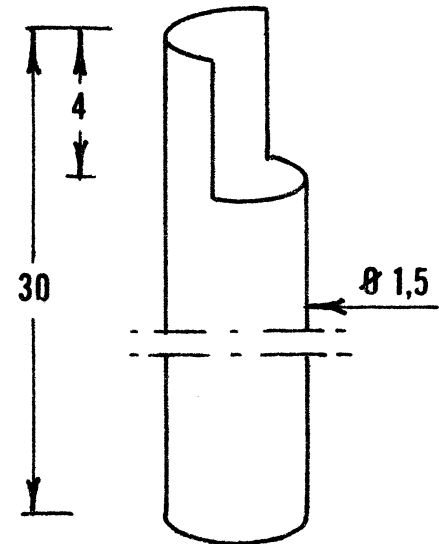
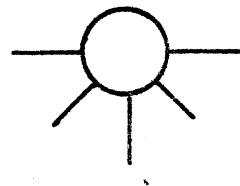


Fig.8

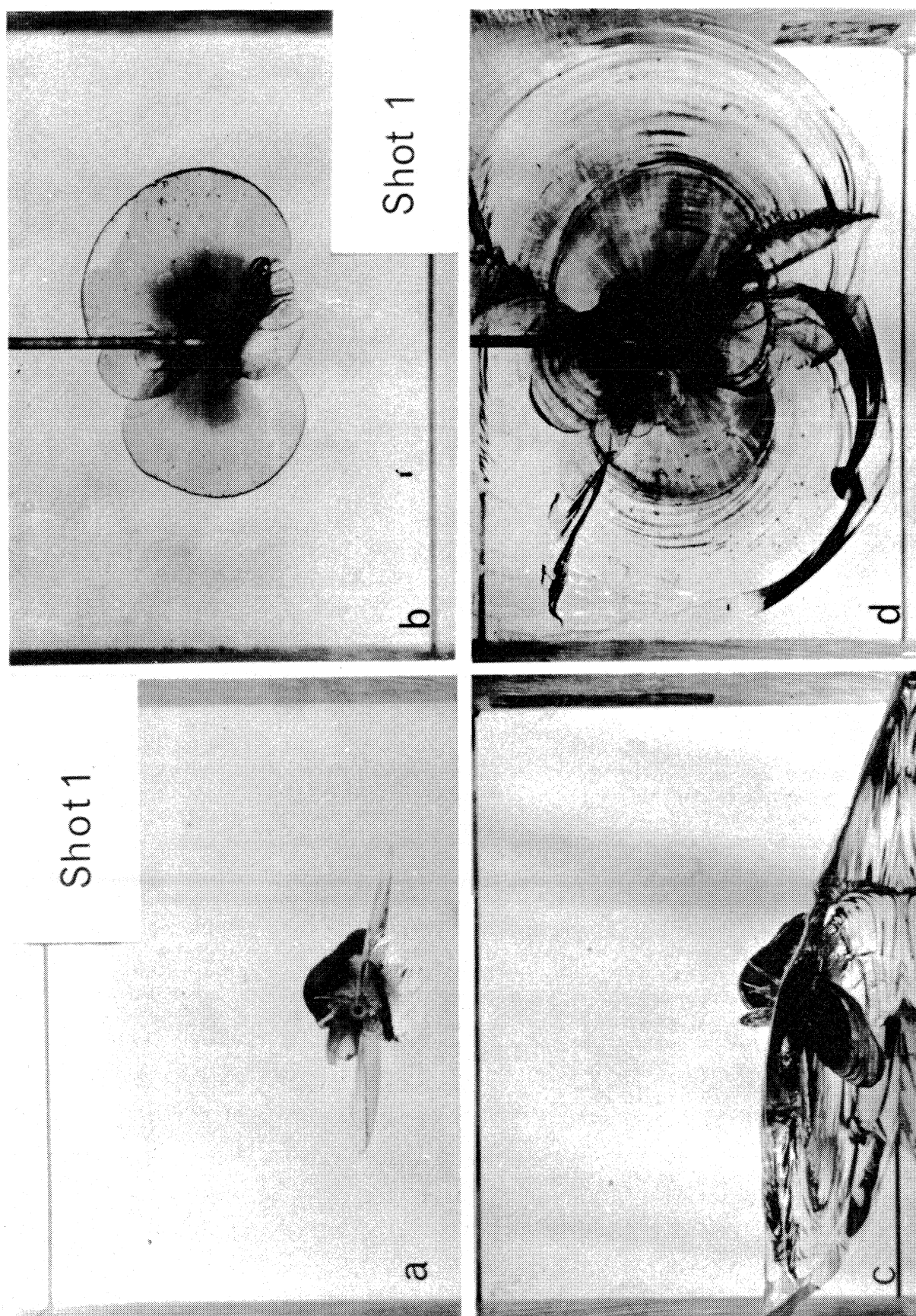
