Bulletin 69

Lined-Cavity Shaped Charges and Their Use in Rock and Earth Materials

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1959

STATE BUREAU OF MINES AND MINERAL RESOURCES
NEW MEXICO INSTITUTE OF MINING & TECHNOLOGY
CAMPUS STATION SOCORRO, NEW MEXICO

For sale by the New Mexico Bureau of Mines & Mineral Resources
Campus Station, Socorro, N. Mex. — Price $1.25

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Introduction

In recent years the attention of mining engineers has been focused occasionally on lined-cavity shaped explosive charges,[1] often called shaped charges, cone bombs, and Munroe charges. At times, especially following World War II, various mining companies and explosives manufacturers have carried out investigations of the use of lined-cavity shaped charges in the mining industry. Most of these projects received little publicity and generally were considered failures in so far as the development of commercially useful applications was concerned.

In view of spectacular military successes with shaped charges, the general lack of success in the development of commercial uses suggests that perhaps the commercial investigations tended to overlook some essential factor in the design of the shaped charges utilized. From what can be determined concerning most of the projects that failed, this was indeed the case.

Two factors appear to have been the source of the disappointments experienced. The first of these lay in the field of applications. Most work was done with the idea of using the lined-cavity charge by itself as a secondary blasting tool; yet the lined-cavity charge is best suited for punching a hole into a target, not for breaking it. The second and most serious difficulty lay in the type of explosive used. Ordinary, low-velocity, low-brisance[2] mining explosives cannot yield a workable lined-cavity shaped charge. Unfortunately, high-velocity, high-brisance explosives are difficult to obtain. The lack of proper explosives, coupled with the fact that relatively little is known of lined-cavity phenomena outside of ordnance circles, meant that many of the early investigations failed to achieve workable shaped charges.

The purpose of this bulletin is to demonstrate that properly constructed lined-cavity shaped charges can yield penetrations that are of value in mining and allied industries. The treatment includes a general discussion of theory and a detailed discussion of charge performance in various target types.

ACKNOWLEDGMENTS

The writer wishes to express appreciation to the staff of the Task W Naval Research group located at Socorro. Mr. M. L. Kempton arranged for the use of Task W testing facilities, Mr. M. E. Pickens provided advice and help with special explosives problems, and Mr. R. N. Heathcock aided with the high-speed photographic studies.

1. *Shaped charge:* Any explosive charge formed into a specific shape. Most commonly used to denote an explosive charge with cavity at one end; the cavity may be lined or unlined.

2. *Brisance:* Shattering power, related to detonation pressure.

Appreciation is also due the ranchers and mining companies who provided target areas for the testing of many shaped charges. Mrs. Barbara Austin provided invaluable assistance in preparing the manuscript. Many members of the staff of the New Mexico Bureau of Mines and Mineral Resources contributed to the completion of this project; G. B. Griswold, J. H. Schilling, and E. H. Kase, Jr. critically read the report and provided many useful suggestions.

History of the Study of Lined-Cavity Phenomena

The first well-authenticated experiments concerning explosive charges with reentrant cavities were those of Charles E. Munroe, published in 1888. Munroe found that the detonation of a block of guncotton with indentations, usually letters, would reproduce those indentations as a mirror image when fired against an iron target with the indentations facing the target. The unlined-cavity effect is primarily known as the Munroe effect in the United States and England. Aside from the printing of designs, no useful applications of the hollow-charge principle were devised, with the possible exception of a practical method for blowing a safe.

Egon Neumann independently discovered the unlined-cavity effect in Germany in 1910. The hollow-charge effect is still called the Neumann effect in much of Europe.

Both Munroe and Neumann experimented and reported only on the unlined-cavity effect. The origin of explosive charges with lined cavities is obscure. It is claimed that Germany had such charges in World War I, and some shaped-charge investigators in the early part of World War II attributed the discovery of these phenomena to Neumann. At present most investigators attribute the discovery of the lined-cavity shaped charge to R. W. Wood, of the Johns Hopkins University.

Dr. Wood's discovery of the value of a liner in a hollow-cavity charge came about through chance. A worker for an explosive manufacturer discovered some years ago that a blasting cap could be loaded with a density gradient in the explosive if the end of the cap were punched in to form a dimple after the explosive was emplaced. The dimpled caps gave excellent results, especially in tests involving the perforation of metal plates. About 1936 a person was killed by a dimpled blasting cap. Dr. Wood was asked to investigate and found that the detonation of a dimpled blasting cap gave a high-velocity jet of metallic particles from the copper sheath comprising the dimple.

In 1944, Korolev and Pokrovskii published an article in Russia on the jets emitted by No. 8 blasting caps sheathed with copper. The design of these miniature lined-cavity shaped charges was fortuitous; yet they yielded very respectable high-velocity jets. Korolev and Pokrovskii found that the jet velocity was 10,000 meters per second at the cap face. Even at distances of 120 millimeters from the cap, the jets were found still to be traveling at 5,000 meters per second.

Following Dr. Wood's discovery, most of the major powers in the world initiated research projects designed to create weapons utilizing the lined-cavity phenomena. These projects were successful. Probably the most widely known military shaped-charge device is the bazooka, which consists of a lined-cavity shaped charge mounted on a small rocket. Numerous other military shaped-charge devices have been developed and used, ranging from warheads on projectiles and missiles to "shapes" for demolition purposes. Unfortunately, the military interest has meant that most of the papers written on the lined-cavity phenomena have been "classified" and are not available to the public. In 1956, Poulter and Caldwell estimated that 1,800 IBM cards were needed to catalog the literature on lined-cavity phenomena; most of this literature was, and still is, classified.

Publications on the fundamentals of the lined-cavity phenomena did not begin to appear until the late 1940's. By then, the mining and allied industries were highly disappointed with the results of many attempts to use shaped charges. Numerous tests and experiments had resulted in failure. The failures can be attributed generally to the lack of fundamental data at the time the tests were made.

Among the first widely distributed articles on shaped charges were two by Volta Torrey in 1945. These articles gave descriptions of some of the military shaped charges, as well as penetration data. Such articles, as well as the personal experience of many individuals who had utilized explosives while in military service, brought about the early research efforts concerning industrial applications.

During 1946, Huttl published an article which speculated on possible uses of lined-cavity as well as unlined-cavity shaped charges for mining usage. In this same year, two articles appeared which briefly discussed a successful application of shaped charges to boulder breakage at the National Tunnel and Mines operations in Utah. During this year, the first of a growing number of articles appeared concerning oilwell-completion methods which utilize lined-cavity shaped charges.

In the following year, further articles were published concerning the possible applications of shaped charges to mining problems. Articles also appeared dealing with university research concerning the use of the lined-cavity phenomena. Work at the University of Utah was published by Lewis and Clark; similar work at the Missouri School of Mines was published by Clark and Bruckner. Other papers appeared which briefly discussed the use of shaped charges at the National Tunnel and Mines operations in Utah, and a paper was published by Argall et al. on the use of shaped charges at the South of Burns mine, at Cripple Creek, Colorado. Roos published an interesting example of the use of lined-cavity shaped charges to break up and remove boulders encountered in the test drilling of placer ground.

In 1948, the U. S. Bureau of Mines reported on attempts to drill blast holes in metamorphic rocks by means of war-surplus pentolite charges. During the same year, the first publication appeared which dealt in detail with the processes of jet formation and target penetration. This was a paper by Birkoff, MacDougal, Pugh, and Taylor. Thus, for the first 3 years of attempted use of lined-cavity shaped charges for industrial purposes, essentially no basic concepts were available which explained the lined-cavity phenomena.

In 1949, a lined-cavity shaped charge was marketed for the mining industry. Unfortunately, the charge did not work well, nor did it conform to the proven concepts of shaped-charge mechanisms. A paper was published during this year by J. C. Clark on X-ray studies of jet formation. Two papers by Kolsky presented another concept of jet formation. In addition, an article appeared on a reportedly successful use of shaped charges at the Consolidated Coppermines operations in Nevada.

Brief articles were published in 1950 and 1951 on the reportedly unsuccessful, but commercially available, shaped charge, which was first introduced in 1949. In 1951, a paper on the fundamentals of shaped charges was published in England by Evans. Since this time, steady additions have been made to the fundamental knowledge of lined-cavity phenomena. These additions have been devoted almost exclusively to the hydrodynamic theory; yet the hydrodynamic theory explains only a few of the many lined-cavity shaped-charge mechanisms.

In 1953, the U. S. Bureau of Mines published a paper on possible applications of the lined-cavity phenomena to mining. The paper did not make full use of the fundamental data available. As a result, field tests of some of the ideas proposed were not notably successful.

In the years since 1946, a steady procession of articles devoted to the perforation techniques used in oil well completions have appeared. These articles engaged in much controversy concerning the type of hole made in the target rock, and apparently the controversy has not been resolved.

To sum up the historical aspects, considerable fundamental literature is now available concerning the hydrodynamic mechanism of jet formation. Only limited data are available for other mechanisms, and very little literature is available concerning the penetration of targets, especially nonductile targets such as rock and other earth materials.

Currently Accepted Theories of Jet Formation

There has been considerable disagreement among the investigators of lined-cavity shaped-charge mechanisms. Such disagreement is the result of a number of factors. Undoubtedly, each shaped-charge investigator who is propounding his own theory can provide concrete evidence to support it. This means that there are a number of possible mechanisms whereby an explosive charge with a lined, hollow cavity can form a high-velocity jet. A given lined-cavity shaped charge can be designed to work according to only one mechanism, or it can be designed to work according to a number of mechanisms, either mixed or in sequence. Only slight variations are needed in the design of a given charge to vary the mechanism by which the jet is formed. The multiplicity of jet-forming mechanisms has been largely unmentioned in the publications on lined-cavity phenomena.

HYDRODYNAMIC THEORY

The hydrodynamic theory published by Birkhoff, MacDougal, Pugh, and Taylor in 1948 is the most widely known of the theories currently held concerning jet formation. This theory accounts for many of the characteristics of jets and also for much that has been observed concerning the typical penetration of solid targets by jets. The hydrodynamic theory apparently is limited to charges utilizing thin-walled, wideapical-angle, straight-walled (conical) liners, as opposed to liners with curved walls, such as hemispheres.

According to the hydrodynamic theory, the detonation of a charge and the collapse of the liner can be treated as steady-state phenomena.[3] In reality these phenomena are violently time dependent.[4] The assumption of steady-state conditions has enabled the development of a workable set of equations to explain the observations made during the detonation of a charge of the required design. Later modifications of this theory have overcome some of the inaccuracies resulting from early simplifications.

Use of the hydrodynamic mechanism requires the assumption that the metal of the liner, a cone, is forced to converge at the cone axis by the explosion. The liner material will split at the point of convergence. The inner surface of the liner will move forward, and the outer surface backward, from the point of convergence. Since the point of convergence itself has a large forward velocity, the jet will have a very high

3. *Steady state:* The phenomena proceed unchanged over a certain time interval.
4. *Time dependent:* The phenomena change with time.

forward velocity, whereas the slug, comprised of the outer surface of the liner, will have a very low forward velocity. The collapse process is illustrated in Figure 1.

A jet which forms as a result of a collapse process conforming to the hydrodynamic theory will have the following general characteristics: (1) a tip traveling at a very high velocity; (2) a velocity gradient with decreasing velocity toward the rear; (3) a low-velocity slug; (4) an ability to lengthen during travel, owing to the velocity gradient; (5) a forward portion comprised of the inner surface of the liner; (6) an afterportion, the slug, comprised of the outer surface of the liner; and (7) an increasing amount of metal toward the rear of the jet.

One aspect of lined-cavity phenomena which always surprises those not acquainted with the jet-forming process is the ability of the jet to lengthen as it travels. The jet penetrates farther as it becomes longer; that is, depth of penetration is a function of jet length. If the charge is fired at a distance from the target, the jet will have a chance to grow longer before it runs into the target mass, thus making a deeper penetration. The distance from the target to the base of the liner is called the standoff.

An optimum standoff is found to exist for each target type as well as for each charge design. If the standoff is too large, the jet will scatter and wander. If the standoff is too short, the jet will not have time to lengthen prior to hitting the target. Of added importance is the fact that the jet is slowed rapidly by air resistance in the case of too long a standoff.

The hydrodynamic theory has been well verified. Flash X-ray studies, radioisotope tagging of liners, and bimetallic liners have all been used to demonstrate this theory. The majority of lined-cavity shaped charges are designed to conform to the hydrodynamic theory because charges which conform to this theory are simple to make and give reasonably good results in the field.

The limits and values imposed by the hydrodynamic theory on charges which conform to it are worth noting. If a conical liner is employed and a plane wave is used to impact the liner, the maximum attainable jet velocity will be two times the detonation velocity of the explosive used in the charge. Charges used in the field come close to achieving the theoretical maximum jet velocity.

A greater refinement in charge design is achieved when the detonation wave is made to conform to the shape of the liner by wave guides or shapers. In charges of this type, the theoretical maximum velocity is now infinite, but as the jet velocity increases, the mass of the jet will decrease, approaching zero as the velocity approaches infinity. The controlling variable, the velocity-mass determinant, is now the apical angle of the liner.

The Los Alamos Scientific Laboratory has published the results of the firing of shaped charges designed to create fast jets. By using cylindri-

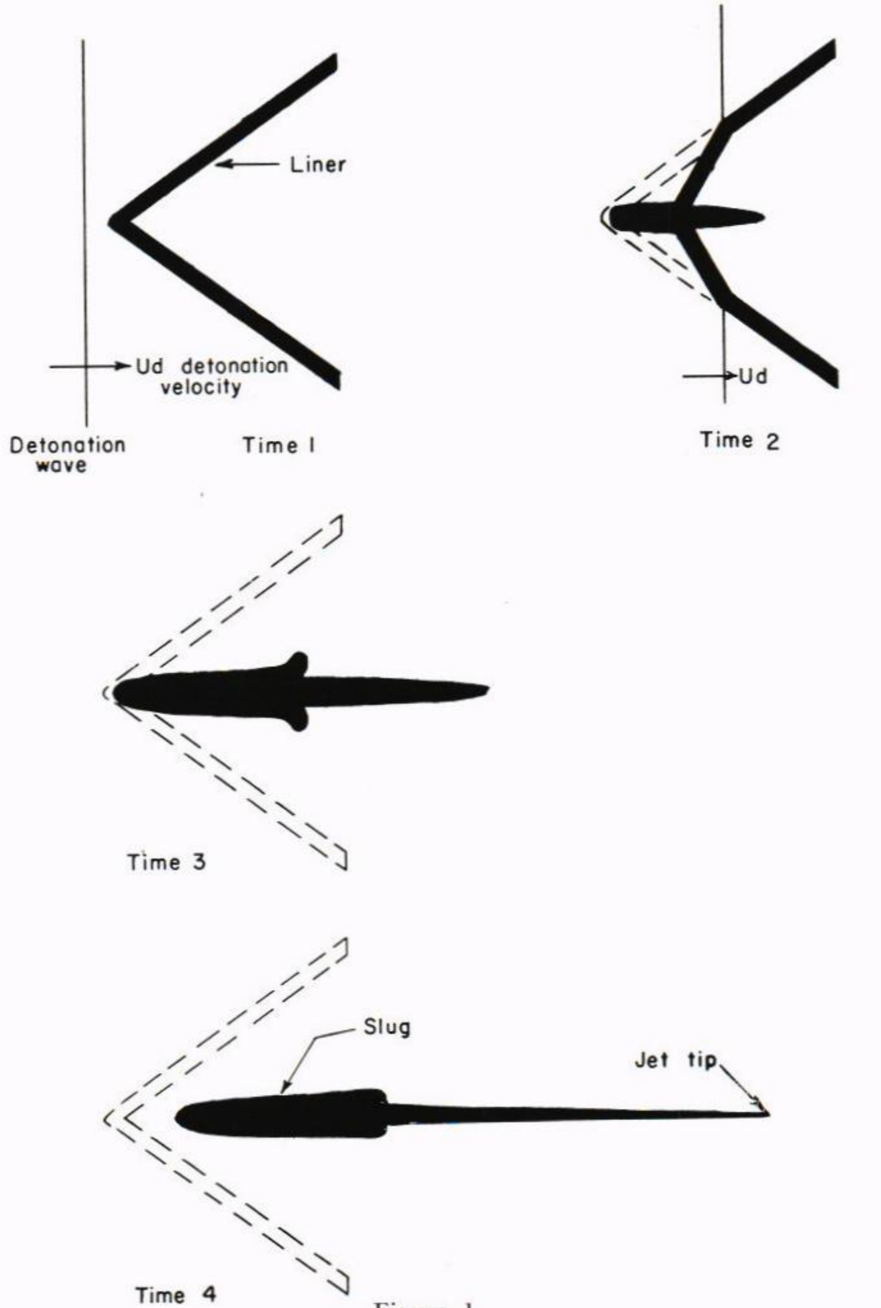


Figure 1

HYDRODYNAMIC COLLAPSE OF A SHAPED-CHARGE LINER

Adapted from Eichelberger and Pugh (1952).

cal liners (that is, liners with a zero apical angle) and converging detonation waves to obtain a maximum of pressure on the liner, the investigators at Los Alamos were able to obtain gaseous jets traveling at about 295,000 feet per second. Interestingly, this group of investigators (Koski, Lucy, Shreffler, and Willig, 1952) concluded that their fast jet had not been formed according to the hydrodynamic concept.

PLASTIC-FLOW THEORY

The plastic-flow mechanism of liner collapse has been outlined by Poulter and Caldwell. It is the mechanism of deformation favored by the collapse of thick-walled, conical liners with small apical angles. A uniform explosive loading over the entire surface of the liner will help to promote plastic-liner collapse and jet formation.

During the plastic deformation of a liner, the entire liner collapses to a solid mass of metal at the original liner axis. Extrusion is believed to occur when this large mass of metal collides along the axis of the liner. The extrusion creates a high-velocity jet. The proponents of the plastic-flow mechanism believe that the high-velocity portion of the jet, its tip, is derived from the central portion of the liner cone. A distinct velocity gradient is proposed, and all the aspects of target penetration and standoff applying to the hydrodynamic theory are equally applicable to the plastic-flow theory. Figure 2 shows how the plastic-flow collapse mechanism can deform a liner to yield a jet, and how the jet tip is believed to break free during deformation.

Flash X-ray studies and bimetallic liners have been used to demonstrate the existence of the plastic-flow mechanism of deformation.

SPHERICAL-CONVERGENCE THEORY

Very early in lined-cavity studies, speculation began to appear that perhaps curved-surface liners collapsed in a different manner from straight-surfaced liners. The spherical-convergence mechanism has been outlined by Poulter and Caldwell, who considered it the jet-forming mechanism for shaped charges with liners made of a portion of a sphere. During spherical convergence, the detonation wave in the explosive is designed to conform to the shape of the liner. When this condition is met, the liner is believed to collapse uniformly, so that the liner becomes thicker as collapse proceeds. The thickness of the liner becomes the length of the jet, and the diameter of the liner decreases to the diameter of the jet. No slug is formed, but the jet is still presumed to have a velocity gradient. Except for the lack of a slug, a penetration with a jet formed by spherical convergence will have the same aspects as a hydrodynamically derived jet. Figure 3 illustrates a spherical-convergence collapse.

