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Some developments in shaped charge technology

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Shaped charges can be used to penetrate solid materials, or to enhance the penetrating capabilities of kinetic energy projectiles. This report reviews the design and performance characteristics of conventional shaped charges and it describes the development of binary shaped charges that remain non-explosive until shortly before use. The technical review outlines the basic principles of shaped charges and gives an idea of the penetration depth and hole diameter for typical charges firing into various target materials. The effects of standoff distance, cone diameter, cone angle, cone thickness, cone material and explosive type are described. Special attention is given to the penetration of frozen ground and ice.

20. Abstract (cont'd)

Current development work on binary shaped charges is discussed, and results of recent tests on permafrost penetration are given.

PREFACE

This report was prepared by Dr. Malcolm Mellor, Research Physical Scientist, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. The work reported here was funded under DA Project 4A762730AT42, Design, Construction, and Operations Technology for Cold Regions, Task Area CS (Combat Support), Work Unit 029, Explosives and Projectile Impact Under Winter Conditions.

Technical review of the manuscript was performed by Donald G. Albert, Dr. Piyush K. Dutta, Dennis R. Farrell and Paul V. Sellmann of CRREL.

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SOME DEVELOPMENTS IN SHAPED CHARGE TECHNOLOGY

Malcolm Mellor

Introduction

Conventional cylindrical shaped charges are used in many types of armor-piercing ammunition and they are also available in most armies in the form of demolition charges for penetrating such things as hard ground, masonry walls and floors, and other materials. Small shaped charges are used occasionally in industry, notably for piercing oil well casings and for tapping blast furnaces in steel mills.

Large shaped charges, with cone diameters in the range 4 to 9 inches (0.1 to 0.23 m), are useful for a variety of peacetime tasks in civil and military engineering. However, large shaped charges are not normally available from commercial suppliers, and within military systems they are difficult to acquire because of stringent controls on storage, transport and release for use. To overcome some of these problems, binary shaped charges are being developed by the author, in collaboration with Thermex Energy Corporation. The binary charges are filled with an innocuous solid material, and they can be transported and stored without major hazard. Just prior to use, the charge is armed by saturating its porous solid filling with a liquid ingredient. This liquid is not explosive (unless boosted by primers) and it can be transported and stored in the same way as other flammable liquids. The armed charge can be initiated by a number 6 or a number 8 detonating cap.

Common binary explosives are not ideal for shaped charges, in that detonation velocity, detonation pressure and bulk density are comparatively low. The design and performance characteristics of existing shaped charges have therefore been reviewed in order to provide guidance for best use of the binary explosive.

This paper summarizes the characteristics of existing shaped charges and gives test results for penetration of frozen ground and ice. It then describes recent experiments with binary shaped charges and outlines the prospects for further development.

Shaped charges, or lined cavity charges

A shaped charge (cavity charge, or hollow charge) is a charge of high explosive (solid or liquid) with some kind of cavity in one of its surfaces. The most common shaped charges are radially symmetrical, either in the form of a cylinder with a cavity at one end, or in the form of a thick cone

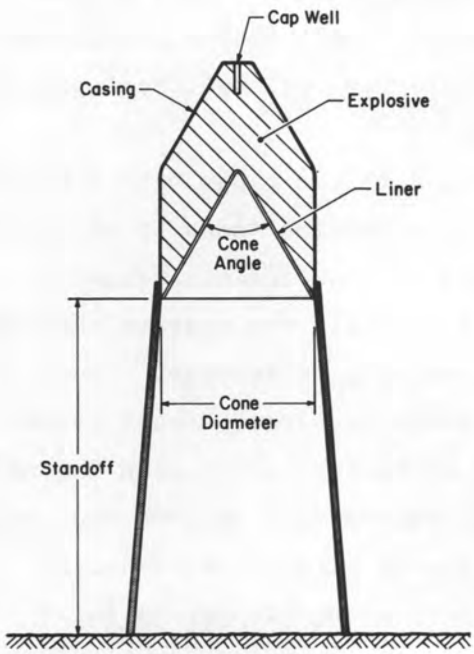

Figure 1. Basic features of a typical rotationally symmetrical shaped charge.

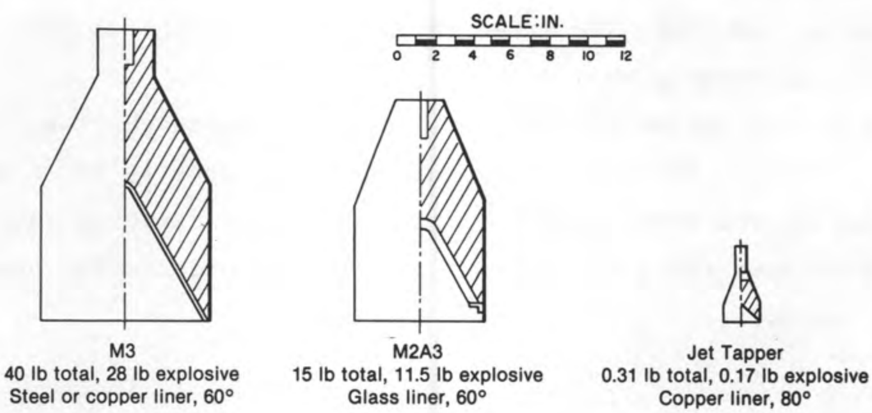

Figure 2. Dimensions and charge weights for some representative shaped charges.

(Fig. 1 and 2). After initiation at the end opposite from the cavity, the detonation wave propagates to the cavity and envelops it, forming a converging shock which focuses into a jet. The cavity in a radially symmetrical charge can be conical, hemispherical, domed, or trumpet-shaped (Fig. 3). Shaped charges can be improvised by packing plastic, granular, or liquid explosive around a suitable mold, such as the bottom of a good wine bottle. Another type of shaped charge is the linear shaped charge, in which the cavity is a vee-groove in a long bar of explosive that has rectangular or triangular cross section (Fig. 4). The linear charge may be either stiff or flexible.

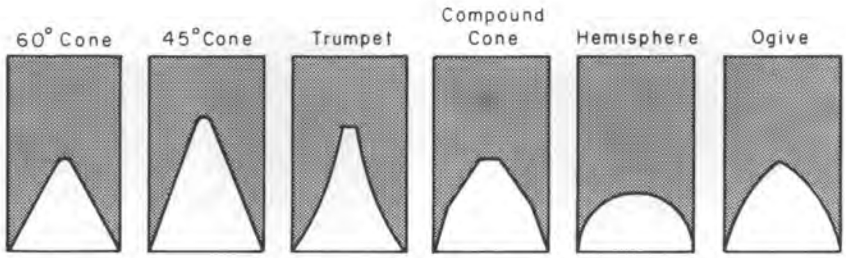

Figure 3. Cross sections of various types of cavities that have been used for shaped charges.

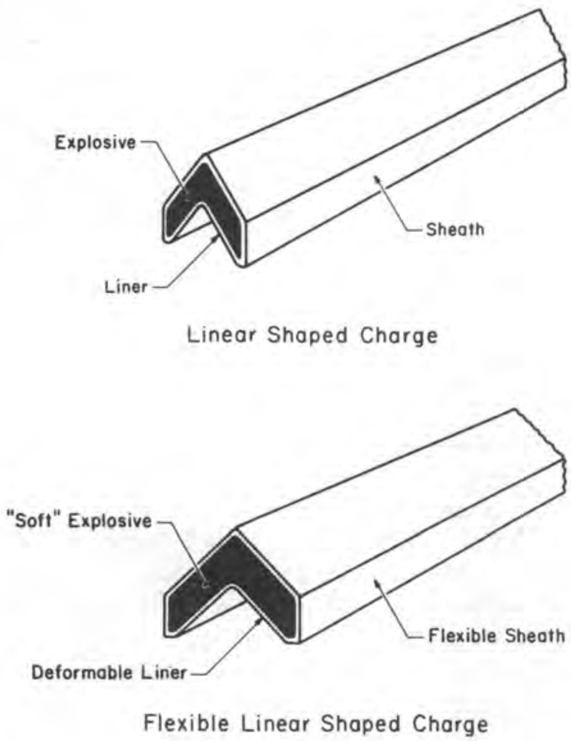

Figure 4. Linear shaped charges. The cross section may be either the chevron shape shown here, or a rectangular shape with a vee cavity. Rigid linear shaped charges can use rigid materials throughout and can have narrow-angle cavities. Flexible linear shaped charges are made from flexible materials as far as possible, but they may be segmented to permit use of a rigid liner material. Flexible charges are likely to have a wide-angle cavity.

Strictly speaking, any charge that develops the cavity effect is a shaped charge, but the term is usually applied to a specific type of charge which has its cavity lined with a thin layer of metal, glass or ceramic. In a lined cavity charge, the converging shock creates high temperature and pressure and causes the liner to collapse, compress and extend into the jet. Collapse starts at the apex of a conical liner, usually causing the cone to squash into a slug and to flow out into a thin needle and/or stream of droplets (Fig. 5 and 6). The slug forms the tail end of this stream,

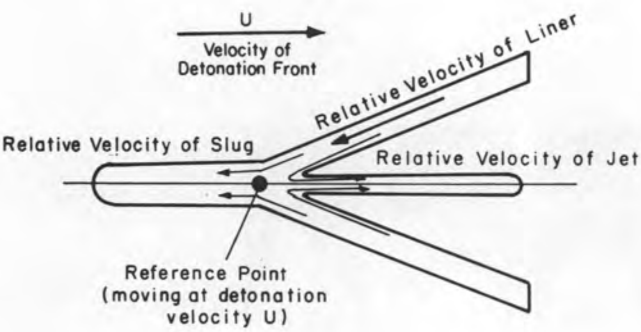

Figure 5. Relative motions during the collapse of a conical liner. The arrows denote motion relative to a reference point on the axis that is traveling at the detonation velocity U. The main body of the slug is left behind by the advancing detonation front, while the jet escapes ahead of the detonation front. The liner material is thus drawn out into a thin filament, which eventually breaks into discrete particles at the tip of the jet. (From U.S. Army 1963.)

