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THE PENETRATION OF ROCK BY HIGH-SPEED WATER JETS

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Abstract - The effect of pressure, stand-off distance and time on the penetration of sandstones by a 0.84 mm. jet of water was investigated. Pressures ranged up to 9000 lb/in ^{2} (62 MN/M^2), stand-off distances to 2 in. (5.08 cm) and time from 0.5 to 30 sec. The effect of using a friction reducing agent was determined. The advantages of allowing the spent jet to escape and not interfere with penetration are demonstrated by both interrupting the jet and by rotating the target rock. Very short time intervals of jet operation were also investigated, and rapid penetration rates obtained. The importance of free access of the jet to the target is emphasized by an experiment with an angled jet and rotating target operating as a type of drill.

1. INTRODUCTION

WATER has been employed in the extraction of minerals for many centuries, but until the present era its use has been confined to the mineral dressing applications and the use of low-pressure jets to flush out minerals from country rock. With increasing strength and reliability of equipment, and the higher pressures to which water can now be raised, it is possible to consider the use of high-speed water jets for the cutting of harder rocks and minerals, either as a method of complete excavation or of drilling rock.

This paper is a report of investigations carried out to define basic parameters of rock penetration by high-speed water jets, and to consider various methods of improving the penetrating power of such jets. Jet velocities of the order of 300 m/s for a 0.84 mm jet have been used to penetrate a variety of rocks, mainly Carboniferous sandstones, with some Oolitic limestones.

2. APPARATUS

The waterjet used for the experiments- was generated by a Huwood 'Uraca' three piston positive displacement pump, which drew water containing a small percentage of soluble oil from a 100 1. reservoir, and then delivered it to the 0.84 mm nozzle. The water pressure of the delivery was controlled by a bleed-off valve which returned surplus delivery to the reservoir (Fig. 1). The pressure in the pipe leading to the delivery nozzle was measured by a pressure gauge. Some preliminary experiments were performed to decide the type of nozzle to be used, and the type recommended by the S.M.R.E. [1] was found to be the most effective at the higher pressures used, of about 9000 lb/in ^{2} (62 MN/M^2 , 613 atm). The nozzle shape (Fig. 2) consisted of an 11^0 straight convergent section leading to a 4 mm parallel section of 0.84 mm diameter. This was the largest diameter nozzle which could be used at the higher pressures, as the output from the pump was limited to 13 l/m. The rock specimens used were 6 x 4 x 4 in. (approx. 15 x 10 x 10 cm) and were held in a clamp so arranged that the specimen could be raised or lowered by a hydraulic

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cylinder, and simultaneously traversed or rotated during the time of jet operation by means of two worm-gear systems.

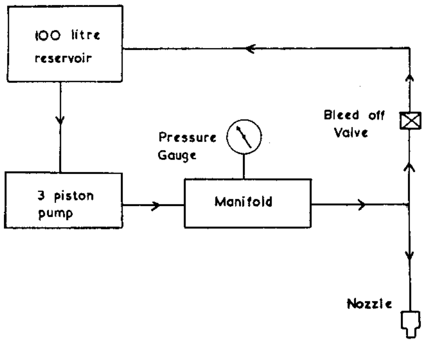

FIG. 1. Schematic diagram of apparatus.

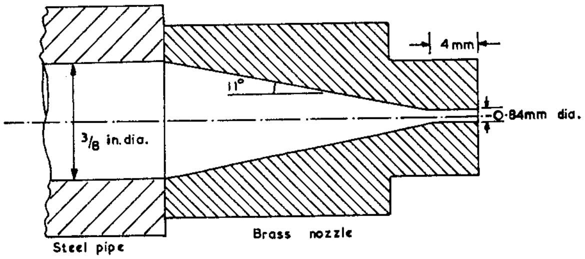

FIG. 2. Jet nozzle (not to scale).