Very little is known about liners with curved surfaces, and much additional research remains to be done. A conflicting theory has been

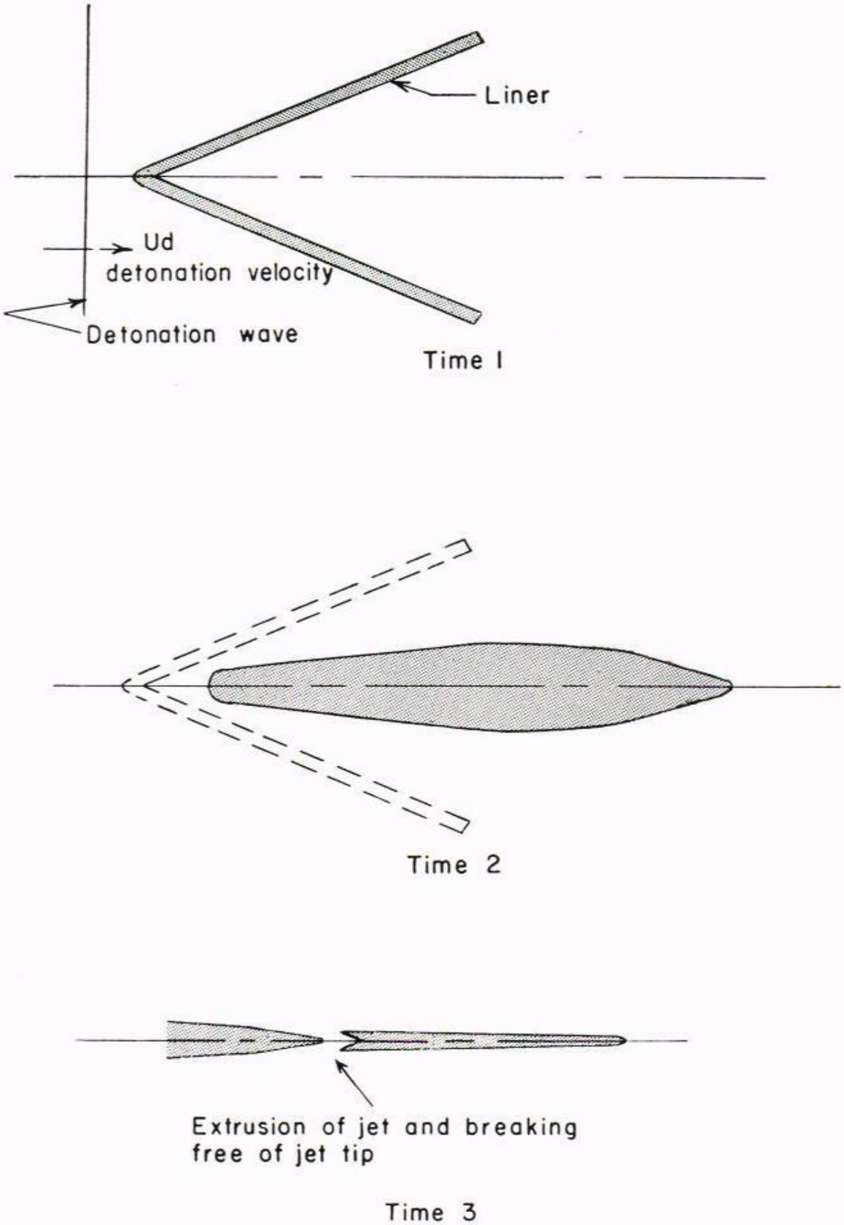


Figure 2

PLASTIC-FLOW COLLAPSE OF A SHAPED-CHARGE LINER

Adapted from Poulter and Caldwell (1957).

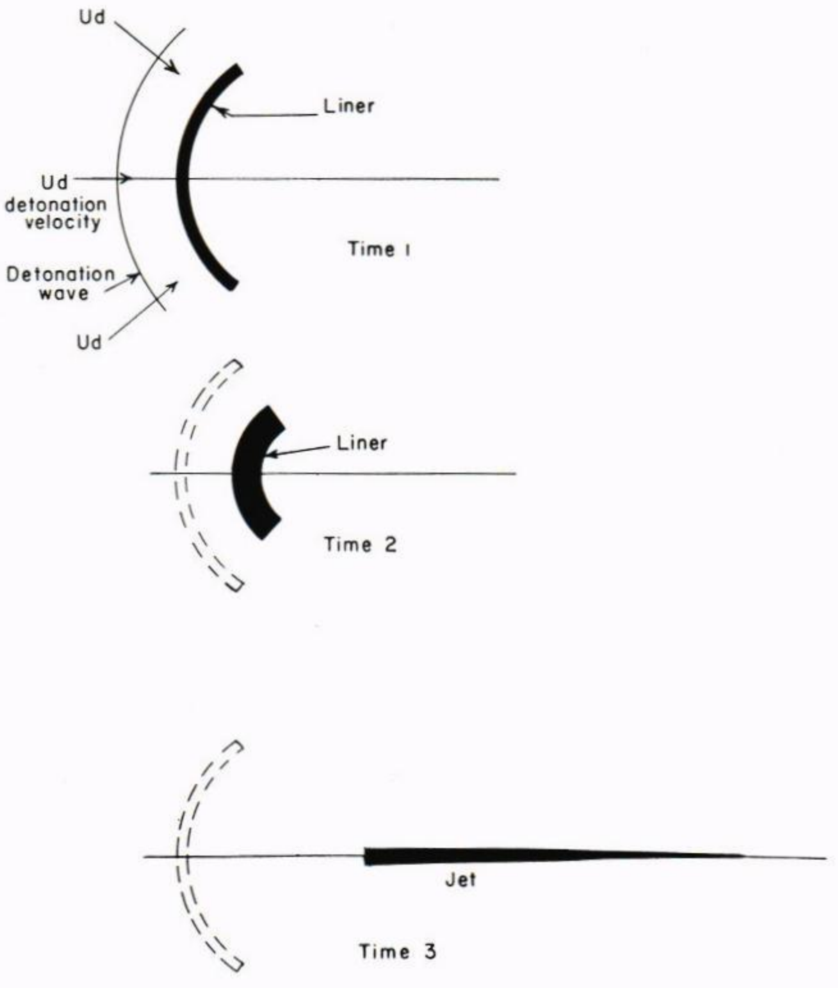


Figure 3

SPHERICAL-CONVERGENCE COLLAPSE OF A SHAPED-CHARGE LINER

Adapted from Poulter and Caldwell (1957).

advanced by Kolsky (1949), who showed that the liners studied by him turned inside out and then broke up into particles.

BRITTLE-FRACTURE THEORY

Another mechanism proposed for jet formation is the brittle-fracture mechanism. The brittle-fracture theory requires a liner made of quartz, glass, ceramics, carbides, or other nonductile materials. When a nonductile liner is struck by a detonation wave, the liner will shatter into very small particles. The particles then act in a fashion similar to the plastic-flow mechanism. As the mass of fine particles is forced together at the axis of the liner, a portion of the liner is extruded as fine particles which form a typical high-velocity jet along the liner axis. The resulting jet has a velocity gradient and behaves in the same manner regarding target penetration and standoff as the other types of jets which have been discussed.

Some writers suggest that further complications in mechanism might be encountered in the event that the liner were of glass, which would partially fuse during jet formation. Other complications will arise when the liner is composed of aluminum or some other metal which explodes on impact.

Much basic research remains to be done concerning jet formation. Research on current problems may have been done by military and other governmental agencies, but research of this type is of no value to industry and other organizations lacking access to classified data.

Target Penetration With High-Velocity Jets

The formation of high-velocity jets is an open subject. The question of what happens when a high-velocity jet strikes a target is even less settled. Perhaps the only aspect of the subject of penetration upon which all investigators will agree is that some sort of hole will be made in the target. The reasons for the disagreements are worth mentioning. The properties of jets are not well known. Their velocity and mass distributions can only be guessed unless very painstaking and complicated experiments are undertaken. Added to the uncertain qualities of the jet are the uncertainties of the target. The reaction of a target to a given type of jet is hard to determine. With targets as heterogeneous as rock or other earth materials, the problem becomes enormous.

PENETRATION OF METAL TARGETS

A theory of penetration for targets of metal or other ductile materials was published in 1948 by Birkhoff, MacDougal, Pugh, and Taylor in their classic paper on lined-cavity phenomena and the hydrodynamic concept. The same theory was published independently by Pack and Evans in England in 1951. Further work was published in 1956 by Eichelberger, who gave revisions of the hydrodynamic theory covering inaccuracies related to some of the simplifying assumptions made in the earlier papers.

The original paper describing the hydrodynamic theory, by Birkhoff, MacDougal, Pugh, and Taylor, summed up the jet-penetration process in ductile targets by likening the penetration of a target material to the penetration of a mass of soft mud by a high-speed jet of water from a nozzle. According to this idea, the target material, in this case mud, is splashed out radially, and the resulting hole is considerably larger in diameter than the jet causing the hole. The large size of the hole results from the target's continuing to flow after the jet has hit the target. In accordance with the hydrodynamic theory, field work shows that soft targets will yield large-diameter holes, whereas hard targets will yield holes of small diameter. Some investigators, however, attribute the large holes in soft targets, such as lead, to the explosion of the target metal upon impact.

According to the hydrodynamic concept of penetration, the depth of penetration by a jet into a given target is dependent only upon the length and density of the jet and the density of the target. The jet velocity is immaterial so long as the jet is above the speed needed to reduce the target strengths to insignificance. The equations developed by the hydrodynamic theory show that the depth of penetration by a given charge should be inversely proportional to the square root of the density of a given solid target. The independence of penetration from the jet velocity is true only in theory; there are many exceptions. A faster jet will have more particles traveling above the critical hole-forming velocity and will make a larger diameter hole to a greater depth. Examples of rapid hole necking readily illustrate the opposite conditions. A jet that is too fast will tend to plug the hole and give a penetration of poor quality. The more recent papers on target penetration have added terms to the basic hydrodynamic equations in order to account for the effects of target strength during the latter stages of penetration.

Early investigations were concerned with whether the jet was continuous or in particles. More recent publications have concluded that the question of particle jets as opposed to continuous jets is not significant. Fundamental investigations have shown that the jet-forming process is not affected by a jet-target impact and that the jet formation can be divorced from the process of penetration.

Some investigators have raised questions about penetrations that are beyond the scope of the hydrodynamic concept. For example, recently published work concerning the vaporization of jets and targets has suggested that target and/or jet particles may well explode to help create large holes in low-volatility targets such as lead.

CHARACTERISTICS OF HOLES SHOT INTO METAL

Mining applications are possible in which a hole might be shot into a metal target such as a valve gate, bulkhead, or pipe. Therefore, coverage of the common results of lined-cavity shots made into metal targets is considered worth while.

Figures 4 and 5 show a bimetallic target after it was shot with one of the author's small lined-cavity shaped charges. These figures will provide illustrations of a number of interesting aspects of metal penetrations.

The lead target yielded a hole of much greater diameter than the armor-plate portion of the target. The large-diameter hole in the lead is the result of the low resistance of lead to deformation, as well as, perhaps, some explosion of the lead.

The target lost no weight despite the large holes in it. The large-diameter hole in the lead target was created without weight loss because the target increased in thickness. Lateral expansion of the target was prevented by making the target large in diameter. if the target had been small in diameter, the hole would have formed through simple radial expansion of the target.

When a target comprised of metal plates is shot with a lined-cavity shaped charge, the plates are bent. The upper plates are bent toward

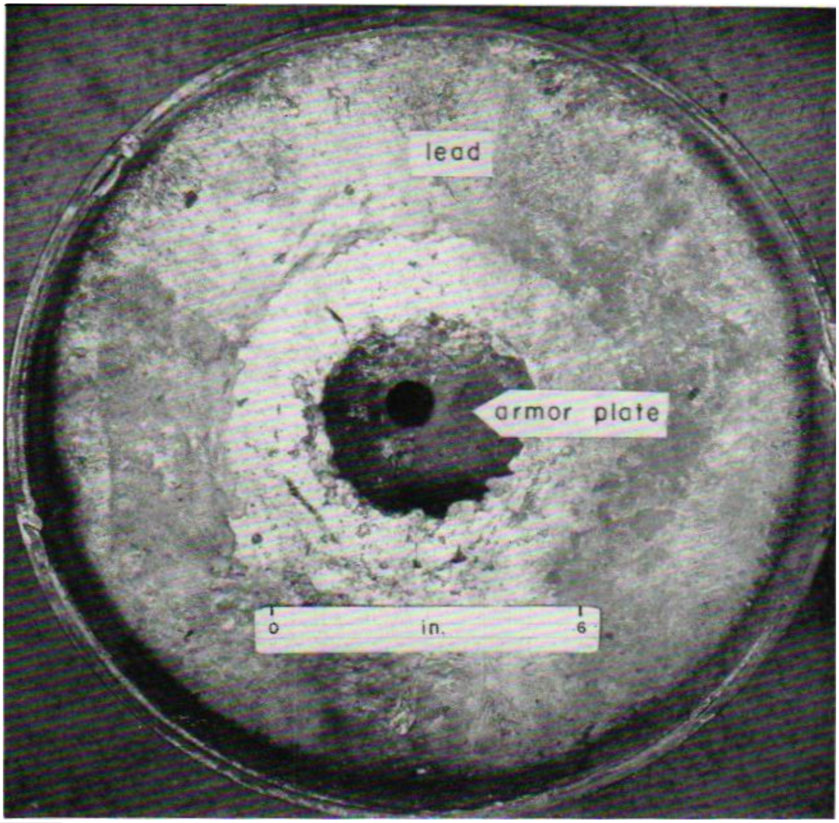


Figure 4

RESULTS OF A SHOT THROUGH A TARGET OF LEAD AND ARMOR PLATE WITH A 4-INCH-DIAMETER CAST IRON LINER

Instead of necking of the hole due to energy losses during penetration, two distinct diameters of hole resulted.

the charge, and, in the event of perforation, the lower plates are bent away from the charge. The bending is due to the transfer of energy from the jet to the target, as well as to the direction of easiest movement, and is not related to the proximity of the explosive charge. Figure 5 is a good example of the bending of a plate during perforation. In this instance, the target plate was lying on loose ground which was too soft to provide support.

The condition of the hole wall, from a practical viewpoint, will depend on the type of target material and the quality of the jet. If the jet is well alined, as a result of a symmetrical charge and liner, the

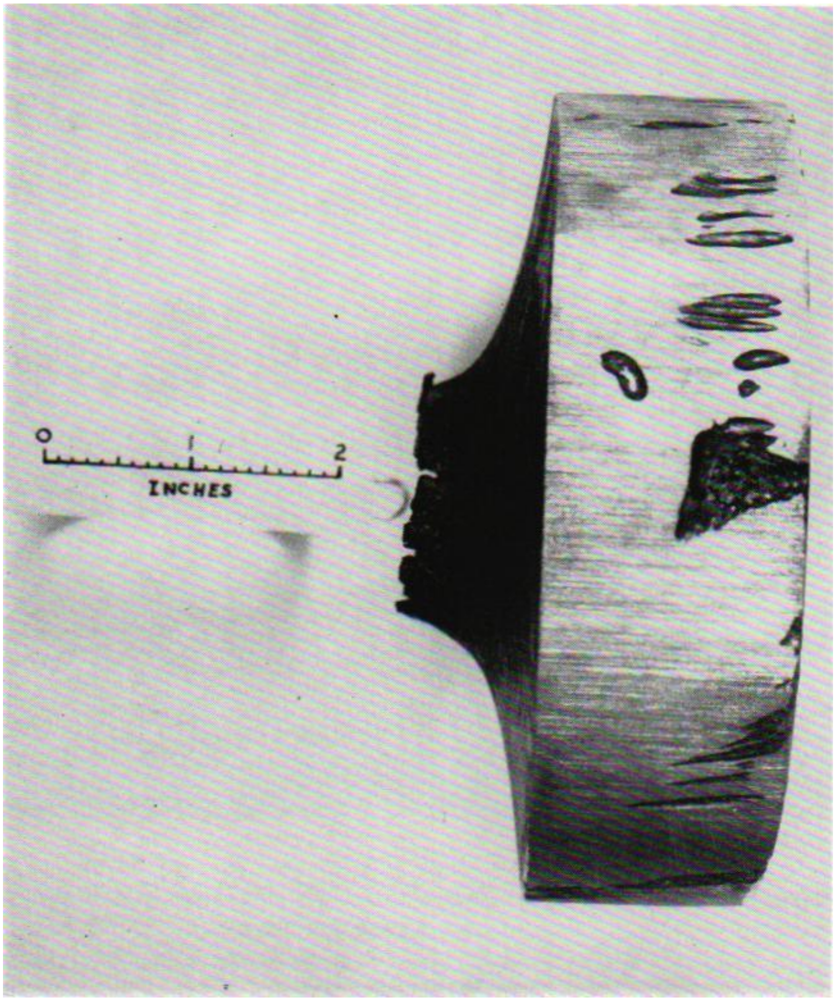


Figure 5

RESULTS OF A SHOT THROUGH ARMOR PLATE WITH A 4-INCH-DIAMETER CAST IRON LINER

resulting hole will be deep and smooth in a target made of a material such as armor plate. A more ragged hole will be produced in a target material such as lead. if the jet is of poor alinement, a ragged, irregular hole will result regardless of the target type.

In summary, a jet fired into a metal target can be expected in actual practice to make a relatively deep, narrow, tapered hole. The exact profile of the hole will depend on the alinement of the jet, the material of the jet and target, and the mass and velocity distributions of the jet material. Variations of the mass and velocity of a given jet with time will cause the hole in a target to widen and narrow as penetration proceeds.

PENETRATION OF NONDUCTILE TARGETS OF ROCK AND EARTH MATERIALS

Governmental and military agencies have expended considerable effort to determine possible mechanisms of ductile-target penetration. The result has been one published theory, the hydrodynamic theory of jet formation and target penetration. The few papers which deal with nonductile targets of rock and other earth materials are in poor agreement primarily because of attempts to provide a universal concept from observations of results in a particular type of target, and also as a result of commercial rivalry. The basic mechanisms of penetration have not been discussed in detail, if at all, in most studies on penetrations in nonductile materials. The disagreements, especially in papers on oil well perforations, center about compaction, hole-wall fusing, wall fracturing, and plugging of the hole by the jet and slug.

Because of the lack of a basic theory for penetration in nonductile solids, a portion of the present project was devoted to obtaining information as to how a high-velocity jet makes a hole in a massive nonductile target such as rock. The subject of rock-penetration mechanisms will be covered in detail in a separate publication but will be discussed here briefly, as knowledge of penetration mechanisms will enable the mining engineer to create a better shaped charge for a particular problem.

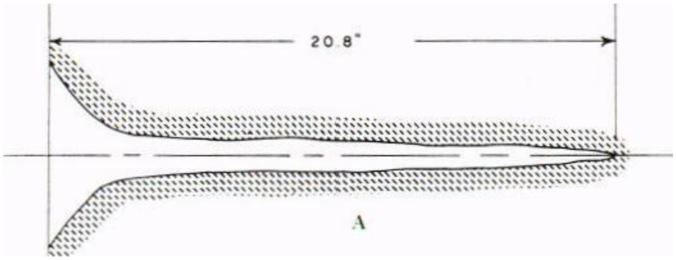
GENERAL FIELD OBSERVATIONS

A typical hole resulting from a lined-cavity shaped-charge blast is relatively deep, narrow, tapering near the bottom, and with or without a crater at the surface, the entire profile being dependent on both the jet and target characteristics. Admittedly, the description is vague; necessarily, for there are so many variables active in any type of lined-cavity blast that the hole may assume a large number of profiles. Figure 6 shows the profiles of two holes shot into the same target with jets of different types. Figure 7 shows the profiles of holes shot into different rocks by means of the same type of jet.

A jet penetration may be divided into the following areas: crater or hole entrance, the hole, and the hole bottom. Each of these will be discussed briefly.

