AD ________________

AD724646

NCG TECHNICAL REPORT NO. 25

STUDY OF EXPLOSIVES FOR LUNAR APPLICATIONS

U. S. ARMY ENGINEER NUCLEAR CRATERING GROUP

LIVERMORE, CALIFORNIA

FEBRUARY 1971

THIS DOCUMENT HAS BEEN APPROVED FOR PUBLIC RELEASE AND SALE. DISTRIBUTION IS UNLIMITED.

182

Destroy this report when no longer needed.
Do not return it to the originator.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Printed in USA. Available from Defense Documentation Center,
Cameron Station, Alexandria, Virginia 22314 or
National Technical Information Service,
U. S. Department of Commerce
Springfield, Virginia 22151

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Engineer Nuclear Cratering Group Livermore, California	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
	2b. GROUP N/A

3. REPORT TITLE

STUDY OF EXPLOSIVES FOR LUNAR APPLICATIONS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

MAJ Richard W. Mattes, U. S. Army

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1971	181	74

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	NCG Technical Report No. 25
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	None

10. DISTRIBUTION STATEMENT

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
N/A	Extraterrestrial Research Agency Advanced Technology Branch Engineering Division Directorate of Military Construction, OCE

13. ABSTRACT

This report describes a preliminary study of the use of chemical high explosives in support of anticipated lunar base activities. The introductory sections present a brief summary of terrestrial chemical high explosives state-of-the-art in the fields of excavation, quarrying, mining, tunneling, shallow-hole drilling and seismic surveying. Explosive excavation is described through discussions of explosive excavation principles, explosives and their properties, methods of charge emplacement and firing, and phenomena and methods of predicting magnitudes of the potentially harmful explosion side effects of ground motion, airblast, and missile (ejecta) throwout.

Based on known and assumed properties of the moon and its environment, a preliminary theoretical study indicates that terrestrial modeling of lunar explosion craters is possible at one-six scale in chambers evacuated to about 30 mm Hg or at full scale by subsequent mathematical adjustment of ejecta ranges, provided an accurate lunar crust model can be constructed. Analyses show that blast waves formed by expanding explosion gases represent no serious hazard in lunar blasting and that missiles (ejecta) will be thrown at least six times farther on the moon as on earth. Current terrestrial ground motion predictive methods are suggested as first approximations to lunar ground motion effects of subsurface explosions. The various elements and suggested techniques of designing lunar explosive excavation projects are discussed. Some applications of explosive excavation techniques are suggested for personnel protection, engineering support

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Construction						
Underground Construction						
Explosives						
Civil Engineering						
Moon						
Excavation						
High Explosives						
Quarrying						
Mining						
Shaped Charges						
Ditching						
Drilling						
Explosion Effects						
Lunar Bases						

of lunar scientific investigations, and lunar base activities. Conceptual designs are presented for six hypothetical applications.

An investigation of the training required for a space crew to perform lunar explosive excavation projects identifies the tasks involved in increasingly complicated projects, examines the background required of a trainee, suggests a course of instruction to prepare space crews for explosive excavation projects of the near future, and assesses Department of the Army capabilities to provide such training.

Areas not fully investigated in this preliminary report are recommended for future research. The recommendations are accompanied by an assessment of the existing capability of Department of the Army agencies to perform the necessary research.

UNCLASSIFIED
Security Classification

BLANK PAGE

TID-4500, UC-35

NCG TECHNICAL REPORT NO. 25
STUDY OF EXPLOSIVES FOR LUNAR APPLICATIONS

U.S. Army Engineer Nuclear Cratering Group
Livermore, California

February 1971

Preface

This report, "Study of Explosives for Lunar Applications," was prepared by the U.S. Army Engineer Nuclear Cratering Group (NCG), Livermore, California, for the Extraterrestrial Research Agency (EXTERRA), Advanced Technology Branch, Engineering Division, Military Construction Directorate, Office of the Chief of Engineers, in accordance with Intra-Army Order for Reimbursable Services, ENG-ENGC 70-1.

The report, prepared by MAJ Richard W. Mattes, is based on information contained in four supporting NCG Technical Memoranda: NCG/TM 70-3, "Chemical Explosive Excavation—State-of-the-Art," by SP5 Randall K. Leu, NCG/TM 70-4, "Explosive Excavation on the Moon," by CPT Robert F. Bourque, NCG/TM 70-5, "Conceptual Lunar Applications of Chemical Explosives," by LT Gene E. Thorne, and NCG/TM 70-6 "Training for Chemical Explosives Employment for Lunar Applications," by CPT Kenneth E. Sprague.

The Chief, EXTERRA, during the conduct of this study was Mr. Harry N. Lowe, Jr., and the Directors of NCG were COL William E. Vandenberg and LTC Robert L. LaFrenz.

Abstract

This report describes a preliminary study of the use of chemical high explosives in support of anticipated lunar base activities. The introductory sections present a brief summary of terrestrial chemical high explosives state-of-the-art in the fields of excavation, quarrying, mining, tunneling, shallow-hole drilling and seismic surveying. Explosive excavation is described through discussions of explosive excavation principles, explosives and their properties, methods of charge emplacement and firing, and phenomena and methods of predicting magnitudes of the potentially harmful explosion side effects of ground motion, airblast, and missile (ejecta) throwout.

Based on known and assumed properties of the moon and its environment, a preliminary theoretical study indicates that terrestrial modeling of lunar explosion craters is possible at one-sixth scale in chambers evacuated to about 30 mm Hg or at full scale by subsequent mathematical adjustment of ejecta ranges, provided an accurate lunar crust model can be constructed. Analyses show that blast waves formed by expanding explosion gases represent no serious hazard in lunar blasting and that missiles (ejecta) will be thrown at least six times farther on the moon as on earth. Current terrestrial ground motion predictive methods are suggested as first approximations to lunar ground motion effects of subsurface explosions. The various elements and suggested techniques of designing lunar explosive excavation projects are discussed. Some applications of explosive excavation techniques are suggested for personnel protection, engineering support of lunar scientific investigations, and lunar base activities. Conceptual designs are presented for six hypothetical applications.

An investigation of the training required for a space crew to perform lunar explosive excavation projects identifies the tasks involved in increasingly complicated projects, examines the background required of a trainee, suggests a course of instruction to prepare space crews for explosive excavation projects of the near future, and assesses Department of the Army capabilities to provide such training.

Areas not fully investigated in this preliminary report are recommended for future research. The recommendations are accompanied by an assessment of the existing capability of Department of the Army agencies to perform the necessary research.

Selected Nomenclature

D_a — Depth of apparent crater for a given explosive energy measured below and normal to original ground surface.

D_t — Depth of true crater for a given explosive energy measured below and normal to original ground surface.

DOB — Depth of burst for a given explosive energy.

H_{al} — Height of apparent lip crest for a given explosive energy measured above and normal to original ground surface.

L/D — Ratio of cylindrical charge length to charge diameter.

R — Range for ground motion effects.

R_a — Radius of apparent crater for a given explosive energy measured at original ground surface.

R_{al} — Radius of apparent lip crest for a given explosive energy.

R_{eb} — Radius of outer boundary of continuous ejecta for a given explosive energy.

R_t — Radius of true crater for a given explosive energy measured at original ground surface.

Y — Explosive energy.

d_a — Scaled depth of apparent crater (m/metric ton $TNT^{0.3}$ or m/$Mcal^{1/3}$).

d_t — Scaled depth of true crater (m/$Mcal^{1/3}$).

dob — Scaled depth of burst (m/kg $TNT^{1/3}$, m/metric ton $TNT^{0.3}$ or m/$Mcal^{1/3}$).

r_a — Scaled radius of apparent crater (m/metric ton $TNT^{0.3}$ or m/$Mcal^{1/3}$).

r_t — Scaled radius of true crater (m/$Mcal^{1/3}$).

Contents

FIGURES

FIGURES (continued)

TABLES

Chapter 1
Introduction

1.1 PURPOSE

This preliminary study was undertaken to identify potential applications of chemical high explosives in selected lunar construction and engineering support activities, to determine those areas of a lunar explosive excavation technology requiring additional research and development, and to outline training requirements for space mission crews that will carry out lunar explosive excavation applications.

1.2 BACKGROUND

Exploration and scientific discovery were and are the primary reasons for man's voyages to the moon. The scientific community is eager to continue these programs on the moon and to extend them deeper into the reaches of space. The moon is a predominant feature in many of the exploratory programs; aside from the knowledge to be gained from the study of the moon itself, the earth's satellite offers a place to observe the rest of the universe, unencumbered by distortions caused by the earth's atmosphere. It may also be pressed into service as a staging place for visits to other celestial bodies. In either case, the need for lunar bases arises.

Unique construction and engineering support problems are posed in connection with lunar scientific investigations and the establishment of bases. Lack of an atmosphere makes internal combustion engines unpractical as power sources and limits the efficiency of machinery operators, due to their cumbersome space suits and to loss of production time when crews must seek protection from temperature, radiation, and meteoroid hazards. The reduced gravity affects all construction equipment whose proper functioning depends on weight, as does ripping or ditching machinery. It is possible that the large amounts of energy available in relatively small packages of chemical high explosives could materially reduce the time, effort, equipment, and, therefore, cost of supporting lunar exploration and exploitation programs. Explosives are already used in spaceflight systems. For example, they have been used as a reliable means of severing the Apollo command module from the lunar and service modules and as a means of opening spacecraft hatches. It is appropriate, then, to consider the use of chemical high explosives to increase the efficiency of lunar operations.

1.3 ORGANIZATION AND SCOPE

This report consists of eight chapters. It examines the use of chemical high explosives, on earth and on the moon, in selected activities. These activities include excavation, mining, quarrying, tunneling, shallow hole drilling, and geophysical surveying.

Chapter 2 is a brief introduction to chemical high explosives and the effects accompanying their detonation on earth.

It discusses explosive excavation principles and explosives characteristics. An explanation of the methods of charge emplacement and firing precedes consideration of potentially harmful explosion side effects and safety. Chapter 3 discusses some specific uses of explosives on earth, presented in three general categories: surface excavation, quarrying, and mining; subsurface excavation and mining; and seismic surveying.

Chapter 4 considers the use of explosives on the moon. A summary of the known and assumed characteristics of the moon and its environment provides a basis for determination of procedures to model lunar explosion craters on earth by altering the length scale and by using full scale. The characteristics required of lunar explosives are determined, and some candidate formulations are suggested. A discussion of engineering design considerations, charge emplacement hole construction methods, and post-detonation operations includes conventional drilling and some systems using explosives. The potentially hazardous lunar explosion side effects of ground motion, blast, and missile throwout are discussed, and methods of predicting their magnitudes are proposed as safety considerations. Chapter 5 discusses the potential requirements envisioned for excavation on the moon to provide shelter, storage, and operating facilities for the lunar base and to exploit natural lunar resources. This chapter goes on to investigate six representative hypothetical projects.

Chapter 6 delineates, for lunar projects of varying complexity, the tasks that a space crew member would be expected to perform in employing explosive excavation techniques. Based on the task analysis, the background of a person to be trained in explosive excavation techniques is established, and a training program is suggested to provide the necessary skills. Finally, an assessment is made of the Department of the Army's capabilities to provide the suggested training.

Chapter 7 outlines those aspects of lunar explosive excavation technology requiring further research and identifies those agencies of the Department of the Army believed capable of conducting these programs.

The report's findings are presented in Chapter 8.

1.4 SUMMARY OF FINDINGS

Explosive excavation methods offer an attractive alternative to mechanical techniques for the engineering support of lunar scientific investigations and for the construction of lunar bases. Subsurface lunar explosions should produce relatively deep craters, with approximately the same level of ground motion, reduced blast levels, and greater missile (ejecta) range and scatter than an identical explosion in identical materials on earth. Lunar explosion craters can be modeled on earth either at one-sixth scale in an evacuated chamber or at full scale with subsequent compensation for the effect of the reduced lunar gravity on fallback.

Some current terrestrial chemical high explosives formulations can be used with little modification in lunar projects. Alternatively, safe, high energy-density explosives similar to the aluminum-liquid oxygen type can be developed expressly for lunar explosive excavation projects.

Explosive excavation techniques would permit rapid emplacement of temporary lunar base structures and ancillary operating facilities. Removal of valuable lunar ore materials could be expedited with explosive excavation techniques by exposing and breaking up ore bodies for further processing.

The Department of the Army possesses adequate capability to train space mission crews in the techniques of explosive excavation. It appears, also, that this agency has good capability to perform the additional research necessary to develop fully a lunar explosive excavation technology.

Chapter 2

Explosive Excavation Technology

Explosive excavation technology has been developed significantly during the last three decades. Much has been learned about explosives, their characteristics, and their detonation side effects. This chapter gives a brief introduction to chemical high explosives. It discusses the effects of subsurface detonations on adjacent materials. It introduces the more important explosives properties and their significance in the various components of an explosive detonation sequence. The various methods of explosive charge emplacement construction, loading, and firing are surveyed. Finally, the potentially hazardous explosion side effects and methods used to predict their magnitude and range are briefly described.

2.1 EXPLOSIVE EXCAVATION PRINCIPLES

Ignition of certain chemical substances produces the rapid reaction known as detonation. This reaction, generally started by an intense shock, radiates outward as a shock wave causing immense increases in pressure, temperature, density, and particle velocity. Temperatures, thousands of degrees Centigrade, and pressures exceeding a quarter of a million atmospheres cause the explosive to vaporize and to react in a narrow zone behind the shock wave. A reaction rate sufficient to sustain the wave velocity will allow the detonation to go to completion; a lesser rate would result in ordinary burning (deflagration) of the explosive material or would cause the reaction to cease altogether.

Explosive excavation principles are based on the consequent changes in the materials surrounding the explosion point. The following discussions describe these effects from a subsurface explosion and the variation of effects possible by changing the burial depth at which an explosion of given energy occurs. They also address the effects of multiple explosion interactions and the manner in which the fractured materials may be moved by the explosion forces toward preselected locations (directed blasting).

2.1.1 Single Subsurface Explosion

The energy contained in the high-pressure, high-temperature explosion gases is coupled to the surroundings and causes fracturing of the subsurface medium. Three major zones of disturbance around the point of detonation can be categorized as shown in Fig. 1. The central area, immediately adjacent to the charge emplacement hole, is termed the explosion cavity. It is the region surrounding the explosion in which the detonation pressure has vaporized and compressed the walls of the charge emplacement hole to form an enlarged void.

Materials beyond the explosion cavity are deformed by the very high stresses caused by the shock wave that travels radially outward at a velocity of several thousand meters per second. The wave energy is dissipated by doing work on the materials it passes through, as evidenced by a reduction in the degree of material disturbance with range. The region immediately adjacent to the explosion cavity is characterized by extensive crushing. Next is found a region of radially cracked material. Cracks in that portion of the region closest to the detonation are subsequently expanded by the gas pressure which lags behind the shock wave. Cracking in the outer portion of the cracked region is considerably less extensive due to degradation of the expanding gas pressure. The amount of crushing and cracking can be reduced through the use of explosives with lower detonation pressures or charges smaller in diameter than the emplacement hole.

By the time the shock wave reaches the outermost region, about 80% of its original energy has been dissipated. This outer region is not stressed to failure, although fracturing can occur if the wave encounters a free surface such as the ground surface. A wave that does reach a free surface is reflected by it, causing tension stresses in the material. Rock is particularly weak in tension and fails readily under this condition; such failure is called spalling.

Cratering is the use of large, concentrated explosive charges to fracture and to eject the broken materials, as contrasted with conventional blasting in which the energy of the explosion is used principally to break up the materials. The cratering mechanism is the same as the conventional blasting mechanism through the point of spall as described above. Cratering results when charges are designed with sufficient energy that the reflected tensile wave returns to the explosion cavity and relieves its nearest boundary, allowing the high internal gas pressure to expand the cavity asymmetrically toward the free surface and eventually to break the surface.

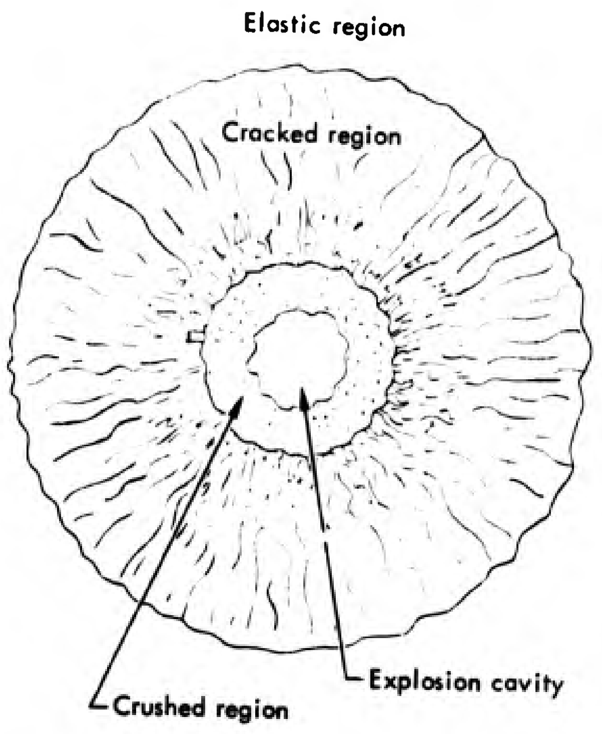


Fig. 1. Disturbed regions around an explosion.

The surface above the detonation mounds until a maximum velocity is attained and then dissociates, allowing the trapped gases to vent (venting gases may further accelerate the broken mound materials). The mound materials decelerate and go into ballistic trajectories. Some of this material is ejected beyond the crater edge to form the crater lips, while the remainder drops back into the crater to form the visible part of the crater, the apparent crater.

2.1.2 Effect of Depth of Burst

The effects produced by a buried explosion vary significantly with the distance between the center of mass of the explosive charge and the nearest free surface, or with the perpendicular distance between

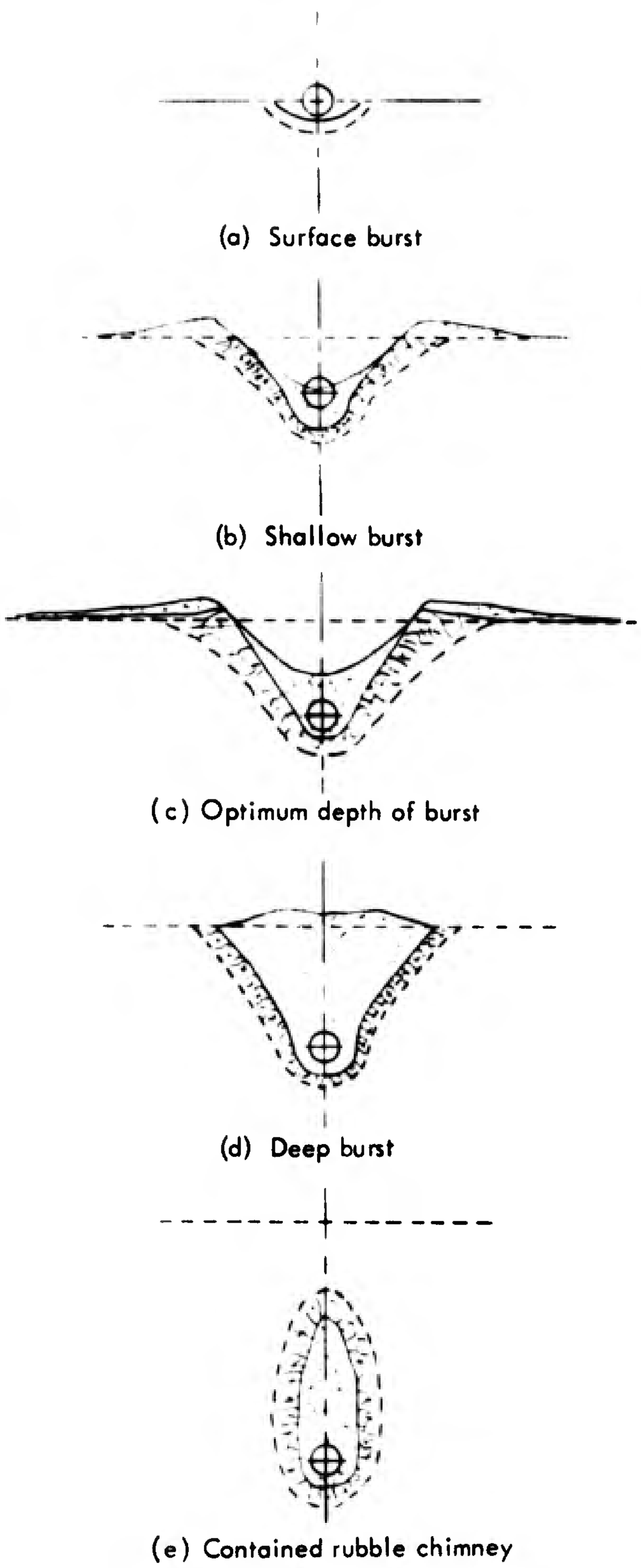


Fig. 2. Variation of crater profile with depth of burst in rock.

the axial centerline of a conventional blasting charge (as a quarrying charge) and its nearest free surface. The latter measurement is also known as the burden. Figure 2 illustrates the changes in shape, size, and degree of fracturing that occur as the depth of burst of a given charge is varied. A shallow depression and rupture zone are formed by crushing, compacting, and scouring the material below a surface burst—Fig. 2(a). Most of the explosion's energy is wasted to the atmosphere. Increasing the depth of burst increases the volume of fractured material and the volume of material thrown out—Fig. 2(b). For excavation purposes, optimum depth of burst is reached when the maximum amount of rock is thrown out, as shown in Fig. 2(c). Continuing to increase the explosion depth causes a greater volume of fractured rock, a desirable condition in most rock blasting—Fig. 2(d). An explosion buried so deeply that no surface expression is apparent, as shown in Fig. 2(e), is called a contained explosion. Here, some of the cracked material above the explosion cavity may collapse and fall into the cavity. Whether the cavity roof collapse will proceed to the surface depends on the competency of the overhead materials and the degree of bulking of the fallen materials. A strong rock layer could stop the collapse by bridging, or the cavity could fill up with broken, bulked material to halt the upward growth of the cavity.

The complexity of the processes involved in explosive excavation has prevented exact mathematical determination of the depth of burst required to obtain desired results. Rules of thumb are used to determine burden in conventional surface blasting, and empirical scaling relationships are used for determining optimum cratering depth of burst. As a general rule, field experiments are conducted to confirm the choice of depth of burst for the site material conditions.

2.1.3 Multiple Explosion Interaction

The excavation process can be made more efficient by the proper positioning and initiation sequence of multiple charges. In this technique, each explosion creates a new free surface to which the succeeding one can break.

As a practical matter, prediction of shock wave interaction from multiple explosions is not feasible. On the other hand, it is possible to take advantage of the effects of the interaction of shock waves and sustained gas pressure from adjacent explosions. The degree of effects interaction depends on the geometry and timing of the detonations. If adjacent charges are detonated individually or with a delay interval so long as to allow the effects of the first detonation to be completed before the effects of the second cause reinforcement, no stress interaction can take place. The effective result, then, is a series of individual detonations; charges in a row should be spaced a distance equal to the burden.

As the delay interval between detonations is reduced, mutual reinforcement of stress effects will tend to offset the energy reduction taking place as the stress wave moves spherically away from the point of detonation. For weak materials, optimum stress interaction occurs with a charge spacing only slightly greater than the burden; maximum effect in more competent materials calls for spacing about 50% greater.

2.1.4 Directed Blasting

The velocity imparted to materials that have been fractured by an explosion, in addition to causing those materials to be ejected from the excavation, can be used to direct the excavated materials toward a preselected location. Directed blasting employs a ballistic trajectory of the ejected materials to accomplish that result. Since the initial velocity of any particle affects its ballistic range, directed blasting is essentially the process of influencing the speed and direction of fractured materials.

Both of those factors (speed and direction) are manipulated by variation of the burden and the geometry of the nearest free surface seen by the explosion. In general, the majority of material throwout from an explosion will be along a line coincident with the line of least resistance between the point of the explosion and the nearest free surface. Since the amount of energy available to impart speed to surface particles is reduced as the line of resistance lengthens, the range of throwout will also decrease.

The ejecta distribution from an explosion behind a plane vertical surface would appear in plan somewhat as shown in Fig. 3(a). The ejecta boundary is seen to be lesser as the distance between the charge and the original ground surface increases. If a hemispherical excavation is formed in the free surface by a preliminary explosion or by mechanical methods prior to detonation of the charge, the ejecta boundary would approximate that shown in Fig. 3(b). Here greater range has been obtained for the majority of the ejected materials by reducing the amount of resistance encountered by the

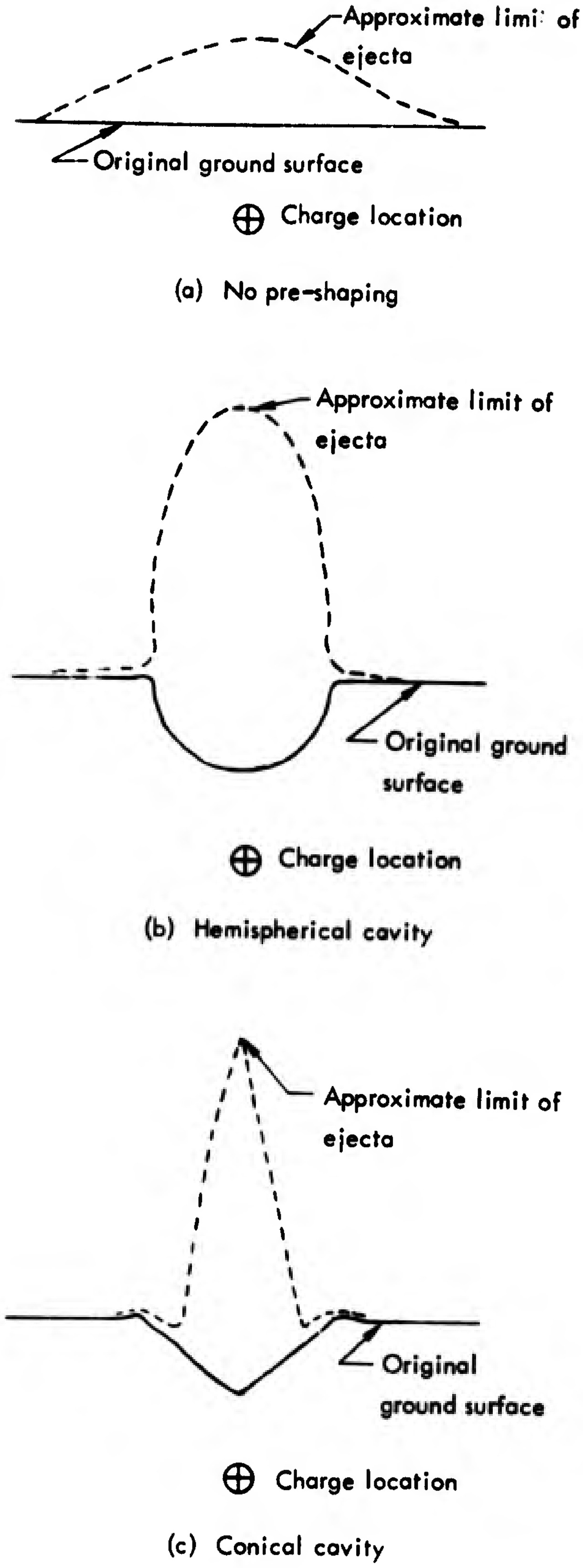


Fig. 3. Examples of directed blasting (adapted from Pokrovskii, Fedorov, and Pokuchaev, 1951).

explosion energy in traveling to the free surface. Detonation behind a conical excavation is illustrated in Fig. 3(c).

2.2 EXPLOSIVES AND DETONATORS

A chemical explosive is a substance that is initiated by heat, impact, friction, or shock to produce an extremely rapid, self-propagating reaction. The amount of heat generated by this reaction is a measure of the capacity of the explosive to do work. This section discusses explosives and detonators, their ingredients and properties, and the characteristics of some explosives.

2.2.1 Primary and Secondary Explosives

Explosive substances react at various rates. The condition in which the reaction front moves through the explosive faster than the local speed of sound in the unreacted material is termed detonation. When the front moves slower than the speed of sound, the term deflagration is used. High explosives detonate; low explosives deflagrate.

Every explosive in cylindrical form has a critical diameter below which it cannot sustain a detonation. This diameter may be in the microscopic range, a condition ideal for detonating cord, or may be as large as 25 cm. It can be reduced by the use of additives, such as fuel oil, reduction of explosive particle size, or confinement in a pipe or borehole. The critical diameter will increase in an explosive packed too densely; therefore a proper balance between particle size and density is needed to produce the desired results.

Primary high explosives are extremely unstable substances; their sensitivity, a measure of ease of initiation to heat or shock, is very high. The critical diameter of a primary high explosive is microscopic. Extreme caution is required when handling those materials, and they should be stored in small quantities, separately from other explosive material. Primary explosives are the principal constituents of detonators.

Secondary high explosives are less sensitive materials, requiring detonators or boosters to initiate detonation. Secondary high explosives are sensitive to shock and heat, although initiation by the latter sometimes requires a large mass of heavily confined explosive to cause detonation.

2.2.2 Explosive Properties

Some of the more important explosive properties are described below. The reported values of these properties will vary with the manufacturer and his method of property measurement.

a. Heat of Detonation

This is the energy released per unit mass of explosive expressed in units of cal/g. It is a measure of the ability of an explosive to do work. This measurement is sometimes given on a volumetric basis known as energy density, cal/cm^3.

b. Density

A characteristic that is usually expressed in terms of specific gravity or cartridge count. (Cartridge count is expressed as the number of 1-1/4- × 8-in. cartridges per 50-lb box.) An approximation of cartridge count is obtained by dividing 140 by the specific gravity of the explosive.

c. Detonation Velocity

Detonation velocity is expressed either as confined or unconfined in terms of meters per second (m/sec). It is influenced by the explosive density, the nature and particle size of its ingredients, the charge diameter, and the degree of confinement. Detonation velocity is increased to the maximum value for a given explosive by decreasing particle size and by increasing charge diameter and degree of confinement. Blasting agents and some explosives are particularly sensitive to diameter changes.

d. Detonation Pressure

This parameter is proportional to the product of density and the square of the detonation velocity. It is expressed in kilobars (kbar) and indicates the strength of the shock wave transmitted into the detonation medium. It is probably the best indicator of the ability of an explosive to break rock.

e. Weight and Cartridge Strength

Both are expressed as a percentage of straight nitroglycerine dynamite. The terms are commonly used by explosives manufacturers as a measure of the energy content of an explosive and the work it is capable of doing, although in practice the terms are inaccurate and misleading. Weight strength compares explosives on a weight basis; cartridge (or bulk) strength on a volumetric basis. A given mass of any explosive is equivalent to the same mass of any other explosive of the same weight strength (and each are equivalent to an equal mass of straight nitroglycerine dynamite having the same weight strength). As a rule, dynamites are rated by weight strength and gelatins by cartridge strength.

2.2.3 Primers, Boosters, Blasting Caps, and Detonating Cord

a. Primers and Boosters

The explosive used to provide the shock wave necessary to initiate the main explosive charge is called a primer. Boosters, sensitive secondary high explosives, are sometimes needed to reinforce the shock wave when the main charge is rather insensitive. Table 1 presents a summary of the properties and the uses of selected primer and booster explosives.

b. Blasting Caps

These devices are used to initiate an explosion either directly or through the use of an intermediate detonating cord. Electric blasting caps, the most common type, consist of two insulated leg wires connected by a thin-filament bridge wire. Electrical current passing through the bridge wire causes it to give off sufficient heat to ignite a flash charge of heat-sensitive explosive, which begins the blasting cap explosive chain. Explosion of the flash charge sets off the cap's primer charge which, in turn, detonates a base charge. The completed blasting cap explosion chain provides a shock wave of sufficient force to initiate a cap-sensitive explosive or detonating cord.

It is possible to build a time delay into the cap's explosive chain by placing a delay element consisting of appropriately compounded and calibrated materials between the bridge wire and the primer charge. Two basic types of delays are available: millisecond delays in increments of 25 and 50 msec, and standard delays in increments of 1/2 and 1 sec.

Table 1. Properties and uses of primer and booster explosives.

Explosive	Specific gravity	Confined detonation velocity (m/sec)	Uses
TNT	1.64	6700 - 6900	Primer and booster for blasting agents; free-running explosive (pelletized form); sensitizer for slurries; component of other explosive mixtures.
PETN	1.76	7600	Detonator priming composition; blasting cap base charge; detonating cord core load.
Pentolite	1.65	7300 - 7600	Primer and booster for blasting agents (consists of equal parts TNT and PETN).
RDX	1.70	8200	Primary ingredient of compositions B, C-3, C-4; detonator base charge.
Composition B	1.65	7600	Primer and booster for blasting agents; shaped charges for oil well perforators and furnace tappers, consists of RDX, TNT, 1% wax.
Tetryl	1.71	7800	Primary boosters.
HMX	1.89	9100	Component of plastic bonded booster explosives.

c. Detonating Cord

Detonating cord is also called detonating fuse. Detonating cord consists of a core of high explosive, usually PETN, protected by a waterproof shield and a flexible reinforcing cover of various combinations of fabric, plastic wire, and waterproofing materials. Detonating cord is used to initiate explosive charges and is itself initiated by a blasting cap. Its insensitivity to external shock and friction significantly reduces the danger of premature detonation since the blasting cap can be connected to the firing circuit just prior to the time of the scheduled detonation.

Delay connectors can be inserted in the detonating cord circuit for delay blasting. They are made with various millisecond delays.

2.2.4 Dynamites, Gelatins, Blasting Agents, and Liquid Oxygen Explosives

These compounds are the essential elements of the main blasting charge. The various types are described below and selected characteristics are given in Table 2.

a. Dynamites

There are two basic types: straight and extra (or ammonia) dynamites. The principal constituents of straight dynamites, nitroglycerine and sodium nitrate, make them highly sensitive to shock, friction, and heat. These hazards, the susceptibility of nitroglycerine to freeze at low temperatures and high cost, account for the gradual decline in the use of straight dynamites. One area in which the sensitivity of straight dynamite becomes an advantage is in ditching operations, where the closely spaced charges can be initiated by sympathetic detonation, eliminating the need for cap or detonating cord connection to each charge.

Extra, or ammonia, dynamites contain ammonium nitrate in place of a portion of the nitroglycerine and sodium nitrate found in straight dynamites. Variation of the density and grain size of the ingredients results in the classification of high density and low density extra dynamites. The reduction in density is accompanied by the lowering of the detonation velocity. The extra dynamites are considerably less sensitive to shock and friction than straight dynamites.

b. Gelatins

A gelatin form of the dynamites is produced by using nitroglycerine or other explosive oil. Blasting gelatin is made by adding nitrocellulose to nitroglycerine. It has a very high detonation velocity and is the most powerful of all commercial explosives. Straight and extra gelatin dynamites have higher detonation velocities than do their counterpart ungelatinized forms. Semigelatin dynamites have a greater proportion of ammonium nitrate than either the extra or extra gelatin dynamites. Unlike other explosives, though, the detonation velocity of the semigelatins is not seriously affected by a lack of confinement.

c. Blasting Agents

Blasting agents are primarily mixtures of inorganic nitrate oxidizers and carbonaceous fuels. None of the ingredients are themselves explosives, and the mixture cannot be detonated by a No. 8

Table 2. Some properties of explosives and blasting agents.

Explosive	Specific gravity	Cart-ridge count	Weight strength (%)	Cart-ridge strength (%)	Confined detonation velocity (km/sec)	Calculated detonation pressure (kbar)	Heat of detonation (kcal/g)	Water resist-ance	Fume class
TNT	1.64	85	a	a	6.7-6.9	220	1.1	good	poor
Straight NG dynamite	1.4 -1.3	100-106	20-60	20-60	2.8-5.8	25- 95	0.98(40%) 0.99(60%)	poor—good	poor
High-density ammonia dynamite	1.3	110	20-60	15-52	2.4-3.8	20- 45		fair	good
Low-density ammonia dynamite									
High velocity	0.8 -1.2	174-120	65	20-50	2.5-3.4	15- 30	0.88(1.2)	poor—fair	fair
Low velocity	0.8 -1.2	174-120	65	20-50	1.9-2.5	10- 20	0.88(0.8)	poor—fair	fair
Blasting gelatin	1.3	110	100	90	7.6-7.9			excel-lent	poor
Straight gelatin	1.7 -1.3	85-105	20-90	30-80	3.4-7.0	60-140	0.82(40%) 1.15(75%)	excel-lent	good—poor
Ammonia gelatin	1.6 -1.3	90-105	30-80	35-72	4.3-6.1	60-105	0.80(40%) 0.99(75%)	excel-lent	very good
Semigelatin	0.9 -1.3	150-110	60-65	30-60	3.2-3.7	25- 40	0.94	fair—very good	very good
Blasting agents		Emplacement hole diameter (mm)	Loading density of hole (kg/m)						
Dry blasting agents	0.5 -1.0	38-305	0.9-70	—[a]	2.1-4.1	—	—	—	—
ANFO	0.75-0.95	—	—		2.7-4.6	60	0.89	poor—fair	good
Slurries	1.05-1.6	—	—		3.4-5.5	60-104	1.4-2.1	excel-lent	good

[a]Not applicable.

blasting cap. A primer charge of high explosive must be used to detonate a blasting agent because of its insensitivity. ANFO, a mixture of ammonium nitrate prills and fuel oil, is the most widely used dry blasting agent.

Slurries, or water gels, contain high proportions of ammonium nitrate and are classed as blasting agents unless some explosive substance is included in the mixture, in which case they are classed as explosives. Slurry blasting agents are not cap-sensitive; slurry explosives may be cap-sensitive. The detonation velocity of a slurry varies with the ingredients and the degree of confinement and density but is not as dependent on charge diameter as is the detonation velocity of a dry blasting agent. The heat of detonation can be increased by the addition of finely powdered metal, such as aluminum. High-velocity explosive primers are required with slurry blasting agents. High-explosive boosters are frequently used to insure complete detonation.

d. Liquid Oxygen Explosives

These explosives, consisting of an abosrbent fuel which is dipped in liquid oxygen, have been used at times in mines. Both components are of themselves non-explosive; the mixture, however, is highly explosive and sensitive to shock and friction. Liquid oxygen explosives do have the advantage, though, of losing their explosive nature after a short time, a distinct advantage in case of a misfire. Their heats of detonation, depending on the fuel used, range from 1500 to about 3800 cal/g. They have unconfined detonation velocities of 330 to 4800 m/sec.

2.3 CHARGE EMPLACEMENT AND FIRING

A number of methods are used in penetrating subsurface materials to form access holes (boreholes) and to provide explosive emplacement chambers. Categorized according to form of attack, they are mechanical, thermal, fluid, chemical, sonic, electrical, and nuclear. Methods of the first three categories are discussed in this section along with a brief treatment of charge loading and firing techniques.

2.3.1 Charge Hole and Cavity Formation

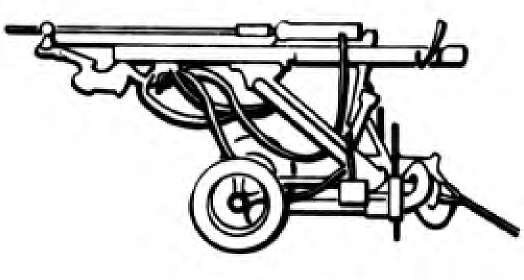
Drilling is the most commonly used form of the mechanical method of charge hole and cavity formation. Some use is made of the jet piercer, a thermal method, where the nature of subsurface materials permits. The use of shaped charges is being investigated as a potential fluid attack form of hole formation.

a. Drilling

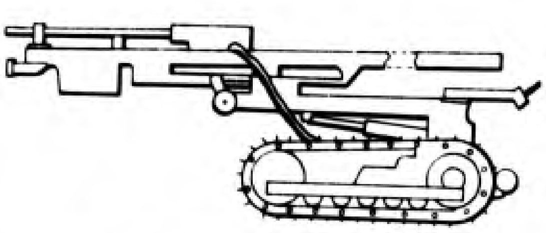
This term includes two basic actions employed in drilling schemes: percussive and rotary. Percussive action drilling equipment uses a chisel-shaped or cross bit that is repeatedly impacted against the material being drilled. The rock is fractured by crushing and chipping. The percussive bit rotates but does so during rebound, when not in contact with the rock surface. The simplest drill of this type is the churn drill, which operates by raising and dropping a chisel-shaped bit by means of a cable. Churn drills are not in common use for emplacement drilling.

Surface hammer drills, such as jackhammers and drifters, operate with the hammer at the surface. Jackhammers are portable, air-operated drills primarily used for drilling in a downward direction. They are capable of drilling holes up to about 63 mm in diameter and 6 m deep. Generally, air is used to cool the bit and remove chips. Drifters, on the other hand, are larger, air-operated drills that are mounted on wheeled or tracked platforms and are capable of drilling at virtually any angle. Wagon (wheeled) drills (Fig. 4) work best for holes up to 76 mm in diameter and about 6 m in depth. They are very difficult to use on steep slopes and are not generally used for holes inclined above the horizontal. Production rate for wagon drills varies up to approximately 15 m of hole per hour.

A much more versatile version is the crawler-mounted drifter (Fig. 4). Hole capability ranges up to 63 mm in diameter and to as much as 30 m in depth. Its angle of penetration is unlimited, and the drill can safely operate on slopes up to 30 deg.



(a) Wagon drill



(b) Crawler-mounted drifter drill

Fig. 4. Drilling equipment.

Compared to wagon drills, crawler-mounted drifters consume about 50% more operating air, but the blast holes they drill can produce three times as much rock.

For underground use, a number of drifters are mounted on rail-transported rigs called jumbos.

Down-the-hole drills have their hammer behind the drill bit in the hole, eliminating the energy loss through long lengths of intervening drill steel. As a result, they are capable of much higher penetration rates than surface hammer drills. Drill bit diameters range from 90 to 240 mm.

Rotary action drills, rather than percussive drills, are used for drilling larger diameter and deeper holes. There are basically two types of bits used on rotary drills: the drag bit, which applies both an axial and a tangential force to the rock, and the roller bit, which acts as a combination of percussion and drag bits.

The auger drill is an example of a drag bit. It is a rapid means of drilling shallow holes of large diameter. The bit consists either of a continuous spiral of metal that lifts the cuttings as the drill shaft rotates or a bucket that collects the cuttings. Cuttings are removed from the hole by pulling the bit to the surface or may be raised by an air- or water-operated system.

Roller bit rotary drills may be truck- or crawler-mounted or, in the case of large rigs, they may be erected on a specially constructed platform on the drilling site. Some type of fluid must be used to remove the cuttings. These drills are for large diameter (meters), deep hole (20 m or more) work. Roller bit drills can penetrate most materials.

For deep holes in high-strength materials, a rotary-percussion drilling system is sometimes used. It combines the percussive and rotary actions, making possible much increased penetration rates.

b. Jet Piercing

Jet piercing is a process of rock penetration that uses thermally induced differential expansion in materials to stress them to failure. This failure mechanism is known as spalling. The jet piercer uses the high temperature and high velocity of a rocket flame to produce the spalling mechanism. Hole size and shape are controlled by the frequency of burner passes along the hole. Some representative shapes are shown in Fig. 5. The ability to concentrate explosive charges in selectively widened sections of the hole significantly reduces the amount of drilling and stemming necessary.

Not all materials are amenable to the use of jet piercers, and, since formations are not homogeneous, some mechanical assistance may be necessary to complete holes to specification. Taconite, an iron ore, has spalling characteristics that make it a suitable application for jet piercing.

Fig. 5. Typical jet-pierced holes.

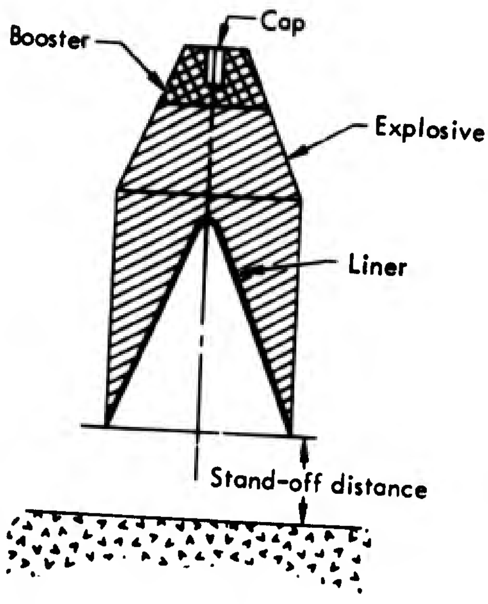


Fig. 6. Typical shaped charge.

c. Shaped Charges

A typical shaped charge is a cylindrical explosive column, tapered at the booster end and containing a metal-lined conical cavity at the other end (Fig. 6). When the charge is placed with its cavity end in the direction of a massive rock target at some stand-off distance from the target and detonated, the target material is penetrated.

The shaped charge is initiated at the tapered end by an electric blasting cap and may require a booster. As the detonation wave passes from the tip of the conical liner to its base, the liner collapses under the detonation pressure. First a stream of very high-speed particles (produced by spall) move in a direction nearly perpendicular to the surface of the original undisturbed linear material, then a lower velocity slug, formed by the collapsed liner material, follows the initial stream of particles and converges along the axis, forming a fast jet which penetrates the rock. Experiments have shown that rock strength influences the depth of penetration. Other observations indicate that, for a given shaped charge and target material, penetration depth increases with charge length, hole radius increases with the radius of the jet, and both hole depth and radius increase with explosive mass and detonation pressure.

Shaped-charge penetration techniques pose some difficulties including obvious ones of blast and flying fragments and the less obvious problem with multiple use. The multiple use problem occurs when successive shaped charges are lowered into the hole and fired (to achieve desired depth). To accomplish this, shaped-charge-formed holes must exceed the charge diameter, or the shaped-charge penetration must be insensitive to standoff distance. Conventionally designed shaped charges are unable to meet these requirements in hard rock, and secondary explosive charges (gauging charges) are necessary to open up the hole.

Use of currently available shaped charges for producing boreholes in rock is expensive. More closely controlled tests are needed to establish the laws of shaped-charge penetration of rock and the effect of different liner materials.

d. Multiple Pass Drilling

Equipment power capabilities may at times limit the hole diameter that can be achieved. A technique known as multiple pass drilling can be used to overcome this limitation by drilling the maximum size hole of which the drill rig is capable, then changing to a larger bit and redrilling the hole while maintaining the same contact area as the maximum-size full-bore bit. The penetration rate during each pass should be approximately the same. The ultimate drill size of which a given item of drilling equipment is capable by this technique is governed by its capability to overcome the increasing bit inertia and by the torsional strength of the drill string. In order to contact the same area on each pass, the incremental radius will become smaller for each successive increase in hole size. There is, then, a practical limit on the number of passes with respect to the gain in hole size.

e. Underreaming

Underreaming is a technique for increasing the diameter of a part of a drill hole, usually the bottom portion, that avoids the need to drill the entire hole full bore. The operation consists of drilling a pilot hole to the desired depth and of adequate size to pass the underreaming mechanism. At the appropriate depth, the underreaming bit (essentially an expandable drill bit) is engaged and increases the diameter of the drill hole. Aside from the restrictions of equipment power and drill steel strength, current underreamers are limited to expanding a hole to twice the pilot hole size. This technique can help to extend the capability of an item of drilling equipment.

f. Hole Springing

Hole springing is a method of enlarging a cavity at the bottom of a blasthole so that a lar e charge may be concentrated without in reasing drilling diameter. Successively larger charges are loaded into the bottom of the drillhole and fired until the desired cavity volume is obtained. The cavity is formed by crushing the rock and removing it from the hole. The springing charge must not be so large that it blasts out the face (craters) or causes subsidence. Air is sometimes used to cool the cavity after a springing detonation in a dry hole to decrease the waiting time before reloading. Because the cavity geometry becomes irregular, free-running (pourable) explosives are most desirable for use to provide proper coupling of the explosive energy to the rock.

Although springing is time-consuming, savings in the overall emplacement costs may be realized where drilling costs are excessive. Springing has been used in some conventional explosive applications but is not a widely used technique. The procedure shows promise in intermediate- and low-strength rock but appears to be inappropriate in soil because the resulting cavity is not self-supporting and fails readily. Springing may offer potential savings for emplacement of large yield charges such as used in cratering excavations. Although the ratio of cavity volume produced to the amount of explosive used depends on the specific explosive and the geologic medium encountered, a cavity volume of 5 liters/Mcal of explosive energy released in rock may be used for estimating purposes.

2.3.2 Charge Loading and Firing Techniques

Charge loading includes placement of the charge, the primer, and the stemming material in a prepared cavity. Charges must be placed to provide the explosive density specified in the blasting design. The primer must be prepared and placed in a manner which will provide the energy necessary to detonate the main charge. Stemming is material, such as sand or drill cuttings, placed in the hole above the main charge and primer to contain the high-pressure gases long enough after the detonation to develop maximum efficiency of the explosive energy in moving the overlying materials.

a. Charge Placement

Dynamites are usually cartridged to make loading easier. To improve contact with the sides of the hole, especially at the bottom, cartridges are slit along each side to allow collapse when tamped into the hole. In rough holes, long, rigid, unslit cartridges work best for placing. Some dynamites, available in perforated wrappers, are satisfactory for storing and handling and can be easily crushed if necessary as emplaced.

Free-running blasting agents come in cartridges or can be poured directly into vertical holes. Pneumatic loading systems are more efficient in most cases and result in higher density charges; hazards of static electricity require that such systems be grounded.

Loading techniques are classified as solid, deck, string, and spaced. In solid loading as much explosive as possible is loaded into the hole. With most types of blasting, a larger concentration of explosive energy is required at the bottom or back of the blast hole to provide adequate fragmentation. This concentration is generally achieved by tamping rather than by the use of various grades of dynamite, since it is generally desirable to stock one grade. The lower part of the charge should be heavily tamped and the balance of the charge placed loosely.

Deck loading can be used if solid loading would result in excess charge loading density above the bottom charge. Explosive charges can be decked, or separated, by alternately placing stemming and explosives. This technique can be used to bypass a weak seam that might vent prematurely. The charge layers must be connected by detonating cord, or primed separately.

String loading and spaced loading techniques are also used to reduce the charge loading density. Cartridges are loaded in an oversize hole one after another as a string of charges in the hole. String loading is fast and easy, but the decoupling air cushion resulting from excess hole size decreases the explosive efficiency. Spaced loading can be used to accomplish a less dense loading if desired. The cartridges can be separated by wooden spacers up to about the size of a cartridge.

b. Priming Charge

The primer is a small, highly sensitive charge containing the detonator. The detonator holds a small quantity of primary explosive, and sometimes contains timing and safety mechanisms. It is used to initiate the detonation of the primer.

In priming dynamite charges, the primer is more effective if the detonator points toward the mass of the explosive charge. Dynamites may be primed with nonelectric caps and fuse, electric blasting caps, or detonating cord. Cap and fuse primers may be undesirable since multiple-charge detonations can sever the relatively slow-burning fuse and cause misfires.

Both instantaneous and delay blasting caps should be placed at the bottom of the hole and directed toward the top. Bottom placement prevents the detonator from being pulled away from the charge. Bottom placement also practically eliminates the leaving of misfired cartridges at the bottom of the hole and facilitates charge removal in the case of misfires. In deep holes, more than one primer per hole may be used to insure complete detonation of the main charge. Detonating cord is occasionally placed in the hole first, providing a continuous line of primer from top to bottom. When cap-sensitive explosives are used, detonating cord initiates every charge it touches. Since detonating cord has a faster detonation velocity than the main charges, misfires that can occur when a slow-burning fuse is used in multiple explosions are avoided.

The performance of blasting agents depends strongly on the adequacy of the primer (booster) used. Nonnitroglycerin primers are safer and may be more convenient to handle than dynamite primers. A good primer for blasting agents must be cap- or detonating cord-sensitive and have a high detonation pressure and velocity to develop the full energy of the main charge. Special primers having high detonation pressures are commercially available for initiating blasting agents.

c. Stemming

Explosives quantity and noise from the detonation are reduced when stemming is used. Materials used for stemming should be free of large, sharp fragments that might sever the detonating cord or the electric blasting cap wires and cause misfires. Water, sand, gravel, and soil are examples of materials that can be used as stemming.

The relative effectiveness of the various types of stemming materials is under study but has not been determined conclusively. In general, it has been indicated that saturated stemming materials are more effective than dry materials.

d. Firing

Electric blasting caps, which explode when electric current is supplied, are commonly used for initiating explosive charges. Electric blasting caps may be placed in the blasthole to initiate the primer charge or, when cap-sensitive explosives are used, the main charge. When detonating cord is employed in the borehole, it can be initiated at the surface or underground by electric blasting caps. For both instantaneous and delay caps, the current must be sufficient to initiate all caps before any one of the caps detonates. Excessive current can damage delay blasting caps and must be avoided. In a series circuit where the current is the same in all caps, the early detonation of one cap cuts the current supply to other caps and misfires may result.

2.4 SAFETY CONSIDERATIONS

Explosions have potentially hazardous side effects, particularly ground motion, airblast, and missile throwout. In any type of explosive excavation project, these hazards must be understood and accommodated in the design. This section discusses the current hazard prediction technology, including the nature of these three effects and the general procedures used to estimate their magnitude and damage potential.

2.4.1 Ground Motion

a. General Safety Considerations

Ground motion, also called ground shock or seismic motion, accompanies all surface and subsurface detonations and may cause structures to move or vibrate. These motions, depending on their magnitude, may cause architectural damage (cracking of finished surfaces, plaster, stucco and breaking of windows) or even structural damage.

b. Basic Seismology

All explosions produce a high-amplitude shock front in the medium surrounding the detonation point. When the explosion is underground the shock front will generate seismic waves which are felt at some distance from the detonation point. As these waves propagate from the source, their amplitude will attenuate due to geometrical divergence and energy dissipation to the propagating medium.

The amount of explosive energy coupled to the medium and transmitted as seismic energy depends on the conditions of emplacement, depth of burst, and type of surrounding medium. The coupling, or seismic efficiency, becomes greater as voids surrounding the explosives are reduced, burial is deeper, and the medium is more dense (granite as opposed to soil). Typically, less than 1% of the total explosive energy is converted into seismic energy.

The factor of most influence on the seismic signal received at any location is the geology underlying the location. Current data indicate that at long distances from a detonation, the surface motion at a site on soil can sometimes be five times as high as the response at a site on rock.

In this report, weak rock is defined as rock having an unconfined compressive strength of less than 280 kg/cm^2; intermediate strength rock, an unconfined compressive strength of 280 to 1120 kg/cm^2; and high-strength rock, an unconfined compressive strength of greater than 1120 kg/cm^2.

c. Ground Motion Prediction

Surface particle velocity and acceleration are the parameters of interest in a description of ground motion and also the parameters that most seismic instruments are designed to measure. Predictable levels of damage occur in residential structures at fairly consistent values of particle acceleration; however, no simple damage-ground motion relationships have been developed for large buildings and other engineered structures to date. Analysis of potential damage to engineered structures requires the expertise of a structural engineer. Although the frequency of the ground motion is also important in determining the response of residential and high-rise or other engineered structures, the capability does not exist to predict reliably the frequency of peak ground motions.

Presented below are procedures for predicting ground motions. These procedures are based on experimentally derived constants for the empirical equation:

$$GM = CY^{m}R^{-n} \qquad (1)$$

where

GM = amplitude of peak particle motion (velocity or acceleration)

Y = explosive energy release in megacalories

R = range from detonation

C = experimentally determined constant related to nature of medium at point of detonation and at point of ground motion prediction

m = experimentally determined constant (0.7 for acceleration; 0.73 for velocity)

n = experimentally determined constant (2.0 for acceleration; 1.87 for velocity).

Equations with appropriate constants for predicting peak amplitudes of ground motion are plotted in Figs. 7 through 10 for selected yields of 10 to 100,000 Mcal. For multiple charges, the total yield of the explosives to be instantaneously detonated is used as the value of Y in the prediction equations.

d. Damage Criteria

The considerable amount of information which is available regarding ground shock and its damaging effects on structures shows conclusively that an absolute threshold of damage cannot be defined. The severity of ground-shock-induced damage to any structure will depend as much on the type and condition of the structure as on the level of ground motion to which it is subjected. Damage levels for various structures and equipment are presented in Tables 3 and 4. The levels are based on structures in an average state of repair. Application of the stated

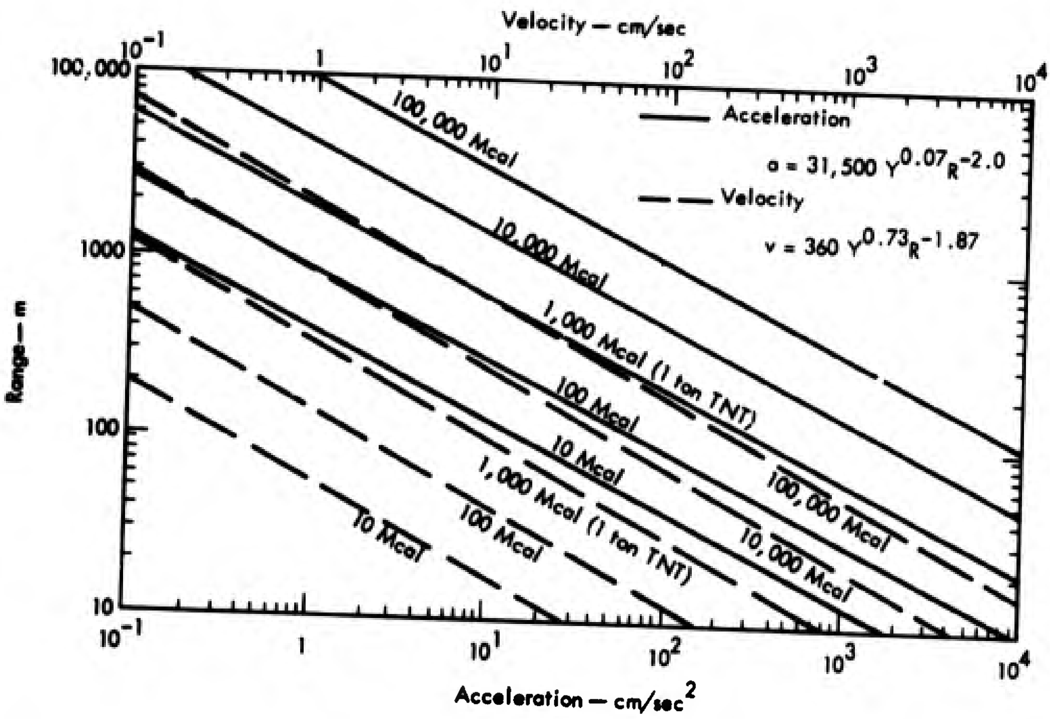


Fig. 7. Ground motion levels from detonations in rock (measured on rock).