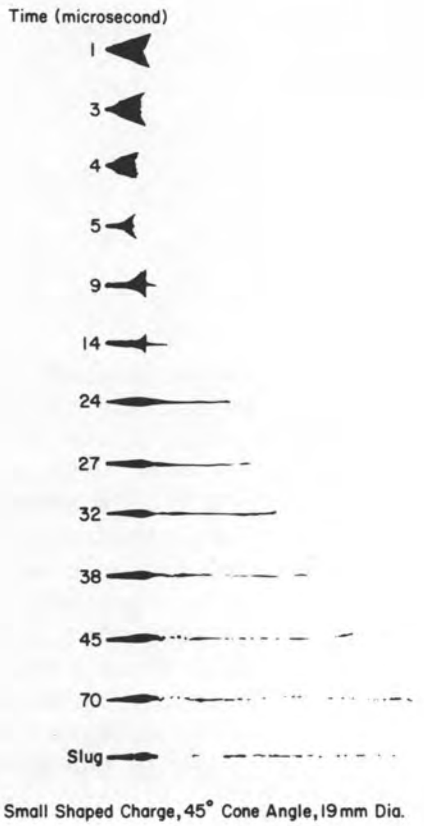

Figure 6. Stages in the collapse of a 45° steel cone, 0.75 in. diameter, in a charge of 50/50 Pentolite. This diagram, sketched from an ultra-high-speed radiograph, shows the formation and drawing of the slug. (After U.S. Army 1962.)

and it enters the target material via the hole made by the front end of the jet. The slug may lodge in the hole, or it may come back out. For a liner that is hemispheric, or has an ogive section, the liner can turn inside out before collapsing into a stream. Incorporation of metal or other dense material into the explosive jet has the effect of increasing jet density and stagnation pressure.

With typical charge size, the jet forms in something of the order of 10^{-4} s. The initial velocity of the jet tip is about 8 to 12 km/s, and average jet velocity is comparable to the detonation velocity of the explosive (Fig. 7). During jet formation the tip travels faster than the tail, so the jet elongates. As the tip penetrates a target it slows down (Fig. 8). Initial contact pressure can be of the order of 250 kilobars. An air gap between the charge and the target (a standoff) is needed to allow the jet to form, but the gap should not be too big, as the effective jet length is limited, even in air.

In simplified jet penetration theory, the jet is assumed continuous and steady, the yield strength of the target material is assumed negligible in comparison with the jet pressure, and standoff requirements are ignored. Hydrodynamic theory then gives target penetration ℓ_t as

$$\ell_t = \ell_j \, (\rho_j/\rho_t)^{1/2} \qquad (1)$$

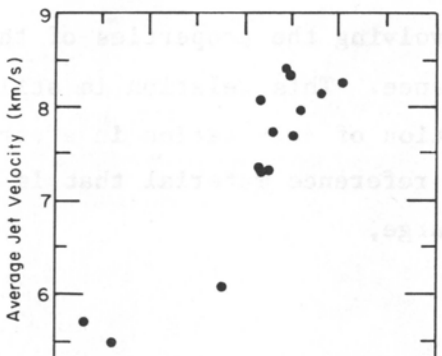

Figure 7. Average jet velocity plotted against detonation velocity for the explosive. (Data from Cook 1958.)

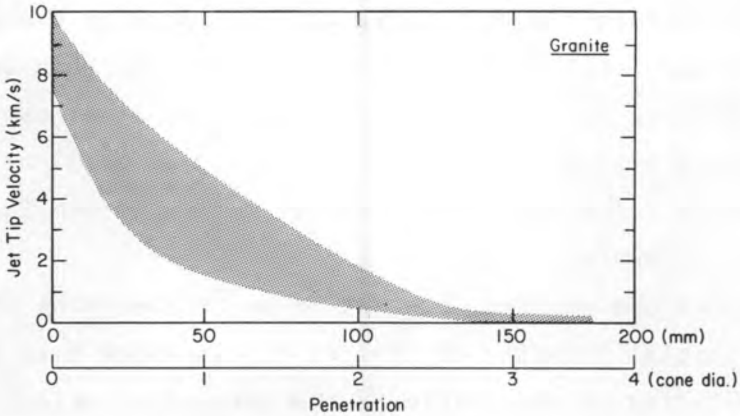

Figure 8. Deceleration of the jet tip as it penetrates granite. The shaded envelope represents data for shaped charges with various liner materials. (After Rollins et al. 1973.)

where ℓ_j is jet length and ρ_j and ρ_t are densities of jet and target respectively. The jet from a lined cavity charge actually contains discrete particles, it is not in a steady state, and it experiences interference with the target and the ejected target fragments. Equation 1 therefore has to be modified to account for properties of the jet and target, typically by a combination of theoretical refinement and empirical adjustment (see Cook 1958 and Rollins et al. 1973). For present purposes, eq 1 can just be rewritten as

$$\ell_t = k(\rho_j / \rho_t)^{1/2} \qquad (2)$$

where k is a factor involving the properties of the charge and target, and also the standoff distance. This relation is still potentially useful, in that it permits prediction of penetration in a certain material when penetration is known for a reference material that is not too different. Thus, for a given type of charge,

$$\frac{\ell_{t2}}{\ell_{t1}} = \left(\frac{\rho_{t1}}{\rho_{t2}}\right)^{1/2} \qquad (3)$$

where the subscripts 1 and 2 denote a reference material and a new target material respectively. However, for some practical purposes, eq 3 could be misleading (Fig. 9), since it ignores the finite yield strength of real materials.

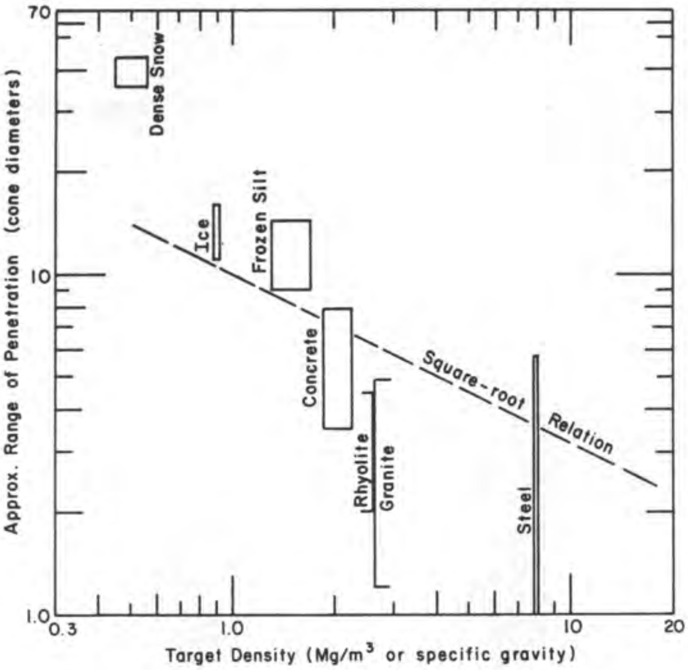

Figure 9. Representative ranges of shaped charge penetration for various target materials, with penetration plotted against target density on logarithmic scales. The dashed line represents the inverse square-root relation suggested by simple theory.

Penetration depth and hole diameter

A shaped charge designed for deep penetration punches a slender hole into semi-infinite target material (Fig. 10). At typical standoff distances, and in typical ground materials, there is an appreciable crater at the mouth of the hole. When the standoff becomes relatively small, the crater size increases and the hole depth increases. Penetration depth is usually measured from the original surface, and the mean diameter of the hole is measured near mid-depth.

For geometrically similar charges made of identical materials, the jets should be geometrically similar, and for a given target material the penetration and hole diameter should be proportional to characteristic dimensions of the charge. It is convenient to express penetration depth, hole diameter, and standoff as multiples of the cone diameter.

By using scaled variables, penetration in different target materials can be compared. Figure 11 gives representative penetration depths for

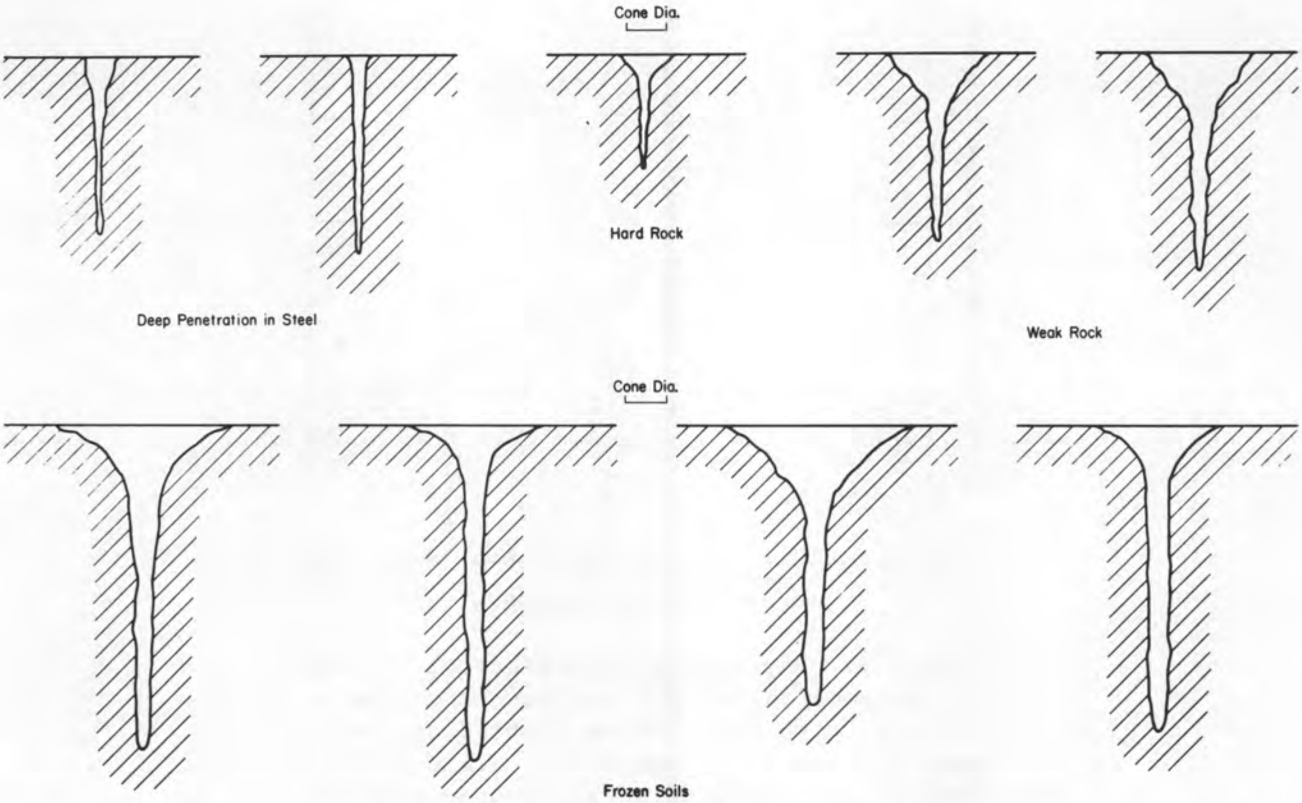

Figure 10. Typical shapes for holes punched into various target materials by conventional shaped charges. The scale is given in terms of cone diameter.

several target materials; this diagram is based on scattered results for a variety of charges and standoff distances. When these rough practical findings are plotted against target density on logarithmic scales, the agreement with simple theory is not very good (Fig. 9), possibly because the yield strength of the target material has been ignored.