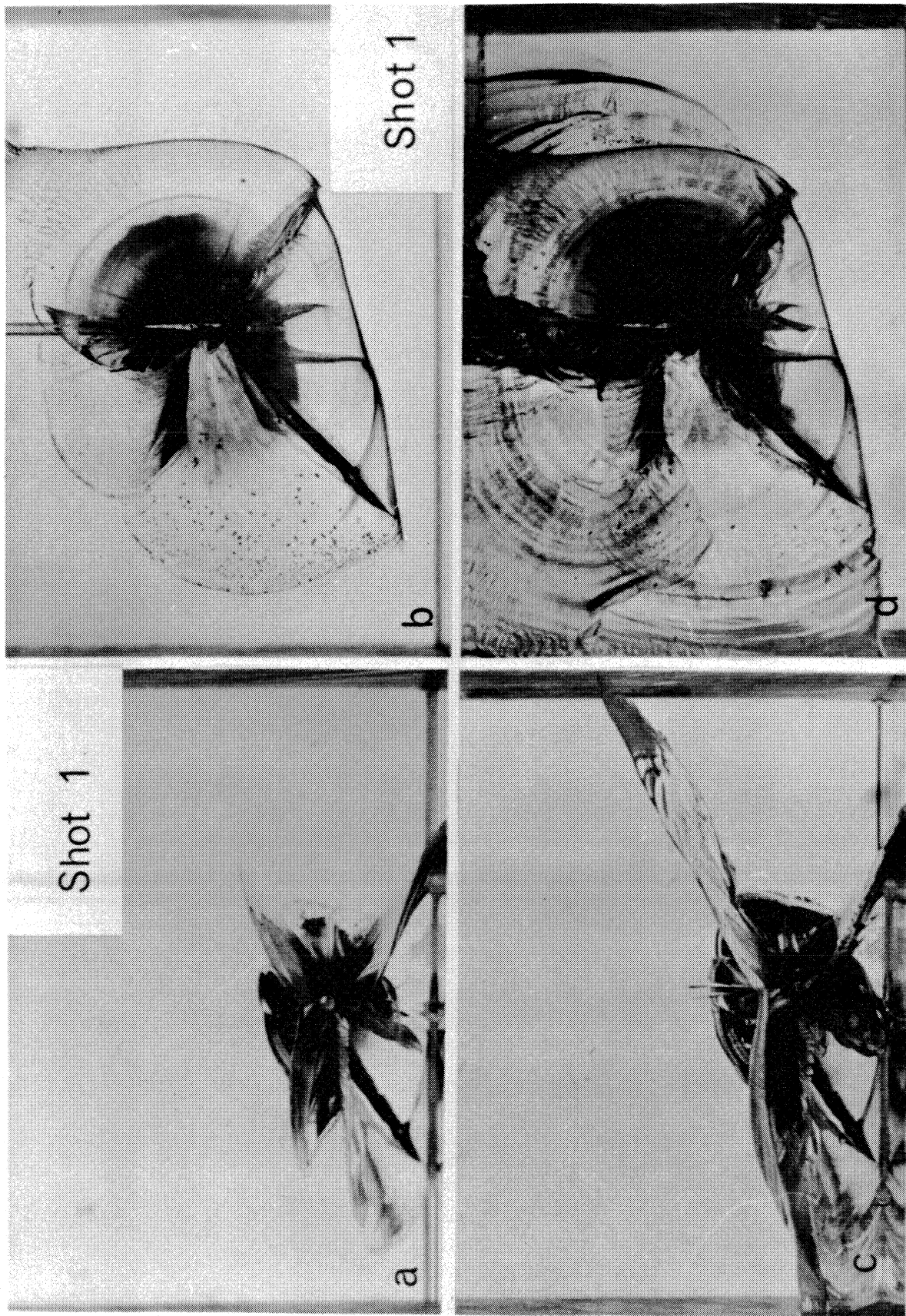


Fig.9

