BLASTING FROZEN GROUND WITH COMPRESSED AIR

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In regions such as Alaska, surface excavation of perennially frozen soils by mechanical means is rarely carried out in winter. This is mainly because such frozen soils often fall above the upper limits of the excavating capability of conventional earth moving equipment due to the high strength of frozen earth materials and also problems with machine traction on frozen surfaces.

As part of its research mission for the U.S. Army, the Terrestrial Sciences Center (formerly the Cold Regions Research and Engineering Laboratory) of Hanover, New Hampshire, has been studying different techniques for rapidly excavating frozen ground. During the winter of 1967-68 a series of tests were carried out in Alaska to evaluate the technique of injecting highly compressed air into frozen ground, as a method of ground fragmentation.

The airblasting technique was developed primarily for blasting coal and shales and has been widely used for this purpose in coal mines in the United States since 1934 and in the United Kingdom since 1955. A typical system consists of a 6-stage air compressor capable of delivering up to 200 cu.in./min. of compressed air at pressures up to 12,000 psi. The air is fed to the work area by a static arrangement of steel pipelines, from the ends of which it is taken to the working face by a system of flexible reinforced rubber and copper lines. From these lines the air is fed via a shooting valve to a steel tube or shell lying in a borehole. When the shooting valve is opened, the compressed air flows into the shell building up pressure until release ports in the discharge head at the end of the borehole are uncovered by the rupture of a disc or movement of a piston within the shell. As soon as the port holes are uncovered, the air discharges into the borehole and the material is thus blasted. Full details of the techniques used and the fundamentals of the process will be found in publications by Wildgoose, 1960; Hawkes, 1962; and Davies and Hawkes, 1964.

In comparison with chemical explosives, airblasting appears to offer the following advantages:

1. Compressed air can be considered to represent stored explosive energy which can be released in a controllable manner. In this form it is available continuously and thus is suitable for a continuous or semi-continuous system of excavation.

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2. It is adaptable for use in conjunction with mechanical excavation systems; the drill used to cut the borehole could also be used as the shell.

3. Dangers associated with chemical explosive misfires are eliminated and there is no waiting for acrid smoke fumes and dust to clear.

The technique has proved adequate and safe for blasting fractured brittle material, such as coal, and therefore the questions to be resolved by this preliminary testing program were:

Will compressed air efficiently blast frozen ground and if so, can continuous systems be designed for both rapid tunneling and surface excavations?

TEST PROGRAM

The object of the test program was to test the concepts of using compressed air in different conditions rather than to obtain precise figures as to quantities blasted, etc., which would not necessarily be relevant on other sites. With this general objective in mind, tests were carried out on five sites at Fox, Alaska (near Fairbanks) . . . two underground in a frozen silt tunnel and three on the surface adjacent to the tunnel site (Figure 1).

Approximately 35 years ago, gold dredging operations at the Fox Tunnel site had left a bluff of frozen silt adjacent to exposed gravel. The bedrock in the area consists chiefly of Birch Creek schist, primarily a graphite quartz-calcite schist or a quartz-mica schist (Sellmann, 1967). Immediately overlying the bedrock is about 13 feet of gravel containing the placer gold deposits. The gravels in turn are capped by about 50 feet of silt (Figure 2). The Fox Tunnel was excavated from the foot of the bluff and into the silts overlying the gold bearing gravels with the object of developing methods for creating underground shelters for personnel and supplies. The material excavated in the tunnel was variable (Figure 3). Table I gives typical physical properties of the tunnel silt. The ice lenses varied in size from small veinlets with hairline dimensions to large lenses and bands with dimensions of several feet. Another distinguishing feature of the tunnel is that it is in a region of near thawing permafrost having a temperature of 29° to 31°F. To prevent excessive thawing, tunneling operations were only conducted in winter, and the ventilation system during this period lowered the ground temperatures by as much as 20°F to a distance 2 feet back from the tunnel walls. Strength data were not obtained during these tests but in comparison with similar materials loaded at temperatures varying from 18°F to 30°F a reasonable high strain rate compressive strength would be 500 to 800 psi.

Surface Test Plot 1 (Figure 1) was an old gravel tailing pile adjacent to the main building and at the toe of the main silt bank. Over the years, silt had washed into the ground and when frozen the resulting mix forms a very strong material. At the prevailing temperatures compressive strengths up to 5000 psi may be expected, making the material as strong as any form of frozen ground likely to be encountered in cold regions.

Surface Test Plot 2 (Figure 1) was on top of the silt bluff, near the edge and overlooking the main buildings. The material consisted mainly of frozen organic silt with plant and tree roots penetrating to depths of 1 foot. Below a depth of 3 feet, the silt was well drained and friable. The strength values were not expected to differ greatly from the material encountered in the tunnel.

Surface Test Plot 3 (Figure 1) was located approximately 100 yards from the edge of the silt bluff and the soil was similar to that at Plot 2 but being poorly drained its ice content was higher.

Tunnel Tests

The tests carried out in the Fox permafrost tunnel were designed to determine whether or not a combined augering/blasting machine would be feasible for tunneling through frozen silt. Holes to accommodate the airblasting shells were augered by conventional methods. The tests involved airblasting to precut slots and also to a free face formed by a previous shot. A comparison of the volume and size range of the material airblasted to that obtained by conventional explosives was made.

Ripping Tests

These tests were made to determine if the action of a tractor drawn ripper blade in frozen ground could be supplemented by discharging highly compressed air at the blade tip. In addition, the tests were intended to determine whether or not such a technique would enable a ripper blade to operate in what would normally be unrippable ground.

Trenching Tests

One of the drawbacks of the airblast-supplemented ripper concept which was apparent following some initial trials at Hanover was the lack of confinement for the air behind the shank (Hawkes et al., 1967). An alternate technique for surface excavation is to inject compressed air into the ground through a vertical drill hole and by constantly breaking to the face formed by the previous shot, trench through the ground.