The diameter of the penetration hole is always less than 1 cone diameter unless the standoff is zero, in which case the shaped charge becomes a cratering charge. Figure 12 gives representative ranges of hole diameter for charges at typical standoff distance. For ground materials, charges designed for deep penetration are likely to give hole diameters in the range 1/3 to 2/3 of the cone diameter near mid-depth. Holes in steel are likely to be somewhat narrrower, say around 0.3 diameter.

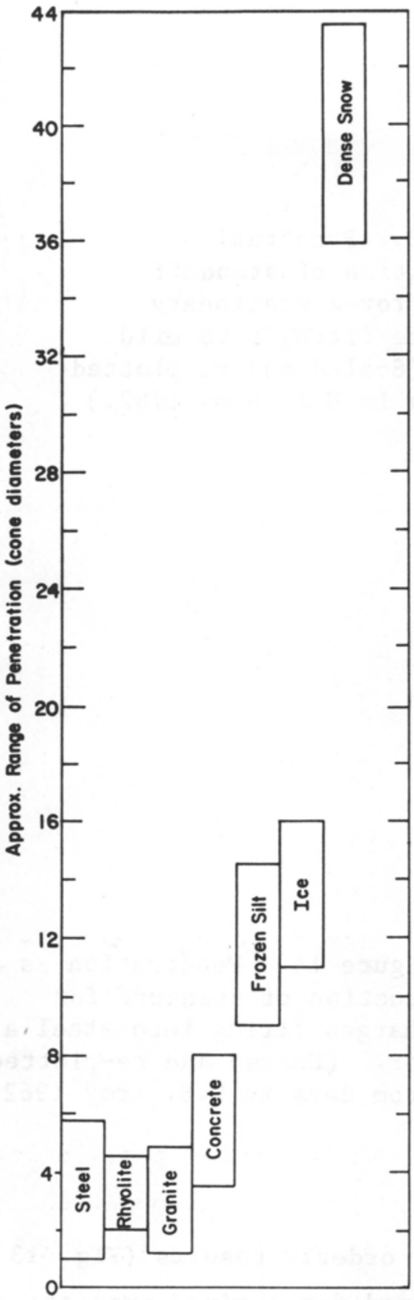

Figure 11. Representative ranges of penetration depth for various target materials and various standoff distances.

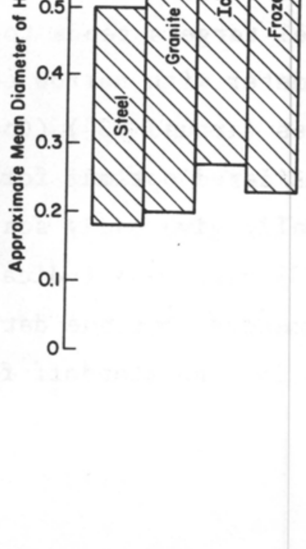

Figure 12. Representative ranges of hole diameter for typical shaped charges firing into various target materials. The large range for each material reflects the variation of hole diameter with depth.

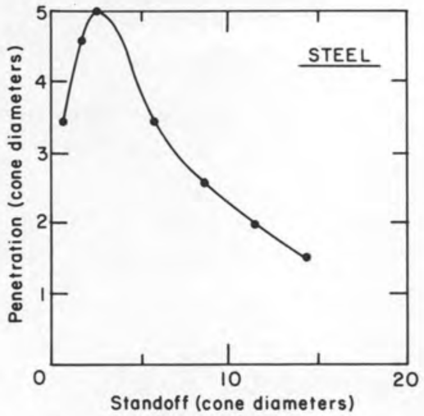

Figure 13. Penetration as a function of standoff distance for a stationary M28 charge firing into mild steel. (Scaled and re-plotted from data in U.S. Army 1962.)

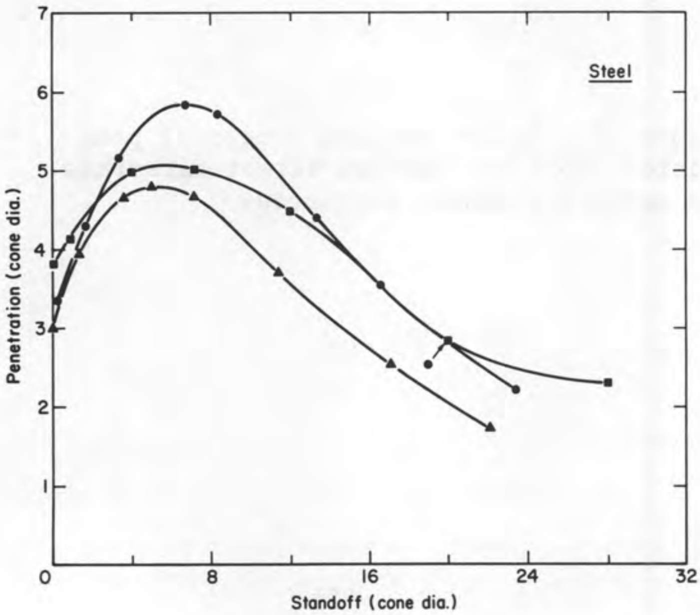

Figure 14. Penetration as a function of standoff for charges firing into steel armor. (Scaled and re-plotted from data in U.S. Army 1962.)

Standoff effects

Standoff tests against steel targets give orderly results (Fig. 13 and 14), and optimum standoff distance can be defined for a given type of charge, typically in the range 2 to 6 cone diameters. Optimum standoff for steel targets tends to increase with the cone angle, from 0.5 to 1.0 diameter with narrow cones (30°), up to 6 to 8 diameters with wide-angle cones (around 80°) (Cook 1958). A standoff of 2 cone diameters has been considered optimum for 44° cones. Standoff tests in rocks and frozen soils usually give badly scattered results. Data for granite (Rollins et al. 1973) give weak indications of an optimum standoff around 3 to 4 cone diameters, but one data set shows no significant correlation between penetration and standoff for the range 1 to 5 cone diameters. Data for frozen soils (Benert 1957, 1963) suggest optimum standoff in the range 2 to 5 cone diameters for 60° charges, and in the range 4 to 8 for charges with wider angles. Benert's data for the M3 military charge showed very little effect of standoff in the range 0 to 7 cone diameters.

As a practical matter, the smallest standoff that gives good results is likely to be the most convenient. The M2A3 charge is packaged to give a standoff of 1 cone diameter. The M3 charge is packaged with a steel tripod that gives a standoff of 1.5 cone diameters.

Effects of cone angle

For general-purpose conical charges of typical high-velocity explosive, the apex angle is typically 60°, but for shaped charges overall the range is from about 18° to 90°. Some jet effect persists at angles up to 150° with certain explosives. A 60° cone has been considered optimum for penetration of metal targets, and test data for granite (Fig. 15) seem to confirm that 60° gives the best penetration in hard rock (Rollins et al. 1973). However, Jones (1971) states that: "If the depth of penetration is the sole criterion for judging the performance of a shaped charge, then the narrow angle cone (42° optimum angle) is the obvious choice." Tests of a

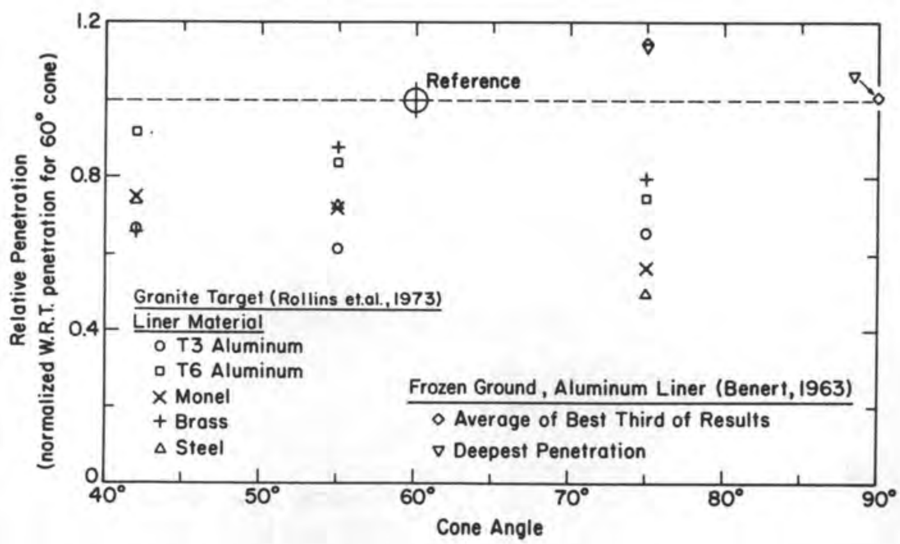

Figure 15. Effects of cone angle on penetration depth. Taking sets of data for which cone angle was the sole variable, each set of results was normalized with respect to the penetration for a 60° cone. For shots into granite, a 60° cone gave the deepest penetration. In frozen ground, a 75° cone gave the best results.