Crater

When a jet of metal derived from a lined cavity runs into a target mass, the surface of the target usually, but not always, yields a crater through a spalling action. Rock targets which failed to yield craters



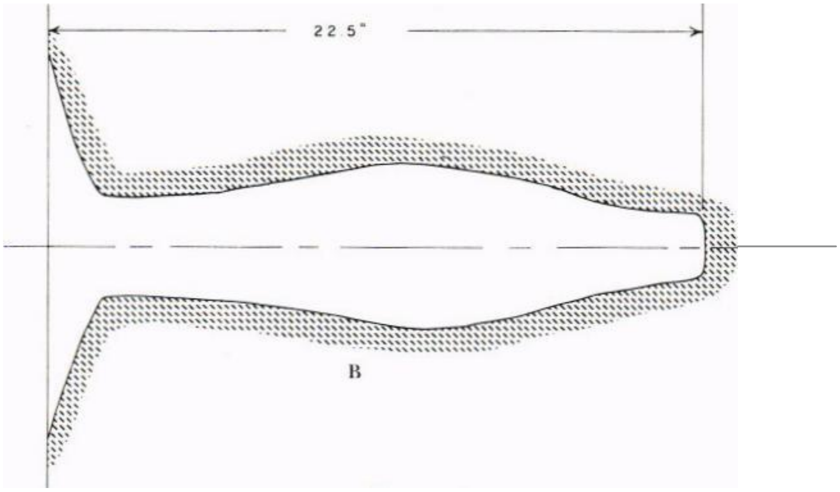


Figure 6

PROFILES OF HOLES SHOT INTO RHYOLITE WITH (A) A 4-INCH-DIAMETER CAST IRON LINER AND (B) A 6-INCH-DIAMETER CAST IRON LINER

consisted of the following: targets with a multitude of fractures prior to the blast, alluvium, and occasionally fresh surfaces of hard rock. Holes which did not have craters at their mouths showed slight flaring near the surface but were essentially straight walled and made virtually right-angle contacts with the original target surface. Figure 8 shows craterless holes shot into altered quartz monzonite; Figure 9 shows a similar hole shot into alluvium.

All the holes shot into limestone and sandstone, and most of the holes shot into rhyolite and altered quartz monzonite, exhibited some

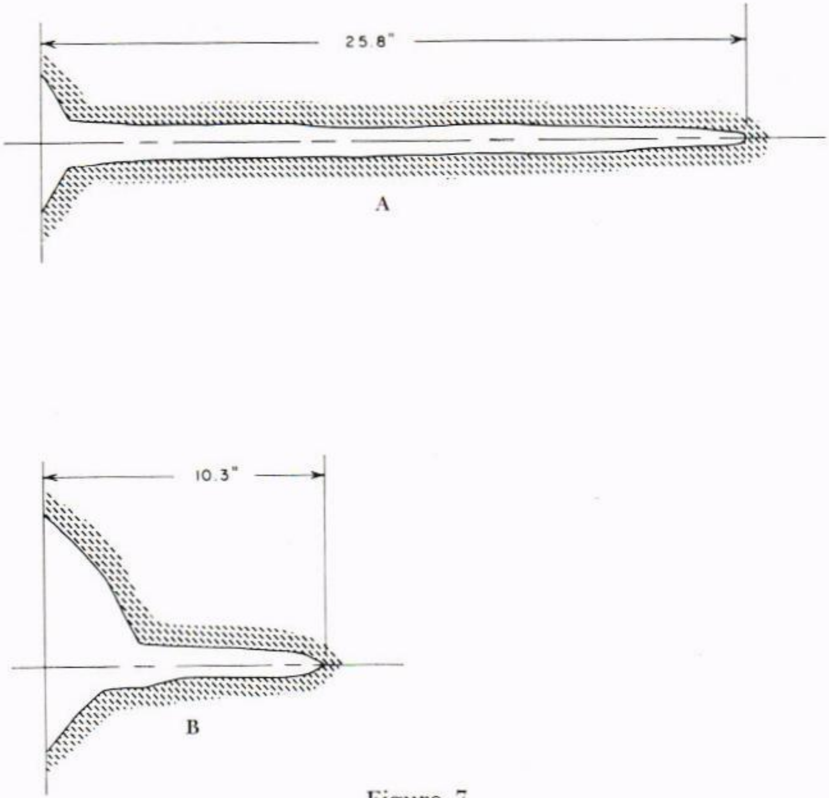


Figure 7

PROFILES OF HOLES SHOT INTO (A) SANDSTONE AND (B) LIMESTONE WITH 4-INCH-DIAMETER CAST IRON LINERS

form of crater at the hole entrance. All the shots into limestone produced rough, irregular craters. The crater shapes were controlled by preexisting fractures, but the predominant form was a cupped crater; that is, a shallow crater with a small diameter. Figure 10 is an example of this type of crater. Some of the shots in limestone yielded broad, deep craters with no penetration beyond the crater. The broad, deep crater forms were made in targets fractured prior to the blast in such a manner as to have no lateral support for the target area. Figure 11 is an example of deep cratering.

Rhyolitic targets gave both cupped craters and broad, deep craters. The shallow, cupped cratering occurred only in the weathered surface of the targets. Thus, in reality, the rhyolite normally presented a two-layer target. The cupped craters most commonly were concave, but a few had straight or convex walls. Figure 12 presents a cupped crater in

Figure 8

CRATERLESS HOLES SHOT INTO ALTERED QUARTZ MONZONITE WITH 4-INCH DIAMETER CAST IRON LINERS

Figure 9

CRATERLESS HOLE SHOT INTO ALLUVIUM WITH A 4-INCH-DIAMETER CAST IRON LINER

rhyolite. Figure 13 shows a number of crater profiles obtained in rhyolitic targets.

The deeper craters in rhyolite were seldom evinced by other than occasional surface fractures. Continued temperature changes due to several months of standing out of doors caused some deep craters to complete themselves through relief of stress. Figures 14, 15, and 16 show a deep crater formed by sudden relief of stress.

A sufficient number of shots were made in rhyolitic targets to allow comparisons between the type of crater and the quality of the hole. The initial volume of the crater was found to be an index of the quality of the penetration. A small, cupped surface crater usually was accom-

Figure 10

FRACTURE-CONTROLLED CUPPED CRATER SHOT INTO LIMESTONE. WITH A 4-INCH-DIAMETER CAST IRON LINER

panied by a deep penetration. Larger, broader surface craters were accompanied by poor-quality, shallow penetrations.

The shots made into sandstone yielded typical cupped craters related to the depth of weathering, as well as deeper and broader incipient craters, in the same fashion as the rhyolitic targets.

The craters formed in the altered quartz monzonite appeared to be controlled by fractures existing prior to the shot. Where the preexisting fractures were few in number, the craters assumed shallow cupped forms that were somewhat broader than in the other rock types tested. Figure 17 is an example of a fracture-controlled crater in altered quartz monzonite, and Figure 18 is an example of a more normal, cupped crater in the same kind of rock.

Questions arise as to why craters are formed and why they assume the forms they do. These questions are related to the fundamental consideration of how a high-velocity jet penetrates a given target. On the basis of field observations, as well as theoretical considerations, the jet is believed to impart a high radial velocity to the target particles located at the point of jet-target contact. For the sake of the immediate discussion, let us momentarily assume that such is the case. The problem of target reaction will be considered in detail in the section on hole-forming processes. The target can be regarded as having infinite confinement downward and radially. If confinement is lacking, the target will simply deform or, in the case of a brittle material, break. In contrast, the air-target interface at the surface presents virtually no confinement. At the start of penetration, the high-velocity, radially moving particles resulting from the jet-target impact will bombard the hole walls near the surface of the target. The extreme compression of the target in this area of only partial confinement (i.e., inward into the target mass and laterally) means that the direction of easiest relief is outward and that failure will occur in this direction. As a result, the target will spall around the hole collar to form a crater. The exact profile of the crater will be determined by the physical characteristics of the target mass on and near its surface. Most of the rock targets utilized were two-layer situations because of weathering. Figure 19 is a sketch of the author's concept of cratering in rock targets.

The shallow, cupped surface craters are not the result of shock phenomena; rather, they are caused by the spalling reaction of the target, which is due to the sudden compression resulting from the hole-forming process. The deeper, broader craters have the appearance of being related to shock-wave phenomena. In this instance, the main target mass

Figure 11

DEEP CRATER SHOT INTO LIMESTONE WITH A 4-INCH DIAMETER CAST IRON LINER

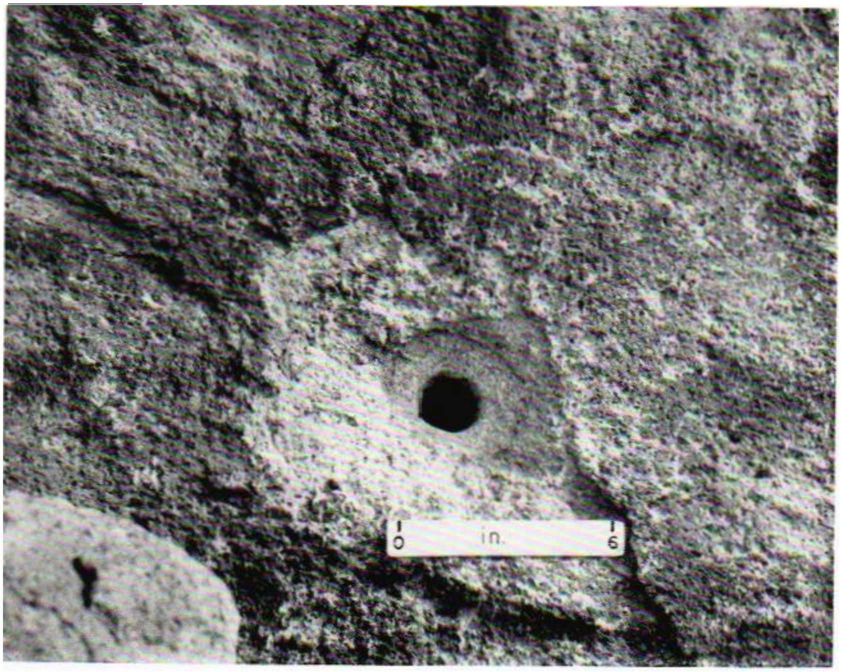


Figure 12

CUPPED CRATER SHOT INTO RHYOLITE WITH A 4-INCH-DIAMETER CAST IRON LINER

exhibits deep, multiple fractures. The shock wave attendant upon the formation of the hole is considered the cause of deep fracturing.

Hole

The hole itself is the most important result of a lined-cavity blast. Therefore, not only how the hole is formed but also the character of the hole are of interest.

The initial hole formed by a jet derived from a lined-cavity is free of debris except at the base or hole bottom. The hole is formed as a result of the jet's imparting radial motion to the target particles at the jet-target interface. As these particles move out away from the jet, they collide with other target particles, either moving or at rest. The net result of the process is the movement of target particles and spent jet material in an axial direction back out of the hole at the same time that the jet is moving axially into the hole. By the time the penetration is complete, the spent jet particles and the broken target particles are swept out of the hole in an axial direction to form what is termed the backblast. This means that the hole is initially free of debris and ob-

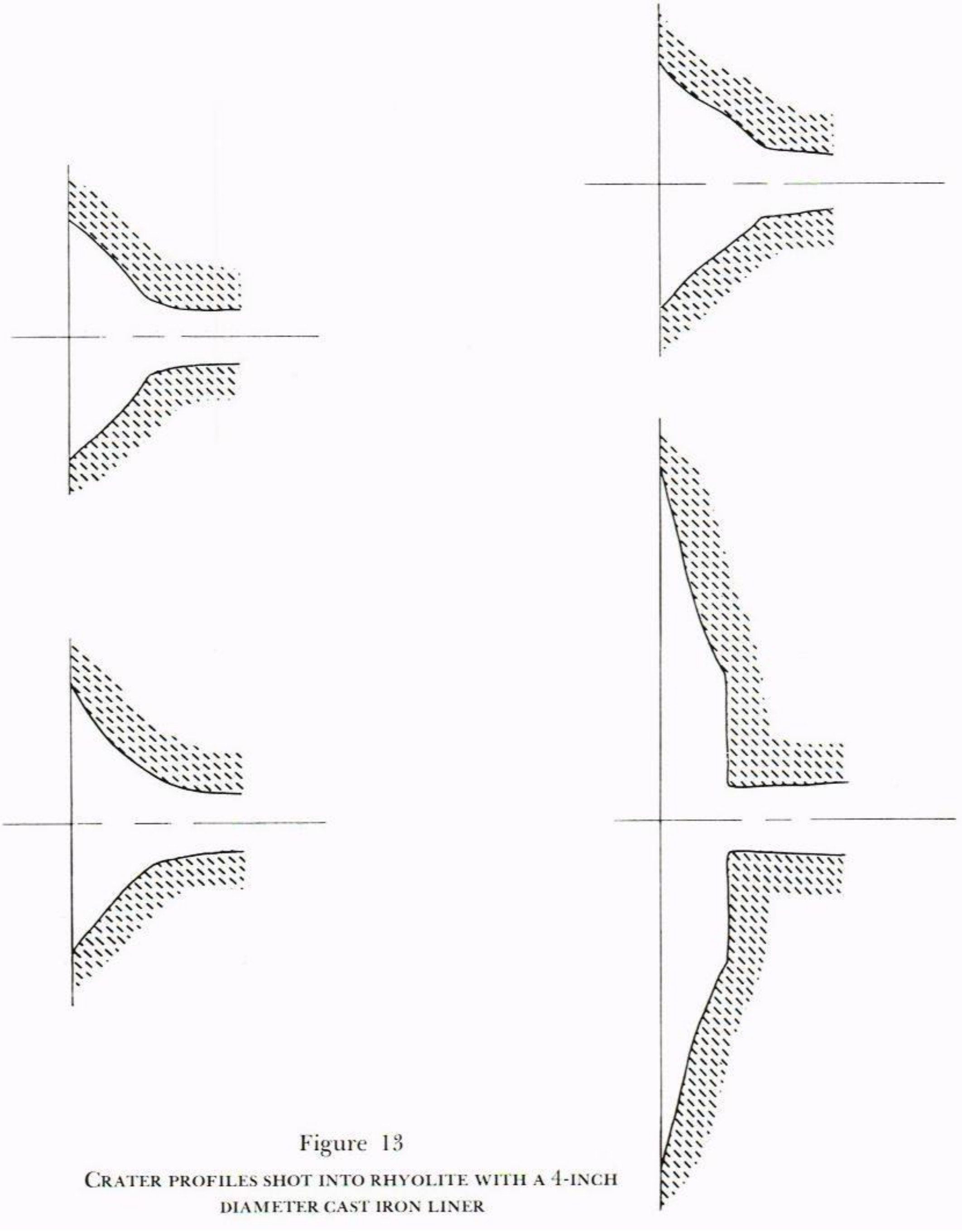


Figure 13

CRATER PROFILES SHOT INTO RHYOLITE WITH A 4-INCH DIAMETER CAST IRON LINER

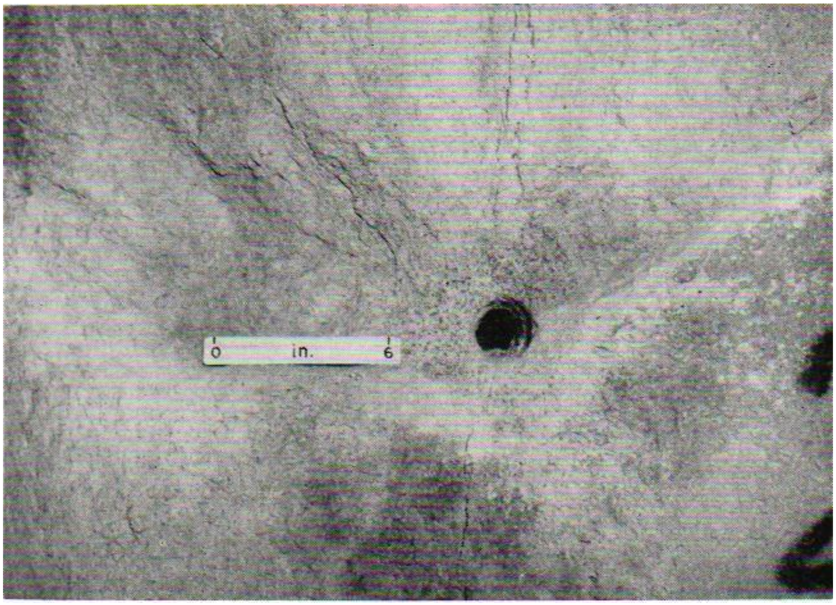


Figure 14

RHYOLITE TARGET SHOT WITH A 4-INCH DIAMETER CAST IRON LINER

structions, although the surface blast from the charge at times will cause loose dirt to fall into the penetration. Figure 20 is the author's concept of the hole-forming mechanism in a solid-rock target.

The next considerations are the condition of the hole walls and especially the reason some holes are filled with crushed rock fragments. The hole walls in a well-formed hole are scoured free of most loose material by the backblast. The scouring action will continue as long as significant penetration is being accomplished. In addition, the hole walls are under tremendous compressive stresses during the formation of any given hole portion. When the jet-target interface has moved past a given point, however, the principal hole-making process stops, and the radial energy imparted to the target diminishes rapidly. There is no longer a compressive load on the hole walls. Rocks are not noted for their compressibility, and compaction or compression does not add significantly to the hole volume during the initial hole-forming process. Despite the lack of significant amounts of compaction, the rapid relief of stress will allow rebounding of some hole-wall material. The wall material that rebounds into the hole will be swept from the hole by the backblast as long as significant penetration is in progress. Following the cessation of penetration, the hole will fill itself with material released during the hole-wall rebounding process. Most holes have very little rebound material in them. It is possible, however, to design a liner that will cause large amounts of rebound. Some holes continue to enlarge themselves through relaxation for several days following certain types of blasts, indicating that some rock compression has occurred. In holes of this type, a relatively smooth, empty hole gives way to a much larger hole filled with crushed fragments of the hole walls. Figure 6 shows a hole shot into rhyolite that enlarged itself through relaxation sufficiently to fill itself almost completely with broken wall material.

Compaction is considered insignificant in the overall process of hole formation. Density measurements of rock adjacent to holes confirm the lack of residual compaction. Relaxation of the hole walls and intense fracturing of the hole-wall area result in slight density losses in the target rock after the penetration is completed.

Figure 15

DEEP CRATER FORMED IN SURFACE SHOWN IN FIGURE 14 AFTER SEVERAL MONTHS' EXPOSURE TO WEATHERING

Figure 16

Portion of target shown in Figure 14 which broke free to form a deep crater

Figure 17

FRACTURE-CONTROLLED CRATER SHOT INTO ALTERED QUARTZ MONZONITE WITH A 4-INCH-DIAMETER CAST IRON LINER

Hole walls differ in appearance according to both the type of penetration and the rock type. Figure 21 shows a section of a hole shot into rhyolite. The hole walls are comprised of a thin veneer of loose, pulverulent rhyolite, then a zone of coarser, fractured rhyolite, and lastly, unaffected target material.

Figure 22 presents a section of a hole shot into sandstone. Such holes show a thin veneer of loose, crushed sand grains along the hole walls. In addition, the sandstone targets exhibit a zone of intense crushing, which forms a series of concentric shells of crushed material surround-

Figure 18

MORE NORMAL CUPPED CRATER SHOT INTO ALTERED QUARTZ MONZONITE WITH A 4-INCH-DIAMETER CAST IRON LINER

ing the hole. Where sampled, there was no regular fracture-pattern development in the hole walls. The crushed concentric shells relax to form large-diameter penetrations in some rock types. In the sandstone targets, significant relaxation was not observed, and some residual compaction may have remained.

Figure 23 presents a section of a hole shot into altered quartz monzonite. Intense crushing is present adjacent to the hole walls. Farther from the hole, the target is fractured and then gives way to unaffected material.

Figure 24 presents a section of a hole shot into limestone. The holes shot into limestone were different from those shot into other rock types. They show no crushing of the walls except for a very thin veneer of crushed and possibly calcined material. In addition, the holes in limestone were lined with iron oxides. In the other target types, small bits of oxidized liner would occasionally be present on the hole walls, but the walls would never be completely coated. The holes shot into limestone also had much rougher walls than those in the other types of target rocks.