3. EFFECT OF PRESSURE, STAND-OFF DISTANCE AND TIME

The first experiment was designed to investigate the effect of the three parameters which were considered to be the most important in determining the penetration of the jet. These were the supply pressure, the distance of the nozzle from the working surface-the “stand-off distance”, and the time for which the jet operates. A factorial experiment was performed with 6 levels of pressure taken, from 4000 to 9000 lb/in ^{2} (27.5 - 62 MN/M^2), five levels of stand-off distance, from 0.3 to 2.0 in. (7.62 – 50.8 mm), and with ten time levels from 0.5 to 30 sec. The target rock used was a ferruginous sandstone from Liverpool, in which test sites 0.75 in. (19 mm) apart were marked by a small spot of paint, it having been established in earlier experiments that there was no interaction between sites at this proximity [2]. The results obtained from this experiment are summarized in Figs 3 - 5, where the average penetration is plotted against one of the chosen parameters. From these graphs it can be seen that within the range chosen the penetration of the jet varied directly with the pressure, and inversely with the stand-off distance. Most of the penetration was effected in the first few seconds of jet action, and this was considered to be significant. FARMER and ATTEWELL [1], and LEACH and WALKER [3] have shown that the effective pressure of the jet is very much reduced with increase in the hole depth, but the mechanism of this is not fully explained. It is suggested, and later work seems to confirm this, that the main cause of the very rapid reduction in penetration rate is the impacting jet striking the water leaving the hole, and this was considered to be the cause of the very rapid reduction in penetration rate after the first few seconds, although the natural break-up of the jet with increase in distance from the nozzle must also contribute to the loss in penetrating power. The direct reading of depth of penetration as the criterion of performance was adopted after preliminary work had indicated that “volume of rock removed” measurements were not reliable in a porous rock.

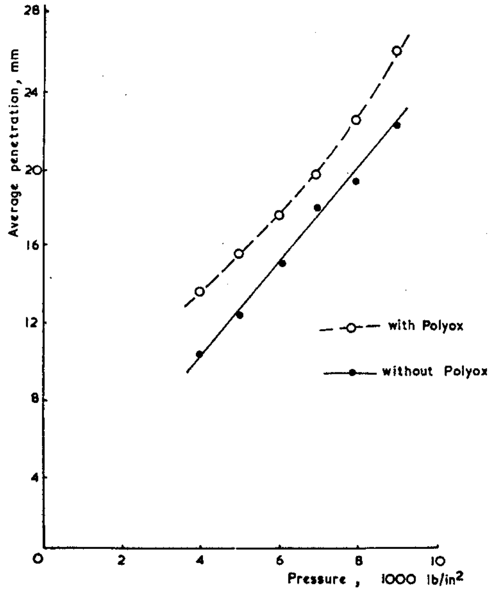

FIG. 3. Average penetration vs. pressure for continuous jet and static target.

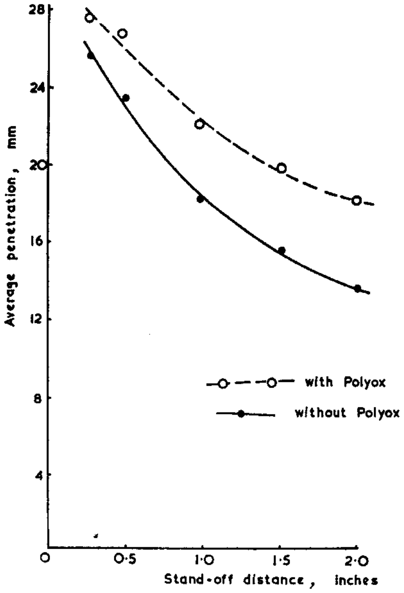

FIG. 4. Average penetration vs. stand-off distance for continuous jet and static target.