42° cone in frozen silt gave good results (Mellor 1971). The shaped charges used in HEAT* rounds for guns and rocket launchers range fom 42° to 60° in U.S. ammunition, and go as low as 18° in some foreign ammunition. The TOW missile has a "biconic" copper liner, with a 45° angle for much of the length and a 30° angle at the apex.

Test data for ground materials do not always give a clear indication of an optimum cone angle for deep penetration (Fig. 15). This suggests that there may not be a strong dependence on cone angle, and therefore other considerations (e.g. hole diameter) can influence the practical choice of cone angle. In general, mean hole diameter tends to increase with the cone angle.

Explosives for shaped charges

Theoretically, penetration is independent of jet velocity, and thus of detonation velocity. However, shaped charge penetration in strong target material seems to be maximized by using explosives that have high detonation pressure and high detonation velocity. Good candidates are dense explosives with detonation velocities around 8 km/s, e.g. RDX, some of the cast and plastic compositions, Cyclotol, Pentolites and PETN. Some

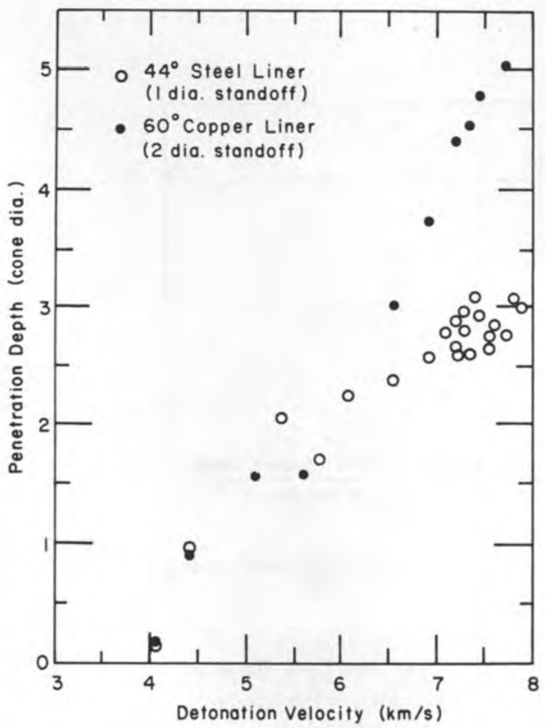

Figure 16. Penetration depth plotted against explosive detonation velocity for two types of charge (target assumed to be steel). (Data from Cook 1958.)

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* HEAT - High Explosive, Anti-Tank.

hydrazine-based liquid explosives have high detonation velocity. Having taken into account stability, sensitivity, compatibility with liner and case materials, and general safety, the penetration efficiency should correlate directly with detonation velocity. Cook (1958) showed hole volume to be directly proportional to detonation pressure. There also appears to be a linear correlation between penetration depth and detonation velocity (Fig. 16).

Effect of charge size

Charge size is usually expressed as charge length, measured axially from the apex of the cavity to the detonator or booster charge. Alternatively, it may be given simply as charge weight. Charge length can be given in dimensionless form as a multiple of charge diameter. Penetration has been found to increase as charge length increases, up to a limit at 3 to 4 cone diameters for unconfined explosive, and up to a limit at 4 or 5 cone diameters with lateral confinement by a steel case (Cook 1958). For armor-piercing shaped charges, conflicting recommendations for charge length have stated that: (a) it should be at least 4 charge diameters, or b) 2 to 2.5 charge diameters is sufficient. Studies seem to support the idea that 2 diameters is sufficient for complete development of the detonation front (Rollins et al. 1973). Actually, commercial shaped charges and military demolition charges are likely to have a charge length of 1 diameter or less, since this gives efficient and economical use of explosive, and it limits undesirable air blast.

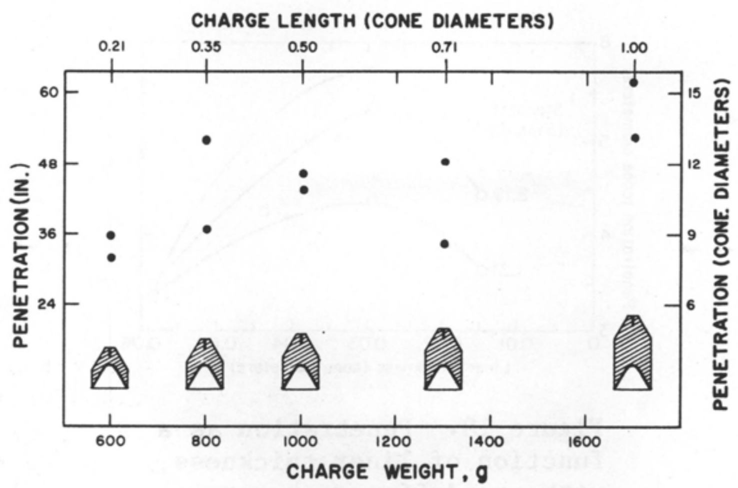


Figure 17. Effect of charge length for charges firing into frozen ground at a standoff of 6 cone diameters. (After Benert 1963.)

Benert (1963) tested charges of different length in frozen ground, finding an increase of penetration with charge length up to a length of 1 charge diameter (Fig. 17).

Effect of liner material and liner thickness

The liner material in a shaped charge should flow readily under extreme temperature and pressure, and it should divide into small fragments when the jet breaks up. High density is desirable to give high jet density. Copper and aluminum are traditional materials that give good results, but for military demolition charges steel is used in the U.S. Army M3, and glass (which does not form a slug) is used in the M2A3. Other materials have been tried, e.g. brass, monel, and magnesium alloys, but they are not in general use.

Tests against steel targets show copper liners (specific gravity ≈ 8.5) giving the deepest penetration, with steel, iron and zinc also giving good results. Aluminum and aluminum alloys (specific gravity ≈ 2.7) give less penetration, and greater standoff seems to be needed for full development of the jet.

If the liner is too thin, it will have insufficient mass to form a dense jet. If it is too thick, the liner will not collapse, form and flow properly. Figure 18 gives an example of the variation of penetration depth with liner thickness. The optimum thickness for a copper liner appears to

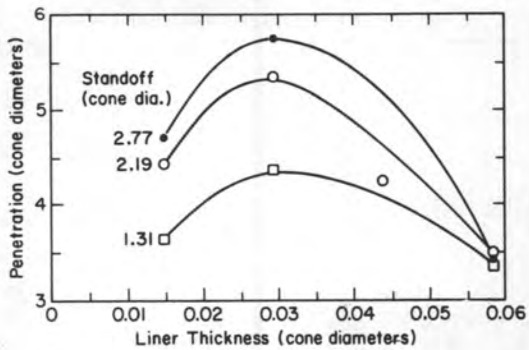


Figure 18. Penetration as a function of liner thickness, with standoff as parameter. Target probably steel. Cone material and cone angle not given, but probably aluminum. (After U.S. Army 1962.)

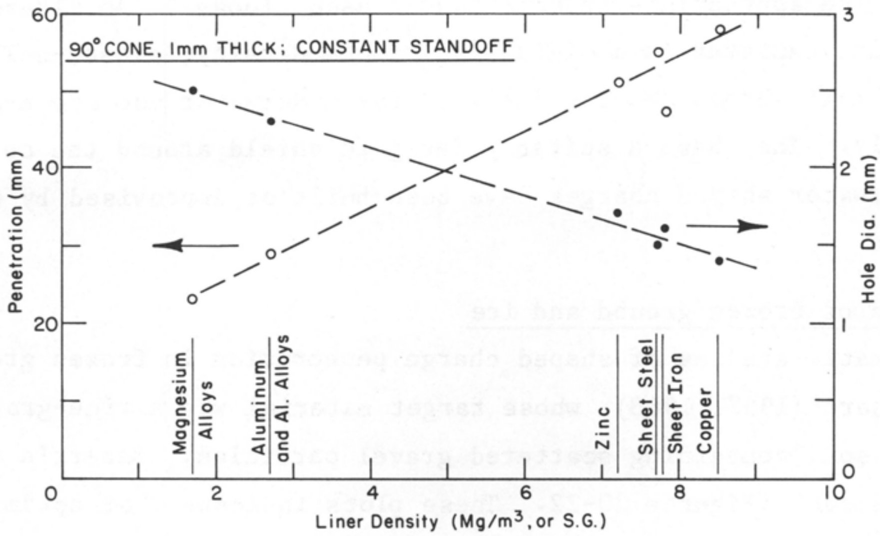


Figure 19. Penetration and hole diameter plotted against liner density for liners of constant thickness. (Data from U.S. Army 1963.)

be in the range 0.015 to 0.021 cone diameter (i.e. 1.5% to 2% of the cone diameter). The optimum value for other materials is usually based on the optimum thickness for copper multiplied by a factor which is the ratio of densities for copper and the chosen material. The usual goal is to design a liner that provides a mass equal to that of the optimum copper liner. For aluminum, optimum liner thickness is usually considered to be around 7% of the cone diameter, although Benert's (1963) data for frozen ground suggest optimum thickness in the range 5% to 6%.

Figure 19 indicates some effects of liner material, using data for 90° cones that were all 1 mm thick (i.e. thickness not optimized for all materials). Penetration depth increases, and hole diameter decreases, as liner density increases. When the penetration data are plotted on logarithmic scales, the relation is not far from the square root relation predicted by simple theory.

Underwater application of shaped charges

When a shaped charge is used underwater, it requires an air space for proper formation of the jet, just as it requires standoff when used on land. Conventional shaped charges can be modified by attaching and sealing an air-filled canister to the cone. However, the canister should be able to withstand water pressure, its base should not add significantly to the target resistance, and the completed assembly should be ballasted externally to give the appropriate orientation if used "loose." An alternative to an air-filled canister is a rigid plug of low-density, closed-cell foamed plastic. Small shaped charges designed for underwater use are available commercially. They have a suitably designed shield around the cone exit. Large underwater shaped charges have been built or improvised by excavation contractors.

