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TITLE

# USE OF CHEMICAL EXPLOSIVES FOR EMERGENCY SOLAR FLARE SHELTER CONSTRUCTION AND OTHER EXCAVATIONS ON THE MARTIAN SURFACE

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# Abstract

The necessity to shelter people on the Martian surface from solar flare particles at short notice and the need for long-term habitats with thick cosmic ray shielding suggests that explosives could be used effectively for excavation of such structures. Modern insensitive high explosives are safe, efficient, and reliable for rock breakage and excavation. Extensive Earth-bound experience leads us to propose several strategies for explosively-constructed shelters based on tunneling, cratering, and rock casting techniques.

## INTRODUCTION

Extended duration manned surface exploration and, ultimately, permanent human presence on Mars will require protection from the constant galactic cosmic ray and intermittant solar flare irradiations. For the relatively short exposures on the Martian surface in the exploratory phase prior to a permanent outpost, the high energy proton flux associated with large, relatively unpredictable solar flares are the largest source of danger. It will be expensive and cumbersome if shelters transported from Earth are used to protect personnel at every point of their potential exposure to these lethal events. However, if indigenous rock materials could be used instead, then large savings in the mass required to be landed on the Martian surface are potentially possible. On the other hand, this approach implies an excavation capability for which the mass of the required construction equipment may negate any savings relative to bringing a preconstructed shelter. In this paper, we call attention to the fact that explosives are very efficient rock-movers. Modern explosive excavation technology can be used to safely, efficiently, and quickly construct a variety of structures that will be required as part of any realistic operations on the Martian surface.

In our discussion, we assume that approximately 50 $gm/cm^2$ shielding for a few hours during the intense phase of a large solar flare and 500 $gm/cm^2$ for long duration exposure to cosmic rays are required. This translates to rock thicknesses of about 20cm and 200cm, respectively. We further assume that 2 PI shielding is necessary and that we cannot expect more than about one hour warning before the effects of an intense solar flare would be felt on the Martian surface. Finally, we assume an operational scenario consisting of five manned landings involving extensive surface explorations using rover vehicles and leading to a permanent manned outpost (the "Columbus Base" scenario, [1]).

## EXPLOSIVE EXCAVATION STRATEGIES

Explosives are a safe, efficient, and practical means of cratering and tunnel driving to provide protective shelters as well as for scientific purposes. Four areas for which explosives are useful on the manned Mars mission are (1) remote shelter construction to protect the rover vehicle crew from intense solar flare protons, (2) construction of the main base shelter such as a tunnel or a rock-covered module placed in an explosively formed trench, (3) providing a tunnel or crater to bury a main base nuclear power reactor for shielding, and (4) an energy source for active seismic experiments as part of the scientific exploration of Mars.

The rover vehicles should be configured so that the floors contain materials such as batteries, water, wastes, and other equipment useful for shielding the crew (Fig. 1). During rover traverses away from main base shelters, a remote shelter large enough for two people could be constructed in less than an hour by producing a trench in the Martian surface using explosives, driving the rover with shielding in the floor over the trench, and then "sandbagging" around the edges of the Rover with thrown-out debris for side protection. The crew (in EVA suits) then takes shelter during the intense phases of the solar flare (a few hours). Life support and communication outlets in the rover floor could be provided for the crew to plug into for increased comfort during their stay.

At the main base, a permanent shelter could be constructed by tunneling into a nearby rock face using drilling and blasting methods. A more useful shelter could be constructed from this simple tunnel by either placing an inflatable envelope within the tunnel or by closing the entrance with a bulkhead and airlock, sealing the tunnel walls with insulating foam, and then pressurizing the inclosed volume. In our opinion, the latter approach is probably the best method of producing large habitable volumes for a permanent manned base. Alternatively, or in addition, appropriately sized modules brought from Earth could be placed in explosively produced trenches and covered with rock and dirt by explosive casting techniques. These same techniques could be used to bury a nuclear reactor to shield against its radiation.