Holes shot into rock and other earth materials by means of lined-

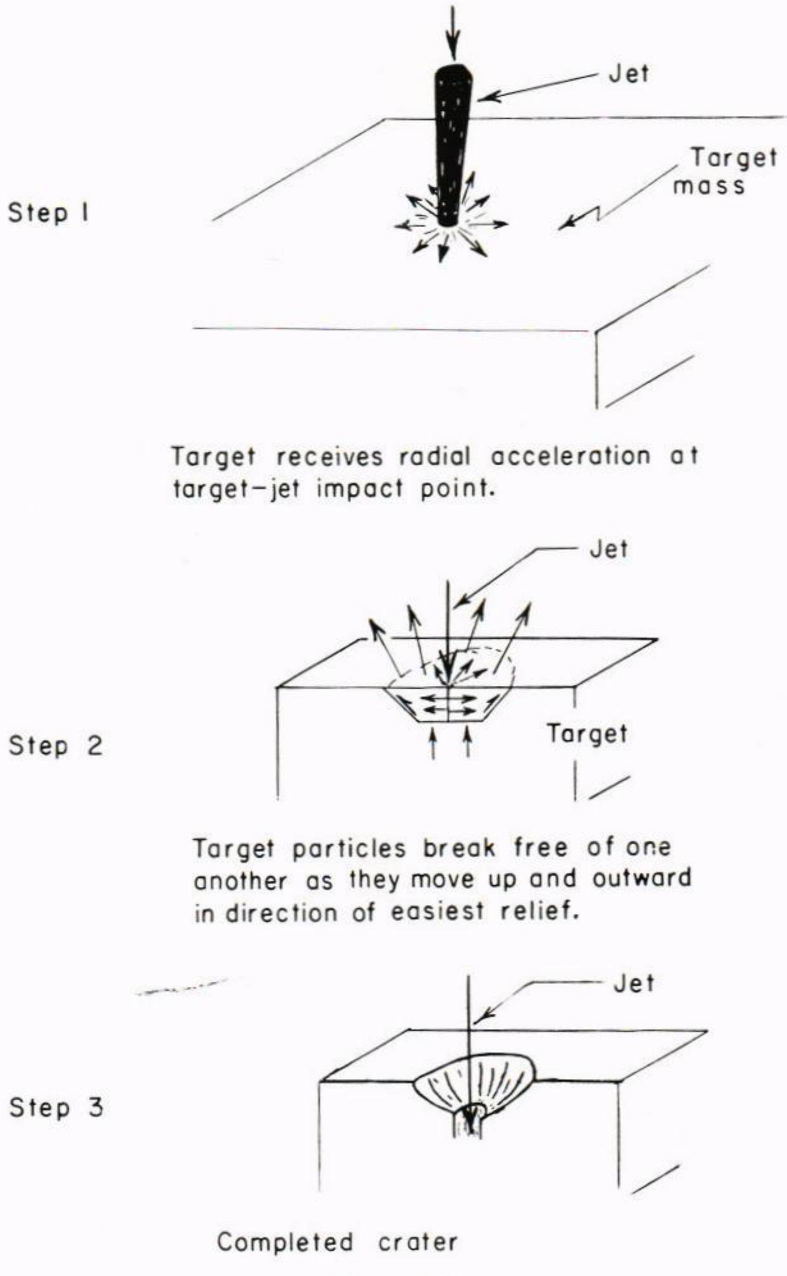


Figure 19

CRATERING MECHANISM IN ROCK TARGETS

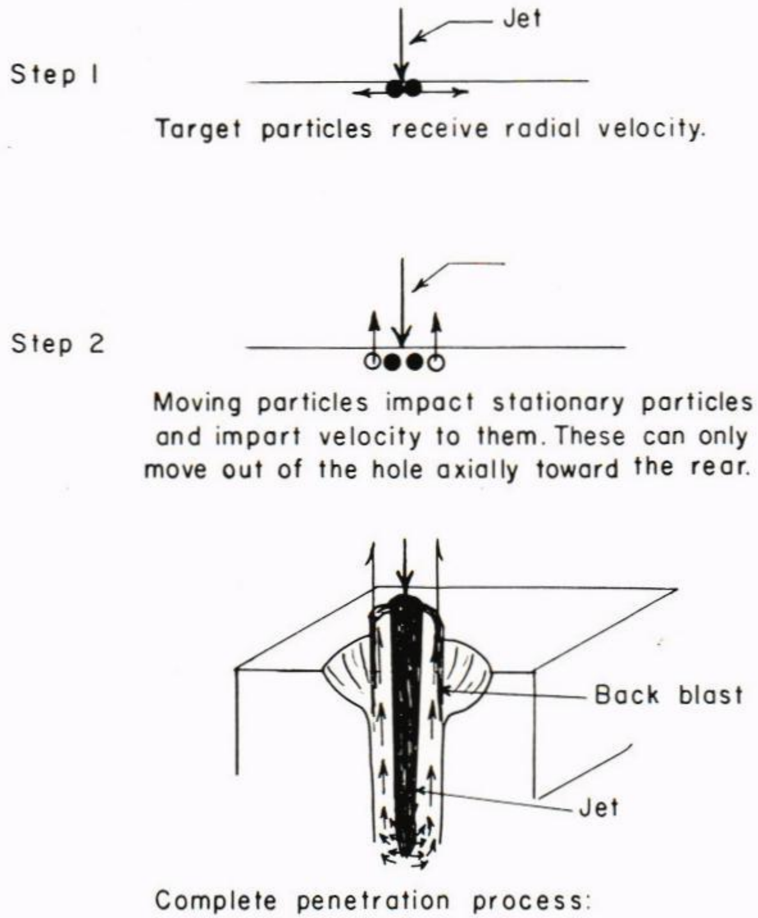


Figure 20

HOLE-FORMING MECHANISM IN ROCK TARGETS

cavity shaped charges can create interesting fracture patterns under proper conditions. Portions of the holes shot into limestone for this project gave good fracture patterns, whereas general fracturing of the target adjacent to the hole was noted in penetrations in rhyolite and altered quartz monzonite. Some of the holes shot into rocky alluvium also exhibited fracture patterns. The predominant feature of the fracture patterns developed in both limestone and alluvium was the radial nature of the principal fractures. The fractures in limestone could be studied in detail since the limestone targets which were employed were sufficiently coherent to allow recovery and sectioning of the target area.

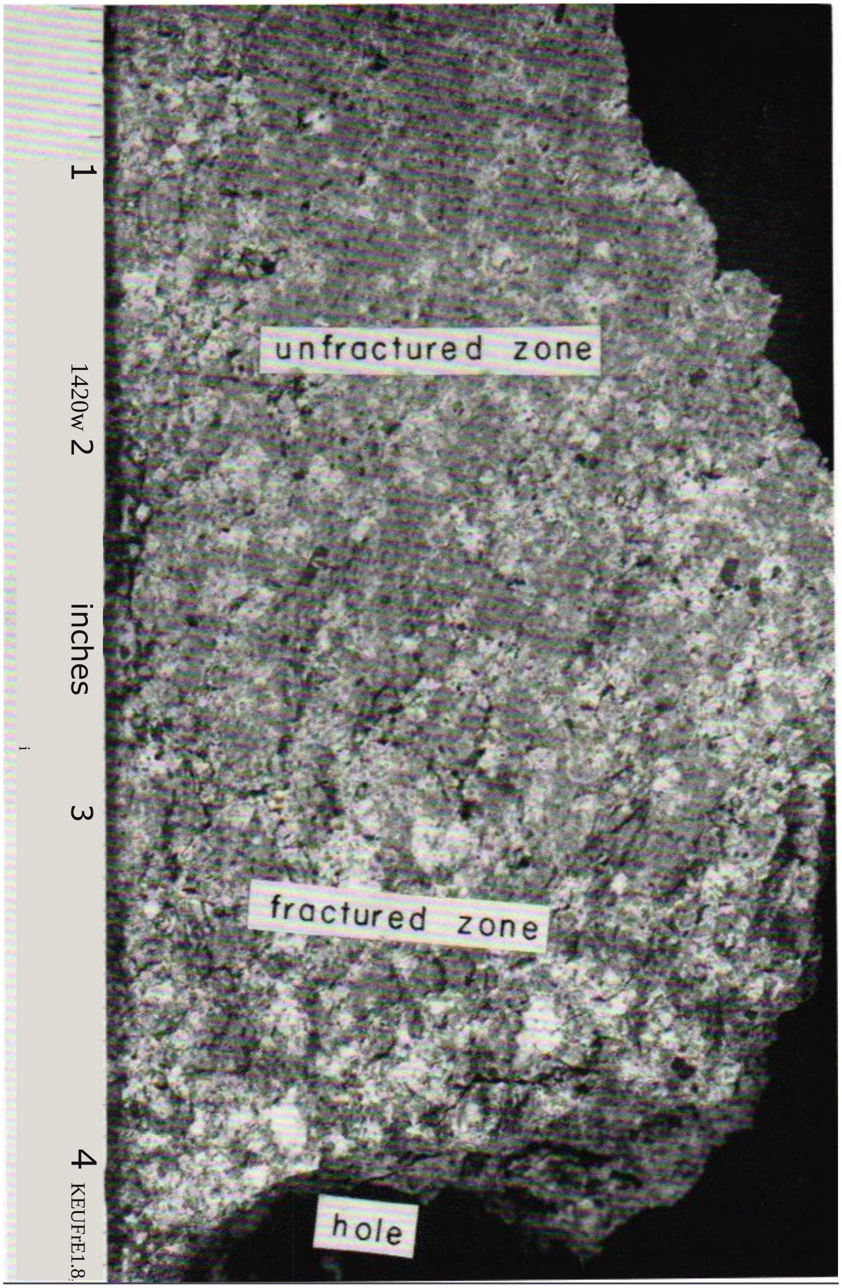


Figure 21

SECTION OF A HOLE SHOT INTO RHYOLITE WITH A 4-INCH-DIAMETER CAST IRON LINER

Section cut perpendicular to the hole axis.

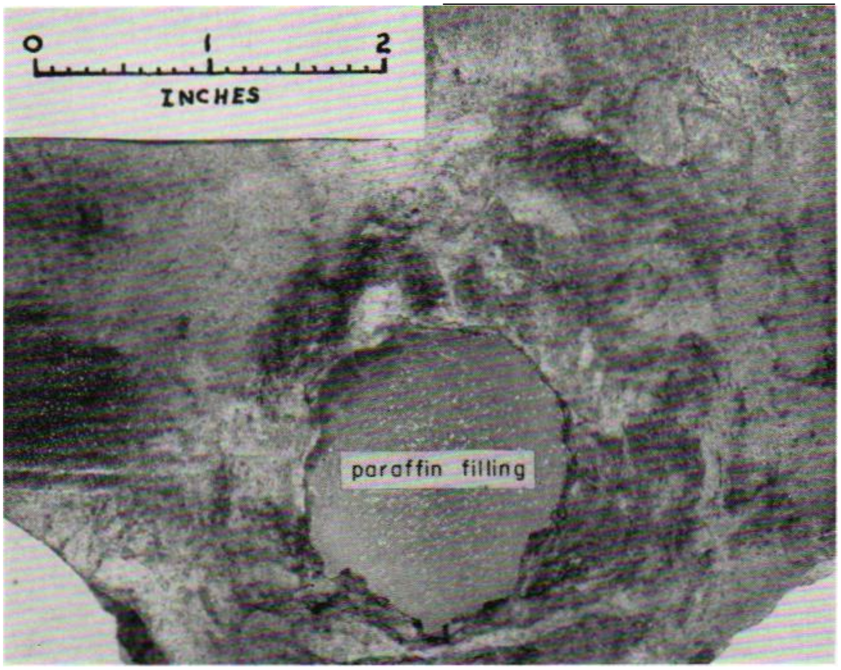


Figure 22

SECTION OF A HOLE SHOT INTO SANDSTONE WITH A 4-INCH-DIAMETER CAST IRON LINER

Section cut perpendicular to the hole axis.

The fracture patterns in limestone were developed only where a prepenetration fracture existed. A fracture of this type provided a free surface and allowed the target to expand as needed in order to form fractures during the penetration process. The fractures made in limestone targets were filled with iron oxides and at times contained small particles of unoxidized cast iron liner material. No doubt, other fractures were formed in the limestone, but only those which were filled with liner-derived metal or oxides were discernible. Fracture patterns produced by lined-cavity shaped charges present an interesting possibility for rock-mechanics studies because they permit the creation of complete fracture patterns without specimen failure after the first fracture is formed. Figures 25 and 26 are sections through fractures developed in limestone targets. Figure 27 shows fractures developed in alluvium.

Hole Bottoms

The final portion of the hole to form represents the target's reaction to a rapidly decelerating jet. The holes in rock taper rapidly near the bottom unless special types of liners are used (see page 45 for liner type). The taper is a natural result since the impact velocity is dropping rapidly and the jet is able to put less radial velocity into the target particles at the jet-target interface. Once the jet velocity drops below the critical velocity needed for penetration, the remaining jet material and the following slug will pack themselves into the hole. The extent of the filling of the hole by the jet and slug will depend on the resistance of the target to penetration (that is, on the hole diameter) and on the characteristics of the jet. By using a jet with mass-velocity relations that cause a large-diameter, relatively nontapering hole bottom, little or no jet material will remain in the hole bottom. Most commonly, the slug from cast iron liners will bounce back out of the hole and be found a few feet from the target surface. If a very narrow, deep hole bottom is created, this portion of the hole will be packed with spongy liner oxides, and at times the slug will be rammed onto the top of this

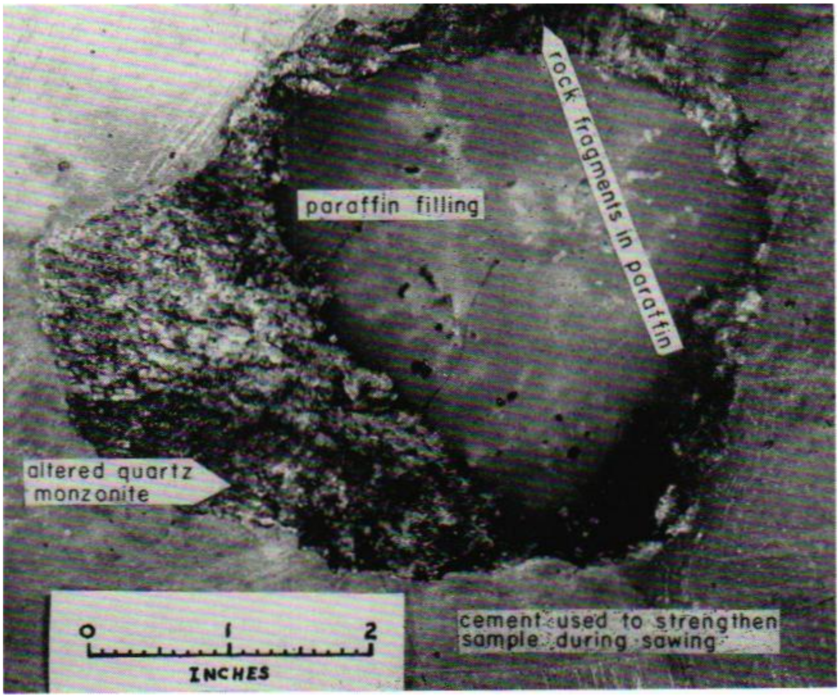


Figure 23

SECTION OF A HOLE SHOT INTO ALTERED QUARTZ MONZONITE WITH A 4-INCH-DIAMETER CAST IRON LINER

Section cut perpendicular to the hole axis.

Figure 24

SECTION OF A HOLE SHOT INTO LIMESTONE WITH A 4-INCH-DIAMETER CAST IRON LINER

Section cut perpendicular to the hole axis.

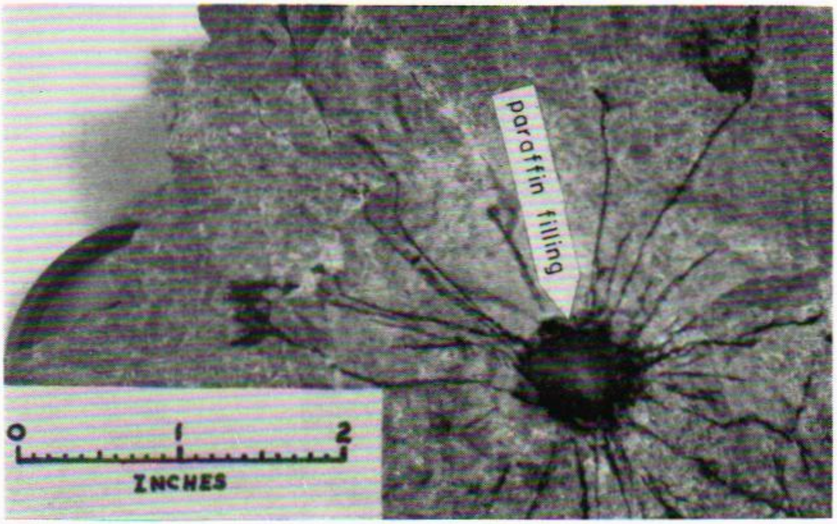


Figure 25

SECTION THROUGH A HOLE AND ACCOMPANYING IRON-FILLED FRACTURES SHOT INTO LIMESTONE WITH A 4-INCH-DIAMETER CAST IRON LINER

Section broken perpendicular to the hole axis.

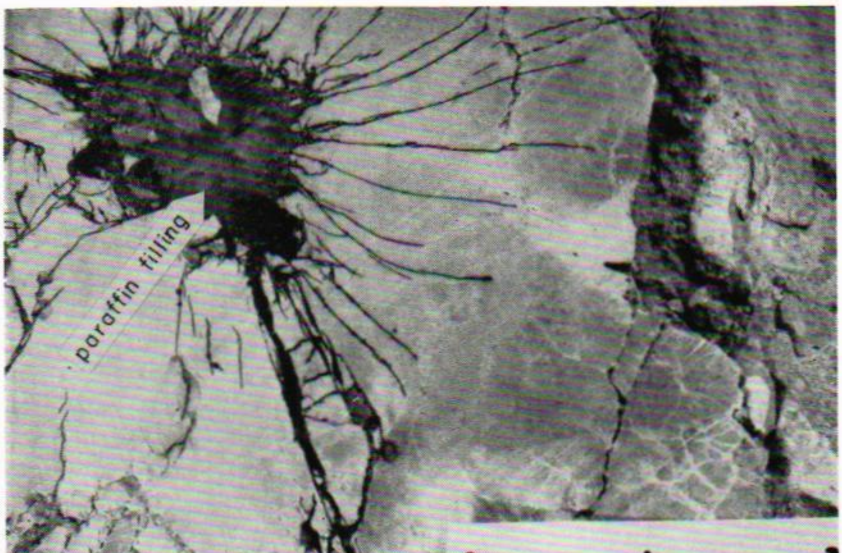


Figure 26

SECTION THROUGH A HOLE AND ACCOMPANYING IRON-FILLED FRACTURES SHOT INTO LIMESTONE WITH A 4-INCH-DIAMETER CAST IRON LINER

Section cut 51 degrees to the hole axis.

Figure 27

FRACTURES PRODUCED IN ALLUVIUM SHOT WITH A 4-INCH-DIAMETER CAST IRON LINER

material. Figure 28 shows the bottom of a hole shot into rhyolite. In this instance, the hole is filled with spongy iron oxide.

In addition to the radial fracture patterns found in limestone targets, the holes shot into rhyolite were found to have fracture patterns at their bases. These iron oxide-filled fractures suggest that the rock is fractured in advance of the penetration. Further evidence of fracturing in advance of hole formation is suggested by the fact that the jet will follow fractures made by the breaking of a target when the confinement is insufficient. Once this type of fracturing occurs, normal penetration will cease, thus indicating that the velocity of fracture in rhyolite, and also in quartz monzonite, exceeds the velocity of penetration for shaped-charge holes. If a massive rhyolite target is not broken, the small fractures in advance of the penetration are held open by iron oxides and can thus be seen when the hole is broken open for examination. Figure 29 shows iron-filled fractures at the base of a penetration in rhyolite.