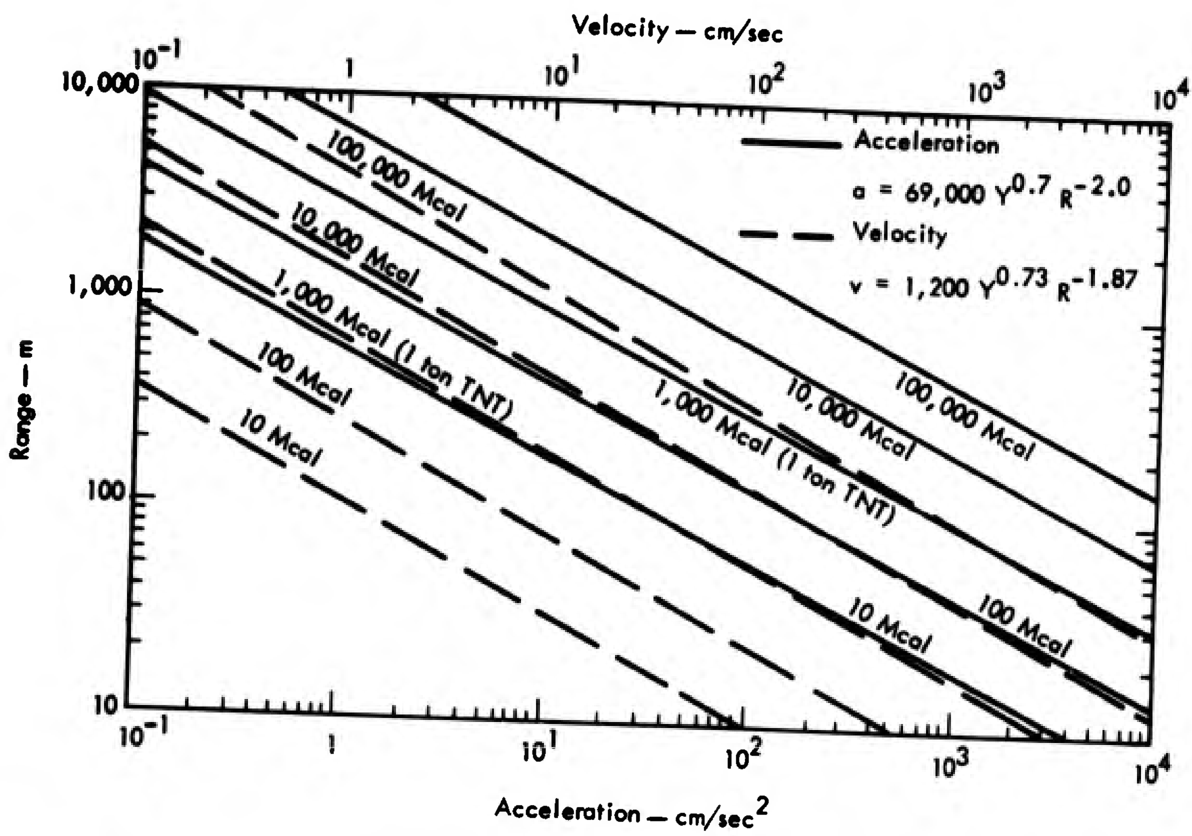


Fig. 8. Ground motion levels from detonations in rock (measured on soil).

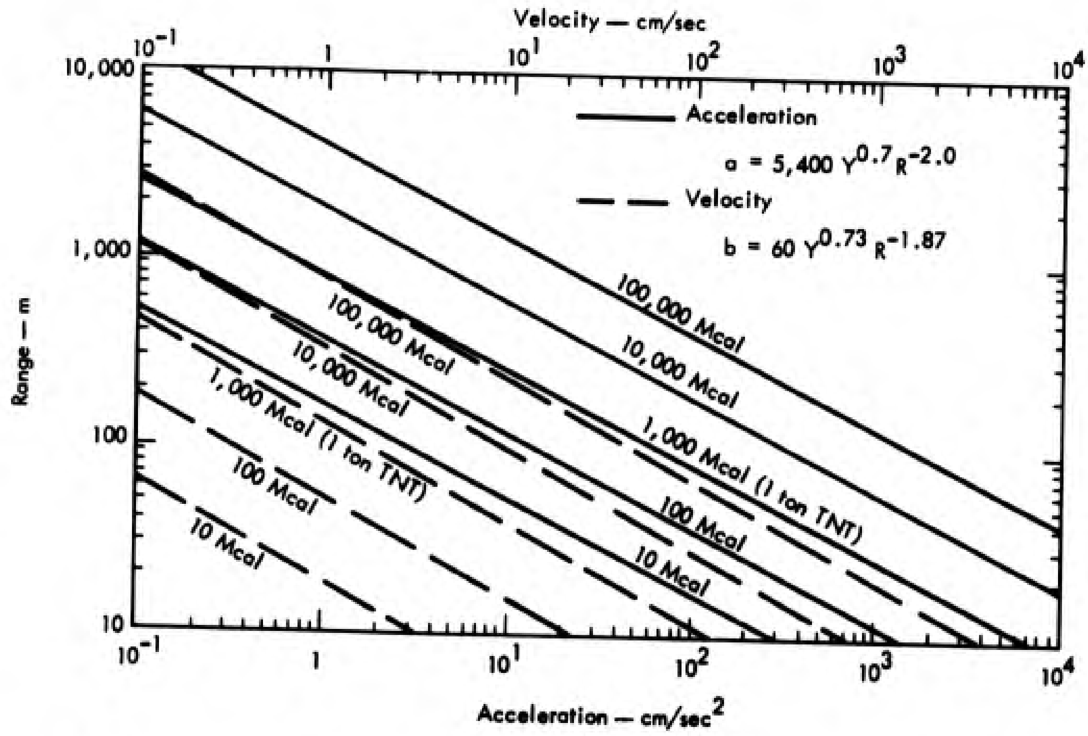


Fig. 9. Ground motion levels from detonations in soil (measured on rock).

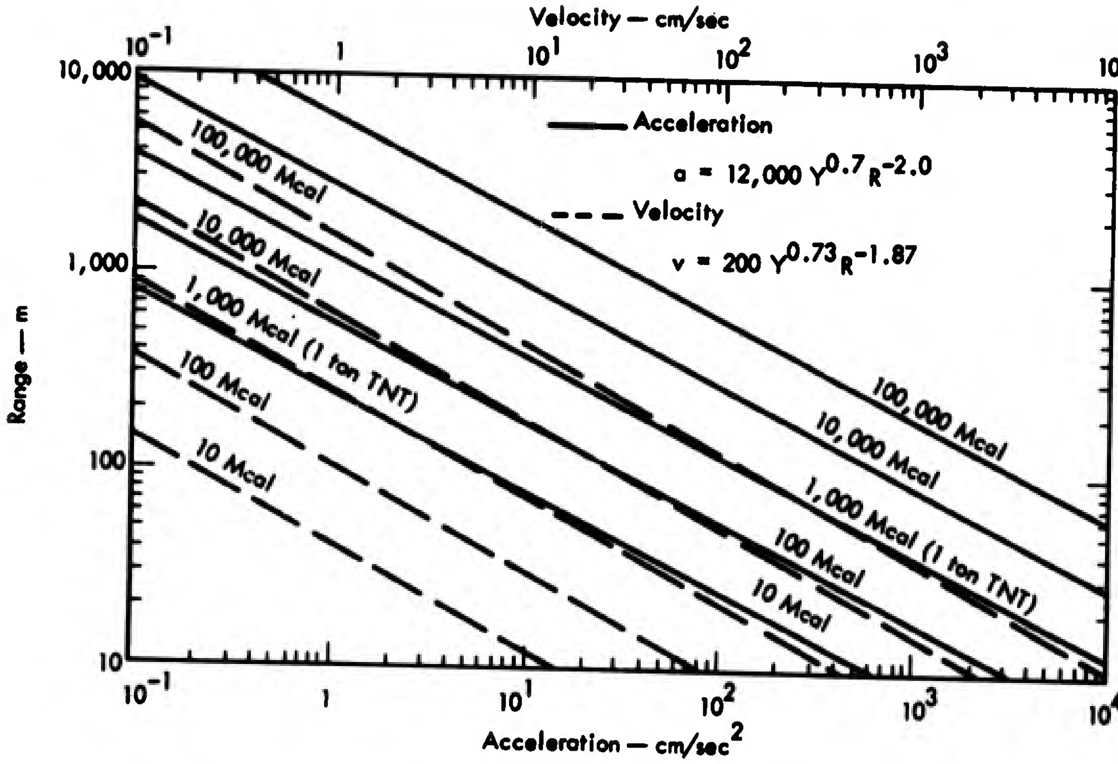


Fig. 10. Ground motion levels from detonations in soil (measured on soil).

Table 3. Residential structure damage criteria (King. 1969).

Acceleration gravity units[a] (g)	Expected damage level
Less than 0.02	No damage
0.02 — 0.10	Possible architectural damage
0.10 — 0.30	Probable architectural damage
over 0.30	Probable structural damage

[a] 1 g = 980 cm/sec^2

limits to structures other than those indicated should be made with extreme caution and by persons experienced in analyzing structural dynamics.

1. Residential Structures—Ground acceleration is the best parameter for use in predicting damage levels to

Table 4. Effect of ground velocity on various facilities (adapted from Cauthen, 1964).

Structure/equipment effect	Threshold (cm/sec)	Degree of damage moderate (cm/sec)	Severe (cm/sec)
Rigid frame buildings:			
Structural damage	150	—	—
Small plywood buildings:			
Structural damage	150	—	—
Skid-mounted engines not tied to ground:			
Failure of suspension system	—	50 to 100	—
Cracks in cast metal	—	50 to 100	—
Skid-mounted engines firmly tied to ground:			
Failure of suspension system	100	—	—
Cracks in cast metal	100	—	—
Steel storage tanks of light construction:			
Rupture	—	—	80
Steel storage tanks specifically designed and built to withstand ground motion:			
Distortion	500	—	—
Wheeled trailers on styrofoam pads:			
Suspension and frame damage	300	—	—
Wheeled trailers with heavy loads:			
Structural damage to suspension and frame	—	—	100
Building equipment:			
Loose objects thrown about (office machines, hand tools, etc.)	30	—	—

residential structures, although in the past considerable data relating levels of damage to ground velocity have been accumulated. Damage to residential structures associated with various accelerations expressed in gravity units is given in Table 3.

2. Miscellaneous Structures and Equipment—The available data pertaining to damage from ground motion sustained by typical structures and equipment associated with construction operations are presented in Table 4.

3. High-Rise Buildings and Engineered Structures—High-rise buildings and other engineered structures involve more uncertainties and higher risk of damage than residential buildings. These structures are susceptible to damage from the low frequency components of the seismic waves approaching the natural frequency of the structure. Since frequency of ground motion tends to decrease with range, high-rise buildings and other large engineered structures are more susceptible to damage at greater range than are residential structures. The frequency of ground motion in soil is lower than that in rock thus extending the damage range for high-rise buildings and engineered structures situated on soil.

4. Area Features—Natural features or man-made structures such as steep slopes along highway and rail cuts, natural embankments, rock formations, dikes, and tunnels are susceptible to damage as a result of ground motions. The variety of features that may exist precludes statement of any damage criteria, but each feature of an area must be identified and evaluated. Where evaluation indicates damage is probable, necessary damage prevention measures and safety precautions should be determined and placed in effect prior to the detonation.

e. Human Injury

Injury to persons as a result of seismic motions from high explosive detonations or natural seismic motions, as earthquakes, could be caused by displaced objects (e.g., falling plaster, items displaced from shelves, loose chimney sections, decorative stone from building facings). Persons in areas where 0.02 g or more is predicted should be evacuated from buildings during the detonation and be required to stay away from any structure a distance equivalent to twice its height.

2.4.2. Airblast

a. Safety Considerations

Airblast from an explosion can damage buildings or injure personnel. At short ranges, airblast may deflect structural members of a building, dish in walls, shatter panels, displace and tumble movable objects, and hurl loose objects through the air as destructive missiles. As distance from the detonation point increases, broken windows and cracked plaster and stucco will be the principal forms of airblast damage. Personnel at close ranges may be injured by being displaced, struck with flying debris or by direct damage to the body organs such as the lungs and eardrums. At longer ranges, injury from broken window glass is possible.

The range at which any of these effects is experienced is a function of the charge size, number of charges, depth of burst, and atmospheric conditions at detonation time.

b. Damage Criteria

Personnel injuries may occur as a result of direct exposure to the airblast overpressures or as a result of being struck by debris set in motion by the airblast. The eardrum of a man is the critical organ to be considered in limiting his exposure to air overpressure. The threshold for damage is 340 mbar, with 1020 to 1360 mbar the value which will produce eardrum rupture in 50% of the population exposed (DASA, 1962). When personnel are within structures the incident air overpressure may be amplified by a factor up to 3 by reflection from the various surfaces of the structure. This possible amplification factor plus the possibility of injuries from flying glass and other debris should be considered in setting the safe distances from an explosion for personnel in buildings.

Table 5 presents general criteria for estimating the possible extent of structural damage resulting from a predicted overpressure, ΔP. When these criteria are used for damage assessment purposes, cognizance must be taken of the fact that strength specifications for window panes are not uniform. In addition, the ability of a sheet of glass to withstand a given overpressure is dependent on its size. The damage criteria in Table 5 are empirical in nature and very qualitative. These criteria may be used, however, in making airblast safety analyses for chemical high explosive construction projects.

Table 5. Airblast damage criteria.

Overpressure, ΔP (mbar)	Degree of estimated damage
2	Possible window damage, particularly to large store windows
3	Probable damage to large plate glass windows
4.5	Probable damage to average size windows
13	Extensive damage to windows, probable damage to average wooden doors
40	Most small casement windows smashed
over 40	Structural damage probable

c. Nature of Air Overpressure Waves

When the initial seismic shock front from an underground explosion strikes the ground-air interface, a wave disturbance in the air is generated by the piston action of the displaced earth. The wave then propagates through the atmosphere at a velocity determined by meteorological conditions. This portion of the air overpressure wave is termed the "ground-shock-induced airblast."

As the gas bubble generated by the underground explosion expands toward the ground-air interface, it transfers additional velocity to the overlying earth and rock. The specific pressure of this gas bubble when it "vents" will determine the magnitude of the second part of the air overpressure wave, which is called the "gas-vent airblast pulse." If there is no gas vent, as in a very deep burial or contained explosion, or if the gas-vent pressure is equal to or less than atmospheric, there will be no observable "gas-vent airblast pulse."

Thus, two distinct pressure wave peaks may exist and be measured from an underground explosion. The maximum excess pressure in the waves above the ambient pressure is referred to as the peak overpressure of the airblast. In making predictions of airblast overpressure only the dominant wave is considered with no specific indication as to whether it is the ground-shock induced or the gas-vent-induced portion of the wave.

d. Meteorological Conditions Affecting Airblast Wave Propagation

Airblast waves generated by explosions attenuate very rapidly to low-amplitude pressure waves which approximate sound waves. The propagation of an airblast wave through the atmosphere is often illustrated by assuming the wave consists of sound rays, which are roughly analogous to beams of light. The path which each sound ray takes is directly dependent on the changes in sound velocity (velocity gradient) in the atmosphere. The velocity of sound in the atmosphere is governed primarily by the speed and direction of the wind and by air temperature. The velocity of sound increases downwind, decreases upwind, and increases with increasing temperatures. If the velocity of sound is uniform throughout the air above the ground surface, the sound rays will move out uniformly in all directions in a pattern analogous to the spokes of a wheel. If the sound velocity decreases from the surface upward, all sound rays will be turned upward away from the ground surface, and the overpressure along the surface will decrease very rapidly. This situation would be desirable from an operational and safety standpoint. If the sound velocity increases with altitude, the rays will be turned toward the ground and possibly intersect or overlap, resulting in a subsequent increase in overpressure at specific locations as compared to that which would result from propagation through a uniform velocity field. This situation would generally be undesirable because it could cause sound rays to focus at points on the ground and the resulting amplification of the overpressure could cause property damage, personnel injuries, or an annoyance to populated areas.

In summary, the velocity of sound and, thus, the airblast overpressure in the atmosphere depends primarily on the speed and direction of the wind and the air temperature.

e. Prediction of Airblast Overpressure for Free Air Bursts

Airblast overpressure amplitudes for free air bursts are usually predicted by scaling the overpressure expected from a 1000 short-ton explosive charge detonated in a standard atmosphere with a zero sound velocity gradient. Several theoretical calculations have been made of the airblast overpressure resulting from a 1000 short-ton free air burst as a function of range from the point of detonation. The standard overpressure-range curve that is used is designated the "IBM Problem M" overpressure-range calculation for a 1000 short-ton free air burst. This curve (Reed, 1969) is shown in Fig. 11. A curve may be generated for any other free-air-burst yield by shifting the IBM curve vertically, horizontally, or (sequentially) both by using the following scaling relationships (Reed, 1964) as applicable. To correct the IBM curve for atmospheric pressure:

$$\Delta P = P_m \left(\frac{P}{P_m}\right) \qquad (2)$$

To scale the IBM curve to a different yield:

$$R = R_m \left(\frac{YP_m}{Y_m P} \right) \quad (3)$$

in which

P = atmospheric pressure at time and place of detonation

P_m = atmospheric pressure at sea level

ΔP = peak overpressure amplitude

R = range

Y = weight of explosive (TNT equivalent)

m = data taken from standard IBM Problem M curve*

Unsubscripted variables represent conditions at the point of interest. Curves, scaled in the above manner, for the free air detonation at sea level (atmospheric pressure 1000 mbar) of explosive yields of 1, 10, and 100 metric tons are also presented in Fig. 11.

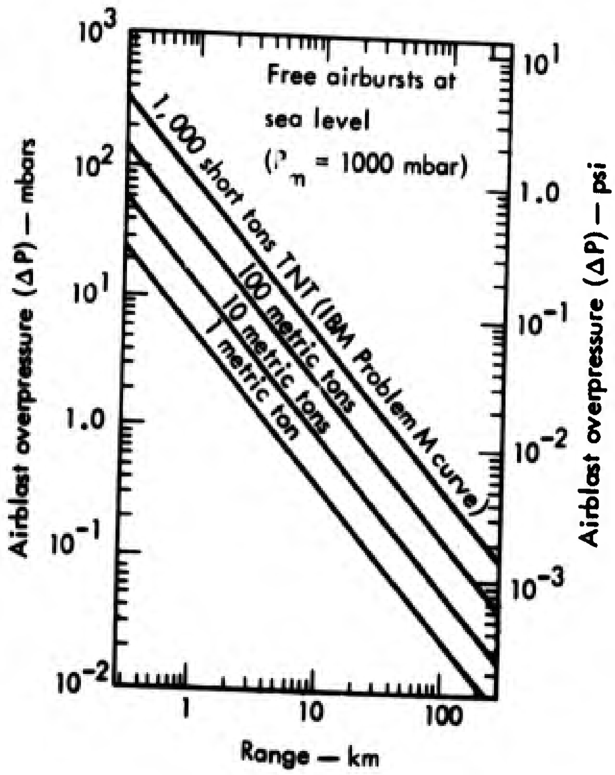


Fig. 11. Overpressure distance curves for free air bursts (adapted from Reed, 1964).

f. Transmission Factor for Underground Cratering Detonations

The parameter used to relate the levels of overpressure for air burst and subsurface cratering detonations is called the airblast transmission factor (TF). The transmission factor is defined as the ratio of peak overpressure amplitude, ΔP, for a subsurface cratering detonation to that expected at the same range from the same yield detonated in free air, or

$$TF = \frac{\text{subsurface burst overpressure}}{\text{free air burst overpressure}} = \frac{\Delta P_{\text{subsurface}}}{\Delta P_{\text{air burst}}} \quad (4)$$

Figure 12 is a plot of the transmission factor as a function of scaled depth of burst in the region of general interest for explosive construction applications (Reed, 1964a).

g. Row-Charge Configuration Multipliers

When the configuration of the explosives to be detonated at one time is varied from a single-charge configuration to multiple charges in a row, correction factors must be applied to the overpressure values predicted for a single charge. To date, correction factors have been derived from a limited number of experiments for chemical high-explosive charges detonated in a row configuration.

*See Fig. 11.

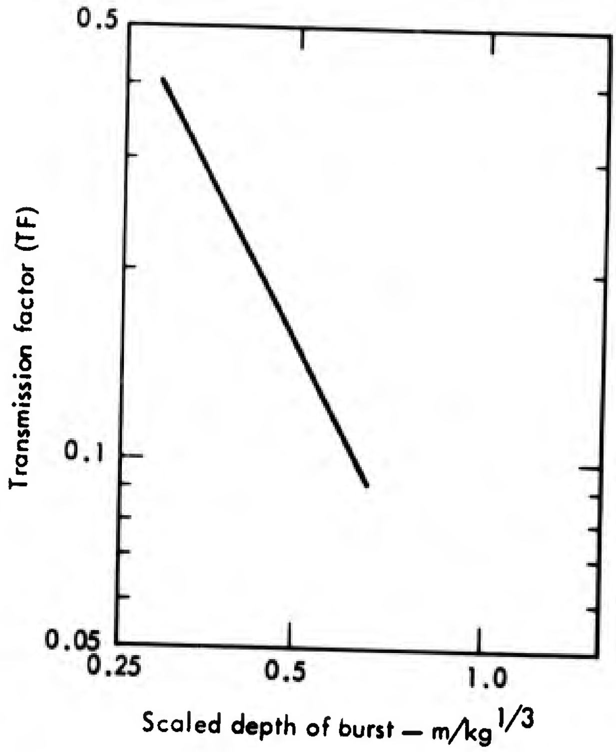


Fig. 12. Transmission factor vs depth of burst (adapted from Reed, 1964a).

For charges in a row configuration, correction factors must be applied to the overpressures propagated perpendicular to the row and off the end of the row (axial direction). Figure 13 is used to determine the appropriate overpressure multiplier to be applied to the overpressure calculated for one of the charges in a row of equal charges or the average yield if the charges are of different yields (Reed, 1969).

h. Prediction of Airblast Overpressure for Ordinary Rock Blasting

In quarrying and mining applications, the scaled explosive depths of burst are deeper than for cratering charges. Thus, the overpressure amplitudes will be less for quarrying and mining detonations. Figure 14, which relates airblast overpressure to the scaled distance from the

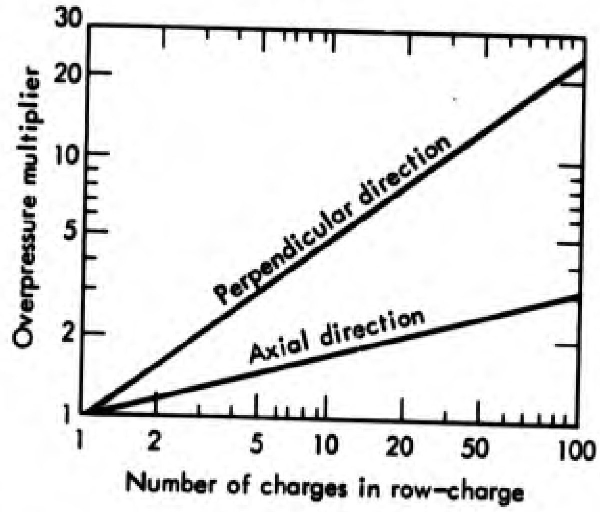


Fig. 13. Airblast multiplier for row charges (adapted from Reed, 1969).

detonation and depths of burst (or burden) pertinent to ordinary rock blasting, can be used to estimate overpressure amplitudes associated with quarrying and mining blasts.

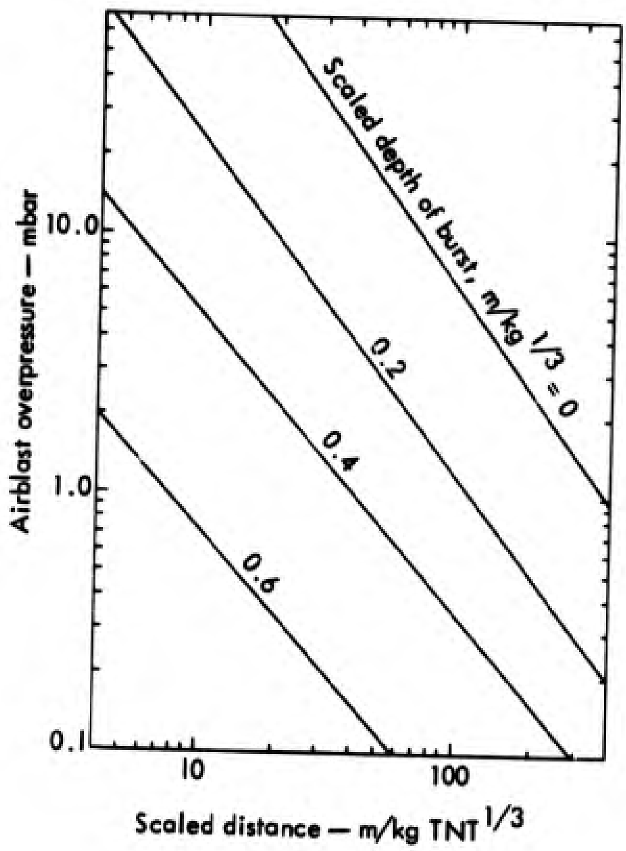


Fig. 14. Overpressure distance curves for quarry blasts (adapted from Pfleider, 1968).

i. Adjustment of Predicted Overpressure for Specific Meteorological Conditions

As previously discussed, if the sound velocity at some height above the surface is higher than the velocity at the surface and intermediate levels, a portion of the blast wave will be bent back or refracted into a ground level sound arc, or ring, some distance from the detonation. This refraction phenomenon (also referred to as ducting or focusing) will produce higher airblast overpressures at that ground level point than would be predicted.

A summary of amplification and reduction factors for overpressures as compared to the standard free-air-burst curve in Fig. 11 is given in Table 6.

2.4.3 Missile Hazards

a. Safety Considerations

Missiles resulting from explosive detonations can be hazardous to personnel at ranges beyond the hazard range for airblast overpressures. Materiel, buildings, and other structures can be damaged or defaced by missile impact. Thus, the missile hazard must be considered when explosive storage areas are selected and when safe separation distances are established for personnel and mobile equipment

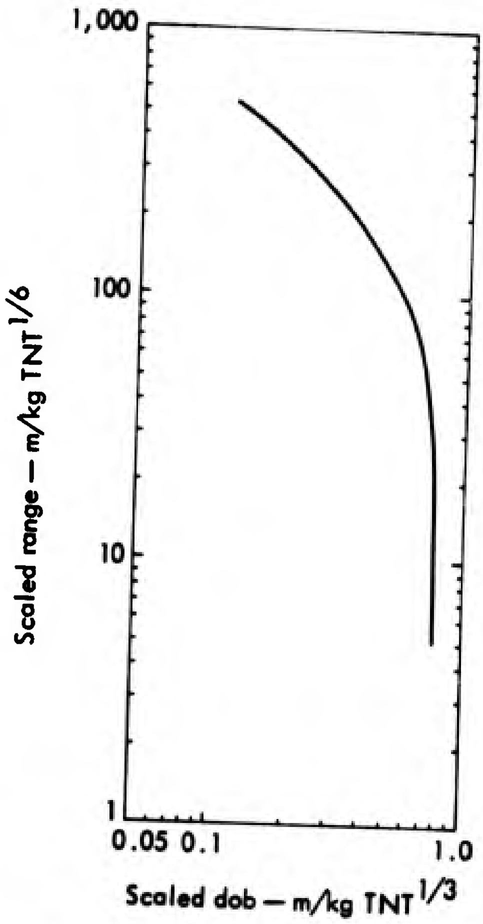


Fig. 15. Maximum missile range vs depth of burst (adapted from Vortman, 1967).

Table 6. Overpressure amplitude correction factors for various atmospheric conditions.

Atmospheric condition	Altitude interval of interest (m)	Correction factor as applied to standard predicted overpressure	Range interval (km)
Atmospheric temperature inversion or downwind	Surface to few thousand[a]	2 to 3	Up to 48
Jet stream winds in troposphere	7,600 to 15,200	Up to 15 (average 3 to 4)	Up to 160
Upwind direction and/or decrease in air ten perature with altitude	all	1/10	160

[a] Perkins and Jackson (1964) presents a detailed procedure for predicting airblast focusing in this altitude range.

from storage areas and detonation points.

In evaluating the missile hazard to personnel and mobile equipment, the maximum range of missiles is the principal concern. Where structural safety or missile impact effects are of importance the maximum missile range, missile size, and distribution per unit area must be considered.

b. Prediction of Missile Range

For buried explosives in the range of 4,500 to 450,000 kg, the depth of burst influences the range of the missiles. A relationship developed from cratering field data for the prediction of maximum missile range is presented in Fig. 15.

The curve was developed for cratering explosions, is conservative for ordinary rock blasting such as quarrying, and reflects, for cratering explosions, the maximum observed missile ranges. Longer ranges may have occurred and gone undetected. Therefore, when used for personnel safety considerations, a safety factor of two has been suggested.

Chapter 3

Terrestrial Applications

Chemical high explosives are used extensively in the construction and mining industries. Some of the methods used on earth have potential application to lunar activities. This chapter demonstrates some specific uses of chemical high explosives in the selected areas of surface excavation, quarrying, and mining, subsurface excavation and mining, and seismic geophysical surveying.

3.1 SURFACE EXCAVATION, QUARRYING, AND MINING

Chemical high explosives are used for varied surface applications including overburden, stripping, highway and railroad cuts, quarrying, and mining. A well-designed blasting program provides a safe and efficient method for increasing production rates. The blasting requirements are generally determined by the size of loading and hauling equipment, the intended use of the excavated material, the intended use of the excavation, and safety considerations.

The use of explosives in excavation of cuts is similar to stripping, but generally requires blasting that will produce stable side slopes for permanent excavations or relatively undisturbed foundations for the building of structures. For deep cuts, a series of smaller benches are usually advanced into the hillside (Fig. 16). For blasting ditches the explosive charges fracture the rock and excavate it as well.

For all practical purposes, the blasting techniques used in quarrying and surface mining are identical to those used for excavation. The desired degree of fragmentation is the only significant difference. In any blasting operation an orderly sequence of drilling and blasting which can be used round after round, or easily modified to satisfy varying conditions, is generally used.

In addition to the conventional uses of explosives in excavation, quarrying, and surface mining, large concentrated charges can be used to produce craters. Single charges buried at optimum depth will excavate the maximum crater volume when detonated. Single charges in a row can be detonated simultaneously to produce row craters. Also, row craters can be connected end-to-end or side-by-side to produce excavations of various dimensions. Next to charge size, the main

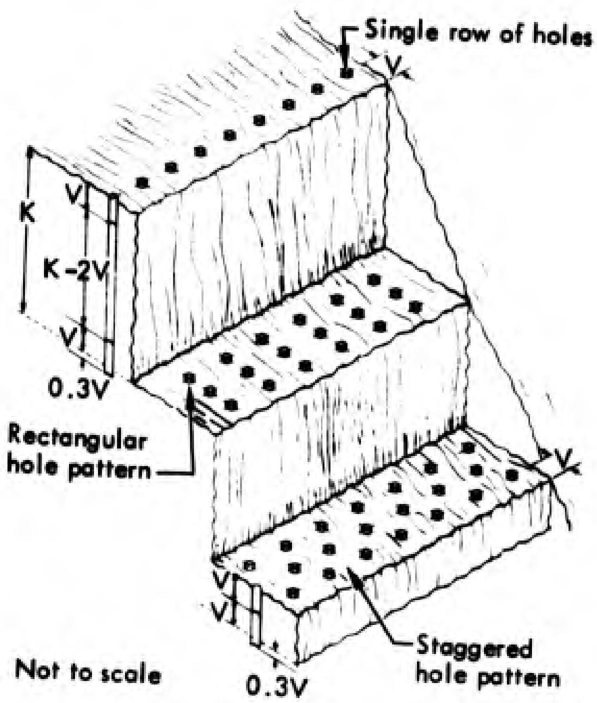


Fig. 16. Bench blasting.

difference between cratering charges and conventional blasting charges is the purpose they serve. Cratering charges are generally buried at a depth at which the detonation will eject the rock as well as fracture it.

Large cratering charges have been used on land to excavate a railroad cut and underwater to excavate a harbor and an entrance channel in coral. Other potential cratering applications include excavations for highways and structures, overburden removal, and quarrying or mining. These applications are made when the size of the product, the displacement of the fractured material, the cost, and other factors are of secondary importance compared to the time required to excavate the material.

In this section, typical drilling and blasting patterns, hole sizes, explosive requirements, and applications are discussed for the basic blasting techniques used for surface excavating, quarrying, and mining. In addition, chemical explosive cratering is presented as a special technique with potential application in some areas.

3.1.1 Basic Surface Blasting Techniques

The basic techniques used in surface blasting applications include benching, coyote blasting, secondary blasting, and ditching. Controlled blasting techniques are used to control overbreak beyond or near the excavation line by the reduction and the better distribution of explosive charges and their effects along that line. Coyote blasting is suited for heavy blasting where the rock is easily fractured and large-scale production is required. Secondary blasting becomes necessary when fragmentation from bench blasting is insufficient. Ditching, a technique which fractures the material and excavates it as well, is an early approach to the cratering technique. The main problems of practical rock blasting lie in the selection of the charge configuration, the quantity and the type of explosive, and the sequence of breakage.

a. Bench Blasting

Bench blasting is the most common technique used in explosive excavation of through and sidehill cuts, and pit-type and side-hill quarry and surface mining operations. A bench is a ledge which forms a single level of operation for excavation from a continuous bank or face above. Material is removed in successive layers, each called a bench. Benches may be operated simultaneously (see Fig. 16). Burden (V) is the distance between the first row of drill holes and the free face or the distance between successive rows of drill holes. Spacing is the distance between adjacent drill holes in the same row.

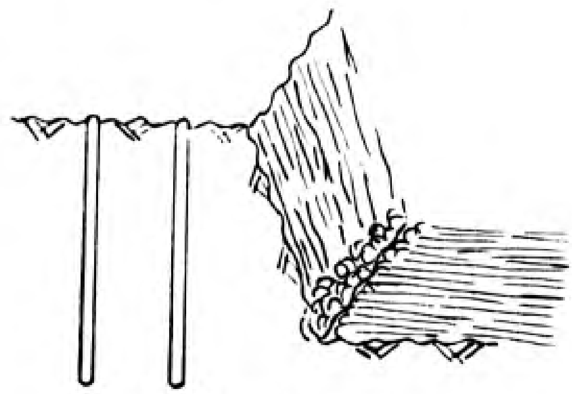
In bench blasting, practical burden is about 40 hole diameters and between 20 and 50% of the bench height. Hole spacing is usually in the range of 1 to 2 V. In ordinary bench blasting the specific charge excavated (the required amount of explosive per unit of volume) varies from 0.15 kg/m^3 for weak rock to 0.60 kg/m^3 for high-strength rock. As an example for a bench height of 11 m, a suitable diameter would be 5 to 13 cm, say 10 cm. Then a suitable burden would be 4 m. A typical spacing of 1.25 V would be 5.25 m. The approximate volume excavated per charge is about 200 m^3. The charge required, at the rate of 0.4 kg/m^3, is about 80 kg.

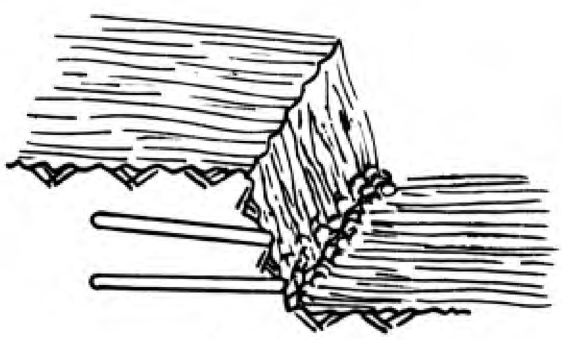
Holes are usually subdrilled 0.3 V below the bottom of the bench to insure a level floor. Charges are distributed in the blasthole as shown in Fig. 16. An analytical approach to blast design can be found in other literature (Langefors and Kihlstrom, 1963; Pfleider, 1968).

1. Drilling Patterns—Some basic drilling patterns used in bench blasting are shown in Fig. 16. For blasting high faces the single row pattern is generally used. When lower faces are blasted, multiple rows arranged in rectangular or staggered patterns generally yield better rock production rates. Irregular arrays can be used for irregular excavations, varying topography or nonuniform site conditions.

Drilling may be accomplished from the upper surface, a side face, or a combination as shown in Fig. 17. Horizontal drilling (snakeholing) is most advantageous when the material of interest is directly under soft overburden or rough terrain which prohibits top drilling. Drilling horizontally for large distances may require starting above the desired level or in a slightly upward direction to compensate for the downward drift of the drill. Removal of loose overburden prior to drilling reduces drilling footage, eliminates the necessity for casings, and may reduce the size of the drilling equipment required.

When blasting in vertical holes, incomplete shearing of the rock mass at right angles to the hole at its bottom may be experienced, and that risk is compounded with the detonation of each successive row due to the increased effective burden. The result would be a rising bench floor as shown in Fig. 18(a). Since there is more freedom of movement at right angles to an inclined drill hole at the base of a


(a) Vertical


(b) Horizontal

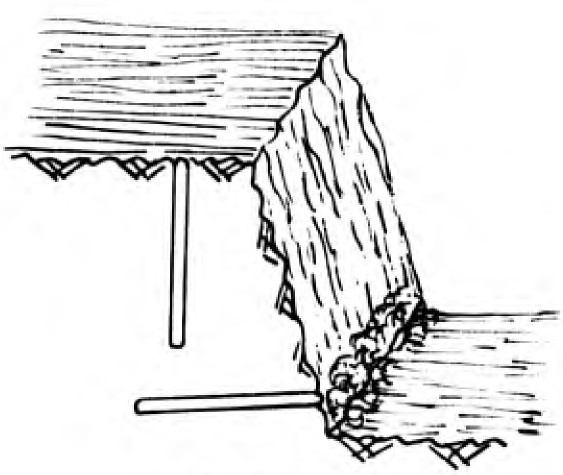

(c) Combined

Fig. 17. Vertical and horizontal drilling.

sloping bench face, the risk of incomplete shearing is reduced as successive rows are detonated. Although a hump might occur from one of the early holes, the resulting bench floor would return to the design level as the detonation sequence progressed—Fig. 18(b). More rock can be blasted per unit of explosive with inclined drill holes than with the same number of vertical holes. According to Langefors and Kihlstrom (1963), the increase amounts to about 10 to 15%. The burden and the spacing can both be increased 5 to 7.5% at a slope of 1:3 to 1:2.

2. Ignition Patterns—Some typical delay blasting patterns for a series of charges in a single row are shown in Fig. 19. Where the charges are initiated in sequence as shown along the lower left-hand face, better fragmentation is obtained when the spacing is 1.1 to 1.5 V. Under ordinary conditions spacing of approximately 1.25 V is typical. Along the upper left-hand face of Fig. 19, identical delay caps are used for all charges in the row. However, because of the spread in the actual delay time of detonators with the same nominal delay, a real but unpredictable delay exists. Best results occur when spacing is about 1.25 V.

For multiple-row blasting, the three basic types of short delay patterns for one row can be applied and combined in various ways. The simplest pattern for the predictable ignition of a laterally constricted multiple-row round is shown along the right-hand face of the upper bench in Fig. 19. Since all the holes in a row, except the edge holes, are ignited during the same delay interval, the hole that happens to be ignited first will have

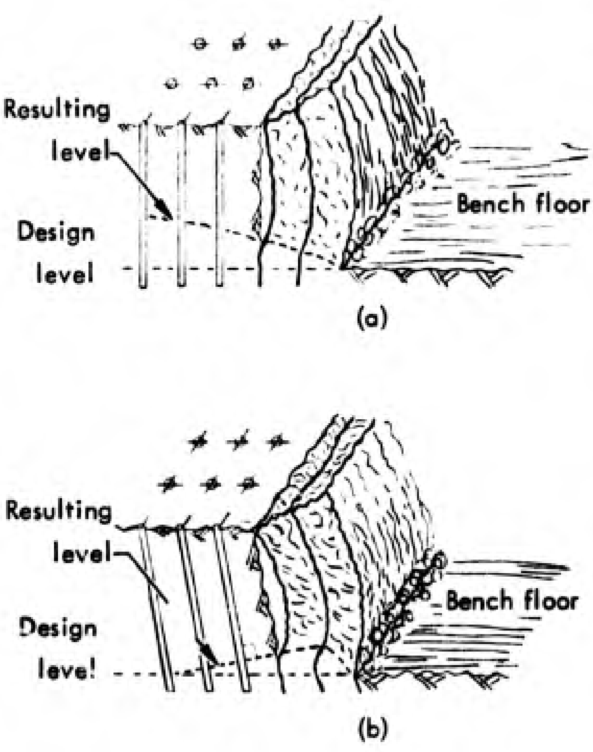


Fig. 18. Influence of inclined holes on bottom breakage (adapted from Langefors and Kihlstrom, 1963).

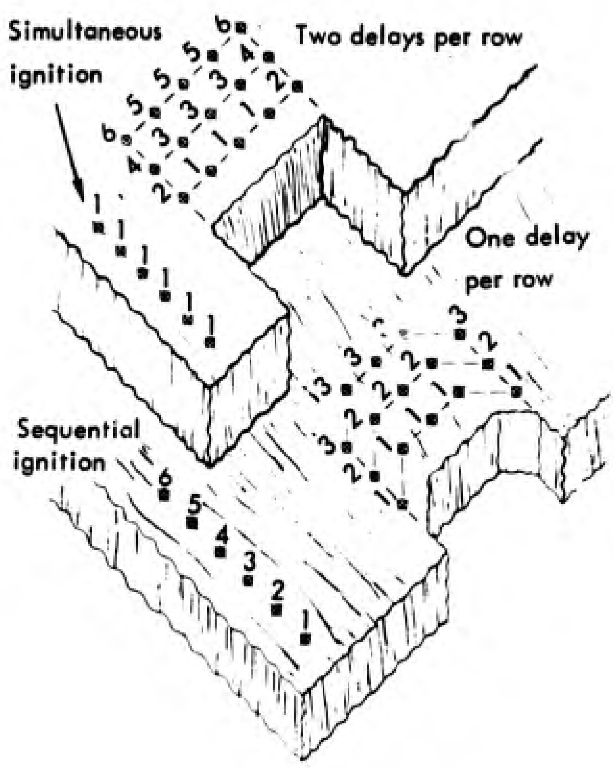


Fig. 19. Typical ignition patterns for multiple-row blasting.

free breakage. This might not be the case if the edge holes with constricted burden were ignited with the same delay. Since the main part of each row is first, then the edge holes for the same row, and then each successive row blasted in the same manner, there is always the least possible constriction for every hole.

The above pattern modified for one delay per row for large multiple-row rounds is shown along the right-hand face of the lower bench in Fig. 19. All holes in a row, except the edge holes, are ignited in the same interval as the edge holes in the previous row. One disadvantage in using this pattern is the constriction of the two holes next to the side holes. There also is a greater tendency for insufficient breakage at the bottom of these constricted holes.

Ignition patterns may be manipulated in many ways to achieve desired results, as control of fragmentation or ejecta scatter.

3. Benching Applications—Bench blasting techniques are used extensively in surface mining, quarrying, excavation, and overburden removal. While the basic techniques remain the same, the individual parameters of the blasting design (burden, spacing, bench height, hole size, specific charge, drill pattern, and firing sequence) are changed to achieve the desired result.

For stripping (overburden removal) fragmentation is needed only to the extent that the pieces can be handled by the loading and hauling equipment. Typical stripping operations call for single level operation with a widely spaced array of charges. The specific charge is quite small compared to ordinary bench blasting. For deep overburden more than one bench may be required as determined by the safe bench height or drilling and loading equipment capabilities.

Bench blasting is used to excavate cuts for the construction of highways and railroads and the excavation for various structures. The most important aspect of the blast design for an excavation of this type is that stable side slopes must be produced, because they are a permanent part of the project. The excavated material may be wasted or used for fill. In the latter case fragmentation control may become an important consideration.

In quarry and surface mine operations, bench blasting is the principal technique used. Bench heights in open pit and sidehill quarries may be 9 to 18 m high, since quarry rock may be strong enough to stand at great heights. Bottom blasting can be used to dislodge such faces; the competent materials of the upper portion would be fractured as a result of their great length of fall. When bench heights are dictated by safety considerations or equipment limitations, a series of lower benches may be preferred.

b. Controlled Blasting

Controlled blasting techniques are used when care must be taken to preserve the finished product. In addition, as compared to ordinary bench blasting, lower benches, smaller burden, closer spacing, and smaller charges are used to protect the permanent excavation. Common applications of controlled blasting techniques are found in the excavation of highway and railroad cuts, and the excavation for such structures as powerhouses and spillways. Presplitting, line drilling, cushion and smooth blasting methods can be combined in many ways to sculpture rock and preserve sound walls and foundations.

The purpose of the many methods of controlled blasting is to limit fracturing at the excavation line through the use of closely spaced holes which provide a plane of weakness. Closely-spaced holes may be unloaded for line drilling and loaded or alternately loaded and unloaded for cushion blasting as shown in Fig. 20. Presplitting is accomplished with closely-spaced charge holes which are blasted ahead of the main charges.

In line drilling, the holes, usually less than 7.5 cm in diameter are spaced two to four times the hole diameter apart along the excavation line. The distance between the line-drill holes and the adjacent row is usually 50 to 75% of the normal burden. The adjacent row spacing is reduced the same amount and individual charges are cut in half. Line drilling is used most successfully in a homogeneous formation of simple geologic structure; irregularities tend to promote shear through the line-drilled holes and beyond the excavation line.

Cushion blasting holes, also less than 7.5 cm in diameter, are loaded with light charges distributed through the hole and completely stemmed. The charges are separated from the finished wall by the stemming as shown in Fig. 20. In order to minimize the charge size, the main excavation can be accomplished before firing the cushion blast. The combination of light charges and the cushion from the stemming results in a neat excavation line with very little overbreak (Dupont, 1966). This technique is referred to as smooth blasting when no attempt is made to cushion the blast from the finished wall. For best results smoothing charges (Langefors and Kihlstrom, 1963) should be spaced less than 0.8 V.

Presplitting employs closely spaced holes with charges about 0.2 to 0.5 the normal size. The spacing is usually less than half that required for smooth blasting. The charges are detonated prior to the main blasting, creating a crack or discontinuity which protects the finished wall from the effects of the main charges. The stronger rocks require closer spacing for good presplitting. Smoothing is often preferred to presplitting because less drilling is required.

c. Coyote Blasting (Nichols, 1962)
Coyote blasting is suited for heavy

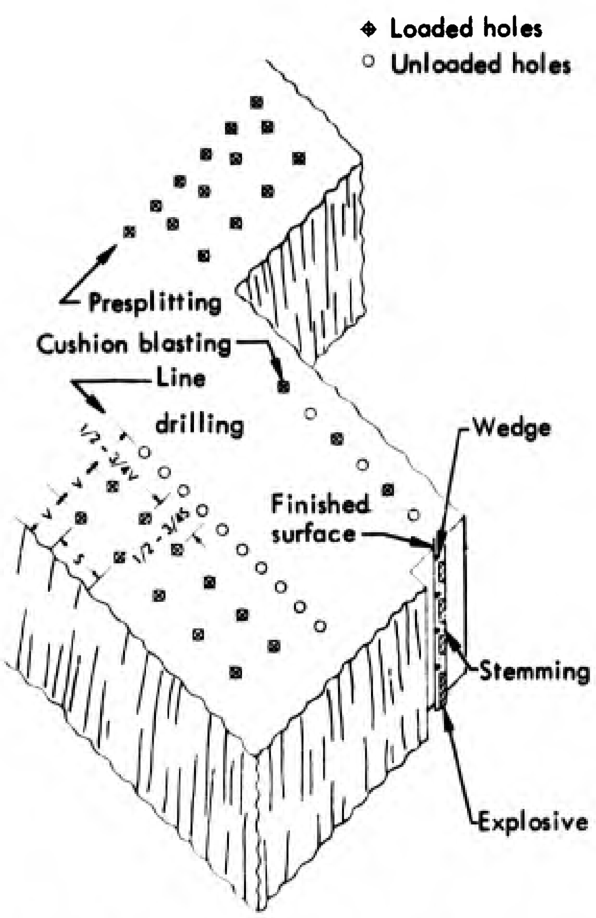


Fig. 20. Controlled blasting techniques.

blasting when overburden is difficult to drill but the rock is easily fractured and large-scale production is required. Coyote adits are usually driven horizontally from the bottom of the face to be blasted. Drifts, small connecting tunnels, are constructed parallel to the face and heavily loaded with explosives. The entrance adit is filled with stemming as shown in Fig. 21. Since the charges are concentrated in large amounts and poorly distributed in the rock the fragmentation is generally poor and unpredictable. In addition, ground shock, airblast and flyrock (missiles) are safety problems when coyote blasting techniques are used. The best application of coyote blasting is realized when large masses must be excavated with little concern for the degree of fragmentation and when the hazards mentioned above can be tolerated or properly controlled. Coyote blasting relies heavily on fragmentation caused by impact with the ground after a great height of fall as well as explosion-induced fragmentation.

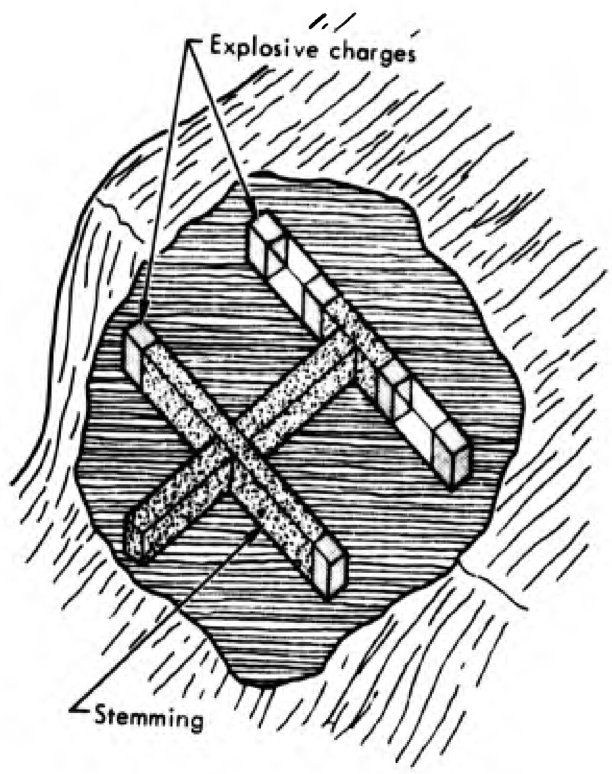


Fig. 21. Coyote blasting.

d. Secondary Blasting

Secondary blasting refers to the blasting of boulders too large for the loading or crushing equipment, toe shooting, and scaling. Toe shooting involves the use of small charges for removing ledges at the bottom of a quarry face after the main muck pile is removed. Scaling is the blasting of overhanging rock which presents a hazard to workers below. Secondary blasting may be done by blockholing or mudcapping.

Blockholing consists of drilling a small hole in the boulder and loading it with the minimum explosive necessary for desired fragmentation. Low detonation velocity explosives should be used when little fragmentation is desired. Where a high degree of fracturing is required, higher detonation velocity explosives should be used. Gelatin explosives are suited for blockholing. The plastic consistency of semigelatin permits easy handling and reduces spillage when partial cartridges are loaded. Small holes and cartridges are used to minimize the tendency to overload when blockholing. Stemming should be used for reasons of safety and economy.

Mudcapping, also known as bulldozing and dobying, may be a more practical method of secondary blasting when drilling equipment is not available or when the rock is difficult to drill or the overhanging ledge presents a hazard to the driller.

It is more expensive than blockholing since 10 to 15 times as much explosive, about 0.7 to 1.0 kg/m^3, is required. However, mudcapping may result in overall savings when that technique can be used to maintain production by high-cost loading and hauling equipment.

The most effective mudcapping explosive is one that provides the highest detonation pressure and the most contact with the rock. To make the charge effective, a 6-in. stiff mud covering is used to provide partial confinement.

e. Ditching

Ditch blasting methods are used to excavate ditches for drainage, pipelines, and utility conduits. Ditch blasting is practical for ditches 0.75 to 3.5 m in depth and 1.25 to 12.5 m in top width. Some advantages of ditch blasting compared to conventional excavation include simplicity and savings in excavation cost and time.

The drilling pattern used for ditch blasting depends on the desired ditch dimensions and the character of the rock. Single rows are generally used for very narrow ditches. For ditch widths 1.25 to 1.5 m in intermediate-strength rock, double rows are used. For wider holes or higher strength rock, at least one more row is needed. Holes 5 to 6 cm in diameter are drilled 0.3 to 0.45 m below grade. Where bottom excavation is difficult, larger holes and greater subdrilling may be needed. Holes are generally placed 10 to 15 cm inside the ditch line and spaced about 0.75 to 1.25 m apart depending on the required specific charge. For ditching, the specific charge varies from 0.6 kg/m^3 in very favorable situations to 3.0 kg/m^3 in high-strength rock and tight confinement.

Ditch blasts are generally fired with detonating cord and delay connectors (Fig. 22). The delays reduce overbreak at the top, increase bottom excavation, and minimize vibration and throw.

3.1.2 Cratering

The cratering technique offers potential savings in excavation time for a wide range of construction projects including excavation for the construction of structures, highways, railroads, channels, and harbors. Other possible applications for cratering techniques include the production of aggregate and mineral ore.

a. Crater Terminology

Figure 23 shows the cross section of a typical crater and the adjacent zones of disturbance. Brief descriptions of those zones follow:

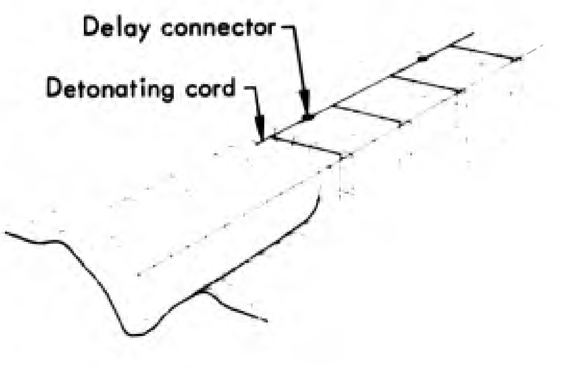
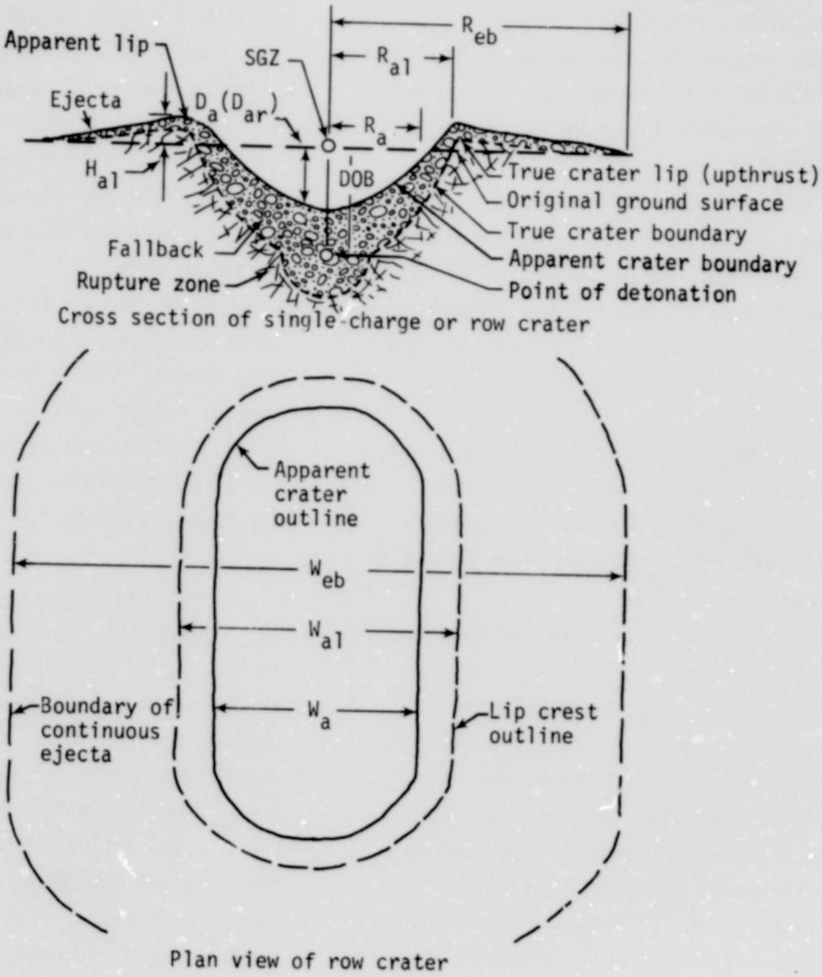


Fig. 22. Ditching.



Nomenclature which applies only to single-charge craters

R_a - Radius of apparent crater measured at original ground surface datum

R_{al} - Radius of apparent lip crest

R_{eb} - Radius of outer boundary of continuous ejecta

D_a - Maximum depth of apparent crater below and normal to original ground surface

Nomenclature which applies only to row craters

W_a - Width of apparent linear crater measured at original ground surface datum

W_{al} - Width of apparent lip crest

W_{eb} - Width of outer boundary of continuous ejecta

D_{ar} - Depth of apparent row crater

Nomenclature and definitions which apply to both single-charge and row craters

H_{al} - Apparent crater lip crest height above original ground surface

V_a - Volume of apparent crater below original ground surface

V_{al} - Volume of apparent lip

V_t - Volume of true crater below original ground surface

DOB - Depth of burst

SGZ - Surface Ground Zero (point on surface vertically above ZP)

Fig. 23. Dimensional data for single- and row-charge craters.

The apparent crater is the portion of the visible crater which is below the level of the original ground surface. The apparent crater would be the net design explosive excavation for most engineering applications.

The apparent lip of the crater is composed of two parts, the true lip and the ejecta. The true lip is formed by the upward displacement of the ground surface and the remainder of the apparent lip results from deposition of ejected material.

The fallback consists of fractured materials which have experienced significant disarrangement and displacement and have come to rest within the crater.

The ejecta consists of material thrown out beyond the true crater.

The true crater is defined as the boundary (below original ground surface) between the loose, broken, disarranged fallback material and the underlying rupture zone material which has been crushed and fractured, but has not experienced significant displacement or disarrangement. The true crater boundary is not a distinct surface of discontinuity, but rather a zone of transition between the rupture zone and the fallback material.

The rupture zone is that zone of crushed and fractured material which extends outward from the true crater. In this zone, displacements and changes in density are evident but the material remains basically coherent in contrast to the disarranged fallback materials.

It should be noted that many of the dimensions given in Fig. 23 are defined only for flat or level terrain.

b. Prediction of Crater Geometry

Of the several means for predicting crater size, simple empirical scaling is accurate and the most practical for engineering purposes. In situations where two or more charges are used to form a row-charge crater, empirical rules presently are the sole means for predicting the results.

Since the apparent crater forms the useful excavation, its size is of greatest importance. There may not be a great number of applications for single-charge craters, but the capability to predict their size forms the basis for predicting the size of row-charge craters.

1. Empirical Scaling of Crater Radius and Depth—The fundamental parameter in scaling is a quantity which represents the ability of an explosive charge to produce a crater. This quantity is a factor which takes into account the necessary properties of the explosive. Usually, the explosive considered in scaling is TNT, with the scaling parameter being charge weight. If another explosive is used, its effectiveness relative to TNT is introduced as an adjustment in the computation. The reference charge in this introductory discussion is one metric ton of TNT. (Scaling can also be based on the weight-related explosive energy of an explosive charge—this method is used later in the report; by way of comparison, TNT has an explosive energy of 1100 cal/g.)

Empirical scaling has been developed to provide a reliable scaling rule over the range of charge weights most often used in practical engineering situations. The scale factor for crater dimensions is the ratio of the charge weights raised to an exponent. The commonly accepted exponent is 0.3; another value, 1/3.4, is found in some other literature. The two exponents are so nearly equal that predictions of crater dimensions differ by only a few percent.