## EXPLOSIVES AND INITIATORS

The explosives will of necessity need to be transported to Mars from Earth, at least for the first manned mission, since it is not known whether all the ingredients needed to manufacture explosives on Mars are present. (If nitrate salts are found or if nitrogen can be extracted from the small amount present in the Martian atmosphere, then _in situ_ explosives production is possible and ultimately desirable.) Some requirements of explosives to be used on Mars are (1) insensitivity to detonation from impact over a wide range of projectile velocities, (2) safe to transport, store, and handle, (3) availability in convenient sizes and shapes, (4) chemically and mechanically stable over a large temperature and ambient pressure ranges, (5) high energy content per unit volume to effectively blast craters, trenches, and tunnels, (6) detonatable in 3 to 5m lengths and 25 to 50mm diameters, (7) detonatable at very low temperatures in a safe and reliable manner, and (8) easily loaded in uneven boreholes. Explosives (military and commercial) vary greatly in energy content, density, sensitivity of initiation, and detonation pressure. Table 1 is a list of a few representative military and commercial explosives in common use for munitions and blasting. Explosive 9502, composed of 5% Kel-F binder and 95% TATB[*] (item 2 in Table 1), is a high-energy, insensitive military explosive. The other two military explosives, PETN and TNT, are much more sensitive. The next three items in Table 1 are commercial blasting agents that are insensitive to initiation by impact and are less energetic than the military explosives. 9502 may be a good choice to perform the excavation on Mars, but no data exists on it's blasting capability. The commercial explosives are used extensively for Earth bound excavations. Item 7 in Table 1 represents a speculative suggestion that hydrogen peroxide might have some attractive features as an explosive for use on Mars. It is less energetic than the military explosives listed but is comparable to many commercial blasting agents. It's main attraction is that it could very likely be easily manufactured on Mars from indigeneous water. Pored as a liquid into irregular

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[*] 1,3,5 triamino-2,4,6-trinitrobenzene

boreholes, it would quickly freeze and couple well to the rock and detonator. More information on its explosive properties is needed before it can be further evaluated.

Initiators or detonators need the following requirements: (1) safe to transport, store, and handle; (2) storable separate from the explosive charges; (3) easily and securely attachable to the charge; (4) sufficiently energetic to detonate insensitive explosives such as 9502 or a blasting agent through a booster arrangement; and (5) must be reliable at very low temperatures, stable chemically and mechanically, and very easy to connect and use in a shot situation. Since insensitive explosives will likely be used for rock removal, a booster explosive will be required between the initiators and the main charges for reliable detonation to take place. Any booster charge used needs to have similar reliability, stability, and ease of use requirements as the detonators. There are several types of electric detonators - standard blasting caps, exploding bridgewire (EBW), and minislappers. Another type of initiator is the nonelectric cap, widely used in the industry. The difference between the electric detonator types is the application of the electrical energy. For EBW or minislapper systems, a large energy density is applied to a small diameter wire (EBW) or foil (minislapper) in less than a microsecond causing the detonation of a primary explosive which in turn detonates the booster charge. The actuation energy for these detonators is 1-3J at several thousand volts. The standard blasting cap is a low energy device that also has a bridgewire, but is not exploded. Instead the wire is heated to the ignition temperature of the primary explosive in contact with the bridgewire. The firing conditions are approximately 5A and 450V. The electric detonators can be fired from small portable firesets. Blasting caps are produced with a large variety of time delays while EBWs and minislappers are instantaneous and require any delays to be built into the firing circuits. The nonelectric system consists of a nonelectric detonator connected to a plastic tube coated with PETN powder on the inside surface that is connected to a detonator. A "starter" (safety fuse or electric detonator) ignites the powder causing the detonator to fire after the burn front propagates the length of the tube. Various delays are also available. The EBW-minislapper systems or the Nonel (trade name for Nitro-Nobel nonelectric detonator system) initiators are very safe and convenient to use, even with military explosives. Many of the systems discussed above (e.g., TATB and EBWs) have been used reliably at temperatures down to -50C but would need to be tested at still lower temperatures for Mars use.

## METHODS

### Cratering

For blasting a crater or trench, the following steps are necessary: (1) select a depth-of-burial based on the general type of material to be blasted and the blasting application; (2) drill the borehole(s) to the selected depth; (3) load the initiation device, booster charge, and explosive to the desired depth-of-burial; (4) connect the detonator/booster assembly to the fire set; and (5) fire the shot(s) after retreating from the explosive site a distance sufficient to prevent damage to people and equipment from fly rock (in the Mars 1/3 gravity, rocks with the same initial velocity will fly three times farther than on Earth). The cratering shots for the remote shelter must be designed to throw as much rock as possible to eliminate the need to muck the crater.