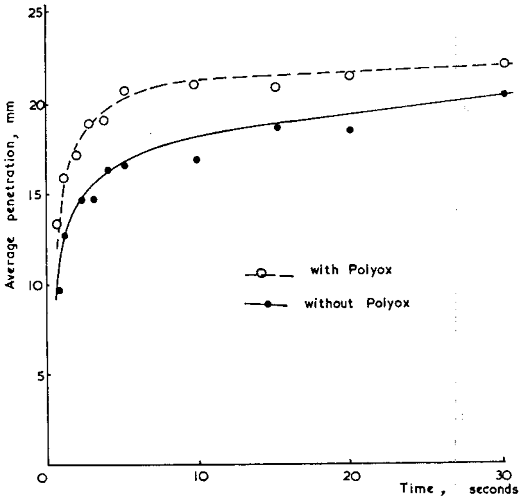

FIG. 5. Average penetration vs. time for continuous jet and static target.

4. EFFECT OF POLYETHYLENE OXIDE

In order to try and overcome the loss in penetrating power of the jet due to its lack of cohesion at distances of 20 mm or so from the nozzle, a commercial additive, normally used as a friction reducing agent, polyethylene oxide -“Polyox” - was introduced into the water and oil mixture at a concentration of 10 g/ 100 1, or 0.01 per cent, and a mechanical mixer used to distribute the additive in the reservoir. The effect of this additive was ascertained by repeating the previous factorial experiment on the same sandstone blocks, with the same levels of the parameters. The results obtained from this experiment are shown in the broken lines added to Figs 3 - 5. An additional check on the effects of the additive was made by flow measurements with and without the Polyox, and these results are shown in Fig. 6, which indicates that an increase in flow, and hence jet velocity, is achieved by the use of the additive. The effect of the Polyox is to make the jet more cohesive, as shown by Fig. 4, where increased penetrations are obtained, particularly at the greater stand-off distances. Increased penetration also occurred for the same jet pressures, as shown in Fig. 3, due to both greater jet velocities and increased jet cohesion. The penetration-time graph (Fig. 5) is again the most significant, as this indicates that almost all the penetration occurs in the first 5 sec when Polyox is used, and that a second stage of slow penetration which occurs with a water jet is not present. The graph also shows that the first second of jet action accounts for about 75 per cent of the total penetration, and this suggested that means of repeating this high-speed performance of the first second, or fraction of a second, would lead to enhanced performance of the jet. Two methods of achieving this were considered, one of frequently interrupting the jet, and one of traversing the jet.

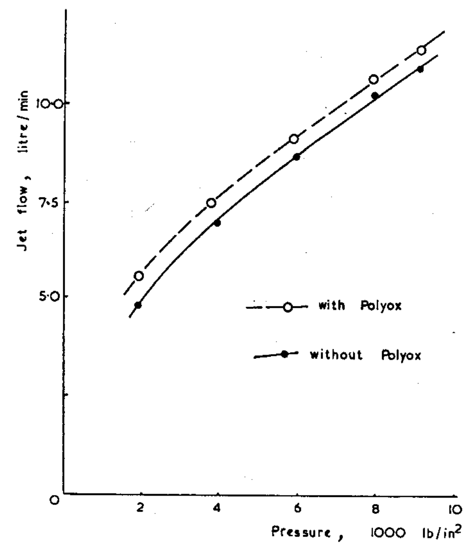

FIG. 6. Jet flow vs. pressure with and without Polyox.

5. EFFECT OF JET INTERRUPTION

Preliminary experiments had indicated that when a continuous jet of water is interrupted to produce a succession of short lengths of moving liquid, there is an increase in the penetration.

TABLE 1. PENETRATION IN VARIOUS ROCKS, WHERE THE JET IS STRIKING THE ROCK SURFACE FOR THE SAME TOTAL TIME

[i.e. the interrupted jet is used over a greater time interval to compensate for the interruption time]

Total jet impact time	30 sec
Jet pressure	6000 lb/in^2 (41 MN/m^2)
Stand-off distance	25 mm.

