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Some Aspects of Rock Cutting by High Speed Water Jets [and Discussion]

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F. THE APPLICATION OF HIGH SPEED LIQUID JETS TO CUTTING

XXVI. Some aspects of rock cutting by high speed water jets

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[Plates 59 and 60]

When rocks are cut in coal mines by steel picks, frictional heating sometimes causes ignition of methane; high speed water jets may provide a method of cutting which is free from this hazard.

A high speed water jet emerging from a nozzle slows down with increasing distance from the nozzle and breaks up into water drops. Studies were made of the behaviour of water jets: in most of the experiments the jets were produced by pressures of 600 atm., but some results are given of experiments at pressures up to 5000 atm. The jets were examined by short exposure optical photography with several different methods of illumination (parallel transmitted, diffuse, and schlieren) and by X-ray photography. In order to find out how the jet velocity decays with distance from a nozzle, and to compare nozzle designs, a target plate containing a hole smaller than the jet diameter was placed so that the jet impinged at right angles on to it, and the target plate was moved until the maximum pressure at the hole was found: this was measured for different distances from the nozzle. Nozzle shapes suggested in literature for minimizing jet dispersion were studied and an empirical investigation of a variety of nozzle shapes was carried out. Several nozzle shapes were found which gave good results, i.e. the maximum pressure on the target plate was half the pump pressure at a distance of about 350 nozzle diameters.

In many cutting applications the first stage in the process would be the impingement of a water jet on a surface at right angles. The initial cutting would depend upon the stress distribution within the target, which in turn would depend upon the pressure distribution produced by the water jet on the surface. A theory is given of the pressure distribution on the target plate, which predicts that the pressure will fall to zero at about 2·6 jet radii: this was found to be in good agreement with experiments.

Preliminary studies were made of the penetration of several types of rock by water jets of velocities up to about 1000 m/s (pressures about 5000 atm).

It was found that a 1 mm diameter jet drills a cylindrical hole about 5 mm in diameter. The pressure that the water jet produces at the bottom of such holes was measured and shown to fall off to about one-tenth of the nozzle pressure at a hole depth of about 4 cm.

1. Introduction

With most conventional machinery used for cutting rocks, or coals in which rock bands are present, there is a possibility of igniting methane by frictional heating. If rock cutting by water jets proved to be a practical method for underground use, the methane ignition hazard might be substantially reduced.

Water jets are being used in U.S.S.R., U.S.A. and Poland to cut coal at water pressures of about 300 atm and high flow rates (about 10 to 50 l./s), the water also being used to transport the coal away from the working face in open troughs (Palowitch & Malenka 1964; Krivchenko & Baka 1962; Borecki, Duczmal, Perek, Raczynski & Mamczarczyk 1963). It is envisaged that rock cutting would be carried out by much higher pressures and much smaller flow rates, which would be obtained by using very small nozzles; no attempt would be made to use the water to transport the rock away. Russian work (Voitsekhovskii, Nikolaev, Ludin, Maier & Chermenskii 1963) has shown that rocks can be rapidly cut by water jets, providing that the velocity is high. Further studies of the penetration of rocks by water jets at pressures up to 1700 atm have been made by Farmer & Attewell (1963). Other applications of water jets have been suggested: cutting wood and metals (Bryan 1963), and cutting concrete and brick (*Steel and Coal* 1962).

Our studies have been mainly concerned with the effect of nozzle shape on the reduction in velocity caused by the passage of the jet through air. The nozzle design has an important effect on the disintegration of the jet and hence on the speed of the jet at some distance from the nozzle.

When a jet is used to cut rock, it will impinge on a surface at some distance from the nozzle. Studies have been made, therefore, of the pressure distribution and maximum pressure that a jet can produce on a surface at right angles to it. In addition, some preliminary investigations of the penetration of rocks by water jets have been made and measurements have been made of the pressure at the bottom of a simulated hole of the type that the jets drill in rock. Two types of experimental equipment have been used, a water pump giving pressures up to 600 atm (water jet velocity 340 m/s) and a hydraulic intensifier giving pressures up to 5000 atm (water jet velocity 1000 m/s).

2. Apparatus for producing and studying the water jets

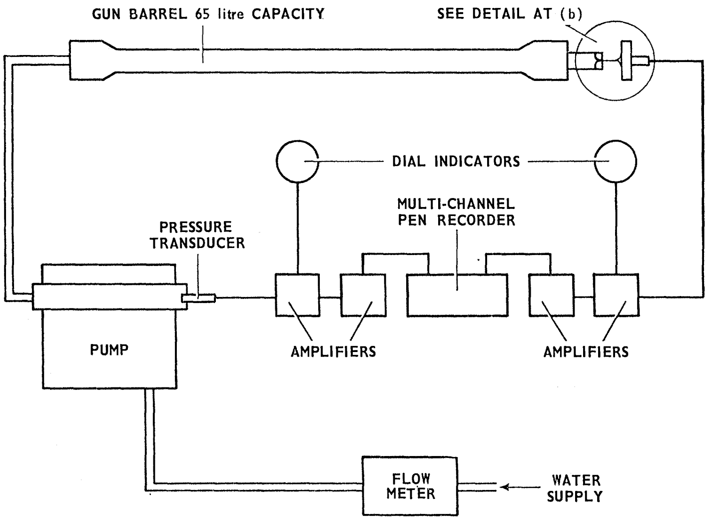
Continuous water jets were obtained from a 90 h.p. electrically driven piston pump, which was capable of passing 45 l./min at a pressure of 600 atm.

The general arrangement of the apparatus is shown in figure 1. In order to reduce the pressure variation during the pump strokes a gun barrel of capacity 65 l. was put in series with the pump. A strain gauge pressure transducer was used to monitor the water pressure behind the nozzle.

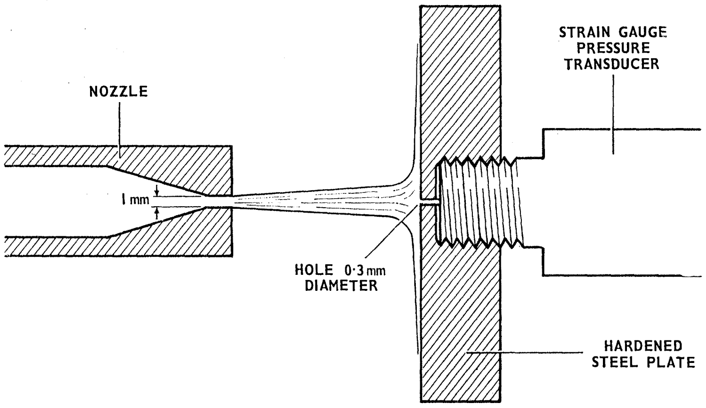
In order to determine the stagnation pressure on the jet axis as a function of distance from the nozzle and also to study the pressure on a surface at right angles to the jet, a block of hardened silver steel with a hole 0·3 mm diameter and approximately 2·5 mm deep, behind which a pressure transducer was mounted, was fixed to a remotely operated three-dimensional traversing gear. This was a modified lathe bed fitted with motors and remote indicators so that the position of the 'target' hole could be measured to 0·02 mm. In the experiments to study the nozzle design the target plate was moved at right angles to the jet, along horizontal and vertical diameters, until the maximum pressure was recorded.

Outputs from both pressure transducers were fed to dial indicators and a multichannel pen recorder. The recorded variation of the target pressure with time always had a similar shape (but with superimposed fluctuations) to that of the pump pressure. Pressure measurements were always taken from a flat portion of the record.

When it was required to study water jets at pressures up to 5000 atm, the energy stored by compressing water at 600 atm was used to power a hydraulic intensifier of ratio 12:1. The gun barrel was filled with water and pressurized by the pump (figure 2). The pistons of the intensifier were restrained by shear pins designed to break at a predetermined pressure. The volume of water contained in the high pressure side of the intensifier was 10 cm^3 which on discharging through a 1 mm diameter nozzle gave a flow duration of the order of 10 ms.



(a) Block diagram



(b) Detail of jet pressure measurement

FIGURE 1. Apparatus for studying water jets at pressures up to 600 atmospheres.

The increase in pressure in the gun barrel was relatively slow and was monitored by a pressure transducer and pen recorder. At the instant the shear pins broke a small reduction in pressure occurred, enabling the primary intensifier pressure to be accurately measured.

3. Photography

The jet was photographed by three methods (figure 3). Parallel illumination (figure (3*a*)) provided by a spark light source of duration $\frac{1}{2}\,\mu$s was used to 'freeze' the motion and to give the angle of the spread of the jet and details of the outer part of the flow.

The core of the jet was studied by diffused-light illumination (figure 3(*b*)) and by X-ray illumination (figure 3(*c*)). With the former method the spark light source was replaced

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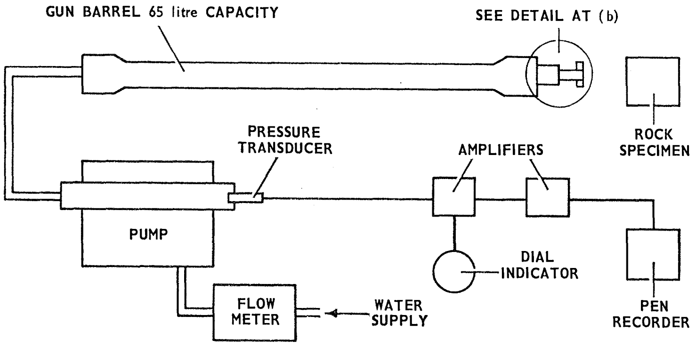
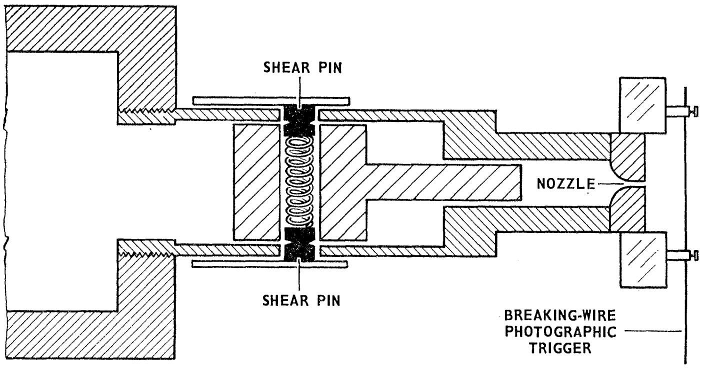
by a flash tube of output duration 2 μs to give greater illumination; this almost 'froze' the motion of the jet. The X-ray photographs were taken with exposure times of about 5 min.