Penetration of frozen ground and ice

Systematic studies of shaped charge penetration in frozen ground were made by Benert (1957, 1963), whose target material was a fine-grained permafrost soil containing scattered gravel particles. Benert's test data are summarized in Figures 20-22. These plots indicate that optimum standoff was in the range 2 to 6 cone diameters for 60° charges, and 4 to 8 cone diameters for 75° - 80° charges. They also indicate that a 75° cone gave the deepest penetration. Copper cones gave the deepest penetration, but aluminum cones gave the best combination of penetration depth and hole

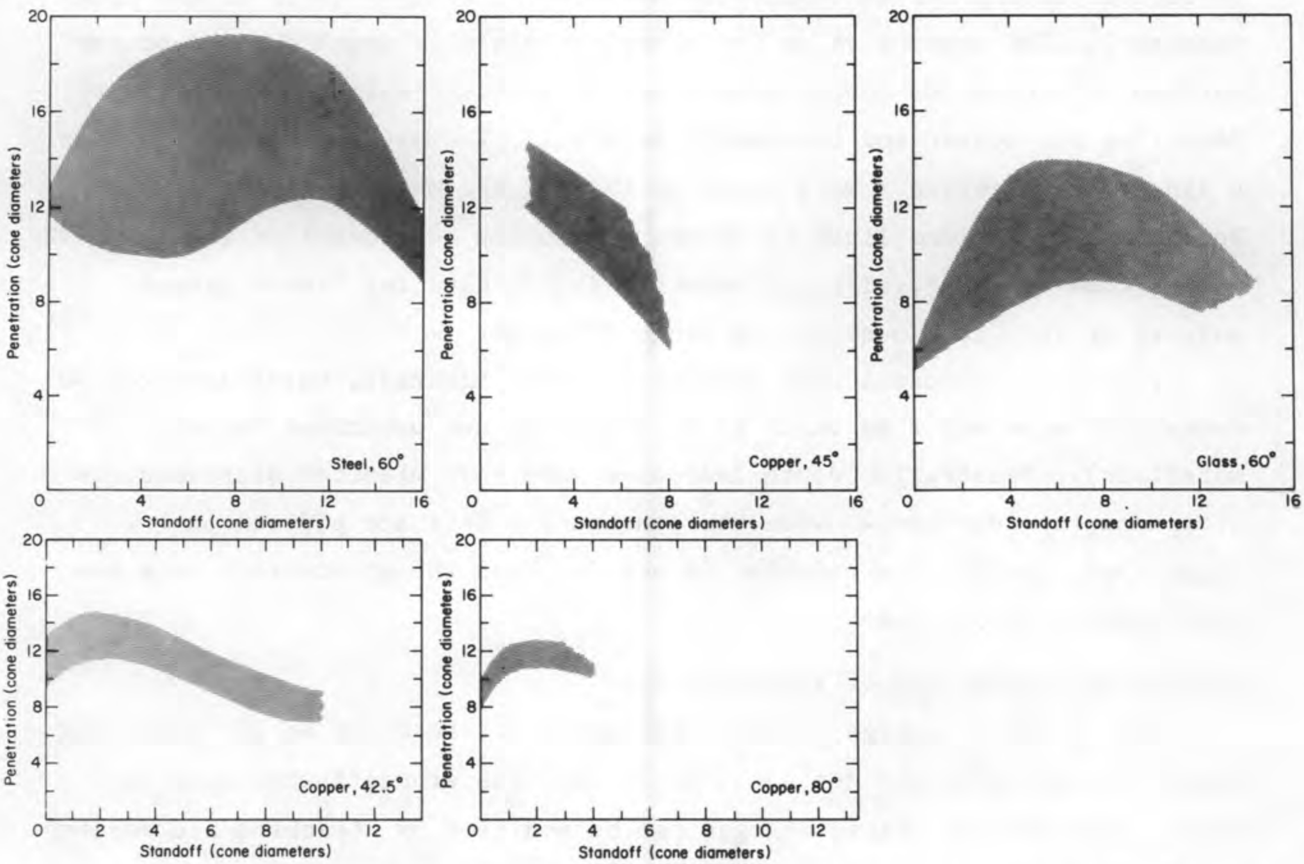


Figure 20. Penetration into permafrost by various types of shaped charges. (Envelopes representing data by Benert 1957.)

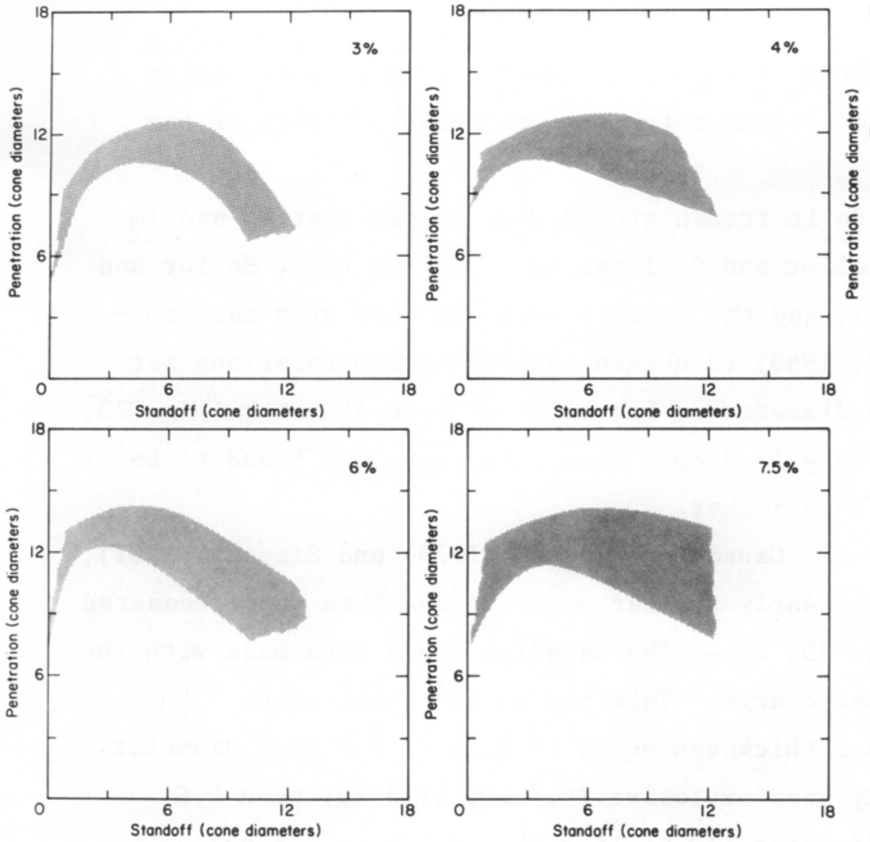


Figure 21. Penetration into permafrost by shaped charges that had 60° aluminum cones with varying thicknesses. (Envelopes representing data by Benert 1963.)

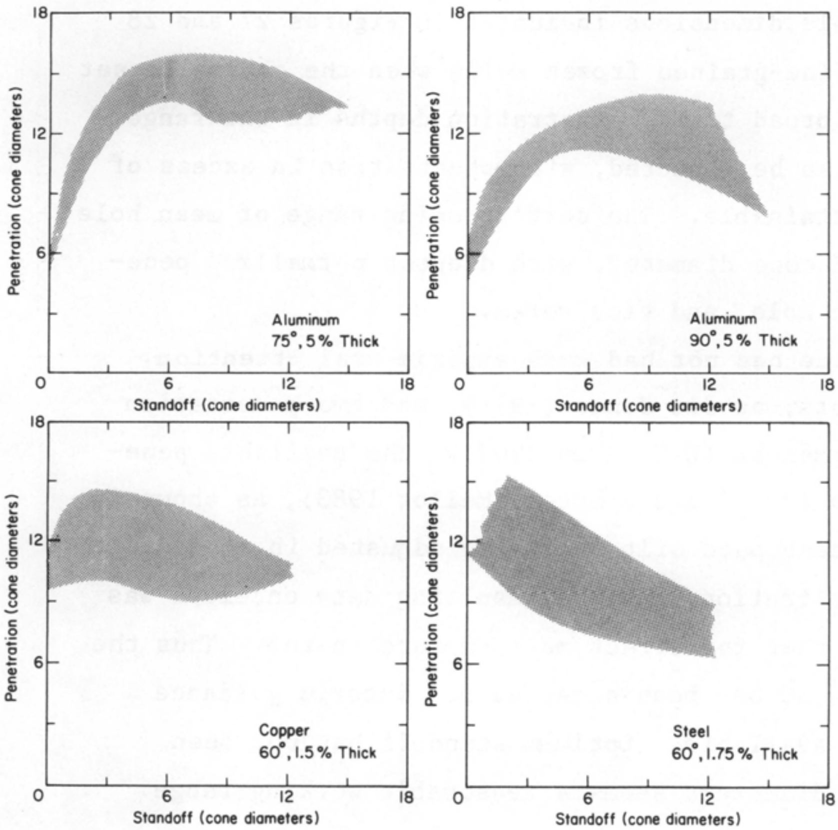


Figure 22. Penetration into permafrost by shaped charges with various cone angles and liner materials. (Envelopes representing data by Benert 1963.)