	Penetration (mm)					
Rock	A	B	C	D	E	F
Uninterrupted jet	2.0	4.5	6.0	8.0	9.0	20.0
Interrupted jet	8.0	25.0	24.0	28.0	36.0	54.0

To find the relationship between rate of interruption of the jet and penetration, a factorial experiment was carried out using Farnley sandstone as the target rock, this being a sandstone of small grain size and of similar texture to the stone used in the previous tests.

The interruption of the jet was obtained by a mechanically rotated disk placed between the jet and target rock, three regular slots of approximate length 5 cm were cut in the disk (Fig. 7) and the flexible shaft attached to the disk was driven by an infinitely variable speed electric motor. Polyox was again added to the water supply.

Five levels of three variables were used to construct a 125-component experiment. The variables were jet pressure from 5000 to 9000 lb/in^2 (34 - 5 to 62 MN/m^2), times from 1 to 5 sec, and interruptor speeds from 2000 to 4000 rev/min. The results of the experiment are shown in Figs 8 - 10. From these graphs it can be seen that as in the previous experiments the penetration varies directly with the supply pressure. However, the use of the interruptor affects the “second stage” of cutting when compared to the effects of a steady jet (Figs 5 and 10). In the first second or so the penetration is very rapid, and in the second stage penetration continues at a reduced steady rate. Over the range of interrupter speeds available, it was found that there was only a slight increase in penetration rate as the rate of interruption was increased.

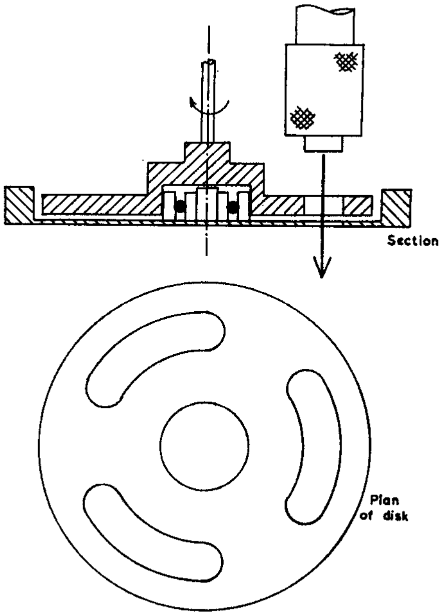

FIG. 7. Interruptor (not to scale).

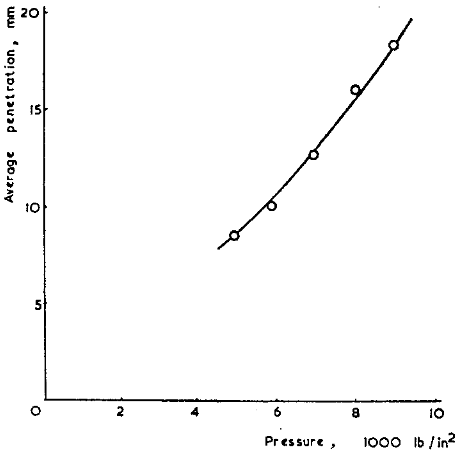

FIG. 8. Average penetration vs. pressure for interrupted jet and static target.

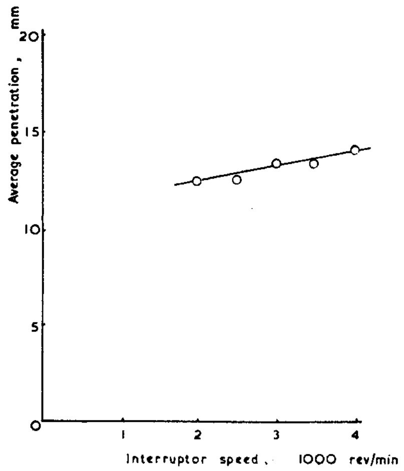

FIG. 9. Average penetration vs. interruptor speed for interrupted jet and static target.