Schlieren photographs of the water jets from the intensifier were taken by means of a six-frame Cranz-Shardin system. The spark light sources were triggered by the jet breaking a fine wire placed close to the nozzle (figure 2).

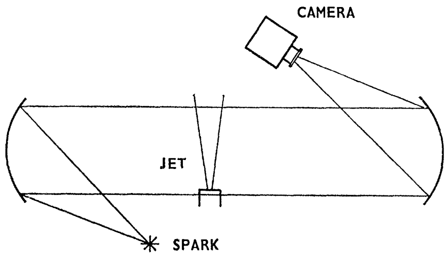


(a) Block diagram

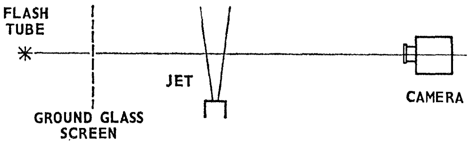


(b) Pressure intensifier

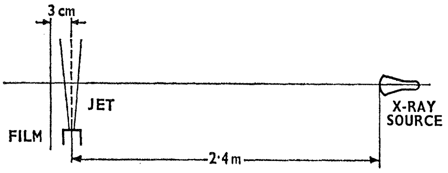
FIGURE 2. Apparatus for studying water jets at pressures up to 5 000 atmospheres.



(a) Parallel-light illumination



(b) Diffused-light illumination

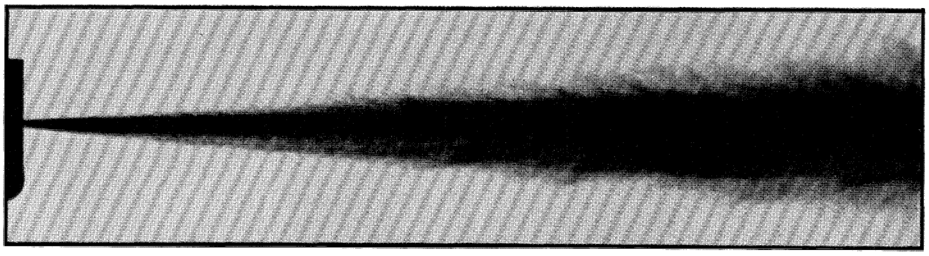


(c) X-ray illumination

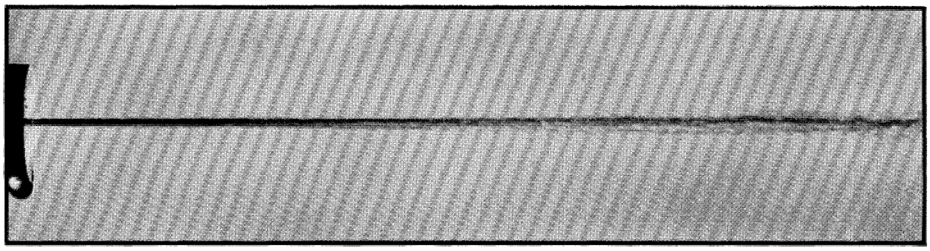
FIGURE 3. Photographic equipment.

4. Comparison of X-ray and optical photographs

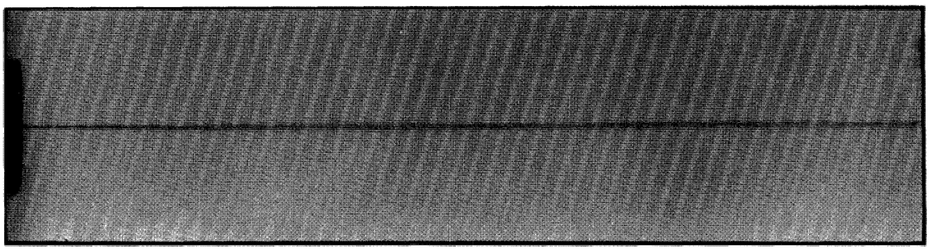
When a high speed water jet issuing from a small diameter nozzle is observed visually, it appears to be completely broken up into a fine spray a short distance from the nozzle. As will be seen later in the paper (§ 5 (*b*)), this is not borne out by pressure measurements made when the jet impinges on a plate. An attempt has therefore been made to obtain a physical picture of the flow from the optical and X-ray photographs. Figure 4, plate 59, shows typical photographs obtained at 130 and 600 atm. Inspection of the photographs suggests the following description of the flow: there is a central core which contains most of the mass of the water (figures 4 (*c*) and (*e*)) but this core is not continuous, except close to the nozzle (figure 4 (*b*)) and surrounding the core is a fine spray of little mass (figure 4 (*a*)) which is responsible for the visual indication of rapid breakup. In the fine spray can be seen the hairlike ligaments described by Castleman (1931). When the pressure behind the nozzle is lower there is less fine spray (figures 4 (*a*) and (*d*)) but there is little change in the core (figures 4 (*c*) and (*e*)).



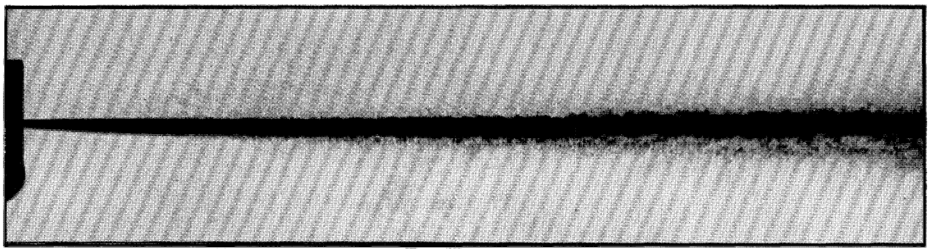
(*a*) Spark source; parallel transmitted light ($\frac{1}{2}$ μs exposure); pressure 600 atm.



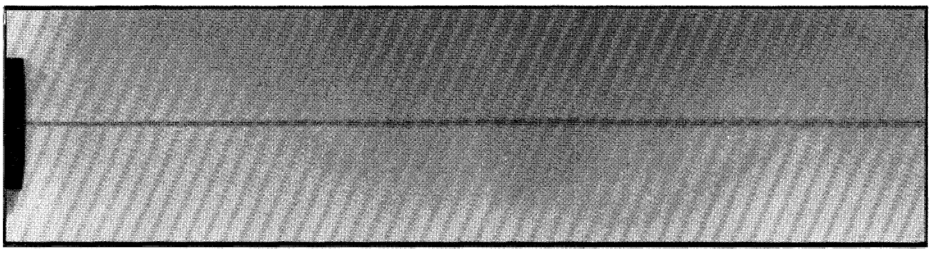
(*b*) Flash-tube source; diffuse transmitted light (2 μs exposure); pressure 600 atm.



(*c*) X-ray source (5 min exposure); pressure 600 atm.



(*d*) Spark source; parallel transmitted light ($\frac{1}{2}$ μs exposure); pressure 130 atm.



(*e*) X-ray source (5 min exposure); pressure 130 atm.

FIGURE 4. Typical photographs.

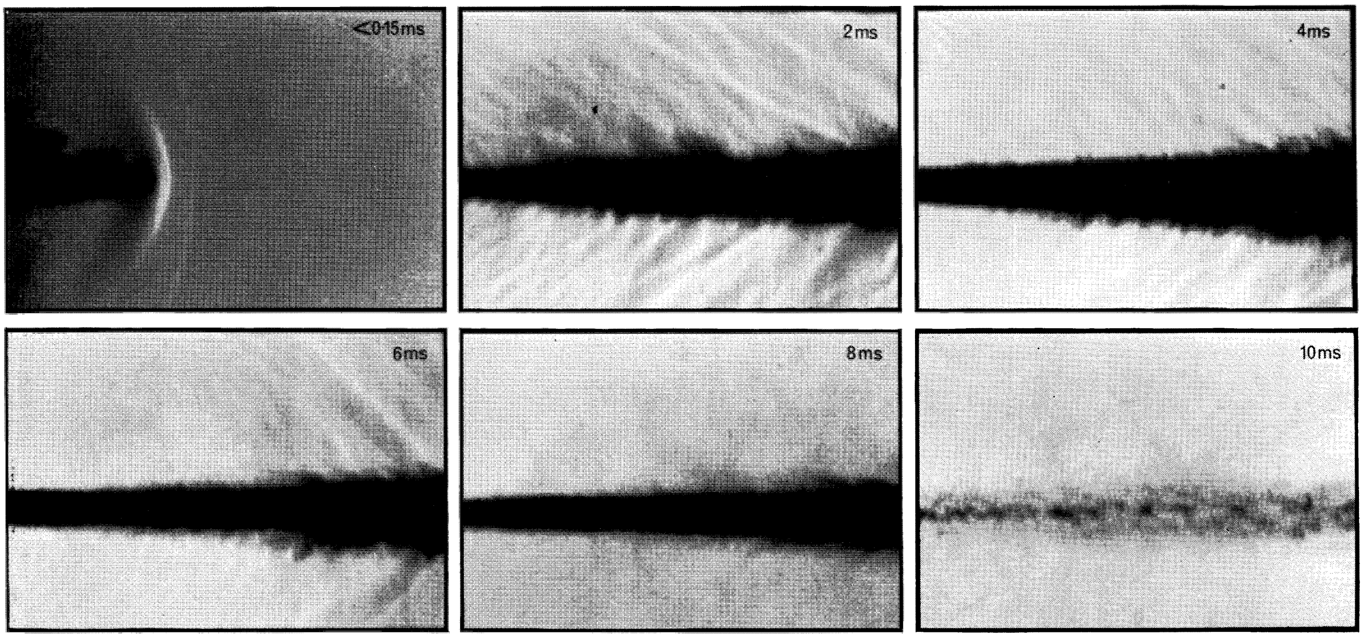


FIGURE 11. A sequence of schlieren photographs of the flow from the intensifier during a single shot. The times after the start of flow are indicated on the photographs. Driving pressure, about 5000 atm; velocity, 1000 m/s.