**Fig. 10**

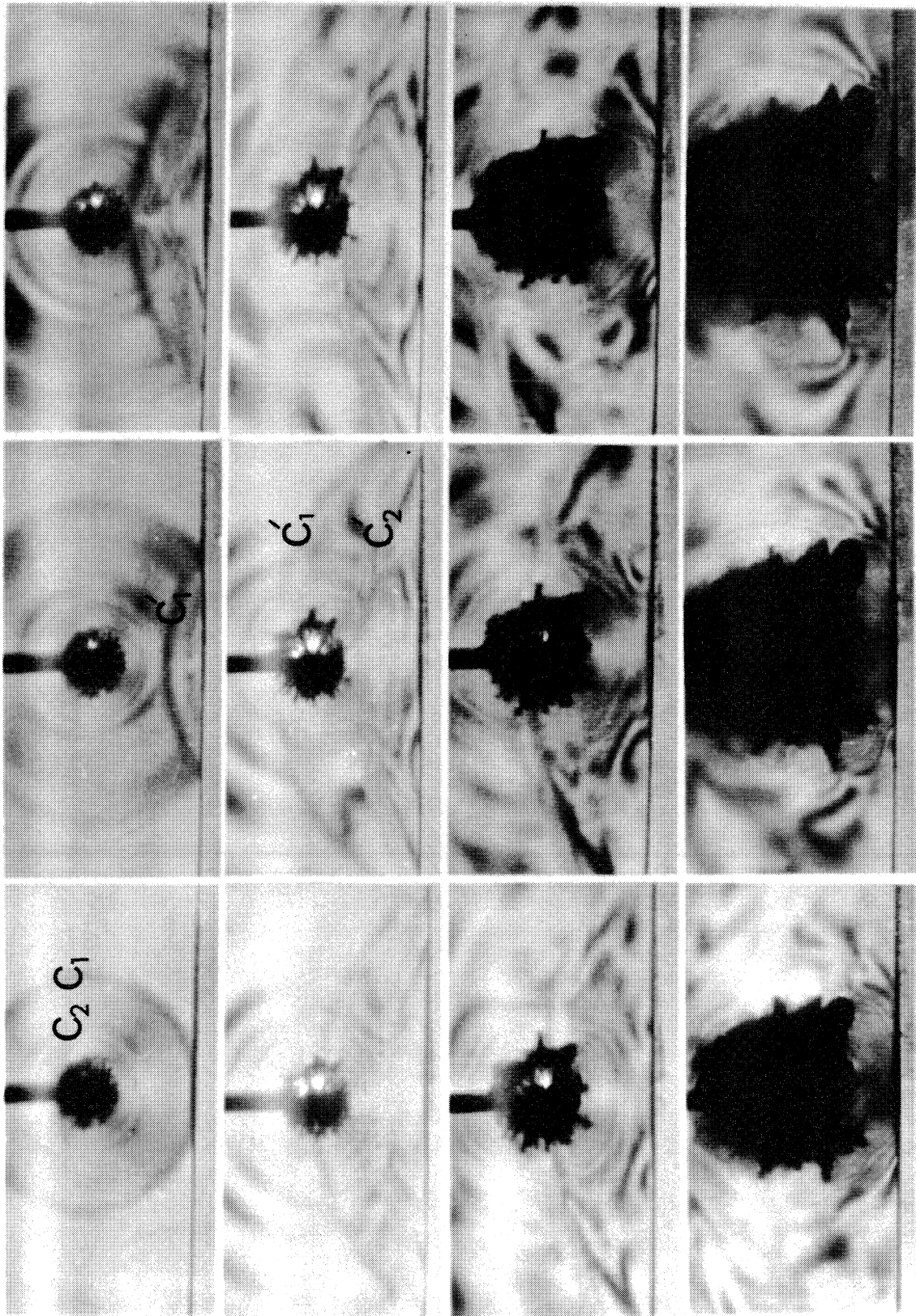


Fig. 11