Tests were designed to evaluate this concept in frozen ground which was difficult to rip using conventional equipment. Results from airblasting tests were to be compared directly with those obtained using explosives.

EQUIPMENT

Airblasting Equipment

The airblasting equipment used during the trials was in all respects similar to that used for airblasting coal in mines and the layout is shown diagrammatically in Figure 4. Two types of blasting shell (Automatic discharge and Receiver) were used during the trials and a description of them and the blasting procedures together with details of the compressor and pipelines is given in Appendix "A". The compressor was housed in a wooden building on the surface near the portal of the tunnel and the compressed air fed to the tunnel and surface sites through the steel tubing with short lengths of copper and reinforced rubber tubing connecting the shells to the steel line. Despite temperatures as low as -40°F no problems were encountered with line freezing although on occasion the steel line valves were stiff to operate.

The majority of the airblasting was carried out at discharge pressures between 8,000 and 9,000 psi with no apparent differences in the blast with a change in pressure, or shell type.

Ripper Tooth Modifications

To use the expansive action of compressed air most efficiently when combining airblasting with ripping, it must be discharged at the tip of the ripper tooth. To achieve this a detachable tooth tip was modified by welding a tube housing to the back face to conduct the air to vertical slots cut in the front face (Figure 5). A receiver shell was then mounted on brackets welded to the tooth so that the end of the discharge tube could be locked into the housing. Numerous mechanical problems were encountered with the equipment and on one occasion the housing at the back of the tooth was blown apart and had to be completely rebuilt.

Auxiliary Equipment

The ripper tooth was mounted on a hinge-type ripper attachment drawn by a D8H Caterpillar tractor. This tractor is of the size range normally used for ripping work and had a weight of 25 tons and a maximum drawbar pull of 52,250 pounds.

The holes for the underground trials were drilled either 2-3/4 or 3 inches in diameter using a hand-held hydraulic auger and two-pronged bits. The holes for the surface trenching tests were drilled 3 inches in diameter using a truck-mounted Failing 43 drill and tricone roller bits.

TEST PROCEDURES AND RESULTS

Tunnel - Large Heading - Airblasting

In the large heading the face to be blasted was 9 feet high by 18 feet wide and consisted of silt interspersed with large lenses of nearly pure ice. To provide free faces for the first round a 6 inch wide, 8 foot deep slot was cut around the perimeter by a JOY 10RU Coal Cutter. Seven holes, 3 inches in diameter, 8 feet deep, were drilled normal to the face using a hand-held hydraulically driven auger (Figure 6). Three additional holes, not shown in this diagram, were drilled at various angles to the face to complete the round. The blasted silt and ice were loaded into a JOY 10SCAC shuttle car by a JOY 8BU Loader after each two or three shots. Figure 7 shows the typical size of the material blasted, although large blocks were detached occasionally from the face. When these were too large to be handled directly by the loader, they were either drilled and reblasted or cut up using the coal cutter.

With precutting, the average solid volume per shot during Round 1 was approximately 4 cubic yards.

The second 8-foot advance was made in the large heading without precutting. A total of 16 shots were fired using both the Receiver and Automatic shells. Each successive hole was individually positioned and angled to take the fullest advantage of the configuration established by the previous shot. Less ice was encountered in the second than in the first round and the ground temperature was higher.

The average solid volume broken per shot in Round 2 was 3.1 cubic yards.

Tunnel - Small Heading - Airblasting

The silt in the small heading was similar in all respects to that in the large heading but the ice lenses were much smaller. Prior to blasting, the face of the heading was flat and square to the line of the tunnel. This meant that there was no free face for the first shot and after two abortive attempts to "break in" using the Receiver shell in a short 4-foot angled hole a vertical slot 6 inches wide, 3-1/2 feet high and 5 feet deep was cut into the face with the coal cutter. Using this slot to provide an initial free face the heading was advanced a distance of 13 feet with 25 shots, 12 with the Receiver shell (Round 1) and the remainder with the Automatic shell (Round 2). Each shot was individually positioned to take advantage of the free faces created by the previous blast as in the large heading (Figure 8).

The numbers relate to the sequence of shots irrespective of the test site. Figure 9 shows the heading after the 5th shot (No. 11). The material broken could usually be loaded out without further size reduction. The average solid volume broken per shot (averaged over 25 shots) was 1.7 cubic yards.

Tunnel - Explosives Blasting

In order to make an approximate comparison of explosives and airblasting, three holes were drilled and loaded with 1, 1-1/2 and 3 pounds of 60 per cent dynamite, respectively. The holes were 5 feet long and were positioned to give what would be comparatively easy burdens for a shot with an airblasting shell. One hole was in the small heading and the other two in the large heading.

The holes containing 1 and 1-1/2 pounds of explosive gave very poor blasts and left sockets 4 feet long. The hole charged with 3 pounds gave a good blast, about equivalent to that which would have been expected from an airblast. Time did not permit further testing with explosives; however, during previous trials in the tunnel McAnerney (1967) showed that the average solid volume of frozen precut silt per pound of 60 per cent dynamite (averaged over 292 shots) was 1.6 cubic yards.

Surface Test Plot 1 - Frozen Gravel

The surface excavation tests in frozen gravel at Test Plot 1 were as follows:

a. Conventional ripping using the modified ripper tooth drawn by a D8H Caterpillar Tractor;
b. Airblast assisted ripping;
c. Trenching by airblasting into vertical drill holes;
d. Trenching by explosives.