Since the remote shelter is basically a conically shaped crater or string of connected craters (trench) with the rover over it, the parameters for the blast must be chosen to provide a crater with an aspect ratio (crater diameter to crater depth) on the order of 2:1 or less in order to maintain adequate head room under the rover. Figure 1 is an illustration of the shelter concept. Based on previous cratering test data [2,3], a 100kg charge in alluvium or a 150kg charge in rock buried at a depth of 2m will produce an apparent crater 2.5m deep and 5.0m diameter. In 1/3 gravity, this apparent crater depth [4] will likely be greater on Mars than on Earth for the same surface material and explosive loading. Cratering from charges placed on the alluvium and rock surfaces is very inefficient! Even shallow burial of the charge greatly enhances the crater volume. A preliminary study of cratering (on Earth at least) indicates that an adequate shelter remote from the base could be constructed quickly using explosives buried at 2 to 3m depth. The unknown factors are the drilling equipment, methods for quick set-up, and reliable operation at very low temperatures.

## Tunneling

At the main base, tunneling by the drill, blast, and muck technique [5] appears to be an efficient means to construct a shelter. The tunnel driving methods are highly developed and seem adaptable to tunneling in Mars rocks. We have chosen a tunnel size of 2.1m square and 10m long (figure 2) as adequate for each of the landing site bases for the first three manned missions. This size requires the removal of $44m^3$ of rock. Using the industry's experience in blasting on Earth, the powder factor, PF (mass of explosive needed to remove one cubic meter of rock), can be calculated from the empirical relation [5]

$$PF = 14/s + 0.8$$

where s = area of the tunnel face. PF for a 2.1m square tunnel is 4 $kg/m^3$. Hence, 175kg of explosive is necessary to remove the required volume of rock. To maximize the usage of this explosive, several tunnel driving parameters need to be included in a predetermined blast plan such as the drill hole pattern at the tunnel face, drill hole diameter, strength properties of the rock, degree of explosive packing in the holes, and the ignition sequence of the round. An example of a drilling pattern for a smooth wall tunnel with a $4.4m^2$ face is given in figure 2. This blast pattern produced an advance of 2.3m per round, so a 10m long tunnel can be blasted with four rounds. Muck removal after each round can be accomplished with a dragline powered by the rover vehicle, electric power winch, or by hand. A crude time estimate for each round is 16 hours, including drilling, loading, mucking, and equipment setup and teardown. We believe this construction time could be substantially reduced by utilization of a specially designed tunneling machine that would combine drilling, blasting, and muck removal in a nearly continuous, semi-automated operation (e.g., ref. [6]).

## Trenching and casting

Trenching to form a protective shelter at the main base is an extension of the cratering process discussed above. A v-shaped trench 2.5m deep, 5m wide, and 15m long could be produced in soil by sequentially firing six row charges spaced 2.5m apart [2]. The charge burial depth is 2m and each charge is 30kg for a total mass of 180kg. In rock, the charge mass is approximately 225kg to form a similar size trench. The shelter module is then placed in the trench and covered by either using machinery or using explosives to cast [7] the soil and rocks from a nearby bench. Figure 3 is a schematic diagram of the technique.

Approximately 65m$^3$ of material is needed to provide a 2m thichness of material over a module that is 2m diameter and 10m long. Assuming a PF of 3kg/m$^3$ and assuming 25% of the material is lost due to excessive flyrock and dispersion, nearly 250kg of explosive is needed to produce the cast material to cover the module. A total mass of 450kg of explosive appears to be sufficient to bury the module in a trench. If a natural ravine near to a bench or cliff could be found in which to place the module, then the explosive usage could be reduced by one half.