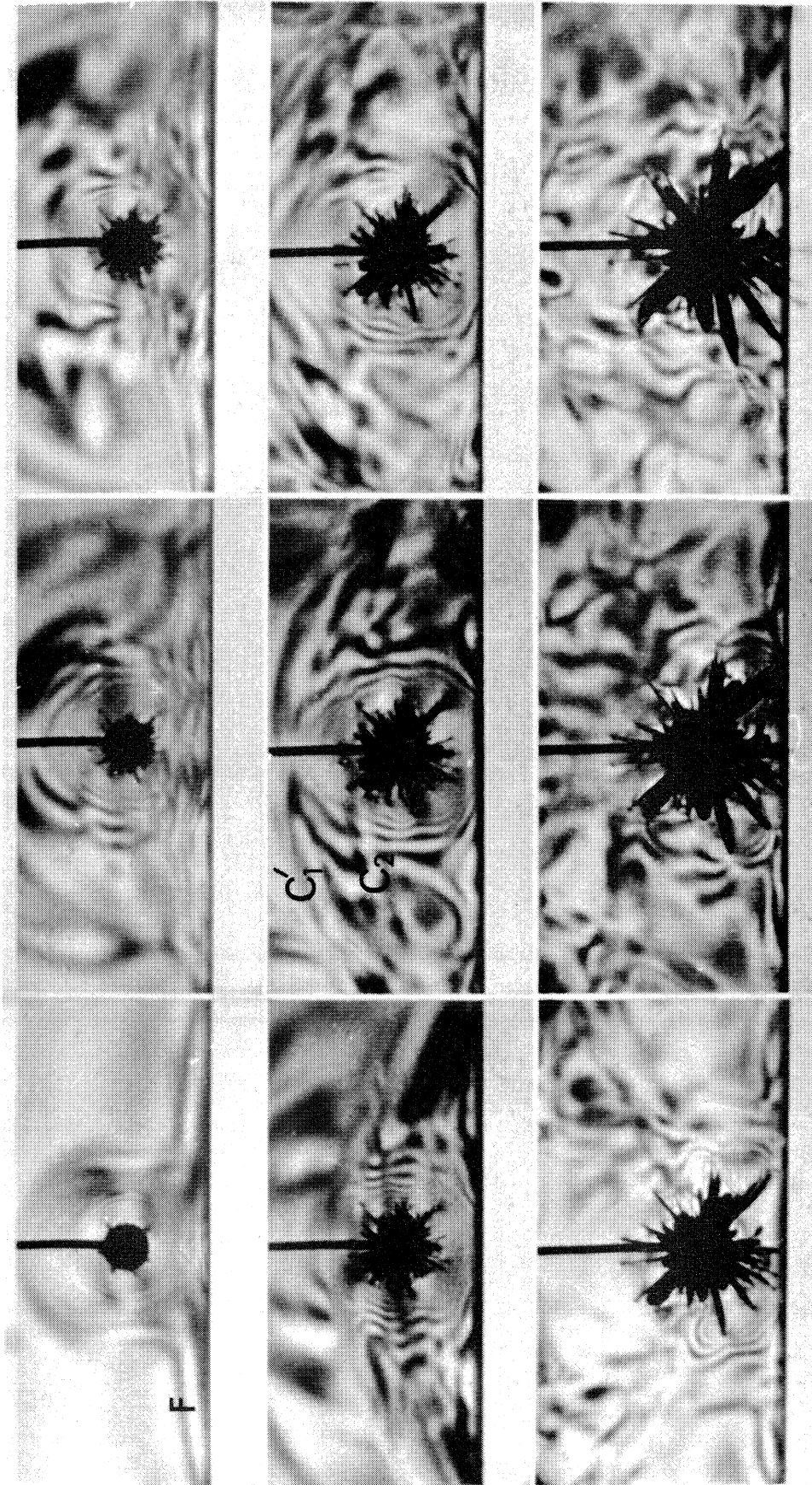


Fig. 12