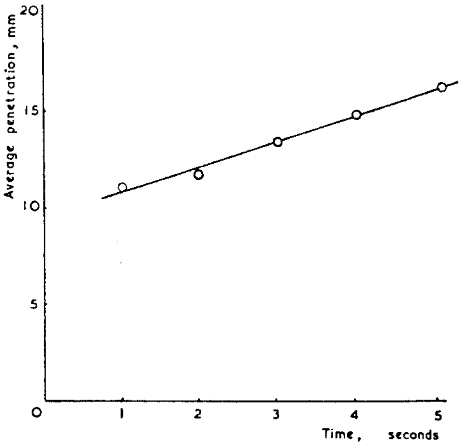

FIG. 10. Average penetration vs. time for interrupted jet and static target.

6. ROTATION OF ROCK TARGET

As it had been found that linear traversing of the target rock was difficult to control, as an alternative the rock was rotated with the jet off-centre, so that an annular slot was cut. This allowed reworking of the cut to occur if long time intervals were employed, and ensured that the jet was in effect continuously striking a new target area. If the radius of the eccentricity is reduced to some critical value, a single hole rather than a slot is produced. This occurred with eccentricities up to approx. 8 mm, and the greatest penetrations were obtained under these conditions of maximum eccentricity to cut a single hole [3]. Figure 11 shows the average penetration achieved vs. time for Farnley sandstone, and a jet pressure of 8000 lb/ in^2 (55 MN/m^2) with Polyox added to the water. It can be seen that the jet continues to penetrate at a fast rate after the first second, and that there is no apparent sudden change in penetration rate, as with the continuous and interrupted jet on a static target. The decrease in penetration rate which occurs at depths of 30 mm or more can be attributed to the natural wasting of the jet with increased distance from the nozzle.

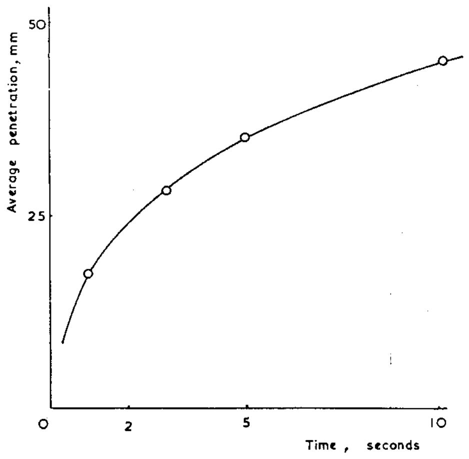

FIG. 11. Average penetration vs. time for continuous jet and rotating target.

7. SHORT PERIOD EXPOSURE

From the results of the preceding experiments it can be seen that very rapid penetration of the rock occurs during the first second, and that much of the total penetration has in fact occurred before the end of the smallest time interval used. In order to investigate this short time period an experiment was conducted to determine the penetrations achieved by the jet over small time intervals. A shutter was placed between the jet and target rock, and the time of exposure measured by an electronic timer triggered by microswitches, with subsidiary peaking circuits, mounted on the shutter (Fig. 12). Only a limited number of results have been obtained to date with this apparatus, and these are given in Fig. 13, which shows the penetration obtained using a pressure of 8000 lb/in ^{2} (55 MN/M^2) and with Polyox added to the supply. The shortest exposure time recorded was 0.0003 sec, when a small crater 1 mm deep was caused by the jet. The length of this jet would be approx. 9 cm at the most, but because of air resistance and blurring of the jet by the shutter, the actual length would probably be less than this.