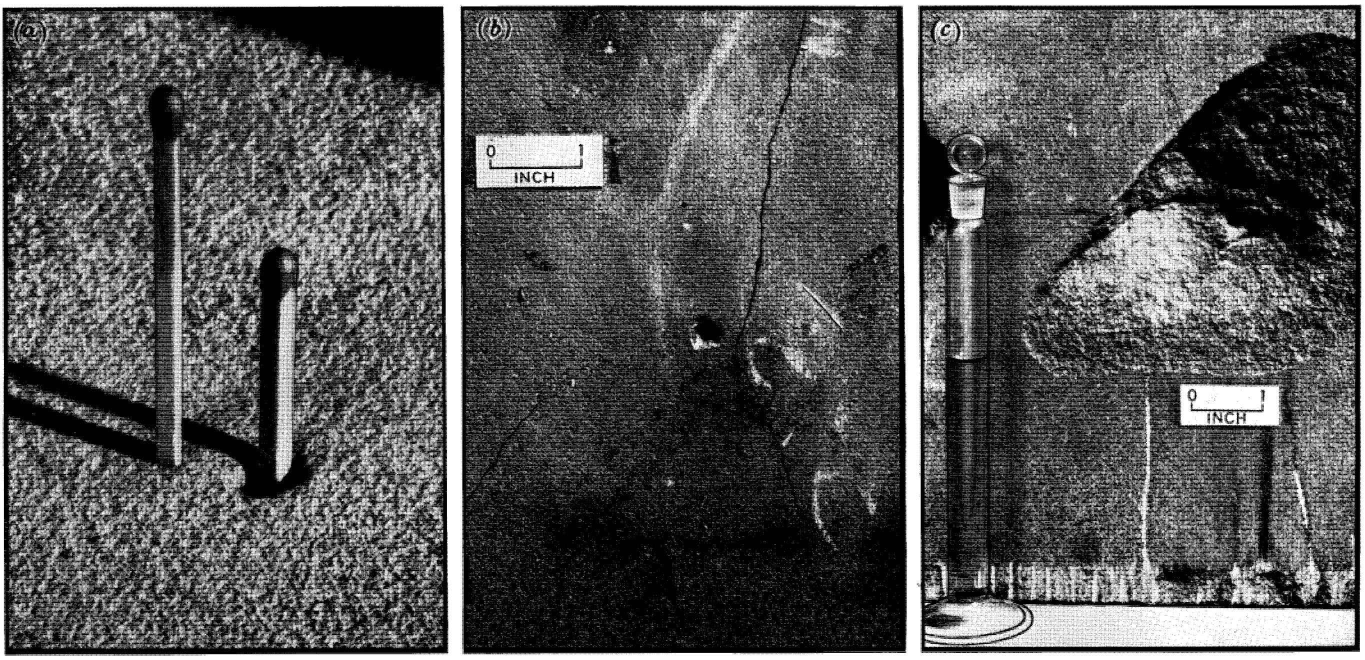


FIGURE 12. Typical examples of damage to Darley Dale Sandstone produced by 10 cm^3 of water at a velocity of about 1000 m/s.

5. Reduction in velocity with distance from nozzle

(*a*) *Introduction*

In many cases where water jets are used for cutting it will be desirable for the nozzle to be some distance from the object to be cut. We, therefore, need to consider the factors that influence the pressure at a distance.

The factors that affect the atomization of a water jet have been considered by Giffen & Muraszew (1953) who grouped them into the following dimensionless parameters:

$$\frac{ud}{\nu_1},\quad \frac{u^2d\rho}{\sigma},\quad \frac{\mu_1}{\mu_2},\quad \frac{\rho_1}{\rho_2},$$

where the first two parameters are the Reynolds and Weber numbers respectively and u is the mean jet velocity, d the diameter of the nozzle, ν_1 the kinematic viscosity of water, ρ_1 its density, ρ_2 the density of air, σ the surface tension of water and μ_1 and μ_2 the viscosities of water and air respectively. For the present studies we should add the level of turbulence and the velocity profile at the nozzle outlet and Mach numbers u/a_1 and u/a_2 where a_1 and a_2 are respectively the speeds of sound in water and air.

The present investigations are mainly confined to studying the effect of nozzle shape, which will influence the turbulence level and velocity profile at the outlet; the effect of the other parameters listed above are also studied over a limited range. The level of turbulence at the outlet will also be affected by the wall roughness, and by the contraction ratio. Some idea of an acceptable roughness height can be obtained by calculating the thickness of the laminar sublayer since roughness within the layer will not affect the flow. The thickness is given by $\delta = 5\nu/v^*$, where v^* is the friction velocity $\sqrt{(\tau_0/\rho_1)}$ and τ_0 is the shearing stress at the wall. With a mean velocity in a 1 mm nozzle of 350 m/s, $\delta \simeq \frac{1}{4}\,\mu$m. In the nozzles investigated this high standard of internal finish was not obtained, but the nozzles were made of brass which was internally polished with commercial metal polish until the surface appeared bright in a low power microscope. The flow upstream of the nozzle will also be important; in the experiments there were 30 diameters of straight pipe before the nozzle, and the junction with the nozzle was made without gaskets in order to minimize the risk of projections or cavities there.

Since no theory of jet break up exists that suggests the desirable velocity profile for minimum dispersion, an empirical investigation was carried out with a variety of nozzle shapes.

The velocity of the water emerging from the nozzle may be calculated from the Bernoulli equation $u = 14\sqrt{P}$ where u (m/s) is the velocity and P the driving pressure in atmospheres less the pressure loss within the nozzle itself, which may not be negligible for some nozzle shapes. For example, if a 1 mm diameter nozzle contains a section of length 10 mm the pressure loss in this section for a driving pressure of 600 atm will be about 60 atm, so that nozzles which contain only a short length of small diameter are to be preferred from this point of view.

(*b*) *Nozzle shape*

The ratio of the maximum pressure on the target plate hole to the pump pressure was measured for several distances from each nozzle. In general, it was found that as the distance from a nozzle was increased the pressure recorded on the target plate became unsteady, which suggests that the jet core is not a continuous stream. The observed pressure fluctuations probably arise from the impact of the individual drops in the core of the jet. This water hammer pressure will be much greater than the steady pressure for water jet velocities of 350 m/s (Brunton 1961; Jenkins & Booker 1960). No attempt was made to measure the water-hammer pressures, because the response time of the strain-gauge pressure transducers was too long.

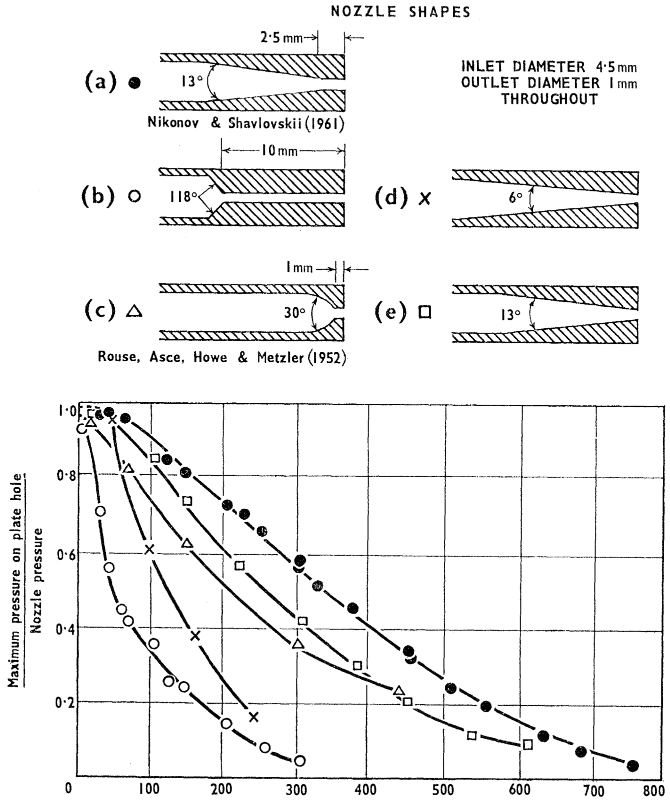


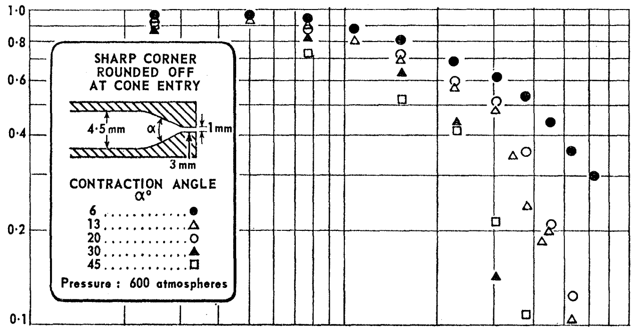
FIGURE 5. Effect of nozzle shape on performance.