Figure 10 illustrates the general nature of the material at this site and layout of the drill holes.

a. Conventional Ripping

The frozen gravel at this site was not economically rippable. The tip of the ripper tooth would not penetrate more than 1/2 inch, and if a high vertical pressure was applied through the ripper attachment, the back end of the tractor was raised and the tracks slipped.

b. Airblast Assisted Ripping

Due to mechanical problems, mainly in connection with the tube housing at the back of the tooth tip, only a limited number of airblast assisted ripping tests could be made, and no definite results were obtained. Figure 11 shows a blast in progress and Figure 5 shows the situation at the tooth tip following the blast. The material adjacent to and behind the tip can be seen to have been blasted away but there is little apparent penetration ahead of the tooth.

c. Trenching by Airblasting

Seven shots were made in connection with the trenching tests, the first five to blast out a shallow trench to provide a 12 foot wide bench for the subsequent shots. Airblasting in vertical holes proved effective for disrupting this type of frozen material. Figure 12 shows the results of Shot 7 in which a volume of approximately 4 cubic yards was blasted (discharge pressure 9,000 psi and hole depth 4 feet). There were no problems in ripping through the ground or dozer blading it after it had been blasted.

d. Trenching by Explosives

To obtain a comparison of explosives and airblasting, four holes, designated Ex. 1, 2, 3, and 4, were drilled between 3 and 4 feet deep into the frozen gravel and fired using 60 per cent dynamite (Figure 10). The holes were charged with 1-1/2, 3, 4 and 5 pounds of explosive, respectively, but only the ground around the hole charged with 5 pounds of explosive broke to the surface (Figure 13).

Surface Test Plots 2 and 3 - Frozen Organic Silt

Trials were run at Test Plot 2 in frozen organic silt to evaluate further the concept of trenching by airblasting into vertical drill holes. Figure 14 illustrates the layout of the test site and shows the position of the 10 airblasting shots. Airblasting was also effective in this material, producing large blocks which could be easily bulldozed using a cable operated blade on a D8H Caterpillar Tractor.

At Test Plot 3 trials were conducted to determine if surface frozen silt could be excavated using conventional ripping and bulldozing techniques. A D8H Caterpillar tractor fitted with an angled blade was used for this test. The top of the ripper tooth normally penetrated about 6 inches and numerous passes were required to break up the material sufficiently for blading out. After approximately 1-1/2 hours of ripping and bulldozing a trench 80 feet long, 18 feet wide and 3-1/2 feet deep was excavated.

DISCUSSION AND CONCLUSIONS

The following comments relate to the various techniques tested during the trials. It is not the intention in this paper to discuss in detail the design of any proposed machine but to look in general at the overall concepts.

Tunneling

A tunneling machine incorporating a combined auger/blast tube is clearly feasible for tunneling in frozen silt. In concerning ourselves with just the blasting of the solid material the main problem would be to build a machine capable of withstanding the impact of the flying debris. Some form of shield would be required to protect the operator and to limit the throw for easy clean up and debris removal. There appear to be no insurmountable problems related to designing a combined auger/blast tube. Such a device can be made robust and capable of withstanding the weight of the falling material.

A direct comparison of airblasting against explosives is not possible without very careful tests made under the same conditions but in frozen silt a conservative estimate is that one airblasting shell discharging around 300 cubic inches of compressed air from a pressure of around 8,000 psi is roughly equivalent to 2 pounds of 60 per cent dynamite.

It is difficult to predict the performance of such a mechanical drill and blast machine in materials other than frozen silt but from the tunnel results it seems a reasonable assumption that it would operate over a fairly wide range of frozen soils. Its efficiency would depend greatly on the ability of the auger to penetrate the ground prior to air discharge. Stronger materials would, of course, also have to be blasted with less overburden.

Ripping

Surface excavation in frozen ground using conventional ripping techniques is often difficult. The tests at the Fox tunnel site showed that the frozen silts were just rippable using a large (D8) tractor although economic considerations based on time and excessive tool wear would probably rule out such an operation. The frozen gravels were not rippable.

Many difficulties were experienced during the airblast supplemented ripping trials, but from the few tests carried out it appeared that this concept is not as attractive as originally envisioned. The main problem lies in confining the air so that it has a surface upon which to act.

The air needs cracks or joints in advance of the tooth tip into which it can penetrate; when these are not present the blasting action is limited. This was particularly apparent in the frozen gravel which was massive and without any joints or fracture planes.

Trenching

As long as it is confined, highly compressed air is an efficient technique for trenching in frozen ground. A shell discharging 300 cubic inches from an initial pressure of 9,000 psi into frozen gravel was roughly equivalent to an explosive blast from 5 pounds of 60 per cent dynamite. It should be pointed out, however, that the airblast was breaking through to a trench and the type of frozen gravel being blasted seemed ideal for airblasting. The upper 3 feet of the gravel was very strong but below this the ground was much more friable thereby facilitating the spread of the compressed air and enabling it to have a heaving action on the upper layers. Nevertheless, the results are sufficiently encouraging to warrant further tests and a machine incorporating a combined drill/blast shell appears to be a feasible proposition for breaking up strong, highly frozen surface layers. The excavation rate would be limited mainly by the speed at which a tool to introduce the compressed air could be forced into the ground.

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This work comprises a portion of the research program of the TSC's Experimental Engineering Division (Mr. Kenneth A. Linell, Chief). Lieutenant Colonel John E. Wagner is Commanding Officer and Director of the Center.

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TABLE I

PROPERTIES OF FROZEN SILT IN FOX TUNNEL

(Sellmann, 1967)

Bulk Density, g/cm^3 (lb/ft^3)	1.43 (89.1)
Dry Density, g/cm^3 (lb/ft^3)	0.79 (49.0)
Void Ratio	2.38
Moisture Content (per cent by weight of solids)	83.4
Specific Gravity (grains)	2.62
Soil Mass (per cent by volume)	27.0
Ice (per cent by volume)	68.5
Organic Matter (per cent by volume)	4.5
Classification (Unified Soil Classification System)	Organic Silt (OL)

Composite of 10 samples in vicinity of large and small tunnel headings. The high value for void ratio is the result of a large amount of segregated ice in the soil matrix.