## SAFETY ISSUES

The development of modern insensitive high explosives has largely removed the danger of transport and use of these materials. Reference [8] describes the many tests that are performed to characterize the sensitivity of explosives and assure their safe use. An explosive based on TATB is capable of surviving a launch pad explosion and fire without detonation. To illustrate this, figure 4 shows a missile containing explosive 9502 impacting a target at high velocity without detonation. The only event that we can conceive of on a manned Mars mission that could unintentionally detonate an explosive like 9502 is the impact of a gram-size meteoroid traveling at several tens of meters per second. This (unlikely) eventuality could be rather easily guarded against by storing the explosive inside a container with shock absorbing walls such as metal-epoxy honeycomb, double-wall, or similar material. A layer about 10cm thick would be adequate to stop a 1 cm diameter meteoroid without propagating a shock wave into the explosive. Normal safety practice would result in separate storage of detonators and initiators in similar containers.

## CONCLUSIONS

The applications for the use of explosives on Mars are extensive. There is probably no better source of stored energy in a small volume and mass than explosives. They are safe, easily handled in the field, and their usage requires very little specialized apparatus. Based on Earth-bound blasting operations, much of the design and planning of the particular blast applications on Mars could be accomplished in the mission planning phases and even tested in rocks and soils simulating materials expected on the Martian surface. Blasting information needed by the crew includes the type of explosive, initiators for the charges, drilling patterns, depth-of-burial of charges for cratering, powder factors, drill hole diameters, spacings for row charges, and delay timings. Once on the surface of Mars, a cratering test in soil and hard rock should be conducted using the 100kg of explosive designated in Table II for testing. This proof test would be conducted on the first manned mission to validate the blasting designs conceived during the planning stages. Parameters to be evaluated in these tests are powder factor, crater size and shape, and effective strengths of Martian rock materials. This information would then be used to produce final designs for cratering, trenching, and tunnel driving.

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## FIGURE CAPTIONS

Figure 1. Concept for a remote solar flare shelter.

Figure 2. An example of a drilling pattern for a single explosive round for a $4.4m^2$ tunnel face (Ref. [6]). There are 28 drill holes each 32mm in diameter.

Figure 3. Schematic illustrating the construction of a protective shelter by using explosives to produce a trench and then cover a prefabricated module.

Figure 4. Impact at 150m/s of a test missile containing insensitive high explosive 9502. The warhead disintegrates due to impact but does not detonate. (Los Alamos National Laboratory).

TABLE I. COMPARITIVE PROPERTIES FOR SEVERAL MILITARY AND COMMERCIAL EXPLOSIVES

| Explosive | Density ($g/cm^3$) | Detonation Velocity (m/s) | Energy (cal/g) | Detonation Pressure (GPa) |
|---|---|---|---|---|
| 1. PETN | 1.78 | 8800 | 1510 | 35.0 |
| 2. TATB (9502) | 1.89 | 7600 | 1200 | 30.0 |
| 3. TNT | 1.65 | 7000 | 1090 | 19.0 |
| 4. Atlas 840 Powermax | 1.34 | 6000 | 940 | 12.0 |
| 5. IREGEL 1175C Emulsion | 1.25 | 5000 | 890 | 8.0 |
| 6. ANFO | 0.85 | 3500 | 900 | 3.0 |
| 7. Hydrogen Peroxide | 1.45 | 7000 | 690 | 7.0 |

TABLE II. EXPLOSIVE (TNT) ESTIMATES FOR FIVE MANNED LANDINGS ON MARS

| | Site A | Site B | Site C | Initial[a] Base | Columbus[b] Base |
|---|---|---|---|---|---|
| * Remote Shelter | | | | | |
| Hard Rock | 150kg | 150kg | 150kg | 150kg | 300kg |
| Soil | 100kg | 100kg | 100kg | 100kg | 200kg |
| * Base Station | | | | | |
| Tunnel (rock) | 175kg[c] | 175kg | 175kg | 300kg | 500kg |
| Trench (rock) | 225kg[d] | 225kg | 225kg | 225kg | 550kg |
| (soil) | 180kg | 180kg | 180kg | 180kg | 360kg |
| Casting (rock) | 250kg | 250kg | 250kg | 250kg | 500kg |
| Reactor (rock) | | | | 150kg[e] | |
| (soil) | | | | 100kg | |
| *Seismic | 100kg | 100kg | 100kg | 200kg | 500kg |
| *Testing (rock) | 50kg | | | | |
| (soil) | 50kg | | | | |
| MISSION TOTALS | 525-825kg | 425-725kg | 425-725kg | 800-975kg | 1300-1850kg |