To apply empirical scaling it is necessary to ascertain the crater dimensions for the reference charge weight in the medium being considered, and to multiply them by the scale factor to predict the results for other charge weights. Usually, the charge burst depth, apparent crater radius, and apparent crater depth are the only crater dimensions considered in scaling. Other crater dimensions, such as lip height, are expressed as a fraction of crater radius, crater depth, or charge burial depth.

Using the reference charge of one metric ton of TNT, the scaling factor P is:

$$P = Y^{0.3} \tag{5}$$

in which Y is the weight in metric tons TNT equivalent of the charge whose crater dimensions are to be computed.

The charge depth of burst (DOB), the apparent crater radius (R_a), and the apparent crater depth (D_a) for a charge of given explosive energy are:

$$DOB = P(dob) \tag{6}$$

$$R_a = Pr_a \tag{7}$$

$$D_a = Pd_a \tag{8}$$

where dob, r_a, and d_a are conventions used to indicate the depth of burst and crater dimensions of the reference unit charge, i.e., scaled dimensions.

The above relationship between charge weight and scale factor indicates that great quantities of explosive are necessary to produce large craters. In general, the linear dimensions of a single-charge crater are doubled when the charge weight is increased by a factor of ten. Single crater volume, being proportional to the cube of linear dimensions, increases by a factor of eight when the charge weight is increased tenfold.

Typical crater dimensions for a one metric ton TNT charge (scaled dimensions) in dry hard rock are shown in Fig. 24. The curves for crater radius and depth are based on data from experiments in basalt with some verification from experiments in granite and tuff. The experiments involved charge weights of 0.25 to 450 metric tons, with weights of 0.5 to 18 metric tons being most common. The optimum burial depths (the depth which will assure the greatest crater volume) and the resulting crater dimensions are listed for three materials in Table 7.

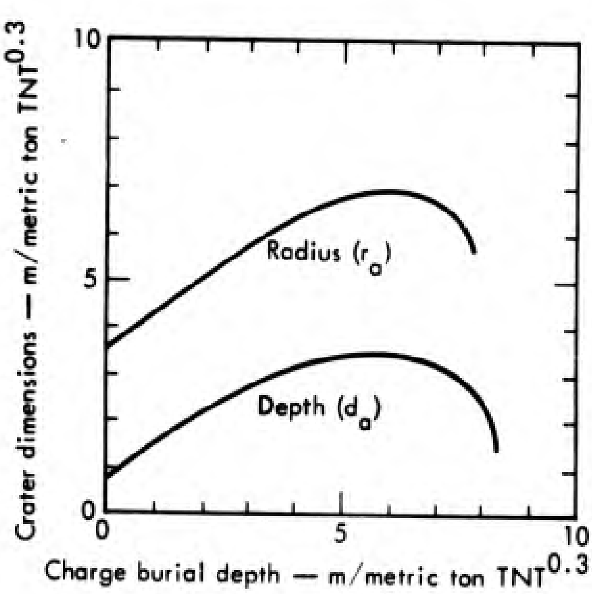


Fig. 24. Crater dimensions for detonations in high strength dry rock.

Table 7. Crater parameters for optimum depth of burst.

	Scaled depth of burst dob m/(metric ton $TNT^{0.3}$)	Scaled apparent crater radius r_a m/(metric ton $TNT^{0.3}$)	Scaled apparent crater depth d_a m/(metric ton $TNT^{0.3}$)
Dry, high-strength rock	5.8	6.4	3.2
Dry soil	6.4	8.0	3.8
Saturated clay shale	5.8	8.6	4.2

Table 8. Supplemental crater parameters.

Parameter	Dry rock	Dry soil	Saturated clay shale
Lip crest radius (R_{al})	1.2 R_a	1.2 R_a	1.4 R_a
Lip height (H_{al})	0.25 D_a	0.15 D_a	0.45 D_a
Radius of continuous ejects (R_{eb})	3.0 R_a	2.2 R_a	3.5 R_a
Radius of rupture zone at surface	4.4 R_a	—	4.0 R_a
Radius of rupture zone at charge elevation	1.1 R_a	—	2.0 R_a

The crater parameters for dry soil apply to desert alluvium, loose, dry sand, some sandstones and materials of similar physical properties. The cratering parameters for high-strength rock and saturated dry shale may be regarded as the lower and upper limits, respectively, for materials not mentioned.

2. Supplemental Crater Parameters—Although apparent crater radius and depth are primary criteria for explosive excavation design, parameters which describe the crater lip, the extent of ejecta, and the extent of the fracture zone are useful. In Table 8 these parameters are given in terms of the crater radius, or crater depth and apply to craters produced by charges at optimum depth of burst. With the exception of lip crest radius, these parameters may vary over a considerable range. The lip height, for example, may vary by a factor of two around the perimeter of a typical crater. Comparable variation may be expected for the radius of continuous ejecta and the size of the fracture zone.

3. Row-Charge Cratering—In many applications it is necessary to use an array of two or more charges to produce a crater of suitable geometry. The most common array is a row of charges. The charges, usually five or more in number, are buried along the alignment of the desired excavation. A properly designed row of charges will excavate a trench having a smooth and uniform cross section.

Furthermore, the excavated volume per unit weight of explosive in the row is greater than that for a single charge of row-charge member weight in the same material.

Factors which influence the size and geometry of row-charge craters include those involved in single-charge cratering with the added factors of charge spacing(s) and time delay, if any, between detonations of adjacent charges. Although the depth of burst of a single charge may be varied over a wide range to alter certain cratering characteristics, the depth of burst for the row-charge is restricted to a narrow range near the optimum for crater volume. Reliable design procedures for row-charges having depths of burst other than optimum have not yet been developed.

A characteristic of row craters is that their width (W_a) and depth (D_{ar}) are generally larger than the diameter ($2R_a$) and depth (D_a) of a single crater excavated by a charge equal in yield to one of the charges in the row. This characteristic is called enhancement, and the size of a row crater can be expressed in terms of single-crater dimensions. Because the enhancement of row crater dimensions increases as the charge spacing is decreased, the size of a row crater can be altered by changing the layout of the charges as well as their yield.

The enhancement of row-crater dimensions, which is used in the design of row-charges, is related to the charge spacing within the row as shown in Fig. 25

A spacing of 1.4 R_a results in a row crater with no enhancement. An important adjunct of the concept of enhancement is the fact that the depth of burst of charges in a row must be the optimum single-charge depth increased by the amount of enhancement.

The nominal length of a row crater formed by N charges is S(N+1). The length of the crater segment having uniform cross section, the linear section, is equal to the distance between the end charges, or S(N-1). If the distance between the end charges is less than twice the crater width, the crater will not have a linear section. Instead, it will be elliptical in plan. For charge spacings of the order of one crater radius, a minimum of five charges is needed to assure that the distance between the first and last charges is comparable to twice the crater width.

In theory there is no reason why the charge weight and spacing cannot be simultaneously decreased to the point where adjacent charges are in physical contact. In practice, however, it is found that certain end effects exist where a row charge having many small charges is

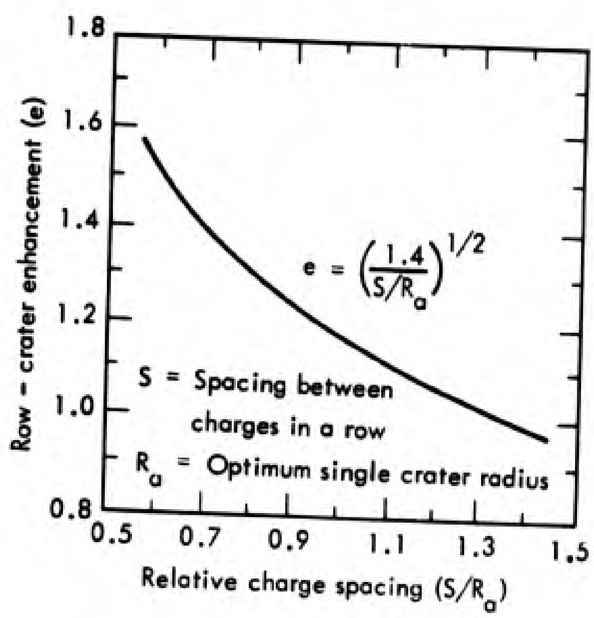


Fig. 25. Row-crater enhancement vs relative charge spacing.

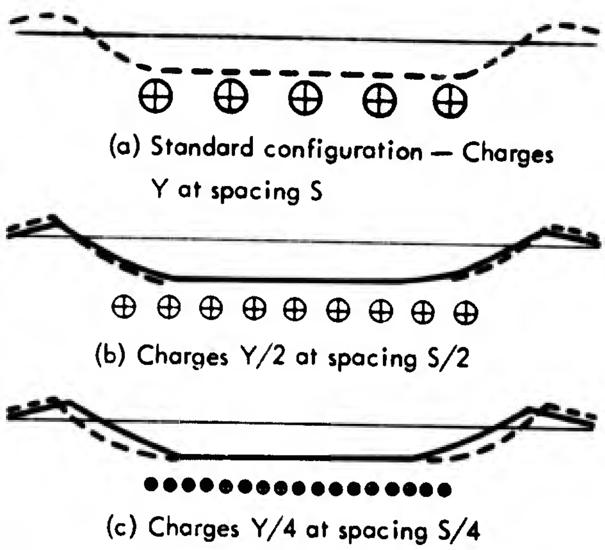


Fig. 26. Effects of charge size and spacing on row crater centerline profile (not to scale).

substituted for one having a few large charges. The end effects lead to an alteration of crater profile as qualitatively illustrated in Fig. 26.

It is not necessary that the charge weight and spacing between charges within the row charge be uniform. In fact, there are many applications where the charge weight and spacing must be varied to produce a uniform cut through varying terrain.

In the preceding discussion it was assumed that all charges in the row charge were detonated simultaneously. If time delays are used to reduce ground shock or airblast from the detonation, a reduction in crater volume results. A delay interval equal to the stress wave transit time between the charges and the ground surface will reduce the crater depth by approximately 10%. As the delay time is increased the decrease in crater depth approaches a limit as the delay is made indefinitely long. For long delays the crater depth is approximately half that for the same charge array simultaneously detonated. The crater width is reduced only slightly.

4. Parallel Row-Charge Cratering — In applications where crater width is more important than depth, it may be advantageous to use parallel rows of charges. Such a charge configuration will produce a crater as much as one and one-half times as wide as the crater from either row of charges acting alone. The crater depth will be approximately the same as for a single row-charge crater.

The charge weight, the depth of burial, and the spacings between charges in either row of the two-row array are selected in the same manner as those of a single row. There is some latitude in selecting the spacing between the rows of charges. If the between-row spacing is equal to half the crater width from either row of charges acting alone, the final crater will have a relatively flat bottom. If the spacing between the rows is increased, a low ridge will form along the center line of the crater.

c. Properties and Behavior of Craters

An engineering knowledge of the nature of the excavation and of the materials comprising the various crater zones is important. It is the properties of these materials that to a large extent determine the serviceability and practicality of the excavation. It is the predicted engineering qualities of the resulting excavation that are used in conjunction with design techniques (1) to forecast the capability of explosive cratering to deliver an excavation that meets project needs, and (2) to estimate the scope of follow-on construction activities.

1. Properties of Fallback and Ejecta—The material comprising the fallback and ejecta is fractured by the explosion, broken into particles of various sizes, lifted into the air, and redeposited in a somewhat predictable pattern. All preexisting discontinuities are destroyed, and these zones are composed of rubble or blocks of material. The surfaces of these blocks are preexisting discontinuities or blast fractures.

The size distribution of ejecta and fallback particles is essentially a function of the natural material characteristics. Engineering properties investigations made to date at craters in rock indicate that particle-size distribution in the fallback and ejecta is related to the preshot material fracture pattern. Weathering will cause some later particle disintegration and increase the proportion of fines, particularly in weak rocks.

Bulking and in-place density of the fallback and ejecta materials have been measured at a number of experimental craters. The material is free-draining and is subject to settlement after depositions. An increase of settlement can be expected if saturation occurs. Settlement will tend to steepen the fallback slopes but will also tend to increase the density of the materials with a resulting increase in shear strength and resistance to sliding.

Permeability has been estimated by a judgment based on the grain-size curves and porosity. In general, the permeability of the fallback is factors of ten larger than the permeability of the preshot media.

2. Effects in Rupture Zone—Deformations occur in the rupture zone in the form of blast-induced fractures, opening of existing fractures, and shearing action, accompanied by significant displacements. These deformations have been visually noted in the lip upthrust, which is that portion of the crater rupture zone above the original preshot ground surface. In the portion of the rupture zone near the true crater boundary, fractures are increased in intensity by several hundred percent as compared to the preshot *in situ* fractures. The majority of blast-induced fractures are aligned in a direction nearly parallel to natural fractures.

The effective porosity of the rupture zone is increased significantly as a result of the cratering detonation. This increase is due primarily to the opening of both natural and blast-induced fractures. Several craters in basalt, having a preshot effective porosity of approximately 2%, have been found to have blast-induced porosities of as much as 25% near the true crater boundary.

Measurements of the permeability of the rupture zone materials have not been made. It is reasonable to assume that the rupture zone permeability will approach that of the fallback near the true crater boundary and will decrease outward with distance in a manner similar to the decrease in fracturing and effective porosity.

The strength of the rupture zone as it affects slope stability will be controlled by the frictional resistance along preexisting discontinuities and blast-induced fractures. Since the surface of these discontinuities is generally irregular, the angle of friction for a discontinuity will vary as a function of the inclination of the surface irregularities, the confining pressure, and the amount of sliding displacement along the discontinuity. In addition, the factor of safety against slope failure in the rupture zone is increased by the surcharge of fallback material which tends to buttress the rupture zone.

d. Potential Cratering Applications

This section presents general information concerning the basic concept of using large-yield chemical high explosives in conjunction with construction projects, and briefly describes those explosive construction applications which are consistent with the purpose of this report and have the most potential from the standpoint of engineering feasibility.

1. Basic Concept of Using Explosives in Construction—The basic concept of using chemical explosives in construction operations involves the subsurface detonation of explosives either to break up and to eject large quantities of rock or soil, or both, and by so doing produce excavations, or simply to fracture subsurface materials for mining or for quarrying purposes.

2. Potential Construction Applications with Explosives—The potential use of large-yield chemical explosive methods for construction covers a wide range of projects. It is reasonable to anticipate that chemical explosives could be used advantageously to excavate for the emplacement of buried structures such as fuel storage tanks, to excavate overburden in order to expose ore bodies or competent rock, to provide cuts and fills which could be incorporated in roadway construction, to clear rights-of-way, and to produce aggregate for use in the construction of rock-fill structures.

The following paragraphs briefly describe those applications which are considered to have the greatest potential for use in construction relevant to this study.

3. Explosive Excavated Cuts—The potential use of a row-charge to excavate a hole for the burial of a structure, such

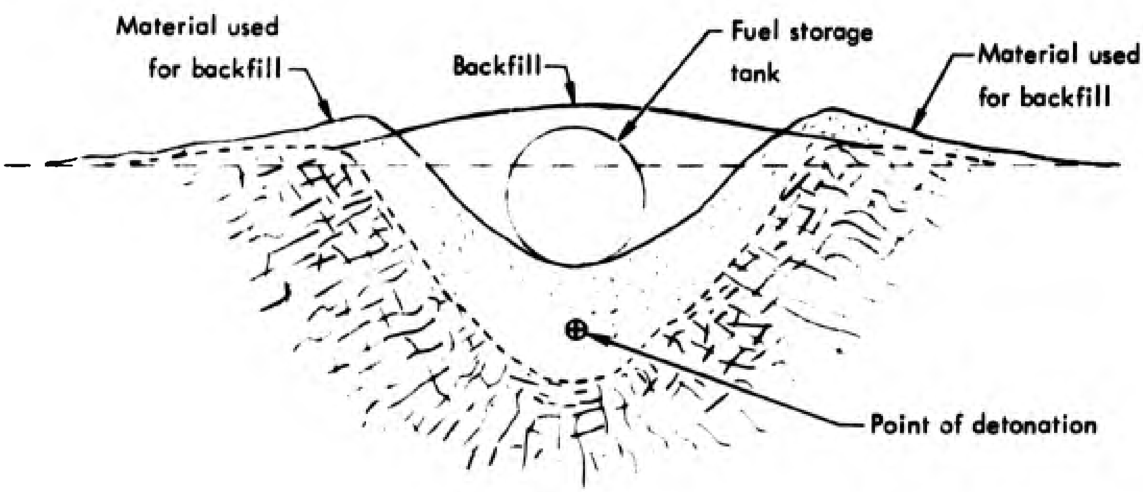


Fig. 27. Row crater used for emplacement of buried fuel storage tank.

as a fuel storage tank, is shown in Fig. 27. The row crater has been excavated to the geometry specified for the emplacement of the tank, and the tank has been placed on the crater floor. Ejecta may be used for backfill material.

The potential use of chemical explosive row-charges to excavate overburden in order to uncover ore bodies or competent rock is shown in Fig. 28. In Fig. 28(a) a row crater has been excavated, removing a portion of the overburden and exposing the desired material layer beneath the row crater. Then, that portion of the valuable layer which lies directly under the crater can be quarried or mined. In Fig. 28(b), the second row-crater has been excavated and the quarrying or mining can be started again. The technique may be repeated as necessary to quarry or mine formations which are buried near the surface.

The concept of a cut-and-fill operation using cratering techniques is shown in Fig. 29. The crater has been excavated on a slope, which provides the specified rock-fill (ejecta) surface with a nearly balanced cut and fill and the maximum use of the explosive energy. The concept assumes failure or sloughing of the slope uphill from the crater.

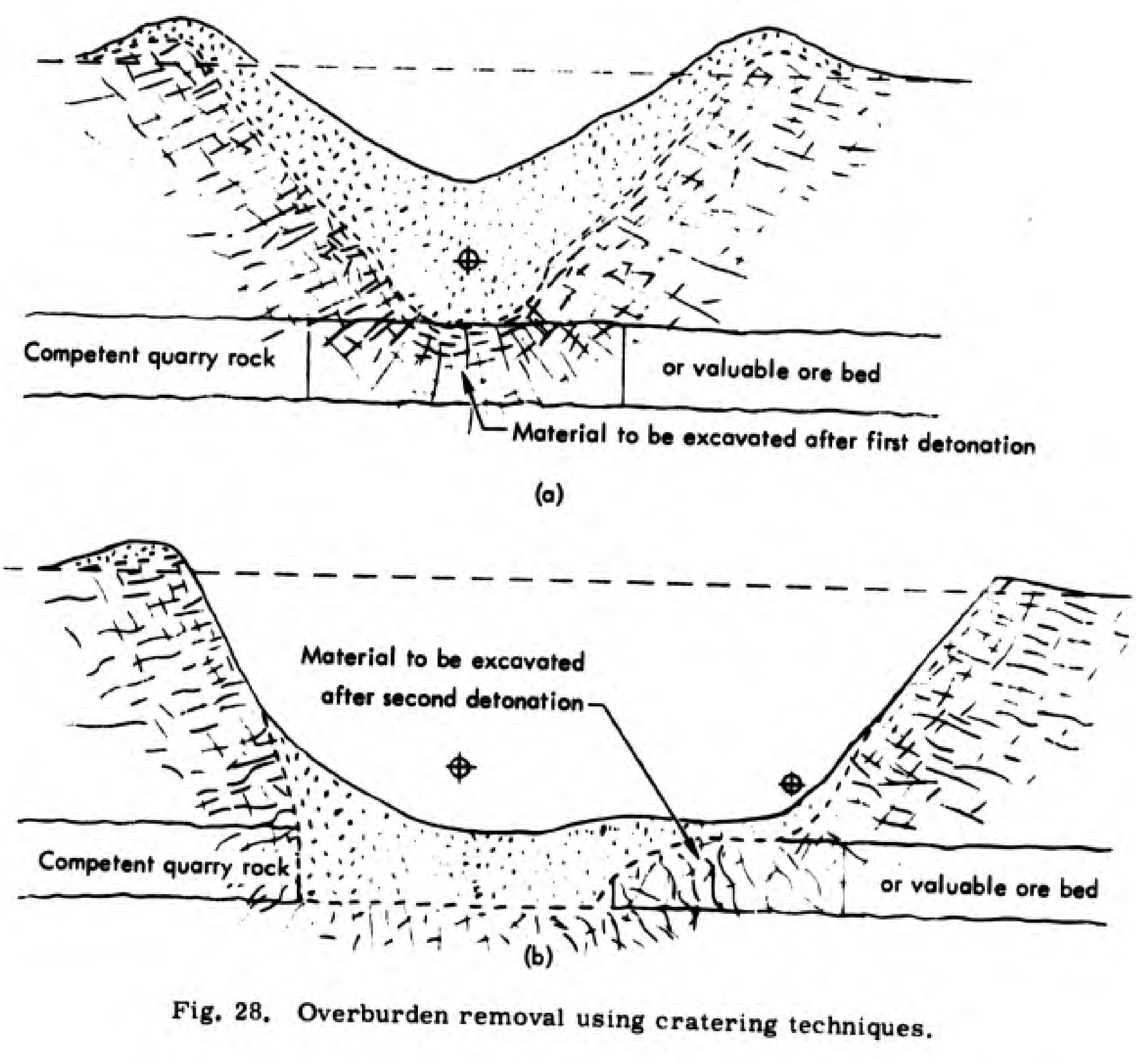


Fig. 28. Overburden removal using cratering techniques.

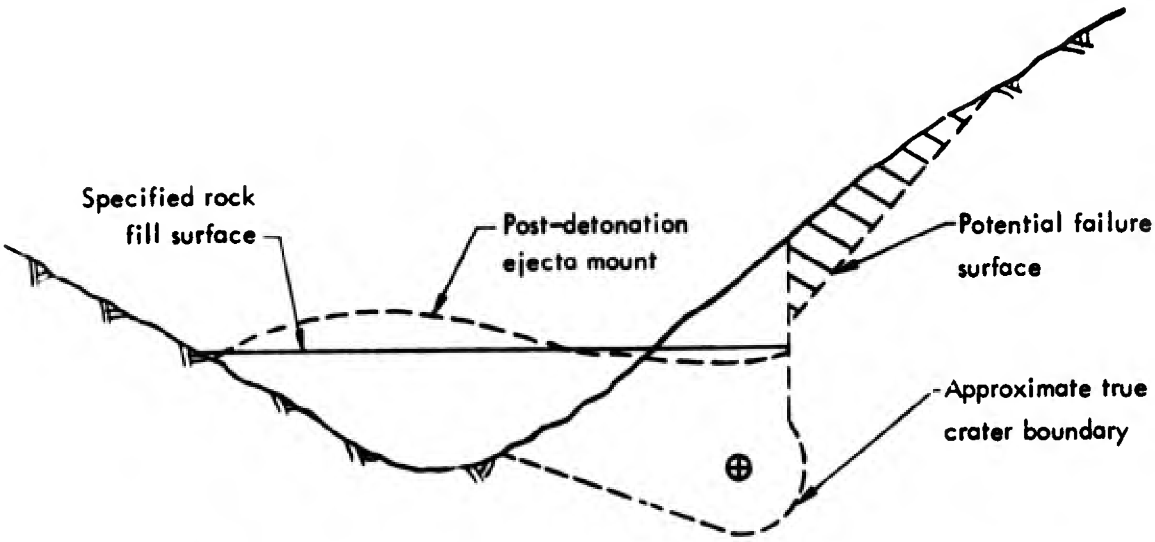


Fig. 29. Cut-and-fill operation using cratering techniques.

On the basis of the cratering characteristics for the various media, the required explosive yields, emplacement depths, and charge spacings are selected so that the excavation is wide and deep enough to satisfy the project criteria at the design grade. All charges should be detonated at optimum depth of burst for the pertinent geologic medium. The maximum number of charges in any detonation is limited only by ground shock and airblast considerations. If safety analyses indicate that the total explosive yield required to excavate a given cut is excessive, it will be necessary to use a series of separately detonated linear craters which would be interconnected by subsequent detonations.

4. <u>Quarrying with Large-Yield Chemical Explosives</u>—The subsurface detonation of a large-yield chemical explosive charge at an appropriate dob (about $7\ Y^{1/3}$ m/metric ton $TNT^{1/3}$,* deeper than optimum for cratering) will produce broken rock without ejecting the material any great distance. The broken rock can be removed and used as aggregate in the construction of rock fill structures. Several cratering experiments and chemical explosive coyote blasts have provided information of significant value in developing cratering quarrying technology. One basic difference exists between coyote blasting and large-yield explosive quarrying. In coyote blasting, gravity is relied upon for part of the fragmentation. However, in large-yield explosive quarrying, fragmentation is caused by the effects of the explosion.

The most favorable topographic location for a quarry is a hillside having an inclination of approximately 30 deg to facilitate recovery. Ideally, the rock would be broken and bulked, and a minimum amount would slide downhill. Excessive depths of soil or deeply-weathered, weak rock should also be avoided in the selection of a quarry site. The rock at the prospective quarry site must meet

*Or 0.9 meters/megacalorie$^{1/3}$ (m/$Mcal^{1/3}$) in terms of explosive energy.

design specifications. An estimate can be made of the in situ block size and the probable block-size distribution of the quarry rock, from a preshot investigation of geology, rock strength properties, and the orientation and spacing of joints and other fractures.

The volume of recoverable rock from a quarry detonation can be approximated by the following:

In situ true crater volume (m^3)

$$= 410\ Y\ (\text{metric ton TNT}) \\ = \pi/8\ m^3/\text{Mcal} \qquad (9)$$

When estimating quarry volume, it is advisable to allow for material loss due to oversize blocks and uneconomically recoverable material deep in the crater. A concept of this type of quarry is shown in Fig. 30.

3.2 UNDERGROUND EXCAVATION AND MINING

Chemical high explosives are used to excavate tunnels, shafts, and stopes for underground construction and mining. Although mechanical equipment can effectively excavate tunnels and shafts, drilling and blasting are effective methods of

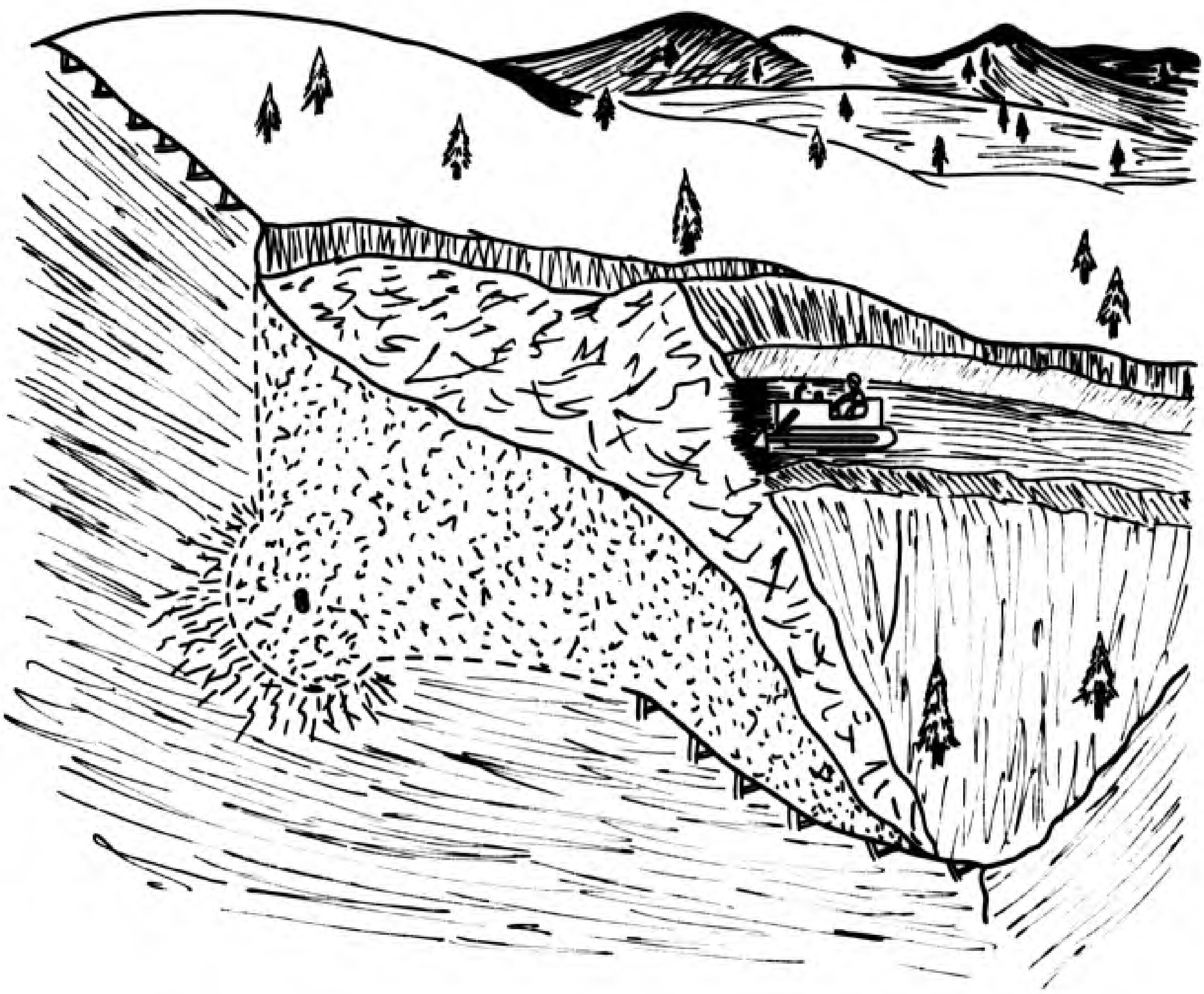


Fig. 30. Quarry concept using large-yield chemical explosives.

driving tunnels in high-strength rock and excavating in underground sites where space for the access and the operation of equipment is limited. Drilling and blasting patterns, explosive requirements, and mucking methods for tunnel driving, shaft sinking, and stope excavation are discussed in this section.

Various types of underground openings are depicted in Fig. 31. Horizontal (or nearly so) underground passageways are

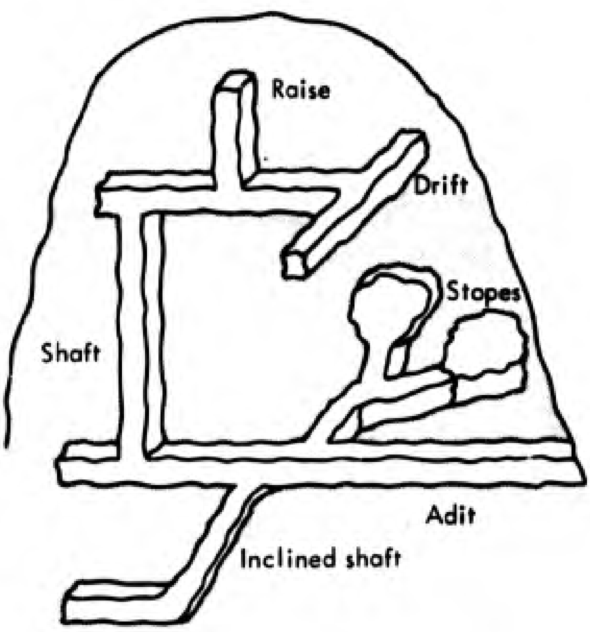


Fig. 31. Tunnel nomenclature.

called tunnels (both ends intersect a surface) or adits (one end intersects a surface). Drifts, small secondary passageways off the main tunnels, also fall in that category. Shafts are underground passageways which are vertical or inclined. When shaft excavation proceeds from a lower to a higher elevation, the shaft is called a raise. Stopes include all underground excavations for purposes other than construction of passageways.

3.2.1 Tunnel Blasting

Tunnel excavation involves the removal of rock, or other material, within a limited cross sectional area which is usually rectangular, circular, or horseshoe in shape. Tunnel nomenclature is depicted in Fig. 32. The heading, or working face, is generally advanced full face in smaller sized tunnels. In larger sized tunnels, however, only a portion of the tunnel cross section is usually developed as a heading. The use of the top heading method is shown in Fig. 32. That method results in a lower bench which can be removed by normal quarry blasting techniques. In tunnel blasting, the heading is advanced by sequentially drilling and blasting the rock and removing (mucking) the rock fractured by the explosions. The operation is cyclic, changing detonation patterns only to accommodate changing rock conditions. Drilling and blasting patterns, explosive requirements and mucking methods are discussed in the following paragraphs.

a. Drilling and Blasting Patterns

The combination of drill holes, charges and blasting sequence associated with a single series of detonations is called a round. A blasting round for removing the rock in the restricted space of a tunnel heading is designed so that the rock is blasted towards successively formed free surfaces. The design must allow for bulking of the rock as it is fractured. An increase of 60% in volume may be expected and, to insure against blockage of the opening, allowance for 100% increase in volume is typical. Various cut and side hole drilling and blasting patterns are discussed below:

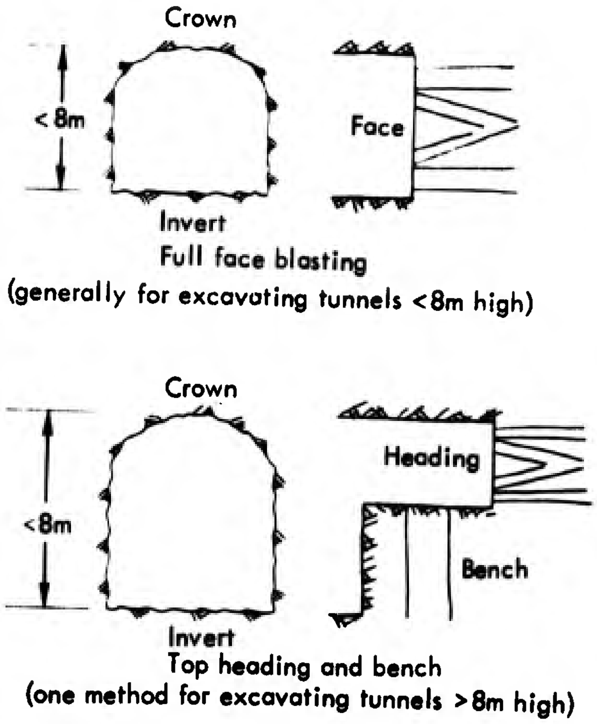


Fig. 32. Tunnels and tunnel nomenclature.

1. Cut Hole Patterns—The charged holes initiated first in a blasting sequence are designed to produce a cut, or opening, towards which the rock can break during subsequent detonations in the round. The cut is usually positioned near the center of the heading. When using drill holes that are angled with respect to the tunnel axis, the length of excavation per round (advance) is limited by the width of the tunnel, and design corrections for varying rock conditions are quite difficult to make. Parallel hole cuts permit greater advances per round and flexibility in design, although the physical size of the larger capacity drilling equipment required to prepare holes may limit the amount of advance obtainable per round.

The fan cut and V-cut, Fig. 33, are typical of angled hole cuts, with the V-cut most practical. Parallel-hole cuts are of three main types: burn cuts, cylinder cuts,

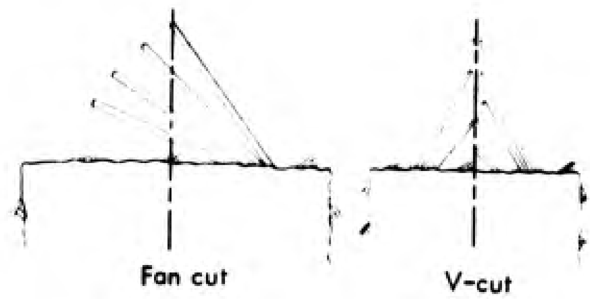


Fig. 33. Drilling patterns for fan and V-cuts (adapted from Langefors and Kihlstrom, 1963).

and crater cuts. These types of cuts, in general, use charged holes that break toward uncharged holes that are located centrally in the pattern. Figure 34 is an example of a cylinder cut.

2. Side Hole Patterns—A side hole drilling and blasting pattern can provide just as great an advance as the cut hole, satisfactory fragmentation, and acceptable throwout of the rock. Moreover, the excavation should extend as near to the excavation line as possible without damaging the rock outside.

A typical side hole pattern used in conjunction with V-cuts is shown in Fig. 35. The numbers at the holes indicate the ignition sequence.

b. Consumption of Explosives

The average consumption of explosives in tunnel blasting may be 4 to 10 times that in normal bench blasting, because (1) smaller fragments are usually desired, (2) drilling deviation has a greater influence, and (3) there exists greater hole restriction. In making a cut, especially with parallel holes, the cut holes may require a specific charge of about 7 kg TNT/m^3, and, in practice, up to 13 kg TNT/m^3 has been used to provide a

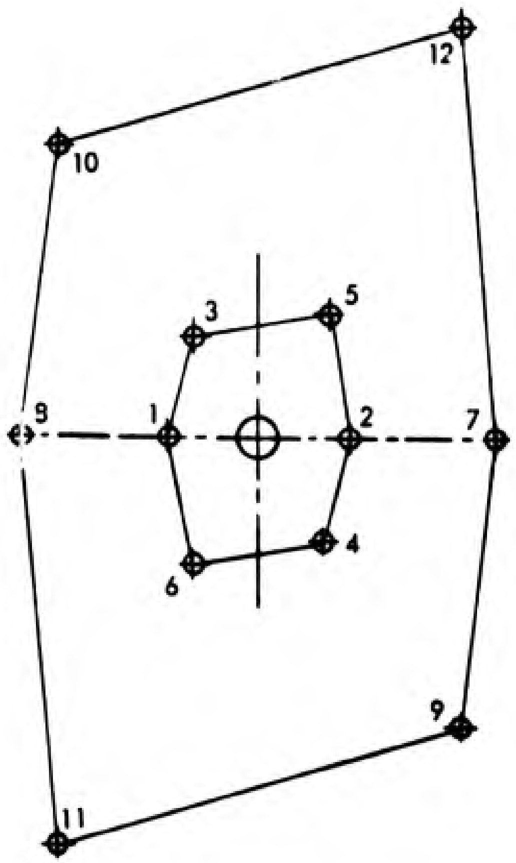


Fig. 34. Typical drilling and ignition pattern for double spiral cut (adapted from Langefors and Kihlstrom, 1963).

margin for complete breakage. In the side holes, the holes below the cut require a greater specific charge than the holes above the cut because the rock must be heaved upward.

c. Rock Removal in Tunnels

Tunnel driving may be cyclic or continuous. In cyclic tunnel driving, the drilling and blasting are accomplished in one shift and blasted rock loading and hauling from the tunnel in another. This approach makes for task specialization, less time lost to ventilation, and improved tunneling efficiency. In continuous tunnel driving, the same personnel do the drill-

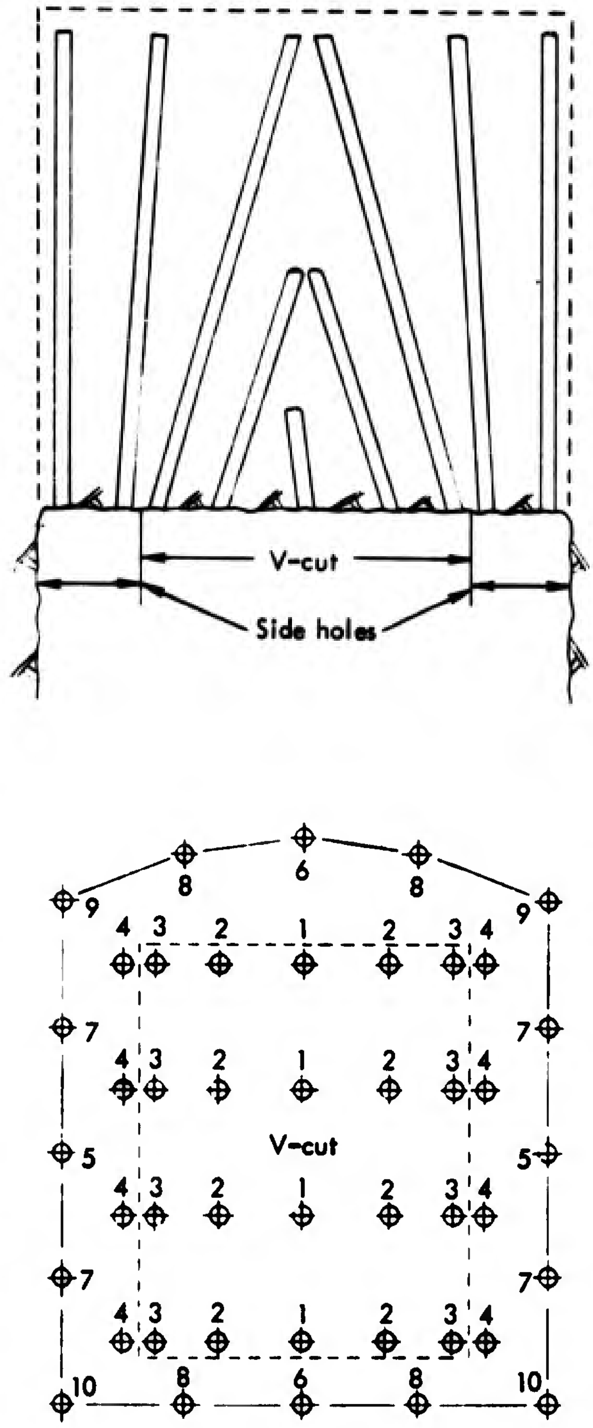


Fig. 35. Typical drilling and ignition pattern for V-cut with side holes.

ing and blasting and the mucking, round after round. This method is suitable when the advance per round is small.

The mucking operation consists of loading the rock into cars which are towed out of the tunnel and dumped. Sometimes a slusher (a stationary, cable-operated dragline) is used to drag the blasted rock from a tunnel being used as a passageway.

3.2.2 Shaft Blasting

Shaft blasting, like tunnel blasting, is a systematic operation involving drilling, blasting, and mucking. However, in shaft blasting, no open face exists to permit lateral movement of the fractured material. The rock must be lifted vertically by the explosion or a free side face must be developed. As a result, heavy charges are required. The cut must provide an open hole to receive the fractured rock, and the overbreak must be carefully controlled. Careful drilling and controlled perimeter blasting are required to eliminate the need for excessive wall supports and lining.

Typical drilling and blasting patterns for shaft excavation are shown in Fig. 36. By alternating sides as in "wedge drilling," drilling may be accomplished on one side while the fractured rock is being removed from the other. During the blasting rounds, the rock is ejected laterally to alternating lower levels. The burn cut, a typical circular shaft drilling and blasting pattern, is easier to drill and to modify than the rectangular pattern (although no space exists for lateral movement during the blast), and mucking must be nearly completed before drilling can be started for the next round.

The removal of fractured rock from a shaft is a time-consuming process. In large hafts, small mechanical loading equipment can be lowered to the floor and used to load the rock into containers, which are then hoisted to the surface, hauled away and dumped. Small shafts require manual loading. This may be an important consideration when the shaft size is chosen, if construction time or labor is a problem.

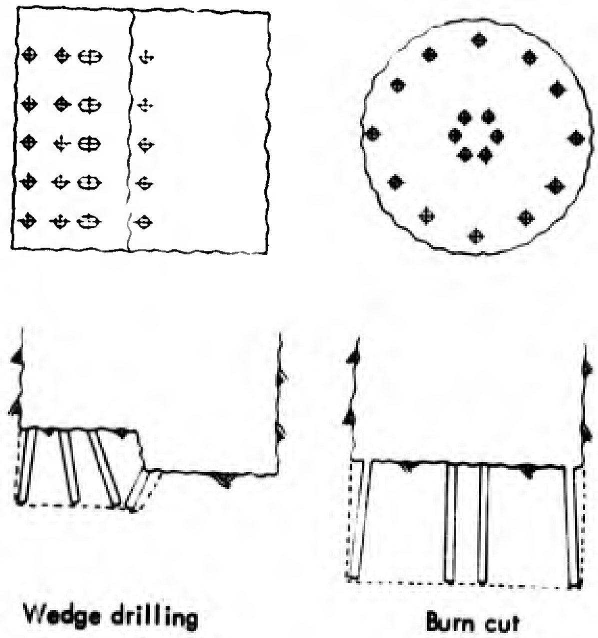


Fig. 36. Drilling and blasting patterns for shaft excavation (adapted from Nichols, 1962).

3.2.3 Stoping

In this report, stoping includes all underground rock blasting for purposes other than construction of passageways such as tunnels and shafts. The excavation which remains after the ore or rock is removed is called a stope. Consumption of explosives in stoping, as for tunnel and shaft blasting, is greater than for surface blasting in similar material because of the confinement of the holes. Stoping methods are many and varied; only a few methods are discussed.

a. Room and Pillar Excavation

In room and pillar excavation, parallel tunnels are driven into the formation and connected at right angles by cross tunnels (Fig. 37). The room and pillar excavation method is suited for mining extensive beds which have a fairly uniform thickness not much greater than the safe span of the roof between the pillars.

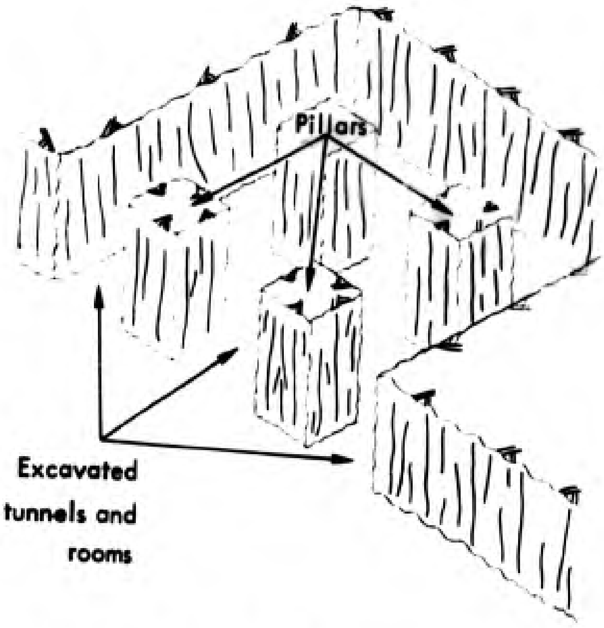


Fig. 37. Room and pillar excavation.

b. Shrinkage Stopes

The shrinkage stope (Fig. 38) is used when the formation is strong enough for wide, unsupported ceilings. The fallen material from overhead drilling and blasting is the floor of the stope for drilling operations. The rate of removal of broken material must be controlled to establish the proper working space height. After blasting in the formation is completed, all the fractured material can be removed.

c. Block Caving (Nichols, 1962)

In block caving, a large area is undermined to cause a cave-in. This process fractures most of the material enough to pass through chutes. The block may be

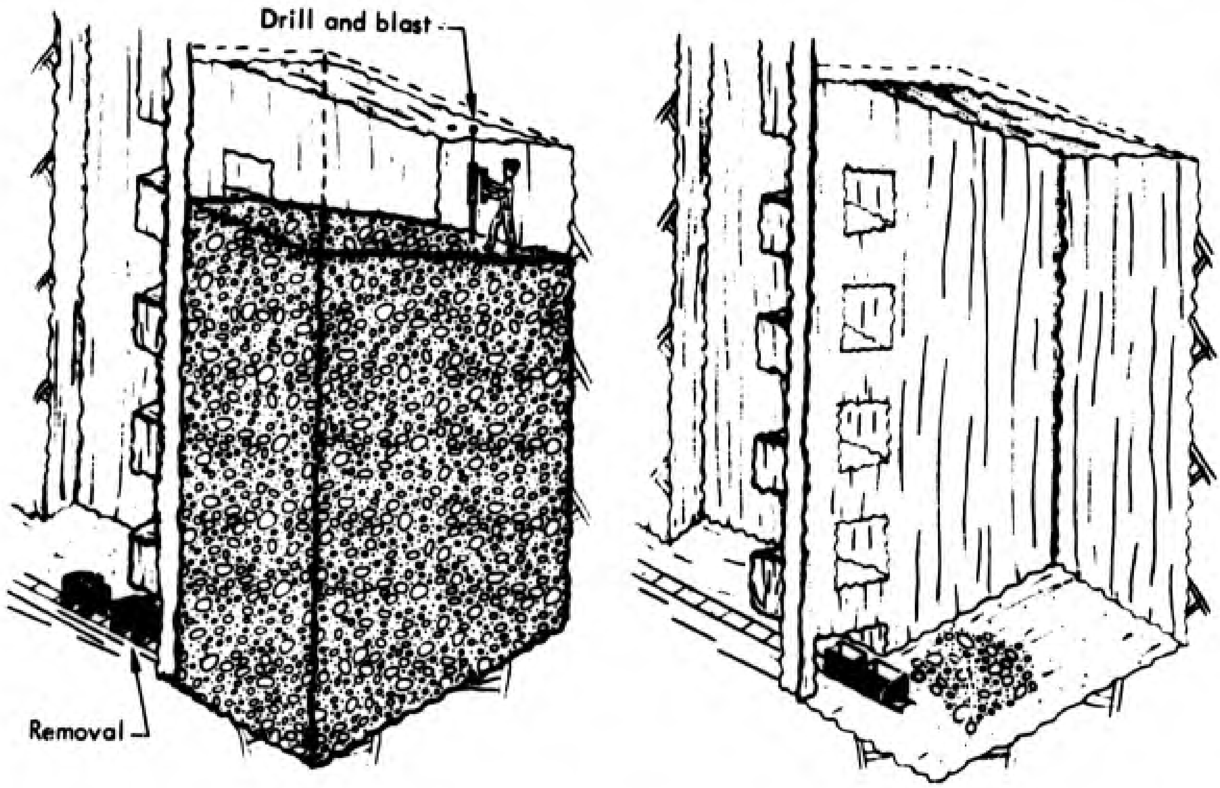


Fig. 38. Shrinkage stoping.

separated from adjoining blocks by shrinkage stopes or by a system of raises or drifts. Three levels of tunnels are required (Fig. 39). The top level is the undercutting level; it is joined to the underlying screening or grizzly level by chutes or finger raises. The grizzly layer is used for sorting and feeding the chutes that lead to the bottom or hauling level.

d. Removal of Material

Gravity is used whenever possible in stoping to convey broken material to loading points or directly into muck cars for tunneling or shafting. Chutes may be used for the gravity feed. They can be constructed by blasting as discussed for shafts and raises. Chutes can be spaced along a tunnel in such a manner that they can be operated simultaneously, with each chute feeding a separate muck car. A screening point between the stope and the chute may be required to prevent oversize rock fragments jamming the chute.

3.3 SEISMIC SURVEYING

Seismic surveying or prospecting methods are well-suited for rapid subsurface exploration of land areas. Velocities and thicknesses of strata can be determined by analyzing the times taken by seismic waves to travel from an explosive energy source to detectors placed on the surface of the ground.

3.3.1 Principles of Seismic Surveying

There are two separate methods of seismic exploration. One, designated reflection shooting, relies upon measuring the time required for a seismic wave to be reflected back to the surface from a subsurface geological boundary. The second method, called refraction shooting, involves measuring the travel times of seismic waves which have been refracted through the various strata. In both methods an explosive impulse is generated near the ground surface. The elastic, compressional waves which radiate outward from this impulsive source are detected at known distances from the source. The arrival of seismic energy at these detectors is recorded with an accurate time base, and travel times can be read directly from the recordings. In the refraction method, only the times of the first motions at the seismometers generally are used; in the reflection method, on the other hand, the times of later motions are of chief importance.

From the travel times and the distances between the explosion and the detectors it is possible to calculate the

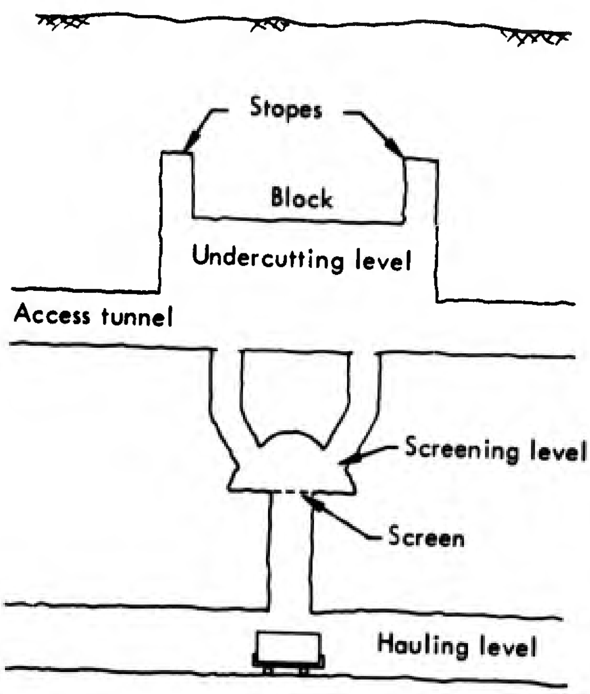


Fig. 39. Block caving.

depths and dips of refracting boundaries or reflecting horizons. The theory which underlies the interpretation of seismic data is essentially the set of laws of geometrical optics. There are a number of excellent references on this subject (Jakosky, 1957; Griffiths and King, 1969; Dobrin, 1960), a more detailed explanation of which is beyond the scope of this report.

3.3.2 Seismic Explosives and Caps

Seismic surveying involves field conditions not always encountered in other explosives applications. Suitable explosives for seismic work should have the following characteristics: high explosive power, effective detonation under pressure, suitable plasticity, rigid packing, high density, and stable physical properties. A wide variety of explosives especially tailored for seismic work are available commercially.

Timing is important in seismic work and travel times are usually measured to a thousandth of a second. Special electric blasting caps have been developed which detonate immediately upon application of the firing current.

Chapter 4

Lunar Explosive Excavation Technology

A lunar explosive excavation technology, as such, does not exist. This chapter presents a basic approach toward establishing the necessary technology to enable the use of explosives for engineering support of lunar scientific investigation and for lunar base construction. It reviews what is known about the moon and its characteristics that would influence explosive excavation. It examines the possibility of modeling lunar explosion craters on earth as an aid in establishing the needed technology. The chapter then goes on to discuss the more important characteristics required of a lunar explosive and suggests candidate formulations. Lunar project design considerations are explored from the planning stage through post-detonation operations. Potentially harmful explosion side effects of ground motion, blast, and missile (ejecta) throwout must be considered in lunar project design just as they are considered in terrestrial projects. Preliminary predictive schemes are proposed to help to evaluate the magnitude of these effects.

4.1 LUNAR ENVIRONMENTAL AND SURFACE CONDITIONS

The physical conditions existing on the lunar surface will require significant departure from terrestrial practice to establish a lunar explosive excavation technology. The physical makeup of the lunar surface will strongly influence that task. To the maximum possible extent, the technology should be developed under simulated conditions on earth, since such efforts on the moon would be prohibitive in terms of time, cost, and transport payload. This section examines available lunar data to develop lunar environment and surface analogs on which to base an estimate of lunar explosion effects.

4.1.1 Lunar Environment

The lunar gravitational acceleration, 1.63 m/sec^2, is one-sixth that on earth, and the moon's environment is harsh in comparison to that of the earth. To a depth of 12 to 100 cm, the daily temperature (about 14 earth days) varies from about -169 to +117°C. The temperature is believed to be relatively constant at about -40°C (Lockheed, 1965) below that depth. The incident solar energy at lunar noon is about 3 cal/m^2.

Atmospheric pressure at the surface of the moon is less than 10^{-12} mbar. This lack of an atmosphere subjects the surface of the moon to radiation and particle bombardment from space. Cosmic rays with energies up to billions of electron volts strike the lunar surface with a normal flux intensity of 1.5 to 4 particles/cm^2/sec. This flux increases thousands of times in a matter of hours during periods of solar flare activity and may last for several days. Solar flares occur infrequently and are not accurately predictable (Glasstone, 1965). Meteoritic particles 1 micron or more in diameter strike the moon with velocities up to 72 km/sec.

The lack of an atmosphere also affects natural lighting on the moon. Light from the sun is not diffused by atmospheric scattering as on earth and causes extremely sharp delineation between lighted regions and shadows. Also, the moon has been found to reflect a large proportion of the incoming light back along its path of incidence. This condition has caused some perception problems during lunar exploration missions (Strickland, 1969a).

4.1.2 Lunar Materials

The most recent facts available on lunar materials came from the Surveyor series, Apollo 11, and Apollo 12 missions. The most detailed surface data resulted from the Apollo landings.

Explosive excavation design depends more on the mechanical properties of materials than on detailed geologic characteristics. Bulk density, porosity, particle size distribution, P-wave and S-wave velocity, angle of internal friction, angle of repose, and in situ block size are sufficient to specify a lunar soil and bedrock model for cratering purposes. For geometric similarity, the thickness of the soil regolith (loose surface materials) must also be known.

a. Tranquility Base

The surface at the Apollo landing site (Aldrin, Armstrong, and Collins, 1969) consists of a very thin layer (0.32 cm) of fine dust which grades into a thin caked layer (0.64 cm), then into a 15-cm layer of slightly cohesive sandy-to-silty material. This cohesive layer varies in thickness with topography. Deeper, the material becomes more firm, finally grading into crystalline igneous rocks and breccias. The rocks resemble terrestrial olivine-bearing basalts (Hess and Calio, 1969); the breccias are made up of recemented rock fragments which may be broken by hand (NASA, 1969).

The thickness of the lunar soil at Tranquility Base, as determined by the examination of local impact craters, ranges from 3 to 6 m, averaging 4.1 m (Shoemaker et al., 1970). The mechanical behavior and cohesiveness of the lunar soil are similar to the behavior and cohesiveness of moist terrestrial soils of the same grain size distribution (Costes et al., 1970). The particle size distribution curve (by weight) is similar to that for glacial till but is skewed towards the fines with a median grain size of 0.62 microns and a modal grain size of 0.20 microns (Duke et al., 1970). No clay fines exist in the lunar soil, but there do exist a great number (about 50% by weight) of spherical glass fines. Bulk densities of the upper few centimeters of the lunar soil range from 1.5 to 1.8 g/cm^2 with porosities ranging from 50 to 42%. At greater depths, the bulk density of the soil is about 2.2 g/cm^3 with a porosity of about 27% (Schreiber et al., 1970). Earlier estimates (Mitchell, 1969) had been 0.6 to 1.2 g/cm^3 for the top layer; 1.0-2.0 g/cm^3 below. The specific gravity of the lunar soil solids is 3.1 compared to about 2.7 for earth (Costes et al., 1970). Friction angle of lightly compacted soil is 35 to 45 deg; the angle of repose is about the same.

The lunar soil grades into a predominantly basalt-like rock which has a density of about 3.1 g/cm^3. This bedrock contains many fissures and cracks which, because of the low gravity field and absence of water, probably extend to considerable depths (Schreiber et al., 1970).

There was no detectable evidence of subsurface stratification at the Apollo 11 site or at any of the five Surveyor sites.

Compressional surface wave velocities are low, about 108 m/sec (Latham et al., 1970). Subsurface P- and S-wave velocities for the bedrock are 1810 to 1890 and 1010 to 1050 m/sec, respectively; seismic velocity increases and attenuation decreases rapidly with depth (Schreiber et al., 1970). This condition suggests the possibility of a seismic wave guide on the lunar surface and long durations for seismic signals (Arnold et al., 1970). The relatively low seismic velocity of the lunar bedrock appears to stem from its relatively high porosity and compressibility (McGregor, 1967).

Near Tranquility Base the lunar surface is enriched in refractories, such as TiO_2 and Al_2O_3, but depleted in volatiles, such as H_2O and Na_2O (Hess and Calio, 1969). Considerable iron exists in the form of FeO and as pure Fe. The iron and titanium serve to increase density without increasing seismic wave velocities (Schreiber et al., 1970).