Variables Controlling Hole Profiles

A hole produced by a lined-cavity shaped charge can exhibit numerous shapes. Such shapes are the result of variations in the characteristics of the jet, variations in the characteristics of the target, and combinations of the two. Figures 6 and 7 have shown how a change in the type

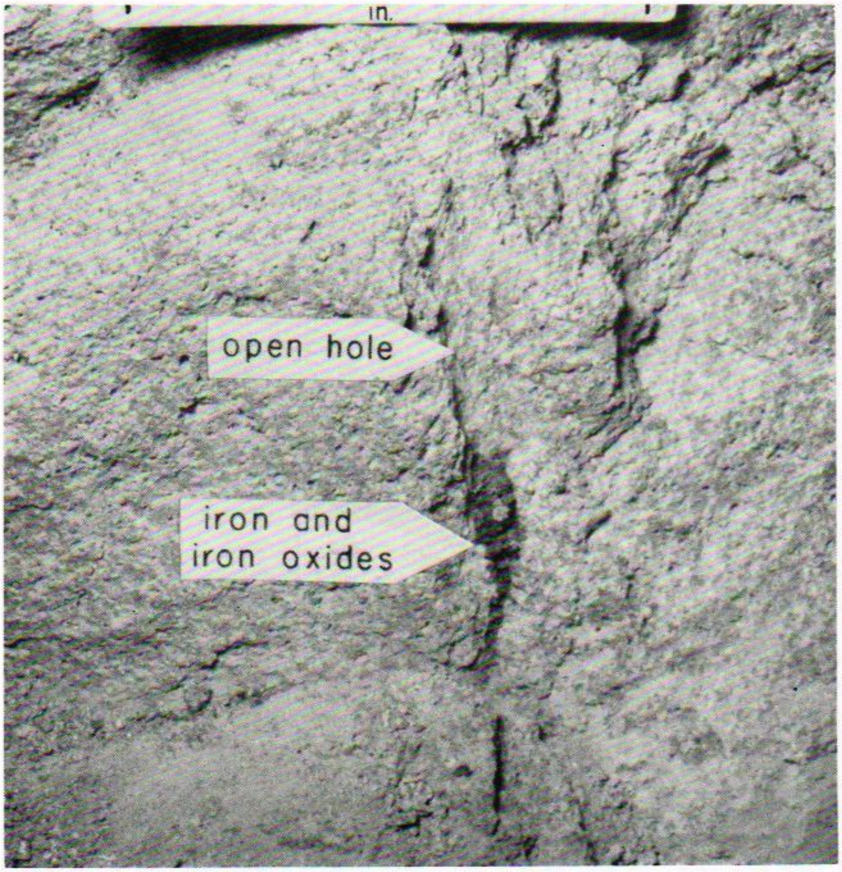


Figure 28

BOTTOM OF HOLE SHOT INTO RHYOLITE WITH A 4-INCH-DIAMETER CAST IRON LINER

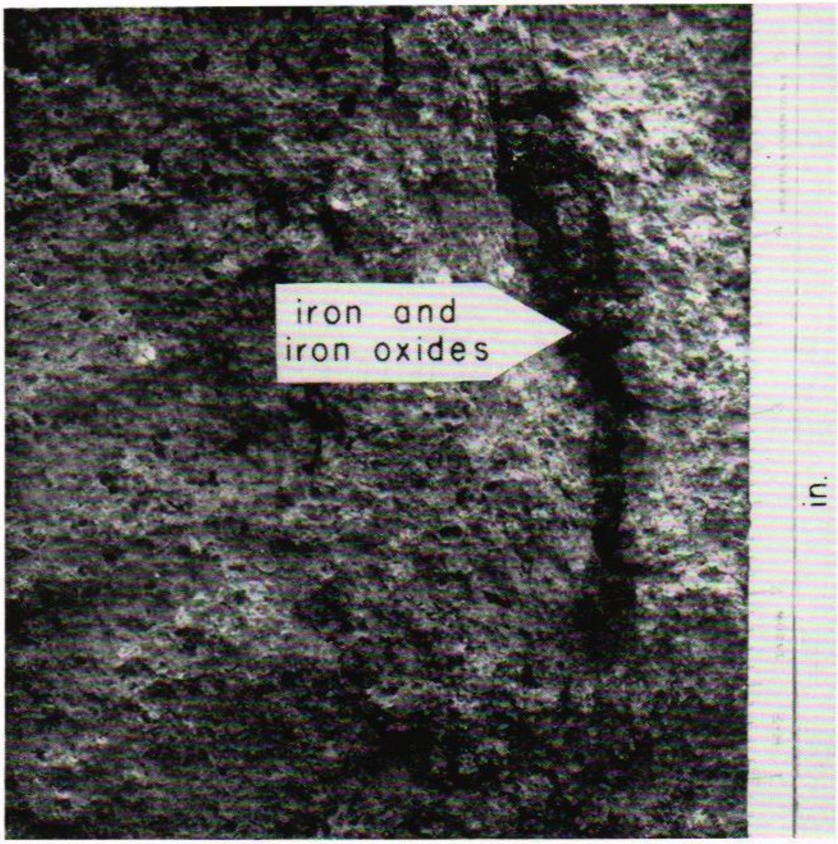


Figure 29

IRON-FILLED FRACTURES IN THE BASE OF A HOLE SHOT INTO RHYOLITE WITH A 4-INCH-DIAMETER CAST IRON LINER

of jet can produce different hole profiles in a given target type. The same type of jet can also produce widely divergent holes in a given target, and it is not unusual for shaped-charge penetrations to widen, narrow, and wander as the target characteristics vary with depth of penetration. Figure 30 shows a sketch of a hole shot into altered quartz monzonite. Where the target was soft, the hole widens; where hard, the hole narrows.

Rock targets often have different strengths in different directions. This is well illustrated in Figure 23, since the hole is far from circular. Elliptical holes result in rock targets which do not offer the same resistance to penetration in all directions. Figure 12 shows a circular hole shot into rhyolite, and Figure 15 shows an elliptical section of a hole shot into the same kind of rock.

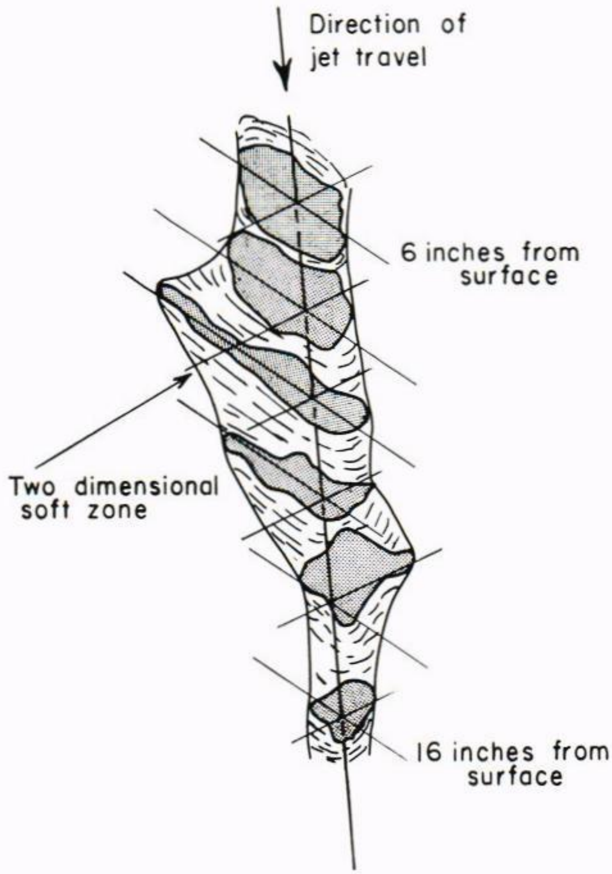


Figure 30

IRREGULAR HOLE SHOT INTO ALTERED QUARTZ MONZONITE WITH A 4-INCH-DIAMETER CAST IRON LINER

Design of Lined-Cavity Shaped Charges

Prospectors, mining engineers, ranchers, and others who write to the New Mexico Bureau of Mines and Mineral Resources for information on shaped charges wish to know either how to make their own shaped charges or where to buy such charges ready made. The major explosives companies would undertake perhaps to make shaped charges with lined cavities on a custom basis, but the cost probably would be prohibitive. Small charges suitable for specimen collecting, pipe and plate perforations, and similar uses are made by a number of companies for oil-well-completion purposes. Larger charges appear cheapest at present when made by the user to suit the particular job at hand.

What should be the design of a lined-cavity shaped charge? There is no set answer, for the charge must be designed to match the job. Certain fundamentals, however, can be presented to guide those interested in designing and making their own lined-cavity shaped charges. The following presentation is far from exhaustive not only because of limited knowledge as to the mass-velocity distributions within a given design of charge, but also because of *even* less knowledge concerning the specific reaction of a given rock or other earth material to a particular type of jet.

There are two prime requisites for a shaped charge with a lined cavity, the liner and the explosive charge. Other considerations are the shape of the explosive container and the method of detonation.

LINER

The liner is simple to make or obtain if conical in form. Cones yield good jets and penetrations of good quality; as a result, they have been used widely for lined-cavity shaped-charge liners employed in research and for military and commercial applications. Liners of small diameter are easily made from sheet copper or sheet steel. All liners must have accurate axial symmetry in order to yield a workable jet. The requirements of a symmetry necessitate butt joints rather than riveted or overlapping joints. Thin liners may be spun, stamped, or bent from sheet stock. Spinning and stamping are best, as no joints are needed.

The wall thickness of a given liner is governed by the size of the explosive charge and the type of liner collapse mechanism desired. For homemade charges, a machined liner is one way of obtaining good axial symmetry, but this requires a relatively thick-walled liner.

The 4-inch-diameter cast iron liners used by the author in this project had thick walls (0.18 inch) and relatively narrow apical angles (55°). These liners conformed either to the plastic-flow type of collapse or perhaps to a collapse mechanism midway between the plastic-flow and brittle-fracture mechanisms. Slugs recovered indicated that the collapse of the cast iron liners began as plastic-flow phenomena, but that most of the jet resulted from brittle-fracture phenomena.

The requirements of liner symmetry cannot be overemphasized. If a liner is left rough or uneven, as in a rough casting, the resulting jet will be poorly alined, and the penetration will be erratic. Figure 31 is a sketch of the hole profile that resulted from shooting a rough liner into rhyolite. Figure 32 shows a rough cast iron liner and a standard 4-inchdiameter cast iron liner that has been machined. As the figure indicates, a completely smooth finish is not critical so long as the liner is symmetrical and all rough blemishes and chills are removed.

Liners used for lined-cavity shaped charges should have smooth, rimless bases. If a flange or rim is used on a liner, the detonation of the charge will convert the protruding portions into high-velocity pieces of scrap, which are a severe hazard. The smooth-bottomed liners used in

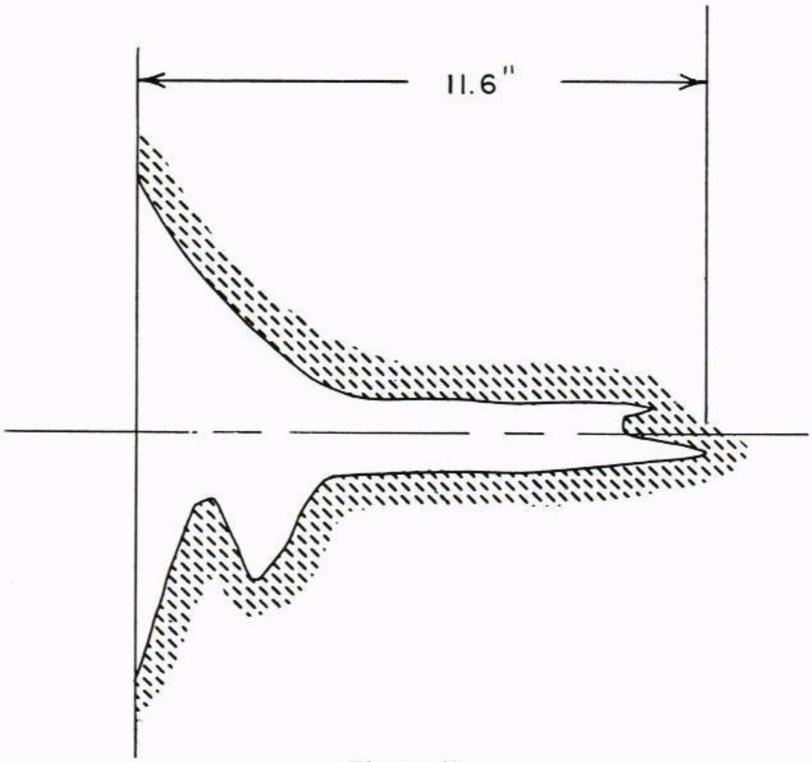


Figure 31

Profile of hole shot into rhyolite with a 4-inch-diameter rough cast iron liner

A

B

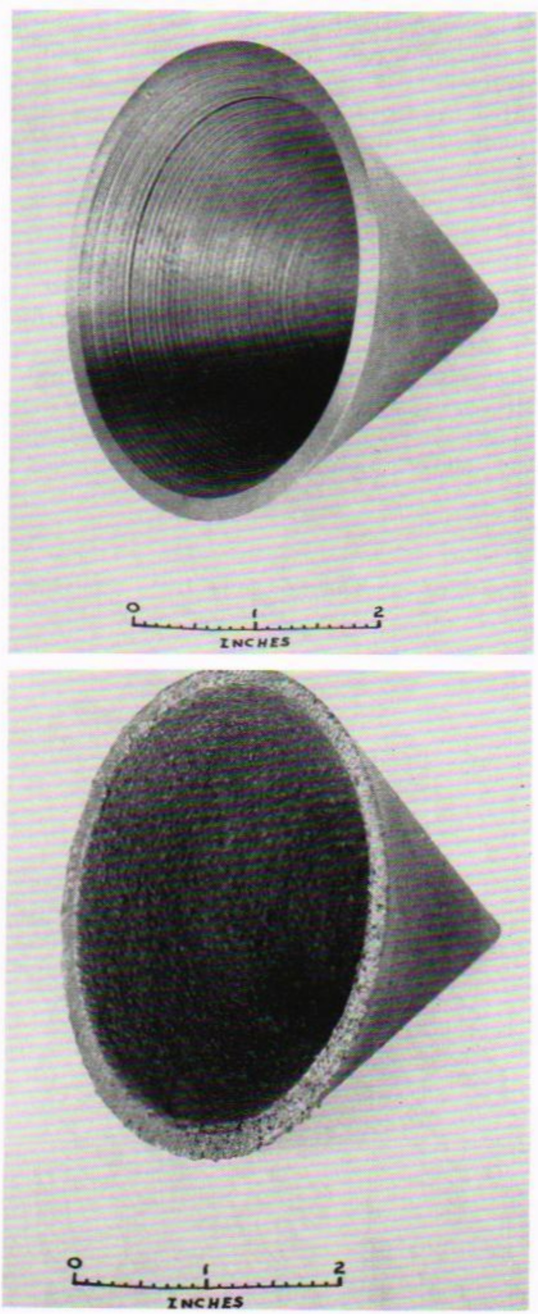


Figure 32

FOUR-INCH-DIAMETER CAST IRON LINERS

(A) Machined casting; (B) rough casting.

the work described in this paper gave no radially moving parts except for pieces of slug which did not enter the penetration but struck the target surface and then bounced off to the sides.

Liners may be parallel walled or tapered. The type of wall used is determined by the desired hole profile and the cost of making the liner. A liner with parallel walls is easier to machine and hence cheaper to make, but liners with parallel walls produce holes that taper sharply near their base. Field experience has shown, as suggested by theory, that a liner with decreasing wall thickness toward its base will produce a hole with little or no taper in a rock target.

The machining problems increase tremendously if a liner other than a cone is used. Parabolic, spherical, and other curved-surface liners are more difficult to make and far more expensive than simple cones. Curved-surface liners have certain advantages at times, such as the slugless nature of spherical surfaces when shot with a spherical detonation wave.

The only unmachined metal liners successfully used in this project were octagonal frustums of pyramids made by welding pieces of ¼-inch-thick steel plate together. Large liners suitable for making pole and post holes in rocky alluvium were fashioned inexpensively by this method.

EXPLOSIVE

Most investigations of lined-cavity phenomena have failed because of the type of explosive used. The explosive must have high velocity and high brisance. Common commercial explosives are of no value in lined-cavity shaped charges. Stumping powder, ditching dynamites, and even high-velocity seismic gelatins do not yield usable jets with lined-cavity shaped charges. The only readily obtainable commercial explosive that gives a usable jet is 100-percent blasting gelatin. Less common explosives which work far better are the military explosives, including C-3, a plastic explosive, and the pentolites and cyclotols, both cast explosives.

One hundred-percent gelatin will give a usable charge but possesses a number of drawbacks. It is difficult to load into a container of any shape other than that of a simple cylinder; even this is difficult inasmuch as 100-percent gelatin has a consistency similar to that of Para rubber. A uniform, dense load is almost impossible to obtain, as the loading of 100-percent gelatin is comparable to packing rubber balls tightly into a container. Another drawback in the use of 100-percent gelatin is that the gelatin explosives possess two velocities of detonation. The low-order or low-velocity detonation will not yield a worth-while penetration. The initiation of a high-order detonation in a small-diameter gelatin charge is difficult. Large boosters must be used, increasing the cost of the charge. There are still other drawbacks. The material is rather sensitive, and care must be used in packing and transporting charges. Furthermore, 100-percent gelatin, as all nitroglycerine-nitroglycol mixes, causes temporary but very painful headaches. The only advantages in using this explosive, aside from the fact that it will work, are that it is easily obtained and not expensive. Figure 33 shows the results of both high- and low-order gelatin detonations against a rhyolite target. Figure 34 is the design of the gelatin charge. Table 1 lists the costs of a gelatin charge and its components.

TABLE 1. COST OF 100-PERCENT GELATIN CHARGE AND COMPONENTS

Cardboard end disk	$0.01
Cardboard tubing	0.18
Masking tape	0.09
Cast iron liner (casting, $0.80: machining, $2.55)	3.35
Lane Wells P-11 auxiliary charge	0.32
Primacord	0.01
No. 6 electric cap	021
100-percent gelatin	2.23
Total	$6.40

Most of the work done by the author has utilized a surplus military explosive designated C-3 or Composition C-3. C-3 is a soft plastic explosive made up of a number of materials, including considerable RDX. C-3 also contains sufficient tetryl to require the use of gloves when handling it. Otherwise C-3 is very safe to use. The mix is quite insensitive and requires either a No. 8 blasting cap or a booster with a No. 6 blasting cap in order to ensure detonation. Because of its plasticity, C-3 is very easily packed into containers of any desired shape. It is easy to handle, safe, and has high velocity and good brisance. In short, C-3 is an ideal explosive for shaped charges. The problem is how to obtain the material. It is available at times as a war-surplus material. Some of the explosives companies have bought up large lots of C-3 in order to recover RDX from it. These companies occasionally will sell C-3 on the open market.

Figure 35 presents the results of firings of various designs of shaped charges packed with C-3. Figure 36 shows the design of these charges, and Table 2 lists the costs of the charges and their component parts.

Numerous other explosives of high velocity and high brisance are manufactured, but they are expensive and hard to obtain. Industries doing work for military or other governmental agencies occasionally have surplus explosives which they can sell on the open market. At times, cast explosives such as cyclotols and pentolites can be purchased, but the cost of a small number of castings is usually prohibitive. A recent price for casting ten 9-inch-long by 4-inch-diameter cylindrical charges using 80-20 cyclotol was $47.50 per charge, including the cost of the explosive and shipping charges from the west coast to New Mexico. Unless sufficient numbers of charges are needed to enable reduction in costs, the use of charges employing commercially cast explosives would be prohibitively expensive.