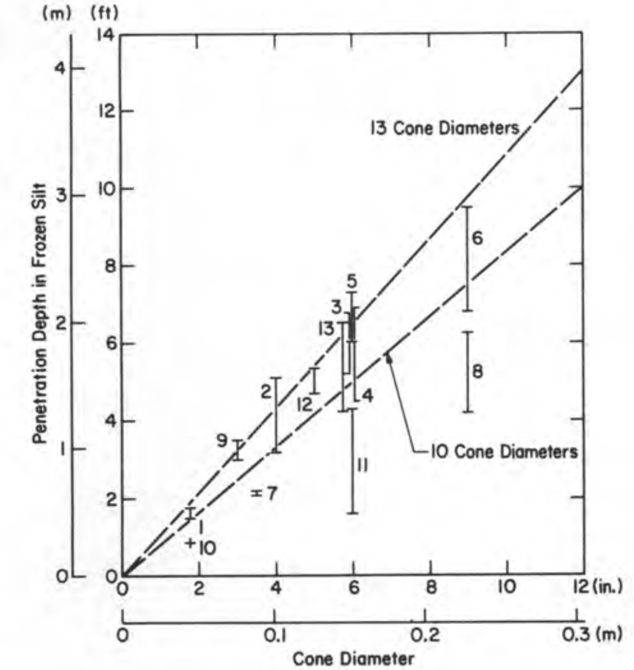
diameter. Variation of cone thickness had a weak effect on penetration depth, and for aluminum the optimum thickness was about 5% to 6% of the cone diameter.

Further tests were made in frozen ground with shaped charges and improvised shaped charges (Mellor and Sellmann 1970, Mellor 1971, Mellor and Sellmann 1974, Mellor 1986), and the results were combined with the tabulated data of Benert (1957, 1963) to obtain representative relations for penetration depth and hole diameter as functions of cone diameter (Fig. 23, 24). Large standoff distances (> 3 cone diameters) were not found to be necessary in work done by this author.

Tests were made in Arctic Canada by Riddoch (1979) and Simpson (1981), whose results showed significantly smaller penetrations than those measured by U.S. investigators (Fig. 25, 26). The Canadian tests were made with the British Beehive No. 1 shaped charge. This has an 80° steel cone, 6 in. (152 mm) in diameter, with a thickness equal to 2.3% of the cone diameter. This charge has appreciably less explosive (6.7 lb, or 3 kg) than U.S. charges of the same cone diameter (10 to 16.8 lb, or 4.5 to 7.6 kg).

Provided that a shaped charge is well designed and properly optimized for deep penetration, the hole dimensions indicated in Figures 27 and 28 are probably realistic for fine-grained frozen soils when the charge is set with adequate standoff. In broad terms, penetration depths in the range 9.5 to 12.5 cone diameters can be expected, with penetration in excess of 11 cone diameters readily attainable. The corresponding range of mean hole diameter might be 0.3 to 0.7 cone diameter, with deepest normalized penetration giving the narrowest hole, and vice versa.

Penetration into deep ice has not had much experimental attention. Benert (1957) made a few tests, as did Jones (1971), and two penetration values are given in an Army manual (U.S. Army 1967). The available penetration data for ice were collected and plotted (Mellor 1983), as shown in Figure 29. Test data for ice-bonded silt were also adjusted in accordance with eq 3 to predict ice penetration, and the resulting data envelope was found to be consistent with that for direct measurements in ice. Thus the relation displayed in Figure 30 has been accepted for interim guidance until more test data become available. Optimum standoff has not been determined, but 2 to 4 cone diameters seems a reasonable working range.



LEGEND

	Charge	Explosive wt. (lb.)	Cone angle (deg.)	Data source
1	Jet tapper	0.14	80	Benert (1957)
2	Series II experimental	2.2	60-90	Benert (1963)
3	M2A3	11.5	60	Benert (1957) Mellor (1986)
4	M2	10	60	Benert (1957)
5	20-lb experimental	16.8	45	Benert (1957)
6	M3	30	60	Benert (1957) Mellor (1986)
7	5-lb experimental	2.4	42.5	Benert (1957)
8	Liquid in steel cans (nitromethane and Astrolite G2)	15	60	Mellor and Sellmann (1970)
9	M28A2	1.9	42	Mellor (1971)
10	Jet tapper (zero standoff)	0.17	80	Mellor and Sellmann (1974)
11	Beehive No. 1	6.7	80	Riddoch (1979) and Simpson (1981, 1983)
12	Binary Type A		60	Mellor (1986)
13	Binary Type B		45/30	Mellor (1986)

Figure 23. Compilation of penetration data for shaped charges firing into frozen ground. The data bars reflect both data scatter and the variation of standoff. Data bars 7, 8 and 11 are for inefficient charges, and point 10 is for inefficient application. Thus 7, 8, 10 and 11 should not be regarded as representative.

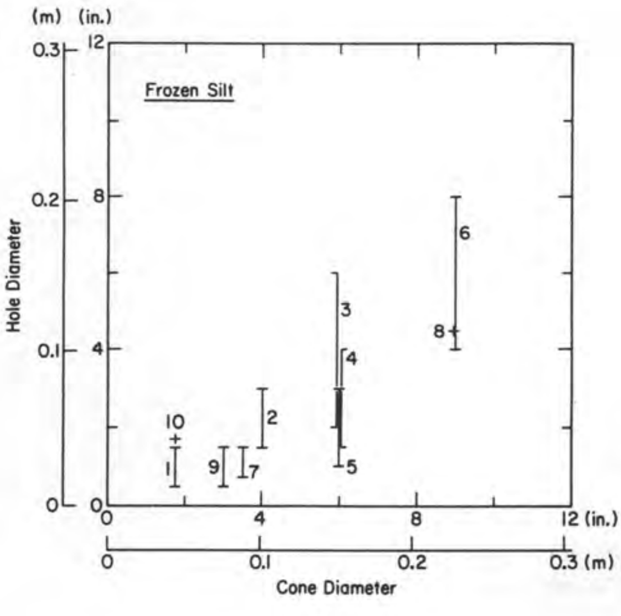


Figure 24. Compilation of data for hole diameter when shaped charges are fired into frozen ground. Some of the spread is due to inconsistencies in measuring procedures among the various investigators. (See Fig. 23 for legend.)

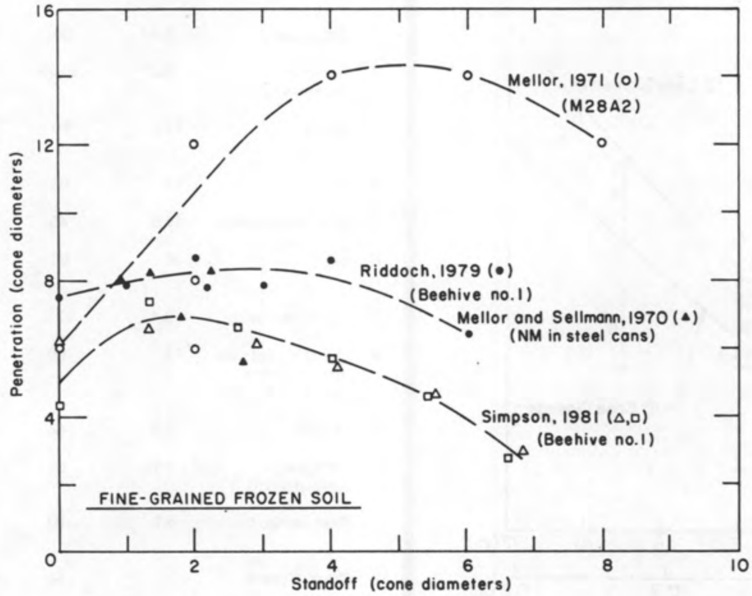


Figure 25. Miscellaneous additional data for penetration of fine-grained frozen soil. The charges improvised by filling pressed steel cans with NM were less efficient than conventional charges. The Beehive No. 1 also appears to be inefficient compared with U.S. military charges.

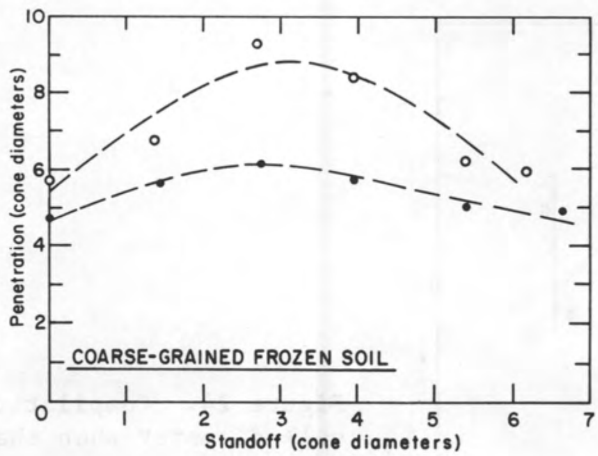


Figure 26. Penetration of coarse-grained frozen soil by Beehive no. 1 charges. (Data from Simpson 1981.)

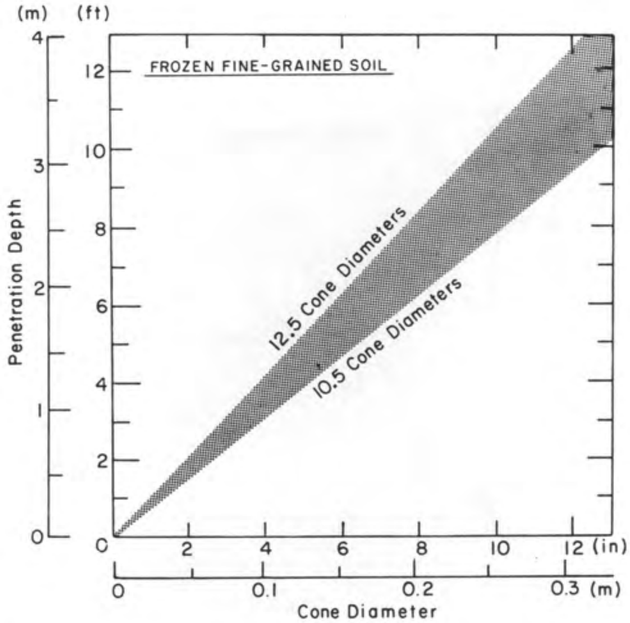


Figure 27. Probable range of penetration in frozen fine-grained soils by well-designed charges set with adequate standoff.