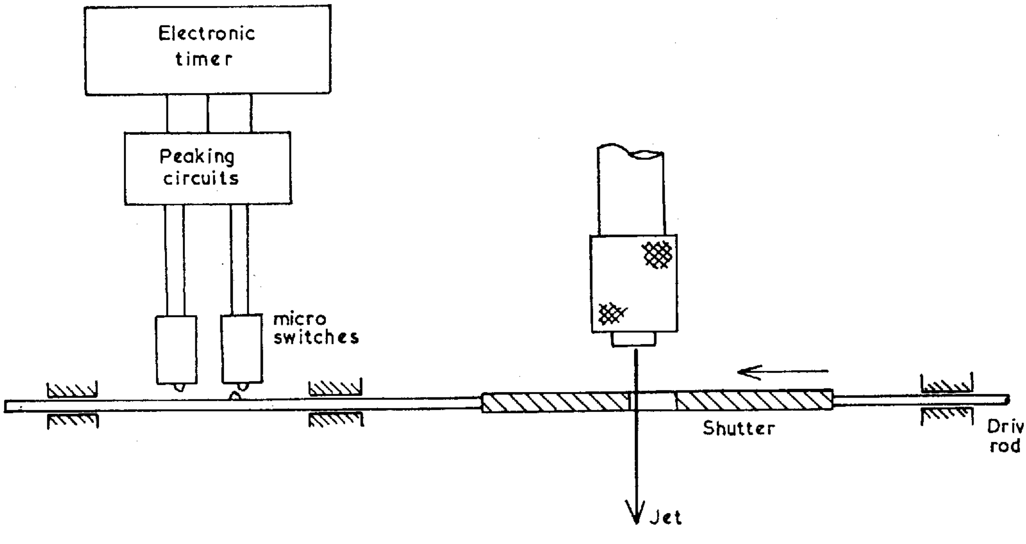

FIG. 12. Schematic diagram of jet shutter.

8. CONCLUSIONS

A considerable decrease in the effectiveness of penetration of rock by a water jet is due to the need for the jet to overcome the escaping water issuing from the impact crater as the jet continues to penetrate. The initial rate of penetration is relatively high, and is of the order of 2 m/s, this being the slope at the origin of the graph shown in Fig. 13. After 1 second or so of operation with a continuous jet and static target the rate falls to about I x 10-1 m/s, and in some cases the rate falls to virtually zero after a few seconds. Any method of operation which allows some escape of the spent jet increases the penetration rate after the first second. Interrupting the jet may increase the rate about tenfold to 1 x 10^{-3} m/s and enable penetration to continue over longer time intervals, whilst rotating the target increases the rate to approximately 5 x 10^{-3} m/s. These are very great increases as compared to the results of using a continuous jet and static target, but are small compared to the initial rate of the first millisecond. These comparative performances are shown in Fig. 14, all for a jet pressure of 8000 lb/in^2 (55 MN/m^2) and Farnley sandstone. The main conclusion to be drawn from the work is that in order to exploit the use of water jets for drilling or comminuting rocks the point of application must be moved sufficiently quickly to allow free access of the jet to the target. A spectacular indication of this was shown by inclining a 0.84 mm. jet and rotating the target rock, at the same time as the target was raised.

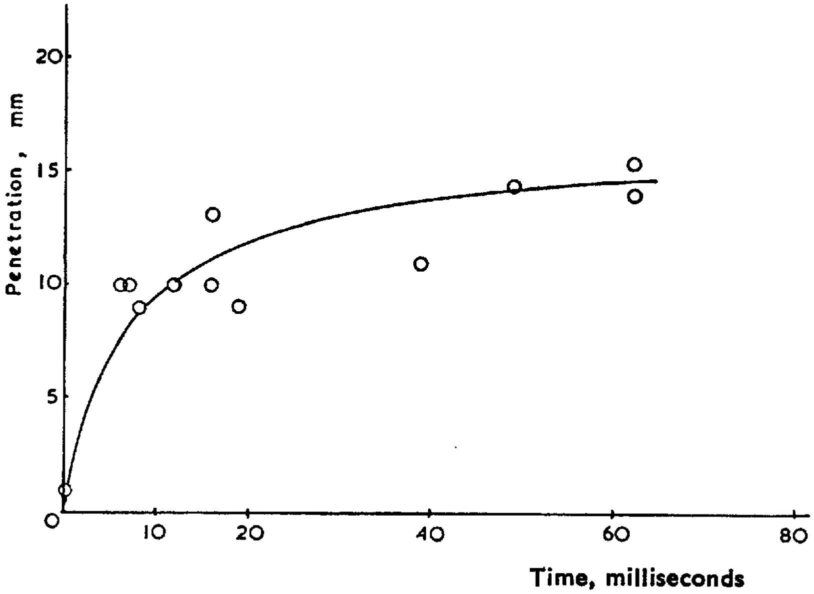

FIG. 13. Penetration vs. time for short times.