The discussion has thus far been limited to the area around Tranquility Base; Surveyor data suggest that the lunar surface is about the same throughout the Sea of Tranquility. Other samples returned by Apollo 11 are anorthosites which are probably ejecta from the Tycho crater in the lunar highlands (Wood et al., 1970). They contain lesser amounts of TiO_2 and FeO but more Al_2O_3 and CaO. The density of anorthosites, about 2.9 g/cm^3, is somewhat less than the mare basalts. The weight percentages of the major components of lunar anorthosites and basalts are compared to average terrestrial rock compositions in Table 9.

Table 9. Composition of lunar and terrestrial surface materials (average weight percent).[a]

Material	Terrestrial	Lunar anorthosite	Lunar mare rock and soil
SiO_2	59.1	45.8	40.8
TiO_2	1.1	0.1	9.5
Al_2O_3	15.3	30.0	11.5
Fe_2O_3	3.1	—	—
FeO	3.8	4.5	17.2
MgO	3.5	4.8	7.0
CaO	5.1	15.8	11.7
Na_2O	3.8	0.3	0.4
K_2O	3.1	—	0.1
H_2O	1.2	—	0.1
Fe	—	—	0.4
Cr_2O_3	—	—	0.3
MnO	—	0.1	0.3

[a](Agrell, 1970; Gillaly et al., 1968; Wood et al., 1970).

The major minerals occurring both in the lunar soil and rock samples taken near Tranquility Base are glass, plagioclase, clinopyroxene, ilmenite, and olivine. Some metallic iron and troilite were also found in igneous rocks.

b. Apollo 12

Samples of lunar material were returned by Apollo 12 from an area south-southwest of Copernicus in the Ocean of Storms. This area differs significantly from Tranquility Base in the following ways (NASA, 1970).

(1) The regolith is only about one-half as thick.

(2) The depletion of volatiles and the enrichment of refractories are less pronounced.

(3) The chemical composition of the fines and breccias differ from that of the crystalline rocks, whereas Apollo 11

fines were similar in composition to crystalline rocks.

(4) The lunar soil is not as firm and may be scooped out by hand as deep as 20 cm. This was not possible at Tranquility Base.

(5) There is visible evidence of stratification in the returned core samples.

(6) Rock blocks several meters across were noted, whereas rock sizes around the Apollo 11 site were 0.5 m or smaller.

Some of the differences between the Apollo 11 and 12 samples may be attributed to the fact that the Apollo 12 site was on a broad ray from Copernicus. Collected samples most likely consist of both native material and ejecta from Copernicus.

c. Terrestrial Analog

Because of the high TiO_2, FeO, and Al_2O_3 content in the lunar material, exact modeling of the lunar surface on earth will not be possible. For the purpose of terrestrial modeling of lunar craters, differences in density, porosity, and seismic velocity will pose minor problems.

The lunar bedrock in the mare region can be simulated by porous terrestrial basalts such as those in Hawaii (Stephens and Lilley, 1970). Terrestrial basalt densities (about 2.9 g/cm^3) are nearly 14% less than the density of lunar bedrock; so that, to match lithostatic heads in the scaling techniques discussed in paragraph 4.2, scaled depths of burst on Earth should be increased by about 16%.

The mare topsoil is similar to terrestrial quartz-feldspar sand and gravel (Stephens and Lilley, 1970); it has a size distribution similar to that of glacial till but skewed toward fines. In developing a lunar topsoil model, the soil should be compacted to a density of about 2.2 g/cm^3 at depth grading to uncompacted soil near the surface. A small amount of moisture is permissible to provide cohesion. For modeling purposes, a topsoil depth of 4 m can be assumed for the Sea of Tranquility.

The lunar highlands probably consist of anorthosite rock similar to that found in the San Gabriel mountains in California. No definite information is available concerning the thickness of the regolith in the lunar highlands, although estimates of 15 to 20 m have been made (Hess et al., 1969).

4.2 MODELING LUNAR EXPLOSION CRATERS ON EARTH

The cost of material transportation, labor, and equipment on the moon is very high, and a technique for engineering construction and scientific program support should be proven before its inclusion in lunar activities planning. Because a lunar explosive excavation project must be undertaken with the same degree of confidence as other proposed and projected lunar activities, it is mandatory to model lunar explosive excavation projects on earth. A scaling study has been performed to identify those differences between physical conditions on the moon and on earth that are significant in duplicating lunar operational conditions for the purpose of setting up an earth modeling program.

This section briefly describes that study. It considers two approaches to earth modeling: (1) alteration of the length scale and (2) full scale terrestrial modeling.

4.2.1 Alteration of Length Scale

As developed in Appendix A, lunar explosion craters can be modeled at one-sixth scale on earth. One of the basic assumptions of the analysis is that the same explosive is used in earth modeling as in the proposed lunar application. The other assumption is that the earth cratering medium has physical properties identical to those of the lunar site being modeled; an approach to developing a terrestrial analog of the lunar crust was presented in paragraph 4.1.2. Selenophysical studies, currently a part of lunar scientific investigations, will provide information needed to refine the analog.

With the explosive and the physical properties established, it was found that most of the significant variables scaled directly except for length, strain rate, and atmospheric pressure. The study indicated that dimensions were related to the one-third power of the explosive energy released by a detonation. Terrestrial experience favors use of the empirically determined three-tenths power, as discussed in paragraph 3.1.2, but that exponent is influenced by gravity and air friction. Fixing the length scale at one-sixth serves to resolve the length difficulty.

The strain rate scale varies inversely with the length scale (Crowley, 1969). The increased strain rate might have some effect on modeling contained detonations at this scale, but the effect on surface craters should be quite small because of the smaller volume of plastically deformed material relative to crater volume.

A more noticeable effect on cratering is suggested by the absence of atmospheric pressure scaling. While there would be no effect on the motion of particles during the time explosion gas pressures are greater than that of the earth's atmosphere, a significant difference would be evident once those pressures were equal. On the moon, particles would continue to be accelerated slightly by the expanding explosion gases. However, on earth they would encounter friction drag from the denser atmosphere. The net result would be an ejecta range somewhat less than would be expected on the moon. The consequences of the effect can be visualized by noting that the ratio of ejecta range in air to that in a vacuum is a function of the ballistic coefficient, which is proportional to the square of the initial particle velocity and inversely proportional to the mean particle diameter. Thus, fine particles would be considerably more affected by the presence of an atmosphere and would fall to the surface nearer the crater than would the larger particles. The effect on crater dimensions would not be significant for shallow depths of burst, but would become appreciable as depth of burst increased. For deeper depths of burst, reliable modeling could be done only in an evacuated chamber.

It has been noted that the explosion gas pressure reaches a level of approximately 0.1 atm at 1 crater radius. If the pressure in an evacuated chamber is maintained at about half that value (about 30 to 40 mm Hg), air drag should have a negligible effect on crater dimensions.

Therefore, earth modeling of lunar explosion craters can be accomplished if:

(1) Same explosive is used.

(2) Model cratering medium is equivalent

in terms of cratering properties to the modeled lunar site.

(3) All lengths are reduced to 1/6. (areas to 1/36, and volumes to 1/216).

(4) Model atmospheric pressure is less than 40 mm Hg.

4.2.2 Full-Scale Terrestrial Modeling

For this analysis, the length scale was fixed at unity and the effects of gravity were investigated (Appendix B). With a length scale of one, all similarity requirements are met except those of gravitational scaling and atmospheric pressure. The similarity violation of gravitational scaling was overcome by adopting a separate length scale for missile (ejecta) range only. That length scale suggests that particles on earth travel one-sixth as far as similar particles on the moon.

Lithostatic head, which does not scale in this situation, has some effect on true crater formation and on initial particle velocity distribution. Seismic velocity, which is affected by the lithostatic head, influences the time of arrival of shock and elastic waves but has negligible effect on their magnitudes. The true crater, formed by shock and elastic wave phenomena, would be relatively unaffected by the difference in gravitational acceleration on earth and on the moon. Lithostatic head, on earth or on the moon, is so small by comparison with the cavity gas pressure generated by the detonation of an explosive that this difference, representing the energy available to impart motion (velocity) to overlying particles, is essentially constant for the depths of burst concerned. Thus, gravity also has a negligible effect on initial particle velocity distribution, and geometrically similar terrestrial and lunar cratering events should be identical except for ejecta range, as previously suggested.

Next, the effect of gravity on particle trajectory and the related questions of ejecta and fallback relationships were studied. The assumptions used as the basis for this part of the study were that distribution of fallback and ejecta could be represented by a normal distribution of a form approximating the distribution formed in previous terrestrial cratering experiments, that particles enter ballistic free flight at the true crater radius, that initial particle velocity distribution is unaffected by gravity as discussed above, and that air drag will not significantly affect the earth modeling accuracy. The latter assumption deserves clarification.

It was recognized earlier that atmospheric pressure does not scale. Air drag will reduce ejecta range substantially. The amount of reduction is particle-size-dependent and is about 20% for mean particle diameters of about 15 cm, less for larger sizes, and more for finer particles. Consequently, it must be recognized that less fallback would occur in a lunar cratering event than in the terrestrial model and that ejecta range would be somewhat greater than that experienced in the terrestrial situation.

For depths of burst near that producing the maximum volume terrestrial crater (optimum dob), lunar explosion craters would have a fallback volume of less than 10% of that in the full-scale terrestrial model. The amount of fallback increases slowly with depth of burst, so that at depths of burst where the terrestrial apparent crater volume approaches 10% of the true crater volume, the lunar apparent crater would still be 76% of true crater volume (assuming equal terrestrial and lunar true crater volumes, as stated above). The predicted relationship between lunar and terrestrial crater volumes is shown in Fig. 40. The "critical" depth of burst at which sprung cavities result depends on the cratering medium properties and is influenced little by gravity. As a result the terrestrial and lunar true crater curves should coincide nearly to that depth.

The effect of gravity on apparent crater dimensions is shown in Fig. 41 for rock and in Fig. 42 for soil materials. These curves were determined by adjusting terrestrial cratering data for the appropriate medium to account for the lower lunar gravitation acceleration, using the method of Appendix B.

Consequently, full-scale earth modeling of lunar explosion craters can be done under the following conditions:

(1) Same explosive is used.

(2) Model cratering medium is equivalent, in terms of cratering properties, to the modeled site.

(3) Fallback and ejecta parameters obtained are mathematically adjusted by the method of Appendix B to account for the increased lunar missile throwout.

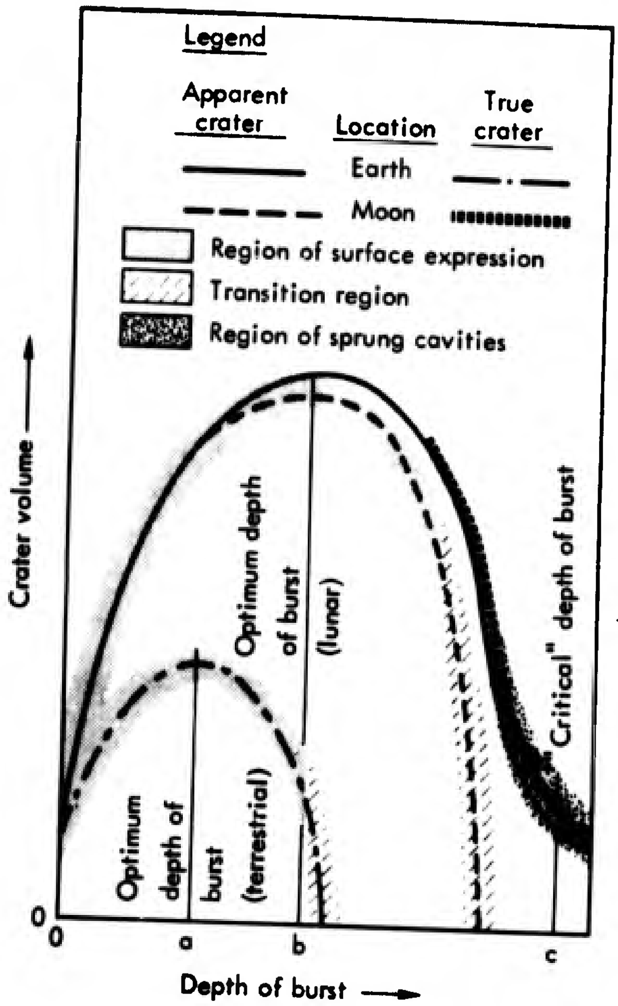


Fig. 40. Variation of terrestrial and lunar apparent and true crater volumes with depth of burst (equal weight charges).

4.3 LUNAR EXPLOSIVES

The nature of the lunar environment, considerations imposed by space transportation systems, and the need for highly efficient cratering place restrictions on the characteristics of acceptable lunar explosives. In this section, the required characteristics of a lunar explosive are discussed and some candidate explosives are suggested.

4.3.1 Lunar Explosive Characteristics

The nature of current space transportation systems makes unit shipping costs extremely high. Development of a more efficient system, as the Space Shuttle, would tend to reduce shipping costs significantly, but large quantities of material for engineering support and construction projects will still represent a severe payload penalty. Consequently, the mass of explosive required for a given project should be minimized. This requirement can be met through the use of explosives

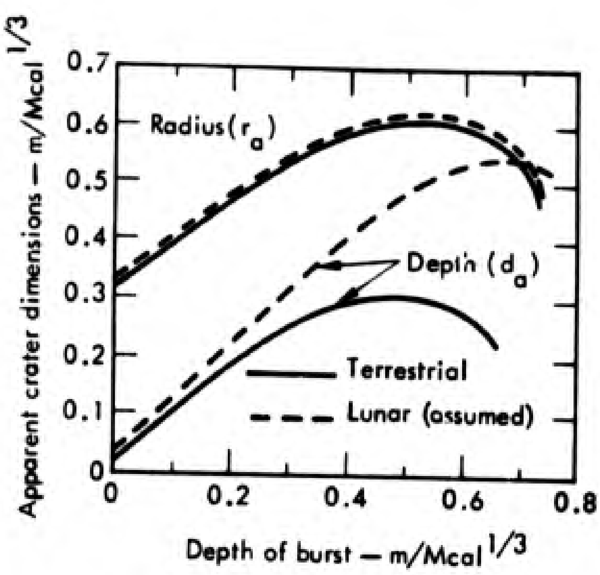


Fig. 41. Apparent crater dimensions for rock.

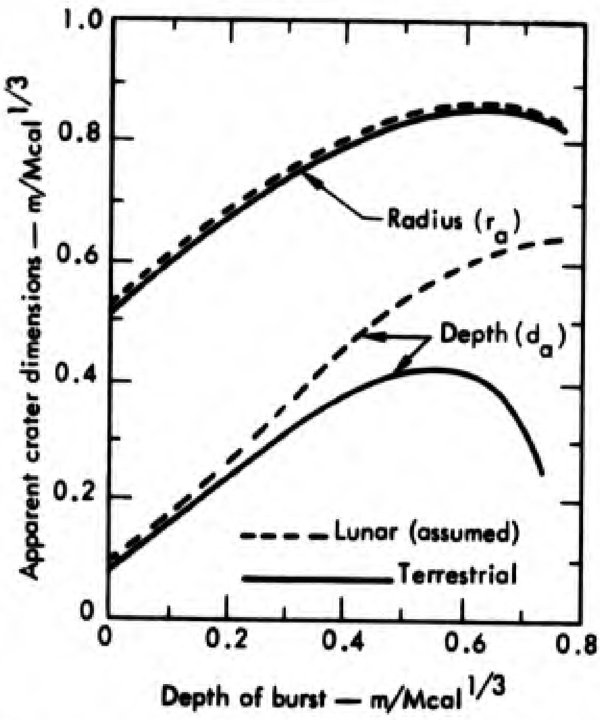


Fig. 42. Apparent crater dimensions for soil.

with the largest possible energy release per unit explosive mass.

Payload considerations also require the explosive to occupy a minimum volume during movement from earth to the moon. Bulk will also be an important factor in handling and emplacement operations on the moon. These conditions call for a high explosive density.

Lift-off, spaceflight maneuvers, and moon-landing will subject the explosive to some degree of shock and vibration loading. Whenever it is exposed, particularly during emplacement operations, there is a possibility, however small, of meteoroid impact. Explosives stored on the moon prior to use, might be subjected to the 286°C temperature variation experienced during the lunar day. To minimize these potential hazards, a lunar explosive must have low shock, impact, and vibration sensitivity and very high thermal stability.

An explosive could be exposed to the lunar vacuum at any time during its presence on the moon. Therefore, it must contain a minimum of volatiles and have a very low overall vapor pressure to minimize the rate of boiling or sublimation and the extent of outgassing.

Lunar operations costs will be very high; so explosives emplacement must be made as uncomplicated as possible. Likewise, the cost of surplus payload is prohibitive; a lunar explosive must detonate without misfire. Conversely, it must not detonate accidentally. Reliability and safety are essential characteristics of a lunar explosive.

The final requirement concerns cratering efficiency. Experience has shown that the explosive detonation pressure must be high enough to fracture the rock above the charge and to provide some surface spalling but not so high as to pulverize excessively the large amounts of rock near the charge. Too high a detonation pressure produces excessive shock wave energy. The latter manifests itself in high ground shock magnitudes which may pose serious problems on the moon. A practical range of detonation pressures for cratering explosives has been found to be between 80 and 150 kbar.

The above requirements are summarized in Table 10 in the order of relative importance. Naturally, safety is overriding and performance must be compromised, if necessary, to give the safest possible explosive.

Table 10. Summary of lunar explosive requirements.

1.	High reliability and safety
2.	Low impact and vibration sensitivity; high thermal stability
3.	Ease of emplacement
4.	High energy release per unit mass
5.	High density
6.	Low overall and constituent vapor pressures
7.	Detonation pressure between 80 and 150 kbar

Conventional blasting explosives, such as ammonium nitrate slurries, can satisfy requirements 1, 2, 3 and 7 of Table 10, but they are too volatile for lunar use and their specific gravity is generally too low. Other explosive formulations are available which can better satisfy the stated requirements, although they are not economical for terrestrial use.

Explosive safety depends upon properties such as impact sensitivity, thermal stability, and explosive containment. Reliability of detonation depends upon these factors and the manner of charge initiation and boosting. To insure successful initiation of a large cratering charge, some 2.25 kg of a contained high explosive booster, such as tetryl, pentolite, or DATB, should be used. Care must be taken that those booster compounds are well insulated from shock, vacuum, and high temperature prior to emplacement in the charge.

Vibration, shock, and impact sensitivity are closely related, and the reduction of the latter will reduce the others. A measure of impact sensitivity can be obtained from a standard drop-hammer test. Generally, if the drop height from which a weight explodes a sample 50% of the time exceeds 70 cm, the explosive is considered insensitive to impact. If the explosive is placed in a sealed canister and reasonably shock-insulated, a drop weight height as low as 30 cm might be tolerated.

The rate of gas evolution and the vapor pressure of an explosive substance are closely related to its melting or sublimation point. Since lunar temperatures may reach 117°C, the melting or sublimation point must be well above this. Gas evolution at high temperature under vacuum is usually measured by a standard vacuum thermal stability test in which a sample of the explosive is placed under vacuum for 48 hr at a temperature of 120°C. The gas evolution is measured in cubic centimeters per gram of explosive. A value of 0.5 cm^3/g or less over that period is necessary for unprotected explosives placed on the surface of the moon. For explosives in sealed reflective or shaded canisters, a value of 1.0 cm^3/g would be acceptable.

Explosive density, total energy, and gas bubble energy (the energy released by the expansion of detonation products) can be increased, and detonation pressure and shock energy (that energy initially radiated into the medium) can be decreased by the addition of aluminum. This would help satisfy requirements 3, 4, 5, and 7. As the percentage of aluminum increases, shock energy first increases and then drops while bubble energy continually increases. For example, the effect of aluminum on underwater shock and bubble energies is shown in Fig. 43, which is a compendium of data for many aluminized high explosives. While the distribution of explosion energy underground will differ somewhat from that under water, the same general trend will occur. Oxygen balance is not necessary since the aluminum will take oxygen from the CO and CO_2 and the H_2O which forms initially; the final products will contain chiefly corundum (Al_2O_3) and free hydrogen, nitrogen, and carbon.

4.3.2 Candidate Lunar Explosives

Some candidate explosives which satisfy the criteria of Table 10 are listed in Table 11. (The characteristics of TNT are shown by way of comparison; TNT is not suggested as a candidate lunar explosive.) Because the explosives listed in Table 11 are not common, a description of each is given in the following paragraphs.

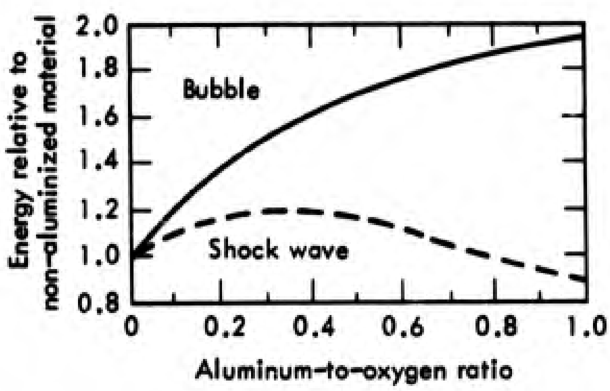


Fig. 43. Effect of aluminum on explosive energy (from Candle et al., 1965).

Table 11. Some candidate lunar explosives.

Name	Composition percentage by weight	Density (g/cm^3)	Detonation pressure (kbar)	Heat of detonation (explosive energy) (cal/g; cal/cm^3)	Impact sensitivity[a] (cm)	Thermal stability[b] (cm^3/g)	Melting point (°C)
DATB	100 DTAB	1.79	250	1000 (1790)	>177	<0.03	295
ALD	65 DATB 35 Al	2.00	~200	1500 (3000)	?	?	295
LX-04	85 HMX 15 Viton A	1.86	330	1320 (2460)	41-74	~0.5	280
ALX	60 LX-04 40 Al	2.20	~270	2000 (4400)	?	?	280
HNS-11	90 HNS 10 Teflon	1.70	~160	1200 (2040)	63	Nil	318
ALH	68 HNS-II 32 Al	2.01	~120	1800 (3620)	?	?	318
MFH	28 Mg 62 Fe_2O_3 10 HNS-II	3.70	?	1100 (3900)	?	Nil	318
ALOX	53 Al 47 Liq. O_2	1.9	?	3810 (7420)	?	?	?
TNT[c]		1.64	220	1100	80-170	0.00-0.048	81

[a]Drop weight heights for 50% probability of explosion.

[b]Gas evolved per gram in 48 hr at 120°C.

[c]TNT is not a candidate lunar explosive; it is shown for comparison, only.

DATB ($C_6H_5N_5O_6$) is similar to TNT in explosive properties but has a much higher melting point and is very insensitive to impact. Its shock sensitivity is fairly low, about the same as TNT (LRL, Livermore, 1965). The relatively high vacuum thermal stability of DATB suggests that it can be left exposed (but shaded) on the lunar surface for a period of four weeks with less than 0.5 cm^3/g gas evaluation. DATB has potential applications as a surface seismic source and for small blasting operations.

ALD is formed by adding sufficient aluminum to DATB to use up all the available oxygen. The resulting detonation products consist mainly of corundum and free carbon, hydrogen, and nitrogen. Although aluminum will probably have little effect on thermal stability, it may slightly reduce impact sensitivity. Solid, pelletized or powered ALD would make an effective cratering charge for uncased drill holes.

LX-04 is a plastic-bonded explosive which consists of a mixture of HMX ($C_4H_8N_8O_8$) and Viton A. Its energy release is greater than DATB, but it is more sensitive to impact and has less thermal stability. Long-term storage requires sealed containers shaded against direct sunlight, but the explosive may be exposed to the lunar vacuum for a period of 24 hr with less than 0.5 cm^3/g gas evolution.

ALX is formed by adding sufficient aluminum to LX-04 to use up the available oxygen. The result is an explosive with high density and energy release but also with a rather high detonation pressure. Its high energy content renders it more effective as a cratering explosive than ALD, and ALX would be preferred whenever long-term storage is not important.

HNS-II was developed by the Naval Ordnance Laboratory as seismic charges for the Apollo Lunar Surface Experimental Package (Kilmer, 1968). Its attractiveness stems from its very high thermal stability and capacity to detonate at very low temperatures. HNS-II consists of HNS ($C_{14}H_6N_6O_{12}$) and teflon. Its normal particle size ranges from 100 to 200 microns, and the explosive can be pressed into any desired shape. HNS-II is now in the pilot production stage. Aluminized HNS-II (ALH) would give an explosive of fairly high density and energy release with moderate detonation pressure. It would be a very good cratering explosive capable of long-term unprotected storage on the lunar surface.

MFH is a mixture of magnesium, hematite, and HNS-II (its most volatile component). The thermal stability of MFH should be very high. Except for ALOX (discussed below) and ALX, it has the highest energy release per unit volume of the explosives listed in Table 11. Thus, it is a potentially good cratering explosive, particularly if the drilling of large-diameter lunar boreholes proves difficult. It is also a suitable seismic signal source since it most closely approaches a point seismic source and can be placed exposed on the lunar surface.

ALOX is potentially one of the most powerful explosives proposed. It is a two-component (aluminum-liquid oxygen) explosive which is mixed just before firing. The liquid oxygen is highly volatile; therefore sealed, insulated, and pressurized canisters must be used. The explosive warrants consideration for two reasons: each component is itself non-explosive; therefore, shipping safety is achieved. Second, energy release is well above those of other explosives. Although all of the other explosives discussed would be suitable for small to moderate sized charges (less than one metric ton), large shots require the maximum possible energy release to keep charge weights and volumes within manageable limits. ALOX is an attractive candidate for large cratering charges because the fractional weight penalty for cryogenic containers decreases as charge weight increases. The two components, aluminum and liquid oxygen, are shipped and stored separately; therefore, there is no hazard of spontaneous detonation. To use ALOX as a cratering charge, a sealed, primed, pressurized canister of fine aluminum powder or wool could be lowered into the ground and stemmed. Next, liquid oxygen would be poured into the canister from the surface through suitable feed lines with pressure relief valves provided for boiloff. Once mixed, the explosive must be detonated within a matter of hours. This type of explosive system has two advantages: first, should a misfire occur, the explosive power of the mixture is lost after a period of time due to oxygen boiloff, and the area can be safely reentered; second, should a cratering mission be aborted before mixing, the liquid oxygen can be used for other purposes.

The list of suggested explosives in Table 11 is not complete but is intended to give a representative sampling of possible lunar explosives. Since most of them have rarely been used in terrestrial applications, considerable research into their properties is necessary.

4.4 PROJECT DESIGN CONSIDERATIONS

A number of factors must be considered when the use of chemical high explosives is planned in an engineering project for lunar mission support. The design elements are similar to those considered in terrestrial applications modified as necessary to account for the differing physical characteristics existing on the moon. The most critical data for explosive excavation design are the physical properties of the lunar materials. Without that data, it will be necessary to make very conservative assumptions of explosive requirements to insure crew safety and successful missions. Thus, it is important that detailed information on lunar materials be available for the first excavation designs and that planning and design for subsequent missions remain flexible to incorporate the latest available data. This section discusses lunar explosive-excavation project design elements including site selection, design parameters, explosive charge emplacement construction, and post-detonation operations.

4.4.1 Site Selection

Development of early lunar bases will be restricted to areas of interest to scientific investigators. Consequently, engineering aspects of site selection, while they must be considered, will be of less importance than the needs of scientific programs. Final choice of a lunar base site will require some detailed engineering information, much of which should be available as a result of pre-liminary scientific experiments.

Information on the geologic conditions and physical properties at a proposed site is necessary to predict cratering characteristics. Detailed information will be required to a depth of about twice the anticipated depth of burst and include such information as thickness of over-burden, transition into competent rock, stratification of rock layers, bedding attitudes, joint and fracture patterns, strength, density, and seismic velocity. For underground applications employing contained explosions, data will be needed for about one cavity diameter below the depth of burst.

Detailed topographic information of the proposed project site is necessary to integrate natural lunar features into the project design and to minimize the effort necessary to obtain the desired configur-ation. Consideration must also be given to project site access from the nearest space vehicle landing site.

4.4.2 Lunar Explosion Crater Properties

The engineering properties of lunar explosion craters must be taken into account when explosive excavation proj-ects are designed. Prediction of those properties is necessary to assess the short- and long-term behavior of explo-sively produced excavations. The follow-ing paragraphs discuss these properties as they are expected to apply to lunar excavation projects.

a. Crater Geometry

As a result of the small amount of fallback expected to occur in lunar exca-vations (Section 4.2 and Appendix B) there will be little distinction between the apparent and true crater boundaries, as shown in Figs. 44 and 45. No significant change in the shape of the rupture zone from that found in terrestrial application is anticipated.

b. Particle Size

Size distribution of broken material from a chemical high-explosive detona-tion has been found to be largely a func-tion of the _in situ_ fracture pattern. Section 4.1 suggests that lunar rock can be likened to terrestrial basalts, and it is assumed that the properties and cratering response of lunar rock are similar to those basalts. It is also assumed that lunar fallback and ejecta size distribution will be similar to that experienced in terrestrial cratering. An average fall-back and ejecta size distribution for lunar materials, based on terrestrial experi-ence is shown in Fig. 46.

c. Bulk Density

The increased quantity and range of ejected materials in lunar explosive exca-vation makes difficult a determination of bulking behavior. Lack of air drag allows relatively larger impact energies for fall-back materials, making possible greater fallback bulk densities, and less bulking, on the moon. Terrestrial experience, as given in Table 12, will be used to estimate the bulking behavior from explosive exca-vation of lunar ejecta and fallback.

d. Blast Fracturing

Explosion forces fracture the material in the region surrounding the true crater boundary and cause existing fractures to open further. This type of fracturing can

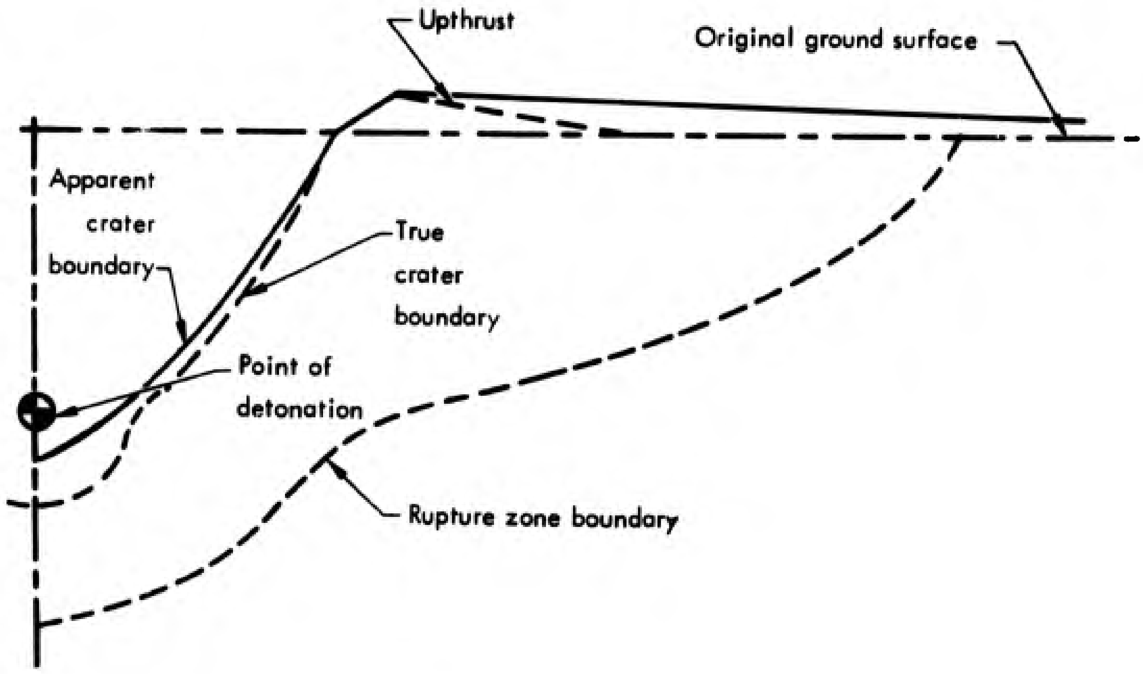


Fig. 44. Profile of single-charge crater or end of row crater in rock.

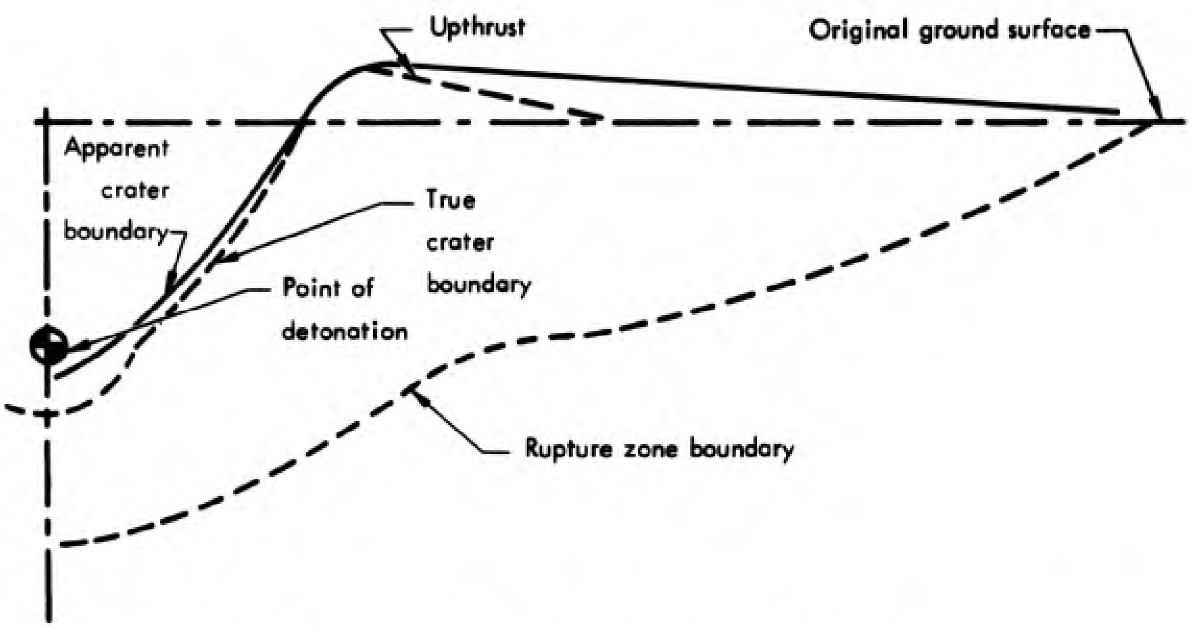


Fig. 45. Profile perpendicular to longitudinal axis of row crater in rock.

be seen in the lip upthrust of terrestrial explosion craters and has been found to exist radially outward from lower areas of the true crater boundary. In the rupture zone adjacent to the true crater boundary, fracturing intensity will increase by several hundred percent through a combination of new, blast-induced

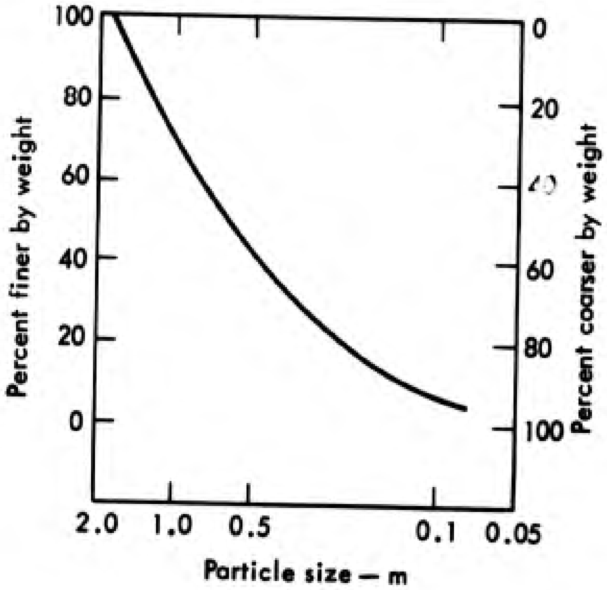


Fig. 46. Assumed average particle size distribution for lunar high-strength rock material.

fracturing and opening of preexisting fractures. Assumed lunar crater fracture characteristics are given in Fig. 47.

e. Mass Strength

The strength of broken rock is influenced both by its crushing strength and the frictional resistance among particles. Immediately after deposition of fallback and ejecta materials, interfacial particle contact would, in most cases, be too small in area to prevent crushing, and the materials would begin to settle. The increased surface area brought about by settlement will eventually be large enough to support the load. Settlement will be less than that occurring in similar circumstances on earth because the weight of superimposed materials and structures will not be as great in view of the lower lunar gravitational acceleration. This should considerably lessen the requirement for compaction in lunar construction. Sliding will take place as settlement proceeds. The amount of sliding also will be less than an analogous terrestrial situation owing to the relatively high frictional resistance along surfaces because of absence of air and water lubricants.

f. Slope Stability

Although studies (Mitchell et al., 1969) of lunar crater slopes reveal an angle of repose of up to 35 or 40 deg, results from Apollo 11 (Costes, 1970) indicate that the angle of internal friction may approach 45 deg. The cohesive nature of lunar soil was suggested during Apollo 11 by these observations: the soil is able to stand on nearly vertical slopes and retain details of an impressed shape; fine grains stick

Table 12. Assumed lunar fallback and ejecta bulking.

Medium	Preshot in situ density, γ_i (g/cm^3)	Postshot bulk density, γ_p (g/cm^3)	Bulking factor $BF = \frac{\gamma_i}{\gamma_p}$	Effective porosity (%)
High-strength rock (as basalt)	2.72	1.60-1.79	1.45-1.6	31-37
Intermediate-strength rock (as rhyolite)	2.27	1.68	1.4	29
Weak rock	2.02	1.66-1.79	1.15-1.23	14-19

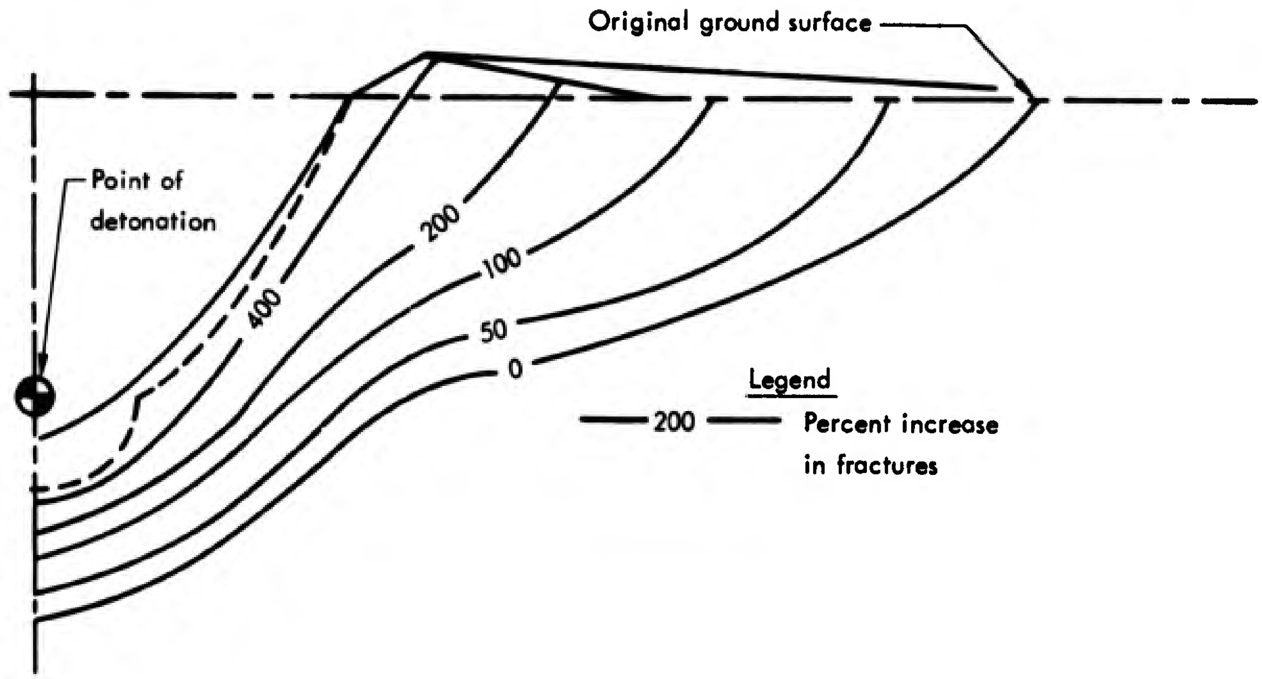


Fig. 47. Assumed variation in intensity of blast-induced fracturing.

together, and soil clumps are sometimes indistinguishable from rock fragments; core tube holes remained intact on removal of the core tube; and material did not pour out of the core tubes. It is considered likely that steep slopes, approaching the vertical, will occur in lunar explosive excavation because of the indicated cohesive nature and high internal friction angle.

4.4.3 Excavation Design

The procedures for designing lunar cratering excavations are similar to those outlined in paragraph 3.1 for terrestrial applications. For the remainder of this report, though, explosive energy will be used as the scaling parameter, in place of the equivalent weight of TNT for the explosive being used. Explosive energies are given in Table 11.

a. Cratering Characteristics

Based on the assumed cratering characteristics for lunar materials given in Figs. 41 and 42 and the assumptions that lunar true crater depth would be 10% greater for rock and 20% greater for soil than the depth of burst, lunar cratering parameters can be established. The form of the lunar true crater is assumed to be that of a paraboloid of revolution in which the base is at the lunar surface (where the apparent and true crater radii are equal) and the distance from base to vertex is 1.1 DOB for rock and 1.2 DOB for soil. The general equation for the parabola, $x^2 = 4\,py$, describing the crater cross section (Fig. 48), becomes

$$r_t^2 = 4pc\ (dob) \qquad (10)$$

where

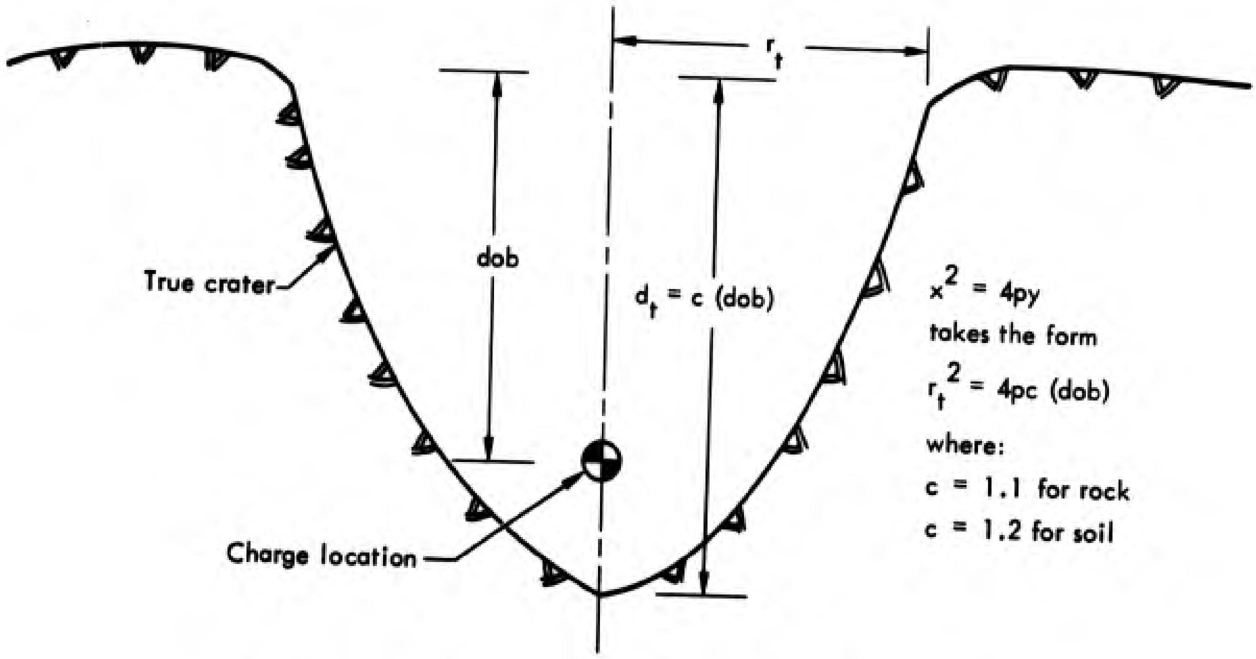


Fig. 48. Lunar explosive crater parameter definitions.

r_t, the scaled true crater radius, has replaced x

c(dob), an appropriate constant times the scaled depth has replaced y, and

p is the distance from focus of parabola to vertex.

Choosing as optimum the dob from Figs. 41 and 42 at which maximum crater radius occurs should result in good slope stability. On that basis, assumed scaled lunar true crater parameters are established as shown in Table 13. The resulting charge yield and parameter relationships appear in Fig. 49. In those instances where maria (soil) material may overlie the rock stratum in which an explosive charge is to be detonated, rock scaling parameters should be used for conservatism in design.

Table 13. Assumed lunar true crater parameters.

Material	Scaled depth of burst dob $m/(Mcal)^{1/3}$	Scaled true crater radius r_t $m/(Mcal)^{1/3}$	Scaled true crater depth d_t $m/(Mcal)^{1/3}$
Rock	0.6	0.6	0.7
Soil	0.6	0.9	0.7

b. Row Craters

As discussed in paragraph 3.1.2, the simultaneous detonation of a row of charges will form a relatively smooth, linear crater in a terrestrial application. Much of this smoothness results from fallback. In a lunar application where fallback is negligible, the parabolic shape of the single crater would result, but careful consideration must be made in the spacing of charges to provide for a linear crater.

Since it has been assumed the terrestrial and lunar true crater characteristics are similar, the same type of charge spacing applies. A method recently proposed by Redpath (1970) for designing a row charge beneath flat terrain will be used. This method uses a concept of maintaining a constant charge weight per unit length of row crater in which the single crater yield, obtained from Fig. 49, is distributed uniformly in equal size charges over an interval along the row crater longitudinal axis of 1.4 crater radii (radius for single crater yield). The total required charge can be distributed among a number of smaller charges provided the constant charge weight per unit length is maintained and the charges are buried at optimum DOB (Fig. 49) for the single-crater energy yield. More drill holes (of the same depth) for charge emplacement will be required for spacings less than the maximum 1.4 crater radii, and this requirement for increased emplacement construction effort must be considered in the design of a row-crater.

Charges in a row should be spaced at 1.4 crater radii or less. Spacings at the upper end of this range may produce cusping of the crater sides and bottom because of the lesser fallback expected in lunar cratering.

Ejecta range relationships are different from those associated with single

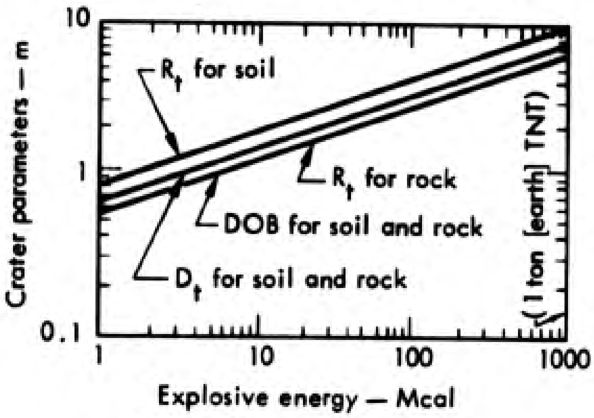


Fig. 49. Assumed lunar true crater dimensions vs explosive energy.

craters because the ejecta from the linear region of a row crater is constrained to move generally perpendicular to the longitudinal axis, rather than in all directions, resulting in greater throwout range on the sides than would result from a single charge. The lips at the end of the row crater are approximately the same as for a single charge.

c. Multiple-Row Designs

Some applications may demand a wide excavation without the increased depth resulting from increased yields in a single row application. This arrangement can be accomplished by a multiple-row-charge configuration.

Current terrestrial design spacing between rows in a multiple-row configuration is 1.5 R_a. In view of the reduced amount of fallback, that spacing will probably have to be reduced to obtain a smooth crater bottom during multiple-row lunar cratering. It is assumed for purposes of lunar excavation that rows of charges would be spaced a maximum of 1.4 R_t apart.

In other lunar applications, it might be desirable to use an array (series of parallel rows in an approximately square overall pattern) of charges. This suggested lunar method would rely on the anticipated long range of ejecta. Rather than detonate the rows simultaneously, they would be detonated separately by row, letting the ejecta be thrown out in leapfrog fashion, thus providing a long, wide excavation.

d. Quarrying Detonations

Quarrying with large-yield explosive charges was discussed in paragraph 3.1.2.

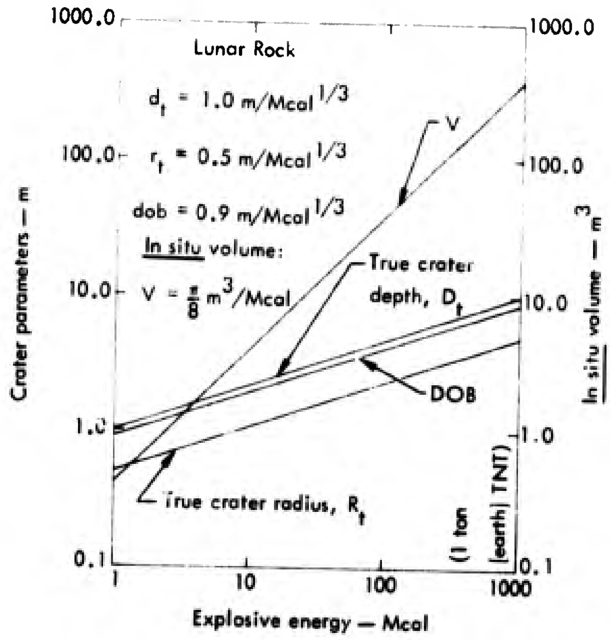


Fig. 50. True crater depth and radius, depth of burst, and in situ volume vs explosive energy for quarrying detonations.

For lunar applications, the parameter-yield relationships are shown in Fig. 50. The in situ volume (unbulked) resulting from a quarrying detonation, assuming a parabolic true crater form, is also given in Fig. 50.

e. Contained Explosions

Depending on the competence of the geologic medium encountered, explosions at a scaled depth of 1.2 m/(Mcal)$^{1/3}$ or greater may form contained cavities with no evidence of surface expression. The radius of the (approximately) spherical cavity formed in competent materials will be about 0.1 m/(Mcal)$^{1/3}$, or about 5 liters of void volume per megacalorie of energy released by the detonation.

For low-energy yields, the cavity will be self-supporting in hard rock and will not collapse. For low-energy yields in incompetent materials, or for large energy yields in either type of material, gravity will act on the intensely fractured zone above the initial explosion-formed cavity causing failure of the cavity "roof." The roof will continue to collapse until either the fallen, bulked materials fill the cavity, preventing further failure, or a relatively competent layer of material is reached which permits the roof to be self-supporting (Fig. 51). For estimating purposes in this report, the maximum size unsupported cavity in rock is assumed to be (a sphere) 3 m in radius. Roofs of larger cavities than that should fail and form a chimney filled with rubble. The total void volume of such a rubble-filled chimney will be the same as the volume of the original explosion cavity. The height of the chimney can be assumed to be about 4 cavity radii; thus, the maximum volume of broken materials the chimney can contain is twice the total void volume. The lateral extent of the chimney may be widened by arranging for multiple or individual subsequent detonations in appropriate geometric configurations.

4.4.4 Emplacement Hole Construction

Charge emplacement hole characteristics are dependent on the nature of the explosive being employed. Prepackaged explosives will require well-aligned boreholes with rather stringent dimensional control; pourable explosives will not demand the same degree of exactness. Theoretically, cratering charges are spherical point charges. In practice, charge geometry is modified to cylindrical shape with a length-to-diameter ratio (L/D) of six. This relaxation of the required hole diameter allows the use of more common drilling methods.

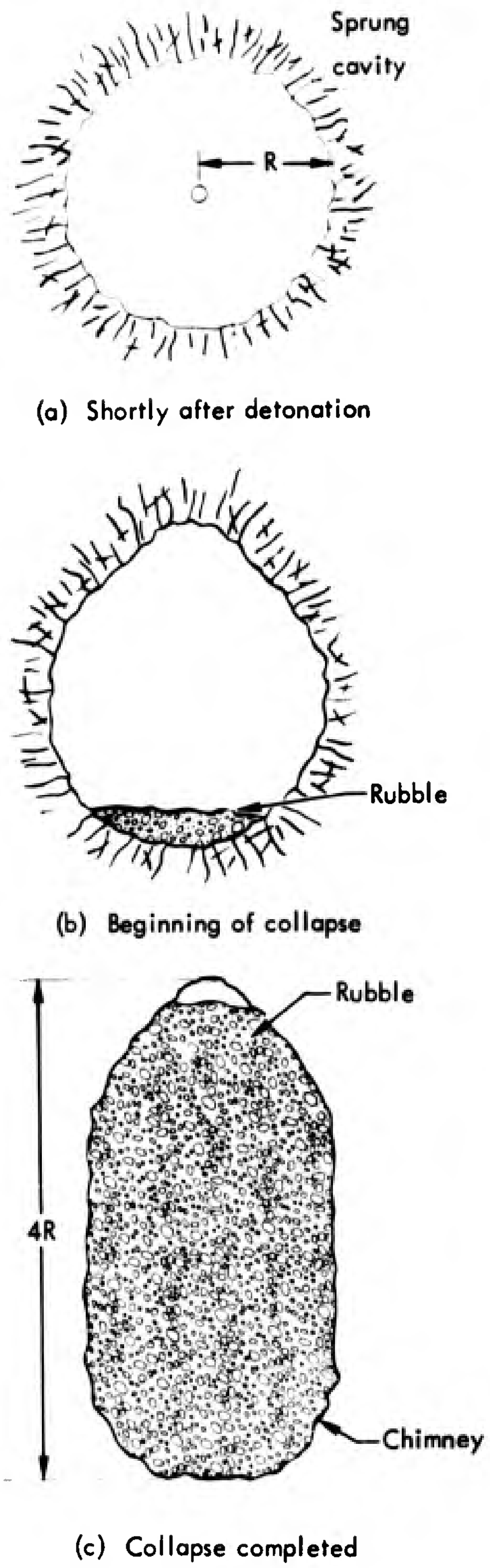


Fig. 51. Rubble chimney formation.

a. Shafting and Tunneling

These methods of obtaining charge emplacement holes would be used for quite large charges, probably during exploitation of valuable resources on the moon. Details of these methods were presented in paragraph 3.2. They are procedures for charge emplacement construction used only in special circumstances, due to their cost in terms of time and labor.

b. Vertical drilling

Standard terrestrial drilling methods, as discussed in paragraph 2.3.1, offer the most highly developed techniques for producing the shallow holes that would be used in lunar emplacement construction operations. Some modifications of existing drill equipment designs will be necessary to use those types of systems in lunar operations. Drills designed for terrestrial use depend on fluid for cooling, lubrication, and flushing cuttings from the hole. Exposure to the extremely low-pressure lunar atmosphere would cause liquids to flash to vapor and gases to expand; also, cuttings would adhere to themselves and to the drill steel. Transporting drilling fluids from earth would clearly be unpractical.

Also, from transport considerations, equipment will have to be lightweight. This will require devising some means of ballasting drill rigs in order to develop the necessary thrust for reasonable drilling rates. The lighter drills will not be capable of drilling the desired hole size required in some applications, particularly in hard rock. In those cases a multiple-pass drilling technique might be used. This consists of drilling to the desired depth as large a hole as possible with the available equipment in a first pass. Subsequent passes could then be

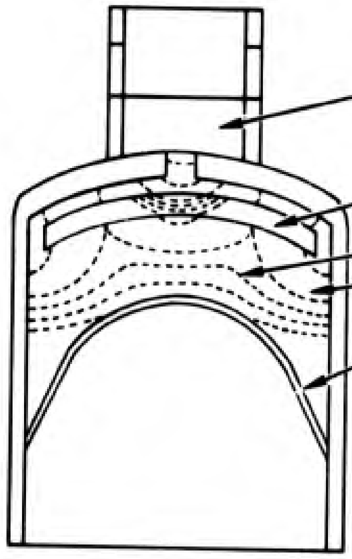


Fig. 52. Advanced shaped charge design (adapted from Poulter, 1956).

made with larger diameter drill bits, each removing an annular area equal to that circular area removed during the first pass. Such a system would extend the hole size capability of a given item of drilling equipment.

c. Shaped charges

The discussion of shaped-charge hole formation in paragraph 4.2 pointed out two difficulties in their use: flying fragments and reduction in hole diameter with repeated detonations for deeper holes. The first problem can be offset by using an uncased, solid explosive such as HNS-II or DATB (paragraph 4.3) in the shaped charge. Achievement of constant-diameter holes by multiple firings requires modification of standard shaped-charge design. For maximum efficiency the detonation wave in the explosive should be shaped so that it converges on the liner as simultaneously as possible. To maximize the mass of the jet (which, for sharp conical liners, Fig. 6, is only about 15% of the cone mass), the liner should be of hemispherical or parabolic shape. To decrease the penetration sensitivity to standoff, soft, ductile materials such as eutectic alloys should be used as liner materials. To increase the width of the hole, the liner should be relatively squat in stature rather than slender as in armor-piercing charges.

Such shaped-charge designs have been investigated and an example is shown in Fig. 52. This particular design increased hole volume in rock by a factor of three without any loss in penetration depth. It is also very insensitive to standoff distance.

d. Other Suggested Concepts

1. Penetrators—Another way of providing an emplacement hole is through the use of a high-velocity penetrator, a long, thin rod made of a strong, dense metal, such as tungsten, fixed to a small, high-impulse rocket. The rocket may be placed nose down on a tripod directly above the location for the emplacement hole, or a homing device may be placed at ground zero and the rocket fired remotely. Upon impact, the metal rod will behave like a shaped charge jet. Since the rod will have a much higher mass than a comparable shaped-charge jet and since it will not break up as shaped-charge jets usually do, penetration will be more efficient and lower impact velocities can be tolerated. Impact velocity, however, must exceed the sonic velocity of the penetrator. A possible penetrator assembly configuration for lunar use is shown in Fig. 53

2. Solar Energy—Concentrated solar energy might be used to bore charge

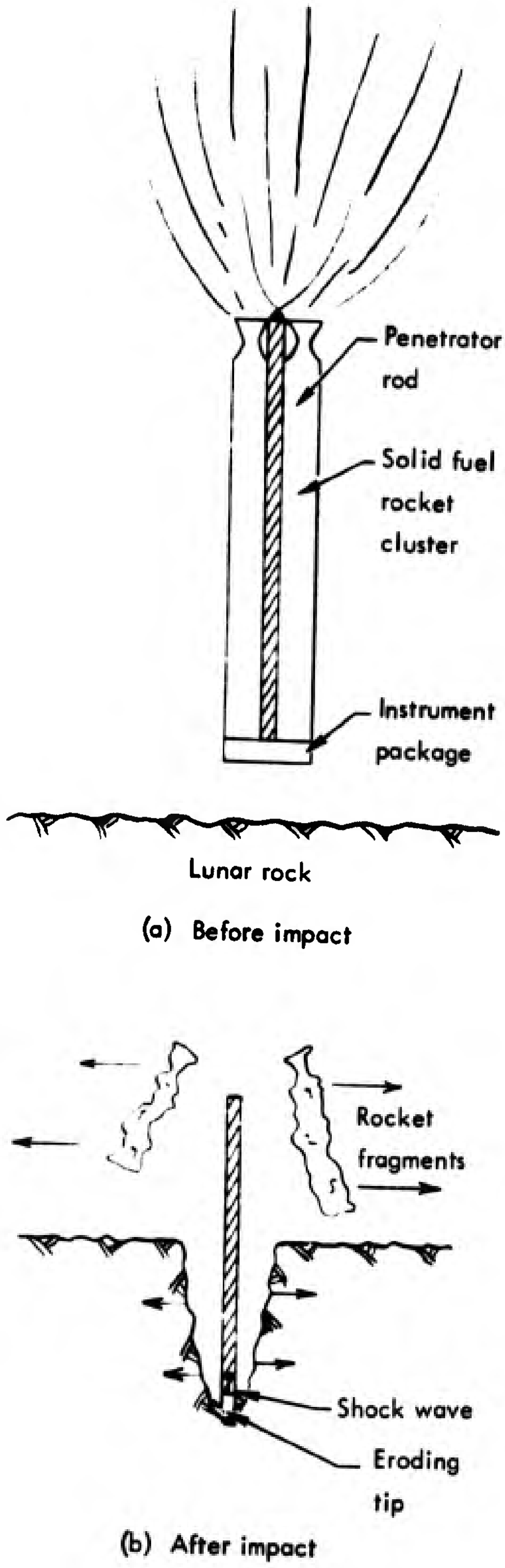


Fig. 53. High velocity penetrator concept.

emplacement holes. Drilling holes by solar energy would take advantage of the relatively high level of solar energy incident on the lunar surface, the absence of a lunar atmosphere, and the long lunar days.