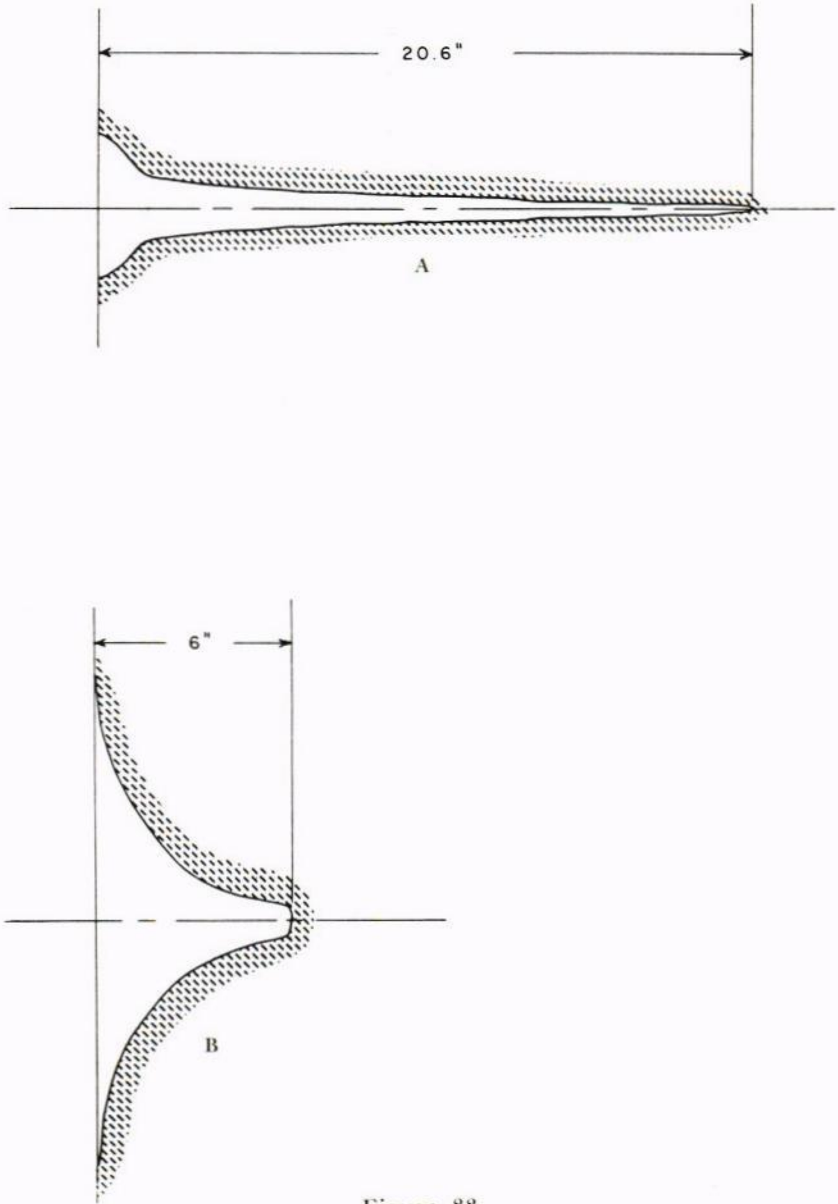


Figure 33

PROFILES OF HOLES SHOT INTO RHYOLITE WITH 4-INCH-DIAMETER CAST IRON LINERS

(A) High-order detonation of 100-percent gelatin; (B) low-order detonation of 100-percent gelatin.

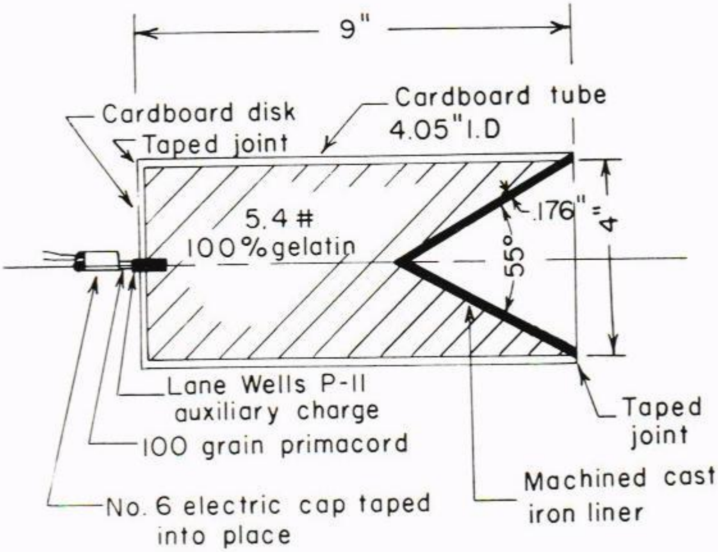


Figure 34

DESIGN OF GELATIN CHARGE

An unconventional explosive used by the author in lined-cavity shaped charges was nitromethane. Nitromethane is very cheap and easily obtained on the open market, although small lots may be hard to obtain except for laboratory purposes. Nitromethane is not readily detonated unless a sensitizer is added; for this purpose, the author used aniline, also readily obtainable. The use of this explosive requires a waterproof or liquid-tight explosives container. The author used both waterproofed cardboard and cardboard wrapped with aluminum foil.

Both nitromethane and aniline are poisonous, but they are insensitive to detonation when unmixed. When mixed, however, a cap-sensitive solution is obtained. Both liquids are flammable, and their vapors can cause explosions.

The nitromethane-aniline mixture is detonated best by a powerful booster. The P-11 auxiliary charges used to detonate C-3 were found satisfactory for the detonation of nitromethane-aniline solutions.

Figure 37 presents a penetration in rhyolite made by means of a nitromethane charge. The liner was too heavy for the charge but gave an indication of the usefulness of this explosive. Figure 38 shows the design of the nitromethane charges used in this project, and Table 3 presents the costs of the nitromethane charges and their components.

A series of blasts were set off involving the use of shaped charges loaded with 45-percent gelatin and 60-percent seismic gelatin. Figure 39 presents the results of these blasts. Even the use of very large shapes with

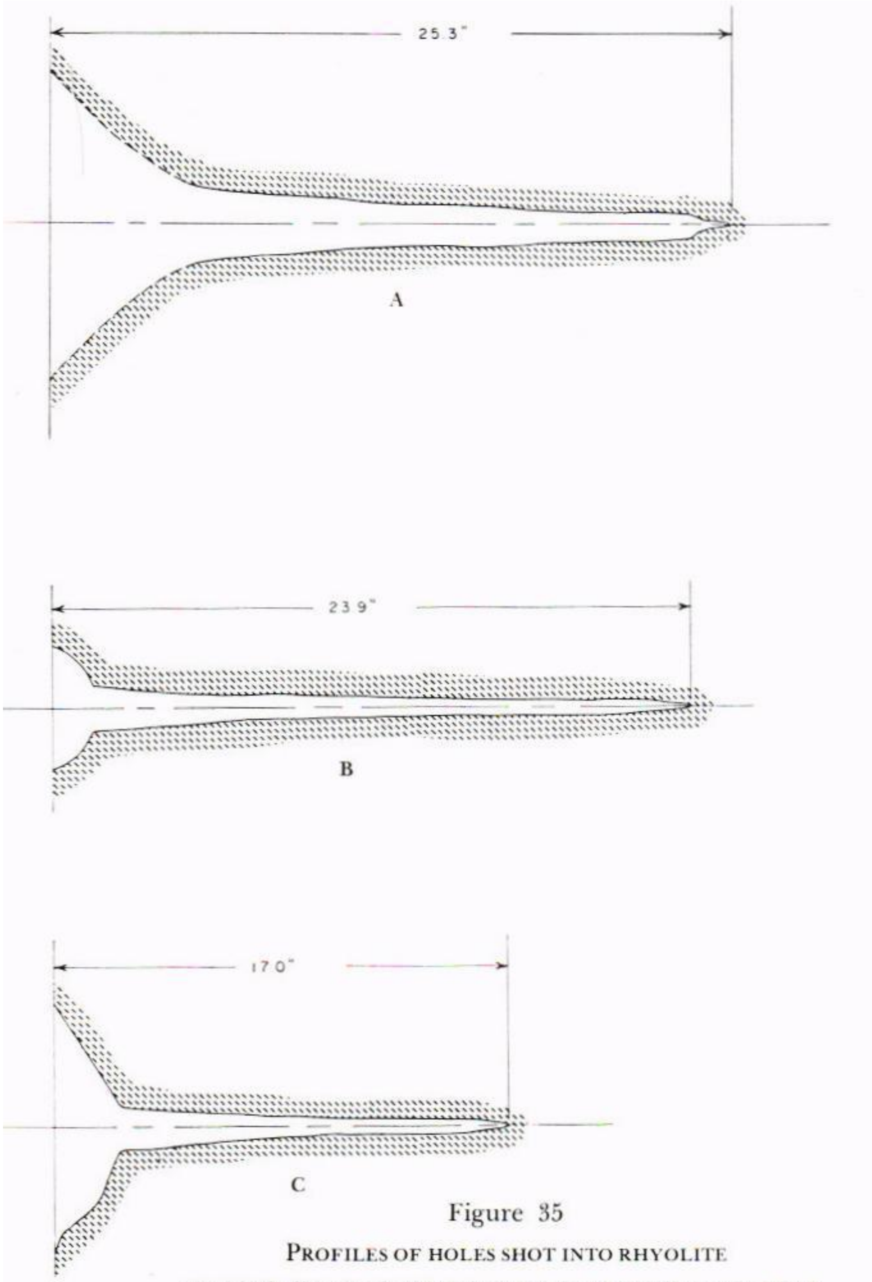


Figure 35

PROFILES OF HOLES SHOT INTO RHYOLITE

(A) 6-inch-diameter beehive charge and cast iron liner; (B) 4-inch-diameter cylindrical charge and cast iron liner; (C) 4-inch-diameter beehive charge and cast iron liner.

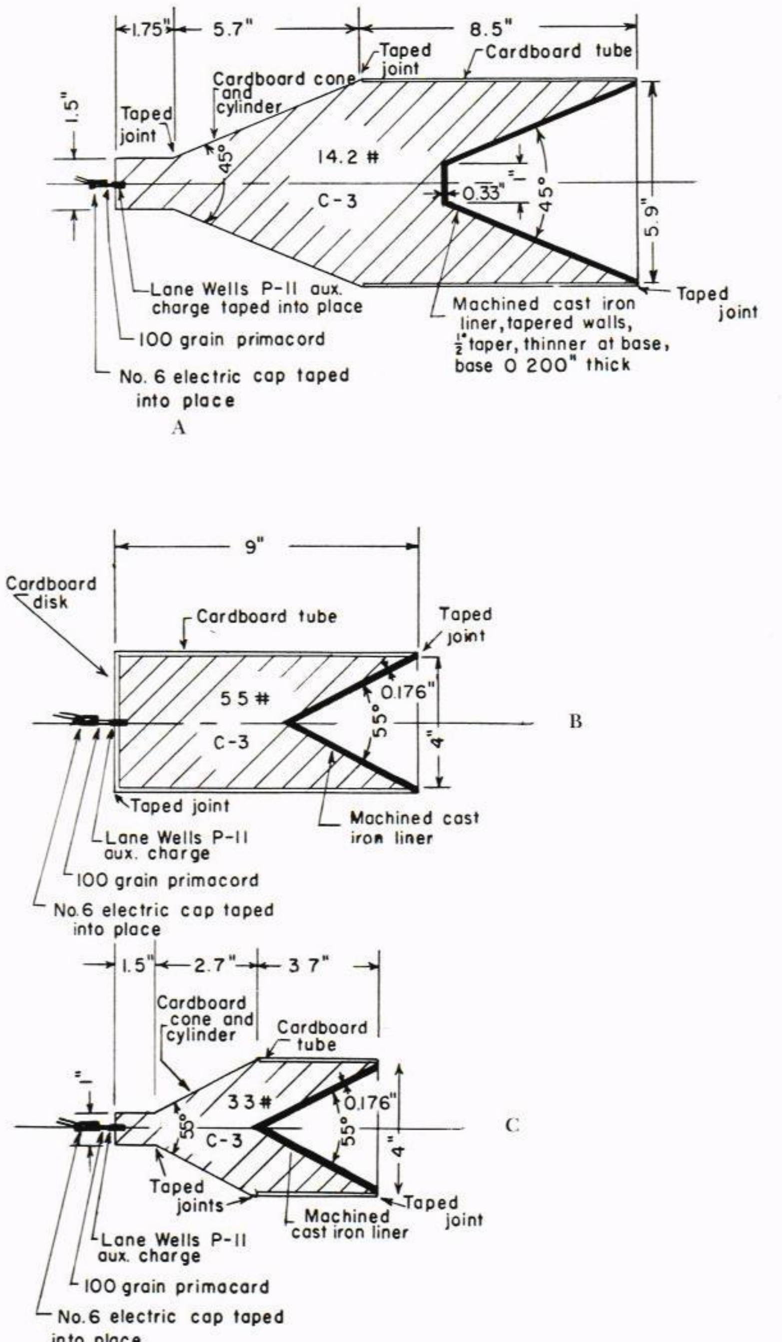


Figure 36

DESIGN OF CHARGES USING C-3

TABLE 2. COST OF C-3 CHARGES AND COMPONENTS

6-INCH-DIAMETER BEEHIVE CHARGE (fig. 36A):	
Cardboard cone	$ 0.02
Small cardboard cylinder	0.01
Large cardboard cylinder	0.25
Masking tape	0.45
Cast iron liner (casting, $3.00; machining, $10.50)	13.50
Lane Wells P-11 auxiliary charge	0.32
Primacord	0.01
No. 6 electric cap	0.21
C-3	6.66
Total	$21.43
4-INCH-DIAMETER CYLINDRICAL CHARGE (fig. 36B):	
Cardboard end disk	$ 0.01
Cardboard tubing	0.18
Masking tape	0.09
Cast iron liner (casting, $0.80; machining, $2.55)	3.35
Lane Wells P-11 auxiliary charge	0.32
Primacord	0.01
No. 6 electric cap	0.21
C-3	2.59
Total	$ 6.76
4-INCH-DIAMETER BEEHIVE CHARGE (fig. 36C):	
Cardboard cone	$ 0.01
Small cardboard cylinder	0.01
Large cardboard cylinder	0.07
Masking tape	0.30
Cast iron liner (casting, $0.80; machining, $2.55)	3.35
Lane Wells P-11 auxiliary charge	0.32
Primacord	0.01
No. 6 electric cap	0.21
C-3	1.55
Total	$ 5.83

TABLE 3. COST OF NITROMETHANE CHARGE AND COMPONENTS

Cardboard cone	$0.01
Small cardboard cylinder	0.01
Large cardboard cylinder	0.07
Aluminum foil	0.02
Masking tape	0.30
Cast iron liner (casting, $0.80; machining, $2.55)	3.35
Lane Wells P-11 auxiliary charge	0.32
Primacord	0.01
No. 6 electric cap	0.21
Nitromethane	0.65
Aniline	0.10
Total	$5.05

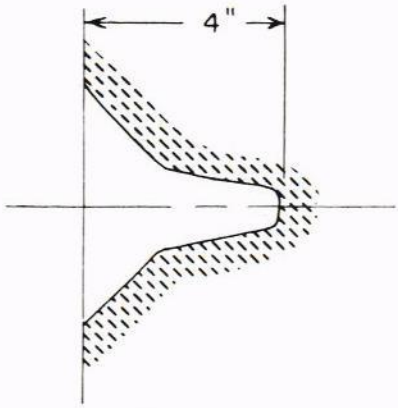


Figure 37

PROFILE OF A HOLE SHOT INTO RHYOLITE WITH A 4-INCH-DIAMETER NITROMETHANE CHARGE AND CAST IRON LINER

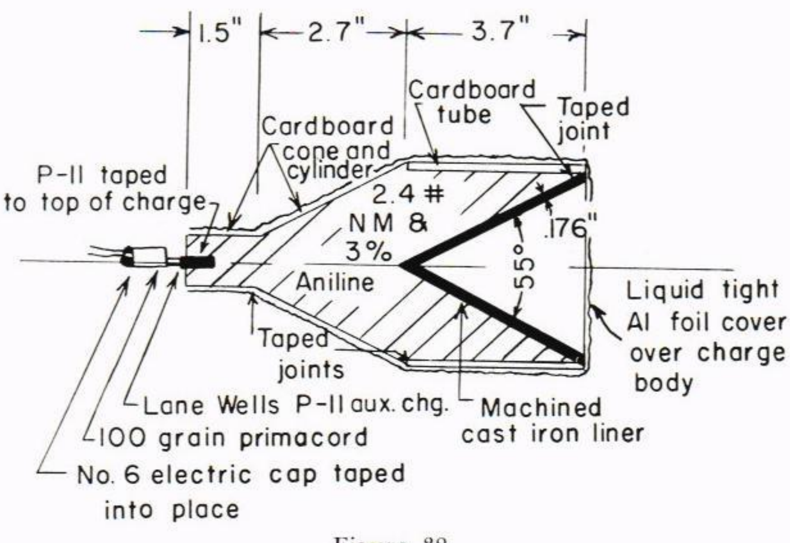


Figure 38

DESIGN OF NITROMETHANE CHARGE

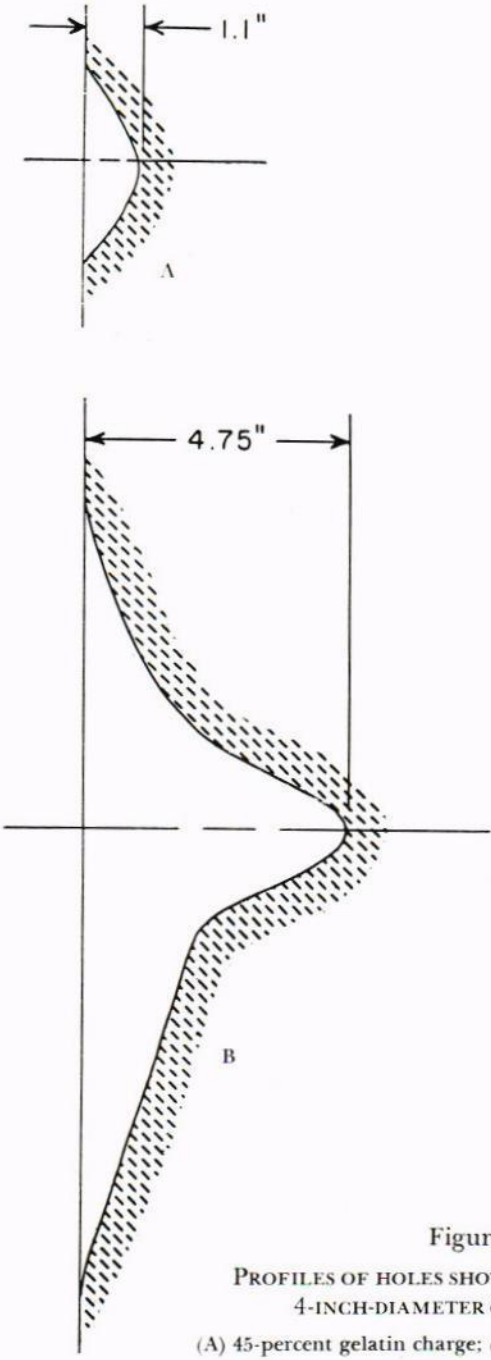


Figure 39

PROFILES OF HOLES SHOT INTO RHYOLITE WITH 4-INCH-DIAMETER CAST IRON LINERS

(A) 45-percent gelatin charge; (B) 60-percent gelatin charge.

low-cost explosives of these types would not overcome the simple fact that they possess neither the velocity nor the brisance to yield worthwhile penetrations.

SHAPE OF EXPLOSIVE CHARGE

The end of the explosive charge which contains the liner will be shaped automatically. The other end, as well as the sides, can be shaped to suit the needs of the user. Reference to Figure 35 will show that variations in shape and amount of explosive in the charge are possible since both shots gave nearly the same penetration. The significant difference between the two charges, one cylindrical and one beehive (i.e., cylindroconical), is in the quantity of explosive required for a desired penetration. Careful shaping of an explosive charge in the vicinity of the detonator will cause a marked decrease in the quantity of explosive needed. Although cylindrical charges are not efficient in their use of explosive, they were used for most of this project because of their ease of loading and construction. Cook, at the University of Utah, has shown that cutting off the end of a cylindrical charge does not appreciably affect the results until considerable explosive is removed. A series of tests were carried out to determine the length of cylinder most suited to the chosen liner design and to penetrations in rhyolite. The penetration values dropped, until little more than cratering resulted with a 3-inch charge length. A 9-inch-long cylindrical charge gave more penetration than expected. The 9-inch length was adopted and used for most of the work done on this project. Figure 40 presents data from these tests.