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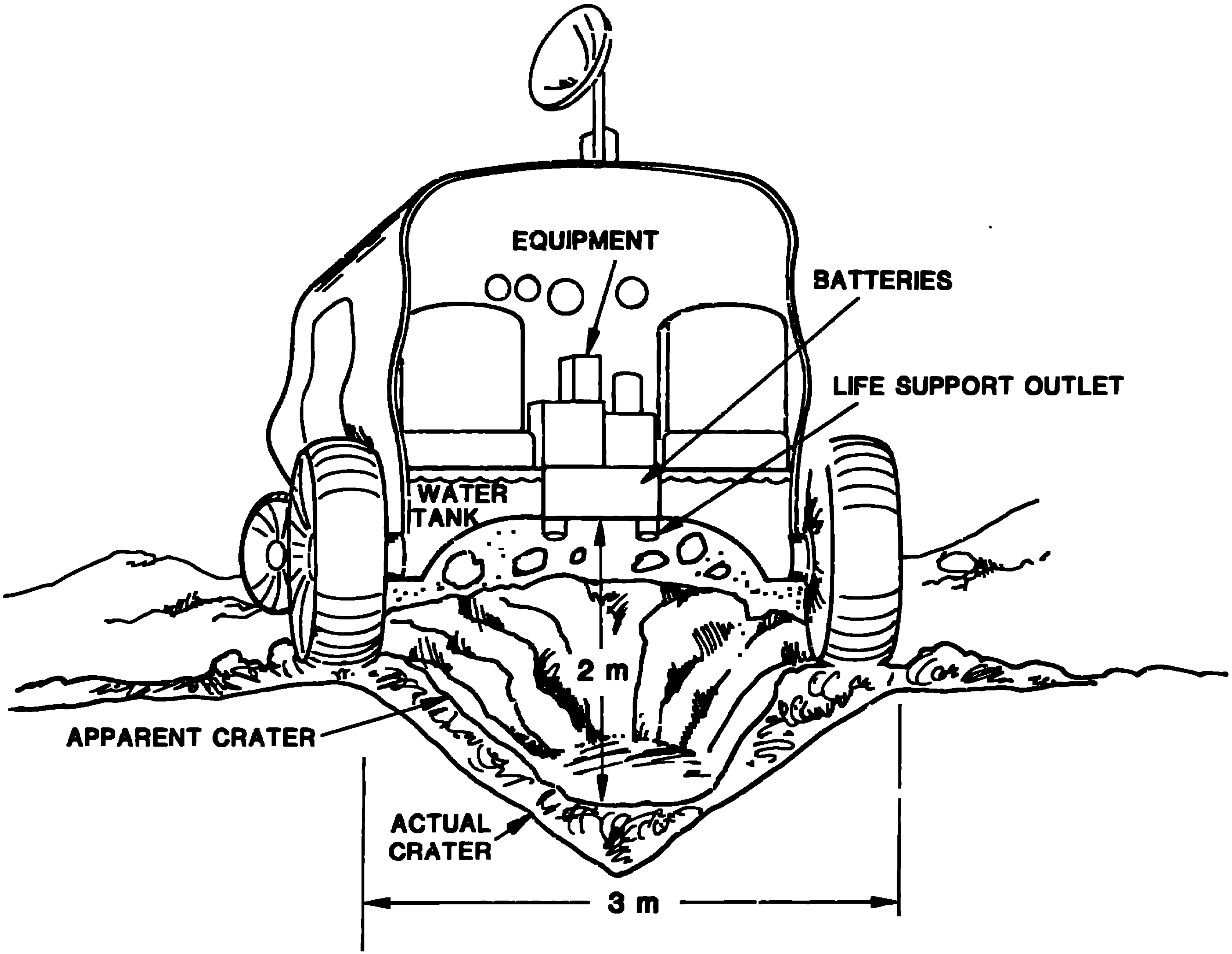
(a) - Enlargement of Site A, B, or C by a factor of 2.

(b) - Enlargement of initial base by a factor of 2.

(c) - Initially, 2.1m square by 10m long; extended in length and diameter for permanent base.

(d) - 2m deep by 10m long trench for placement of module that is subsequently covered by casting.

(e) - Crater 2m deep by 8m diameter.