Figure 5 compares five 1 mm outlet diameter nozzles at a pump pressure of 600 atm. The best results were given by shape *a* suggested by Nikonov & Shavlovskii (1961) which was developed from investigations of nozzle shapes for 'hydraulic monitors' (i.e. relatively low pressure high flow experiments).

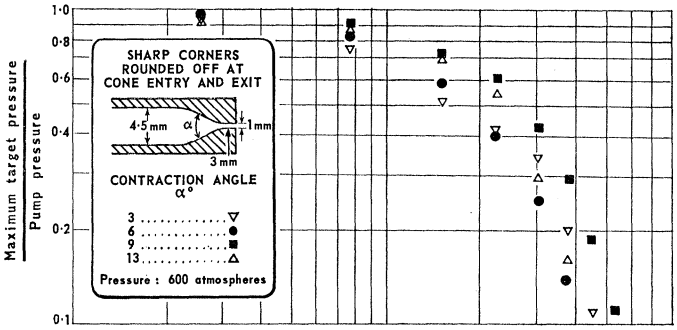
Nozzle *b* is essentially a long straight length of 1 mm diameter pipe and this gave poor results. Good results were given by nozzle *c*, a shape suggested by Rouse, Asce, Howe & Metzler (1952) who empirically found the nozzle shape which gave the least spread of the water jet in fire-fighting applications.

Nozzles *d* and *e* were conical without a final straight section; the results obtained with the 13° cone were better than the 6° cone but inferior to nozzle *a*.

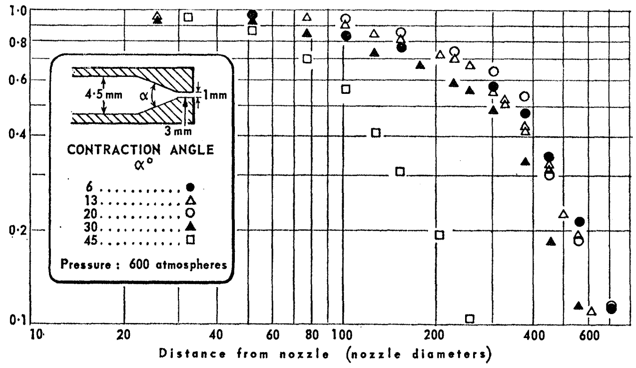
Figures 6 (*a*), (*b*) and (*c*) show measurements made with 14 nozzle shapes, all of which were in the form of a contraction followed by a 3 mm long section of 1 mm diameter; the contraction angles varied from 3 to 45°, with and without the internal corners of the nozzle rounded. The results show that several nozzle shapes give good results; poor results are obtained for large contraction angles ($> 20°$); and the nozzles with sharp internal corners are slightly better than those with rounded corners.



(a) Rounded inlet corners



(b) Rounded corners at both ends of contraction



(c) Sharp corners

FIGURE 6. The effect of contraction angle on nozzle performance.

The effect of the length of the final straight section for a 13° contraction with sharp corners was studied. Figure 7 shows the distance from the nozzle to the point where the pressure had fallen to 75 % of the driving pressure as a function of the length of the straight section. Each experimental point refers to a different nozzle and not to repeated measurements with the same nozzle. The best results are given by a straight section of length about 3 mm. The results obtained for a zero length were somewhat uncertain as the end of the nozzle showed evidence of wear when the measurements were finished. For all other nozzles studied the nozzle appearance was unchanged by use and no fall off in performance could be detected after several hours use.

From these studies we conclude that the pressure behind the nozzle can be applied to a target 100 nozzle diameters away without great losses; e.g. for several nozzles the pressure at this distance was over 80% of that behind the nozzle. This means that it is not necessary in a practical application for a nozzle to be brought so close to the rock surface that damage to the nozzle by impact on the surface is likely. This is important since a small projection into the flow at the nozzle outlet causes the jet to be broken up. The simplest nozzle shape that performs well is a small-angle cone (6 to 20°) followed by 2 to 4 nozzle diameters of straight section.

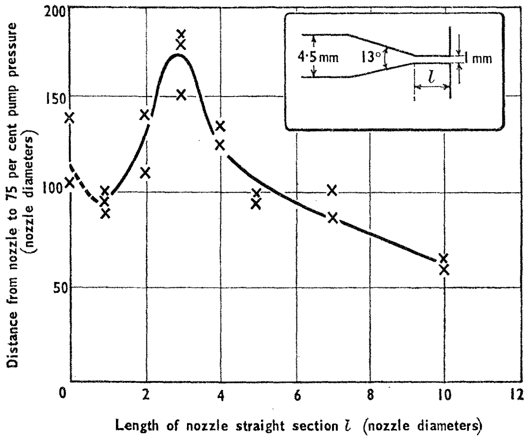


FIGURE 7. The effect of length of nozzle straight section on performance.

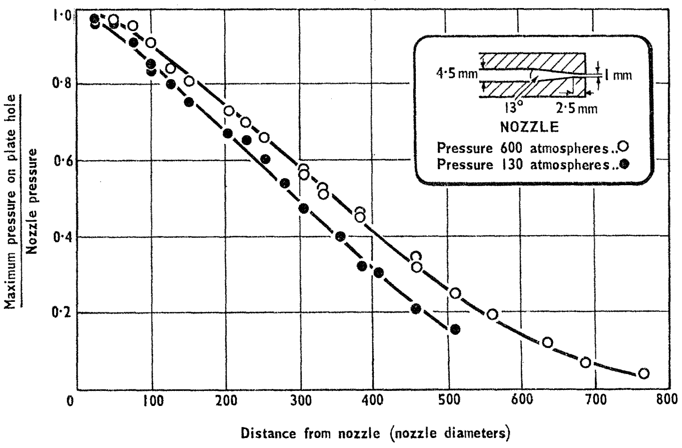


FIGURE 8. Variation of maximum pressure on plate hole with distance from nozzle, for pump pressure of 600 and 130 atmospheres.

(c) *Factors other than nozzle shape*

A change in the driving pressure changes the Reynolds, Weber and Mach numbers, and figure 8 shows measurements made with the nozzle shape suggested by Nikonov and Shavlovskii, for driving pressures of 130 and 600 atm. (Reynolds numbers $1{\cdot}79 \times 10^5$ and $3{\cdot}85 \times 10^5$, Weber numbers $3{\cdot}49 \times 10^8$ and $1{\cdot}6 \times 10^9$, Mach numbers 0·5, 1 (air) and 0·1, 0·2 (water) respectively.) The different pressures have little effect on the relative pressure at a distance from the nozzle. Similar measurements were made for many of the nozzle shapes studied in figures 5, 6 (*a*), (*b*) and (*c*) and the results shown in figure 8 were typical.

The Weber number can be changed, without significantly changing other parameters, by adding a detergent to the water; also the viscosity can be changed by adding a small amount of sodium carboxymethyl cellulose.

Figure 9 shows the effect of these additives on the pressure on the jet axis for a driving pressure of 600 atm. The additives all produce an improved performance; the sodium carboxymethyl cellulose does so over all distances from the nozzle, and the detergent for distances greater than about 250 nozzle diameters.

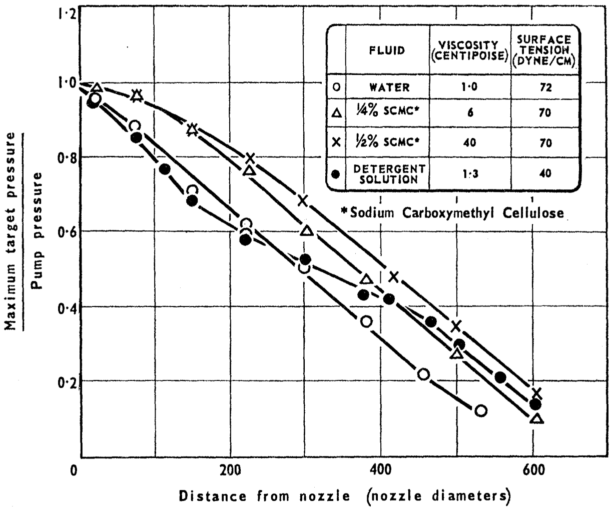


FIGURE 9. Effect of changes in viscosity and surface tension.

The solution of sodium carboxymethyl cellulose forms a non-Newtonian, viscoelastic fluid and the viscosities and surface tensions quoted are those given by the Redwood and Jaeger methods respectively. The improvement in performance produced by adding sodium carboxymethyl cellulose may be due to the non-Newtonian behaviour of the fluid.

It is hoped to extend the studies of nozzle shapes and fluid additives to jet velocities of up to 1000 m/s, when compressibility effects may become important.

6. PRESSURE DISTRIBUTION ON A SURFACE AT RIGHT ANGLES TO THE JET

The simplest case of a jet used for cutting is that of a steady state jet impinging at right angles on to a flat plate. The fluid will spread out radially over the plate from the centre of impact. The jet will exert a force on the plate, which will be associated with a static pressure in excess of the ambient pressure.

At the centre the pressure will be equal to the stagnation pressure of the jet. The pressure will decrease with distance from the centre until eventually the excess pressure is virtually nil. The following theoretical calculation of the pressure is due to P. L. Bakke (private communication).

From momentum considerations the net force on the plate in the direction of the jet will be equal to

$$\pi a^2 \rho u^2, \tag{6·1}$$

where a is the jet radius, ρ is the density of the jet fluid, and u is the mean jet velocity.

This force will be equal to

$$\int_0^R (p-p_0)\,2\pi r\,\mathrm{d}r, \tag{6·2}$$

where p is the pressure on the plate, p_0 is the ambient pressure, r is the radial distance from the centre, and R is the value of r where $p \simeq p_0$.