An increase in penetration with less explosive, as suggested by the 9-inch-length charges, is not surprising. Many dynamic firings of shaped charges with lined cavities give results quite different from their static firings. The results of dynamic firings vary from better to far less than normal penetrations. The added velocity of a dynamic firing will increase the jet velocity with respect to the target. It is possible to have a jet travel too fast for a given target, as well as too slowly. In both cases, the penetration suffers. If the jet is too fast, it will enter the hole at a rate that is greater than the rate of penetration, and will fill the hole and have to penetrate itself before it can hit the target. If the jet is too slow, it may never reach sufficient velocity to start the hole-forming process. According to hydrodynamic theory, penetration is independent of the jet velocity as long as the velocity is high enough, but this does not tell the entire story, since the velocity can also be too high. The effect of varying the jet velocity with respect to the target is involved in the anomalous penetrations obtained with a 9-inch-long cylindrical charge.

A simple method of changing the characteristics of the jet is to increase the confinement of the explosive charge. Figure 41 presents two

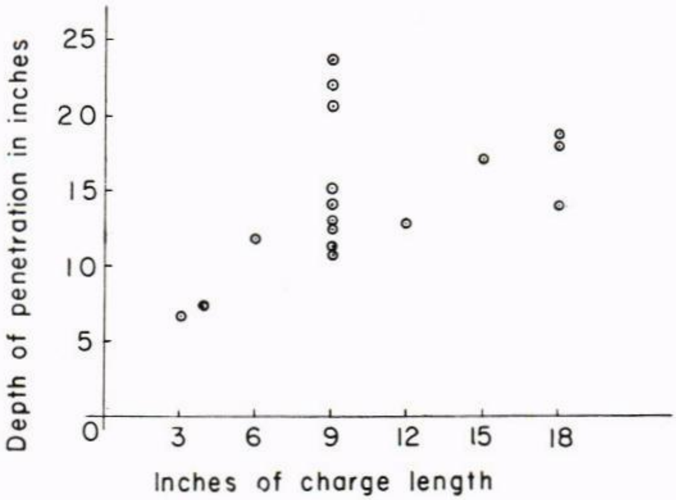


Figure 40

TESTS OF REDUCTION OF CHARGE LENGTH VERSUS PENETRATION

Four-inch-diameter cylindrical charge and cast iron liner fired into rhyolite.

hole profiles shot with long cylinders, one steel-cased, the other cardboard-cased. The steel-cased charge did far more surface damage to the target. Figure 42 presents typical surface damage to a rhyolite target as a result of firing a steel-cased charge. Flying parts from charges of this type are a severe hazard. Steel-cased charges can be used only in uninhabited areas, underground, or in similar sheltered locations.

INITIATION OF THE EXPLOSION

A detonator or detonator and booster system must be used which will give 100-percent certainty of high-order detonation. A P-11 auxiliary charge was found reliable in detonating gelatin, C-3, and nitromethane-aniline solutions. The P-11 charge was crimped onto primacord, and this in turn taped to either No. 6 electric blasting caps or No. 6 heat caps. When the charge was ready to be fired, the P-11 booster was inserted into the main explosive charge.

POSITIONING FOR FIRING

A lined-cavity shaped charge can be fired in any direction. The best penetration will be obtained when the jet is perpendicular to the target face. Angles of jet-target incidence smaller than 90 degrees will yield penetrations until the angle of incidence approaches 30 to 45

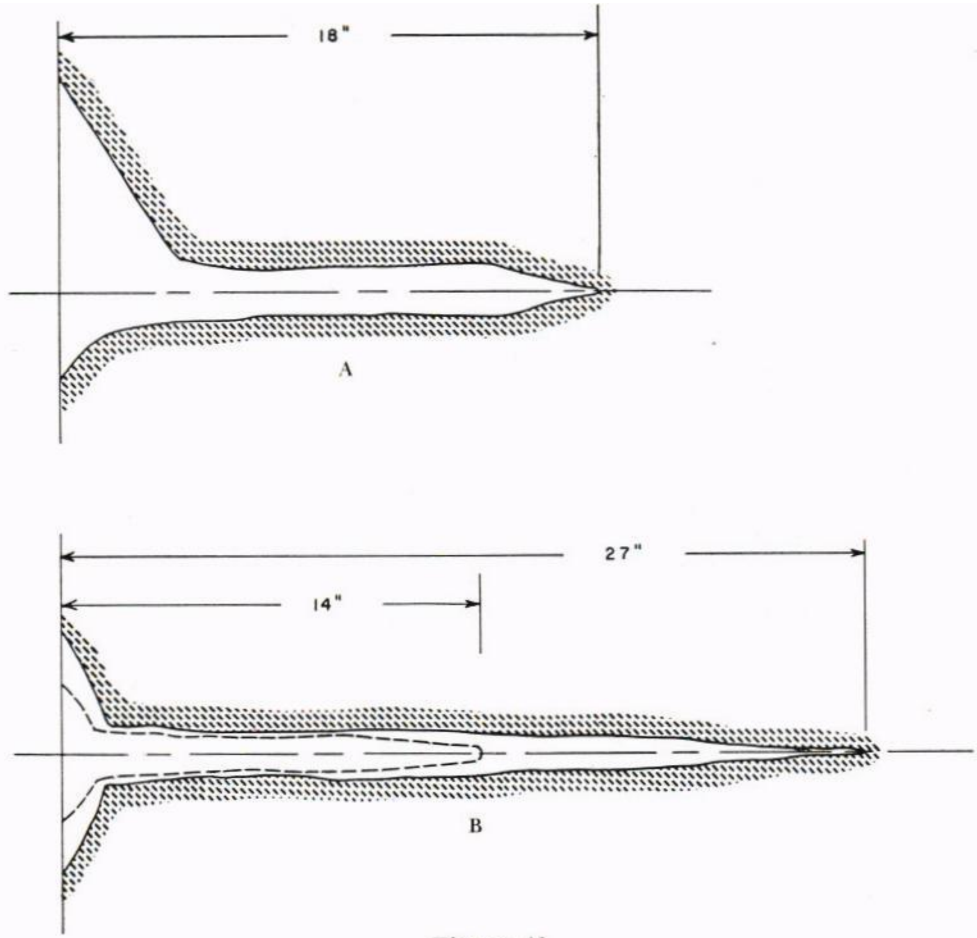


Figure 41

PROFILES OF HOLES SHOT INTO RHYOLITE

(A) Steel-encased 4-inch-diameter charge 18 inches long with a cast iron liner; (B) 2 cardboard-encased 4-inch-diameter charges 18 inches long with cast iron liners, both fired down the same hole.

Figure 42

SURFACE DAMAGE TO A RHYOLITE TARGET SHOT WITH A 6-INCH-DIAMETER STEEL-CASED CHARGE AND CAST IRON LINER

degrees. At this angle, or near it, penetration ceases, and only cratering results, the exact angle depending on the target and jet characteristics.

The requirements of standoff can be met in several ways. A simple method is to tape three legs onto a charge. These legs can be of any material strong enough to support the charge. Figure 47 shows a shaped charge taped to a wooden pole, three slats of wood providing the standoff. A more refined method of providing standoff is to use cardboard tubing of the same diameter as the charge body. This is cut to the desired length and taped into position. At times, the author has positioned shaped charges by taping them to a single stake or pole that has been wedged into position or driven into the ground. Where convenient, the author also has positioned shaped charges by simply laying them on a rock or board at the appropriate distance and angle with respect to the target to be penetrated.

Limitations in the Use of Shaped Charges With Lined Cavities

At present, lined-cavity shaped charges will not replace conventional drilling techniques in mining or other industrial activities. This is because of a number of inherent limitations. These limitations are the result of the mechanisms by which the charge works and the fundamental design of the charge. Among the drawbacks are cost, air blast, fire hazard, and fumes. These limitations are interrelated, and the reduction of one limitation may lead to reduction of other limitations in the future. Another limitation is that, regardless of expense and care in construction, a lined-cavity shaped charge can only be used once. The explosive and the liner are destroyed entirely with each shot.

COSTS

Shaped charges with lined cavities are expensive. Reference to Tables 1, 2, and 3 will show the costs of the author's charges. The costs presented in these tables are for a few charges made on a do-it-yourself basis. A lined-cavity shaped charge consists of relatively few parts. These are the charge container, the liner, the explosive, and the detonator and booster; simple, yet still expensive. Table 4 presents the costs of various-sized holes made with shaped charges. Only material costs are included. Setup time and labor for packing explosives into the charges are not included in the cost figures. It must be emphasized, however, that the costs given are maximums; mass-production methods can cut the costs of charges to a fraction of the values given.

AIR BLAST

An inherent drawback to all explosives is the simple fact that they involve explosions. Shaped charges require extremely brisant explosives and can cause large air blasts, which may result in damage to nearby structures and injury to personnel. The open-pit mining operation is ideal for the use of shaped charges because of the large amount of room and the massive equipment in use. Underground the picture changes. Confinement is the problem, and firing a large shaped charge in a long, straight drift is comparable to standing in the bore of a cannon when the propellant charge is fired. Loose, slabby ground and the presence of timbers also restrict the use of large shaped charges underground.

A number of tests were conducted at the New Mexico Bureau of Mines and Mineral Resources in order to evaluate some of the hazards involved in shaped-charge blasting. Tests were made for air-blast damage by evaluating the breakage of window glass and also injury to nearby

TABLE 4. SUMMARY OF SHAPED-CHARGE COST AND PERFORMANCE

Target rock	Penetration (inches) max.	Penetration (inches) min.	Penetration (inches) ave.	Number of shots	Type of charge	Liner diameter (inches)	Liner metal	Liner thickness (inches)	Liner type	Explosive type	Explosive weight (lb)	Cost of charge
rhyolite	23.9	10.9	16.6	8	cylindrical*	4	cast iron	0.18	cone	C-3	5.5	$6.76
altered quartz monzonite	38.4	15.9	25.2	8	cylindrical*	4	cast iron	0.18	cone	C-3	5.5	$6.76
wood			47.2	1	cylindrical*	4	cast iron	0.18	cone	C-3	5.5	$6.76
limestone	10.4	8.5	9.5	3	cylindrical	4	cast iron	0.18	cone	C-3	5.5†	$6.76
rocky alluvium	44.3	27.8	35.8	4	cylindrical*	4	cast iron	0.18	cone	C-3	5.5	$6.76
sandstone	25.8	20+	23+	2	cylindrical*	4	cast iron	0.18	cone	C-3	5.5	$6.76
rhyolite	17.0	15+	16+	2	beehive*	4	cast iron	0.18	cone	C-3	3.3	$5.83
rhyolite			20.6	1	cylindrical	4	cast iron	0.18	cone	100% gelatin	5.4	$6.40
rhyolite	25.3	22.5	23.9	2	beehive	6	cast iron	½° taper to 0.20 at base	frustum of cone	C-3	14.2	$21.43
rhyolite	11.6	11.5	11.6	2	cylindrical*	4	cast iron‡	±0.2	cone	C-3	5.5	$4.21
rhyolite			18.6	1	beehive	4	aluminum	0.18	cone	C-3	3.3	$7.03
rocky alluvium	24.0	19.5	21.8	2	cylindrical*	4	cast iron‡	±0.2	cone	C-3	5.5	$4.21
rhyolite			8.5	1	beehive	4	fired ceramic	±0.2	cone	C-3	3.3	$3.53§
rhyolite			4.0	1	beehive	4	cast iron	0.18	cone	NM plus aniline	2.4	$5.05
rocky alluvium			48+	1	beehive	6	steel	0.25	frustum of pyramid	C-3	11.3	$13.07‖

*3.3-lb beehive equals 5.5-lb cylinder in performance.
†One of the 3 shots was made with an 18-in.-long by 4-in.-diameter charge using 11.5 lb of C-3.
‡Rough, unmachined castings.
§Liner cost of 25 cents.
‖Liner (welded octagonal frustum of a pyramid) cost $10.00.

ersonnel. Glass breakage was utilized because it has been shown by the U. S. Bureau of Mines to be the first structural damage encountered in buildings.

Glass-breakage tests were conducted by means of window boxes. The window boxes were plywood-covered boxes with one side containing two panes of single-strength glass. The results of the tests for unconfined air blasts are presented in Table 5. The tests were conducted by suspending a 1-pound charge of C-3 in air and moving a set of boxes closer

TABLE 5. UNCONFINED AIR-BLAST TESTS WITH C-3

CHARGE SIZE (lb of C-3)	TYPE OF TARGET*	DISTANCE TO TARGET (in feet)	DAMAGE SUSTAINED
5	Glass	200	None
5	Glass	150	None
5	Glass	100	None
5	Glass	50	Minor to box; none to glass
5	Glass	50	Minor to box; none to glass
5	Glass	50	Minor to box; projectile broke one pane
5	Glass	50	Minor to box; projectiles broke both panes
5	Glass	50	Minor to box; none to glass
5	Glass	50	None
5	Glass	40	Box sprung; both panes broken
5	Glass	40	Box sprung; both panes shattered
5	Glass	40	Box sprung; one pane shattered
5	Glass	40	Box sprung; both panes broken
5	Glass	40	Box sprung; one pane broken
5	Glass	30	Box sprung; both panes shattered
5	Glass	30	Box broken; both panes shattered
5	Glass	20	Box broken; both panes shattered
1	Glass	30	Minor to box; projectile broke one pane
1	Glass	30	None
1	Glass	30	None
1	Glass	20	Minor to box; one pane broken
1	Glass	20	Minor to box; both panes shattered on edges but intact in centers
1	Glass	20	Minor to box; both panes shattered
1	Glass	10	Box destroyed; both panes shattered
1	Glass	10	Box destroyed; both panes shattered
15	Glass	80	Minor to box; none to glass
15	Glass	60	Minor to box; both panes shattered
1	Person	400	None
1	Person	350	Slight ringing of ears
1	Person	300	Ringing of ears
1	Person	250	Ringing of ears
1	Person	200	Ringing of ears when cotton plugged
1	Person	200	Ringing of ears; ears pressure sensitive and painful for several hours

* All glass targets composed of 2 panes of single-strength glass, 15 in. by 24 in., mounted in an enclosed plywood box.

to the blast until positive damage was recorded. Once the $S_{\bar{g}}^{o}$ value[5] was determined, larger blasts using shaped charges were made to confirm the exponents involved. For C-3 in air, the value obtained for $S_{\bar{g}}^{o}$ is 25 ft-lb$^{-0.4}$.

When testing for injury to personnel, the problem is to devise a receiving device with the same response to damage as the human ear. A simple solution adopted was for the author to stand a little closer to each blast. When the distance from 1 pound of C-3 suspended in air was 200 feet, the pressure pulse became painful and ear disturbances lasted for 6 to 8 hours after the shot. It is possible for a person to stand much closer to larger blasts with no discomfort if a sizable solid object is located between the blast and the observer. Earth banks, large rocks, or buildings serve as such obstructions.

Data for underground or confined air blasts were also obtained by means of window boxes. The boxes were used in a narrow timbered drift in a silver mine owned by the New Mexico Institute of Mining and Technology. Underground tests, summarized in Table 6, indicated the value of $S_{\bar{g}}^{o}$ as 56 ft-lb$^{-0.4}$ for the test conditions used. The mine is timbered on 4-foot centers with 8-inch timber and is fully lagged. The clear opening inside a set is 3 feet at the back and 4 feet at the bottom, and the back is 6 feet high. No large blasts were set off underground because of the heavy nature of the ground. Even 0.75-pound charges were sufficient to knock sets out of line, and larger charges would have caused severe caving.

An estimation of the value of S_i for personnel in underground locations suggested that a person would need to be 450 feet from a 1-pound charge suspended in a straight drift comparable to the drift in the Institute mine. Much larger shapes and charges may be fired underground if several bends in the workings are between the shot and the observer. The use of bulkheads would greatly facilitate the use of larger shaped charges in a working place. In all mines, the use of brisant, unconfined explosive charges should be approached with caution unless the mine operators have had previous experience with large unconfined blasts underground.

Further problems to consider underground are shaking in of a working place and the creation of loose slabs. In the small silver mine in which the underground tests were made, even 0.75-pound blasts of C-3 would knock large amounts of loose muck and slabs into the mine opening. The ground, however, in which the mine is located is very loose, broken landslide rubble and is unable to stand unsupported.

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5. $S_{\bar{g}}^{o}$ is defined by Cook as follows: $S_i = S_i^{o} M^{0.33}$, where S_i is the distance for the ith type of damage (for glass $S_i^{o} = S_g^{o}$) produced by M pounds of explosive. S_i^{o} is the corresponding distance for 1 pound. $S_{\bar{g}}^{o}$ is the average value used for glass-damage distance for 1 pound of explosive.

TABLE 6. CONFINED AIR-BLAST TESTS WITH C-3

CHARGE SIZE (lb of C-3)	TYPE OF TARGET*	DISTANCE TO TARGET (in feet)	DAMAGE SUSTAINED
3/4	Glass	50	Minor to box; both panes shattered
1/2	Glass	50	None
1/2	Glass	50	None
1/4	Glass	50	None
1/4	Glass	50	None
1/4	Glass	36	None
1/4	Glass	31	Minor to box; one pane shattered, one pane broken
1/4	Glass	26	Minor to box; both panes shattered

* All glass targets composed of 2 panes of single-strength glass, 15 in. by 24 in., mounted in an enclosed plywood box.

FIRE HAZARD

A fire hazard was disclosed by the first shot made with a lined-cavity shaped charge in this project. The blast, using a 6-inch-diameter cast iron liner, ignited oak, grass, and prickly pear for a distance of 75 to 100 feet from the hole and axially in line with the hole. The backblast, as it is called, was found to occur with all lined-cavity shots. The fire hazard is caused by the intense heating of the liner particles by their high-velocity impact with the target material, and also by the burning of metallic-liner particles following impact with the target. Smaller metallic-liner particles will burn because of friction and heat from liner deformation, even when the liner is shot out into air. When the back-blast leaves the penetration, it is traveling at about 200 miles per hour. This low velocity enables the hot backblast material to be entrapped by brush, timber, and other combustibles, which are promptly set afire.

Backblast materials from shots made with metallic liners consisted of oxidized metal, unoxidized fragments, and sintered rock fragments entrapped in the liner oxides. Figure 43 consists of two photos, one-sixty-fourth of a second apart, of a backblast resulting from the shooting of a 4-inch-diameter cast iron liner into a massive rhyolite target. The first picture was taken one-sixteenth of a second after the blast. Copper and zinc exhibit much lower heats of formation for their oxides than iron. A brass liner was shot into the same rhyolite target. Figure 44 presents the backblast from this shot for the same time intervals as Figure 43. Although the brass liner did not start a brush fire, as did the cast iron liner, it emitted sufficient incandescent material to be a fire hazard.