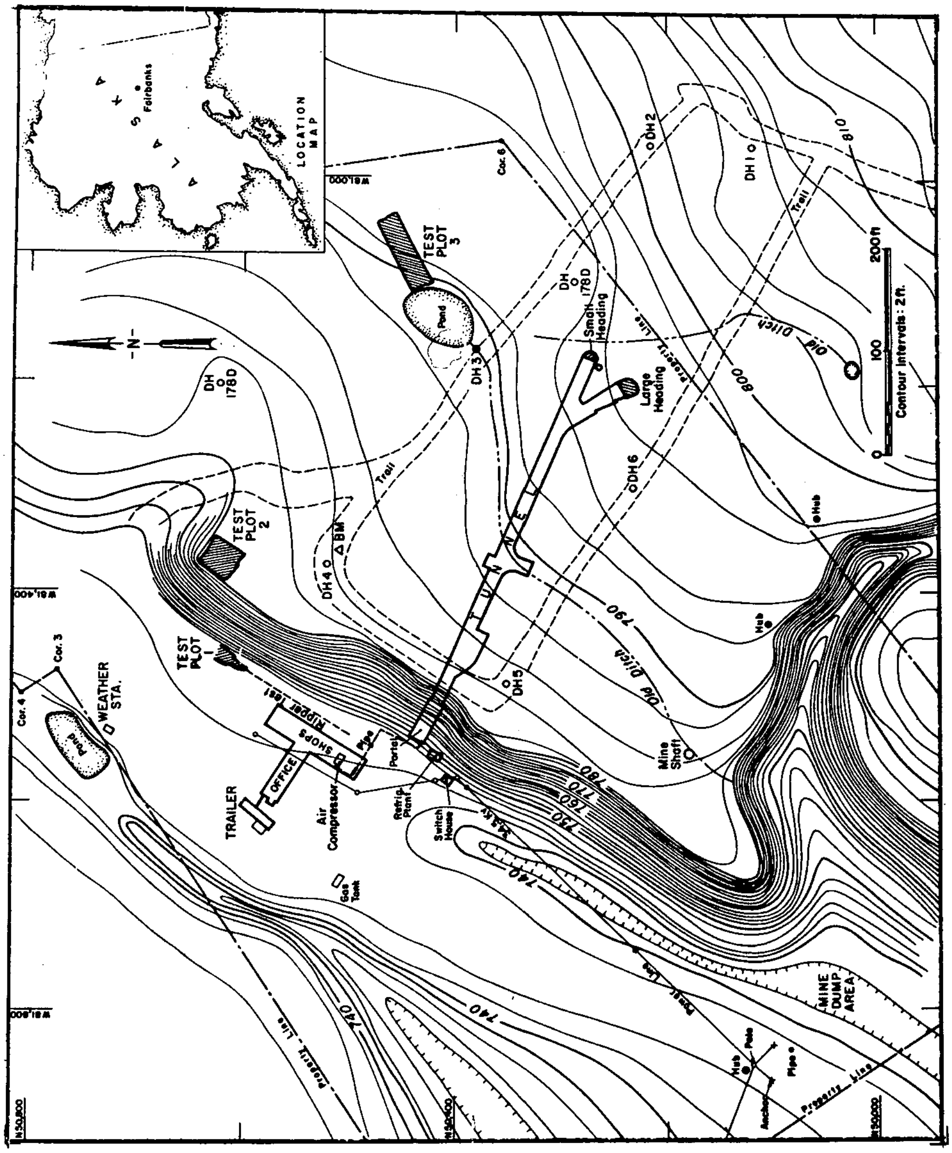

Fig. 1 General Site Plan.

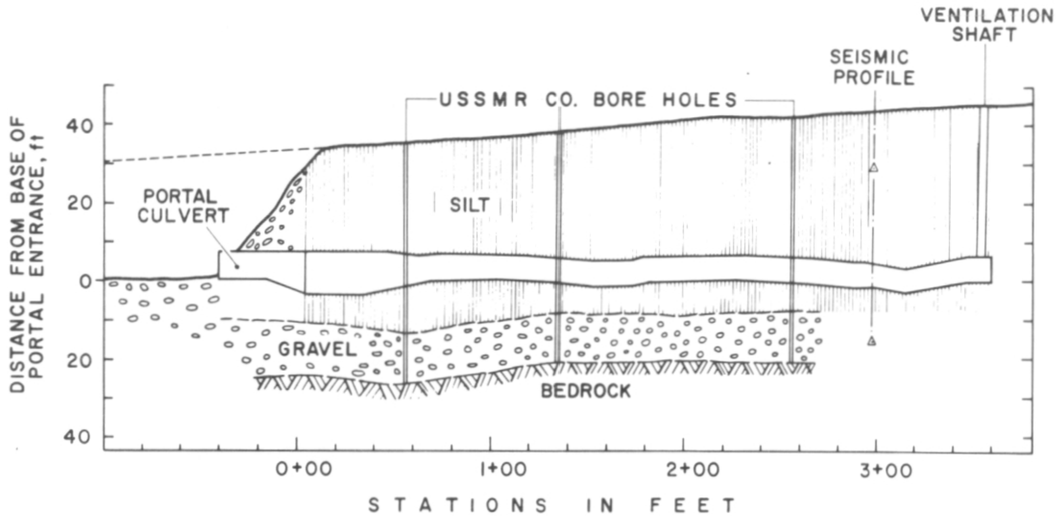

Fig. 2 Sectional view of the USA TSC permafrost tunnel. Depth to gravel and bedrock based on U.S. Smelting, Mining and Refining Company borehole records (Sellmann, 1967).