ROVER VEHICLE

Fig 1

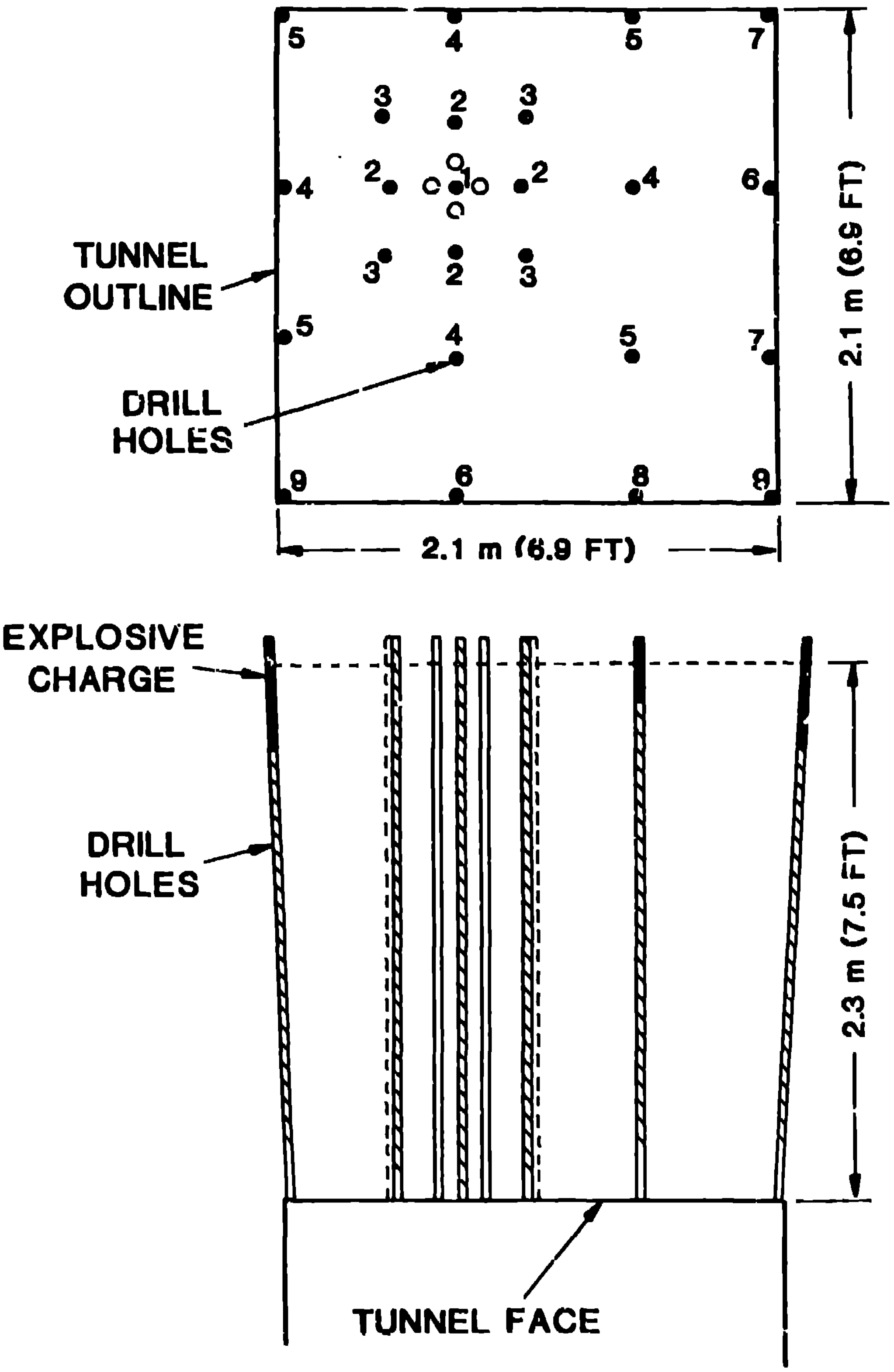

TUNNEL OUTLINE
DRILL HOLES
2.1 m (6.9 FT)
2.1 m (6.9 FT)
5
4
5
7
3
2
3
2
1
2
4
4
6
3
2
3
5
4
5
7
9
6
8
9
EXPLOSIVE CHARGE
DRILL HOLES
2.3 m (7.5 FT)
TUNNEL FACE