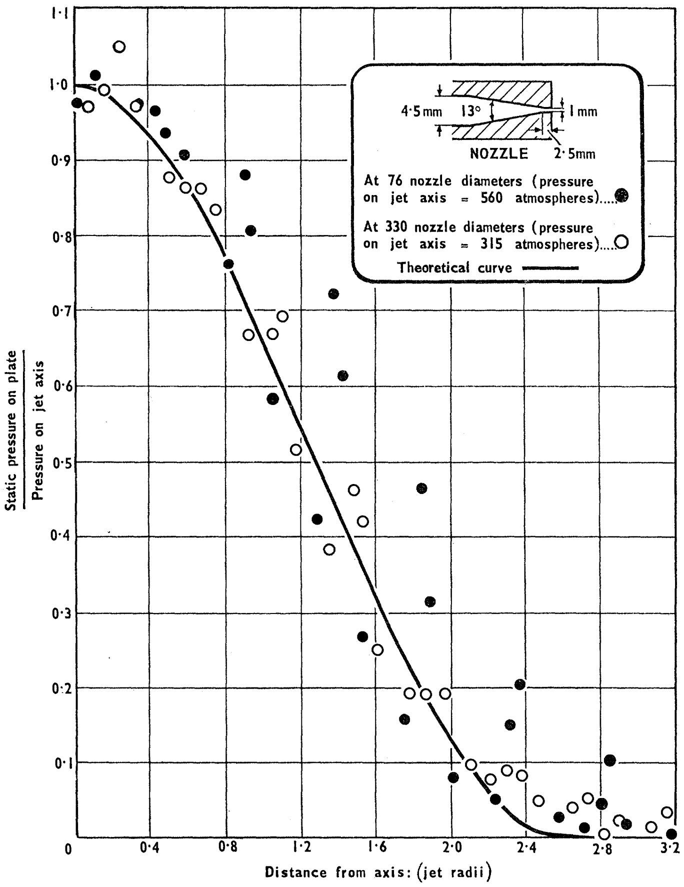
Physical intuition suggests that the pressure distribution will be of the form

$$\frac{p-p_0}{\frac{1}{2}\rho u^2} = f\left(\frac{r}{R}\right); \tag{6·3}$$

For brevity, r/R will be denoted by r' and the function $f(r/R)$ by p'. (6·4)

From (6·1), (6·2), (6·3) and (6·4) we get

$$\left(\frac{a}{R}\right)^2 = \int_0^1 p'r' \,\mathrm{d}r'. \tag{6·5}$$



Pressure behind nozzle = 600 atmospheres

FIGURE 10. Static pressure distribution on a plate at right angles to the jet.

To evaluate the integral we substitute for p' in the integral a polynomial which satisfies $p' = 1$ and $\mathrm{d}p'/\mathrm{d}r' = 0$ for $r' = 0$, and $p' = 0$ and $\mathrm{d}p'/\mathrm{d}r' = 0$ for $r' = 1$.

The polynomial is

$$p' = 1-3(r')^2+2(r')^3. \tag{6·6}$$

With (6·6) we get from (6·5):

$$R/a \simeq 2·6. \tag{6·7}$$

From this we see that the region where the pressure is significantly greater than the ambient pressure is confined to about 2·6 jet radii, and the distribution of pressure in that region is given by equation (6·6) (see also figure 10).

Figure 10 shows typical experimental results compared with the theoretical curve with a in equation (6·7) chosen to give the best agreement. Similar results have been obtained with nozzles b and e (figure 5) for nozzle pressures of 130 and 600 atm at several distances from the nozzle. Agreement between experiment and theory is similar to that shown in figure 10 and the pressure falls to a negligibly small value at approximately the predicted distance from the axis. The theoretical curve was used by Seager & Simpson (1966) to calculate the stress distribution behind an infinite plane surface on which a water jet impinges.

G. Artingstall (private communication) has calculated the shear stress on the plate for $r/a > 2{\cdot}6$. He assumed the shear stress is governed mainly by the velocity profile near the wall and that the velocity at the free surface of the jet at $r/a = 2{\cdot}6$ is equal to the mean free jet velocity, i.e. that the jet turned through a right angle without a significant change in velocity. Using the usual velocity profile for turbulent boundary layer flow he showed that the shearing stress is too small to have any important influence on the stress distribution within the target.

7. Rock penetration

Pressures up to 5000 atm were produced by the hydraulic intensifier described in §2. Figure 11, plate 60, shows a sequence of six schlieren photographs taken during the discharge of the intensifier through a 1 mm diameter nozzle. Since the water is issuing from the nozzle faster than the speed of sound in air (Mach number about $3\frac{1}{2}$) shockwaves are formed ahead of the flow and Mach lines can be seen surrounding the jet in the flow behind the head of the jet; these Mach lines correspond to an air velocity of about Mach 2.

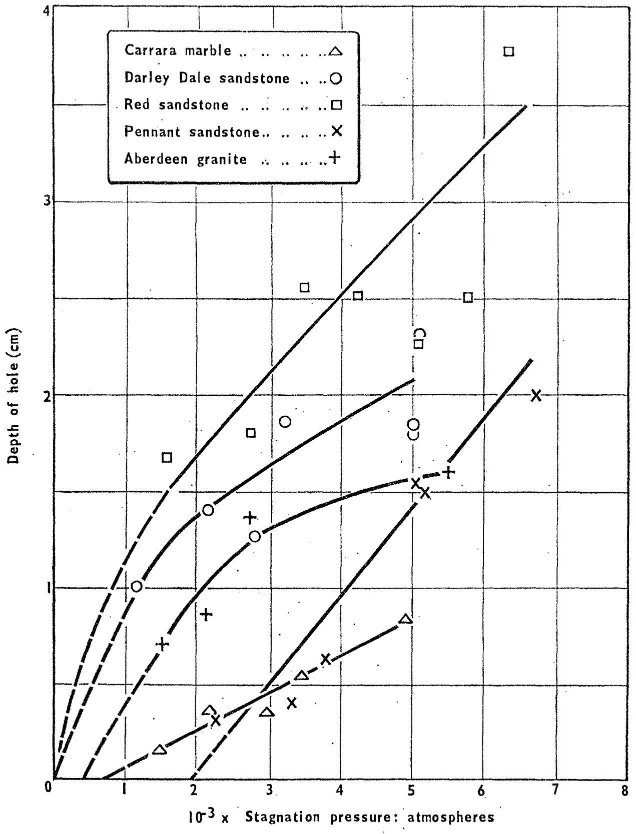
Some preliminary studies were made of the damage to 30 cm cubes of rock, produced by the water jet from the intensifier. The three types of damage observed are illustrated in figure 12, plate 60 for Darley Dale Sandstone. In each case the rock was placed $2\frac{1}{2}$ cm from the nozzle so that the jet impinged at right angles to the rock surface at the centre of a face, and 10 cm^3 of water were ejected at a velocity of about 1000 m/s. Figure 12 (*a*) shows the most commonly observed damage, a hole of diameter 5 mm and depth 2 cm. On rare occasions, large cracks were produced (figure 12 (*b*)) or a large shallow crater was formed (figure 12 (*c*)) at the same time as the cylindrical hole.

Figure 13 shows measurements of the variation of hole depth with pressure for five rocks: Red Sandstone, Darley Dale Sandstone, Aberdeen Granite, Carrara Marble and Pennant Sandstone (compressive strengths approximately 330 and 1100 atm respectively for Red Sandstone and Carrara Marble (Farmer & Attewell 1963), 670 and 1460 atm for Darley Dale and Pennant Sandstones (Price 1958) and 1370 atm for Aberdeen Granite (N.P.L. 1929)).

In all cases the hole diameter was 5 ± 1 mm. The results for the three harder rocks suggest that there is a critical pressure below which significant penetration does not take place which is as high as 2000 atm for Pennant Sandstone.

Figure 14 shows how the hole depth increases with repeated shots of the intensifier at the same point on the block for Darley Dale and Pennant Sandstones. The hole diameter did not change significantly with increasing depth.

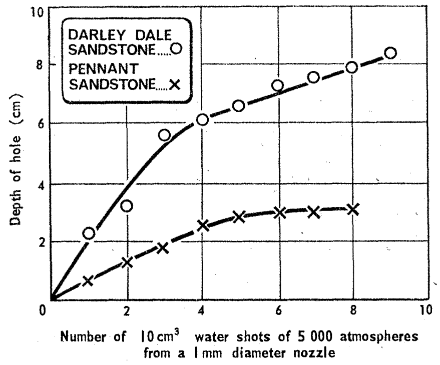
Figure 14 suggests that penetration ceases after a certain depth of hole for Pennant Sandstone and in order to see if this was associated with a pressure at the hole bottom less than the 'critical' pressure suggested by figure 13 for significant penetration, 'holes' were constructed of diameter 5 mm and depths from 0·5 to 15·2 cm in brass blocks. A small hole (diameter 0·3 mm) connected the centre of the bottom of the simulated 'hole' to a pressure transducer. Unfortunately suitable apparatus was not available for making the pressure measurements with the intensifier and the water pump was used at pressures of 130 and 600 atm. Figure 15 shows the experimental results for pressure measurements made on the hole axis. The flow is such that the pressure falls rapidly with increasing hole depth and reaches a constant value of about one-tenth the pump pressure for hole depths greater than 10 hole diameters for both values of the driving pressure. If we assume that these results can be extrapolated to a driving pressure of 5000 atm then the decrease in successive penetrations with successive shots shown in figure 14 for Pennant, but not for Darley Dale Sandstone, is explained by a fall off of pressure to below the 'critical' pressure at the bottom of the hole.