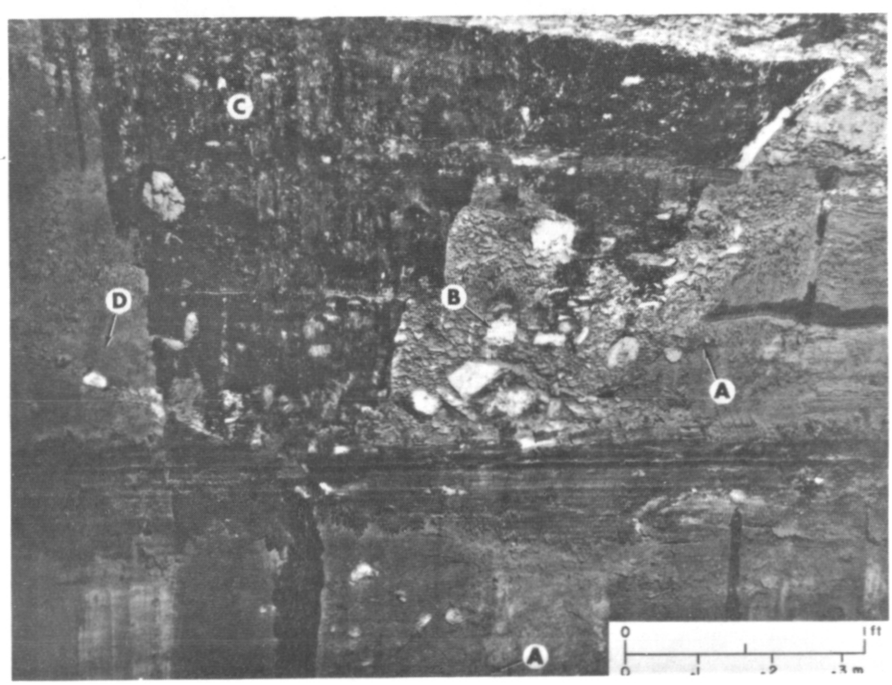

Fig. 3 Tunnel station 00+96. Note the extreme variability of the material: (A) organic material (B) rock fragments, (C) massive ice and (D) silt (Sellmann, 1967).

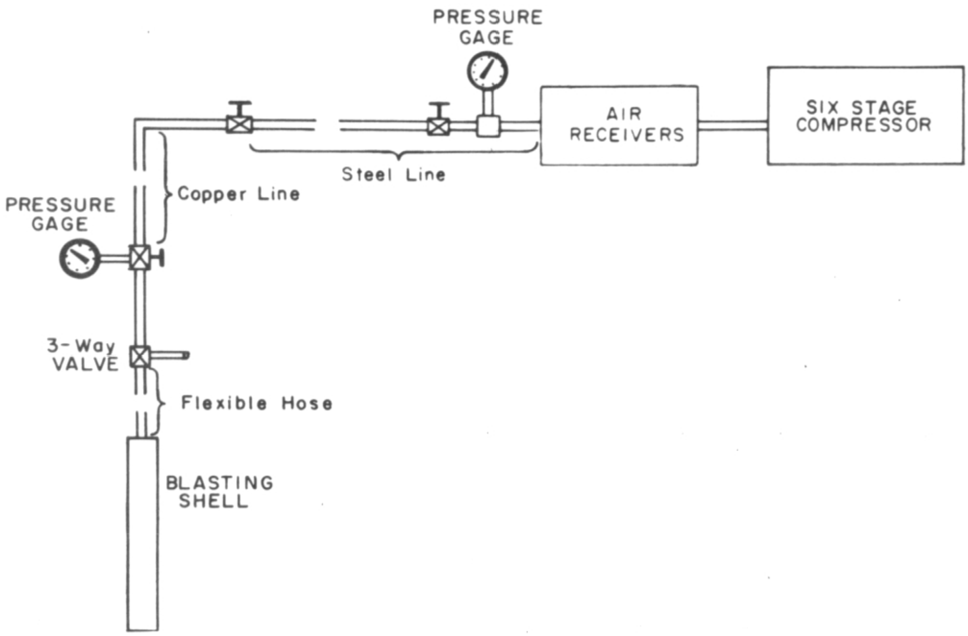

Fig. 4 Diagram of airblasting system.

Fig. 5 Tip of ripper tooth showing blast tube attachment.