The concept behind concentrating solar energy is to raise a small area of the lunar surface (say several centimeters in diameter) to its melting temperature and then maintain that temperature while heat is being conducted toward the lunar interior. The rock vapor pressure will considerably exceed the very small lunar atmospheric pressure, and the rock will sublimate.

Solar energy may be concentrated by using inflated parabolic reflectors developed in the manner of the Echo satellites. This involves employing two large surfaces of transparent plastic or mylar bonded together and reinforced at the edges so that a small quantity of gas injected between them will expand the assembly to two spherical or parabolic segments. This concept is shown in Fig. 54. The interior of the lower surface is coated with a reflecting material everywhere except for a small area in the center. The upper surface is transparent except in the center where a small diverging reflector is placed to collimate the sun's rays. The rear side of the small reflector is blackened to maximize the radiation of absorbed energy. Suitable reflectors are used to direct the solar energy toward the surface. The length of the lunar day should permit long drilling times without constant adjustment of the reflectors.

Shipment to the moon poses little problem because the large membranes can be folded into a very small package. The support ring and other members can be sectionalized into convenient-sized components.

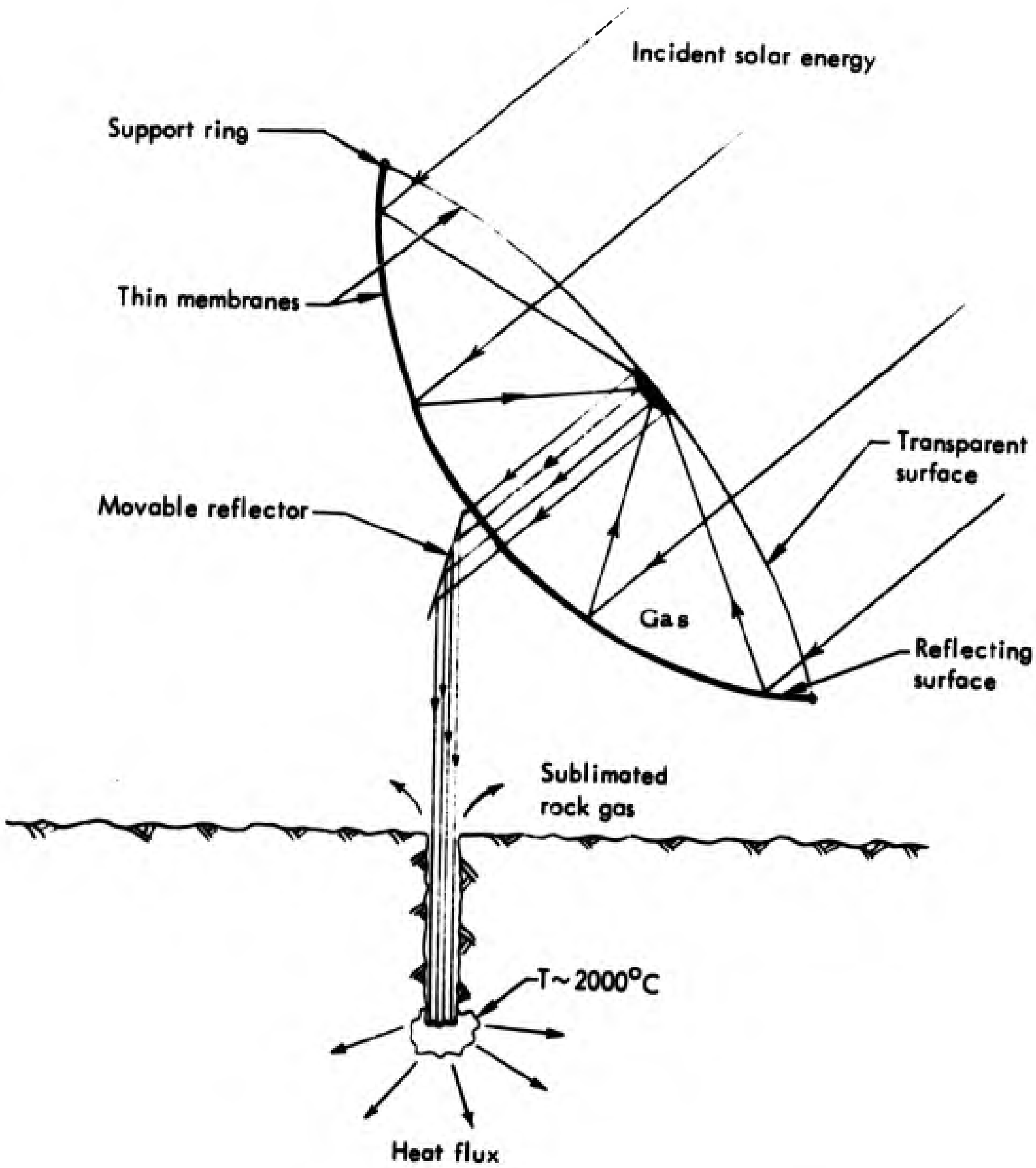


Fig. 54. Concept for drilling with solar energy.

A feasibility study of such a device must involve a study of heat conduction through the lunar surface while the hole is being drilled. It must be determined whether it is possible to concentrate enough solar energy over a given small area so that the surface is maintained at its melting temperature while heat is conducted into the moon.

Concentrated solar energy might be used to power a laser for drilling small holes. However, such concentration would be less efficient than the use of the sun's rays directly, because an energy conversion system would be required. Nevertheless, the feasibility of laser drilling should be evaluated.

e. Hole Clusters

An alternate method of emplacing the charge might be possible for cases in which the required charge size, due to the

L/D restriction of six, cannot be contained in the maximum size drillhole available. This technique calls for drilling a number of holes, equally spaced (1.5 hole diameters in rock, 3.0 hole diameters in maria) in a tight cluster approximating a closest-packing geometry. Since the charge is not concentrated, some slight loss is expected in the cratering efficiency from detonation in such a configuration. To compensate for that loss, it is assumed that a 10% increase in the total quantity of explosive energy will be necessary to produce the planned crater size.

By virtue of the cluster geometry, the charge will have an effective diameter larger than the individual drillhole size. This effective diameter is assumed to be equal to the individual drillhole diameter multiplied by the square root of the number of holes in the cluster. Retaining the L/D restriction of six, and taking into account the 10% increase in explosive volume over the single-hole design, the number of holes in a cluster is given by the expression

$$n = (0.234\ Vd^{-3})^{2/3} \tag{11}$$

where

n = number of holes per cluster
V = required volume for single-charge design
d = diameter of individual drillhole

The number of holes calculated by this method should be rounded of. to the next integer.

f. Hole Enlargement

Lunar drillholes will be of small diameter because of the lightweight equipment likely to be dictated under earth-to-moon transport considerations. Hole springing, discussed in Chapter 2, offers a means of enlarging the bottom of a drill hole to a size adequate for the quantity of main charge explosive to be emplaced, with about 5 liters of void produced per megacalorie of energy released by the springing detonation (specific values depend on the explosive used and the type of geologic medium in which the detonation takes place).

Another form of springing, linear springing, may provide a means of obtaining sufficiently large diameter holes yet require only lightweight, easily managed drilling equipment. The procedure has not been proven and is suggested here only as a potential method. This technique involves drilling a small-diameter hole, filling the entire drill hole with explosive, and detonating. In addition to enlarging the hole, a small crater will also be formed at the surface (Fig. 55). The enlarged hole can then be filled with the required quantity of cratering explosive, and the rest of the hole stemmed with lunar soil.

g. Casing Requirements

Reports from Apollo 11 and 12 concerning the ability of lunar soil to stand on high slopes suggest that casing may not be necessary to support the drillhole. On the other hand, casing may be necessary near the top of the hole when hole springing is employed. The relative merits of transporting the bulky casing versus possible reopening of the emplacement hole by drilling will have to be evaluated.

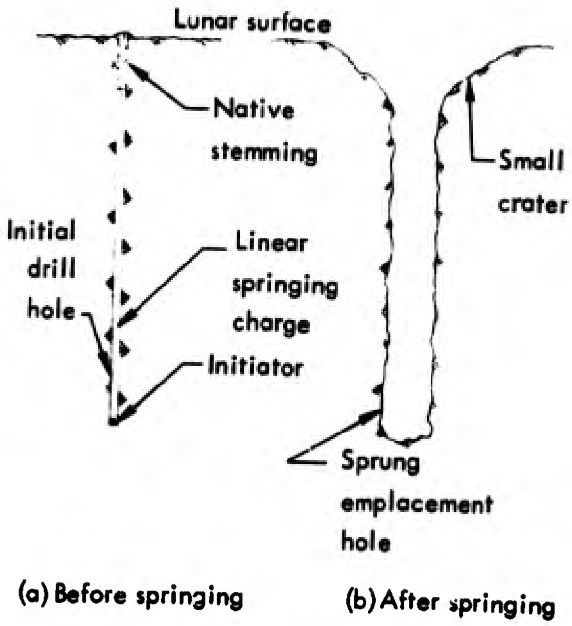


Fig. 55. Linear springing.

4.4.5 Charge Placement and Firing

The manner of explosive charge placement in lunar operations depends on the method of explosive packaging used. An explosive that is ready for immediate use will probably be in some type of container which can be primed and lowered into place with no additional preparation. A two-or-more-component explosive would have to be blended at the project site. Such an explosive would be more desirable from a safety standpoint because it would not become sensitive until mixed. Emplacement would require some type of fill line and pumping equipment to introduce the separate components (for explosives blended in place) or mixed explosive into the borehole and a seal to isolate the detonation chamber from the lunar atmosphere. It may also be necessary to seal the detonation chamber with a sealant or inserted liner to prevent leakage of the explosive prior to firing.

The method of arming the explosive charge will depend on the explosive used. Some might require blasting caps, others a sparking mechanism, and yet others some means of remotely combining substances that will explode when mixed.

Stemming materials, probably native lunar materials (as drill cuttings) will be placed in the hole directly on the explosive charge or on the atmospheric seal, if used.

Firing of the charge will be done from a remote, protected location. A radio command is the most likely, although a timing mechanism could be used.

4.4.6 Post-Detonation Operations

Some post-detonation work will be required to complete an explosive excavation project to insure that it meets specifications and satisfies operational objectives. This work falls into three general categories of operations; post-detonation survey, supplementary excavation, and backfill or materials handling.

The type of survey can range from visual observation by standard terrestrial surveying techniques to television-relay of photogrammetric observations. The degree of sophistication a survey takes will depend on the dimensional control necessary in the completed operation. For instance, the size and shape of an explosively produced quarry would be much less critical than that of an excavation into which a prefabricated structure must be placed.

The need for supplemental excavation may be revealed by the post-detonation survey. Possible ways to accomplish this supplemental work include manual, mechanical, and explosive rework. Very minor discrepancies could conceivably be corrected by hand labor, but that is a very inefficient and hazardous approach due to the confines of the space suit in which an astronaut-worker must operate. Mechanical methods offer a good solution to the requirement for supplemental excavation. It is likely that some multipurpose vehicle will be available for transport, erection, and light construction tasks on any mission in which excavation techniques would be required. Explosive rework should be considered for supplemental excavation involving large quantities of materials. Constructing charge emplacement holes in broken and disturbed materials is difficult and should not be attempted for tasks involving small quantities of excavation that would be in the domain of mechanical excavation equipment.

Movement of materials in backfilling or materials handling operations will be affected by the low gravity and lack of atmosphere on the moon. Six times as much volume of similar materials can be lifted for the same effort required on earth. Pushing, as with a dozer, will be more difficult, requiring more tractive effort on the moon than on earth to move the same mass because of the greater frictional resistance resulting from the lack of air lubrication for the particles being moved. Pushing machinery may have to be ballasted or anchor and winching tractive systems used. The complexity of lifting equipment versus the relative simplicity of pushing machinery along with the intermediate modes of materials handling, lifting and turning, lifting and hauling, and lifting and pushing will have to be evaluated to determine the most practical approach for the project concerned.

4.5 LUNAR SAFETY CONSIDERATIONS

Lunar explosions produce side effects similar to those on earth: ground shock, blast, and missile throwout. The magnitude of the effect, however, is influenced by the lack of atmosphere and reduced gravity. These effects have been studied and preliminary predictive techniques suggested for use in establishing safety controls. This section discusses these first attempts at developing effects prediction procedures for ground motion, blast, and missiles.

4.5.1 Ground Motion

The peculiarities of lunar seismic signals were mentioned in paragraph 4.1. The surface wave guide, long-duration seismic signal, and apparent seismic signal scattering phenomena have not been investigated sufficiently to make positive predictions regarding the behavior of lunar materials with regard to explosion-generated shocks.

The apparent resemblance of the lunar subsurface to terrestrial basalts suggests that, as a first approximation, terrestrial seismic experience may be used to indicate lunar ground surface velocity and acceleration. At the same time, the possibility of some detrimental effects on lunar man-made structures from the longer duration signals must be recognized and investigated in further detail before recommending firm lunar safe distances.

The technique outlined in paragraph 2.4 should be used to predict ground motion levels from lunar explosions until more seismic information is available for the lunar subsurface. Perhaps the remaining

Apollo missions may shed more light on the topic. The design of structures for lunar use to withstand anticipated levels and duration of ground motion should not be a significant problem.

There is one aspect of lunar ground motion that should be mentioned. A seismic signal moving along or near the surface of the moon will generate another phenomenon, not encountered on earth, which may be considered more of a nuisance than a hazard. The pressure behind the seismic wave will tend to be relieved by particle motion normal to the direction of wave motion; i.e., upward. Since the lunar surface appears to consist mainly of unconsolidated powder and there is no atmospheric blanket, a dust cloud may develop and extend some distance from the shot point. This cloud can be expected to be short-lived, since, although the pull of gravity is low, there are no atmospheric currents to hold the particles in suspension, and, therefore, they may be expected to return quickly to the lunar surface.

4.5.2 Blast

The negligible lunar atmosphere provides no medium to propagate the ground-shock-induced blast resulting from terrestrial detonations as discussed in paragraph 2.4. The explosion gases expand upon dissociation of the mound to produce a form of a lunar blast wave. This lunar blast is a more direct phenomenon because the explosion gases themselves constitute the overpressure as contrasted with the terrestrial situation, in which the overpressure is produced by an air shock radiated from the explosion gases. A detailed discussion of the lunar blast phenomenon is given in Appendix C.

Terrestrial airblast overpressures generally vary inversely with the first power of distance from their source. On the other hand, lunar blast overpressures resulting from the expansion of vented explosion gases should vary inversely proportional to the cube of the distance from their source. Figure 56 shows pressure-range relationships that were developed from the procedures given in Appendix C, for selected explosive energies. This figure illustrates the minor nature of the hazard presented by lunar blast.

4.5.3 Missile Hazards

In paragraph 4.2 it was noted that missile (ejecta) throwout range for the same depth of burst would be some six times as far on the moon as it is on earth from detonations of the same energy in similar materials because of the difference in gravitational acceleration. For the smaller particle sizes this factor of six must be considered a lower limit because of the lack of lunar atmosphere. The essentially zero atmospheric pressure tends to increase particle velocities for smaller particles in two ways.

First, air drag is eliminated. This factor tends to increase range for particles smaller than about 15 cm (see also paragraphs 4.2.1 and 4.2.2 and Appendix B). Second, the net force available to accelerate ejecta particles would be nearly that of the venting explosion gases. (On earth it is the difference between the gas pressure and atmospheric pressure.) Again, the smaller particles would be

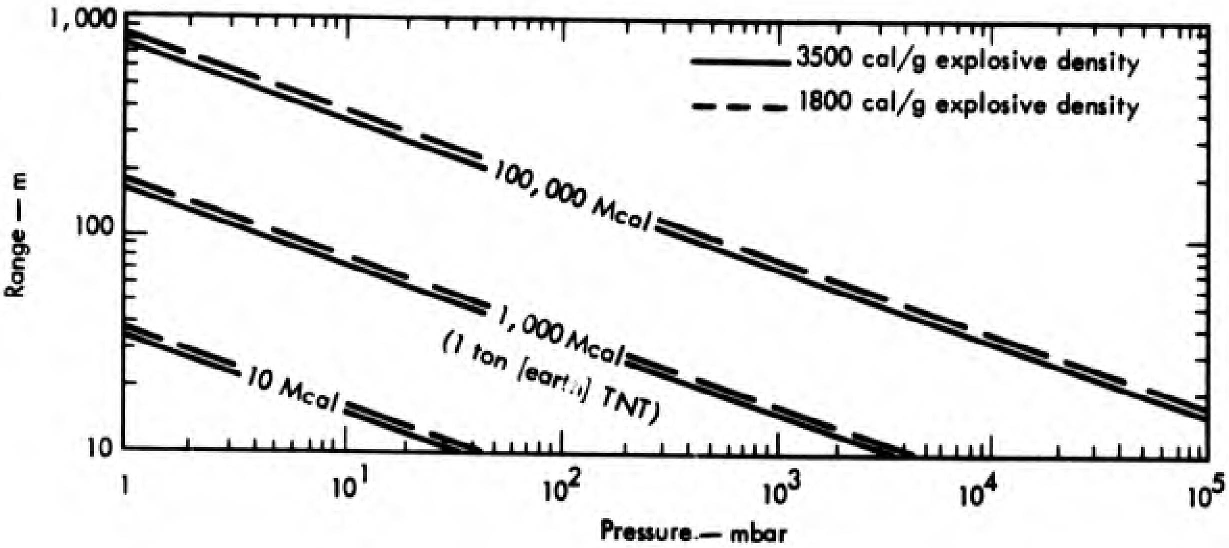


Fig. 56. Lunar blast pressure-range relationships.

affected most. Their velocities could approach, as an upper limit, the radial velocity of the venting gas. They could not reach that velocity because, first of all, the gas velocity would be reduced as the particles were accelerated; therefore, the terminal gas molecule velocities would be less than those obtained in a free expansion into a vacuum (Appendix C). Also, since the distance between gas molecules increases as the gas expands, a point is reached when collisions between molecules and particles effectively cease, beyond which time no more energy could be transferred to the particles to increase their speed.

Consequently, it is assumed that particle acceleration ceases once the distance between molecules is of the same order as the particle dimension, and that particles reach their maximum velocity before the gas has completed its expansion. So it is that ejecta particle velocities range between initial particle velocity at venting and gas velocity after free expansion.

These velocities can be estimated by the procedures developed in Appendix D. Assuming that particle velocities are functions only of particle size and that particle size distribution is uniform throughout the rising mound just before venting, maximum missile range can be predicted by suborbital ballistic equations as a function of particle and charge size. Ejecta velocity and maximum range as functions of particle and charge size for an example situation are given in Figs. 57 and 58.

The figures show that it is theoretically possible for particles to gain lunar orbital velocity (1680 m/sec) and go into circular orbit around the moon. These particles would be small, 0.3 mm or less for a 2-metric-ton charge (a 0.3-mm particle at orbital velocity carries an energy of about 0.5 joule). The likelihood of circular orbit is negligible, though, because it requires that the particle have the correct speed and inclination (tangent to the lunar surface upon entering ballistic

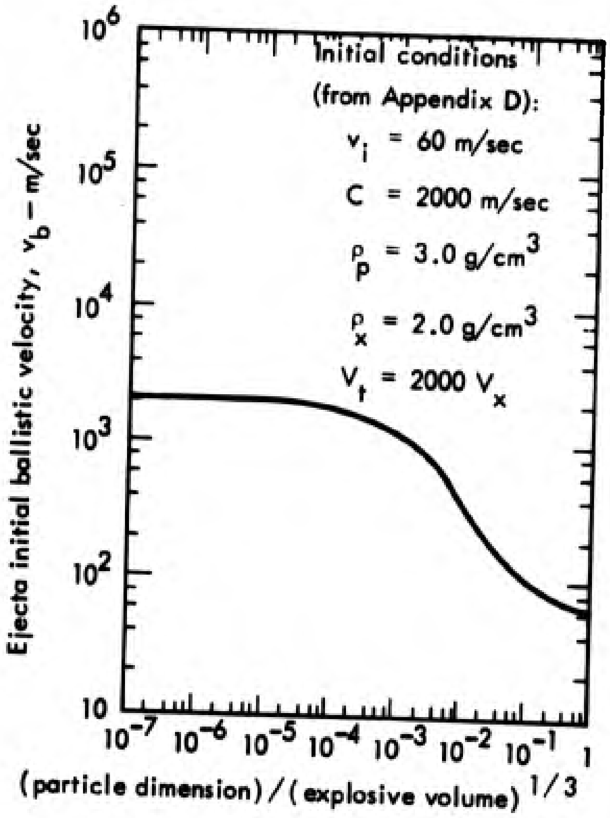


Fig. 57. Distribution of ejecta velocities.

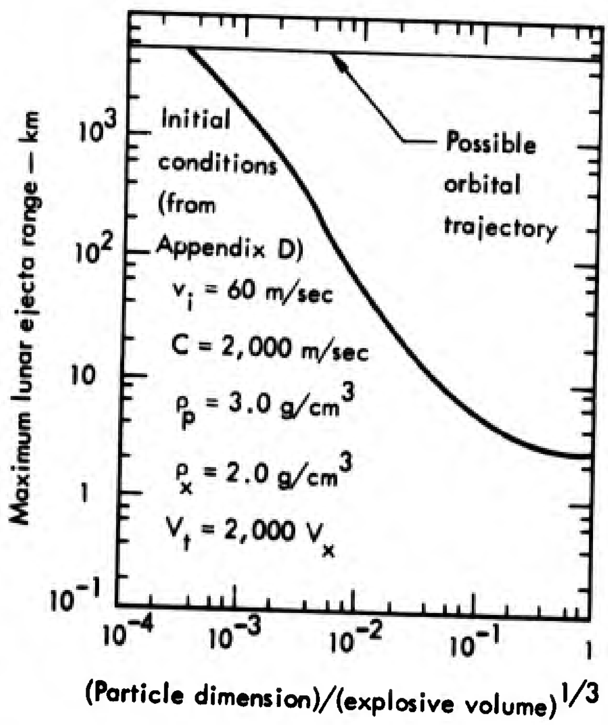


Fig. 58. Distribution of ejecta ranges.

tic phase) and that it not strike any lunar surface feature. The same 2-metric-ton charge, however, could have sufficient energy to throw 1.0-cm particles as far as 80 km; 10-cm particles 5 km; and 1.0-m blocks 2.5 km.

The magnitude of the threat this situation represents cannot be assessed at this time. Missile density decreases rapidly with distance from the point of detonation, a fact that will decrease the probability of missile impact in a given area. An estimate of that probability will require information regarding particle size distribution at the time of mound breakup. This aspect of missile throwout will require further study to allow determination of safe distances from lunar subsurface detonations.

4.5.4 Personnel and Equipment Protection

The cost of damage in lunar operations will be much greater than that experienced in similar terrestrial operations, and it is necessary to approach as nearly as possible a 100% fail-safe operation. The difficulty of a rescue operation, the lack of replacement parts, and the high initial costs make safe, certain operations a requirement. Construction methods or operations employed outside the lunar landing vehicle or support base will be restricted in scope by man's ability to do useful work in a space suit without compromising safety.

Methods of protection for personnel and equipment from the effects of the detonation of a buried explosive fall into two categories. The object(s) to be protected can be removed to a distance or insulated in place. The effect is the same; i.e., protection is derived from an energy-absorbing medium, either distance or material. Either method has potential, depending on the application. For activities (e.g., solar wind experiments) whose purpose requires that they remain where placed, movement is unpractical and the incorporation of a protective barrier of some sort is required. Man, in the absence of existing shelter (as a bunker), will be best protected by removing himself a safe distance. Protection might be gained for equipment by placing it in defilade from the trajectories of low-angle ejecta from a cratering detonation and at a range for which the high-angle ejecta impact probability is acceptable. A natural lunar crater could provide a trajectory mask for low-angle ejecta at that range. The merit of such a "shadow" protection technique would have to be evaluated once the impact probability-range relationships can be assessed.

Detonation procedures in terrestrial applications are frequently carried out from a protective bunker. In early generaction lunar operations, it may be prudent (lacking lunar surface facilities) that the detonation be initiated via radio from an orbiting command station or from earth.

Chapter 5

Lunar Applications

There is quite a wide variety of possible applications of explosive excavation techniques in lunar activities. This chapter suggests some potential applications to provide shelter, storage, and operating facilities and to aid in possible exploitation of natural lunar resources. It proposes some concepts that may be useful in conducting scientific lunar investigations and developing lunar bases.

For convenience of discussion, projects involving possible explosives applications are categorized in three phases, distinguished by an expected order of occurrence and degree of complexity. The following activities serve only to signify the beginning of a phase; these activities will likely continue during subsequent phases:

(1) Phase I. Initial period of lunar activities in which small quantities of explosives would be used, as in selenophysical surveying and other investigative work, with no subsurface explosives emplacement required.

(2) Phase II. Characterized by subsurface explosives emplacement and development of emplacement techniques to the point at which relatively simple excavation would be performed for, say, a temporary lunar shelter.

(3) Phase III. Operational period in which explosive excavation takes its place as a construction support technique. Lunar activities include construction of a permanent lunar base complex and exploitation of lunar resources.

A few conceptual designs for Phase II and Phase III projects are presented to illustrate the lunar explosive excavation technology presented earlier. The situations described are hypothetical but serve to demonstrate potential uses of that engineering technique. Certain of the applications require only minimal extension of the current state-of-the-art and are considered to be feasible in the near future. In other cases, both technology and hardware must undergo significant development; these are far-term projects associated primarily with a lunar exploitation program.

5.1 POTENTIAL LUNAR EXPLOSIVES APPLICATIONS

Some type of construction effort will be necessary to support scientific investigations on the moon and to develop the sustaining lunar bases, whatever their degree of sophistication. For those instances in which large quantities of material must be fractured or moved, or both, or in which lesser quantities must be moved quickly, explosive excavation may provide an economical means, in terms of effort, time, or cost, of performing the required work.

This section discusses some potential applications of explosive excavation in lunar activities. The suggested applications are general in nature to illustrate the variety of tasks that might be undertaken.

5.1.1 Selenophysical Investigations

Seismic methods have been used in

terrestrial prospecting operations to locate those geological structures favorable for the accumulation of minerals. It is likely that they will find similar utility in lunar exploitation ventures.

In site exploration and, to a lesser extent, in larger-scale seismic work, measured values of seismic velocity can be useful in estimating rock properties, such as elastic constants and porosity. Seismic methods offer appropriate means of obtaining information about near-surface and deep lunar geologic structures.

Seismic studies will permit the development and the confirmation of predictive schemes for determining lunar response to explosions on or below the lunar surface. These results can be used in evaluating explosive excavation designs.

5.1.2 Surface Applications

Conceivable lunar surface projects to which explosive excavation would apply may be grouped into four general categories. They include personnel shelters, experimental and operating facilities, storage facilities, and resources exploitation.

a. Personnel Shelter

Extended lunar operations will require personnel shelters in which crews can work and live in a shirt-sleeve atmosphere. The shelter must be capable of maintaining a stable internal pressure and temperature and of providing protection against the lunar surface temperature variation, ionizing radiation, and meteoroid impact. Shelters would be prefabricated on earth as complete units or in modular form, probably in cylindrical configuration to conform to the shape of the space transport vehicle.

b. Experimental and Operating Facilities

Conduct of lunar studies and operation of a base complex will involve excavation tasks of varying extent.

Scientific equipment emplaced on the moon for long-term observation as, for example, an observatory telescope, may require excavation for installation or for protection from temperature variation and solar flare or micrometeorite storms. Communications or radio astronomy antennae might make use of the parabolic shape of the single-charge explosion crater to gain efficiency otherwise requiring that more bulky, heavy antenna components be transported from earth and assembled on the moon.

An attractive method of food production for a lunar base is the use of a hydroponic farm (Douglas and Sholto, 1956) in which plants can be raised in nutrient solutions without the need for soils, in which nutrients are less concentrated. Another method that has been suggested for life support in lunar bases uses a continuous bio-regenerative system. This is a closed loop system producing chickens as the food element that returns via man to the loop (gas exchange, waste treatment, water reclamation, and food production). Both methods require a stabilized thermal environment and protection from radiation, conditions conveniently met by cut-and-cover installations.

Operating facilities including medical, recreational, laboratory, utility, maintenance and repair, and inter-structure passageways will be incorporated into the lunar base complex in some stage of its development. The need for protection from lunar surface long-term hazards will apply to all.

Storage facilities for food, fuels and propellants, equipment, and spare parts will not require the life-support capability necessary for shelter and operating facilities but will need protection from direct effects of the lunar "elements."

The moon has potential as a staging and quarantine location for outbound and incoming space missions. In that role, it will require space vehicle launch and support facilities, construction of which will require excavation operations.

Access to certain areas of the moon by surface vehicles will make some types of surface modifications necessary. Explosives offer the energy required to produce needed cuts and fills quickly and efficiently.

Due to the immense logistical tail needed to support a lunar base, early efforts will be made to locate natural lunar resources that can be processed on the moon to provide water, oxygen, and fuel and propellant components. Recovery of those resources will require some type of mining effort. Ideally, the desired ores would be sufficiently near the surface to permit the use of surface mining techniques, for they lend themselves more closely to automation than do subsurface approaches.

5.1.3 Subsurface Applications

Tank-type storage may be necessary for some aspects of lunar base operations. Supplies such as water, cryogenic materials, gases, fuels, and propellants would benefit from that type of storage facility. Tanks would be needed to protect the stored product from the low lunar atmospheric pressure, from the wide range of surface temperatures, and from possible radiation damage. The tanks themselves would have to be protected from meteorite impact, and a subsurface storage mode would be a significant benefit.

Underground living and working facilities for lunar bases is an attractive concept. Such facilities would provide occupants greater protection from lunar surface hazards of temperature, radiation, and meteorite impact than surface (or near-surface) facilities while eliminating the need to transport a prefabricated structure that would require a cut-and-cover method of installation as discussed in the preceding paragraph. Underground chambers, sealed against air leakage, could be used as the basis for a permanent lunar base. An underground facility of this type would be best located in a hill mass to allow horizontal access from a valley and to avoid the requirement for vertical access systems requiring lifting mechanisms.

Underground passageways providing access to lunar subsurface projects do not lend themselves to the use of large explosive excavation charges. Tunneling and shafting would likely be accomplished on the moon in the same manner as on earth using the techniques discussed in paragraph 3.2, with small diameter drilling, small explosive charges, and mucking operations.

Valuable lunar ores located at depths that make surface mining infeasible could be exploited by means of large high-explosive charges detonated at or below containment depth in a form of block caving. After ore removal, the resulting chamber could be used as the basis for a shelter or storage facility.

5.2 PHASE I PROJECTS

These will consist primarily of selenophysical investigations. Seismic surveying methods can reduce the time and cost involved in obtaining lunar subsurface information. They offer rapid means of determining depths and velocities of subsurface strata to a reasonable degree of accuracy.

The first uses of explosive seismic methods are scheduled to be included in upcoming Apollo Program flight plans. The method employs a mortar-type device that launches small seismic charges to be detonated either by command or on impacting the lunar surface. (Hautz, 1970). The surface detonations will be recorded by seismographic instruments and enable investigators to begin lunar subsurface studies.

Subsequently, seismic charges detonated in shallow holes will help to develop more precisely the findings of the initial subsurface investigations mentioned above by providing a more accurate determination of the explosive energy input signal to the lunar surface. This method will provide more extensive determinations of lunar materials characteristics.

Application of an explosive excavation technology involving energy yields much higher than conventional seismic charges will make possible subsurface information at long ranges. Wider seismograph nets could be used to obtain significantly greater detail.

5.3 PHASE II PROJECT CONCEPTS

These conceptual designs describe two straightforward explosive excavation projects involving subsurface emplacement and detonation of explosive charges. The projects require only small amounts of construction support equipment. They would be used in establishing the early generation temporary lunar bases and, perhaps, in the first stages of permanent lunar base construction.

5.3.1 Temporary Shelter Emplacement

One of the first requirements of a lunar base operation of any duration will be a shelter that can provide living and working space and some degree of protection from the lunar "elements." During these early generation projects, time, effort, and equipment will be particularly limited. The lunar landing vehicle cannot provide adequate or long-term facilities for the lunar base crew. The crew itself will not represent a great amount of available effort, since it will be small in number—probably about three persons. The earth-moon transport system will limit the amount and capability of equipment support available to meet payload cargo restrictions and to insure simplicity and reliability.

a. Shelter Structure and Transport Systems

The structure is envisioned to be in the form of a right circular cylinder, 6 m in diameter and 9 m long (total volume about 254 m^3). It will, of course, be structurally capable of withstanding launch and landing stresses. It will also be designed to support as a minimum the dead load of

Table 14. Payload masses and volumes.

Item		Mass (kg)	Volume (m^3)
Shelter		20,000	254[a]
Scientific equipment		200	1.4
Expendables		2,500	6.0
Communication and power sources		250	1.6
	Subtotal	22,950	9.0
Mass and volume available for construction equipment and materials		7,050	55.0
	Total	30,000	64.0

[a]Of this total, 64 m^3 is available for payload.

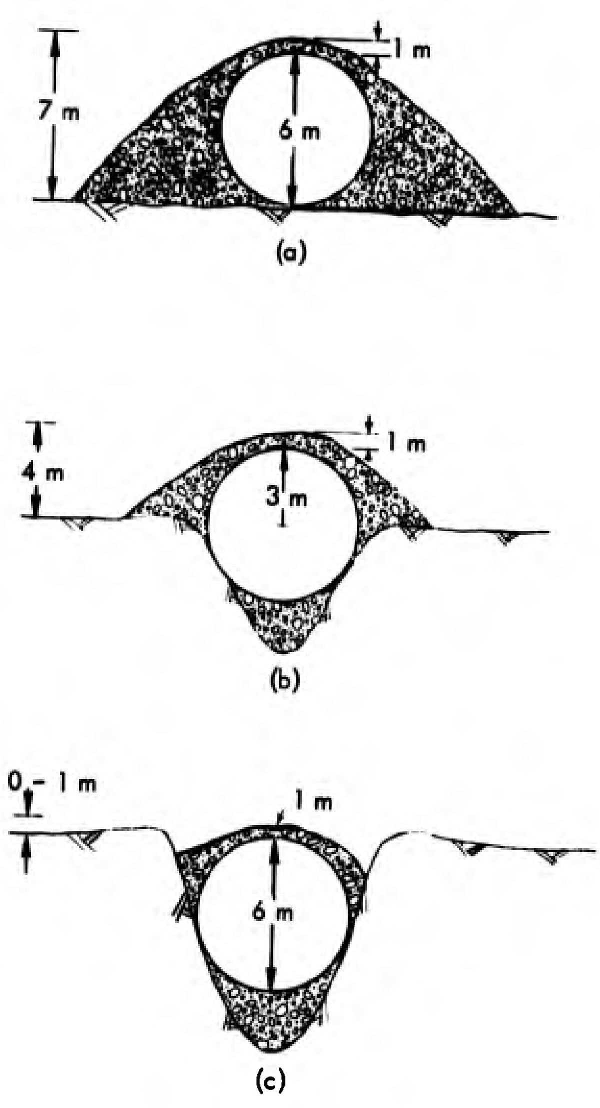


Fig. 59. Structure burial modes.

one meter of lunar material cover and the live loads to which it will be subjected during installation (placement of structure and cover material). Operating access to shelter would be best provided by a portal in the circular end. Access could be through a conning tower arrangement on the cylinder, but such an arrangement would permit less overhead cover at the point of access and would require additional assembly operations during installation.

A space transport system based on 188% uprated Saturn V rockets (Choate, 1969) is assumed available to provide the necessary lift capability for the project. Each such vehicle would have a landed payload of about 30,000 kg (volume 260 m^3); maximum payload diameter would be 6.6 m. A breakdown of the assumed cargo vehicle payload is given in Table 14. Note that 25% of the shelter volume (about 64 m^3) is assumed to be available for internal material stowage. It is assumed that three men could be transported to the lunar surface by one of these rocket vehicles, including command module, lunar landing vehicle, and earth-return system, with little other payload capability. Thus it is seen from Table 14 that payload restrictions on construction support materiel for installation of the shelter are about 7,000 kg and 55 m^3.

b. Concept of Installation

Figure 59 depicts the envisioned cut-and-cover concept of shelter installation based on a row-crater. Varying amounts of backfill are illustrated. Mode (a) avoids the need for excavation by resting the shelter directly on the lunar surface but demands equipment with a minimum lifting capability of 7 m and a large material volume capacity. Mode (b), in which the center of the structure is at the elevation of the lunar surface, requires some excavation but reduces the equipment lifting capability requirements to about 4 m. Still deeper burial increases the excavation requirement but makes a minimal lifting capability demand on backfill equipment. For purposes of this example, it is assumed that the shelter will be buried as shown in mode (c), its top tangent with the lunar surface.

A simple, reliable backfill system would incorporate a cable-operated drag scraper as shown in Fig. 60. The hoist and tail towers could be secured by anchor bolts installed in holes produced by small shaped charges or by a recoilless explosive device similar to the cartridge type currently used in terrestrial construction. This system would be set up following a post-detonation survey determination that the excavation meets specifications. A drag scraper would be attached to the cable system for backfilling as necessary to smooth the crater bottom sufficiently for uniform shelter support.

The shelter would be installed in the prepared crater by attaching it to the hoist system in place of the scraper and moving it to crater on inflatable collars (Fig. 61). Once in the hole, the structure can be rotated in the collars to the required orientation and released from the cable system. Lunar cover material would then be placed to the desired thickness by the drag scraper system as shown in Fig. 62.

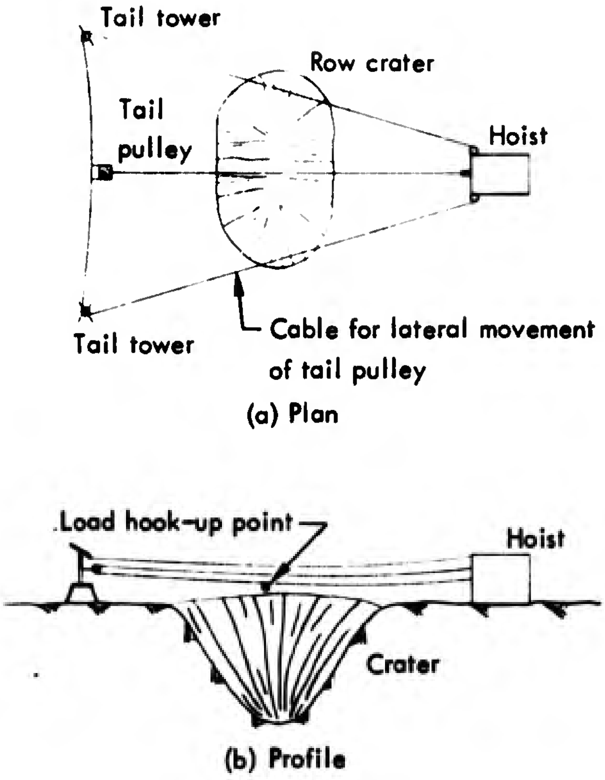


Fig. 60. Hoist system.

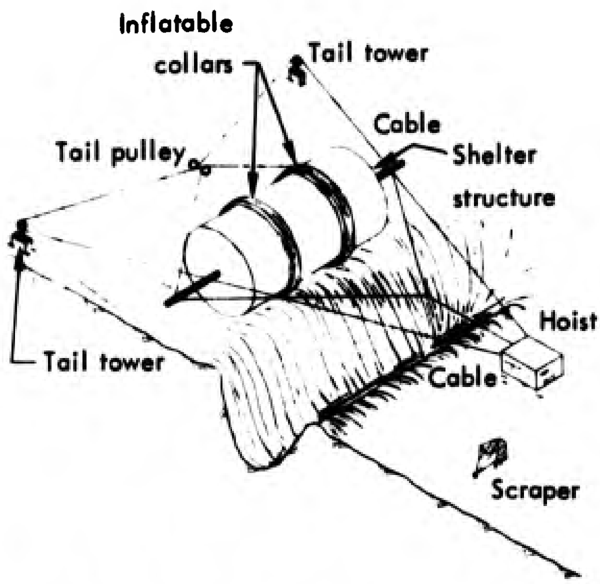


Fig. 61. Shelter emplacement method.

c. Equipment and Explosives

The mobile drill available for emplacement hole construction is assumed to have maximum capabilities of 15-cm diameter and 8-m depth. Intermediate drill sizes of 8.7 and 12.2 cm are available for a

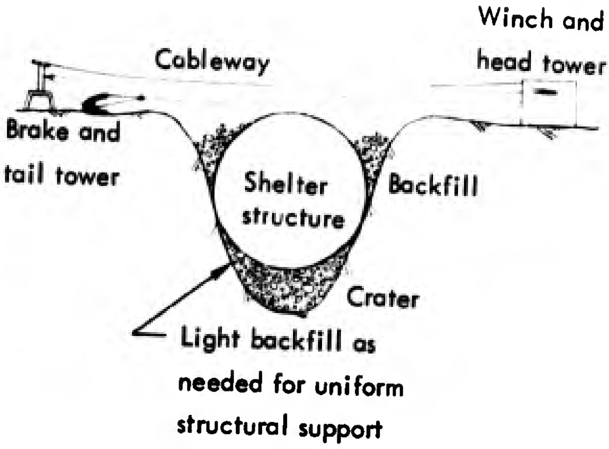


Fig. 62. Backfill method.

multiple-pass drilling technique. The penetration rate for each pass in rock is assumed to be 3 m/hr (net rate of 1 m/hr for a 15-cm hole). In maria material fewer passes would be necessary, and a net rate of 3 m/hr is assumed. Neither material should require casing. Travel speed of the drill is 5 km/hr. Average set-up time should be about 20 min, including placement of lunar ballast material on the drill platform.

A clutch-operated, 3-drum hoist powered by a hermetically sealed 20-hp electric motor will be used to operate the drag scraper and to install the shelter structure. Using a 1/4 m^3 drag scraper, this system can move backfill material at an average of 5 m^3/hr. Maximum structure rolling speed is limited to 1-km/hr during placement of the shelter.

Four roll-up solar cells, capable of producing 4,000 W each will provide electrical power for the operation of the construction equipment. Operations are therefore limited to the 14 earth-day lunar sunlight period.

An explosive of the ALH-type, with characteristics as given in Table 11, is assumed to be available for this project. Charges would be prepackaged in cylinders 15 cm in diameter × 90 cm in length to meet the required L/D ratio of 6.

All other miscellaneous equipment can be hand-carried by crew members. Lines for lowering charges into emplacement holes will be integral parts of the arming system. Hole stemming can be done by hand shovel. Detonation will be initiated by radio signal. A summary of equipment characteristics is given in Table 15. All equipment can be operated by a single crewman.

d. <u>Explosive Excavation Design</u>

To emplace the cylindrical shelter structure in the parabolic true crater in lunar high-strength rock as shown in Fig. 59(c) requires a D_t of 6.1 m. This depth makes necessary a single-charge explosive energy of 660 Mcal with its corresponding 5.2-m DOB and 5.2-m R_t (Fig. 49). Applying this information in the row-crater design procedure of paragraph 4.4.3 with a 9-m crater length and 1.4 R_t charge spacing results in a unit explosive energy requirement of 91 Mcal/m of crater length, or 820 Mcal total (456 kg of ALH) explosive energy. Since the L/D-restricted, prepackaged explosive container holds only 58 Mcal of ALH, the total energy requirement is met by using 15 charges, at a charge spacing of 0.64 m. The total drill length per emplacement hole is the sum of the DOB plus half the length of the explosive container, or 5.7 m. Thus, the total length of drill hole required is 86 m. Backfill volume for 1 m of overhead cover is about 400 m^3.

If the shelter is to be emplaced in maria material, a 6-m D_t is necessary.

Table 15. Construction equipment mass, volume, power requirements and sources.

Equipment	Mass (kg)	Volume (m^3)	Power (watts)
3-drum hoist and anchoring system	2,000	2.0	15,000
Cable	130	0.03	—
1/4 m^3 drag scraper	230	0.3	—
Drill system (capacity 8-m depth, 15-cm dia.)	500	2.0	15,000
Power source: roll-up solar cells	480	2.0	Producing 16,000
Miscellaneous arming, stemming, and firing equipment (includes detonators, wire, tamping equipment, instrumentation, etc.)	300	1.0	—
Total	3,640	7.33	

This would require a total of 530 Mcal (295 kg of ALH), emplaced in 10 holes at 5.1 m DOB. The true crater radius would be 7.7 m. Emplacement holes would be 5.6 m deep and spaced 1.1 m on centers. Backfill volume for this approach is about 730 m^3.

The estimated schedule given above includes a four (earth) day buffer during the lunar day period of time for contingencies. No construction operations are considered during the lunar night period for these early generation lunar base projects.

e. Project Time Requirements

Construction operations time estimates are given in Table 16 for rock emplacement conditions. Assuming the three-man crew can operate three 8-hr shifts per (earth) day, the drilling operation will be completed by the end of the fourth (earth) day. The project can be readied for detonation during the fifth day, and firing operations completed by the sixth. Shelter placement and backfilling could be finished by the end of the tenth (earth) day after the start of the project. Since solar cells are being relied upon to power construction equipment, operations should be started close to the beginning of the lunar day.

f. Safety Considerations

An estimate of explosion side effects is presented here as an indication of the orders of magnitudes that should be con-

Table 16. Shelter emplacement time requirements.

Operation	Element		Total time (hr)
Drilling	Set-up	5	
	Drill	86	
	Tear down—move	5	
	Job		96
Loading	Job		5
Arming	Job		2
Stemming	Job		8
Firing	Job		3
Emplacing structure	Job		15
Backfill	Job		80

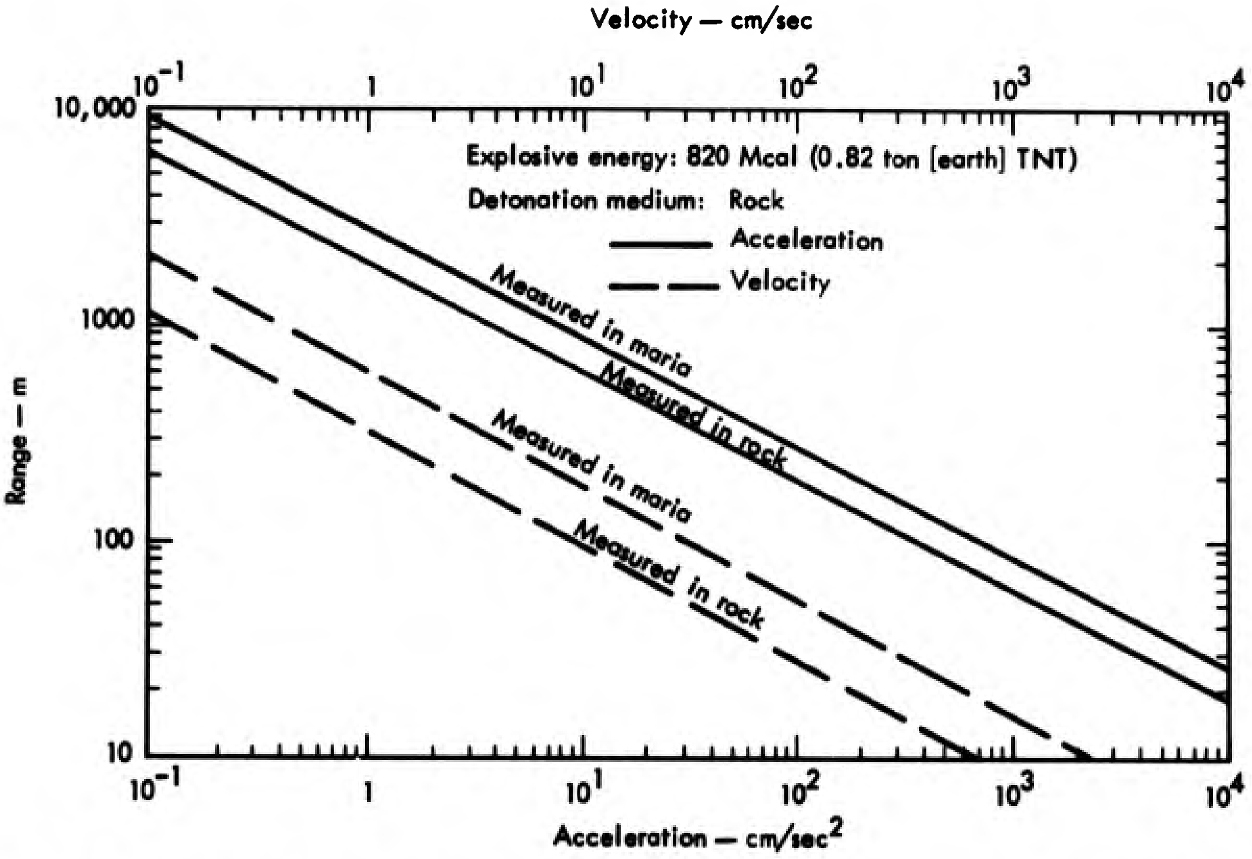


Fig. 63. Ground acceleration and velocity vs range for shelter emplacement crater.

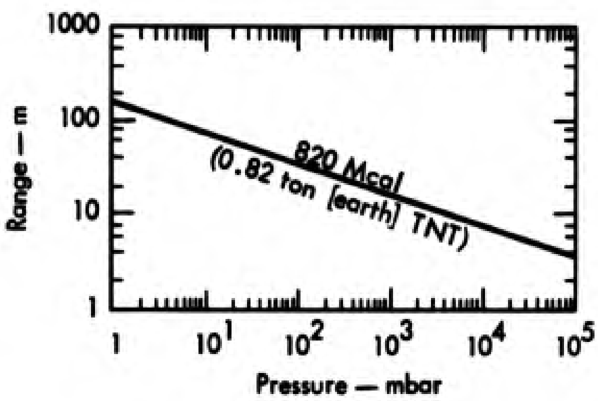


Fig. 64. Blast pressure vs range for shelter emplacement crater.

sidered in designing and locating structures and equipment. The effects are predicted based on a detonation in high-strength rock. Ground shock, blast and ejecta effect ranges are shown in Figs. 63, 64, and 65 respectively.

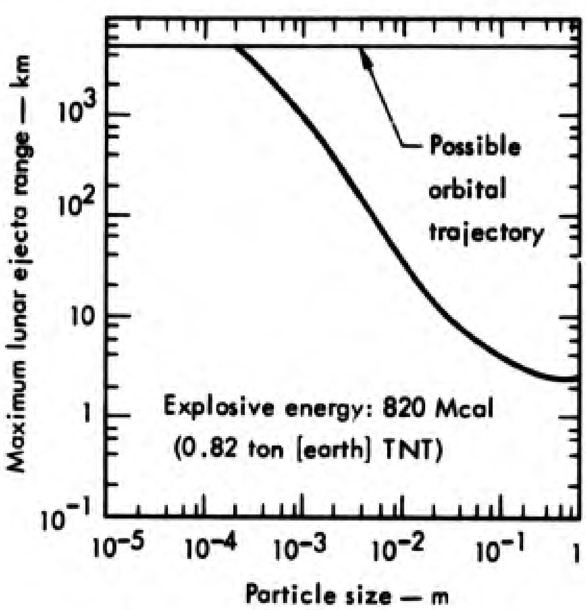


Fig. 65. Ejecta ranges for shelter emplacement crater.

g. Summary of Pertinent Data

Table 17 summarizes the pertinent aspects of this conceptual design for the use of chemical high explosives in the emplacement of a temporary lunar shelter. Note that in both rock and maria emplacement media, there is more than enough pay-load capacity for the mass and volume of the anticipated material requirements.

Table 17. Summary of shelter emplacement project data.

Item	Rock	Maria
Number of charges	15	10
Charge spacing on centers, m	0.64	1.1
Depth of burst, m	5.2	5.1
Depth of borehole, m	5.7	5.6
Total construction time, days (earth)	10	9
Total mass of ALH explosive, kg	456	295
Mass of construction equipment, kg (Table 15)	3640	3640
Payload mass for project, kg	4096	3935
Total volume of ALH explosive, m^3	0.23	0.15
Volume of construction equipment, m^3 (Table 15)	7.33	7.33
Payload volume for project, m^3	7.56	7.48
Backfill volume, m^3	400	730

5.3.2 Power Generation Unit Installation

At some time after a shelter is established in the temporary lunar base, the requirement for a continuously operating electrical power generation plant using a nuclear heat source is expected to arise. Outlined below is a conceptual design for using an explosive excavation technique for burying the nuclear reactor to shield personnel and equipment on the lunar surface from the reactor's emitted radiation.

a. Nuclear Power Plant

The power plant assumed for purposes of this illustration consists of a SNAP 8 nuclear reactor heat source using a NaK coolant primary loop and a mercury Rankine cycle secondary loop linked by an intermediate heat exchanger (Crim, 1970). Condenser heat would be rejected by heat radiation at the lunar surface. The reactor would operate at about a 1000 kw(t) level to produce about 100 kw(e). The reactor and primary coolant system would be buried under a 5-m thickness of lunar material to reduce the radioactivity level at the lunar surface to 1.5 mrem. Secondary loop mercury lines would extend from the buried intermediate heat exchanger through the lunar material shielding to the power generation equipment on the surface. The buried components would be contained in a right circular cylinder configuration with a diameter of 2 m and a height of 2 m. The subsurface components container is assumed to be capable of withstanding all loads placed on it during emplacement operations and by the emplaced shielding material.

b. Concept of Installation

The configuration of the components container lends itself readily to emplacement in a single-charge crater. After the primary system has been placed in the crater, the connecting mercury lines installed, and the plant checked out, ejecta materials or loose surface materials would be used to backfill the crater.

c. Equipment and Explosives

It is assumed that the mobile drill employed during shelter emplacement would be available for charge emplacement hole construction and that a modification could be made to uprate the drill capability to permit drilling of a 20-cm diameter hole to a depth of 10 m. It will be powered by roll-up solar cells, as in the case of the shelter project. Four drilling passes would be required in rock to produce a hole of those dimensions using diameters of 10, 14.2, 17.3, and 20 cm. Penetration rate in high-strength rock is assumed to be 3 m/hr for each pass with an average net penetration rate of about 0.7 m/hr for the maximum size hole. Average net penetration in maria material is assumed to be 3 m/hr. Neither medium will require casing the hole.

A lunar multipurpose vehicle (LMV) is assumed to be in use in the temporary lunar base activities at this time. It would be adaptable to many tasks from exploration traverses to supplies hauling, to construction operations. Its versatility derives from attachments such as a dozer, backhoe, or crane (Fig. 66). An on-board rechargeable power cell would be capable of supplying all required power for a minimum of 100 hr (operating) between power cell recharges. General purpose construction hand tools would be available as part of the LMV on-vehicle tool box. The LMV would have a top surface speed of 30 km/hr and would be limited only by very steep terrain. With the crane attachment, it has a lifting and hauling capability of 8,000 kg. The 2-m wide dozer attachment enables the LMV to move loose materials at the rate of 12 m^3/hr. This is assumed to be the first requirement for the crane and dozer attachments, and their transport is charged to project payload.

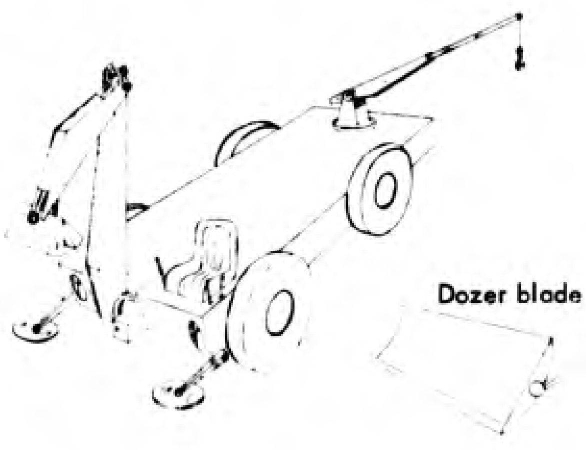


Fig. 66. Lunar multipurpose vehicle.

An ALX-type explosive (Table 11) will be employed in this application. It is assumed to be prepackaged into cylinders whose dimensions and L/D ratios permit their use in a hole formed by any of the above-cited four drill diameters.

A summary of equipment characteristics is given in Table 18.

d. Explosive Excavation Design

The parabolic shape of the true crater requires a D_t of 7.2 m to insure the necessary 5 m of shielding material over the reactor package. From Fig. 49, this requires a single explosive charge of 1100 Mcal energy (250 liters of ALX). Its corresponding DOB is 6.2 m and R_t is 6.2 m. The charge capacity of a 20-cm hole is limited to 37.6 liters because of the L/D restriction of 6; a 37.5-cm diameter hole would be needed for 250 liters. Thus, due to available drilling capability, a cluster of four 20-cm diameter holes containing 1210 Mcal (10% increase) of explosive energy with a mass of 605 kg would be required to give the explosive cluster sufficient cratering effectiveness (paragraph 4.4.4). The holes would be arranged in a square pattern, 30 cm over centers, with each hole containing 303 Mcal of ALX. The effective cluster charge diameter is 40 cm. Individual holes would be 7.3 m deep, for a total drilling length of 29.2 m. Total backfill for the project is about 430 m^3.

Table 18. Reactor project mass, volume, power requirements, and sources.

Equipment	Mass (kg)	Volume (m^3)	Power (watts)
Lunar construction vehicle:			
Original equipment mass[a]	10,000	175	20,000 (self contained)
Attachments	3,000	3	—
Drill system:			
Original equipment mass[a]	500	2.0	15,000
Attachments and materials needed for strengthening	200	1.0	—
Power source:			
Roll-up solar cells[a]	480	2.0	Producing 16,000
Miscellaneous:			
Arming, stemming, and firing equipment	200	1.0	—

[a]Not chargeable to payload for this project.