30 cm cube of rock, 2·5 cm from nozzle, single shots of 10 cm³

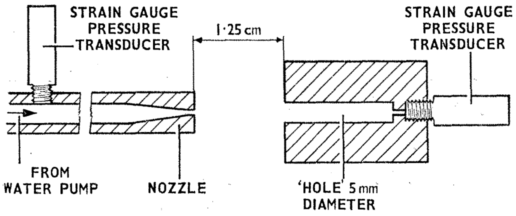
FIGURE 13. Variation of hole depth with water pressure for different rocks.

It is interesting to speculate on the practical application of water jets for rock cutting. We imagine a continuously operating water jet of 5000 atm traversing across a surface at a rate based on the hole width produced by a single shot of the intensifier, i.e. 0·5 cm in 10 ms or 50 cm/s; and we assume that the jet cuts strips with square cross section from a plane rock face by making successive horizontal traverses with the jet directed normal to the face, alternated with horizontal traverses at the back of the cuts with the jet directed vertically, i.e. parallel to the face. If we further assume that the square cross section of the strips are of side given by the penetration shown in figure 15, then for Red Sandstone a cutting rate of 40 Kg/min will be obtained. This is not as high a rate as would be obtained by mechanical methods for a similar power expenditure (500 horse power at the nozzle outlet). However, Palowitch & Malenka (1964) reported that, with coal cutting by water jets, the overall cutting rate rises rapidly with traversing speed; if this effect is found for rocks then much greater cutting rates should be possible. It is proposed to carry out further work with an intensifier giving up to 2 l. of water at 5000 atm, in order to study traversing effects.



Distance from nozzle to centre of one face of a 30 cm cube block = 2·5 cm

FIGURE 14. Rock penetration by water jets.



Experimental arrangement

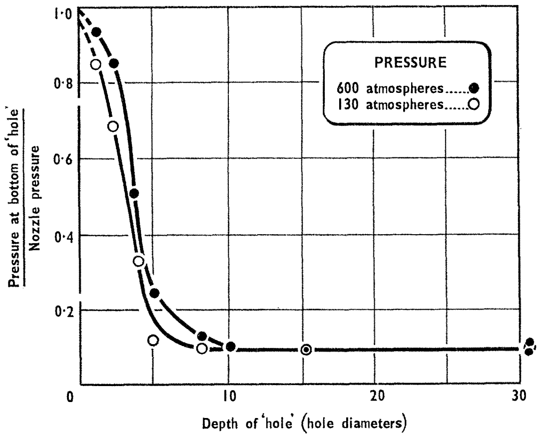


FIGURE 15. Pressure at the bottom of a simulated hole.

We thank Mr P. Jones and Mr M. Fowler for assistance with the experiments, Mr G. Winder and Mr R. Baines for the design of the hydraulic intensifier and Dr G. Artingstall and Mr P. Bakke for much helpful advice and criticism.

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REFERENCES (Leach & Walker)

Borecki, M., Duczmal, M., Perek, J., Raczynski, A. & Mamczarczyk, T. 1963 *Ann. Rep. Central Mining Institute* (*Glowny Instytut Gornictwa*). Katowice (Poland).
Brunton, J. H. 1961 *A.S.T.M. Tech. Publ.* **307**, 83.
Bryan, E. L. 1963 *Forest Prod. J.* **13** (8), 305.
Castleman, R. A. 1931 *J. Res. Nat. Bur. Stand.* **6** (3), 369.
Farmer, I. W. & Attewell, P. B. 1963 *Mine Quarry Engng*, **29**, 524.
Giffen, E. & Muraszew, A. 1953 *The atomisation of liquid fuels*. London: Chapman and Hall.
Jenkins, D. C. & Booker, J. D. 1960 *Aerodynamic capture of particles*, p. 97. Oxford: Pergamon Press.
Krivchenko, A. A. & Baka, A. V. 1962 *Ugol' Ukr.* **6** (8), 17.
N.P.L. 1929 *Results of tests on stone having varied petrological characteristics* (Nat. Phys. Lab. Rep.).
Nikonov, G. P. & Shavlovskii, S. S. 1961 Gornye Mashiny i Avtomatika, *Nauchno-Tekh. Sb.* **1** (18), 5.
Palowitch, E. R. & Malenka, W. T. 1964 *Min. Congr. J.* **50**, 66.
Price, N. J. 1958 *Mechanical properties of non-metallic brittle materials*. Butterworth Scientific Publications.
Rouse, H., Asce, M., Howe, J. W. & Metzler, D. E. 1952 *Trans. Amer. Soc. Civil Engrs*, **117**, 1147.
Seager, J. S. & Simpson, S. P. 1966 To be published.
Steel and coal 1962 **185** (4913), 530.
Voitsekhovskii, B. V., Nikolaev, V. P., Ludin, V. M., Maier, O. F. & Chermenskii, G. P. 1963 *Izv. sib. Otdel. Akad. Nauk SSSR, Ser. tekhn. Nauk*, **1** (2), 7.

XXVII. Discussion

A. V. Smith

With reference to Dr Brunton's paper 'High speed liquid impact', there is photographic evidence of a flash of light occurring at impact of a high speed liquid jet on a solid surface, apparently caused by adiabatic compression of the air between the impacting surfaces.

Would not the possibility of such a phenomenon occurring in mine operation not entirely eliminate the hazard of explosion?

S. J. Leach and G. L. Walker

It is likely that for adiabatic compression of air to occur as a result of the impact of a water jet on a surface, the air would have to be restrained in a pocket of surface material. It is possible in these conditions for the air to attain high temperatures (about 3000 °C for a water jet of 6000 atm), but in conditions of this nature the volume of the ignition would be small and take place within the water itself, which would probably limit the effect.

I. W. Farmer (Department of Mining, University of Sheffield)

Water jets have been used by mining engineers with some success during the past decade to cut alluvial deposits and soft rocks, such as coal, having a maximum compressive strength of 140 Kg/cm^2. Interest now centres on the cutting of harder rocks in the strength range 300 to 1000 Kg/cm^2, where the recent introduction of large scale mechanization in coalmines has revealed a potential ignition hazard.

The transition from relatively large jets at pressures below 300 atm which are sufficient to cut coal, to the higher pressures which will be required to cut harder rocks presents many difficulties. A rock with a compressive strength below 140 Kg/cm^2 represents little more than an unconsolidated aggregate or, in the case of coal, a well striated vegetable residue and the water jet action merely loosens and washes away already discrete particles. On the other hand, the primary function of jet attack on a harder rock must be to fracture the rock, partly by compression and shear, partly by the induction of reflected tensile stresses in the impact zone, and partly by hydraulic wedging action. It is important not to confuse these different actions and it is doubtful whether any experience obtained from jet penetration of soft materials can usefully be applied to hard rocks.

Water jet impact tests conducted on a series of rocks at pressures up to 1700 atm (Farmer & Attewell 1965) have shown that most rocks are relatively easily penetrated by water jets to form a cylindrical or cylindri-conical crater varying in depth according to the quantity of water present, and the velocity and diameter of the jet.

Results based on a fixed volume of water (92 cm^3) ejected from a compressed air operated intensifier may be summarized in the form:

$$S = kd_n\,(v_0/c)^{\frac{2}{3}},$$

where S is the depth of penetration, d_n the nozzle diameter, v_0 the impact velocity, c the elastic wave velocity in the rock, and k a constant. Obviously the efficiency obtained in drilling a crater at right angles to a rock surface is low and although it may be increased by traversed or oblique impact, water jets will be economically feasible only when large scale fracture can be induced. This is only possible at pressures below 1700 atm in small rock specimens. However, tests at 4000 atm with a larger intensifier (Farmer 1965) have demonstrated that at this pressure it is possible to fracture quite large blocks of concrete and soft sandstone (having a compressive strength of 260 and 540 Kg/cm^2 respectively) with an equivalent amount of energy to that used in conventional rock fracture methods.

The difficulties inherent in obtaining a continuous water jet flow of reasonable diameter at very high pressures suggest that it may be impracticable to think in terms of a continuous jet to fracture rocks, but rather to consider the desirability of a series of short intermittent jets, particularly since it seems likely that the damage potential of a jet at impact is greater than in continuous erosion from a single stream.

References (Farmer)

Farmer, I. W. & Attewell, P. B. 1965 Rock penetration by high velocity water jets. *Int. J. Rock Mech. Min. Sci.* **2** (2), 135–153.

Farmer, I. W. 1965 Penetration of rocks by water jet impact. Ph.D. Thesis, University of Sheffield.

S. J. Leach and G. L. Walker

One of the reasons why the impact of water jets or drops on a surface produces greater damage than a steady jet is the water hammer pressure on impact. This is very important at low velocities, but becomes much less so when the water is moving at a velocity close to the velocity of sound in water. Furthermore, the experiments described in §§3 and 5 (*b*) of our paper suggest that a steady water jet breaks up giving a rapid succession of 'water hammer' impulses on the target in nominally steady jets. For these reasons jets which are made deliberately intermittent may not prove to be useful at high pressures.

Traversing a rock surface by the water jet may increase the efficiency of rock cutting, as suggested in §7, where pieces of rock would break off eventually without having to be reduced to fragments by the jet.