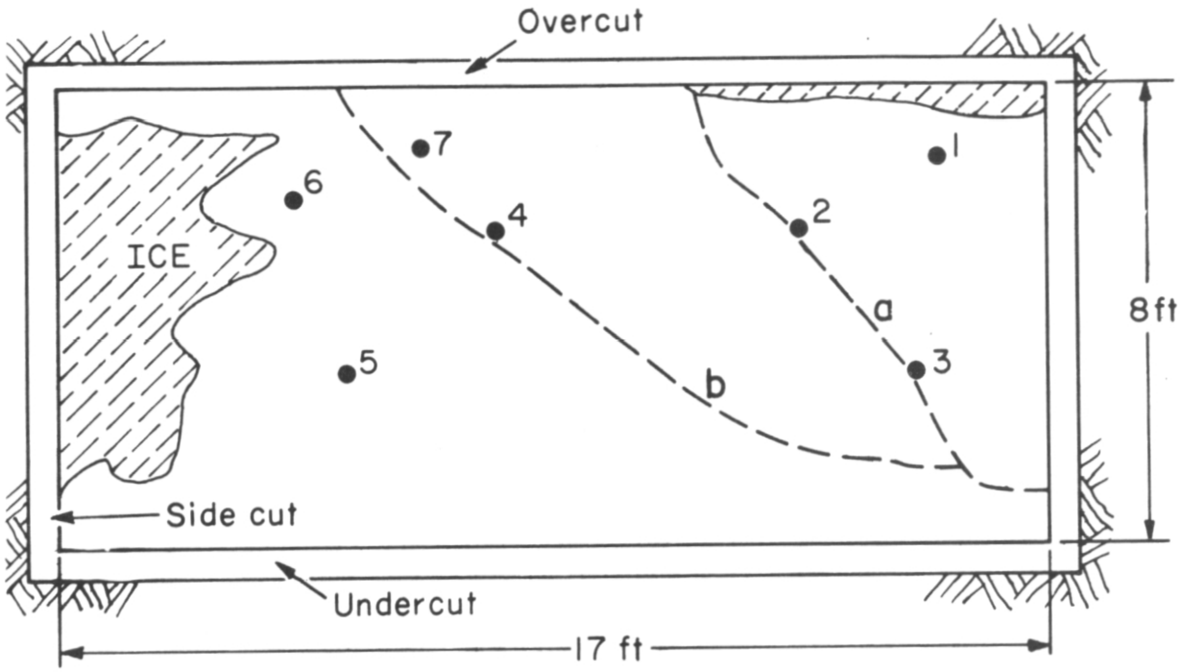

Fig. 6 Face of tunnel large heading (Round 1). Shots are numbered by firing sequence. Dashed lines "a" and "b" show breakage.

Fig. 7 Coarse muck pile - large heading.

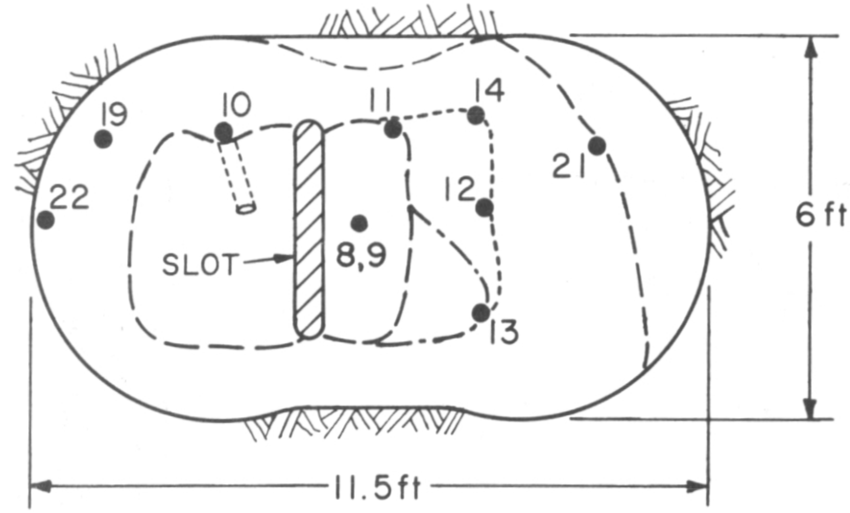

Fig. 8 Face of tunnel small heading (Round 1). Shots are numbered by firing sequence. Dashed lines show breakage.

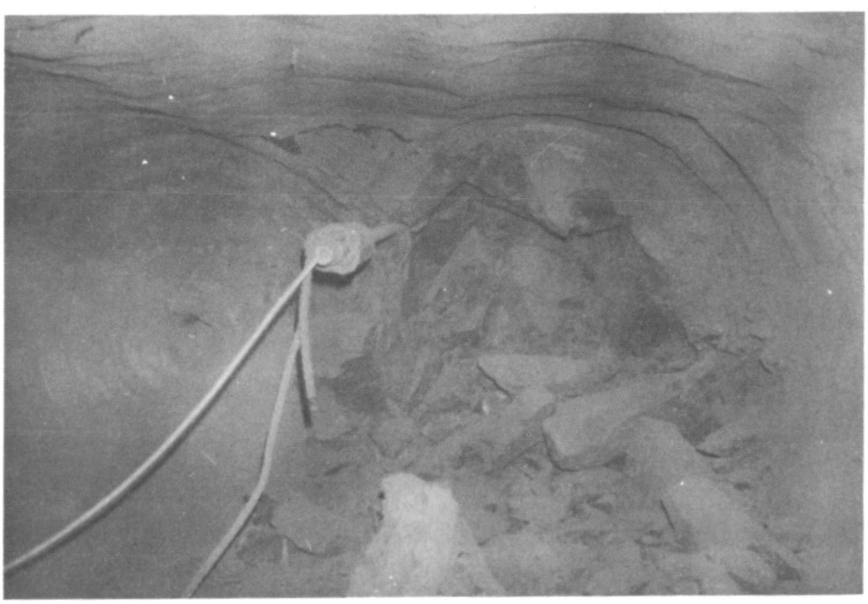

Fig. 9 Small heading. Receiver shell has just fired shot no. 11.