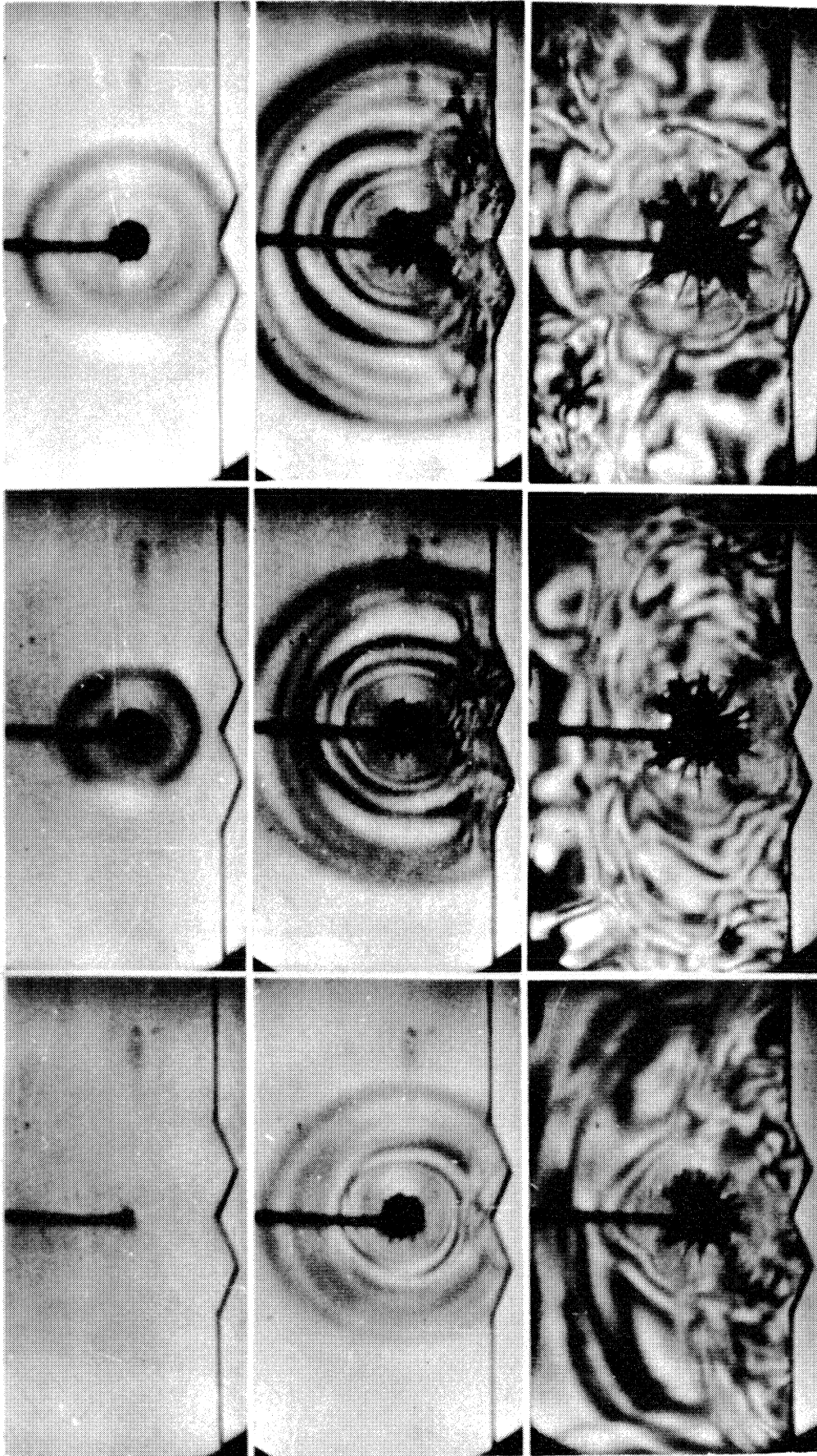
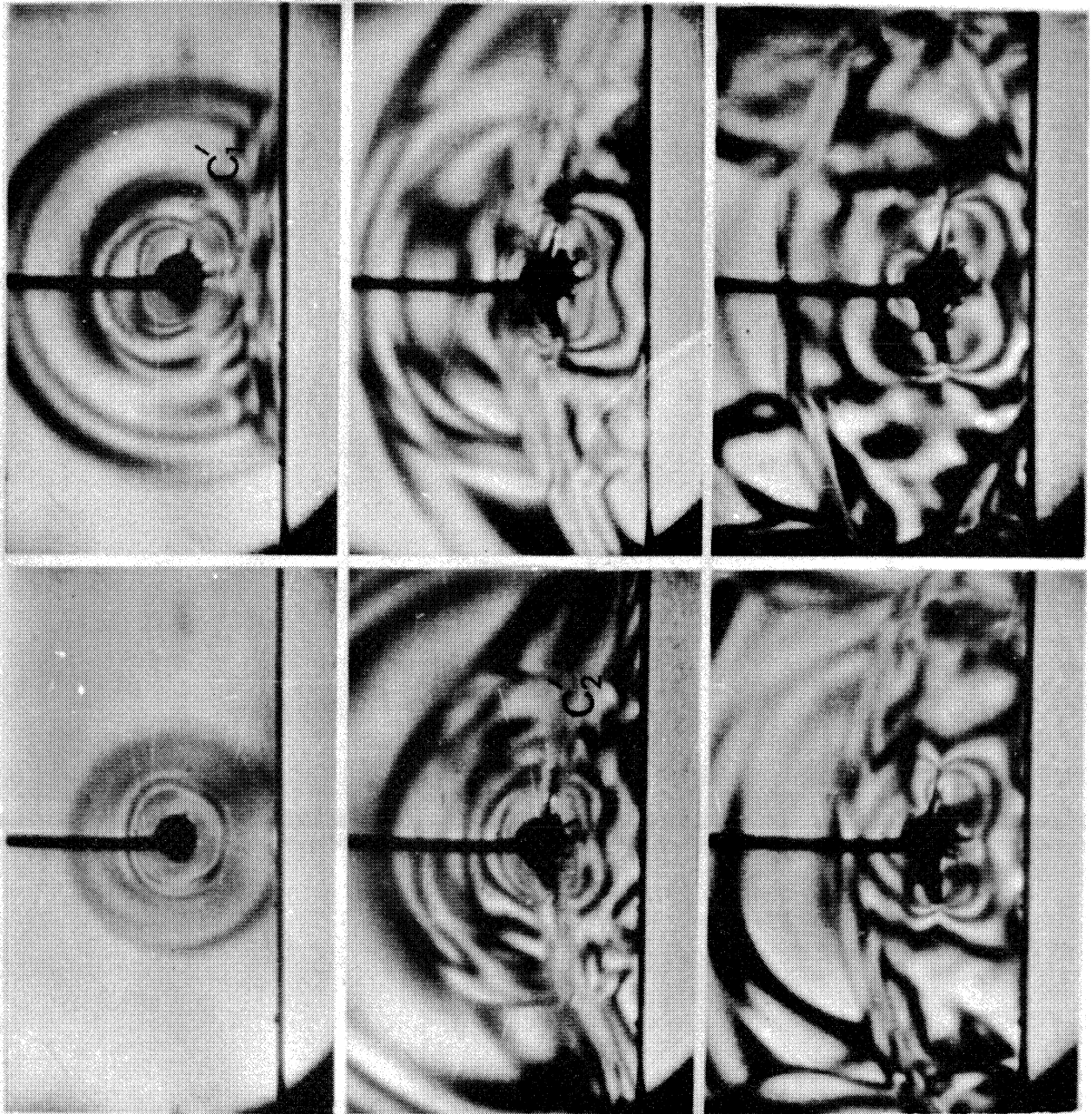