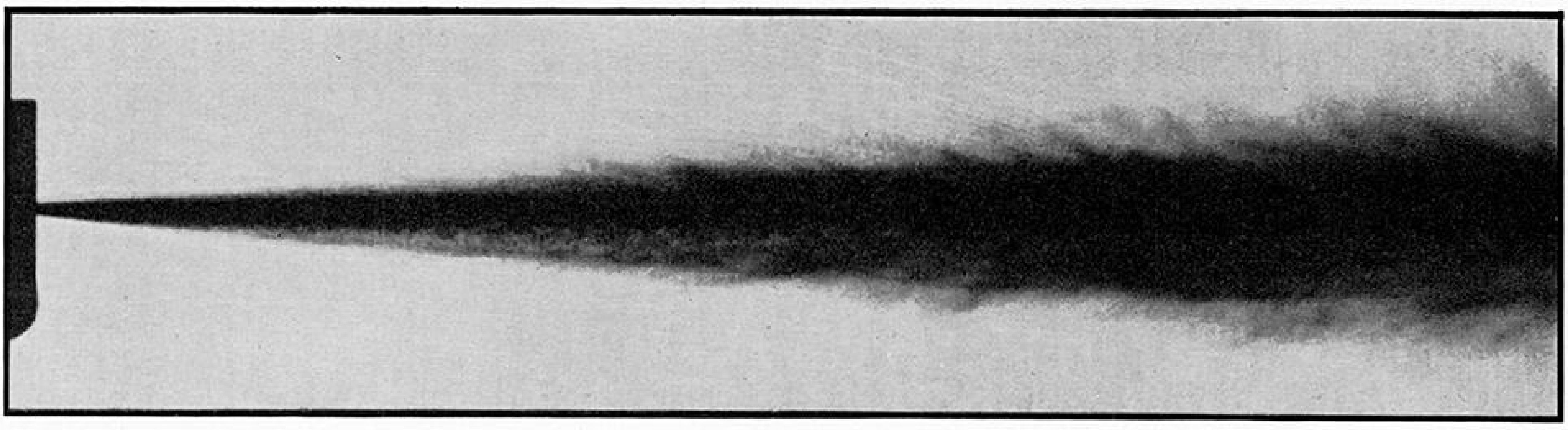
The study of the effect of rock cutting by water jets under laboratory conditions unless very large rock specimens are available, may be affected by edge effects. In a mine the rock being cut will be constrained by lateral stresses. In the experiments that we propose to undertake described at the end of §7, we intend to constrain and preload our target material with stresses of the order of those found in mines.

Sir Geoffrey Taylor

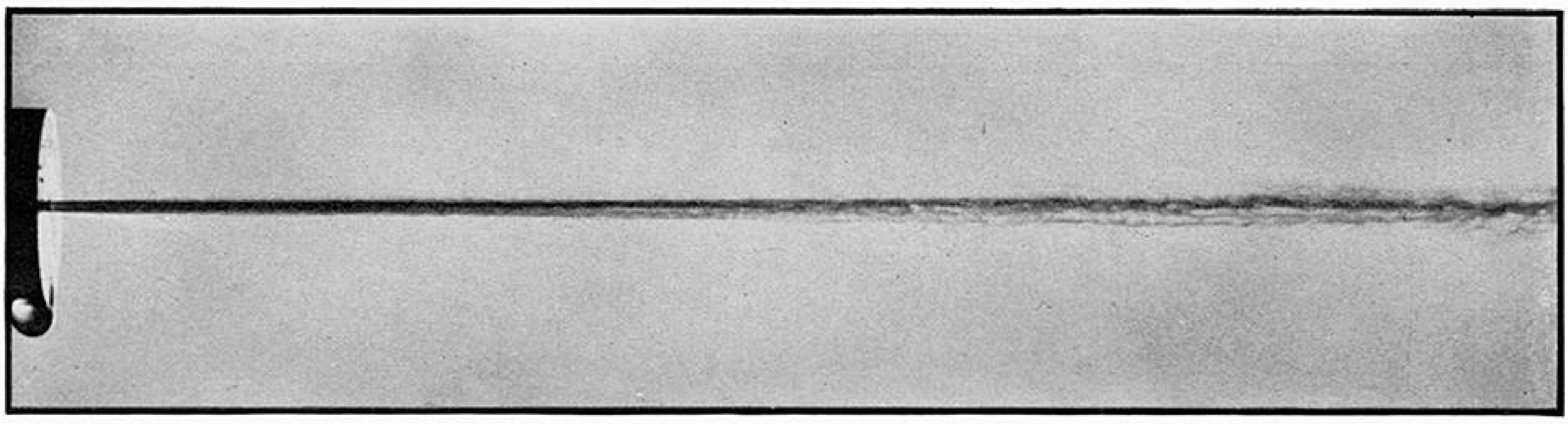
Has Dr Leach tried a sharp edged orifice instead of converging orifices? In the very small jets I used in the experiments described earlier, sharp edged jets were better than converging jets, but these were only jets under a head of a few metres of water.

S. J. Leach and G. L. Walker

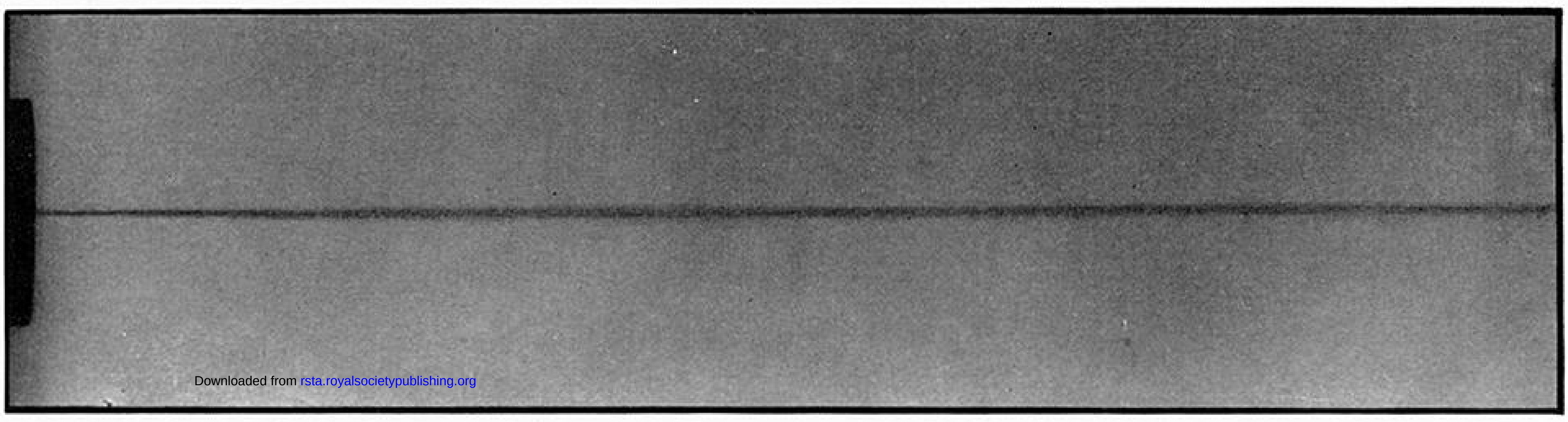
We have carried out experiments using a pipe of diameter 19 mm sealed by a plate with an axial hole 1 mm diameter, 1 mm long, with sharp edges. At the experimental pressures (up to 600 atm) nozzles of this form were found to be significantly inferior to the nozzles recommended in §5 (*b*) for minimum dispersion.



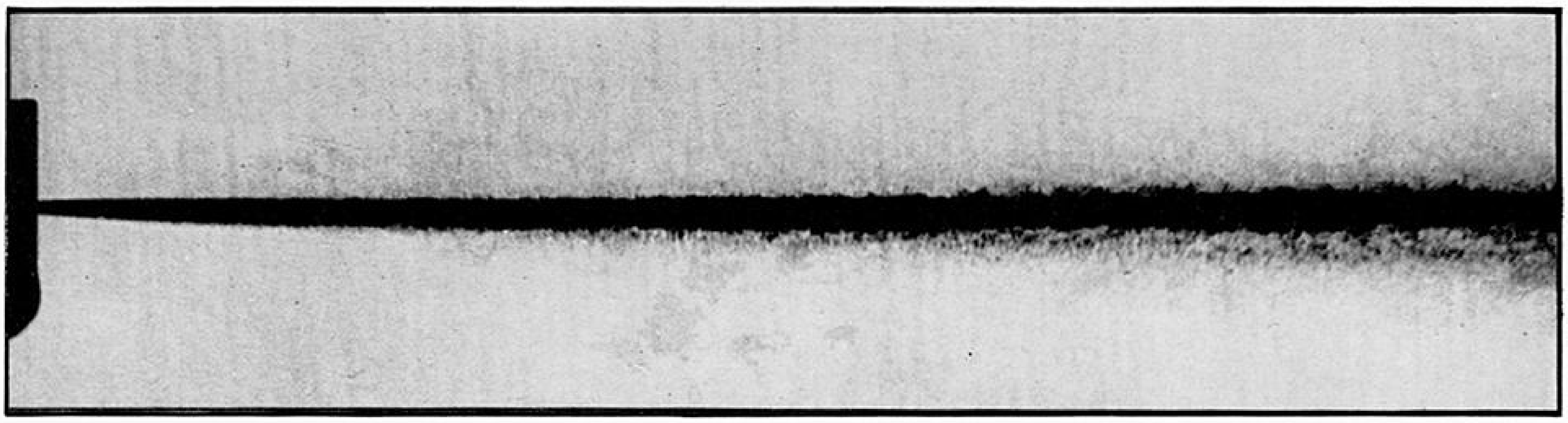
(*a*) Spark source; parallel transmitted light ($\frac{1}{2}$ μs exposure); pressure 600 atm.