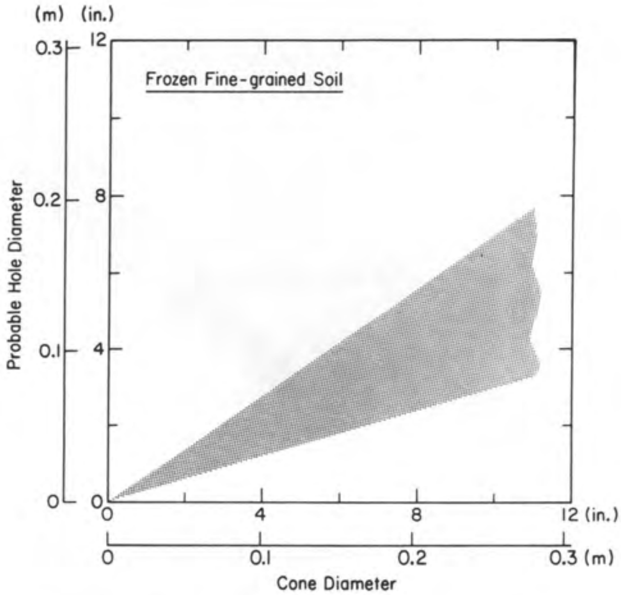


Figure 28. Probable range of hole diameter near mid-depth when well-designed charges are fired into fine-grained frozen soil at typical standoff distances.

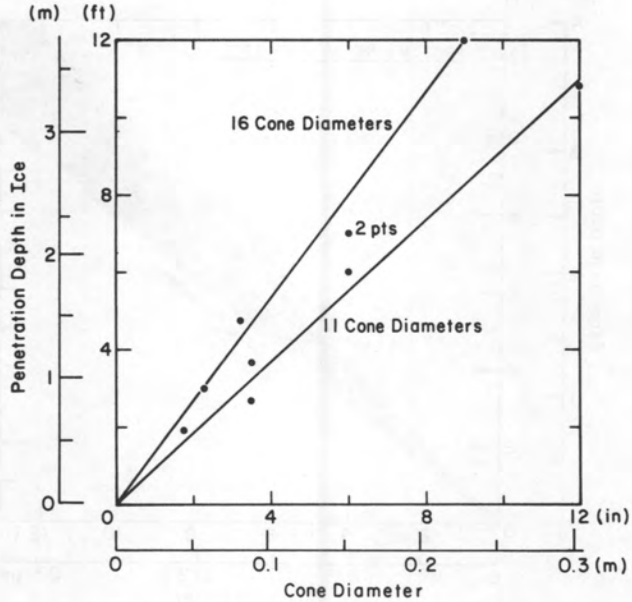


Figure 29. Penetration data for ice which is thicker than the maximum penetration depth. (Data from Benert 1957, Jones 1971, U.S. Army 1967.)

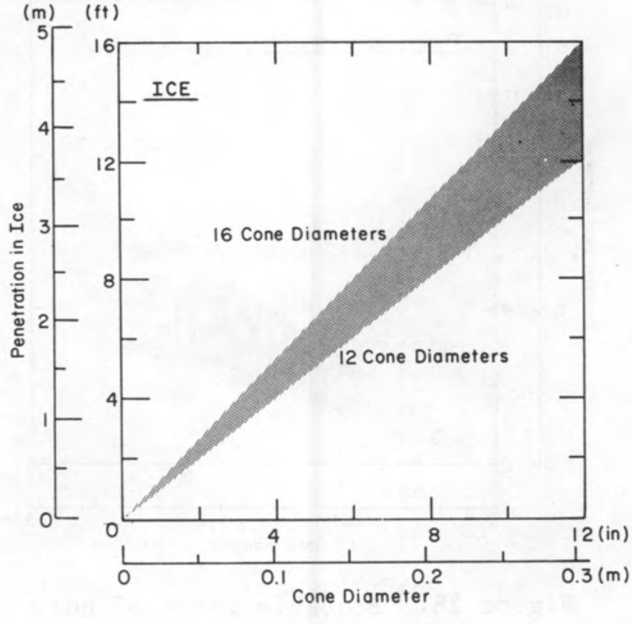


Figure 30. Probable range of penetration into massive ice by well-designed charges set with adequate standoff.

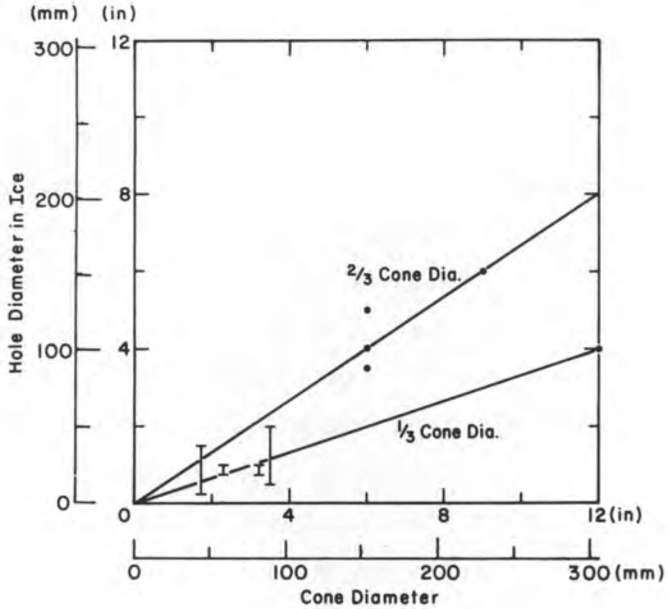


Figure 31. Diameters of holes punched in ice by a variety of shaped charges. (Data from Benert 1957, Jones 1971, U.S. Army 1967.)

The few measurements of hole diameter in ice yield the plot shown in Figure 31. This is very similar to the corresponding plot for frozen silt, and until more data become available the same guidelines are being applied for both ice and frozen silt, i.e. hole diameter in the range 0.3 to 0.7 cone diameter. The narrowest holes are expected to be made by narrow-angle cones (≈ 45°) and the widest holes by wide-angle cones (60° to 80°).

Binary shaped charges

A binary, or two-component, explosive is formed by mixing two insensitive or non-explosive ingredients just prior to use. At least one of the ingredients is liquid in order to facilitate mixing. The idea of binary explosives goes back almost a century, but early formulations never caught on. In recent years, binary explosives have become more attractive in the civil sector because of increased regulation of the sale, storage and transport of conventional cap-sensitive explosives.

Like all chemical explosives, binary explosives contain oxidizer and fuel. They are commonly made, or improvised, by sensitizing liquids that can be made to explode, or else by sensitizing and adding fuel to oxidizing salts such as ammonium nitrate. Nitromethane, which is commonly used as an industrial solvent and as a fuel additive for race cars, can be turned into a cap-sensitive liquid explosive by adding certain chemicals, or by introducing a suspension of glass microspheres. Nitromethane plus 5% to 7% of ethylene diamine (PLX-Picatinny Liquid Explosive) is cap-sensitive and it has been used in pressed steel cans to provide expedient 15-lb shaped charges (Mellor and Sellmann 1970). Proprietary formulations of two-component liquid explosives, believed to involve hydrazine and nitric acid, were also used in shaped steel cans. A well-established proprietary line of binary explosives (Kinepak, Kinestik, Kinepouch) uses finely ground ammonium nitrate as one ingredient (oxidizer) and a small quantity of nitromethane as the sensitizer and fuel. The detonation velocity of the resulting explosive is rather low for shaped charge application when the quantity of the relatively expensive NM is minimized.

For binary shaped charges now being developed at CRREL, the casing of the charge is filled with oxidizing salt. For the first stage of development, this was finely ground ammonium nitrate mixed with glass microspheres and a polymer bonding agent (substitution of ammonium perchlorate for the nitrate would give somewhat higher velocity at appreciably greater cost). The oxidizer was introduced to the case as a free-running powder; it was then pressed to the required porosity and allowed to cure into a coherent solid. The second ingredient was nitromethane, in sufficient quantity to produce a balanced reaction and fairly high detonation velocity. Simple shaped charge cases were made at CRREL, using plastic pipe and two types of copper liners purchased from a defense contractor. The cases were filled at one of the plants of Thermex Energy Corporation, which also supplied nitromethane in appropriate packaging. The shaped charges and the bottles of arming fluid were shipped in separate packages by truck freight or by parcel service, labeled "oxidizer" and "flammable liquid" respectively. The copper cones were coated inside to prevent reaction with the ammonium nitrate, and the filled charges were well wrapped to protect the hygroscopic AN against moisture.

Two types of large shaped charges were tested (Fig. 32). Type A has a cone diameter of 5 in. (127 mm); the copper cone has a 60° angle and a thickness equal to 1.7% of the cone diameter. The cylindrical casing is 10 in. (254 mm) long overall, giving a charge length (measured from the cone apex) of approximately one cone diameter. The case contains 1.89 kg (4.17