For emplacement in maria material, the parameters would be identical except for the true crater radius and the amount of backfill. In that case R_t would be 9.3 m and backfill would be about 970 m^3.

e. Project Time Requirements

Emplacement in rock material is estimated to require the amounts of time indicated in Table 19. Only drilling operations are restricted to lunar sunlight periods because of their dependence on solar energy. Other construction operations would not be so restricted. With a three-shift operation, the construction schedule would make the reactor emplacement excavation available within 4 (earth) days. Drilling operations should be completed in 2 (earth) days; the charge could be detonated during the third day. At that time the excavation should be available, with, perhaps, some minor supplementary trimming, filling or compaction, for placement of the reactor. After the power plant system had been assembled and checked out, backfill operations could be completed in about 2 (earth) days.

f. Safety Considerations

Explosion side effects predictions for the project, based on detonation in

Table 19. Reactor emplacement time requirements.

Operation	Element	Total time (hr)	
Drilling	Set-up	1.3	
	Drill	41.7	
	Tear down—move	1.0	
	Job		44
Loading	Job		2
Arming	Job		1
Stemming	Job		2
Firing	Job		3
Emplacing system[a]	Job		10
Backfill	Job		36

[a]Excludes mechanical hook-up and testing.

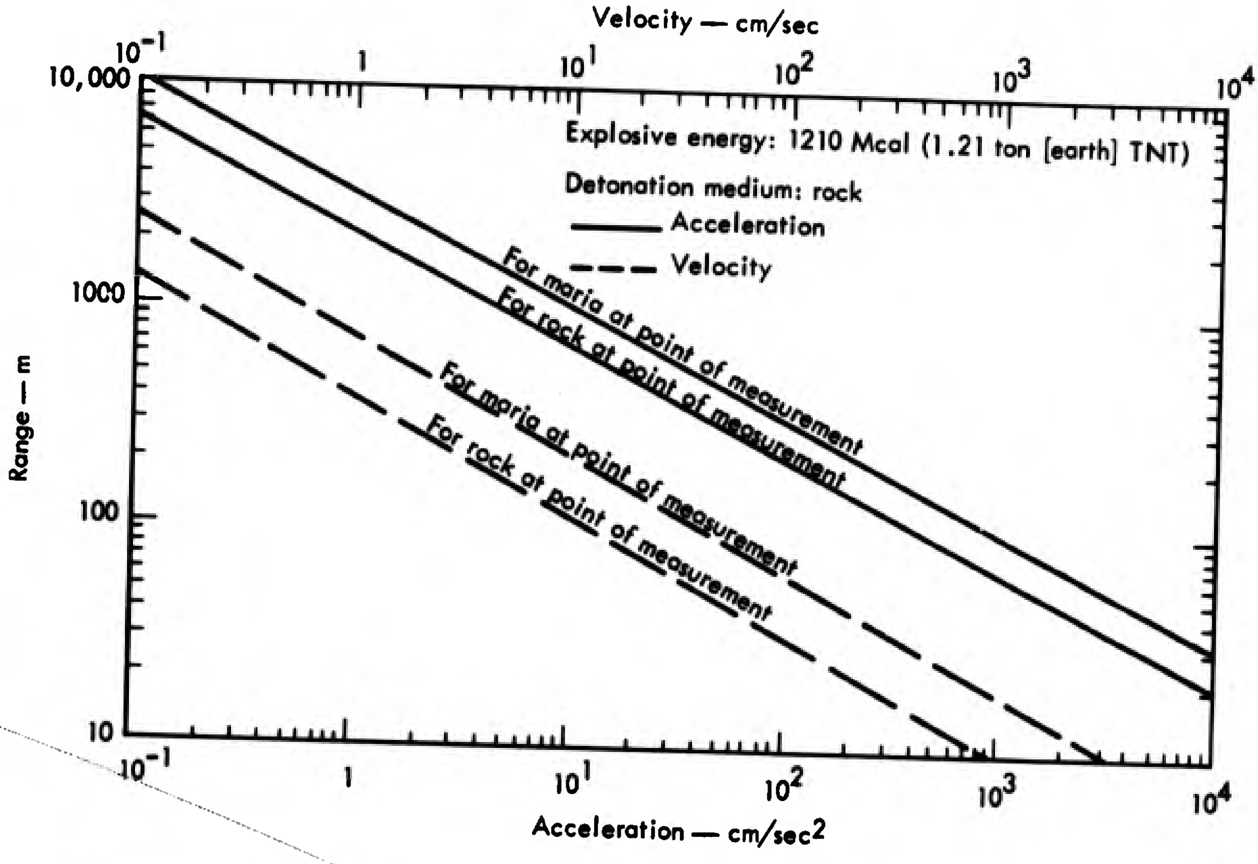


Fig. 67. Ground acceleration and velocity vs range for reactor emplacement crater.

high-strength rock, are shown in Figs. 67, 68, and 69.

g. Summary of Pertinent Data

Pertinent aspects of the conceptual design to excavate the emplacement hole required for installation of the nuclear power plant heat source are given in Table 20.

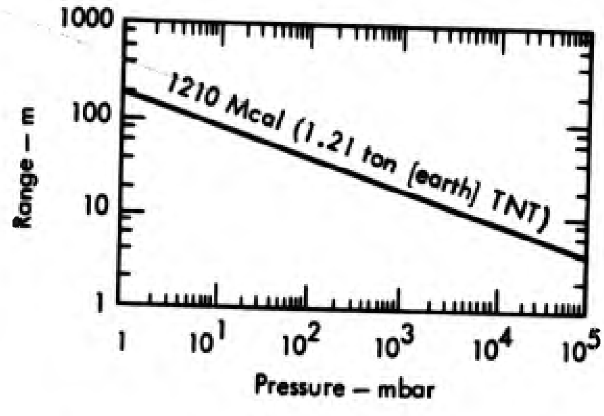


Fig. 68. Blast pressure vs range for reactor emplacement crater.

5.4 PHASE III PROJECT CONCEPTS

Phase III projects are of a more extensive and intricate nature than those of Phase II and represent concepts that will require considerable development before they are considered to be practical construction techniques. They are of the type envisioned for use during construction of permanent lunar base facilities or during exploitation of lunar materials. It is expected that the previously described Phase II concepts would have been developed more fully and have reached a degree of sophistication that enables them to be classified as standard construction techniques.

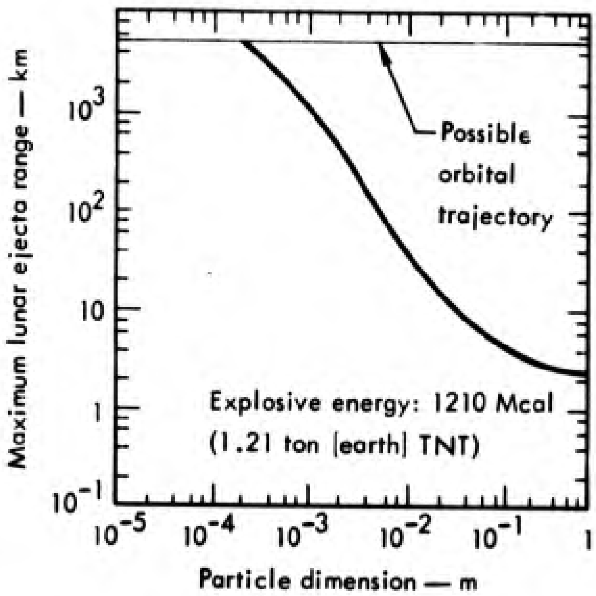


Fig. 69. Ejecta ranges for reactor emplacement crater.

5.4.1 Subsurface Fluid Storage Facility

This example suggests a method for excavating a subsurface storage chamber for fluids such as water, cryogenic materials, gases, and similar substances. An application such as this would avoid the need to transport prefabricated tanks from earth and the need to employ the cut-and-cover installation techniques described in the previous applications.

a. Storage Tank Characteristics

This discussion assumes a requirement for a spherical water tank 2 m in diameter. This 4190-liter storage volume has been suggested as adequate for 30 men over a period of about 50 days (Johnson, 1969) if no regenerative cycle is used. A subsurface tank would require heating and insulation to protect the water from freezing.

b. Concept of Construction

A sprung cavity would provide the simplest method of excavating the necessary subsurface storage volume. After detonation of a chemical high-explosive charge at or below containment depth, the resulting explosion cavity could be insulated with a spray-on substance and sealed with a bladder or spray sealant. A capping arrangement at the surface would allow pressurization and heating of the water. This concept is depicted in Fig. 70.

Table 20. Summary of reactor emplacement project data.

Item	Rock	Maria
Number of charges	4	4
Charge spacing (square layout), cm	30	60
Depth of burst, m	6.2	6.2
Depth of borehole, m	7.3	7.3
Total time for construction, days (earth)	5	5
Total mass of ALX explosive, kg	605	605
Mass of construction equipment, kg (Table 18)	3400	3400
Payload mass for project, kg.	4000	4000
Total volume of ALX explosive, m^3	0.28	0.28
Volume of construction equipment, m^3 (Table 18)	5	5
Payload volume for project, m^3	5.3	5.3
Backfill volume, m^3	430	[illegible]70

c. Equipment and Explosives

A mobile drill and an LMV would be the only major items of equipment required. The 20-cm mobile drill used in the reactor burial concept is assumed to have an increased capacity (15 m) provided by additional drill string. Solar cells or the installed reactor could be used to power the mobile drill.

The LMV would be augmented with a grab bucket attachment to perform the final explosion-cavity clean out operations. A spray head attachment capable of operating from the grab bucket boom would also be provided to apply the cavity insulation (Fig. 71). The LMV would be capable of operating from its on-board power sources.

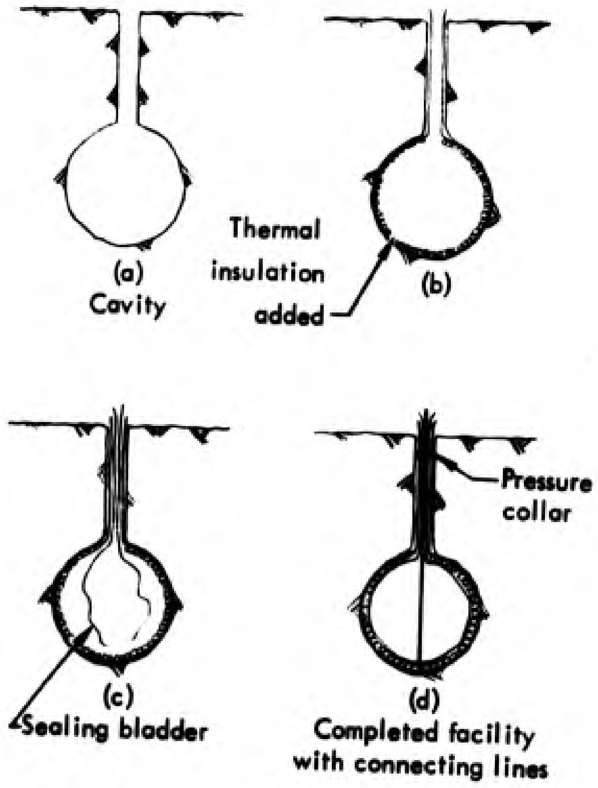


Fig. 70. Conceptual methods of insulating and sealing underground storage cavities.

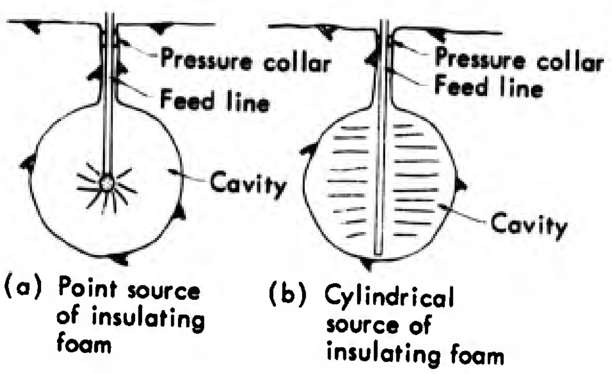


Fig. 71. Applying thermal insulation.

For this application, an explosive in pelletized form similar in explosive energy and characteristics to ALD (Table 11) will be used.

d. Explosive Excavation

The contained explosion necessary to produce an underground cavity was seen in paragraph 4.4.3e to occur at a dob of 1.2 m/(Mcal)$^{1/3}$ and to produce a cavity of 5 liters/Mcal of explosive energy. For the case at hand, then, 840 Mcal (560 kg) of ALD would be required at a DOB of 11.5 m. The volume of the required charge, is 280 liters; however, a 20-cm hole can contain only a 37.6-liter volume of charge with an L/D ratio of 6. Because of the intended use of the excavation, a cluster of charge emplacement holes cannot be employed. Instead, the volume required for emplacement of the main explosive charge would be obtained by a preliminary hole springing detonation. This preliminary charge would require 56 Mcal (57.4 kg of ALD) to form a 280-liter main charge emplacement cavity and would occupy only 15 liters of the 20-cm drilled emplacement hole. Depth of the emplacement hole for the preliminary springing charge would be 11.7 m.

Following detonation of the preliminary springing charge, it may be necessary to redrill through the stemming material to the sprung cavity. Most of the debris in the bottom of the hole would be blown out by a 10-kg ALD cleaning charge; the remainder would be removed by use of the grab bucket. After cleanout, the main charge would be poured into the resulting cavity, stemmed, and detonated. After redrilling through the stemming, two successive 100-kg ALD cleaning charges would be used to remove the broken rock from the final cavity. Again, final cleanout would be done with the grab bucket.

e. Project Time Requirements

The project time estimate is presented in Table 21. On the basis of a three-shift

Table 21. Subsurface cavity time requirements.

Operation	Element	Total time (hr)	
Drilling (3)	Set up (3)	0.3	
	Drill (1)	16.7	
	Redrill (2)	7.5	
	Tear down — move (3)	0.3	
	Job		24.8
Preliminary springing	Load	0.3	
	Arm	0.2	
	Stem	0.5	
	Fire	2.0	
	Job		3.0
Cleaning charge	Load	0.3	
	Arm	0.2	
	Fire	1.0	
	Grab bucket	1.0	
	Job		2.5
Main charge	Load	0.7	
	Arm	0.3	
	Stem	0.7	
	Fire	2.0	
	Job		3.7
Cleaning charges (2)	Load (2)	1.0	
	Arm (2)	0.4	
	Fire (2)	2.0	
	Grab bucket (1)	9.0	
	Job		12.4
Insulating and sealing cavity	Job		24

operation this project would be available for installation of operating fittings and ancillary equipment in approximately 3 (earth) days.

f. Safety Considerations

Ground shock will be the principal concern during this project (Fig. 72). Some missiles will be thrown up by the cleaning shots, but these will be very few in number and will probably impact in the immediate vicinity of the job site. There will be no appreciable blast; that which does occur will be directed vertically upward.

g. Summary of Pertinent Data

Pertinent data for this application are listed in Table 22.

5.4.2 Overburden Removal

By such time as exploitation of lunar natural resources takes place, the techniques

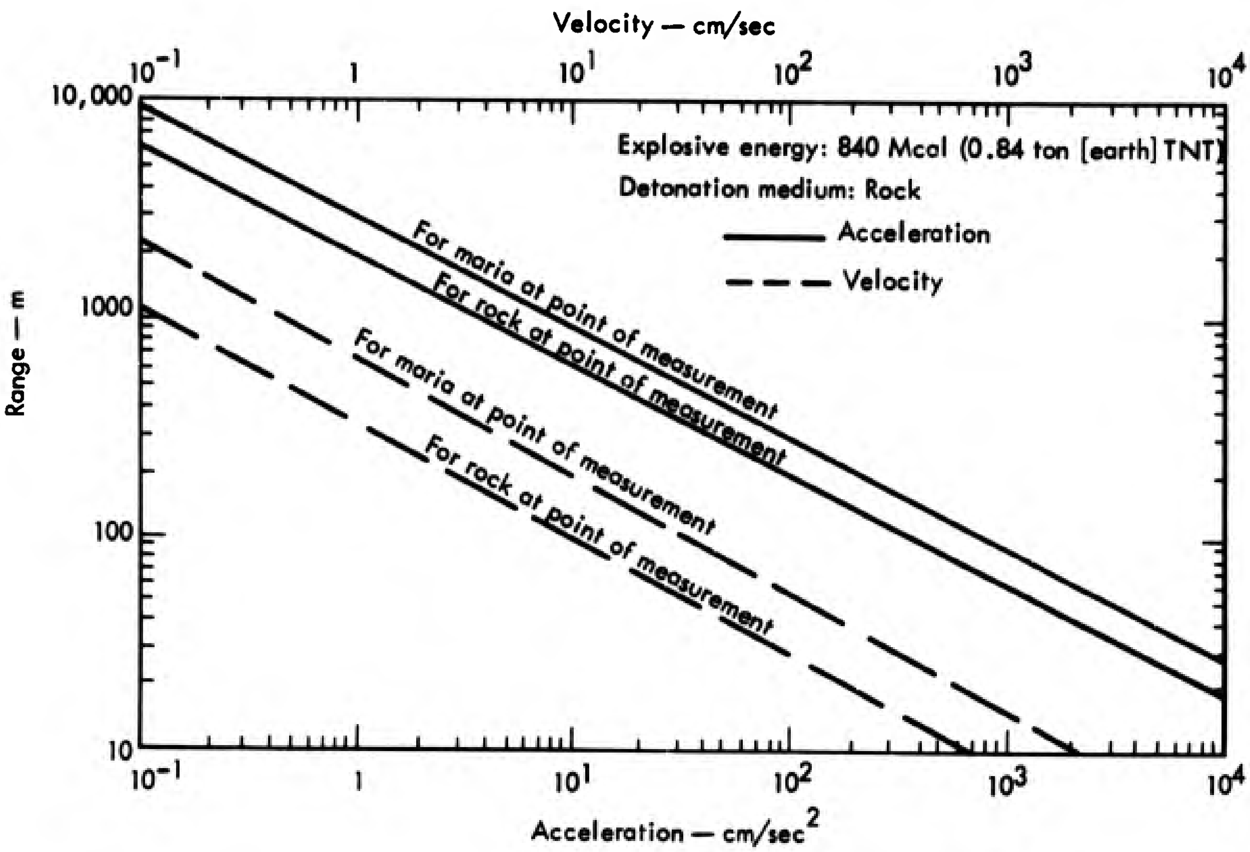


Fig. 72. Ground acceleration and velocity vs range for subsurface cavity.

Table 22. Summary of subsurface cavity project data.

Number of main charges	1
Depth of burst, m	11.5
Depth of borehole, m	11.7
Total time for construction, days (earth)	3
ALD charges:	
1 springing charge, kg	37.4
1 10-kg cleaning charge, kg	10
1 main charge, kg	560
2 100-kg cleaning charges, kg	200
Total ALD explosive (approx.), kg	810
Miscellaneous equipment, kg	50
Payload mass for project, kg	860
Total volume of ALD explosive, m^3	0.43
Volume of construction equipment, m^3	0.75
Payload volume for project, m^3	1.2

described below could be developed to remove overburden as part of a surface mining operation.

a. General Situation

A lunar ore body is overlain by overburden consisting of layers of maria and rock materials 6 m in total depth. It is planned to work an area of the ore body about 15 by 30 m. The first project is to be overburden removal (Fig. 73).

b. Concept of Excavation

For this application, it is desired that an excavation be made similar to that

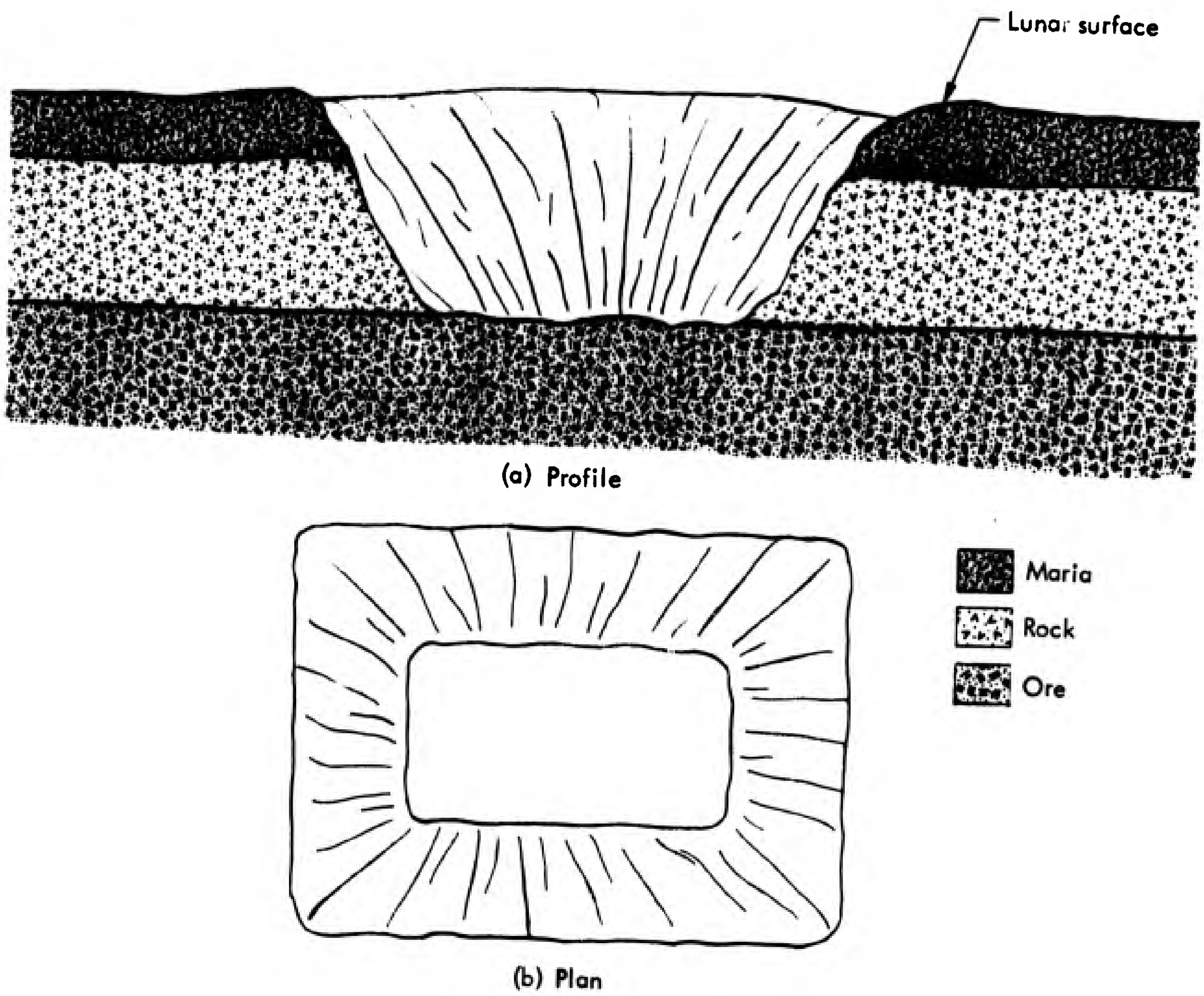


Fig. 73. Overburden removal.

shown in Fig. 28. The excavation would be accomplished by means of a multi-row explosive excavation. Because the amount of fallback would be much less in lunar operations, it is planned to excavate the entire area in a single detonation with delays between rows, rather than by separate, successive detonations as in Fig. 28. This should reduce the amount of ejecta interaction and, thus, fallback.

In this type of application, it is desired to detonate the explosive at the optimum dob for maximum d_a.

c. Equipment and Explosives

Two drills of the 20-cm diameter, 15-m depth capability would be used for this project. Net drilling rate per drill for the 20-cm hole in four passes is 0.7 m/hr.

Details of the ore removal and processing operations, as well as those of the associated excavating and hauling systems are beyond the scope of this discussion.

An operation of this magnitude is expected to have available a continuously functioning electrical power source. Solar cells would suffice, if necessary, but would restrict operations to the lunar day period.

The high-energy ALX-type explosive (Table 11) used in this application is assumed to be prepackaged in cylinders of diameters compatible with the four drill pass diameters and of lengths readily varied to obtain the desired amount of explosive energy.

d. Explosive Excavation Design

Maximum d_a occurs at a dob of 0.7 m/(Mcal)$^{1/3}$ (Fig. 41). The relationship between the DOB, R_a, and D_a, and the required explosive energy is given in Fig. 74. That figure shows that for an overburden depth of 6 m (D_a = 6 m), a single-charge explosive energy of 1650 Mcal is required. This amount of charge energy produces R_a of 6 m when detonated at 8.4-m DOB.

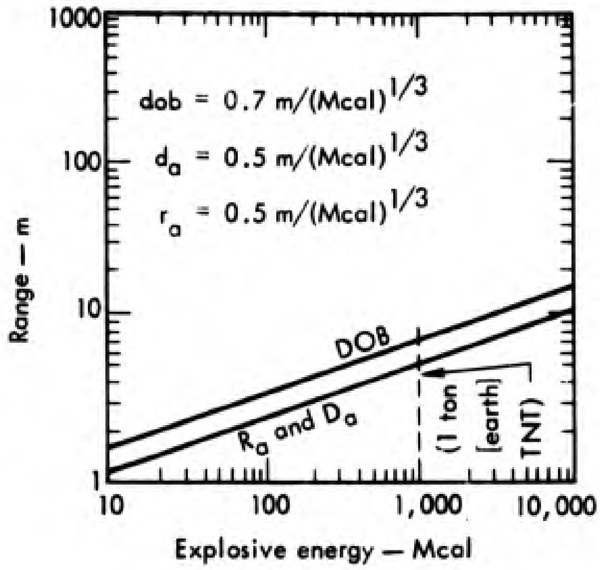


Fig. 74. Crater parameters for overburden removal.

Assuming a true crater side slope of 56 deg (6 vertical on 4 horizontal), it will require crater dimensions of 23 by 38 m at the surface to expose a 15- by 30-m expanse of the ore body whose top is 6 m below the surface. With a maximum charge spacing between rows of 1.4 R_a, three rows would be required to obtain the 23-m minimum surface dimension; the in-row maximum charge spacing of 1.4 R_a requires five charges per row for the 38-m surface dimension. Based on the single-charge explosive energy requirement of 1650 Mcal, the explosive energy distribution along each row must be 197 Mcal/m. Thus, each row will require five 1500-Mcal charges.

Since the 20-cm diameter hole can hold only 37.6 liters, and each 1500-Mcal charge of ALX occupies 341 liters, a clustered emplacement hole design will be used. That system calls for five holes per charge, with a 10% increase in charge energy of 330 Mcal of explosive per hole. The charge hole configuration is shown in Fig. 75. The DOB for the 5-hole clusters remains at 8.4 m. Depth of drill holes is 9.6 m; drill length per charge cluster is 48 m.

The detonation will require a total explosive energy of 24,750 Mcal (12,400 kg of ALX); total drill length for the 75 emplacement holes is 720 m.

c. Project Time Estimates

Time estimates for the operations involved in this overburden removal project are given in Table 23.

f. Safety Considerations

The use of delays between row detonations reduces the magnitude of ground shock at a given range to that predicted for the total explosive charge in one row. Figure 76 depicts the ground acceleration

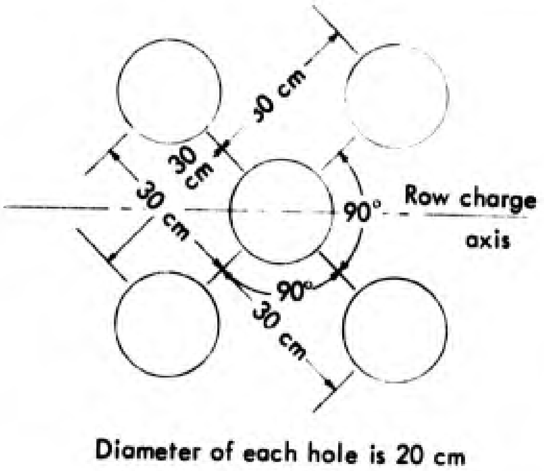


Fig. 75. Single cluster pattern for overburden removal application.

Table 23. Overburden removal time requirements.

Operation	Element	Total time (hr)	
Drilling	Set-up	25.0	
	Drill	514.0	
	Tear down—move	18.7	
	Job		557.7
Loading	Job		25.0
Arming	Job		12.0
Stemming	Job		25.0
Firing	Job		3.0

and velocity at various distances from the job site.

Estimated blast magnitudes are shown in Fig. 77. Magnitudes are based on the single-row charge; delays between row detonations should prevent reinforcement of the blast wave by contributions from subsequent detonations.

Missile ranges for various ejecta sizes are shown in Fig. 78. They are based on the explosive energy of a single 5-hole cluster charge, the maximum energy to which a particle should be subjected.

g. Summary of Pertinent Data

Table 24 gives a summary of pertinent data for this application.

5.4.3 Lunar Quarrying

The mass and bulk of quarrying and mining processing equipment would place this type of explosives application far in the future at a time when permanent lunar base construction operations would be taking place. The necessary equipment would be developed to be relatively lightweight and compact, but space transport of such equipment as a practical matter would depend on the development of a space shuttle system.

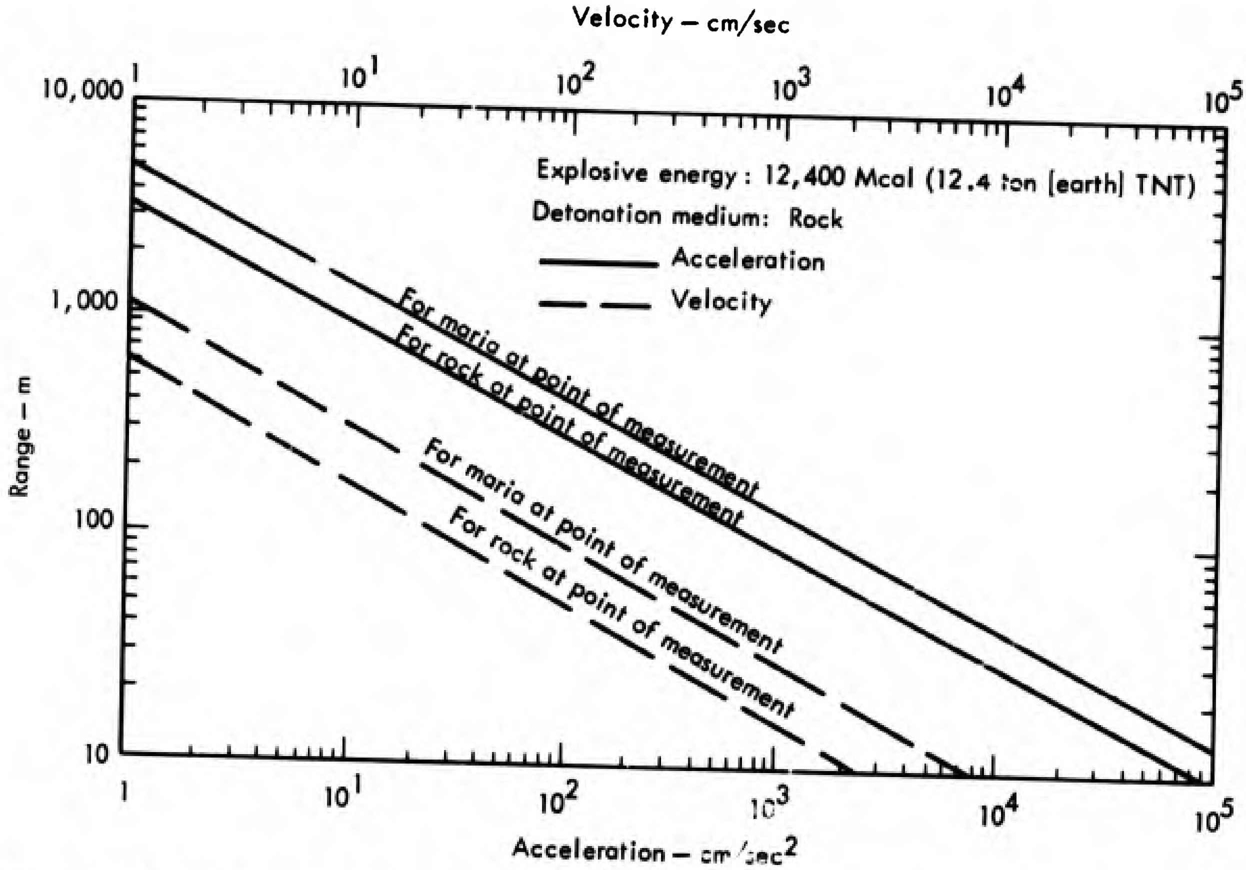


Fig. 76. Ground acceleration and velocity vs range for overburden removal application.

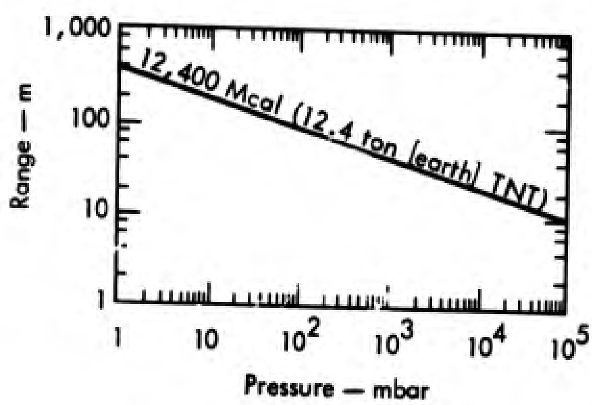


Fig. 77. Blast pressure vs range for overburden removal application.

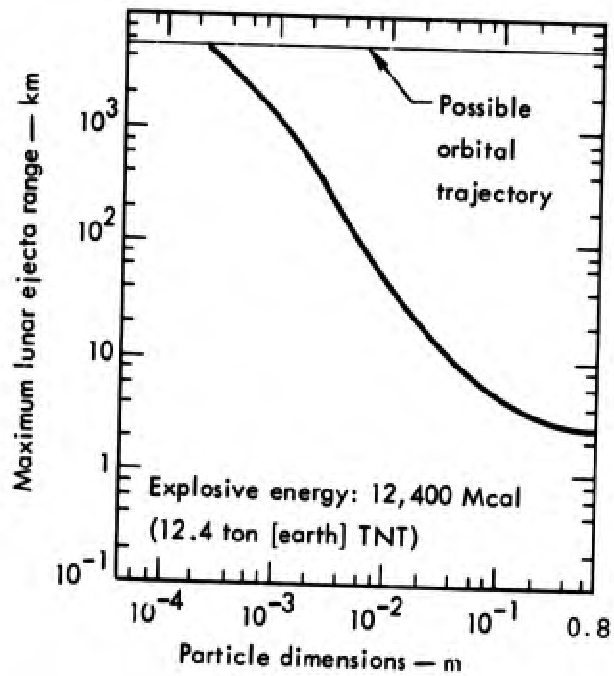


Fig. 78. Ejecta ranges for overburden removal application.

a. Quarry Operation

This discussion addresses only the explosives portion of a lunar quarry project. Loading and hauling equipment are not considered because they would be a

Table 24. Summary of overburden removal project data.

Area of lunar ore to be exposed, m	15 × 30
Number of rows	3
Number of clusters/row	5
Number of holes/cluster	5
Number of charges	75
Depth of burst, m	8.4
Depth of borehole, m	9.6
Total mass of ALX, kg	12,400
Second drill, kg	700
Miscellaneous equipment, kg	100
Payload for project, kg	13,200
Total time for explosive operation, days (earth)	25
Total mass chargeable to explosive portion, kg	13,200

standard feature of the overall operation, regardless of the technique by which the desired materials are initially broken.

The specifications assumed for illustrative purposes call for 100 m^3 of material with sizes between 10 and 100 cm. A bulking factor of 1.4 is assumed and post-detonation particle size distribution would be as shown in Fig. 79. Thus, about 64% of the material will meet specifications.

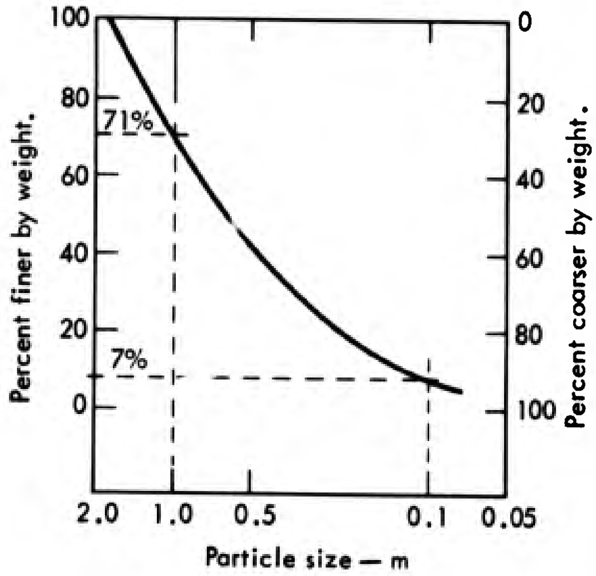


Fig. 79. Assumed average particle size distribution for lunar high-strength rock material.

b. Quarrying Concept

A single charge buried at a depth between optimum and containment dob will fracture a large volume of material with little or no ejecta throwout. The broken material can then be removed and processed by usual quarry operation methods. The concept is illustrated in Fig. 80.

c. Equipment and Explosives

A mobile drill with the 20-cm diameter and 15-m depth capability of the preceding application would be used during quarry operations. An underreaming attachment

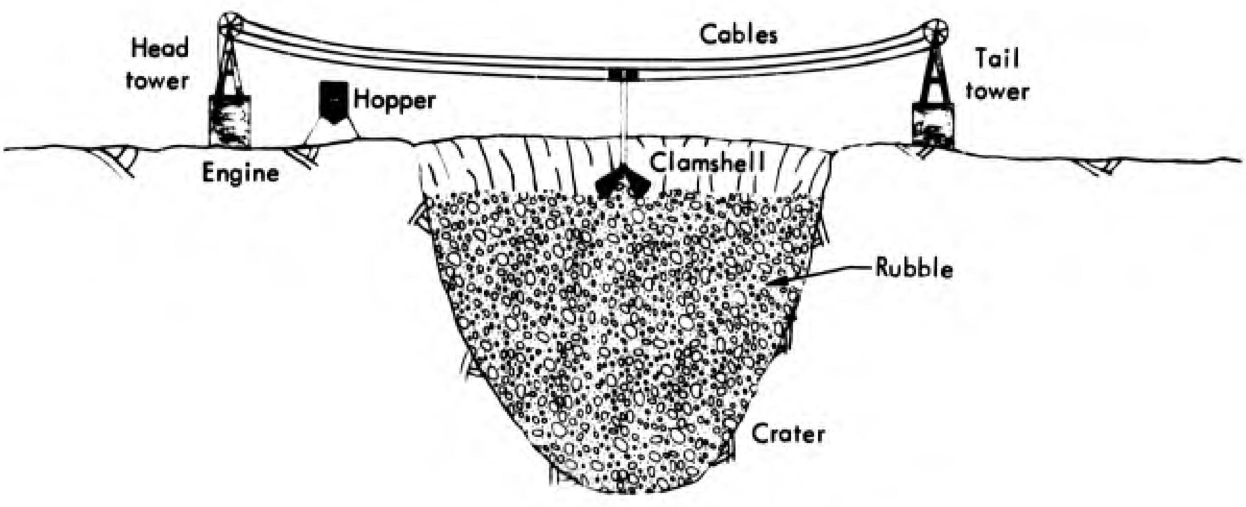


Fig. 80. Quarrying concept.

capable of expanding the emplacement hole diameter to 30 cm on this drill rig is assumed to have been developed and to be available.

The broken material will be removed by a cable-operated 1/2-m^3 bucket clamshell system, as shown in Fig. 80. This system is assumed to be capable of removing material from the crater area at the rate of 10 m^3/hr.

The quarry equipment would operate from a continuous electrical power source, if available; otherwise a solar cell system would be adequate for remote locations but would limit operations to the lunar day period.

An explosive capable of being stored for long periods of time, with explosive properties similar to ALH (table 11), is to be used in the quarrying operation. It would be prepackaged in cylinders with diameters compatible with the four drill pass diameters and with lengths that can be adjusted readily to obtain the desired explosive energy.

d. Emplacement Design

It is assumed that 20% of the material shattered by the explosion will be unavailable because of inaccessibility or handling difficulties. Taking into account the bulking factor and fraction of materials meeting the size specifications requires shattering some 140 m^3 of *in situ* material to produce the desired 100 m^3. Shattering that volume of rock requires 350 Mcal (195 kg of ALH) of explosive energy (Fig. 50), at a DOB of 6.3 m.

That amount of explosive occupies a volume of about 97 liters, which exceeds the L/D restriction for a 20-cm drillhole, and makes it necessary to underream the charge cavity to a diameter of 28 cm. The emplacement hole would be drilled to a depth of 7.1 m.

e. Detonation Time Requirements

This system of shattering rock in a quarrying operation is estimated to require the times shown in Table 25 for each 100 m^3 of usable rock.

f. Safety Considerations

The quarrying detonation is essentially contained; there would be no blast hazard. Some broken materials might be ejected a short distance from the site of the detonation, but these would be very few in number. Prediction of the ground shock magnitude for this detonation is shown in Fig. 81.

g. Summary of Pertinent Data

The pertinent information concerning this quarrying detonation is listed in Table 26.

5.4.4 Subsurface Mining

Large-scale exploitation of lunar resources could involve subsurface mining operations for particularly valuable ores.

Table 25. Quarrying time requirements.

Operation	Element		Total time (hr)
Drilling	Setup	0.4	
	Drill	10.1	
	Underream	2.0	
	Tear down—move	0.3	
	Job		13.0
Loading	Job		1.0
Arming	Job		0.5
Stemming	Job		1.0
Firing	Job		3.0
Rock removal	(continuous operation)		15.0

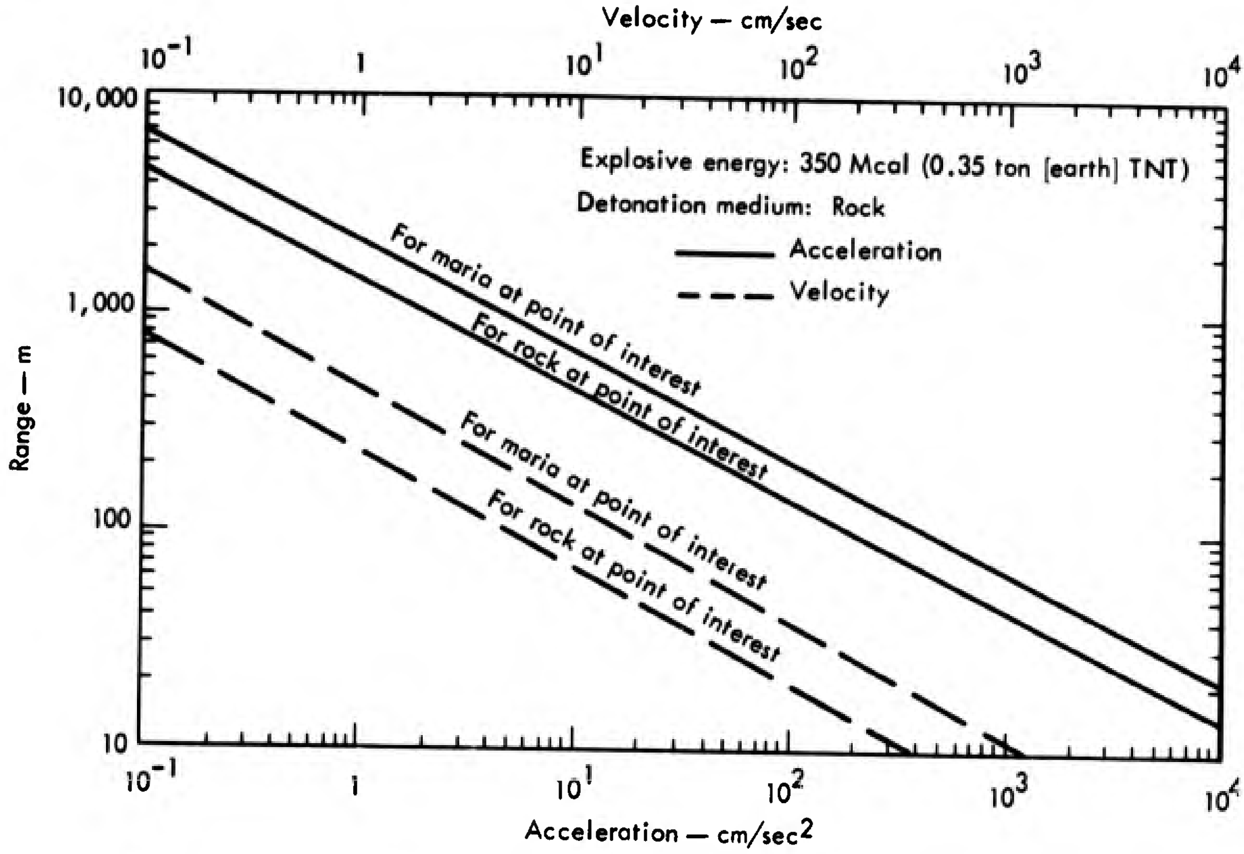


Fig. 81. Ground acceleration and velocity vs range for quarry detonation.

Table 26. Summary of quarry project data.

Rock volume desired, m^3	100
Size range, cm	10-100
Quarry volume, m^3	140
Number of charges	1
Depth of burst, m	6.3
Depth of borehole, m	7.1
Total time for operation, days (earth)	2
Total mass of ALH explosive, kg	195
Miscellaneous equipment, kg	50
Payload mass for project, kg	245

a. General Situation

A lunar ore body lies deeply buried below the lunar surface near the edge of a natural crater. It is located so that surface mining techniques cannot be used to retrieve the ore (Fig. 82). The ore must be shattered to allow its extraction.

b. Concept of Mining Operation

Conventional shafting and tunneling methods would be required to provide access to the ore body; entrance from the side of the natural crater would be the most practical arrangement. This discussion addresses the operation of shattering the ore body to facilitate ore removal. A series of separate, successive detonations is planned in a variation of the block caving mining method (Fig. 39). In this case, a single explosive charge would be detonated at containment depth to provide a chimney of collapsed material (Fig. 51). The explosives emplacement chamber would be formed during the access tunneling operation. At the location planned for the first detonation of the series, the ore body is 20 m thick.

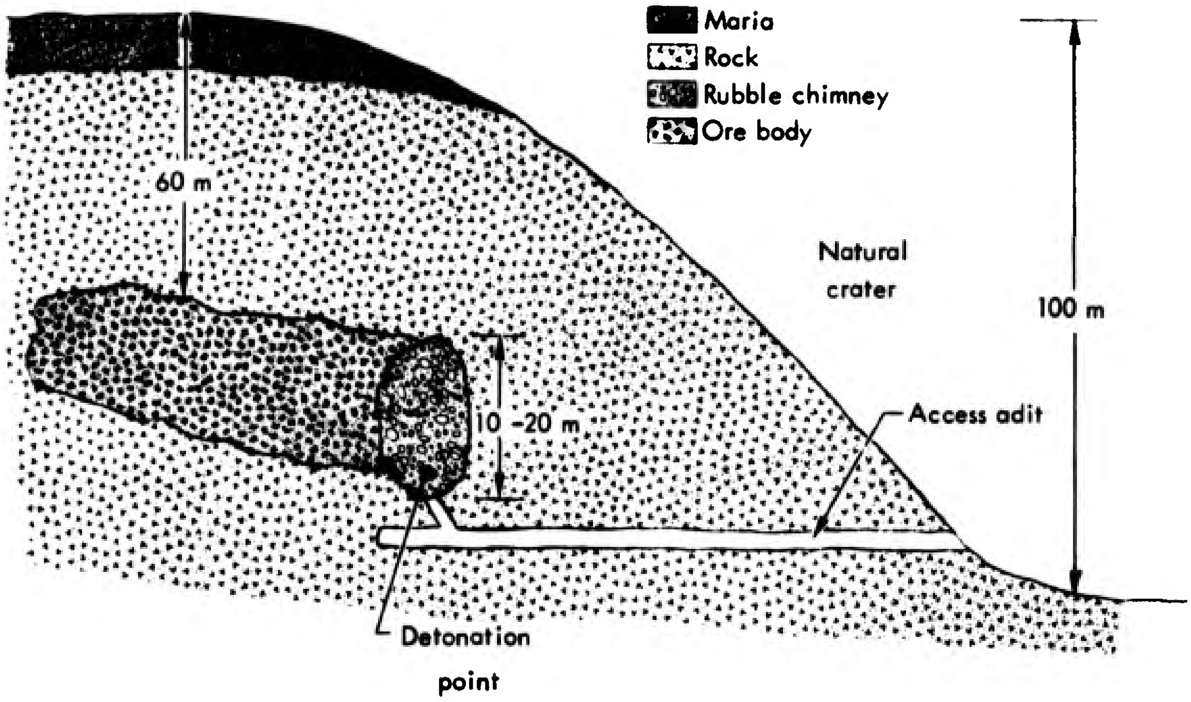


Fig. 82. Underground mining project.

Succeeding detonations would form similar chimneys to permit full exploitation of the ore body.

c. Equipment and Explosives

Terrestrial tunneling and shafting equipment or explosive methods described in paragraph 3.2 would be used to gain access to the ore body and to excavate the explosives emplacement chamber.

An ALX-type explosive (Table 11) would be used in this kind of application because of its high energy-density. It would be prepackaged into blocks for ease of handling and efficiency in emplacement. Stemming consisting of sandbags filled with lunar materials, possibly spoil from the access tunneling, would be used to seal the emplacement chamber.

d. Emplacement Design

To produce a chimney whose height is 20 m (the thickness of the ore body) will require an explosion cavity 5 m in radius. That radius is greater than the 3-m radius minimum for roof collapse (paragraph 4.4.3) and will be used in the design.

The 5-m radius represents a volume of 523,000 liters. An explosive energy of 1.05×10^5 Mcal (52,500 kg of ALX) would be needed to produce the required explosion cavity size. It would be necessary to provide an emplacement chamber of 23.9 m^3 capacity. This chamber would have to be approximately $3 \times 3 \times 4$ m to provide both explosives stowage capacity and room for maneuverability.

e. Project Time Requirements

The time estimates given in Table 27 deal only with the explosives aspects of this subsurface mining operation. On a three-shift basis, ore retrieval could begin about 6 days after excavation for

Table 27. Underground mining project time requirements.

Operation	Total time (hr)
Excavating explosives chamber	100.0
Loading	17.5
Arming	2.0
Stemming	4.0
Firing	3.0
Post-detonation reentry	50.0

the charge emplacement chamber is begun.

f. Safety Considerations

No blast or missile throwout hazards would be presented by this deeply buried, completely contained explosion.

The ground motion magnitude predictions for this detonation are shown in Fig. 83. It should be noted that the range indicated must be interpreted to be the slant distance from the point of detonation to the location at which the ground motion is measured; it is not the surface distance from the ground zero above the detonation point.

g. Summary of Pertinent Data

Significant items of interest concerned with this ore shattering project are listed in Table 28.

It should be recognized that the assumed uprated Saturn V space transport system would be severely taxed by the mass transport requirements for this

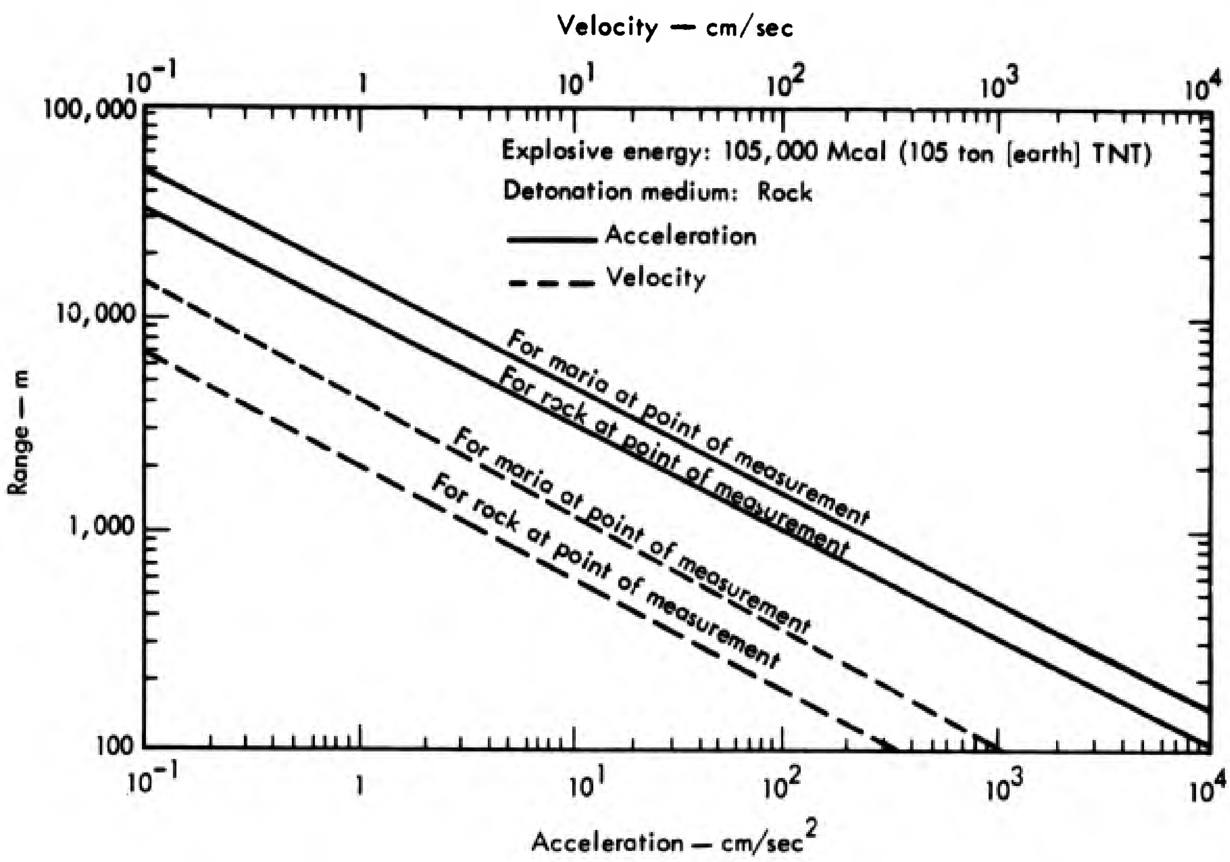


Fig. 83. Ground acceleration and velocity vs range for underground mining project.

type of project. A lunar exploitation project of this nature, though, is not expected to take place for many years. In the intervening time, a space transportation system of expanded capacity is expected to be developed. The proposed space shuttle is one possible method. Also, highly energetic explosives of the ALOX type (Table 11) might be developed and would reduce the payload requirements.

Table 28. Summary of underground mining project data.

Height of ore chimney, m	20
Radius of ore chimney, m	5
Volume of broken ore, m^3	1046
Emplacement cavity volume, m^3	23.9
Total time for explosive operation, days (earth)	6
Total mass of ALX, kg	52,500
Miscellaneous equipment, kg	200
Payload mass for project, kg	52,700

Chapter 6

Training for Lunar Explosives Employment

The present training philosophy for crews of space missions is a practical approach in which each crew member receives the type and amount of instruction necessary to enable him to assist in carrying out the assigned mission. Each investigation and experiment is organized by a principal investigator, generally a non-crew member, who establishes the requirements and identifies the related tasks; he may also suggest crew training requirements and methods. NASA's Manned Spacecraft Center incorporates the required tasks into specific mission plans with the assistance of the principal investigator and has the overall responsibility for crew training. Training methods include briefings and reviews, special purpose training, and simulation exercises. The instructors may include the principal investigator, NASA personnel, and outside agencies with expertise in the topic of interest.

This chapter discusses the training required to prepare a space crew to accomplish the tasks involved in using chemical high explosives in lunar activities. It identifies the tasks involved, examines the background required of such trainees, and suggests a program of instruction appropriate to accomplish the necessary training.

6.1 TASK ANALYSIS

The complexity of explosive operations tasks can vary from those represented by simple checklist types to many-faceted ones requiring on-site judgment with little or no guidance available. The expertise necessary in the various explosives operations tasks to be performed by a lunar crew member will vary substantially.

6.1.1 Operational Considerations

To appreciate the demands on a crew member in performing explosives operations, one must consider the constraints placed on him by the unfamiliar environment in which he must work, further compounded by the protective clothing and apparatus he must use.

It was noted earlier (paragraph 4.1.1) that most light on the lunar surface is reflected along its path of incidence. This means that the amount available to an observer varies with the angle between his line of sight and the line of light reflection. Such a difficulty was reported on the Apollo 12 mission (Strickland, 1969a). In addition, the helmet visor transmits only 10% of available light. Visual aspects of explosives operations will require close attention.

Another consideration is the reduction by 50% of fine dexterity in handling small objects as pins, knobs, and switches. The crew member's life support system and helmet visor assembly raise his center of gravity and introduce an unusual balance condition.

Special designs in equipment necessitated by the low lunar gravitational acceleration and atmospheric pressure and the temperature extremes may dictate new operating procedures.

6.1.2 Phase I Tasks

Phase I includes the current program of lunar experimentation and exploration up to emplacement of explosives beneath the lunar surface. The purpose of programs requiring the use of explosives will be to determine the physical properties of the lunar surface and interior. Regardless of construction method or proposed location of a lunar base, knowledge of the physical properties of the lunar material is of highest scientific interest.

Initial use of chemical high explosives on the lunar surface will be in seismic investigations. These investigations have high priority in mission plans for the Apollo program as did deployment of the Passive Seismic Experiment Package (PSEP) on Apollo 11. Active seismic investigations differ from passive ones in that the location and strength of the seismic source are controlled. In passive seismic investigations, the seismic source would be a moonquake; whereas, in active investigations, the seismic source is generally an explosive emplaced by the worker-astronaut.

Several levels of effort for active seismic investigations have been proposed (NASA, 1965; North American, 1966; Kovach, 1967; Fryer, 1970; and Kovacs, 1970). Those that do not require subsurface emplacement of explosives are discussed below.

The experiment requiring minimum emplacement activity would be a measurement of the "P" or compressional wave seismic velocity over a 1- to 5-m distance at the surface (North American, 1966). This experiment would establish basic parameters for later seismic experiments in addition to providing some elastic properties data regarding the lunar surface material. The experiment would be deployed as shown in Fig. 84. An explosive squib would drive a tamper against the lunar surface to generate the source pulse. By enclosing the explosively driven tamper in a geologist's staff the astronaut can insure that the seismic source is directly coupled to the lunar surface.

An alternate or follow-on investigation would be the short seismic refraction array experiment (NASA, 1965), which would consist of a linear array of at least three detectors over a distance of at least 100 m. The energy source could again be a squib-activated tamper deployed by the worker-astronaut. Information derived would be similar to the 1- to 5-m experiment except that wave penetration depth to 25 m could be expected.

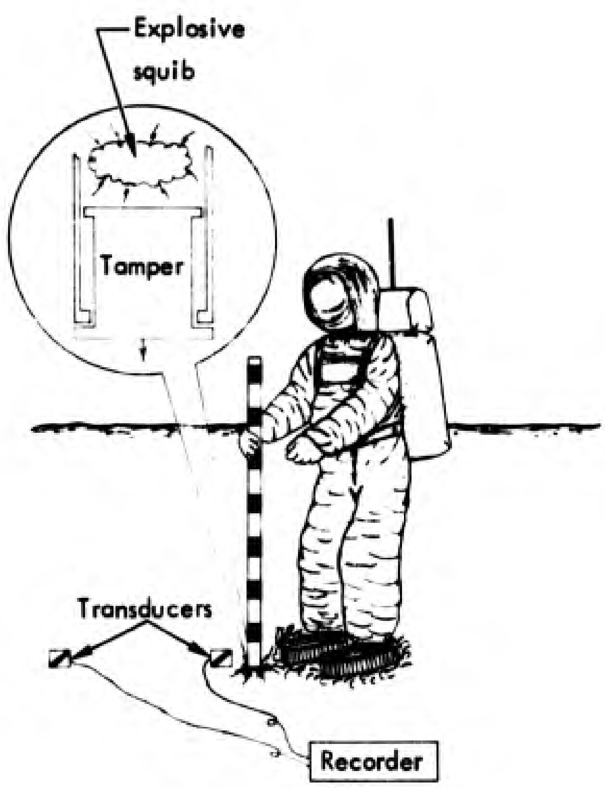


Fig. 84. Explosive tamper.