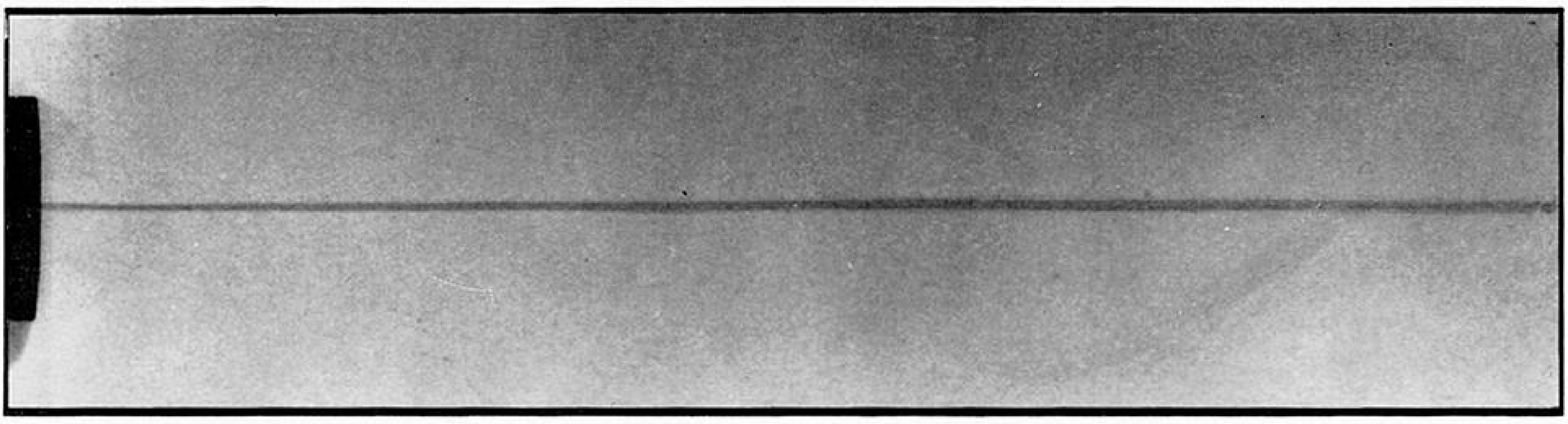
(*b*) Flash-tube source; diffuse transmitted light (2 μs exposure); pressure 600 atm.



(*c*) X-ray source (5 min exposure); pressure 600 atm.



(*d*) Spark source; parallel transmitted light ($\frac{1}{2}$ μs exposure); pressure 130 atm.



(*e*) X-ray source (5 min exposure); pressure 130 atm.

FIGURE 4. Typical photographs.

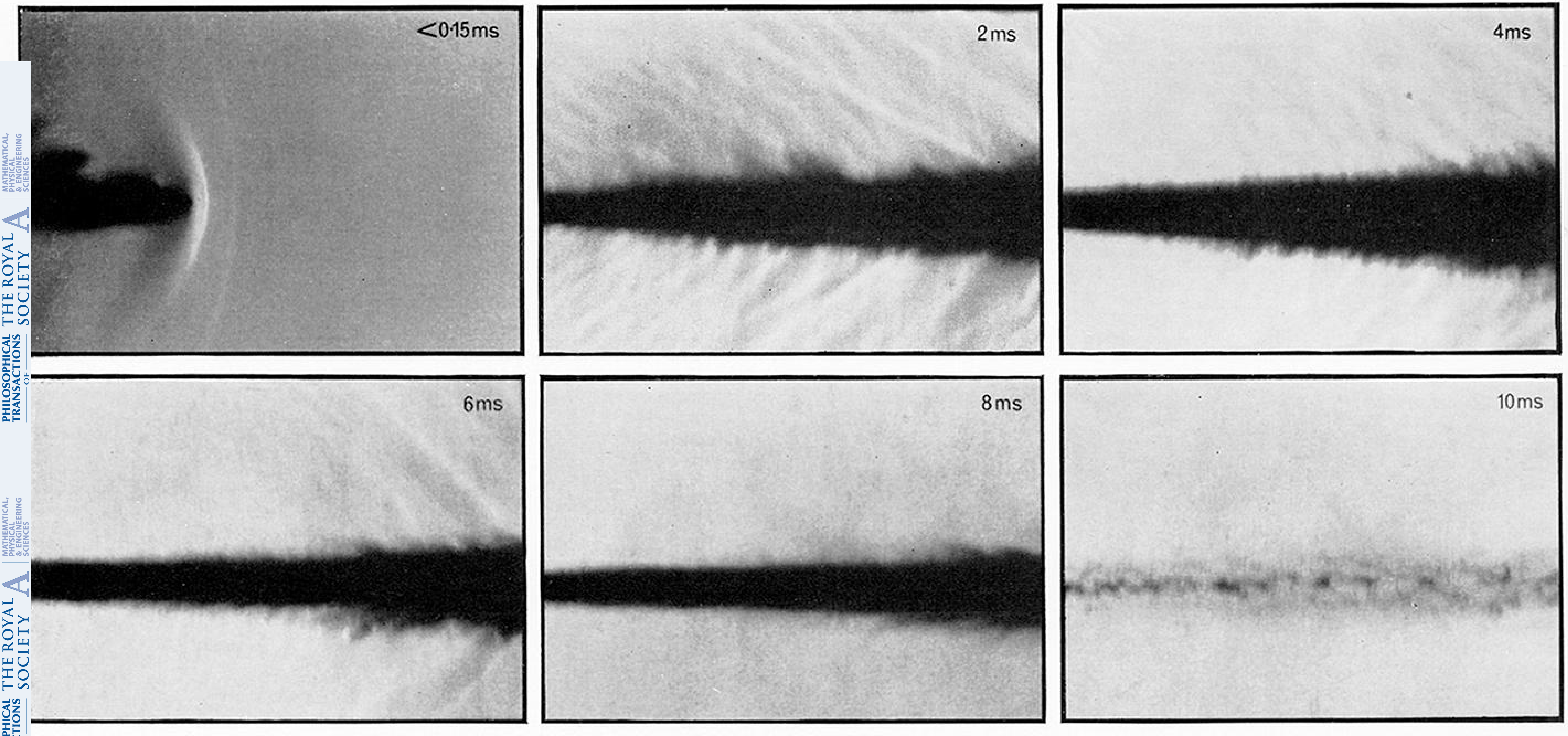


FIGURE 11. A sequence of schlieren photographs of the flow from the intensifier during a single shot. The times after the start of flow are indicated on the photographs. Driving pressure, about 5000 atm; velocity, 1000 m/s.

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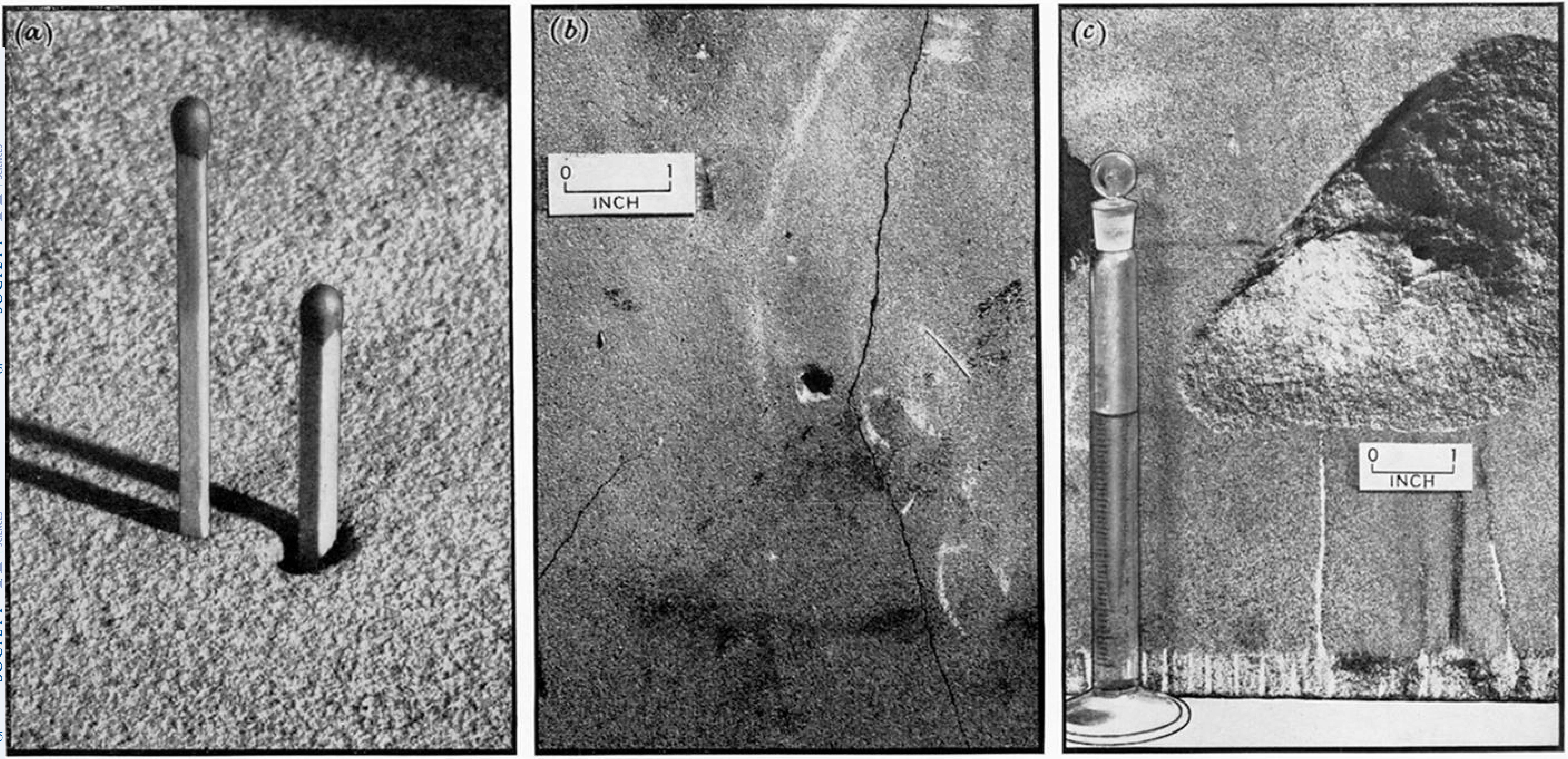

FIGURE 12. Typical examples of damage to Darley Dale Sandstone produced by 10 cm^3 of water at a velocity of about 1000 m/s.