The small amount of incandescence in the backblast from a brass liner indicated that the major portion of the incandescence resulted from oxidation of the liner material. This suggested that the firing of a ceramic liner, composed of silicates and oxides, would cause very

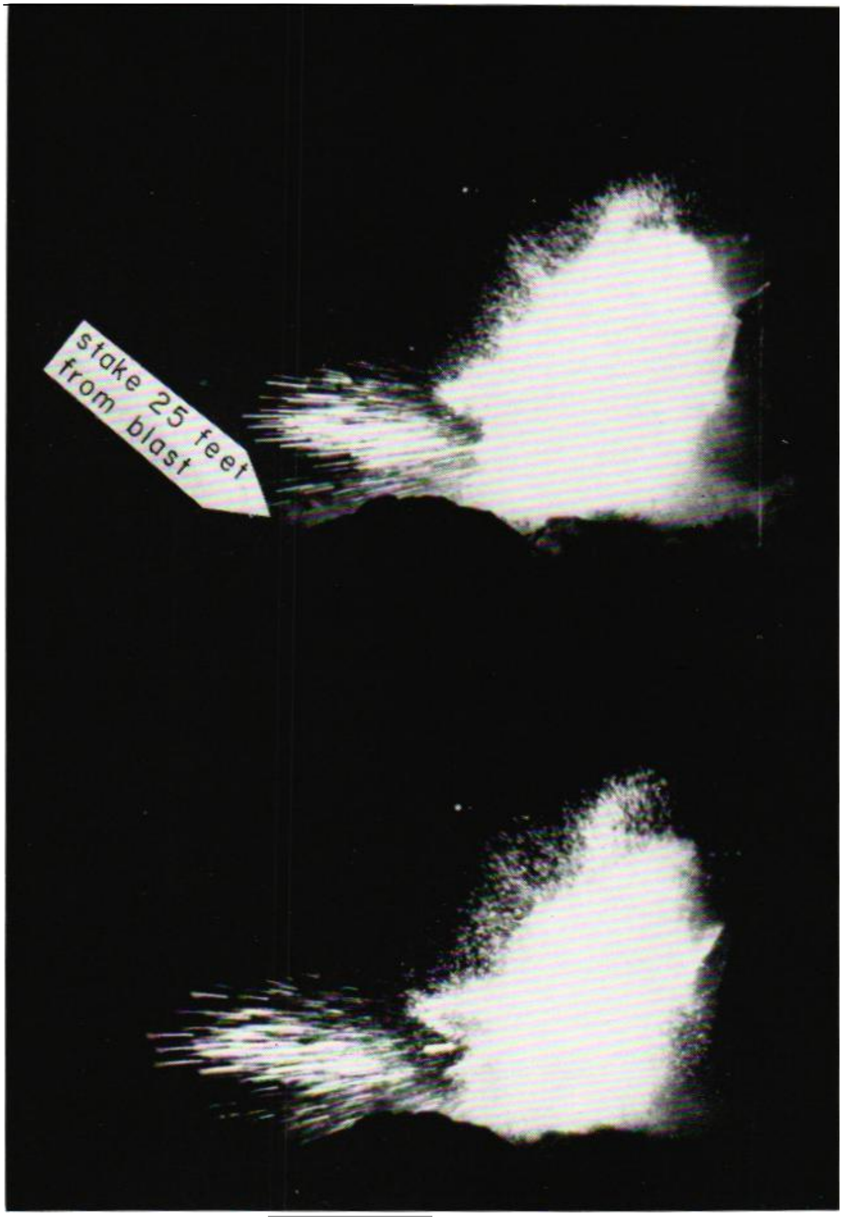

Figure 43

BACKBLAST FROM A 4-INCH-DIAMETER CAST IRON LINER SHOT INTO RHYOLITE

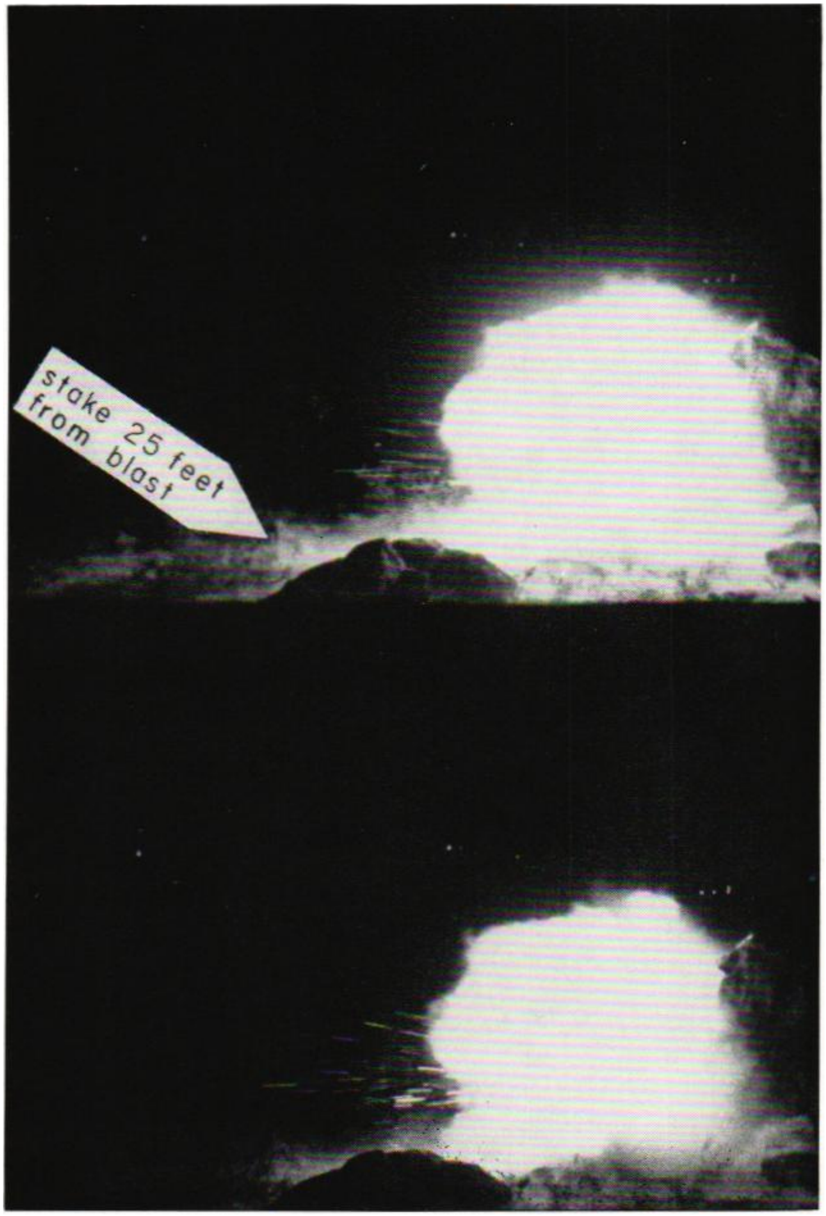

Figure 44

BACKBLAST FROM A 4-INCH-DIAMETER BRASS LINER SHOT INTO RHYOLITE

Figure 45

BACKBLAST FROM A 4-INCH-DIAMETER CERAMIC LINER SHOT INTO RHYOLITE little fire hazard. The ceramic liner fused when fired into rhyolite. Fused liner material in the backblast, heated by collision with the target, was hot enough to cause a brush fire in the target area. Further research is needed to develop a liner which will yield only very fine fragments in the backblast. Fine fragments lose their velocity quickly, cool rapidly, and present less fire hazard. The backblast from a ceramic liner is shown in Figure 45. The timing interval and framing rate are the same as for the two other backblast photo sequences given.

FUMES

Fumes from the explosion of a shaped charge are of little consequence in surface blasting. The same cannot be said for blasting in confined places, such as small mine workings. In underground mine workings, high explosives suitable for shaped charges require excellent ventilation to prevent hazardous accumulations of explosion products. Both nitromethane and aniline are volatile and poisonous when inhaled. Aniline is also a severe contact poison. Mention has been made of the severe, temporary headaches caused by nitroglycerine and nitroglycol.

EXPLOSIVES

Caution is urged for all who handle explosives. A shaped charge with a lined cavity, however, is no more hazardous than any other explosive and often is less so because of the insensitivity of many high-velocity, high-brisance explosives to accidental detonation. If a shaped charge is accidentally fired, it will present two hazards: one hazard is the jet, the other is the air blast. The hazard due to the jet is limited to a few hundred feet in air in the direction in which the shape is pointing, the actual hazardous distance depending on the size of the shaped charge. The air-blast hazard is slightly greater than for a comparable amount of ordinary mining explosive because of the high-brisance explosives used in constructing shaped charges.

All explosives should be treated with respect. The same respect should be accorded detonators and boosters. Persons making their own shaped charges should obtain the manufacturer's recommendations for the particular devices being used to make the charge. The author would strongly caution against any homemade attempts to mix or cast pentolites, cyclotols, and similar types of explosives.

Applications

CURRENT INDUSTRIAL USES OF LINED-CAVITY SHAPED CHARGES

The oil industry makes considerable use of the lined-cavity shaped-charge phenomena in inaccessible locations. In addition to ease of use, the shaped charge offers special advantages for making oil well completions by means of perforation.

The steel industry uses the concept of jet perforation in the field of open-hearth tapping, a hazardous location. The object of using a shaped charge for tapping is to remove all personnel from the drilling or tapping area at the time of drilling and to obtain full-sized openings in a very short time interval.

Some attempts have been made at using shaped charges for secondary boulder breakage in mining. This application has met with only limited success.

POSSIBLE USES FOR LINED-CAVITY SHAPED CHARGES IN MINING AND ALLIED INDUSTRIES

With the present costs for explosives and liner materials, and in the current state of technology, the lined-cavity shaped charge cannot compete with more conventional drilling techniques except for certain specialized applications. The economically favorable applications lie in the following areas: (1) drill sites presenting hazards to the driller; (2) drill sites in inaccessible locations; (3) drill sites where drilling time is of importance; (4) drill sites where only a few holes are required.

In all the above situations, the use of lined-cavity shaped charges also requires that relatively shallow holes be needed. Most uses for shaped-charge penetrations involve more than one of the above areas of application. A list of uses for penetrations would fill many pages and probably would be far from complete. Only a few uses which were tried in the field are presented, but they serve to illustrate general types of applications, as well as the great variety and range of possible uses.

SURVEY POINTS

Holes were shot into solid rock by a number of different types of lined-cavity shaped charges. The holes made were all usable for setting survey points. A wooden plug could be driven into them and a spad set, or, in the case of a permanent survey, a steel pin could be grouted into place.

ANCHORS

Shaped-charge penetrations in massive rock are ideal for the quick setting of anchor bolts, J bolts, pins for staging, slusher tail sheaves, etc. When the target rock is massive, the penetration usually does not produce sufficient deep cratering or fracturing to impair the target's resistance to tensile loadings. To illustrate this, a 1-inch-diameter carbon-steel rod was slotted and set by means of a wedge in the hole illustrated in Figure 14. A tensile load on this bolt broke the bolt with a pull of 19 tons. Failure occurred in the threaded end of the bolt. The rock did not fail in any way. When desired, anchor bolts can also be grouted or leaded into place in shaped-charge penetrations. Figure 46 illustrates the 1-inch bolt set in a penetration in rhyolite, as used in the above-described tests.

BOULDER BLASTING

Precise data on boulder blasting is difficult to obtain unless a great many tests are carried out and averages used. The reason for this is that, unfortunately, the same boulder cannot be tested by more than one method, and precise comparisons are thus not possible. A lined-cavity shaped charge is not believed to be as efficient as a good plaster shot.

Figure 46

STEEL ANCHOR BOLT SET IN A HOLE SHOT INTO RHYOLITE

Hole made with 2 charges using 4-inch-diameter cast iron liners. Only one shot was actually needed for an adequate hole; the second shot was related to other experiments carried out in the same hole prior to setting the bolt.

When a boulder is very large, however, the size of the plaster shot becomes cumbersome, especially in confined places or areas where air blast is a problem. A shaped charge can be used in situations of this type to drill a hole which is loaded with explosives and shot.

An example of this type of boulder shooting occurred in the area used for many of the field tests made for this project. A grader was being employed to level an area in rocky alluvium. An almost spherical boulder was encountered which was over 4.5 feet in diameter. The boulder, of rhyolite, projected only a foot above grade, and mechanical removal would have required a large excavation. A 3.3-pound beehive charge was fired on the top of the boulder. The rock was cracked and a hole made in it that was open for 15 inches and then filled with loose dirt swept in by the blast. A bucket of water was poured into the hole to cool it, for although penetrations in rock yield cool hole walls, the iron and iron oxides rammed into the hole bottom will be very hot. After letting the water stand in the hole for a few minutes, two sticks of powder were dropped into the hole and shot. The boulder was demolished. In any shot made into a boulder, one or more of the following three things will occur: (1) the boulder will break; (2) the boulder will have a hole drilled into it; (3) if the boulder is in a hangup underground, the hangup will be shaken free by the blast. Boulders frequently are found in underground mining in areas where drilling is hazardous or impossible. Shaped charges can be used to drill in locations of this type. Figure 47 shows a 4-inch-diameter cylindrical shape ready for firing. The shot made a hole in the altered quartz monzonite target that was 38 inches deep, 2.5 inches in diameter at the hole collar, and 0.5 inch in diameter at a depth of 38 inches. Drilling would have been out of the question, as the shot was located under an overhang in a cave area. The hole resulting from the shot could have been loaded and fired to bring down considerable muck.

POSTHOLES, WATER WELLS, AND SIMILAR EXCAVATIONS

Lined-cavity shaped charges can be used to dig holes in rocky alluvium and other clays or soils. The hole in ordinary compacted alluvium will be open; that is, the hole does not require extensive cleaning out. By the use of shaped charges, posts can be set in rocky ground that would defy any attempt at ordinary posthole digging. A shaped charge is hardly practical, however, for well digging. A shaped charge can be used to start a well and to drill holes in large hand-dug wells for the purposes of blasting or boulder removal, and shaped charges can be dropped down a well to crack boulders that are encountered at depth. This last use, breaking of boulders, should be approached with caution in order to avoid wrecking the hole already drilled. Small shaped charges can be used for normal perforation-completion techniques, as in the oil industry.

Figure 47

FOUR-INCH-DIAMETER SHAPED CHARGE READY TO BE FIRED IN A LOCATION WHERE DRILLING WAS HAZARDOUS

Charge held in position by masking tape.

MISSED HOLES

A lined-cavity shaped charge can be used to shoot through several feet of stemming in order to detonate missed holes. Field tests of this idea showed that care should be exercised when shooting into a hole loaded with a fuse and heat cap. The jet would, at times, ignite the fuse and thus cause a delayed blast. No trouble was encountered in shooting into holes loaded with electric caps. When the stemming in a drill hole was too deep for penetration with one shot, several shots were used until penetration reached the explosive loaded into the hole.

TIMBER AND STUMP REMOVAL

Shots were made into timber targets during this project for the purpose of slug and jet entrapment. Shots of this type also illustrated

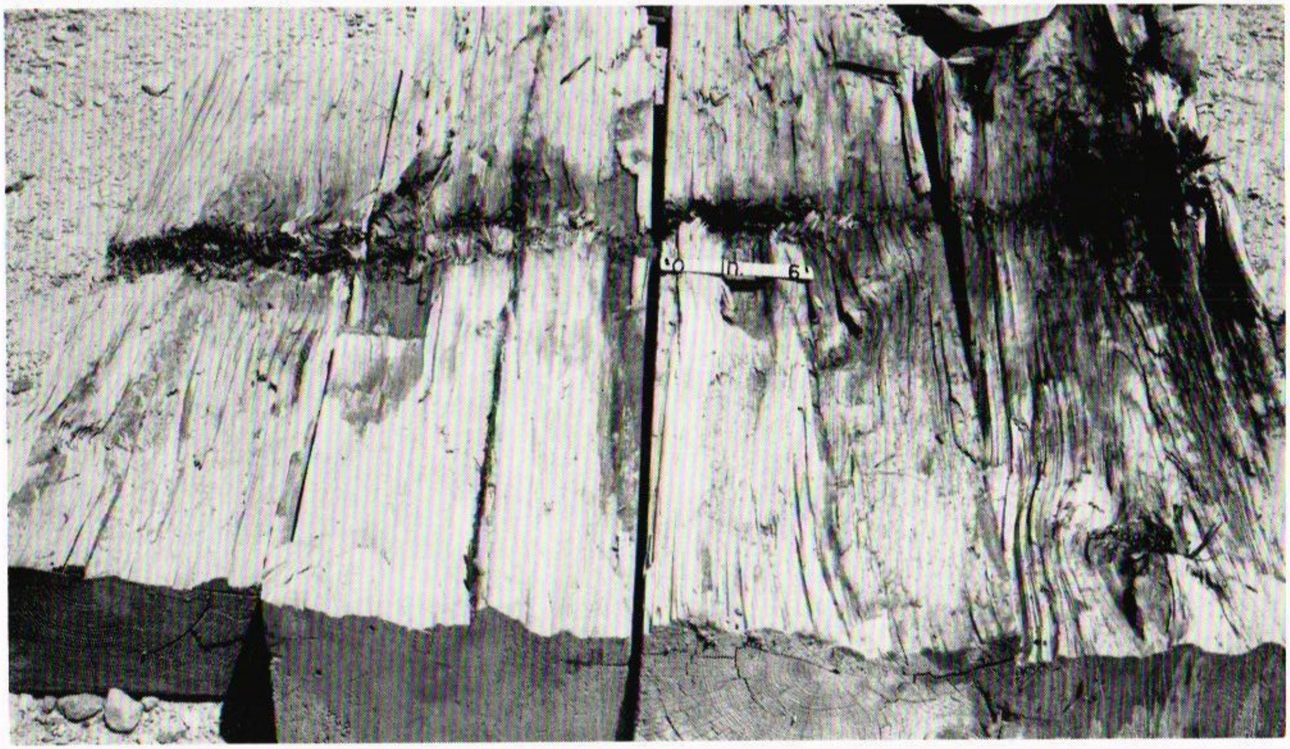

Figure 48

HOLE SHOT INTO TIMBER WITH A 4-INCH-DIAMETER CAST IRON LINER the feasibility of boring holes into timbers and stumps. Figure 48 shows a section of a hole shot into timber. For stump removal, a hole can be shot vertically into the stump and loaded with explosives, or else a hole can be shot under a stump from the side. These holes can be loaded with explosives but should, like all shaped-charge holes, be cooled first.

SAMPLING

Lined-cavity shaped charges can be used for sampling purposes where samples or specimens are required from massive rock areas. Situations of this type arise in fossil and mineral collecting, in sampling pillars and old workings in mines stripped of equipment, and in many inaccessible locations on exploration projects. This application is comparable to boulder blasting in that the shaped-charge hole will be cooled and loaded with explosives following the penetration.

METAL TARGETS

Large castings, plates, and other metal shapes can be penetrated or perforated by means of lined-cavity shaped charges. Tests were conducted during this project in which air lines were perforated while under pressure, with no damage to the air line other than the hole shot into it. The use of charges of proper size enabled holes to be punched into only one side of pipes as small as 1.5 inches in diameter. Following perforation, a sleeve, gasket, and valve assembly was slid over the perforation and tightened into position, to give a rapid means of access to a high-pressure air line. Valves, bulkheads, and numerous similar pieces of equipment can be perforated by means of shaped charges with virtually no extraneous damage.

DRIFTING

Drifting with shaped charges used for the drilling method is possible but prohibitively expensive. This type of operation could only be justified where extreme hazard would prevent ordinary drilling methods, or where a small distance would need to be opened in a very short time, especially in inaccessible locations. During drifting, the shaped charges would best be fired singly unless the ground were very strong. If the ground could stand the blast, all the shapes for an entire round could be mounted on a wooden rack and fired simultaneously by means of one cap and carefully constructed primacord lead-ins. Simultaneity is required to prevent any charge from being disturbed by its neighbor prior to initiation.

Conclusions

The lined-cavity shaped charge can be designed to give useful penetrations in targets composed of rock and earth materials. To be of value, shaped charges must be constructed of high-velocity, high-brisance explosives, and the liner must be symmetrical. The entire charge, with its resulting jet characteristics, should be matched to the particular target to be penetrated.

The use of a lined-cavity shaped charge for any job is expensive. The use of such charges will be limited to applications where drilling would be hazardous, where drilling is required in inaccessible locations, where drilling time is of importance, and where only a few holes are required. In all cases, the holes desired must be shallow. Repeated shooting in the same hole will deepen it, but efficiency drops rapidly after the second shot.

Caution must be used when firing shaped charges. Air blast presents hazards to personnel, equipment, and buildings, and can be very destructive in small, confined, underground workings. A fire hazard also is present because of the backblast. This precludes firings of lined-cavity shaped charges in many locations where otherwise applicable.

Only a few general applications are mentioned in the text of this report. The number of possible applications is limited only by individual inventiveness and imagination, and by the requirements of the particular operation under consideration.

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