Fig. 13

**Fig.14**

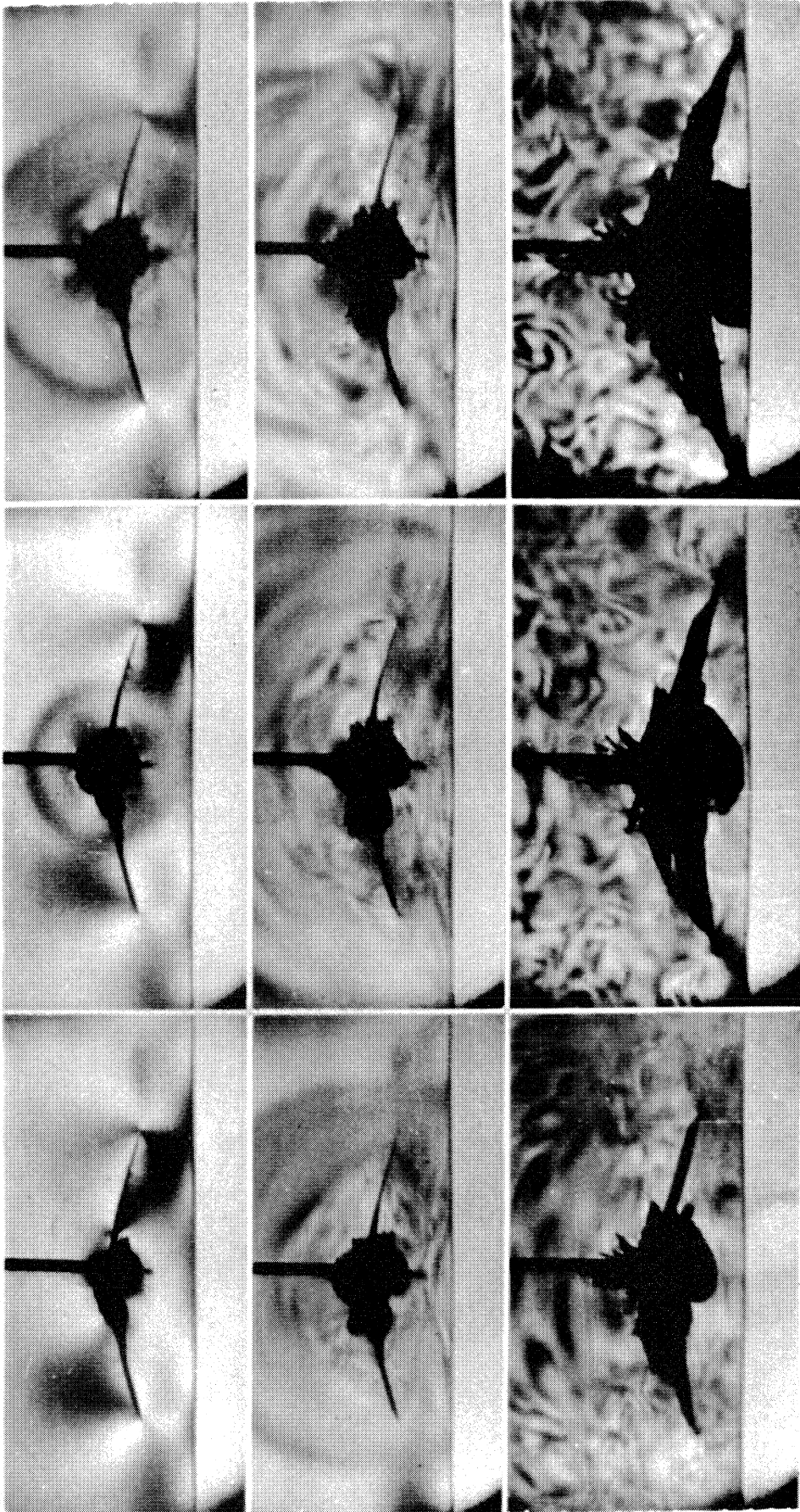