The tasks associated with these two experiments involve deploying geophones or other detector instruments and then activating the explosively driven tamper against the lunar surface. Although loading of additional squibs might be done from an external supply, a more practical method could employ a revolver-type mechanism to present subsequent charges for activation. That configuration would have the advantage of minimum handling. This type of explosives utilization should require minimal astronaut training in explosion effects and equipment use.

The largest scale active seismic experiment proposed that would not require subsurface emplacement of either explosives or instrumentation would utilize a mortar scheme for explosive deployment out to ranges of 1.5 km (Hess, 1965; Kovach, 1967; Kovacs, 1970). Although the mechanism would be largely automatic, some handling and arming of explosives might be necessary; therefore, training in safety, handling, and storage as well as in detonation techniques would be in order. The development of the mortar, explosive projectile, and detonating fuse is within current state-of-the-art technology. Design would incorporate features that would insure vacuum and thermal stability of the explosive. Examination of the explosive projectile impact area from this experiment will yield the first information on lunar material response to explosion effects.

One of the earliest applications of explosives in seismic experiments requires a shallow hole in the lunar surface. This Seismic Velocity Subsurface Logging experiment (North American, 1966) would generate a vertical seismic velocity profile of the "P" wave by having the astronaut hold an accelerometer against the side of the hole and then activate the explosively driven tamper at the surface. These actions would be repeated at intervals along the borehole. Other than creating the hole, no new tasks are required by this experiment.

In addition to the above experiment, many investigations during the early period of exploration will require holes in the lunar surface. These holes will find use in lunar strata electromagnetic and radio frequency subsurface propagation, thermal gradient, and heat flow studies as well as in obtaining sterile samples fo bioscience experiments.

The worker-astronaut can be expected to perform tasks associated with the development of lunar drilling technology. Two key experiments are: gas requirements for lunar core drilling, and lunar drill bit technology (North American, 1966). These studies will be of value towards developing large size drills to aid in emplacing explosives for Phase II and Phase III activities.

Phase I applications are characterized by the use of small yield, prepackaged or encapsulated explosive charges requiring minimal crew handling. There is no emplacement of explosives, and firing systems are incorporated into the operational mechanisms. Explosives technology must provide devices that will exhibit the thermal and vacuum stability necessary for the lunar environment.

6.1.3 Phase II Tasks

The beginning of Phase II will be marked by the emplacement of explosive charges beneath the lunar surface. The scope of activities will range from purely experimental, through developmental, to limited surface modification for construction of a temporary lunar shelter.

One experimental program in this phase that will make use of explosives is the measurement of explosive energy coupling in lunar materials (North American, 1966). A range of energy yields at varying depths of emplacement are to be correlated with coincident seismic recordings. This small-scale cratering study would use both directed and nondirected blasting techniques with charges placed in drill holes remaining from earlier experimental investigations. A variety of stemming procedures would also be examined.

In addition to energy transfer information, seismic data for surface properties studies and the first location of a possible seismic horizon might be derived from the same series of experiments. Controlled photographic recording of crater and ejecta geometries would be collected.

This experimental program is the first that will require a full range of explosives employment skills and techniques. Safety, handling, and storage of explosives will be important. One benefit of the smaller scale is that small quantities of explosives may be stored more simply and at closer distances to work areas and landing vehicle locations than larger qunatities. Because of dexterity limitations, handling problems may be increased. The small-scale aspect will not mitigate safety considerations because of the extreme vulnerability of life support systems; what might be merely a disabling injury on earth could be fatal on the moon.

The program should also provide the information necessary to implement a surface modification development program. Data on ground shock and missile hazard radius can be compared to theoretical calculations and extrapolated for large-yield blasts to provide for safe distance requirements for workers and equipment in subsequent operations.

Holes drilled in conjunction with previous geophysical investigations would be used to emplace the charges. Design explosive emplacement depths may differ from those of the original holes. For greater depth requirements, the original drilling could be continued to the desired depth; for shallower design depths of burst, the hole could be backfilled with drill chips, core materials, lunar soil, grout, or other material and tamped to the desired density.

The design depth of burst might require modification based on an examination of cores or cuttings from the holes as drilling progresses. Although the worker-astronaut should be able to recognize the evidence of discontinuities, strafication and other changes that could influence the emplacement design, modification of the experiment would be accomplished at the direction of the earth-based principal investigator.

Tasks involved in the experimental program include:

(1) Remove explosives and firing equipment from lunar vehicle.

(2) Drill holes; perform fundamental geophysical experiments, and deploy seismic array (geophones and instrumentation).

(3) Backfill or continue holes drilling (as required) to the design depth.

(4) Transport explosives to work area.

(5) Transport detonator to work area

(Tasks performed in work area should be monitored and checked via TV by PI.)

(6) Mate detonator to explosive.

(7) Emplace explosive train in drill hole.

(8) Stem (as required).

(9) Complete firing circuit.

(10) Perform safety check.

(11) Withdraw to safe area.

(12) Detonate remotely (upon release to fire from PI).

(13) Carry out misfire procedures (if required).

(14) Complete post-detonation measurements.

The explosive energy coupling experiments would grade into those to develop explosive employment techniques for surface modification. On the basis of earth-conducted research programs as well as the identification of lunar material physical characteristics and previous explosives experiments, an explosive surface modification program would be conducted, possibly by using a variety of explosive types as well as emplacement designs. Effectiveness of shaped charges and other special explosive devices could be determined. Predictive schemes for effects on crater formation, ejecta pattern and missile hazard radius would be verified. First priority would be to obtain empirical relationships for use in surface modification for construction of a temporary lunar shelter; that information also would be useful in Phase III mining and excavation for permanent base construction. Experiments in hole springing may be included if larger diameter drilling or underreaming, or both, appear impractical.

As the investigatory sequence progresses, it may be advantageous to modify experimental designs; this action would be initiated by the principal investigator on earth. The worker-astronaut would not be required to perform the necessary analysis or to make independent changes to the investigations; however, he would provide the necessary information to the principal investigator.

Since a variety of explosives may be present at one time, it is necessary that the type of explosive as well as the quantity be readily discernible. All work in the emplacement area should be monitored via TV by earth-based investigators. This portion of the investigative program with its variety of emplacement designs and explosives types is potentially the most hazardous of all the explosive utilization concepts.

Considering the broad range of these preliminary investigations, an actual surface modification, as for the emplacement of a temporary lunar shelter, might seem somewhat routine; however, because of the total energy release involved and the degree of excavation control necessary for successive operations, the design for the shelter emplacement project will require careful preparation and execution. Coordination in emplacement site selection for the experimental explosives investigation program will be important to minimize the number of experiments required to generate the data needed for the design of a shelter emplacement excavation. For actual shelter emplacement operations, selection of the site becomes important. Not only must the general site area be of scientific interest, but also the specific site must be amenable to explosive excavation. A particularly restrictive operation is encountered if the design requires hole springing. The boreholes must remain intact, even if they must be sprung with successive charges. Care must be exercised to match the springing explosive type and quantity to the site material to preclude losing a hole through subsidence or cratering action on the part of the springing charge.

After site selection, the shelter burial concept requires explosive excavation, shelter emplacement, and backfill with ejected material.

The following specific tasks are to be carried out in the construction of a temporary lunar shelter:

(1) Investigate potential sites (may include seismic surveying and test drilling).

(2) Select site (concurrence of principal investigator required).

(3) Review emplacement design (continues through emplacement).

(4) Select drill hole positions.

(5) Drill emplacement holes; if necessary:

- (a) Underream, or
- (b) Spring the holes.
  - 1 Determine quantity of springing explosive required.
  - 2 Subdrill (if required).
  - 3 Emplace surface casing (if required).
  - 4 Transport springing explosive to work area.
  - 5 Transport detonator to work area.
  - 6 Mate detonator to explosive.
  - 7 Emplace springing charge in borehole.
  - 8 Complete firing circuit.
  - 9 Check safety.
  - 10 Withdraw to safe area.
  - 11 Detonate remotely.
  - 12 Follow misfire procedures, if necessary.
  - 13 Measure volume of sprung cavity.

(6) Monitor drill cores or chips for indications of changes in properties that might influence emplacement design.

(7) Transport cratering explosive to work area.

(8) Transport detonators to work area.

(9) Mate detonators to explosive (mix two-component explosive).

(10) Emplace explosive train in borehole.

(11) Stem holes.

(12) Complete firing circuit.

(13) Make safety check.

(14) Withdraw to safe area.

(15) Detonate remotely.

(16) Follow misfire procedures, if required.

(17) Make post-detonation measurements.

(18) Complete supplemental mechanical or explosive excavation, if required.

(19) Prepare shelter for emplacement.

(20) Emplace shelter in explosively excavated cut.

(21) Backfill, cover, and compact as required.

All work with explosives in the project area should be monitored and checked via TV by the principal investigator at ground control.

Except for unusually large variations from expected results, the most likely means for supplemental excavation would be to use the equipment provided for backfilling operations. A design that provides for initial overexcavation might reduce the possibility of a requirement for supplemental excavation.

Details of shelter emplacement depend on the shelter design, the distance to be moved, and the available transport means. The emplacement will require coordination of effort, skill with the motive force equipment, and an understanding of the handling characteristics of the shelter.

An alternative to excavating completely with explosives would be to use buried high-explosive charges to loosen the lunar material with only moderate displacement. Earthmoving equipment could then excavate to the desired configuration.

6.1.4 Phase III Tasks

The period of permanent base complex construction and exploitation of lunar resources may follow immediately after the initial construction of a temporary lunar shelter, although complex construction might occur sometime later and require a substantial interim period of investigation and development prior to the commitment of the larger scale resources necessary. The year 1980 has been suggested as the earliest time for lunar shelter construction; a base complex would first appear after the turn of the century (Conrad, 1969).

Whereas the effort to emplace a simple shelter may be expressed in terms of man-days, the effort to construct a permanent lunar base complex could be expressed in man-years. Instead of a team of two, as for the shelter, the lunar base could involve 6 to 12 men (U.S. Army, 1959; LaPatra, 1968; Vail, 1968). With the larger crew, it is likely that individuals will specialize in various areas such as power and utilities operation and maintenance, earthmoving equipment operation and maintenance, drilling and blasting, welding and structural assembly operations, and specialities such as geophysics, medicine, and astronomy.

The relatively simple project of emplacement of the temporary shelter could be accomplished with relatively inexperienced personnel, because the activities are sequential and allow the engineering judgment and operational control to be remotely exercised by the earth-based principal investigator. The situation is more complicated for Phase III tasks in which the multiplicity of events and skills required for permanent base complex construction make the exercise of management, coordination, and construction judgment via real time TV or other data links quite difficult. A better solution would place the engineering expertise in residence on the moon. An on-the-job construction supervisor would have the ability to collaborate with earth-based groups to seek solutions to problems; however, he must have a basic understanding of all of the activities involved in the construction process.

In addition to the skills in explosive emplacement required for Phase II applications, many additional skills will be necessary. As the complex is constructed or close-in resources are developed, large-scale blasting will require a knowledge of structural response to ground shock and missile impact. Larger scale earthmoving will require familiarity with equipment operational characteristics and capabilities to coordinate activities for balanced productivity. A practical knowledge of soil mechanics and foundation design would be essential.

The key to the entire operation will be to have a construction supervisor who will direct the diverse operations and coordinate the competing demands for personnel and equipment. The position demands mature judgment, management skills such as planning, coordinating, and motivating, and technical experience in construction activities. The construction supervisor must have the ability to establish and to maintain an effective leadership role to assure effective implementation of the construction program. An important aspect of his role would be to insure that the construction program is properly integrated within the constraints of overall scientific mission priorities.

6.2 TRAINEE BACKGROUND

The trainee's background is a major factor in definition of the training requirements for chemical high-explosives employment on the moon. It is basic in designing the scope of activities comprising training procedures and the development of training support facilities.

Training must be based on the trainee's background to make effective use of the time available between the formalization of a mission that requires the use of explosives and its deployment on the lunar surface. That length of time will increase as projects become more complex. Sophistication implies a greater requirement for versatility and in-depth expertise in the trained worker. The number and nature of contingencies due either to natural phenomena or to systems performance will increase. These unexpected events will require that the worker be able to observe the significant information or event, relate it to his background and training, and then institute the proper actions.

In 1959, the National Aeronautics and Space Administration (NASA) began to select and to train pilots for space programs. Since the inception of the program with the selection of seven astronauts for Project Mercury, the general requirements for selection have remained the same: an astronaut must be in excellent physical condition, must be intelligent with a resourceful mind, and must exhibit emotional stability under a wide variety of physiological and psychological stress (VanBockel, 1970).

Physical condition relates not only to good health but also to coordination, visual acuity, strength, and endurance. These criteria for physical condition established for space flight should provide adequate screening for the physical ability needed to operate drilling and earth-moving equipment.

Intelligence and resourcefulness are required to absorb the highly technical and detailed plans for lunar missions and to be able to react appropriately in the event of unexpected conditions. Specific criteria are for the astronaut to have a degree in engineering or in one of the physical or life sciences or have equivalent experience. Advanced degrees are preferable and are evident in recent selection groups. Personnel in this category should be able to assimilate the rules and logic of explosives employment and to use the limited mathematics needed in emplacement design.

Specific criteria for astronaut selection has broadened considerably since the first group (Americana, 1968) was selected.

As spacecraft design has advanced, astronaut physical size and age requirements have varied. The most significant change has been in the area of flight training. The original seven were required to be graduates of military test-pilot school and have a minimum of 1,500 hr of flying time. For the second group selected, civilian test piloting was acceptable; for the third group, some were not even test pilots. The members of the fourth selection group are designated scientist-astronauts and are scientists first and pilots second. The most recent group selected includes many who were not pilots when selected; however, they received jet aircraft qualification training shortly after entering the astronaut program (O'Leary, 1970). One factor in the reduced requirement for previous flight training is the requirement for more substantial scientific qualifications; another factor is that the length of time between astronaut selection and integration into a mission crew allows the scientist-astronaut to accumulate a considerable number of flight hours (NASA, 1969a). It is anticipated that future missions, including those that will require explosives employment, will include astronauts who have been selected on the basis of requirements for their technical expertise as well as their potential ability to assist in space flight operations.

6.2.1 Astronaut Training

Some of the current training for Apollo astronauts provides background for training in explosives employment. The explosion effects anticipated are dependent on media response, so that a knowledge of geology and rock reaction mechanics as well as explosive technology is pertinent. All astronauts scheduled for the current series of Apollo flights are receiving extensive geologic training. This program of geologic instruction, which is more than 500 hr long, is divided roughly into thirds.

The first period of instruction is concerned with classroom type presentations with lectures, demonstrations, and laboratory work predominating. Although the bulk of the instruction in the principles of geology, petrology, and mineralogy is conducted by NASA and United States Geological Survey (USGS) geologists, specialists from outside agencies sometimes participate.

The second third of the course takes place in field training areas where physical characteristics similar to those anticipated at the lunar mission site are developed. Although special emphasis is placed on impact crater and volcanics geology, a wide variety of geologic terrain is examined in the field training. The USGS has been instrumental in planning field training and in selecting field training sites.

The last portion of the instruction is more highly mission-oriented and is keyed to the specific Apollo mission. The program includes work in simulated materials and terrain mock-ups. Actual experimental procedures are rehearsed in shirt-sleeve as well as pressure-suit environments. When possible, the principal investigators work with the astronauts to resolve difficulties in executing geologic experiments (Conrad, 1969). This phase could provide the interface with training for explosives applications.

Rock reaction mechanics are not currently emphasized in the program of instruction. The transition discipline of geological engineering would provide the best source material. However, the information would require minor expansion of the present course of instruction to provide the background necessary for explosives employment.

Continuation of this course of geologic instruction is dependent upon the requirement to train astronauts who do not have an adequate background in geology. It is necessary that astronauts selected for missions requiring the employment of explosives have a background equivalent, by training or experience, to this current course of instruction.

6.2.2 Additional Prerequisites

Additional prerequisites must be based on the skill levels required and the feasibility of acquiring the requisite knowledge after astronaut selection.

For Phase I, the tasks are primarily checklist operations with no requirement for skills beyond those developed in normal mission training. The task requiring the most intensive training, if the astronaut had no prior experience, is drilling. If novel drilling equipment and techniques are developed, prior experience might be of limited benefit. In any event, the skills can be gained after astronaut selection; therefore, it is not required that he have any prior drilling experience.

For Phase II applications, explosives emplacement becomes the dominant task. With the sequential events allowing earth-bound principal investigators to monitor and to direct the operation, the requirement for explosives training falls within the category of skills that can be taught subsequent to astronaut selection. Certain preselection backgrounds are desirable to facilitate training and to reduce mission dependence on the long distance communications system. Desirable backgrounds include geologists (geophysicists) who have been directly involved with explosives use in seismic work, mining, or excavation, military engineers who have worked with a variety of explosives types in construction or demolition operations, or military pilots who have worked with explosive ordnance items.

Phase III poses an entirely different problem. As the lunar effort passes from experimental to developmental and operational, the scope of activity will increase substantially. While a lunar construction project will be based on the idea the division of labor (U.S. Army, 1959; LaPatra, 1968; Vail, 1968), the end result is not simply that of task specialization. The division of labor in developmental projects cannot guarantee that tasks performed by a worker will effectively relate to the tasks performed by other workers (Wolek, 1970). Developmental activities are based in part on new technology which has a sufficient degree of uncertainty associated with it that task relationships cannot be assumed to be constant throughout the construction period. Certainly trade-offs between conventional earth-moving and explosive excavation should be anticipated. Therefore, while much of the work will be specialized and assigned to appropriately trained lunar workers, effort will be required to integrate the work performed in the specialties and to review and to modify the relationships as necessary. The integration of effort demands not only analysis and task definition but also requires an understanding of the entire scope of required activities.

It is not feasible to train an astronaut to function as the lunar construction project manager. The basic managerial and construction-related skills must already be mastered by the selectee, although limited training on specifically developed concepts and equipment would be in order for him subsequent to selection and prior to deployment.

The rest of the skills involved in Phase III could be taught to basic astronauts. Prior experience would be helpful but not necessary. With the advent of more routine lunar travel, it might be possible to reduce the requirement for the generalist astronaut (pilot-engineer-scientist) and to allow technicians to travel as passengers (Imgram, 1969; Leany, 1969). In the event it would be possible to recruit the specialists required based on their technical expertise with the additional requirement that they be physically and emotionally capable of performing in the lunar environment. For this circumstance, training would provide the transition between conventional skills and those required for the lunar concept involved. Cross training would also be applicable.

Although the above analysis is for construction operations, the scope and difficulty of mining or other resource development operations would require comparable managerial and mining skills that would not be amenable to post-selection training.

6.2.3 Background Summary

The background requirements for trainees selected to implement lunar explosives applications vary for the three phases of employment.

Phase I concepts require:

(1) Excellent physical condition to meet the physical demands of deploying the experiments on the lunar surface.

(2) An intelligent, resourceful mind to absorb the training for explosives employment and to apply it to the problems that might arise.

(3) Emotional stability to handle explosives safely and effectively under psychological and physiological stress.

(4) Geological training to aid in selecting sites for experimental deployment.

Phase II requirements, in addition to those above, include:

(1) A degree in engineering or science (preferably engineering) to provide a frame of reference for training and operations.

(2) Geological training or experience to relate explosives emplacement methods and explosion effects to lunar material characteristics and to site selection criteria.

Phase III adds the requirement that the construction or mining supervisor has previously demonstrated an ability to manage projects of similar scope and difficulty. A technician may not be required to have the generalized astronaut's high skill levels, but may be expected to have significant experience in his own technical field.

6.3 TRAINING PROGRAM

Since explosives selection, lunar material response, emplacement techniques, and firing schemes — i.e., a lunar explosive excavation technology — have yet to be determined, a training program suggested now can provide only a general view of the instruction required to prepare future space crews to perform lunar explosive excavation projects.

Training for Phase I activities should be dependent upon the physical design of the hardware involved but would come generally under the headings of safety, handling, and storage. Training would probably consist of briefings from the principal investigator and equipment fabricator, simulation sessions, and full-scale crew drill.

Phase III applications will be based in part on the results of Phase II experimental and developmental studies and lunar investigations; however, the explosives aspects would be similar to those of Phase II surface modification investigations. Therefore, the training program discussed will generally apply to the Phase II applications.

Training must provide the skills necessary to perform lunar explosive excavation activities. In addition to explosives training, considerations for training in materials handling equipment operations are included in this section. The methods of instruction should include classroom presentations and briefings, practical exercises (possibly including seismic surveys in conjunction with geologic field trips), simulation sessions, and full-scale crew drill.

Existing training material and lesson reference files for instruction in explosives applications and demolitions were examined and compared with the task discussions of section 6.2 to determine the scope and duration of training required.

An estimated minimum of four weeks of instruction based on training for conventional explosives applications should be required to teach explosives; safety, handling, and storage; emplacement designs and techniques; and misfire procedures. Additional time may be required to gain the needed proficiency in hole drilling if the system developed differs markedly from conventional drill rigs. An estimated minimum of eight weeks of training should be required for the worker-astronaut to gain an operational capability with an item of materials handling equipment. This estimate is based on training for conventional earthmoving equipment operation. A suggested training program is outlined in Appendix E.

As with current astronaut training (Strickland, 1969), the duration and scope of training may be modified as required during the instructional period to accommodate the individual trainees. Small class size provides a high instructor-to-student ratio and allows for a dynamic instructional atmosphere, where the instructor is an integral part of the process and has the capability to select more than one avenue of approach to a difficulty. In addition, the astronaut is capable of making subjective decisions as to the degree of proficiency attained; the nature of the missions involved provides the motivation necessary for a critical self analysis.

6.3.1 Explosives

Whereas the chemistry and physics of explosion phenomena are scientific studies, the use of explosives in commercial borehole blasting is largely an art that is constantly developing and is generally in the unpublished domain of the commercial explosives industry and commercial users.

A detailed study of explosives is applicable to the scientists, engineers, and technicians who will develop the explosives necessary for lunar applications but not necessary for the worker-astronaut. Ideally, the astronaut would participate in the explosives development process; however, with the many competing demands on the astronaut's time, such participation would not be mandatory. Nonetheless, grounding in explosives theory is necessary both to supply background in safety, handling, and storage requirements and to enable him to anticipate explosion effects as an aid in the modification of emplacement design.

Fundamental to any use of explosives is a firm understanding of safety, handling, and storage criteria. Although much benefit can be gained from familiarization with the hazards of explosives by memorizing a list of "Do's and Don'ts," such as the one developed by Dupont (1966) and adopted by the Institute of Makers of Explosives, a real understanding can come only from a grounding in explosives theory and characteristics.

Although emplacement design and blasting criteria are largely empirical and based on experience factors of mining engineers and explosives technicians, such criteria are predicted on the basis of explosives properties and media characteristics. Even experienced explosives technicians must rely on explosives theory in selecting initial emplacement designs and detonation schemes when working with unfamiliar media or using a new explosive.

Training in explosives theory and characteristics should be largely classroom work with lectures predominating, although films and, to a lesser extent, live demonstrations should also be used. After an introduction to the uses for explosives, the course work should continue with study of explosion phenomena including a description of detonation, the concept of critical explosive diameter, and nonideal detonation and deflagration. Lectures should be supplemented with film presentations on explosives sensitivity testing, the mechanics of detonation, and the mechanics of rock reaction.

Although the explosive for a given lunar application may have already been selected prior to the initiation of explosive training, the need for detonators, primers, and boosters requires that the worker be familiar with various types of explosives and their characteristics. Course work would include commonly employed explosives as well as, perhaps, the more exotic forms that may be developed for lunar use. The worker should be familiar with explosives characteristics including detonation velocity and pressure, total energy, density, and shock and bubble energy, the physical characteristics influencing safety, handling, and storage such as impact sensitivity, thermal, and vacuum stability, and the manufactured form or physical state.

An important segment of explosives instruction should involve the interaction between the confining media and the detonating explosive. The transition between the theory and the characteristics of explosives and emplacement design is the mechanics of rock breakage by explosive charges. At this point, the instruction should include the concept of matching the acoustic or detonation impedance of the explosive with the acoustic impedance of the confining media to enhance transmission of shock energy to the media. The worker-astronaut should become familiar with the various mechanisms of rock reaction mechanics such as initial crushing, spall from the reflected tensile wave, and displacement from the pressure of the expanding gas bubble.

The principles of shaped charges or lined-cavity charges should be presented. Emphasis would depend on the role that such devices might have in lunar missions. Material on characteristics, mechanisms involved, and emplacement criteria would be presented as one block of instruction because of the specialized nature of the devices.

The level of presentation and quantity of instruction involved with explosive theory and characteristics would be dependent upon the mission requirements. Instruction for Phase I utilizations would be minimal, due to the prepackaged nature of the explosives and the marginal requirement for understanding explosion effects. Although many sources of information on explosives exist, the material for use in this training would be extracted and tailored for the concepts involved.

Lectures should be supplemented with film presentations on explosives sensitivity testing, the mechanics of explosive detonation, and the mechanics of rock reaction.

6.3.2 Safety, Handling, and Storage

The hazards of an explosion to a pressure-suited man on a lunar mission are greater than to a worker in the earth's atmosphere because of the vulnerability of the life support system and the spacecraft itself to explosive effects. The vulnerability, coupled with the condition of a confined area in the spacecraft during transit and an increased missile range while on the lunar surface, make the value of adequate safety precautions, proper handling, and adequate storage apparent.

A safety program should be presented at an early period in the training cycle to enable the worker-astronaut to gain first-hand knowledge in the handling and use of explosives. For explosives developed and packaged for use in a lunar environment, special procedures must be formulated and presented. Most of the material should be based on the explosive system selected for a given mission. Procedures are to be established and presented for the contingencies of impact or thermal damage to the explosive package. The range of missiles from a lunar blast must be determined, and an explosive quantity versus safe distance requirement for worker and equipment safety must be prepared. The development and use of blasting mats or screens to provide worker and equipment safety should be considered.

Training for explosive safety should include demonstrations as well as lectures and films. Emphasis should be placed on practical exercises, simulations, and crew drill in the proposed concept. Safety, handling, and storage training should be presented both as a separate subject as well as integrated in all other training for explosives utilization. The topics of safety and handling during emplacement and in case of misfires must be covered in the appropriate block of instruction.

6.3.3 Emplacement Designs and Techniques

The formulation of an explosive that can be subjected to earth-lunar transport, stored on the lunar surface, easily handled by the worker-astronaut, and detonated by the desired firing method is only part of the development necessary for the utilization of chemical explosives for lunar use. Selection of emplacement design and physical emplacement of the explosive in such a manner as to obtain the most work from the available explosive energy are features that may require the greatest degree of worker-astronaut judgment. Even though the emplacement design will be largely determined prior to launch, information from drill cuttings or cores and other geologic evidence may indicate the need for on-site modifications to the design. It is not anticipated that the worker-astronaut will be required to perform design calculations; however, an understanding of the design process would be valuable in providing data upon which design modification could be made by earth-based principal investigators.

The worker-astronaut should be able to relate energy yield and depth of burst for a given rock type to crater dimensions such as crater radius, crater depth, lip height, lip crest distance, and distance to the outer edge of the ejecta. For row cratering, the effect of charge spacing parameters would be presented. The effects of inhomogeneity of the lunar material, layering, jointing, and seams would be discussed. The use of shaped and gauging (clean out) charges is a possibility. Their use would be a straightforward application of explosive devices and would be covered in the training period on explosives. The method of instruction would be lectures supplemented with films of modeling studies performed in conjunction with the development of explosive characteristics in the lunar environment.

The most likely technique of charge emplacement construction appears to be a form of conventional hole drilling. Early experiments will probably use drillholes created by a rig similar to that shown in Fig. 85. Training in the use of a device of this type would include operational theory and required maintenance as well as on-the-job training. The use of simulation techniques could be valuable in developing the required degree of skill. Operating this type of machinery in close proximity to a pressure suit can be hazardous. Underwater training should provide the closest parallel to lunar use because a pressure suit and lunar gravity environment could be easily simulated (Clarke, 1968). Also, use of the mobile partial-gravity simulator (Hammersly, 1970) shown in Fig. 86 could provide appropriate responses. The partial-gravity simulator has the advantage of being transportable to locations of simulated lunar terrain and materials. Lectures and, as possible, practical work would cover the problems associated with vertical, horizontal, and inclined drilling as well as the effect of fractures, joints, layers, and seams on drilling.

The emplacement of explosives for construction and for Phase III exploitations will require greater drilling depths than can be easily accomplished by a hand-held drill. The use of vehicle mounted drills will follow the same general training scheme as for hand-held drills except that stability will be greater and intimate contact with moving parts should be substantially reduced.

The requirement for hole springing for construction and other cratering type operations will depend on hole size, acceptable charge length-to-diameter (L/D) ratios, and explosives characteristics. Training in hole springing would include the amount of charge required, sub-drilling requirements, and measurement of the sprung cavity volume.

The physical emplacement of the explosive may be as simple as lowering a completely prepackaged explosive into the borehole. At the other end of the complexity scale would be the use of explosives that must be mixed near or in the borehole just before emplacement. The use of volatile components such as liquid oxygen places additional requirements on timing, stemming, and firing design. The method of physical placement of a charge in the hole is highly dependent on the explosive; therefore, the training should be tailored to the explosive actually selected for the mission. Training would be largely practical in nature with simulated materials and equipment.

Arming, initiating, and boosting the explosive should be taught based on the systems developed for lunar applications. Prime considerations for these systems are reliability and safety. Extreme care is required in the design of the firing system to insure that accidental or premature firing is precluded. If the emplacement designs require the use of firing systems, the instruction should include the use of delay caps and associated circuitry. It is not anticipated that the operation of the firing system would require detailed or complex efforts. All that should be required of the worker-astronaut is an understanding of the operation of system components, the

Fig. 85. Apollo lunar surface drill (courtesy of Martin Marietta Corporation).

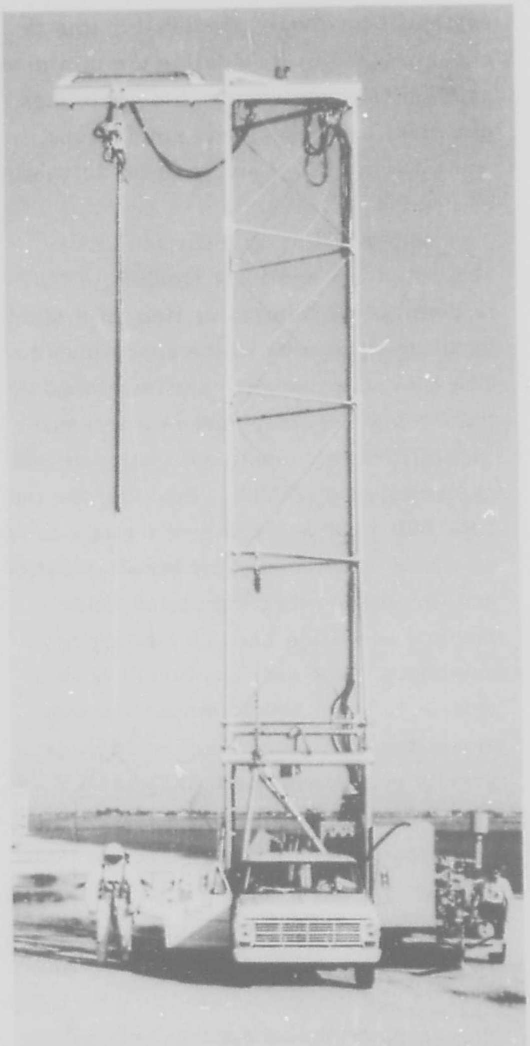


Fig. 86. Mobile partial-gravity simulator (truck permits training at various walking speeds).

ability to use safe handling procedures and the ability to follow a checklist of operational instructions.

6.3.4 Misfires

The explosive and firing system will be designed for reliability in the lunar environment; however, with any real system there exists the possibility of failure. Misfires can range from apparent failure to initiate the main explosive charge to a less-than-expected explosive yield. Immediate action exercises to include retransmission of the fire command and the checking of the electrical circuitry should be included in the training program. All decisions other than for immediate corrective actions would come from earth control. Training could also include methods of stemming removal, placement of supplemental boosters, and use of supplemental firing systems.

Procedures for disposing of explosives that are partially consumed by fire or detonation should be presented; however, no disposal action would be initiated without release by earth control. Simulation techniques similar to those used in space mission training would aid in providing practice in handling a wide variety of contingencies. Training for the possibility of misfires must emphasize safety.

6.3.5 Materials Handling Equipment

Several tasks associated with the use of chemical high explosives on the moon may be made easier by, or require the use of, materials handling equipment. Although many of the initial explosives applications will probably be limited to small size charges, later efforts in construction and mining may require charge weights in thousands of kilograms. Tasks for which mechanical assistance may be of benefit include off-loading explosives and equipment from the lunar landing vehicle, transportation to storage sites, transportion to firing sites, and physical emplacement of the explosives. Some possible equipment configurations include crane, forklift, and scoop loader. Training should provide operating skills including mass distribution and load capabilities on anticipated lunar terrain.

Many applications will require the movement of the explosively disturbed material in supplemental excavation, or backfill operations. Some of the possible means to accomplish these tasks include the use of a bulldozer, sccop loader, backhoe, slusher (dragline), or the inefficient use of the worker-astronaut for pick-and-shovel work. Training should include the anticipated characteristics of the lunar material, in situ and disturbed, as well as the operating characteristics and response of the machine developed for lunar use. A task of considerable magnitude is the handling of the temporary lunar shelter in Phase II, or components for a lunar base or mining activity in Phase III. Training could include moving a mock-up assembly over simulated lunar terrain.

A possible training scheme would provide operational training on similar conventional earthmoving and materials handling equipment and transition training on the equipment developed for lunar use. This scheme has advantage when the developmental item of equipment may not be complete until shortly before mission deployment.

As with current astronaut training programs, training should be formulated to provide a grasp of the fundamentals and skills required followed by periods when the materials, equipment, and instructors would be available to develop the requisite skill level. Quite often the attainment of the requisite skill is a subjective evaluation on the part of the astronaut involved. Generally, this is accomplished by scheduling the minimum number of hours required for briefings, practical exercises, and simulations, and allowing individual training to continue as needed.

The Lunar Roving Vehicle (LRV) scheduled for Apollo 16 (Kudish, 1970) is the nearest thing to an item of materials handling equipment in the space inventory. The LRV was designed and developed by the Boeing Company based on astronaut capabilities and functional requirements as furnished by NASA. Training for the LRV will include the use of a static mock-up which is primarily for familiarization and for use in other simulated lunar surface activities such as loading and unloading. The astronauts will have a chance to learn how to mount and dismount the LRV under simulated lunar gravity conditions during KC-135 1/6 "g" simulation flights. Using a 1-g version, the astronauts will use the LRV in conjunction with two-day geologic field trips. Six or seven trips are anticipated; however, the training program is extremely flexible and is expected to conform to the rate at which the astronauts master the LRV operation. This training formulation method with rate of progress feedback is characteristic of the astronaut training program and should be considered for inclusion in training for operation of materials handling equipment as well as explosives operations.

All training methods discussed above are characteristic of the astronaut training program. They should be included in the training program both for explosives operations and for materials handling equipment operations.

6.4 DEPARTMENT OF THE ARMY TRAINING SUPPORT

The United States Army does not have a course of instruction in its inventory to provide training specifically for lunar explosives employment, but it does have significant capabilities to adapt current training programs to meet the requirement.

The Department of the Army operates one of the most extensive training systems in existence, not only in terms of the number of students, but also in the variety of course material presented. Training is provided in formal courses of resident instruction, correspondence courses, or on-the-job training.

The bulk of the training is provided by resident instruction at either a branch school, such as the Engineer School at Fort Belvoir, Virginia, or at an Army Training Center which provides basic and advanced individual training. Both the branch schools and the Army Training Centers come under the jurisdiction of the United States Continental Army Command (USCONARC) with headquarters at Fort Monroe, Virginia. The branch schools provide resident instruction to over 370,000 men per year; the Army Training Centers, over 200,000 men per year.

In almost all cases skills learned are enhanced by on-the-job training (OJT) programs; in some cases OJT programs constitute the entire training program. On-the-job training is extensively used by Department of the Army activities for both military and civilian personnel involved in experimental or developmental programs. These OJT programs may be totally informal, with the individual trainee's supervisor responsible for the rate of exposure to new material or situations and for the degree of proficiency required and attained.

6.4.1 Explosives Training Capability

The Department of the Army has several facilities that provide some manner of explosives training. The one that provides instruction most nearly correlating with the training required for lunar uses of chemical high explosives is the Army Training Center, Engineer, Fort Leonard Wood, Missouri. Advanced individual training is also given there to selected enlisted personnel in construction equipment operations.

The course which includes explosive handling and emplacement is that for Powderman. This four-week course includes primary blast hole drilling with crawler-mounted, wheel-mounted, and hand-held percussion drills, geology of pits and quarries, characteristics of quarry explosives, blasting calculations, placement of charges and drilling records, and safety. It is geared to military quarry operations; however, the tasks required in quarrying parallel those required for lunar operation, and such a course could be used as the basis for one covering lunar explosives employment. Facilities are available for classroom work, demonstrations, and practical training on equipment and explosives. Well qualified, experienced instructors are available; the current instructor-to-student ratio is 1:5 for practical applications which range from charges of 500 g in explosive demolition training to 500 kg for quarry training.

An alternate or supplemental source of formal instruction in explosives is the

U.S. Army Missile and Munitions Center and School, Redstone Arsenal, Huntsville, Alabama. Although the eight-week Guided Missile Propellant and Explosives Course is intended to provide a working knowledge of inspection and maintenance operations for rocket and guided missile propellant and explosive items, a considerable portion of the course work concerns safety, handling, and storage of explosives. Instruction also includes the preparation and the use of electric and nonelectric priming and boosting charges for demolition of propellants and explosives. Proximity of this facility to NASA's Marshall Spaceflight Center, also at Huntsville, might offer some advantages for instruction in Phase I explosives applications which do not involve subsurface emplacement.

In addition to the formal schools program, several Department of the Army activities conduct OJT in explosives handling and use. Noteworthy is Picatinny Arsenal, near Dover, New Jersey, which is responsible for the research, development, engineering, procurement, quality control, and other services for conventional munitions including mortar ammunition, demolition devices, boosters, propellants, and explosives. The arsenal uses a generally informal OJT program to provide or upgrade the required skills for explosives handling, although the safety program is becoming a formal portion of employee instruction. In conjunction with its responsibilities, the arsenal has excellent facilities for explosives development and testing.

Another agency which provides its own OJT is the Harry Diamond Ordnance Fuse Laboratory in Washington, D.C. The laboratory has its own explosive test facility as well as access to Aberdeen Proving Ground in Maryland. Diamond Laboratory specializes in fusing and firing systems design. Both Diamond Laboratory and Picatinny Arsenal have a wealth of personnel who are experts in explosive systems and techniques.

6.4.2 Explosive Excavation Technology

Explosives applications under consideration are based on relatively large-yield chemical high-explosive cratering charges. The state-of-the-art in explosive cratering or excavation is being developed by the U.S. Army Engineer Nuclear Cratering Group (NCG) located at Livermore, California.

A part of the mission of NCG is to manage and to conduct research in the development of effective and economical techniques of employing large-yield chemical high explosives on civil works construction projects or in support of the engineering requirements of the U.S. Army. NCG also provides technical advice and assistance concerning the use of large-yield chemical explosives to other elements of the Corps of Engineers, government agencies, and other organizations, as directed.

A major portion of NCG's research effort involves small-scale modeling and full-scale chemical high explosive experiments with the purpose of advancing the explosive excavation technology. The experiments may serve a variety of purposes including testing explosive excavation theory, testing emplacement designs, comparing the effectiveness of different kinds of explosives, or providing data with which the performance of explosives in various materials and applications may be predicted.

This active role in explosive excavation technology provides the basis for NCG participation in the formulation of training for lunar explosives selection and emplacement design. Briefing material could be supplemented with demonstrations of various crater configurations at the NCG Explosive Excavation Test Facility, Site 300, Tracy, California.

6.4.3 Related Skills

Some of the Phase II applications and all of the Phase III applications will involve materials handling equipment or earthmoving equipment. The advanced individual training instruction at Fort Leonard Wood offers a variety of engineer equipment operators courses including crawler tractor operator, rough terrain forklift and loader operator, crane-shovel operator, wheeled tractor/scraper operator, grader operator, and general construction machine operator. Each course is approximately eight weeks long with course work including operating principles, capabilities, and limitations of the equipment and attachments. Considerable time is allocated to practical work in equipment operation and maintenance. Mechanical skills learned at these courses could have value in training on specific lunar oriented equipment.

Phase III applications may require additional supporting skills for construction and mining operations. Courses for welders, machinists, and blacksmiths which could provide needed metal-working skills are offered by the U.S. Army Ordnance School, Aberdeen Proving Ground, Maryland. Courses in power production equipment operation and maintenance, utilities functions, and nuclear power production are offered by the U.S. Army Engineer School, Fort Belvoir, Virginia. In addition, the Engineer School teaches courses in utilities, explosives and demolitons, quarrying, and earthmoving equipment operation and management for supervisory level students as part of career development programs.

Chapter 7

Future Research

In striving to establish a lunar explosive excavation technology, this study has identified many areas in which further research is needed. These areas must be satisfactorily explored before explosive excavation techniques can be used in lunar operations. Most of the needed research can be conducted on earth and much of it is within existing or slightly expanded capabilities of Department of the Army research agencies.

This chapter recommends research topics and assesses the capabilities of selected DA agencies to perform the associated research tasks.

7.1 TOPICS FOR RESEARCH

There are several areas which must be explored in depth to define a lunar explosive technology. This preliminary study has exposed the topical areas requiring further research and development. Some research may be more appropriately conducted on earth, while other information may be developed only on the moon. It should be noted that the necessary research and testing of ideas, materials, and equipment may, in some instances, have to be done both on earth and on the moon to verify terrestrial results and predictive schemes. Early generation lunar explosive excavation projects will be sources of information, and designs for later projects should have provisions for incorporating new discoveries.

7.1.1 Lunar Materials Characteristics

To construct an accurate model of the lunar crust and subsurface conditions, detailed lunar topographic, geologic, and selenophysical data are required. Good topographic information describing and locating land forms is necessary to formulate typical conditions to be anticipated in lunar explosive excavation projects.

Geologic information is most important. Facts such as material types, distribution, fracture patterns, grain and particle size distribution, and material properties including compressive and shear strength, internal friction angle, static and dynamic stability of both constructed and natural slopes under loaded and unloaded conditions, and particle cohesion and adhesion characteristics must be determined in sufficient detail to permit synthesis of an accurate terrestrial model of the lunar crust.

Seismic information must be available in sufficient detail to permit reliable determination of explosive energy coupling and seismic effects range.

7.1.2 Explosives

Some lunar explosive formulations have been suggested in this report to meet the postulated characteristics requirements. A thorough research program is in order to examine the characteristics of these suggested formulations and to determine whether others of greater energy density and safe handling characteristics can be synthesized. Once a lunar resources inventory is established, efforts should be made to determine whether explosives of some type might be manufactured on the moon. Such explosives would not have to meet the stringent requirements now necessary from space transport considerations.

All potential explosives will have to be tested both in the laboratory and in the field for physical, detonation, and cratering characteristics, particularly under conditions of temperature and pressure simulating those existing on the moon. Explosive devices, such as shaped charges and high velocity penetrators, should be included in this research.

7.1.3 Effects

The direct and side effects of an explosion in lunar physical and geologic conditions will have to be predicted and verified by tests on earth and on the moon. It is essential that one-sixth scale and full-scale modeling of lunar explosion craters be conducted to determine the exact size and shape of both the true and apparent crater forms. It is necessary that this information be determined for both single-and multiple-charge detonations in both homogeneous and layered media. It is important that the influence of depth of burst and charge geometry on crater formation be verified to determine optimum cratering depth and containment depth. Degree, extent, and orientation of fracturing in materials surrounding the true crater should be investigated. The springing techniques, both hole springing and linear springing, should be investigated and developed, if possible, to reduce the emplacement hole equipment requirements.

With regard to side effects, this program should include a careful study of energy coupling, and propagation, levels of magnitude, and range of ground motion as a function of explosive energy release. The effects of seismic signals on lunar geologic and man-made structures are most important to insure safe construction operations.

To predict and to verify predictions of the blast effect created by the expansion of explosion gases into the low pressure lunar environment, studies should be made under vacuum conditions. It appears that relatively easily attainable vacuums of about 30 mm of mercury will suffice to simulate blast effects under lunar conditions.

The third major side effect of lunar subsurface explosions is that of missile, or ejecta, throwout. It is essential that accurate schemes be developed to predict the range, pattern, and particle size distribution of debris thrown from the site of a subsurface explosion. The influence of the range-increasing factors, reduced atmospheric friction and reduced gravity, must be carefully assessed. For terrestrial modeling purposes, this requires determination of mound velocity, particle size distribution in the mound, and angle of departure and speed of particles at the time of mound breakup.

7.1.4 Equipment

The severe mass and bulk penalties represented by existing types of construction equipment make necessary the development of efficient, lightweight machinery for use in lunar projects. It is necessary that rigs capable of drilling emplacement holes of appropriate size and depth be developed early in any research program, because they will strongly influence the final criteria established for explosives development. A relatively small hole size capability will dictate rather high explosive energy-density requirements. Regardless of capabilities, drill development will have to address methods of cooling drill bits, obtaining reasonable penetration rates, decreasing wear rates, removing cuttings from drillholes, lubricating equipment, and supplying the necessary operating energy. These must be achieved within the basic constraints of a simple, reliable machine. Advanced concepts such as solar and laser drills should be investigated.

Appropriate methods of emplacing explosives should be developed. Equipment and techniques must be designed for emplacing prepackaged, pourable, and pumpable forms of explosives. It may also be necessary to develop a method of sealing the emplacement cavity to protect the emplaced explosive from lunar environmental conditions.

7.1.5 Engineering

The results of effects research will form the basis for establishing lunar explosive excavation technology. A proper mix of explosives, equipment, and operating techniques should be designed to accomplish the desired result once effects have been reasonably well-established. Engineering considerations will have some influence on the direction in which other research areas proceed. Development of the clustered emplacement hole concept is an example of the way in which individually restricted operations might be combined to produce a desired result. The explosive density, drillhole size, and charge L/D restrictions may be overcome by that technique.

Multiple-charge detonations of various configurations, as rows and arrays, with simultaneous and delayed pattern ignition systems should be investigated, as, perhaps, should a system of multi-level arrays, detonated with delays between levels for obtaining deeper excavations.

It is important that different approaches be developed as additional types of applications are identified.

7.1.6 Management

The many-faceted program of research and development suggested above will require coordination for efficient development of a lunar explosive excavation technology.

7.2 RESEARCH CAPABILITY OF THE DEPARTMENT OF THE ARMY

The Department of the Army has agencies conducting research in many disciplines. The capabilities of a number of these agencies were reviewed with respect to research in the topical areas outlined above. The agencies and those areas in which they might contribute to the research effort necessary to develop a lunar explosive excavation technology are listed in Table 29.

Table 29. Requirements for lunar explosive excavation technology research.

Topic	Agency[a]									
	ATC	BRL	FRL	HDL	MERDC	CERL	CRREL	NCG	TOPO	WES
Lunar Materials Characteristics										
Topography									x	
Geology					x	x	x	x		x
Selenophysical						x				x
Explosives										
Formulation			x					x		
Lab testing			x							
Energy determination (underwater test)								x		x
Field cratering tests					x			x		x
Shaped charge design		x			x			x		
Shaped charge testing		x			x			x		
High velocity penetrator design		x	x		x			x		
High velocity penetrator testing		x			x			x		
Effects										
Crater geometry (modeling)					x	x		x		x
Charge geometry					x	x		x		x
Depth of burst					x	x		x		x
Blast fracturing					x	x		x		x
Springing					x	x		x		x
Seismic					x	x	x	x		x
Blast		x						x		x
Missile (ejecta) range		x			x			x		x
Missile (ejecta) impact probabilities		x			x			x		x
Equipment										
Mechanical drill design	x				x					x
Mechanical drill testing	x				x			x		x
Solar drill design and testing		x	x	x	x			x		x
Laser drill design			x		x			x		x
Explosives emplacement					x			x		x
Construction equipment	x				x					
Firing systems			x	x				x		
Engineering								x		x
Research Program Management								x		x

[a]ATC - USA Automotive and Tank Center, Detroit, Michigan
BRL - USA Ballistics Research Laboratory, Aberdeen Proving Ground, Maryland
FRL - Feltman Research Laboratory, Picatinny Arsenal, Dover, New Jersey
HDL - Harry Diamond Laboratories, Washington, D.C.
MERDC - Mobility and Equipment Research and Development Command, Ft. Belvoir, Virginia
CERL - USA Engineer Construction Engineering Research Laboratory, Urbana, Illinois
CRREL - USA Engineer Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire
NCG - USA Engineer Nuclear Cratering Group, Livermore, California
TOPO - USA Engineer Topographic Laboratory, Silver Springs, Maryland
WES - USA Engineer Waterways Experiment Station, Vicksburg, Mississippi

Chapter 8

Findings

This preliminary study has examined a number of areas associated with the use of chemical high explosives to assist in engineering support of lunar scientific investigations and lunar base construction. The findings of the study are given in the following paragraphs.

Chemical high-explosive excavation techniques show considerable promise for early generation lunar base excavation requirements at a time when mass and bulk payload restrictions will be very stringent. The recent experience of crew exhaustion while Cone crater was being explored during the Apollo 14 mission points up the necessity for minimizing the requirement for human effort in lunar activities. Explosives offer compact sources of energy that can reduce the effort required to perform excavation tasks. Excavation for emplacement of a temporary shelter, one of the first types of construction support likely to occur, could be accomplished by means of an explosively produced row crater, the shelter emplaced, and protective cover backfilled within a two-week lunar daylight period. A single cratering charge would provide the excavation needed to emplace a nuclear reactor and the broken material needed to provide the reactor shielding to protect lunar base personnel from the radiation emitted by the reactor. Emplacing the reactor by this method would take about five (earth) days plus the time needed to assemble and check out the associated power generation equipment. For later generation bases of a more permanent nature, contained explosions might produce underground cavities that can be used as the basis for fluid storage chambers. Explosive excavation of this type would avoid the need for excavating to emplace a tank fabricated on earth and shipped to the moon. The cavity could be sealed, insulated, and readied for use with much less effort and equipment.

Lunar natural resources could be exploited with the aid of large charges, thereby avoiding the repetitive drill and shoot cycles commonly used on earth that are so costly in both time and effort. Overburden might be removed from shallow ore beds by the detonation of an array of explosives. The exposed ore could be subsequently exploited by surface mining techniques in which rock materials or lunar ore beds would be fractured by mounding detonations to facilitate removal. Deeply buried ore concentrations could be shattered by large, single-charge explosions in a variation of the mining method of block caving, although this technique will require development on earth. Once the broken ore has been removed, the remaining chimney-like excavations might be used as the basis for underground living or working facilities. Other underground mining operations, as shafting and tunneling, will rely heavily on modified terrestrial subsurface mining techniques of cyclic drilling, shooting, and mucking.

The use of explosives in conjunction with seismic surveying projects is already planned in the Apollo program. The results of those investigations will materially aid in verifying the assumption that terrestrial techniques can be used to predict ground motion levels on the moon; later explosive excavation detonations can be used to extend knowledge of the lunar subsurface through seismic surveying methods.

Some differences in effects of subsurface explosions will occur in lunar detonations in comparison with terrestrial experience. The smaller lunar gravitational acceleration and the almost nonexistent atmosphere will permit materials to be thrown six or more times farther on the moon than on earth. Thus, the range and scatter of missiles (ejecta) is greater, but fallback into an explosively produced crater will be significantly less, such that the volume of the lunar apparent crater will approach that of the true crater, within about 10% at optimum depth of burst. To reduce the associated safety hazards, charges could be detonated at a depth greater than optimum with little loss in cratering efficiency. The blast effect of explosion gases expanding into the rarefied lunar atmosphere cannot be propagated long distances from the point of detonation; blast overpressures decay inversely with the range cubed and are reduced much more quickly than those generated by a similar terrestrial explosion. Blast represents no special hazard. Little is known regarding seismic signal propagation on the moon; consequently, it is assumed that terrestrial predictive techniques can be used to provide a first approximation to ground motion levels resulting from identical explosions in materials of identical properties on earth and on the moon.

Because of the time and expense involved in lunar experimentation, proposed lunar explosive excavation projects should first be modeled on earth. Modeling can be done at either of two different scales. All important similarity requirements, including gravity, are satisfied by a terrestrial model at one-sixth length scale. A charge, 1/216 the mass of the planned lunar charge, of the same explosive should be used. The modeling detonations should be carried out in an evacuated chamber at pressures of 30 to 40 mm of mercury to avoid the influence of atmospheric friction. Full-scale modeling can also be used and will accurately reproduce lunar true craters; lunar apparent crater dimensions can then be determined by adjusting the terrestrial fallback volume to account for the differences in gravity. Modeling at either scale requires a faithful terrestrial analog of the geological medium at the planned lunar project site.

Lunar chemical high explosives will require these characteristics: (1) high reliability and safety, (2) low impact and vibration sensitivity with high thermal stability, (3) ease of emplacement, (4) high energy release per unit mass, (5) high density, (6) low overall and constituent vapor pressures, and (7) detonation pressure between 80 and 150 kbar. Some existing explosives may meet the requirements with little modification, but a high energy-density explosive consisting of aluminum and liquid oxygen would be most attractive as a lunar explosive, if it can be developed. Development of other than mechanical excavation techniques for charge emplacement and hole and chamber construction is desirable. Shaped charges may be developed to meet this need.

Current NASA astronaut selection qualifications are considered to be adequate background for the explosives training a space crew member would perform on an explosive excavation project on the moon. The necessary explosive excavation training support is within the capability of the Department of the Army. The recommended five-week training program consists of 26 hr of instruction and field work on explosives; 8 hr on safety, handling, and storage; 18 hr of instruction and 4 hr of field work on emplacement design; and 48 hr of instruction with 72 hr of field work on the various types of equipment associated with an explosive excavation project. This training program should be augmented with geological training by the United States Geological Survey, as is current NASA practice.

Areas in which additional research is needed to refine the findings of this study are listed in Chapter 7. The ability to conduct that research appears to be within the existing capability of Department of the Army research agencies. Determination of the specific requirements for future research is beyond the scope of this study.

References

Agrell, S. O. et al., 1970, "Mineralogy and Petrology of Some Lunar Samples," Science 167, 583 (1970).

Aldrin, E. E., N. A. Armstrong, and M. Collins, 1969, Crew Observations, NASA, Washington, D.C., SP-214, 1969, pp. 35-39.

Americana, 1968, "Astronauts," in Encyclopedia Americana (Americana Corporation, New York, 1968), pp. 562-569.

Arnold, J. et al., 1970, "Summary of Apollo 11 Lunar Science Conference," Science 167, 449 (1970).

Caudle, K. F., J. A. Goertner, and N. O. Holland, 1965, Explosives—Effects and Properties, U.S. Naval Ordnance Laboratory, Silver Spring, Md., NOLTR 65-218 (unclassified excerpts), 1965.

Cauthern, L. J., Jr., 1964, "The Effects of Seismic Waves on Structures and Other Facilities," in Proceedings of the Third Plowshare Symposium (U.S. Atomic Energy Commission, Oak Ridge, Tenn., 1964).

Choate, J. S. et al., 1969, "A Manned Lunar Mission for Water Exploration in the Marius Hills," in Proceedings of the Seventh Annual Working Group on Extra-terrestrial Resources, June 17-18, 1969, NASA, Washington, D.C., SP-229, pp. 75-86.

Clarke, M. F., 1968, "Underwater Simulation of a Lunar-Surface Traverse," in Proceedings of 6th Annual Meeting of Working Group on Extra-Terrestrial Resources, Feb. 19-21, 1968, Brooks Air Force Base, Texas, NASA, Washington, D.C., SP-177, pp. 253-262.

Conrad, C., 1969, "Conrad Stresses Real-Time Value of EVA," Aviat. Week Space Technol. 91 (2), 16 (1969).

Costes, N. C., W. D. Carrier, J. K. Mitchell, and R. F. Scott, 1970, "Apollo 11 Soil Mechanics Investigation," Science 167, 739 (1970).

Crim, W. M., Jr., 1970, Study Director, Typical SNAP-8 System with Partial Shielding for a Lunar-Based Power Plant, 100 KW(e), U.S. Army Engineer Reactors Group, Ft. Belvoir, Va., Report RT-1017, June 1970.

Crowley, B. K., 1969, Scaling in Rock Mechanics Experiments, Lawrence Radiation Laboratory, Livermore, Calif., UCRL-71879, 1969.

DASA, 1962, The Effects of Nuclear Weapons, S. Glasstone, Ed. (U.S. Atomic Energy Commission, Washington, D.C., 1962).

Dobrin, M. B., 1960, Introduction to Geophysical Prospecting, (McGraw-Hill Book Co., Inc., New York, 1960).

Douglas, J. W. and E. H. Sholto, 1956, "Farming on the Moon," J. Brit. Interplanet. Soc., 15, 17 (1956).

Duke, M. B. et al., 1970, "Lunar Solid Size Distribution and Mineralogical Constituents," Science 167, 648 (1970).

Dupont, 1966, Blasters Handbook (E. I. duPont de Nemours and Co., Wilmington, Delaware, 1966).

Ehriche, K. A., 1962, Space Flight II Dynamics, Chapt. 1 (D. Van Nostrand Company, Inc., Princeton, N. J., 1962).

Fryer, R. J., 1970, "Apollo Mission Plans," Spaceflight 12, 120 (1970).

Gilluly, J., A. C. Waters, and A. O. Woodford, 1968, Principles of Geology (W. H. Freeman, San Francisco, 1968), 3rd ed.

Glasstone, Samuel, 1965, Sourcebook on the Space Sciences (D. Van Nostrand Company, Inc., Princeton, N. J., 1965).

Griffiths, D. H. and R. F. King, 1969, Applied Geophysics for Engineers and Geologists (The Leagrave Press Ltd., Luton and London, 1969).

Hammersly, V., 1970, Project Officer, Mobile Partial-Gravity Simulator, NASA, Houston, Texas, private communication, Aug. 1970.

Hautz, E., 1970, Project Officer, LRV, The Boeing Co., Marshall Spaceflight Center, Huntsville, Alabama, private communication, Aug. 1970.

Hess, W. N. and A. J. Calio, 1969, "Summary of Scientific Results," NASA, Washington, D. C., SP-214, 1969, pp. 1-7.

Hess, W., R. Kovach, P. W. Gast, and G. Simmons, 1969, "The Exploration of the Moon," Sci. Amer. 221, 54 (1969).