Fig 3

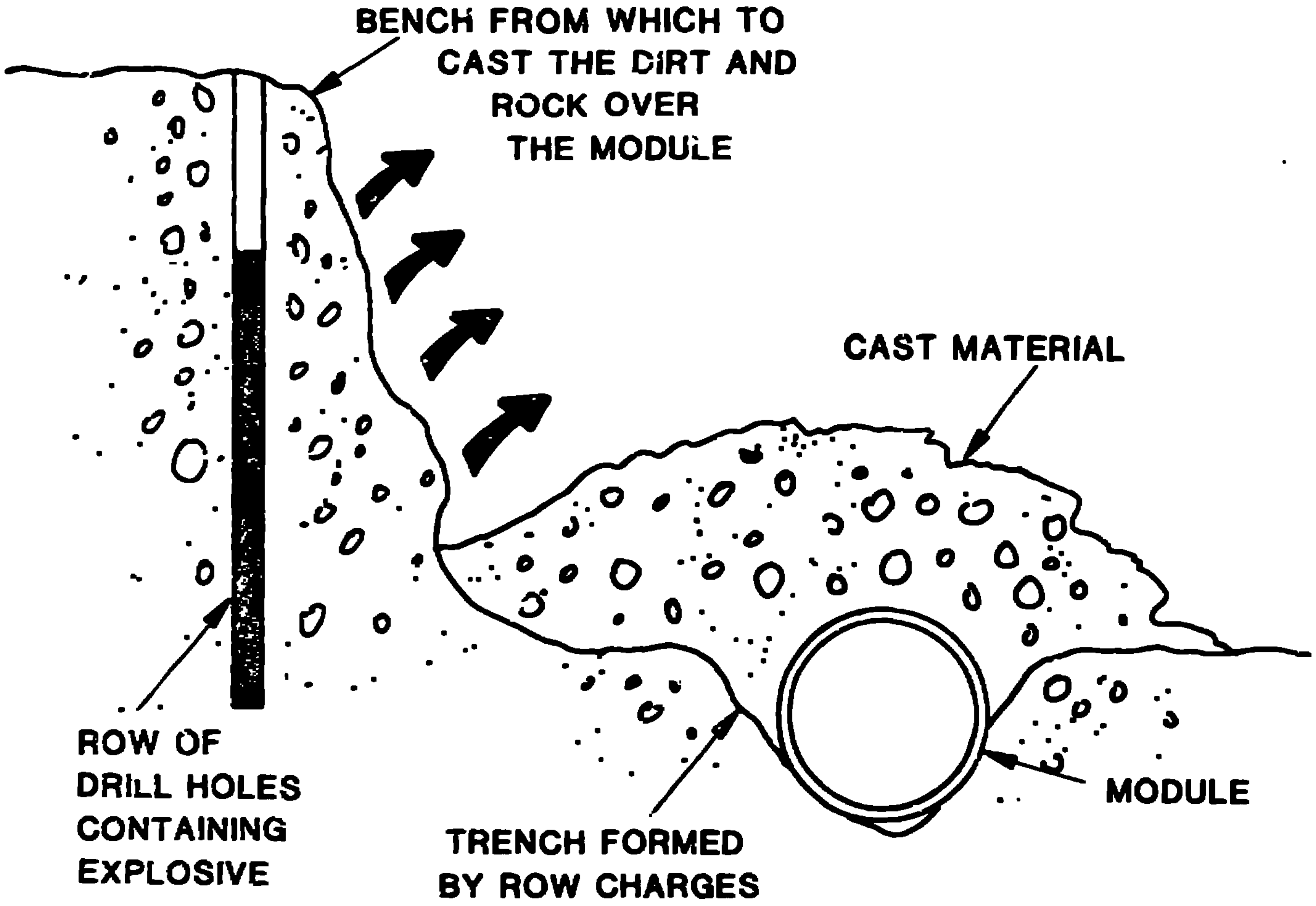

BENCH FROM WHICH TO CAST THE DIRT AND ROCK OVER THE MODULE
CAST MATERIAL
ROW OF DRILL HOLES CONTAINING EXPLOSIVE
TRENCH FORMED BY ROW CHARGES
MODULE

Fig 2