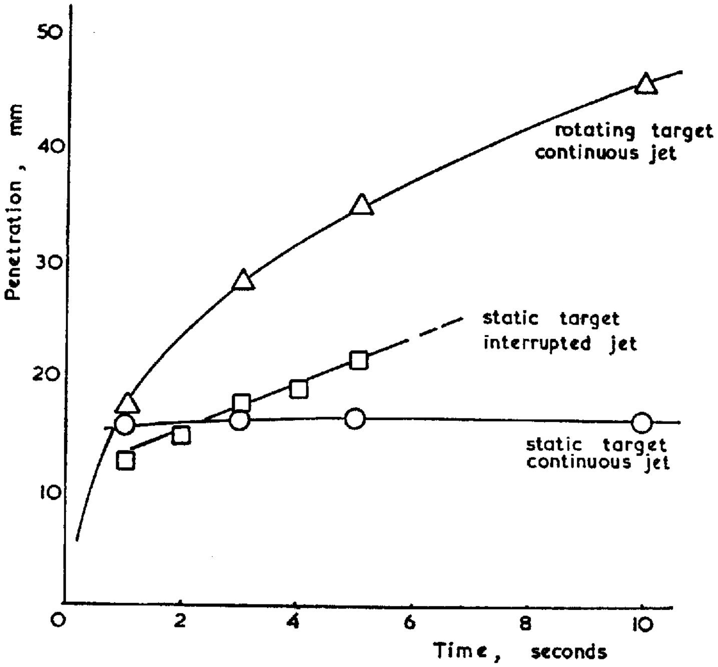

FIG. 14. Penetration vs. time for various jet uses.

The inclined jet was able to penetrate the rock sufficiently to allow the nozzle assembly to be fed into the rock, and a large hole some 5 cm. diameter and 10 cm deep was "drilled" in about 15 sec (Fig. 15). A similar method was also found to give an effective penetration in specimens of granite, which had not previously been penetrable by a jet. This was merely a preliminary experiment, and the rate was not necessarily the best which could be achieved. Further work is to be done to determine the best rotation rate and other parameters for efficient penetration of rock by this method.

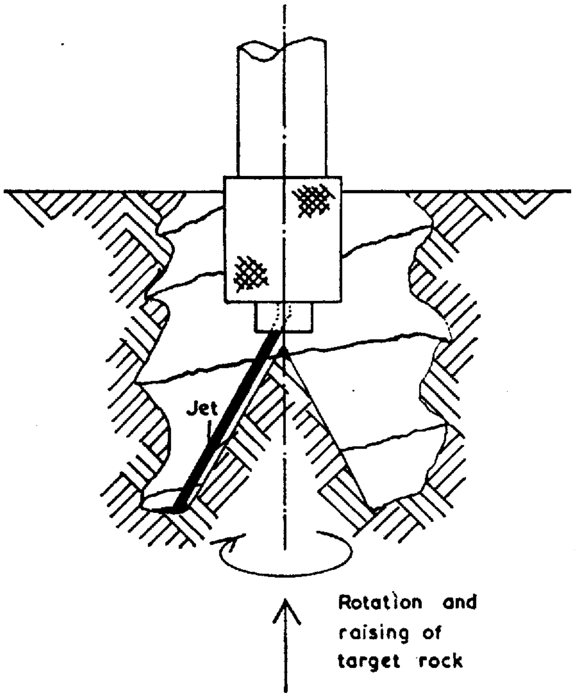

FIG. 15. Diagram of type of hole produced by inclined jet and rotating target.

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