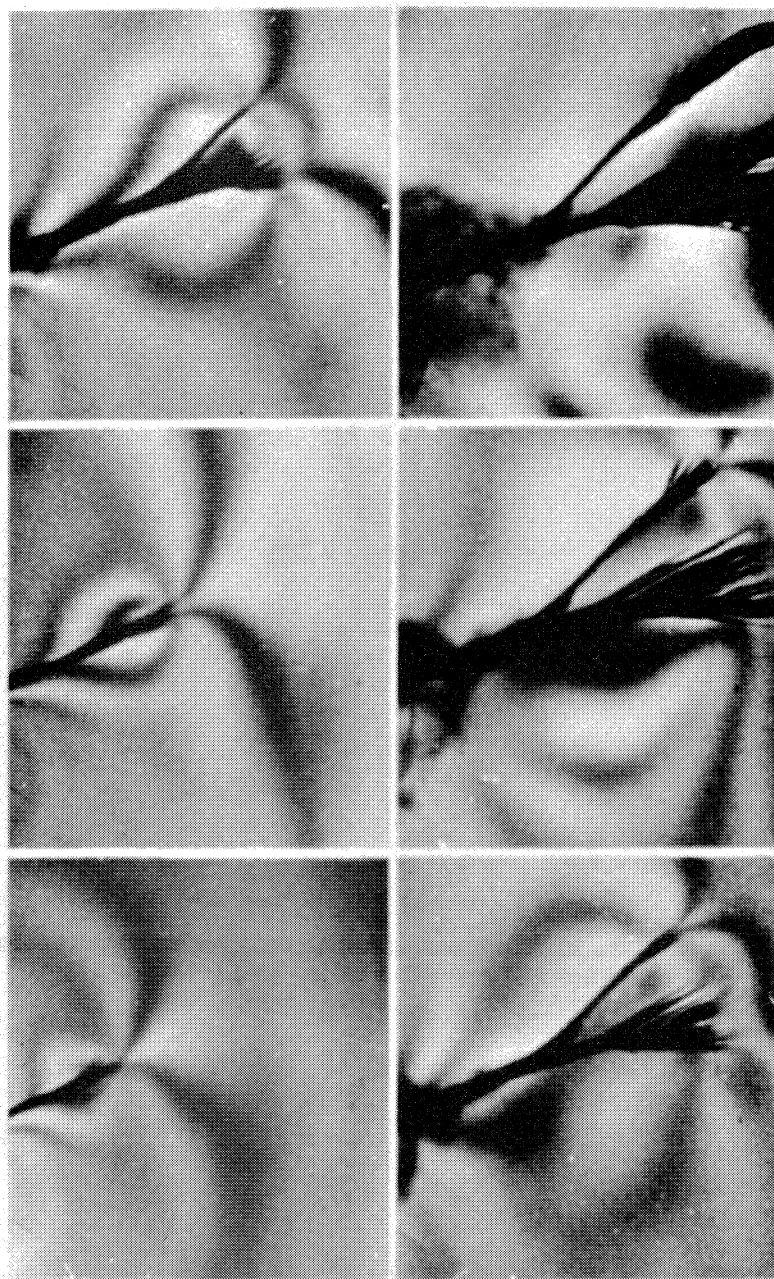


Fig.15

**Fig.16**