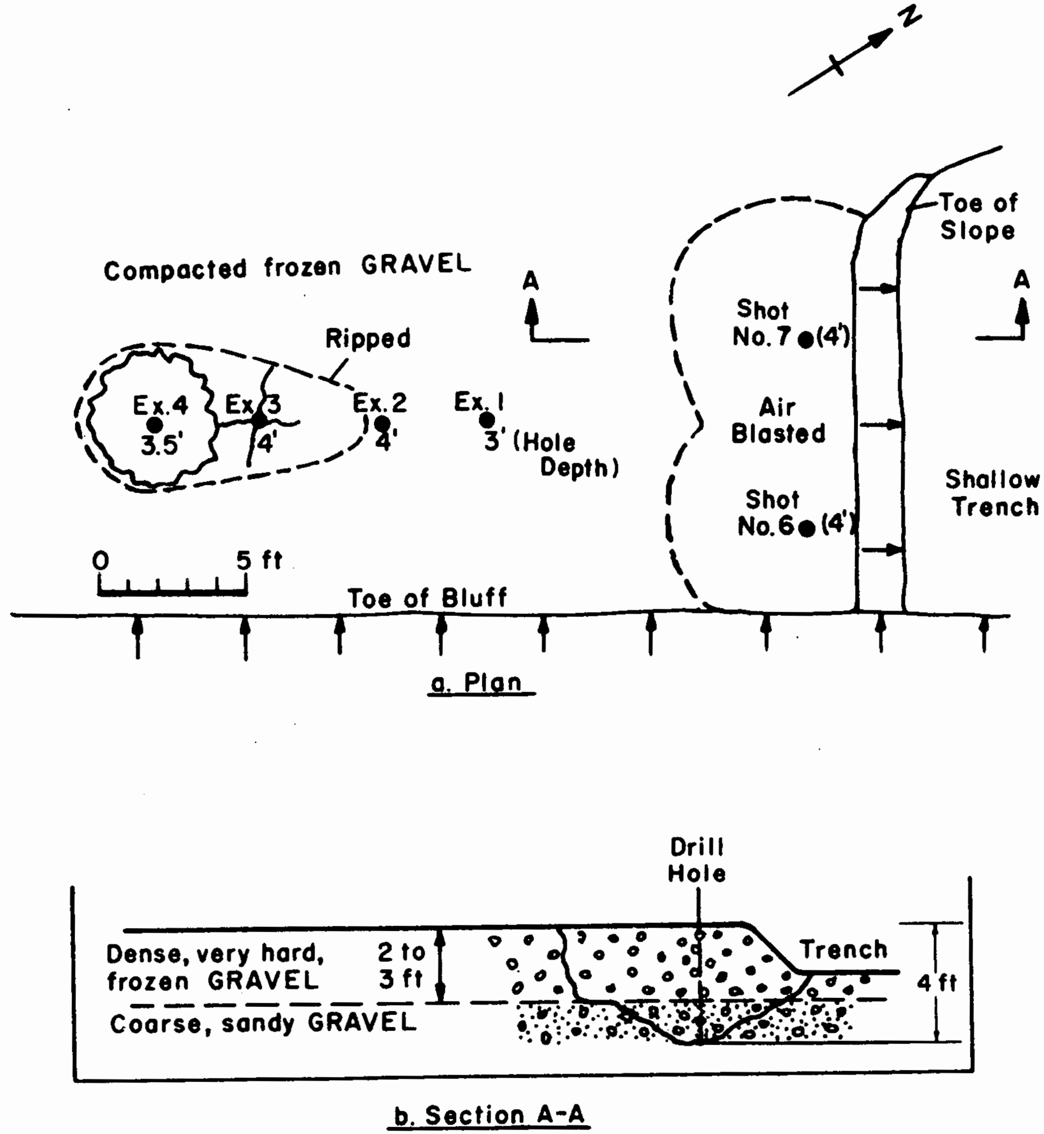

Fig. 10 Surface test plot 1. Dashed lines indicate breakage.

Fig. 11 Air blasting with ripper tooth in frozen gravel, surface test plot 1.

Fig. 12 Fragmented frozen gravel after airblast in vertical borehole, surface test plot 1.

Fig. 13 Result of 5 lb-60% dynamite blast, explosive shot no. 4, surface test plot 1.

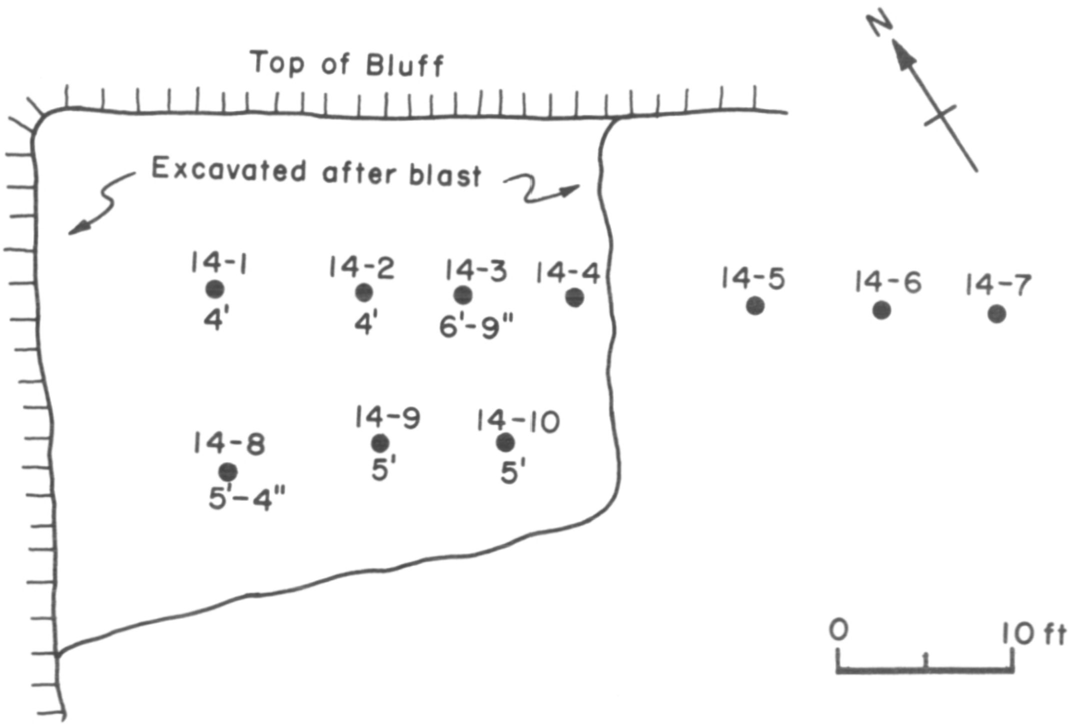

Fig. 14 Plan view of surface test plot 2. Shot sequences and hole depths are indicated.