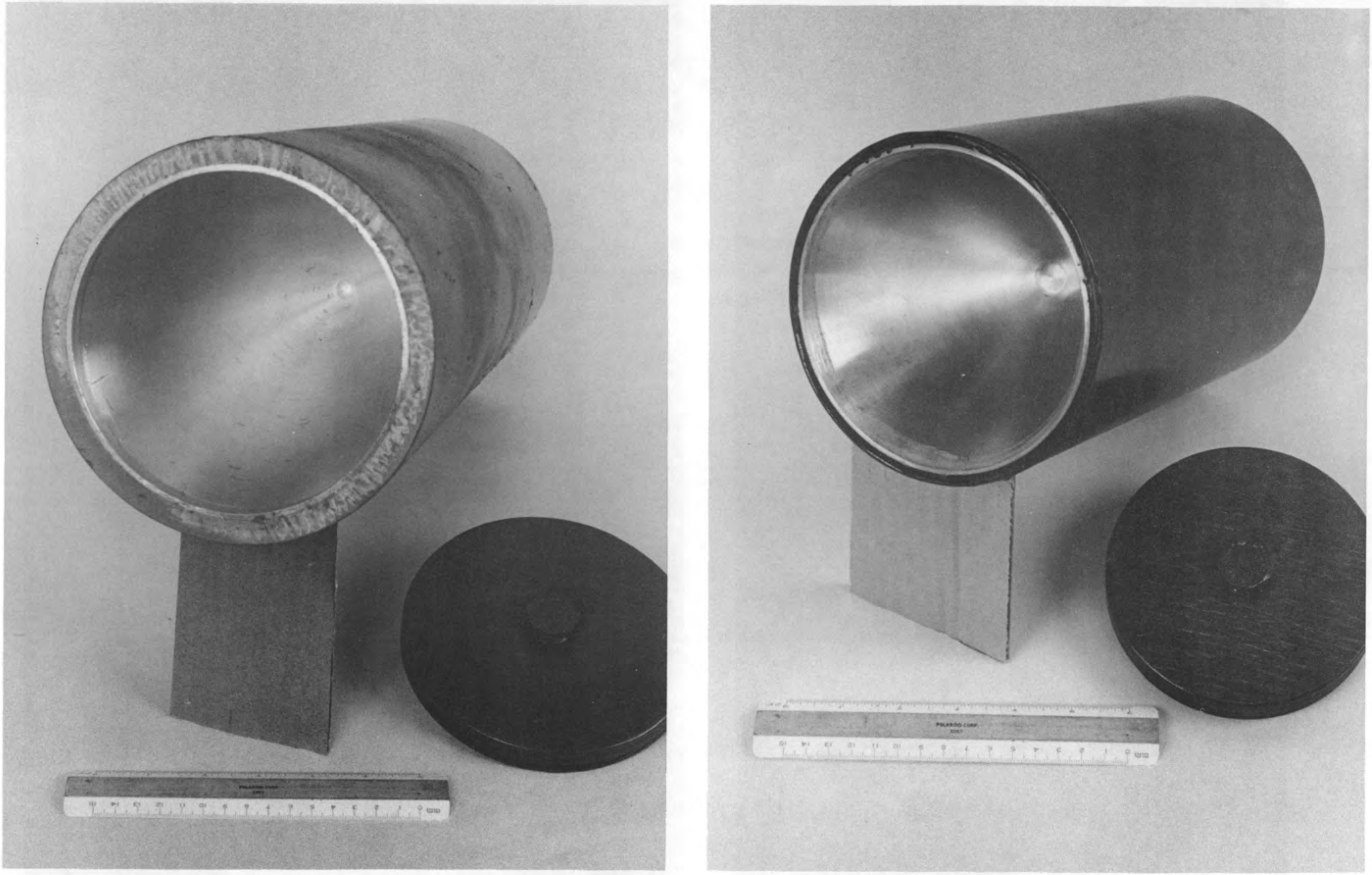


Figure 32. Cases and liners for experimental binary shaped charges. The smaller charge has a 60° copper cone with a 5-in. mouth diameter. The larger charge has a 45°/30° biconic copper liner with a 5.75-in. mouth diameter.

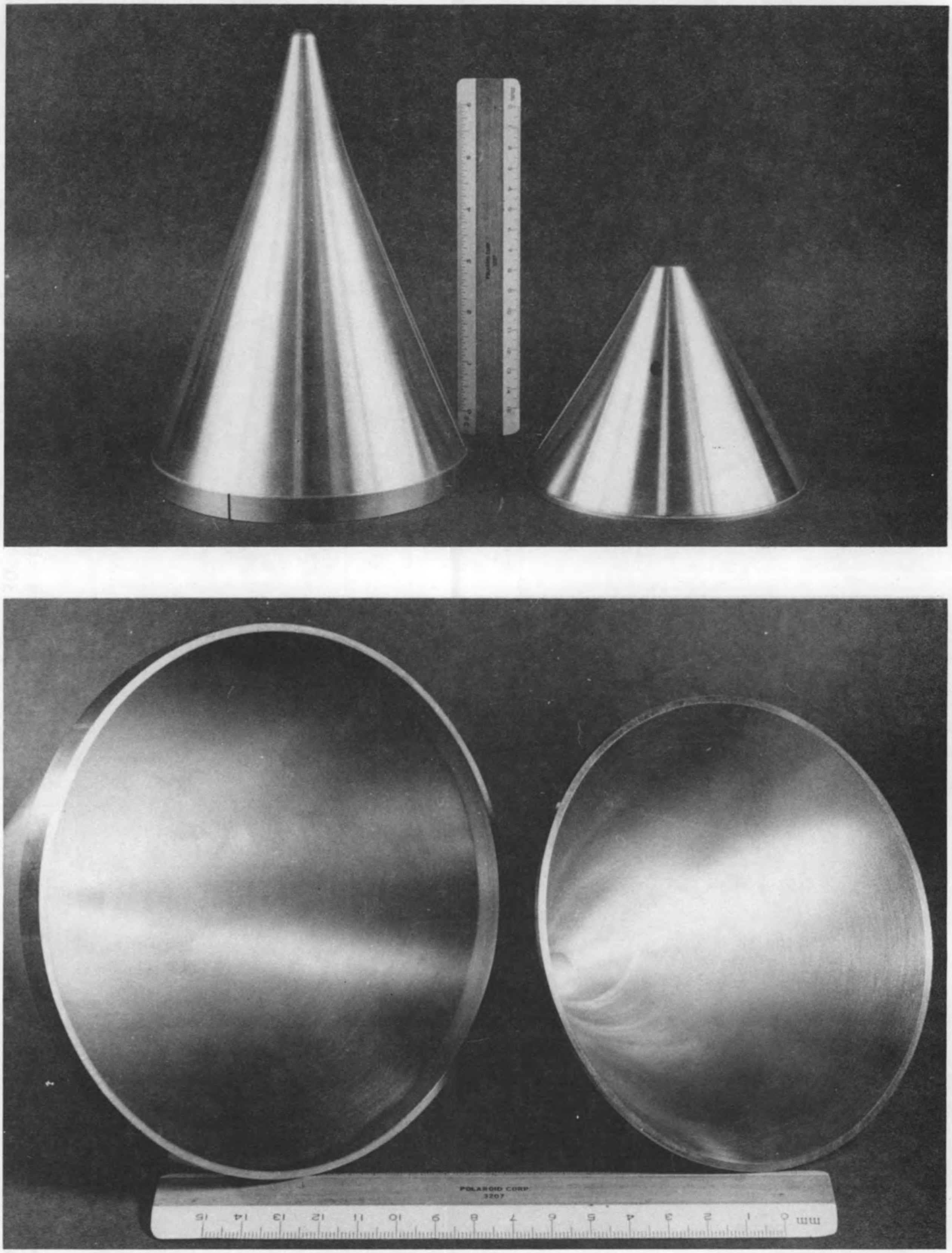


Figure 32 (cont'd).

lb) of dry AN mix, and it is armed with 1.05 kg (2.32 lb) of NM liquid. The total explosive mass is thus 2.94 kg (6.48 lb). Type B has a cone diameter of 5.75 in. (146 mm). The copper cone is biconic, with a 45° included angle for much of the length and a 30° angle at the apex. The thickness of the liner is again about 1.7% of the cone diameter. The cylindrical casing is 15.5 in. (394 mm) long overall, giving a charge depth (measured from the apex of the cone) of approximately 1.1 cone diameters. The case contains 3.95 kg (8.71 lb) of dry AN mix, and it is armed with 2.19 kg (4.84 lb) of NM liquid. The total explosive mass is 6.14 kg (13.5 lb).

In addition to the big binary shaped charges, improvised binary mini-charges were tested. The mini-charge has a 60° cone with a diameter of 1.05 in. (26.7 mm). For practical convenience, the cone is pressed into the end of a standard Thermex 1/2-lb binary cartridge. The charge behind the cone has a diameter of 1-1/4 in. (in a 1-3/8-in.-OD casing). Before firing, some of the cartridge can be cut off and discarded to reduce air blast. For present testing, the effective charge length is 2.6 cone diameters.

The first test firing of the binary charges was carried out over dense caliche clay in New Mexico, with a standoff of 3 cone diameters. The Type A charge penetrated 15 cone diameters. The Type B charge penetrated 8.9 cone diameters into clay underlain by limestone rock. Later tests were made in silt permafrost in Alaska (Mellor 1986), and a direct performance comparison was made against military M2A3 and M3 charges. The binary

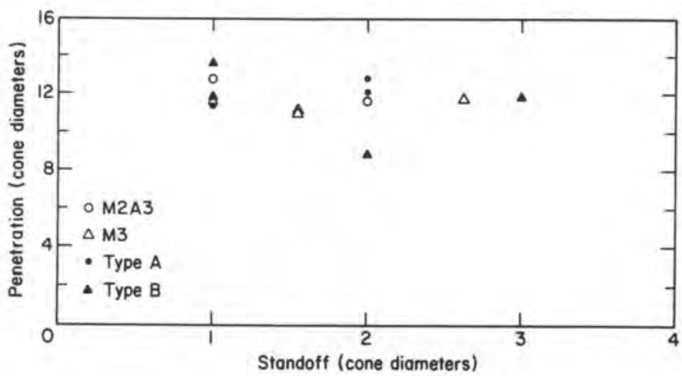


Figure 33. Comparison of penetration into silt permafrost for binary charges and conventional military charges.

charges give about the same normalized penetration as the military charges (Fig. 33), in spite of the relatively low detonation velocity and low density of the AN/NM mixture. The holes produced by the binary charges had elliptical cross sections, leading to a suspicion that the liquid component might not be diffused uniformly in the solid. Corresponding tests in deep ice are planned for the near future.

Prospects for further development of binary charges

So far, the results obtained with binary shaped charges are encouraging. In frozen soil, it seems likely that binary charges can match the performance of conventional military charges. Further testing is needed to determine how well the binary charges can perform in hard rock and concrete. Minor development is needed to improve the packaging and arming.

It should be possible to produce binary shaped charges at costs significantly lower than those for conventional military shaped charges, especially if a cheaper liner can be substituted for the copper cones of the experimental charges. It would be interesting to fit the glass cone of the M2A3, and possibly the steel cone of the M3, to binary charges.

A major advantage of binary charges is the ease with which they can be shipped and stored. Binary charges can be shipped by ordinary commercial truck freight or by parcel services. The charges (but not the liquid component) can be shipped by normal air freight. Neither the charges nor the arming liquid require storage in an explosives magazine.

Another advantage is that custom-designed charges can be produced and delivered rapidly and inexpensively. If the cylindrical binary charges prove successful, large linear shaped charges will be tested.

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