Imgram, D., 1969, "Man in Space: Designing for Experimentation," Space/Aeronautics 52, 66 (1969).

Jakosky, J. J., 1957, Exploration Geophysics (Trija Publishing Co., Newport Beach, Calif., 1957) 2nd ed

Johnson, R. W., "The Lunar Colony," Sci. J. 5, 32 (1969).

Kilmer, E. E., 1968, "Heat-Resistant Explosives for Space Applications," J. Spacecraft 5, 1216 (1968).

King, C. Y. and M. E. Nadolski, 1969, The Effect of Ground Motion from Nuclear Excavation—Interim Canal Studies, Lawrence Radiation Laboratory, Livermore, Calif., UCIR-426, Sept. 1969.

Kovach, R. L., 1967, "Lunar Seismic Exploration," in The Physics of the Moon, American Astronautical Society, Science and Technology Series, Vol. 3, pp. 189-198, 1967.

Kovacs, R., 1970, "Explosive Seismic Sources for the Moon," Geophysics 35, 33 (1970).

Kudish, H., 1970, "The Lunar Rover," Spaceflight, 12, 270 (1970).

Langefors, U. and B. Kihlstrom, 1963, The Modern Technique of Rock Blasting (John Wiley and Sons, Inc., New York, 1963).

La Patra, J. W. and R. E. Wilson, 1968, Moon Lab, A Study by the Stanford-Ames Summer Faculty Workshop in Engineering Systems Design, Stanford University, Calif., 1968.

Latham, G. V. et al., 1970, "Passive Seismic Experiment," Science 167, 455 (1970).

Leany, F., 1969, "Man in Space; Stations and Bases," Space/Aeronautics 52, 54 (1969).

Lee, J. F., J. W. Sears, and D. L. Turcotte, 1963, Statistical Thermodynamics (Addison-Wesley Publishing Co., Inc., Reading, Mass., 1963).

Lockheed, 1965, Study of Deployment Procedures for Lunar Exploration Systems for Apollo (LESA), Vol. 1, Summary, Lockheed MSV Co., Sunnyvale, Calif., Final Report, 1965.

LRL, Livermore, 1965, Properties of Chemical Explosives, Lawrence Radiation Laboratory, Livermore, Calif., UCRL-14592, 1965.

McGregor, K., 1967, The Drilling of Rock (C. R. Brooks Ltd., London, 1967).

Mitchell, J. K., I. S. E. Carmichael, R. E. Goodman, J. Frisch, and P. A. Witherspoon, 1969, Material Studies Related to Lunar Surface Exploration, Space Sciences Laboratory, University of California, Berkeley, NASA-CR-107176, March 1969, and NASA-CR-107174, April 1969.

Murphy, G., 1950, Similitude in Engineering (Ronald Press, New York, 1950).

NASA, 1965, NASA 1965 Summer Conference on Lunar Exploration and Science, Geophysics Group Report, NASA, Washington, D.C., SP-88, 1965, pp. 182-199.

NASA, 1969, Preliminary Examination of Lunar Samples, NASA, Washington, D.C., SP-214, 1969, pp. 123-142.

NASA, 1969a, "NASA Considers Geologist for 1970 Apollo-15 Crew," Aviat. Week Space Technol. 91 (2), 15 (1969).

NASA, 1970, "Preliminary Examination of Lunar Samples from Apollo 12," Science 167, 1325 (1970).

NCG, Livermore, 1966, Military Engineering with Nuclear Explosives, U.S. Army Engineer Nuclear Cratering Group, Livermore, Calif., DASA 1669, June 1966.

Nichols, H. L., Jr., 1962, Moving the Earth (North Castle Books, Greenwich, Conn., 1962).

North American, 1966, Scientific Mission Support for Extended Lunar Exploration, Vols. 1-3, North American Aviation, Inc., Downey, Calif., NASA, Washington, D.C., CR-87399, Dec. 1966.

Nugent, R. C. and D. C. Banks, 1966, Project Danny Boy, Engineering-Geologic Investigations, U.S. Army Engineer Nuclear Cratering Group, Livermore, Calif., PNE-5005, Nov. 1966.

O'Leary, B., The Making of an Ex-Astronaut (Houghton-Miflin Co., New York, May 1970).

Perkins, B., Jr. and W. F. Jackson, 1964, Handbook for Prediction of Airblast Focusing, Aberdeen Proving Ground, Md., BRL-1240, Feb. 1964.

Pfleider, E. P., 1968, Surface Mining, The American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York (The Maple Press Co., York, Penn., 1968), 1st ed.

Pokrovskii, G. I., I. S. Fedorov, M. M. Pokuchaev, 1951, Theory and Practice of Dam Construction by Directed Explosions (State Press for Literature on Construction and Architecture, Moscow, 1951).

Poulter, T. C., 1956, Low Order Detonation and Lined Shaped Charges, Stanford Research Institute, Menlo Park, Calif. (1956).

Reed, J. W., 1964, "Airblast from Cratering Explosions," in Proceedings of the Third Plowshare Symposium, April 21-23, 1964, University of California, Davis, AEC, DTIE, Oak Ridge, Tenn., TID-7695 (1964).

Reed, J. W., 1964a, Microbarograph Measurements from Underground Tests, Sandia Corp., Albuquerque, N. M., Report WT9006, Dec. 1964 (Confidential).

Reed, J. W., 1969, Acoustic Wave Effects Project: Airblast Prediction Techniques, Sandia Laboratories, Albuquerque, N. M., Report SC-M-67-332, May 1969.

Redpath, B. B., 1970, U.S. Army Engineer Nuclear Cratering Group, private communication, Sept. 1970.

Schreiber, E., O. L. Anderson, N. Soga, N. Warren, and C. Scholz, 1970, "Sound Velocity and Compressibility for Lunar Rocks 17 and 46 and for Glass Spheres from the Lunar Soil," Science 167, 732 (1970).

Sherwood, A. E., 1967, "Effect of Air Drag on Particles Ejected During Explosive Cratering," J. Geophys. Res. 72, 1783 (1967).

Shoemaker, E. M. et al., 1970, "Lunar Regolity at Tranquility Base," Science 167, 452 (1970).

Snay, H. G., 1961, The Scaling of Underwater Explosion Phenomena, U.S. Naval Ordnance Laboratory, Silver Spring, Md., NOLTR 61-46, 1961.

Stephens, D. R. and E. M. Lilley, 1970, "Compressibilities of Lunar Crystalline Rock, Microbreccia and Fines to 40 Kilobars," Science 167, 731 (1970).

Strickland, Z., 1969, "Rigorous Training Precedes Moon Lift-Off," Aviat. Week Space Technol. 91(1), 59 (1969).

Strickland, Z., 1969a, "Apollo-12 Landing Accuracy Praised," Aviat. Week Space Technol. 91(2), 13 (1969).

U.S. Army, 1959, Project Horizon Report, Vols. 1, 2, Department of the Army, Washington, D.C., 1959.

Vail, E., 1968, Man as Resource on the Moon, NASA, Washington, D.C., SP-177, 1968, pp. 263-273.

Van Brockel, J., 1970, Training Coordination Group, Flight Crew Support, Manned Spacecraft Center, NASA, Houston, Texas, private communication, May 1970.

Vortman, L. J., 1967, Maximum Missile Ranges from Surface and Buried Explosions, Sandia Corp., Albuquerque, N. M., Report SC-RR-67-616, Sept. 1967.

Wolek, F., 1970, Engineering Roles in Development Projects, Wharton School of Business, Pennsylvania University, National Science Foundation, NSF-GM-S99, 1970.

Wood, J. A., J. S. Dickey, Jr., U. B. Marvin, B. N. Powell, 1970, "Lunar Anorthosites," Science 167, 602 (1970).

Appendix A
Modeling of Lunar Explosion Craters on Earth at Reduced Length Scale

In this appendix it is shown that a proposed lunar cratering experiment can be first modeled on earth by dividing all important dimensions (e.g., charge size and depth of burial) by a factor of six.

For a scaling study as this, it is convenient to express all physical variables in terms of ratios. Units then become unimportant and constants appearing in the equations of motion are eliminated. In the definitions of terms listed below, primed terms refer to lunar physical variables and unprimed terms to their terrestrial counterparts.

$L = l/l'$ where l is any linear dimension,

$T = t/t'$ where t is the time for an event in the cratering process to occur,

$U = u/u'$ where u is any particle or shock wave velocity at corresponding points at a time t,

$C = c/c'$ where c is any elastic wave velocity,

$A = a/a'$ where a is any particle acceleration at corresponding points at time t,

$G = g/g'$ where g is the acceleration of a mass due to gravity,

$Q = q/q'$ where q is any hydrodynamic energy,

$P = p/p'$ where p is any pressure at a time t,

$V = v/v'$ where v is any volume,

$R = \rho/\rho'$ where ρ is any density,

$S = \sigma/\sigma'$ where σ is any material stress, strength, or modulus,

$E = e/e'$ where e is any strain,

$\dot{E} = \dot{e}/\dot{e}'$ where $\dot{e}$ is any strain rate.

The following five requirements must be met if similarity in all respects is to be achieved (Snay, 1961):

(1) Geometric. All corresponding linear dimensions must be of the same scale, L, and consequently

$$V = L^3. \tag{A1}$$

(2) Kinematic. All particle velocity and acceleration terms must dimensionally correspond to the length and time scales, i.e.,

$$U = L/T \tag{A2}$$

and

$$A = L/T^2\ . \tag{A3}$$

(3) Dynamic. Pressure scales must be compatible with density and velocity scales. Also, energy scales must be consistent with pressure and volume scales. Thus

$$P = RU^2, \tag{A4}$$

and

$$Q = PV. \tag{A5}$$

(4) Gravitational. The velocity scale must correspond to the length and gravitational scales in the form

$$U = (GL)^{1/2}. \tag{A6}$$

(5) Mach scaling. Mach numbers for particles and shock waves must be equal at geometrically similar points, i.e.,

$$U = C. \tag{A7}$$

To assure similarity, one constraint will now be imposed: the explosive used in the earth model must be the same as that used on the moon. This constraint requires that ratios of detonation pressure, velocity, explosive density, and sound velocity be unity. It can be shown that the ratios of all other corresponding variables with like units must also be unity (Crowley, 1969; Murphy, 1950). Therefore,

$$S = P = U = R = C = 1. \tag{A8}$$

Consequently, the cratering medium used must have the same modulus, density, and seismic velocity as that found on the moon. A terrestrial analog of the lunar crust is necessary.

Turning now to the similarity requirements which must be upheld, note first that Eqs. (A4) and (A7) are also satisfied by the explosive constraint. Next, from Eqs. (A1), (A5), and (A8)

$$L = Q^{1/3}, \tag{A9}$$

which is the well-known cube root scaling law. Also, from Eqs. (A2), (A3), and (A8),

$$T = L \tag{A10}$$

and

$$A = 1/L. \tag{A11}$$

Equations (A10) and (A11) state that, as the length scale of a cratering event is decreased, the time for a given event to occur (e.g., venting) is decreased proportionately and the acceleration of a given particle is increased in inverse proportion to this length scale. Finally, from Eqs. (A6) and (A8),

$$L = 1/G. \tag{A12}$$

That is

$$L = \frac{1}{\Gamma} = \frac{g'}{g} \cong \frac{1}{6}, \tag{A13}$$

where

$$g' = 1/6\ g$$

under the conditions of this study. The length scale is no longer free for manipulation but must be inversely proportional to the gravitational scale.

Before the implications of this result are developed, some points should be clarified. The weight of overburden or lithostatic head is another item that must scale like any other pressure. It does, as shown by

$$\frac{\rho g h}{\rho' g' h'} = RGL = 1 , \tag{A14}$$

where h is the depth of burial. Strain and strain rate scaling must be considered next. Since an identical medium is to be used for modeling, the modulus scale is unity and, therefore,

$$E = S, \tag{A15}$$

where S refers to stress and is, as shown previously, also unity. A strain scale of unity satisfies geometric similarity since the deformation scale is equal to the length scale when the stress scale is unity. This of course is limited to the elastic range of the medium. The extent of this elastic range depends upon the rate of strain, being larger for higher strain rates. Crowley (1969) has shown the strain rate scale to be given by

$$\dot{E} = 1/L. \tag{A16}$$

Strain rate does not scale. For small-scale cratering detonations, elastic deformation will exist at higher stress levels than for larger shots; consequently, the plastic deformation zone near the charge will be relatively thinner. This may have some effect on the modeling of underground sprung cavities, but it is unlikely that strain rate will significantly affect surface crater modeling since the volume of plastically deformed material in all cases is much smaller than the volume of the craters. Inaccuracies resulting from unscaled strain rates can therefore be expected to be small.

The other variable that does not scale is atmospheric pressure. However, since explosion pressures are so much greater than atmospheric pressure, acceleration and velocity scales are unaffected. The existence of an earth atmosphere in modeling experiments will induce friction drag on the airborne debris. Ejecta ranges on earth from one-sixth scale cratering shots then will be less than one-sixth the lunar ejecta range.

The ballistic coefficient (the ratio of initial drag force to gravitational force) is directly proportional to the square of the initial particle velocity and inversely proportional to the mean particle diameter (Sherwood, 1967). The ratio of ejecta range in air to that in a vacuum is a direct function of ballistic coefficient. Thus, missile range is affected more by air drag in the case of fine particles than it is for large blocks, and the fallback from a terrestrial model will have a skewed particle distribution with fines lying near the crater and the larger particles farther out. This means that drag should have a greater effect on maximum missile range than on crater volume.

For charges detonated at shallow depths (where the apparent crater depth approaches or exceeds the depth of burst), air drag will have little influence on crater dimensions, but its influence on apparent crater depth will increase with increasing fallback material. At depths of burst where considerable material falls back into the crater, reliable modeling can be done only in an evacuated chamber.

The level of vacuum required in an evacuated chamber to offset the effects of air drag depends not only on the absolute pressure of the air but also on the absolute pressure of the venting explosion gases. Air drag due to atmosphere will be overshadowed by the pushing effect of the explosion gases whenever the pressure of the latter exceeds that of the former. Provided the explosion gas pressure predominates beyond the true crater boundaries, ejecta will be directed away from the crater and air drag will have negligible effect on crater dimensions. An estimate as to the maximum allowable atmosphere in an evacuated chamber has been made from experimental data. For example, one pound of composition C-4 can excavate a crater in sand with a maximum radius of about 0.75 m. The pressure of the explosion gases once they expand to a sphere of that radius is slightly greater than 0.1 atm. If the atmospheric pressure in the evacuated chamber is then kept to about half of this (about 30 to 40 mm Hg), air drag will have negligible effect on crater dimensions. This level of pressure is easily attainable, even in large chambers. Since crater radii generally scale in direct proportion to charge dimension, this level of pressure will serve for all charge sizes.

In summary, lunar explosion craters can be modeled on earth provided:

(1) The same type of explosive is used.

(2) An accurate terrestrial analog of the modeled lunar medium is used.

(3) All lengths (such as burial depth of the charge and charge size) are reduced to one-sixth, areas to 1/36 and volumes to 1/216 of the lunar counterparts.

(4) Atmospheric pressures are 30 to 40 mm Hg or less.

Appendix B

Full-Scale Modeling of Lunar Explosion Craters on Earth

In this appendix, the converse approach to that of Appendix A is examined. The length scale is set at unity and the effects of gravity on the motion of ejected particles are examined.

If, as before, the same explosion and medium are assumed, examination of the five similarity requirements discussed in Appendix A reveals that, since $L = 1$ (symbols are defined in Appendix A),

$$T = U = C = A = Q = V = P = S = R = E = \dot{E} = 1 \ . \tag{B1}$$

Gravitational scaling, however, violates this convenient result since

$$(GL)^{1/2} \neq 1. \tag{B2}$$

If, however, a separate missile range length scale is adopted, this similarity violation may be examined. Let L_e be l_e/l'_e, the ejecta missile range scale. Then, to satisfy gravitational similitude (Eq. A6), it is necessary that

$$L_e = 1/G \ . \tag{B3}$$

For the same initial particle velocity distributions, the ejecta range scale is

$$L_e = l_e/l'_e = g'/g = 1/6 \ . \tag{B4}$$

That is, ejecta particles travel only one-sixth as far from their starting point on earth as on the moon (assuming similar initial particle velocity distributions). The amount of material falling back into lunar craters then is much less, while lunar missile ranges are much greater.

This result is employed later to determine lunar explosion crater dimensions from existing earth cratering data. First, however, a digression is necessary to determine the influence of gravity during the initial stages of crater development. This matter must be dealt with since lithostatic head no longer scales—see Eq. (A14)—and the effect of such a violation of similitude must be determined.

The true crater is formed by the various shock and elastic wave phenomena accompanying the detonation of a buried explosive. This mechanism is dependent on gravity only in that seismic velocity in a given medium is affected by lithostatic head. While this will affect the times of arrival of shock and elastic waves at various points, it will have negligible effect on their magnitudes. The effect of gravity on the zones of fracture is therefore negligible, and it follows that true crater formation is relatively unaffected by differences in gravitational field.

Because the effects of gravity are relatively unimportant, geometric similarity prevails, and true crater volume varies linearly with explosive mass with crater dimensions proportional to the cube root of the explosive mass.

The question remains concerning initial particle velocity distribution. The initial particle trajectory velocities resulting from a buried explosion depend upon the net driving force (cavity gas pressure less lithostatic head), the time interval available for the application of this force, and the mass (not weight) of material moved. Since the lithostatic head is very small compared to the cavity gas pressure, the former can be neglected and gravitation field again has a negligible effect. Assuming similar media, initial trajectory velocities are unaffected by the difference in gravitational acceleration on the earth and on the moon. For geometrically similar terrestrial and lunar cratering experiments, it has been shown from similitude that the initial velocity distributions are identical.

From the foregoing discussions, the difference between terrestrial and lunar explosion-produced apparent craters lies only in the ballistic phase of motion which affects the distribution of the fallback and ejecta. Once a relationship between lunar and terrestrial distributions is known, terrestrial models are possible. A method is developed in the following paragraphs which accounts for the effect of the gravitational field on fallback and ejecta distribution.

First, it is necessary to determine the form of the terrestrial fallback and ejecta distribution. It can be shown that the results that follow are not particularly sensitive to the exact form of the distribution chosen. The distribution chosen should, however, realistically portray available data.

As an example, the distribution of fallback and ejecta for one radial of the Danny Boy crater is presented as a solid line in the graph in Fig. B1. Depths are measured from the estimated true crater boundary for $r<a$ and from the uplifted surface for $r>a$. If the natural tendency of the fallback material to slide after impact toward the center of the true crater is accounted for by increasing the y values near $r = a$ and decreasing those near the center accordingly, then a normal distribution of the form shown in the figure is approached. The parameter n in a generalized version of this distribution

$$y = y_0 \exp(-nr^2/2a^2) \tag{B5}$$

is a free variable which may be adjusted as shown below to fit a predetermined ratio of apparent to true crater volume. In Eq. (B5), y_0 is the adjusted fallback depth along the crater axis and a is the true crater radius.

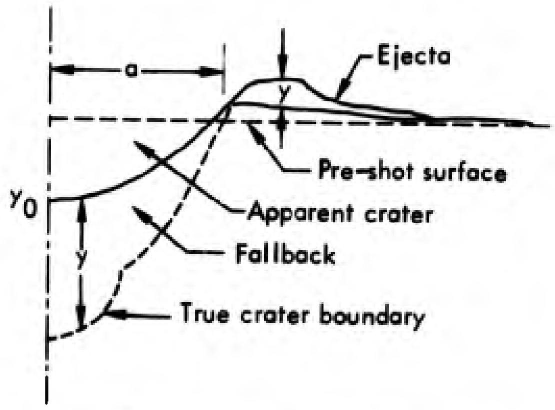
The volume of a thin cylindrical shell of fallback or ejecta of radius r, thickness δr and height y is

$$\delta V = 2\pi r y \delta r ,$$

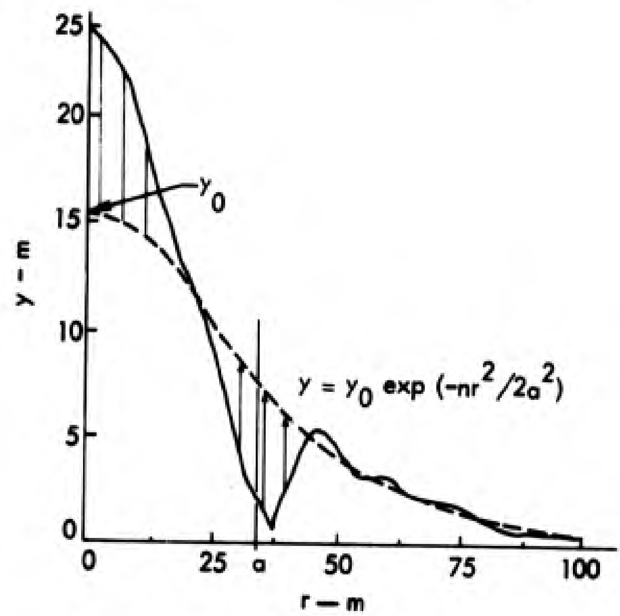
which, after substituting for y from Eq. (B5), is

$$\delta V = C_1 r \exp(-nr^2/2a^2)\, \delta r, \tag{B6}$$

where $C_1 = 2\pi y_0$. If, for convenience, we introduce a dimensionless radial coordinate p defined by



(a) Half profile of Danny Boy crater



(b) Distribution of fallback and ejecta. Note that a normal distribution is approached when a correction is applied for post-impact sliding. (Nugent, 1966).

Fig. B1. Danny Boy crater.

$$p = r/a\ , \tag{B7}$$

Eq. (B6) becomes

$$\delta V = Cp \exp(-np^2/2)\ \delta p \tag{B8}$$

where $C = a^2 C_1$.

The volume of fallback or ejecta within a boundary of radius p is found by integrating Eq. (B8) from zero to p and is given by

$$V(p) = \frac{C}{n}\left[1 - \exp(-np^2/2)\right] . \tag{B9}$$

The volume of material which fell back into the crater is found by substituting p = 1 into Eq. (B9) and is

$$V_f = \frac{C}{n}\left[1 - \exp(-n/2)\right] . \tag{B10}$$

If bulking is neglected and if the limit of continuous ejecta is at p = q then the true crater volume is approximately that found by integrating Eq. (B8) from zero to q which results in

$$V_t = \frac{C}{n}\left[1 - \exp(nq^2/2)\right] . \tag{B11}$$

The gravitational acceleration on the lunar surface is one-sixth that of earth. It can be shown that a particle with a given initial trajectory velocity will travel at least six times higher and farther from its starting point on the moon than on earth.* As mentioned before, the initial trajectory velocity distribution is unaffected by gravity so that corresponding particles will have the same initial velocities in both cases.

The point at which a particle enters free flight is not distinct, nor is its origin in the preshot ground surface. Many experimenters have shown that the maximum range particles originate in the ground along an approximately 60-deg conical surface which has its apex at the shot point. These particles are accelerated by the expanding gases up through the time of venting and shortly thereafter. The ballistic phase does

*Fine particles will travel more than six times farther due to acceleration by the venting gases. While this effect on fine particles will influence missile range, it will have little effect on the volume of fallback material and is therefore ignored. This matter is discussed further in Appendix C.

not begin until the mound is rather thoroughly broken up, at which time most of the particles are about one crater radius from surface ground zero. To impose precision on a rather imprecise boundary condition, the beginning of the ballistic is hereafter assumed to be at the true crater radius or at p = 1.

Letting primes denote lunar quantities then for identical terrestrial and lunar events, the lunar limit of continuous ejecta, q', lies six times farther from the start of the ballistic phase than the terrestrial limit. That is,

$$q' - 1 = 6\,(q - 1). \tag{B12}$$

But it has already been suggested that true crater volume is independent of gravity. Therefore

$$V_t' = V_t. \tag{B13}$$

Combining Eqs. (B11), (B12), and (B13) gives the remaining lunar parameters in terms of terrestrial variables:

$$\frac{C'}{n'} = \frac{C}{n}; \qquad \frac{n'}{n} = \frac{q^2}{(6q - 5)^2}. \tag{B14}$$

The lunar equivalent of Eq. (B10), the fallback volume, expressed in terrestrial terms, is found from Eq. (B14) and is written,

$$V_f' = \frac{C}{n}\left\{1 - \exp\left[-nq^2/2(6q - 5)^2\right]\right\}. \tag{B15}$$

Using Eqs. (B10) and (B15), the ratio of lunar to terrestrial fallback volume is

$$\frac{V_f'}{V_f} = \frac{1 - \exp\left[-nq^2/2(6q - 5)^2\right]}{1 - \exp(-n/2)}. \tag{B16}$$

Once n and q are known, the amount of lunar fallback material and, conversely, the apparent crater volume can be found from Eq. (B16). V_f, n, and q may be determined from terrestrial cratering experiments.

Air drag will introduce an error into the value of q, making it smaller than it would be were the atmosphere nonexistent. The extent of the error depends upon the ejecta size. As discussed briefly in Appendix A, the horizontal range through which a particle travels in air, x, compared to what it would travel in a vacuum, x_v, depends on the ballistic coefficient, B, of the particle and its angle of inclination with the horizontal. The ballistic coefficient is the ratio of initial drag force to gravitational force and is defined by

$$B = \frac{3}{4} C_d \frac{\rho}{\rho_p} \frac{U^2}{gD}, \tag{B17}$$

where

C_d = drag coefficient (≈1)
ρ = air density (1.2×10^{-3} g/cm^3)
ρ_p = particle density (≈2.5 g/cm^3)

U = initial velocity, cm/sec

g = gravitational acceleration (980 cm/sec^2 on earth)

D = mean particle diameter, cm.

The ratio of air range to vacuum range of an ejecta particle, x/x_v, as a function of the ballistic coefficient and angle of inclination θ_0 is shown in Fig. B2. It is seen from the figure that neglecting air drag in terrestrial cratering shots leads to an error greater than about 25% whenever the ballistic coefficient exceeds about one. From Eq. (B17), this error occurs whenever $U^2/D > 2.5 \times 10^6$ cm/sec^2. Surface mound velocities from cratering detonations rarely exceed about 60 m/sec except at very shallow burial depths. Therefore, vacuum range for crater ejecta particles will not exceed about 1.25 times the air range provided mean particle diameters exceed about 15 cm. Consequently, air drag may be ignored for particles of this size or greater and q can be accurately determined provided larger particles are selected.

Two sample cases are now examined: first, a terrestrial model with near optimum explosive burial depth and, second, one with near total containment explosive burial depth.

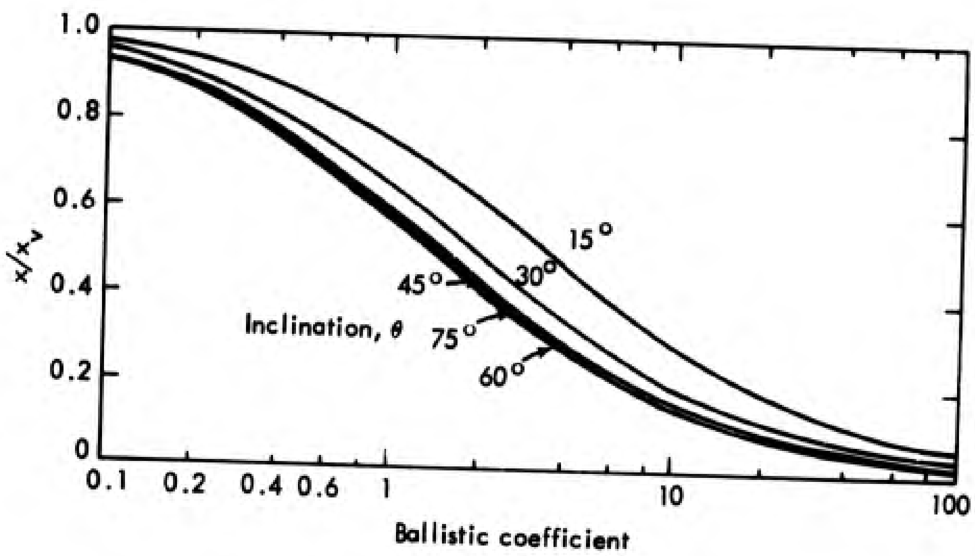


Fig. B2. Relative ejecta particle range vs ballistic coefficient for various initial angles of inclination (Sherwood, 1967).

Terrestrial Model with Near-Optimum Explosive Burial Depth

From the many terrestrial cratering events in hard rock already accomplished, it is found that, at a charge burial depth producing maximum apparent crater volume, the ratio of true crater volume to fallback volume is about two. Also, the outer limit of continuous ejecta lies typically at three crater radii. Applying the conditions, then, that

$$\frac{V_t}{V_f} = 2, \text{ and,}$$

$$q = 3,$$

to Eqs. (B10) and (B11) gives a value for n of about 1.5. The ratio of lunar to terrestrial fallback volume, as given by Eq. (B16), becomes

$$\frac{V_f'}{V_f} = 0.10 .$$

Hence, most of the material is ejected and the lunar apparent crater volume roughly equals the true crater volume. To a first approximation, apparent and true crater radii are equal, and the true crater volume may be calculated by assuming the true crater to be a paraboloid of revolution with a base equal to the apparent crater diameter and altitude equal to 1.1 times the depth of burst for rock and 1.2 times the depth of burst for soil.

Terrestrial Model with Near-Containment Explosive Burial Depth

In this example, it is assumed that the apparent terrestrial crater volume is only 10% of the true crater volume and the limit of continuous ejecta is 1.5 crater radii from the center of the crater (i.e., $V_f/V_t = 0.9$, $q = 1.5$).

Using the method developed above, it can be shown that n = 6. The corresponding ratio of lunar to terrestrial fallback volumes, again using Eq. (B16), is

$$\frac{V_f'}{V_f} = 0.27 .$$

As in the previous case, much more material is still ejected from the lunar crater. Of course, this process does not continue indefinitely and, at deeper charge burial depths, the lunar fallback increases until, at some burial depth, total containment occurs. Based on discussions in the previous sections and on existing terrestrial data, a lunar cratering curve is estimated below.

The depth of burst at which surface expression ceases and sprung cavities begin depends upon the shock transmission and strength properties of the medium and is not strongly dependent on gravity. The true crater curves for terrestrial and lunar environments then must coincide up to somewhere near this "critical" depth. The change in gravitational acceleration has negligible effect on true or apparent crater radii (which are assumed equal). The lower lunar gravitational field will serve to decrease apparent lip height somewhat and increase apparent crater depth. Both changes occur because fallback and ejecta are distributed over a greater area.

The effect of gravity on apparent and true crater volume is shown qualitatively in Fig. 40. As would be expected, the optimum charge burial depth for maximum apparent crater volume tends to increase as gravitational acceleration is reduced.

In summary, lunar explosion craters can be expected to be deeper but of about the same radius as terrestrial craters formed with the same charge mass of the same explosive. Since there is little fallback in most lunar explosion craters, their apparent depths will be nearly the depth of burial of the charge.

Appendix C
Analysis of Blast in a Vacuum

The expansion of a high-pressure gas into a vacuum is quite different from expansion into an atmosphere. In the latter case, collisions between the atmosphere and the expanding gas confine the gas to a small volume, and pressure discontinuities are equalized by a shock wave radiating into the atmosphere. The detonation gas remains homogeneous and the expansion ceases shortly after it reaches atmospheric pressure. In a vacuum, the explosion radiates its gas unfettered, and the closest thing to a blast wave is the outer boundary of molecular flux moving radially away from the blast center.

While the detonation gas is at high pressure and temperature, its molecular energy is distributed among translation, rotation, and possibly dissociation and ionization modes. As the expansion proceeds, energy transfers occur in the reverse order of that listed until a sufficiently low temperature is reached at which practically all molecular energy exists as translation (kinetic energy). From this point on until intermolecular collisions all but cease, the "simple" Kinetic Theory may be employed. This theory assumes molecular collisions to be elastic. According to the theory, a gas mixture contains several molecular species whose individual velocity distributions follow unique normal distributions, and molecular velocities are nondirectional. The distribution of molecular speeds for species i (i.e., the number of molecules with speeds between C_i and $C_i + dC_i$ is found by integrating the normal velocity distribution over all directions and is given by (Lee, et al., 1963):

$$dn_i = \frac{4n_i}{\sqrt{\pi}} \left(\frac{m_i}{2kT}\right)^{3/2} C_i^2 \exp\left(-\frac{m_i C_i^2}{2kT}\right) dC_i , \tag{C1}$$

where

n = number of particles per unit volume

m = molecular mass (molecular weight divided by Avogadro's number)

k = Boltzmann's constant

T = gas temperature, °K.

Equation (C1) is plotted in Fig. C1 for several gas temperatures. The area under each curve in the figure is the molecular number density which is found by integrating Eq. (C1) over all speeds.

From Eq. (C1), it can be shown that the root mean square (rms) molecular speed for species i is C_{ri},

$$C_{ri} = \left[3kT/m_i\right]^{1/2} . \tag{C2}$$

This speed represents the average kinetic energy of the molecular species and is also shown in Fig. C1.

According to the Kinetic Theory, kinetic energies are partitioned equally among the existing molecular species. The average molecular kinetic energy is then given by

$$\epsilon = \text{constant} = m_i C_{ri}^2/2 \ . \tag{C3}$$

If n is the total number of molecules per unit volume, i.e.,

$$n = \sum_i n_i \ , \tag{C4}$$

then the total energy per unit volume is $n\epsilon$ and the total energy per unit mass is

$$Q = n\epsilon/\rho = \epsilon/m_a \tag{C5}$$

where ρ is the density of the gas mixture and m_a is the average molecular mass. The rms speed of each molecular species in terms of Q is found by combining Eqs. (C3) and (C5) and is

$$C_{ri} = \left[2 \frac{m_a}{m_i} Q \right]^{1/2} \ . \tag{C6}$$

On the average, then, lighter molecules travel at higher velocities than heavier molecules.

During the free expansion of the gas into a vacuum, no work is done and negligible heat is radiated. The average molecular kinetic energy, ϵ, and therefore C_r, remain constant. A result of the free boundary, however, is that all directions of molecular velocities cease to be equally probable and the radial direction becomes preferred. Since the molecular species of the detonation products have differing masses, stratification of the species will commence, the lighter gases moving out ahead of the heavier ones. A pressure detector located close to the blast will sense a rapid pressure rise when the outer boundary of the uniform gas arrives and a decay to zero pressure thereafter as the gas continues to expand. A pressure detector located a great distance from the blast will experience a discrete sequence of pressure pulses corresponding to the arrivals of each molecular species. The pressure pulses will be characterized by long rise times and the shape of each pressure-time curve will resemble a mirror image of one of the curves in Fig. C1. Typical pressure-time traces for near, intermediate, and far ranges are shown qualitatively in Fig. C2. The lumpy intermediate range curve in the figure represents the range at which molecular species have only partially stratified.

It is shown in the following paragraphs that close-in peak pressures decay according to the cube of the range. At far ranges where stratification has occurred, the gas occupies an expanding spherical shell and, therefore, peak pressures decay roughly according to the square of the range. At such far ranges, pressure levels have decayed to insignificant values.

It is assumed that all molecules assume a purely radial motion as soon as free expansion (i.e., venting) begins. In addition, it is assumed that molecular segregation

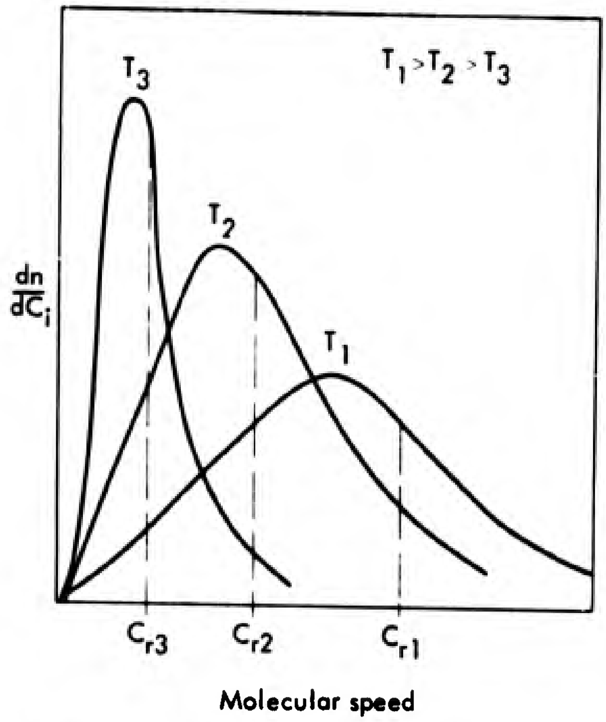


Fig. C1. Molecular speed distribution for three temperatures (area under each curve is total particle density).

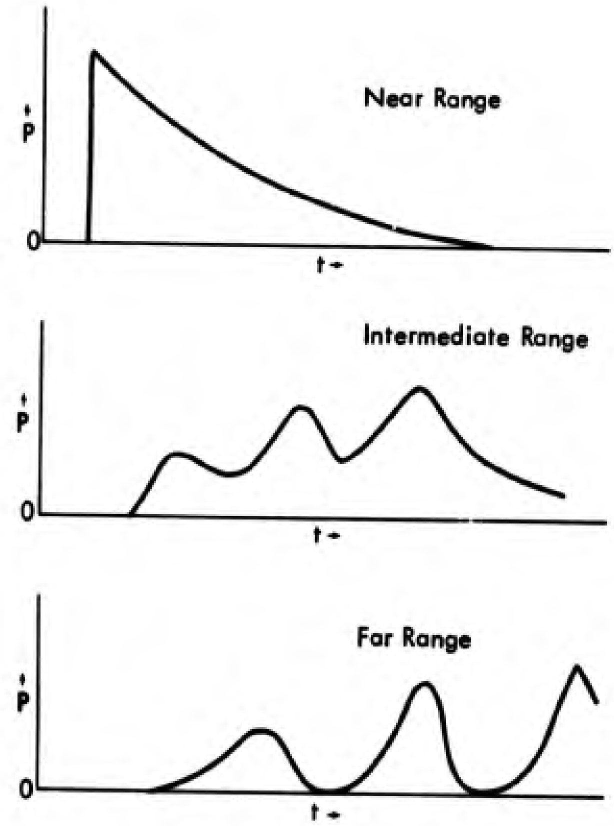


Fig. C2. Pressure-time curves for gas mixture expanding into vacuum.

due to differing speeds has not yet become significant. The two assumptions are somewhat contradictory, since both events are dependent on molecular velocities and collisions. They do, however, greatly simplify the analysis and tend to give upper limits of expected pressure levels.

Let Q now represent the total internal energy per unit mass at the onset of the free expansion. Since no work is done in a free expansion, Q is invariant and, after expansion to zero pressure, represents the radial kinetic energy of the molecules. The rms velocity after expansion is given by Eq. (C6).

The pressure produced by the molecular flux may be determined by calculating the change in momentum of molecules striking a rigid surface. Assuming elastic collisions, the impact pressure for each molecular species can be shown to be given by

$$P_i = m_i n_i C_{ri}^2, \qquad \text{(C7)}$$

and the total impact pressure by

$$P = \sum_i P_i . \qquad \text{(C8)}$$

Interestingly, Eq. (C7) gives a pressure value which is three times that which the gas had at the start of the free expansion. This result contradicts neither continuum flow theory nor kinetic theory. It must be remembered that, at the onset of the expansion, molecular velocities were random in direction and therefore only one-third of the molecules had velocity components which allowed them to strike a surface. Once purely radial motion has been established, however, all the molecules will strike a surface placed normal to the direction of motion. (For inclined surfaces, the peak pressure will depend on the cosine of the angle of inclination.)

The assumption of elastic collisions gives the upper limit of impact pressure. The lower limit is determined by assuming that the molecules are captured by the surface and, in that case, the pressure is half that given by Eq. (C7). As a conservative estimate, it is assumed that elastic collisions prevail and the impact pressure is in fact that given by Eq. (C7).

Combining Eqs. (C6) and (C7) gives the impact pressure in terms of the internal energy of the gas at the onset of the free expansion:

$$P_i = 2m_a n_i Q. \tag{C9}$$

Since the expansion is purely radial and if particle density is assumed to be uniform within the gas, then from particle conservation

$$n_i(r) = n_{i0}(r_0)\left(\frac{r_0}{r}\right)^3, \tag{C10}$$

where r_0 is the radius of the gas volume at the onset of the free expansion; i.e., where the particle density is n_{i0}. Equation (C9) can now be written

$$P_i = 2m_a Q n_{i0}\left(\frac{r_0}{r}\right)^3 = 2\rho_0\, Q\, \alpha_i\left(\frac{r_0}{r}\right)^3, \tag{C11}$$

where $\rho_0 = m_a n_0$ is the density in g/cm^3 at the onset of the free expansion,

$$n_0 = \sum_i n_{i0}, \tag{C12}$$

the total particle density at that time, and

$$\alpha_i = n_{i0}/n_0, \tag{C13}$$

the molar fraction of the molecular species i.

The decay of the pressure pulse can be deduced from Eq. (C11). At a given distance r from an explosion venting into a vacuum, each molecular species will produce a sudden pressure pulse reaching a peak given by Eq. (C11) at a time $t_i = (r - r_0)/C_{ri}$ which decays according to t^{-3} thereafter. That is

$$P_i(t) = P_i(t_i)\left(\frac{t_i}{t}\right)^3, \quad t \geq t_i. \tag{C14}$$

The total impact pressure at a time t on a surface a distance r away is the sum of that produced by all molecular species.

As an example, suppose the molar products of detonation of an oxygen-rich mixture of ALOX (see Table 11) turns out to be

$$Al_2O_3 + \frac{1}{3} O_2 .$$

Such an explosion, properly buried, will form a true crater with a volume about 3000 times the volume of the explosive. The volume of gases at venting may be assumed to equal the true crater volume.

Now the energy in the gas at venting, Q, depends upon the initial energy, Q_0, and the volume expansion ratio, η. It can be shown that

$$\frac{Q}{Q_0} \approx \eta^{1-k} , \tag{C15}$$

where k is the slope of the reversible adiabatic expansion curve when plotted on log-log coordinates. Values of k may exceed 2.0 near the detonation state but drop to about 1.2 at moderate to low pressures. For convenience, k is taken here to be 1.2.

For the explosive specified above, Q_0 is about 3500 cal/g. Substituting this, and also $\eta = 3000$ into Eq. (C15) gives an energy at venting of $Q = 3500\ (3000)^{-0.2}$ ≈ 700 cal/g $= 292 \times 10^8$ erg/g.

The initial explosive density was about 1.9 g/cm^3 (Table 11) so that the density of the gas at the onset of the free expansion, ρ_0, is about 1.9/3000 or 6.3×10^{-4} g/cm^3.

Let i = 1 refer to Al_2O_3 and i = 2 refer to O_2. Then

$$\begin{aligned}
\text{molecular weight}_1 &= 102 \\
\text{molecular weight}_2 &= 32 \\
m_1 &= 102/6.025 \times 10^{23} \\
&= 16.9 \times 10^{-23}\ \text{g} \\
m_2 &= 32/6.025 \times 10^{23} \\
&= 5.31 \times 10^{-23}\ \text{g} \\
m_a &= m_1 + m_2/3 \\
&= (16.9 + 1.77) \times 10^{-23} \\
&= 18.7 \times 10^{-23}\ \text{g}.
\end{aligned}$$

Other numbers to be calculated are as follows:

$$C_{r1} = 2\left[\frac{18.7 \times 10^{-23}}{16.9 \times 10^{-23}} (292 \times 10^8)\right]^{1/2}$$

$$= 25.4 \times 10^4 \text{ cm/sec} = 2540 \text{ m/sec}$$

$$C_{r2} = 2\left[\frac{18.7 \times 10^{-23}}{5.31 \times 10^{-23}} (292 \times 10^8)\right]^{1/2}$$

$$= 45.4 \times 10^4 \text{ cm/sec} = 4540 \text{ m/sec},$$

$$\alpha_1 = 1/(4/3) = 3/4$$

$$\alpha_2 = (1/3)/(4/3) = 1/4,$$

$$P_1 = 2\,(6.3 \times 10^{-4})\,(292 \times 10^8)\,(3/4)\left(\frac{r_0}{r}\right)^3$$

$$= 27.6 \times 10^6 \left(\frac{r_0}{r}\right)^3 \text{ dyne/cm}^2$$

$$P_2 = 2\,(6.3 \times 10^{-4})(292 \times 10^8)\,(1/4)\left(\frac{r_0}{r}\right)^3$$

$$= 9.2 \times 10^6 \left(\frac{r_0}{r}\right)^3 \text{ dyne/cm}^2 .$$

The oxygen molecules move at almost twice the velocity of the aluminum oxide molecules and will, therefore, attempt to move ahead of the latter. They will, however, continue to collide with the aluminum oxide molecules until the gas becomes somewhat rarified. These collisions will tend to retard stratification. As a conservative estimate, then, the peak pressure at a near- to intermediate-range station may be assumed to be the sum of that produced by each species and, as the aluminum oxide generates the larger pressure, the time of arrival may be assumed to be the time of arrival of the aluminum oxide. Thus

$$P = P_1 + P_2 = 36.8 \times 10^6 \left(\frac{r_0}{r}\right)^3 \text{ dyne/cm}^2,$$

$$t_1 = (r - r_0)/2540 \text{ sec} .$$

For a 1000-kg charge, for example,

$$r_0 = \left[\frac{3(1000 \times 10^3)}{4\pi(6.3 \times 10^{-4})}\right]^{1/3}$$

$$= 723 \text{ cm} .$$

The peak impact pressure 100 m from the explosion is then

$$P = 36.8 \times 10^6 \left(\frac{7.23}{100}\right)^3$$

$$= 13{,}900 \text{ dyne/cm}^2 .$$

This of course assumes a spherical expansion. For a hemispherical expansion as would occur on the surface of the moon, the peak impact pressure would be about twice this or 27,800 dyne/cm^2.*

The time of arrival of the blast is

$$t = (100 - 7.23)/2540 = 0.037 \text{ sec}.$$

The pressure decay can now be written in the form

*0.40 psi

$$P = 27{,}800\left(\frac{0.037}{t}\right)^3 \text{ dyne/cm}^2 .$$

Even from this elementary study, it is evident that gas-generated blast poses no serious problem on the moon. This is especially true in the light of expected missile ranges which are discussed in Appendix D.

Appendix D
Motion of a Particle by a Gas Expanding into a Vacuum

A subsurface explosion will accelerate the material above it to a velocity of the order of 60 m/sec. Venting gases, which escape after mound breakup, will accelerate the ejecta still further. In this appendix, the velocities of the ejecta as they enter the ballistic phase of motion are estimated and missile (ejecta) ranges are estimated.

For simplicity, the following assumptions are made concerning initial conditions (i.e., at venting):

(1) Ejecta speed is 60 m/sec everywhere on the mound. In fact, ejecta speed is maximum at the peak of the mound and decreases toward the outer edges. This assumption gives somewhat higher values of missile range for larger particles.

(2) Ejecta particle size distribution is independent of position on the mound. The combination of this and the previous assumption suggests that there will always be a particle with a given velocity and angle of inclination which maximize range (as shown below, this angle is not necessarily 45 deg).

(3) All particle acceleration by the venting gas occurs while the gas is at a fairly high density. The Reynolds number of any ejecta particle, based on an average particle dimension and the relative velocity of the particle with respect to the gas, can then be expected to be very high initially. Therefore, the coefficient of drag, C_d, may be assumed to be unity. This assumption will give slightly lower ejecta ranges for the finer particles.

(4) The velocity of the venting gases, as suggested by Appendix C, immediately assumes a constant value, C.

(5) The density of the venting gases varies with the inverse cube of the distance from the source of radius r_0, the radius of the gas volume at venting.

(6) Since ejecta particles are of various shapes, the frontal area of the particle, A, equals the mean dimension, D, squared. For convenience, the notation and assumed constants to be used are summarized below:

$a = a(t)$, particle acceleration

$A = D^2$, particle frontal area

C = gas velocity just after venting

C_d (drag coefficient) $= 2F/[\rho A(C - v)]^2 = 1$

D = mean particle dimension

$F = F(t)$, drag force on particle

$M = \frac{\pi}{6} \rho_p D^3 \approx \frac{1}{2} \rho_p D^3$, mass of ejecta particle

$r = r_0 + Ct$, radius of the gas envelope

r_0 = radius of gas envelope at venting

r_m = 1741 km, the radius of the moon

t = time ($t = 0$ at venting)

V_t = true crater volume

V_x = explosive volume

v = $v(t)$, ejecta velocity

v_b = ejecta velocity at the start of the ballistic phase

v_c = 1680 m/sec, lunar circular orbit velocity at the surface

v_i = mound velocity just before venting

x = ejecta missile range as measured along curved lunar surface

δ = one half the ejecta range angle as measured from the center of the moon

ρ = $\rho(t)$, gas density at $r = r(t)$

ρ_0 = gas density at r_0

ρ_p = ejecta particle density

ρ_x = initial explosive density

υ = v_b/v_c

θ = initial angle of inclination of the ejecta velocity vector with respect to the local horizontal.

The formula for the drag on a particle moving in a fluid is

$$F = \frac{1}{2} C_d \rho A (C - v)^2 \qquad \text{(D1)}$$

Now, because C_d is assumed to be 1, $A = D^2$, and since

$$\rho = \rho_0 \left(\frac{r_0}{r}\right)^3 = \rho_0 \left(\frac{r_0}{r_0 + Ct}\right)^3 . \qquad \text{(D2)}$$

Eq. (D1) may be written

$$F = \frac{\rho_0 D^2 r_0^3}{2} \frac{(C - v)^2}{(r_0 + Ct)^3} . \qquad \text{(D3)}$$

The acceleration produced by this force is

$$\frac{dv}{dt} = F/M = \frac{\rho_0 D^2 r_0^3}{2M} \frac{(C - v)^2}{(r_0 + Ct)^3} . \qquad \text{(D4)}$$

Now

$$\frac{D^2}{M} = \frac{2}{\rho_p D} .$$

Letting

$$\alpha = \frac{\rho_0 r_0^3}{\rho_p D} , \qquad \text{(D5)}$$

Eq. (D4) becomes

$$\frac{dv}{dt} = \alpha \frac{(C - v)^2}{(r_0 + Ct)^3} . \tag{D6}$$

Equation (D6) may be separated and then integrated. The limits of integration are from v_i to v for velocity and from 0 to t for time. The result is

$$\frac{1}{C - v} - \frac{1}{C - v_i} = -\frac{\alpha}{2C} \left[\frac{1}{(r_0 + Ct)^2} - \frac{1}{r_0^2} \right] . \tag{D7}$$

Beyond a certain short time interval, the acceleration of the particle by the gas becomes vanishingly small and, in the absence of other forces, the particle velocity remains constant indefinitely. The particle velocity at the start of the ballistic phase can be thus found by letting t go to infinity in Eq. (D7). This gives

$$\frac{1}{C - v_b} = \frac{1}{C - v_i} + \frac{\alpha}{2r_0^2 C} . \tag{D8}$$

Letting

$$\beta = \frac{\alpha}{2r_0^2} = \frac{\rho_0 r_0}{2\rho_p D} , \tag{D9}$$

and inserting into Eq. (D8) gives the initial ballistic velocity of the ejecta:

$$v_b = C \left[\frac{v_i + \beta (C - v_i)}{C + \beta (C - v_i)} \right] . \tag{D10}$$

The effects of the size and density of the particle and the volume and density of the gas are included in β. It is seen from Eq. (D10) that if β is small, $v_b \approx v_i$, while if β is very large, $v_b \approx C$.

The angular distance around the moon, 2δ, that a particle with an initial free-flight velocity v_b and an angle of inclination θ will travel before impact is given by Ehriche (1962) as

$$\tan\delta = \frac{\upsilon^2 \sin 2\theta}{2 - 2\upsilon^2 \cos^2\theta} . \tag{D11}$$

The maximum range depends on the angle of inclination. The optimum angle for maximum range, θ_m, is a function of υ and is given by

$$\tan \theta_m = (1 - \upsilon^2)^{1/2} . \tag{D12}$$

It may be noted that $\theta_m = 45°$ for low velocities and drops to 0 deg at circular orbit velocity.

As stated in the assumptions, there will always be a particle of a given velocity which has the proper angle of inclination with the horizontal which maximizes range.

From Eqs. (D11) and (D12) the relation for maximum angular missile range can be shown to be:

$$\tan \delta_m = \frac{\upsilon^2}{2\,(1 - \upsilon^2)^{1/2}} \,. \tag{D13}$$

Finally, the maximum arc distance traversed along the lunar surface from initial point to impact is given by

$$x = 2r_m \delta_m \,. \tag{D14}$$

Equation (D9) may be examined in order to select a suitable independent variable to plot initial ballistic velocity and missile range. Here it is noted that the quantity D/r_0 provides a convenient dimensionless quantity. But r_0 is proportional to the cube root of the explosive volume. Therefore, the independent variable

$$D/V_x^{1/3}$$

will serve as the dimensionless variable. If the gas volume at venting is assumed equal to the true crater volume, V_t, then

$$\frac{r_0}{V_x^{1/3}} \approx \left(\frac{V_t}{V_x}\right)^{1/3}$$

and thus

$$\frac{D}{r_0} \approx \frac{D}{V_x^{1/3}} \left(\frac{V_x}{V_t}\right)^{1/3} \tag{D15}$$

Therefore, from Eqs. (D9) and (D15),

$$\beta = \frac{\rho_0}{2\rho_p} \left(\frac{V_t}{V_x}\right)^{1/3} \left(\frac{D}{V_x^{1/3}}\right)^{-1} \tag{D16}$$

The gas density at venting is given by

$$\rho_0 = \rho_x \frac{V_x}{V_t} \,, \tag{D17}$$

where ρ_x is the initial explosive density. Equation (D16) can thus be written in terms of quantities which are either known or easily estimated:

$$\beta = \frac{\rho_x}{2\rho_p} \left(\frac{V_x}{V_t}\right)^{2/3} \left(\frac{D}{V_x^{1/3}}\right)^{-1} \,. \tag{D18}$$

Equations (D10) and (D18) were used to generate the ejecta velocity curve in Fig. 58; Eqs. (D13) and (D14) were used to produce the range curve of Fig. 58. The constants used in the calculations are as follows:

$\rho_p = 3.0 \text{ g/cm}^3$

$\rho_x = 2.0 \text{ g/cm}^3$

$V_t/V_x = 2000$

$r_m = 1741 \text{ km}$

$v_c = 1680 \text{ m/sec}$

$v_i = 60 \text{ m/sec}$

$C = 2000 \text{ m/sec}$.

A discussion of these initial conditions and the simplifying assumptions appears necessary to understand the direction which the errors introduced may take.

The radial gas velocity, C, is the most difficult initial condition to estimate. It is less than the free expansion velocity as determined in Appendix C. How much less must be determined by an energy balance: the added kinetic energy acquired by the ejecta particles must equal the molecular kinetic energy lost by the gas. Since ejecta kinetic energies depend upon ejecta velocities which in turn depend on ejecta particle size, the ejecta particle size distribution must be known. At present, the latter remains an unknown. Once it is determined, the following computational scheme can be used: First, determine the total energy of the explosion gases at venting and the mass of material thrown up by the explosive. Then, estimate a value of C and calculate the corresponding decrease in gas energy. Using Eqs. (D10) and (D18), determine v_b and the corresponding kinetic energies for each narrow range of particle size. By summation, determine the total kinetic energy added to the particles by the gas (do not include the initial kinetic energy of the mound). Repeat the entire calculational sequence with revised values of C until the energy lost by the gas equals that gained by the particles.

The value of C chosen in this report is predicated on the assumption that the heavier Al_2O_3 products dominate the particle acceleration process. If lighter and faster products are present, they will also have some influence. The estimated value of C in the example problem shown in Figs. 57 and 58 is 2000 m/sec. Note that this is close to the lunar circular orbit velocity (1680 m/sec). If the actual value of C is less than 1680 m/sec, as it may be, then no ejecta particles, regardless of size, can go into orbit. Nevertheless, such particles, even if suborbital, can be expected to travel long distances before coming to rest. With no atmosphere to slow the particles, their velocities upon impact will be nearly the same as their initial ballistic velocities.

The relatively high estimate of initial ejecta velocity, v_i, and the assumption of its invariance anywhere on the mound affects the larger particles but not the fine particles. (The latter are relatively unaffected because their initial ballistic velocity, v_b, is so much higher than v_i that the latter is insignificant by comparison.) Ejecta ranges for the larger particles will then be somewhat lower than the predictions.

The explosive properties, ρ_x and V_t/V_x, influence ejecta range in the manner shown in Eq. (D18). Generally, a decrease in ρ_x is accompanied by a corresponding decrease in V_t/V_x. It is seen from Eq. (D18) that the two are somewhat self-cancelling, and, therefore, the two properties have little effect on ejecta range.

The coefficient of drag, C_d, was assumed to be unity. As the gas expands and as the finer particles approach the gas velocity, Reynolds Number decreases with a corresponding increase in C_d (tenfold or more) and, therefore, drag force increases as well. Ejecta velocities and ranges for the finer particles will then be somewhat higher than the predictions.

Appendix E

Suggested Course Schedule for Training for Lunar Chemical Explosives Employment

This appendix presents a suggested schedule for the training required to prepare a worker to accomplish Phase II chemical explosive applications. It is assumed that the explosives and emplacement systems selected for lunar use will not differ radically from the current state-of-the-art (Cauthen, 1964).

The time estimates for each subject area and the sequence of presentation as shown in Table E1 are based on Department of the Army courses of instruction and on an examination of existing explosives training source material.

In consonance with current NASA training philosophy, additional time would be made available at the facilities at Fort Leonard Wood so that the astronauts could sharpen their skills at their own pace prior to embarking on the field exercises at sites selected by the U.S. Geological Survey (USGS).

Table E2 suggests sources for training materials and instructors. All activities at the USGS selected sites would be integrated with the geological training program presented by USGS.

Table E1. Subject time allocation.

Subject Area	Hours per 8-hr training day				
Explosives	2 8 6 2 -	- - - - -	2 2 ——[a]	- - - - -	- - - 2 2
Safety handling storage	2 - - 2 -	- - - - -	2 2 ——[a]	- - - - -	- - - - -
Emplacement design	2 - 2 2 4	4 - - - -	2 2 ——[a]	- - - - -	- - - 2 2
Emplacement equipment	2 - - 2 4	4 8 8 8 8	2 2 ——[a]	8 8 8 8 8	8 8 8 4 4
Training week	One	Two	Three	Four	Five
Location	Fort Leonard Wood, Missouri			USGS Selected Sites	

[a]The last three days of the third week are set aside in order that the trainees may improve their skills on an individual basis using facilities and instructors as needed.

Table E2. Subject area course outline: time, location, and sources required.

Subject Area	Time (hr)	Training location	Training material source[a]	Instructor source[a]
Explosives	22 4	Ft. Leonard Wood USGS selected sites	OCE Picatinny Manufacturer	OCE
Safety handling storage	8	Ft. Leonard Wood	OCE Picatinny Manufacturer	OCE Picatinny
Emplacement design	18 4	Ft. Leonard Wood USGS selected sites	OCE NCG	OCE
Emplacement equipment	48 72	Ft. Leonard Wood USGS selected sites	Manufacturer OCE	Manufacturer OCE

[a]The symbol OCE indicates that the Office of the Chief of Engineers would be responsible for providing the indicated services; Picatinny refers to Picatinny Arsenal; Manufacturer refers to the organization providing the explosives or fabricating the equipment; NCG is the U. S. Army Engineer Nuclear Cratering Group.