APPENDIX "A"

Details of the Airblasting Equipment are as follows:

Compressor - Long Airdox Compressor, 6 stage horizontally opposed cylinders, air cooled, rated at 54 scfm at 12,000 psi delivery, powered by 50 hp electric motor

Air Receivers - 6 tubes 2-5/8 in. O.D., 7 ft long, coupled in parallel, total capacity 1500 cu. in.

Pipe Line - copper tubing - 3/8 in. O.D. x 0.175 in. I.D.
reinforced flexible hose - 3/16 in. I.D.
steel line - 5/8 in. I.D. x 1 in. O.D.

Airblasting Shells

Figure A-1 illustrates the design of the Automatic Discharge and Receiver Shells used during the trials.

Details of the Receiver Shell are as follows:

Overall length - 9 ft 11 in.
Diameter of receiver chamber - 6 in. O.D., 5-1/2 in. I.D.
Length of receiver chamber - 13 in.
Length of discharge tube - 98 in.
Capacity - Receiver chamber, 302 $in.^3$; tube, 274 $in.^3$

Details of the Automatic Discharge Shell are as follows:

Overall length - 10 ft.
Diameter - 2-5/8 in. O.D.
Capacity - 315 $in.^3$

A detailed description of the mechanics by which these shells discharge compressed air is beyond the scope of this paper; however, a brief description is given herein. The Receiver Shell is operated by suddenly dropping the air pressure in the input line thereby causing a differential pressure to act across the piston C thus moving it toward the inlet and lifting the valve G from its seat. The air then flows down the discharge tube and out through the ports I.

The Automatic Discharge Shell operates when a certain pressure level is reached as determined by the compression in spring K. Pressure acting through hole I forces piston J back which releases a little air through port M. The differential pressure now acting across piston F moves it to uncover the main ports E and thereby allows air discharge.

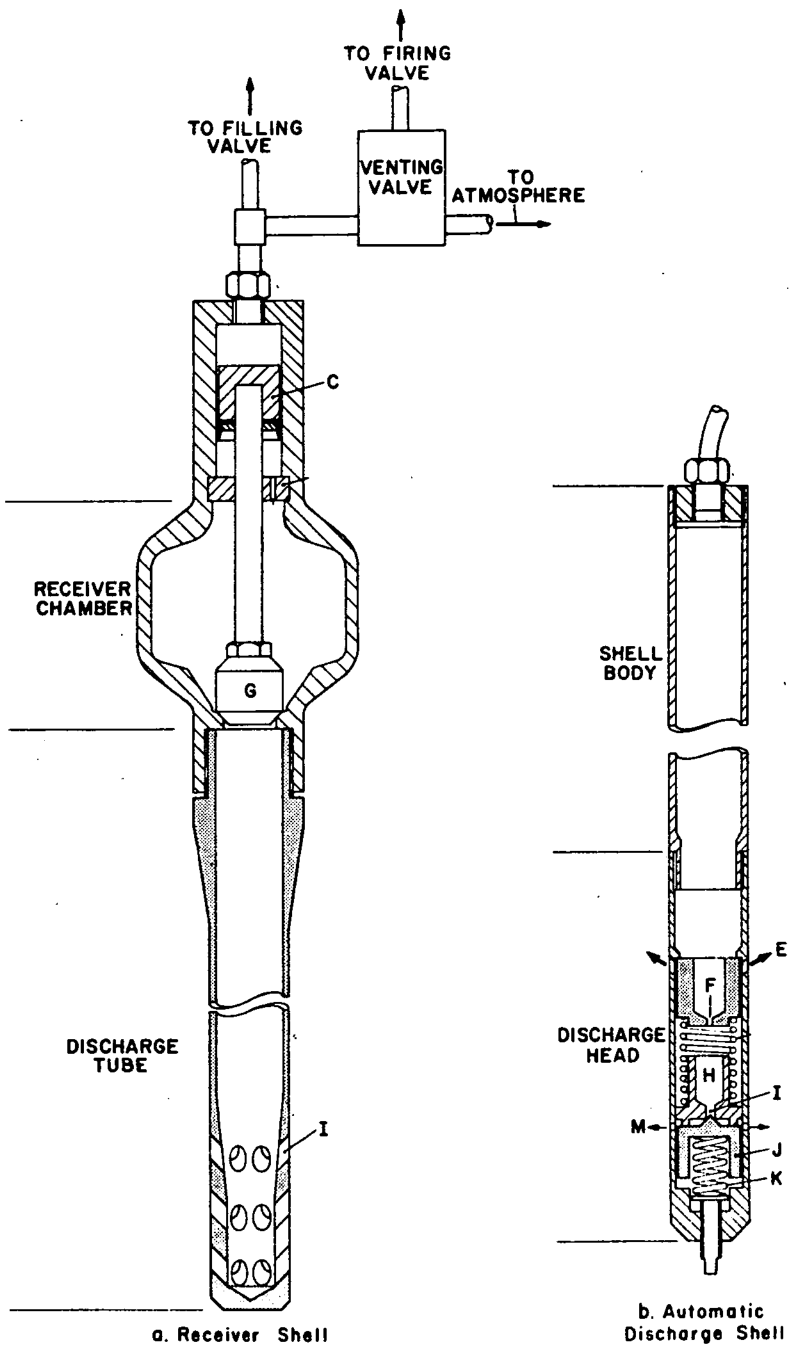

Fig. A-1 Detail of the two airblasting shells used.