Pyrotechnics in Industry

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chapter 5

Shaped Charges

Shaped charges are the only form of pyrotechnics that attempt not only to control the direction of the explosive energy but also to concentrate it. In many instances the energy intensity of an explosive can be increased more than a thousand times. Later in this chapter a comparison of the quantities of explosives required to perform a given task will be made with and without the technological precision of shaped charges.

MONROE EFFECT

During the nineteenth century, miners learned that detonating sticks of dynamite that had one end arranged in a circle on the ground with their opposite ends tied together in the shape of a cone resulted in a much deeper hole being blown into the earth than if the same number of dynamite sticks were simply tied together with their axes parallel as shown in Figure 5-1. Although the miners did not understand the physical laws that had caused this phenomenon, they unknowingly had discovered the rudiments of shaped-charge pyrotechnology. The causation of this phenomenon is due primarily to the fact that energy forces of an explosive radiate predominately perpendicular from the surface of the explosive. Figure 5-2 illustrates how the energy forces of the three dynamite stick arrangements of Figure 5-1 are distributed by analyzing an enlarged section perpendicular to the target (the ground line) and through the center of the three configurations. Even though the quantity and distribution of energy from each individual dynamite stick is the same, the relative position of adjacent sticks can greatly influence the total amount of useful work accomplished. The angle between opposing sticks in the conical configuration causes the explosive energy forces radiating from the inside surface of the cone to intersect near the centerline. Here the horizontal components of these opposing energy forces collide head on and cancel each other. The vertical components, headed toward the target, are cumulative. Since configuration *a* has a far greater quantity and concentration of cumulative vertical vectorial energy forces contacting the target, the resultant hole is much deeper even though all three

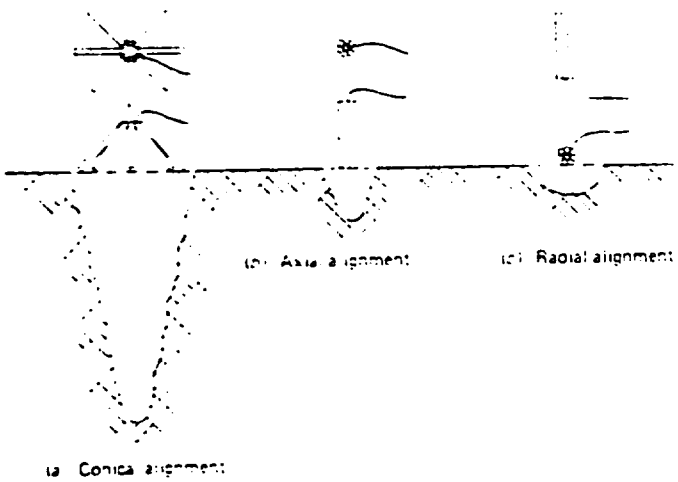

FIG. 5-1. Relative blast effects of eight dynamite sticks in three different arrangements

configurations used the same number of dynamite sticks (8). Additional refinements of this basic discovery have enhanced even more the efficiency of shaped charges.

Shaped charges can be subdivided into three classifications: conical shaped charges (CSC); linear shaped charges (LSC); and flexible linear shaped charges (FLSC). The subdivisions have evolved as a result of their particular applications and will be discussed individually in this chapter. The following discussion of the principles of shaped-charge pyrotechnology are applicable to all three subdivisions. They were first analyzed and tested in 1888 by Charles E. Monroe. He observed that when the engraved lettering in a block of explosive was placed next to a metal plate and detonated, the image of the lettering was imparted (engraved) in the plate. In honor of his efforts the principle of the shaped charge is known as the Monroe Effect.

Figure 5-3 is a simplified illustration of a shaped charge in cross section

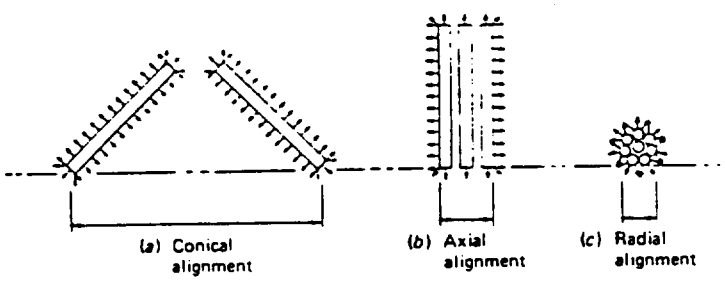

FIG. 5-2. Simplified dispersion of explosive energies of Figure 5-1. Arrows indicate area over which energy is distributed. (*Note*: Nearly half the total explosive energy of the conical alignment is utilized to blast hole in the ground.)

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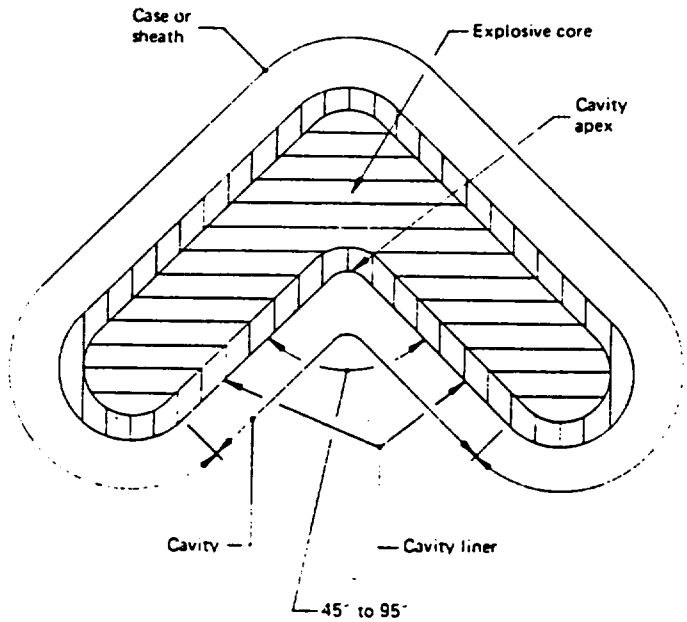

FIG. 5-3. Nomenclature of simplified shaped charge.

and identifies its major components. The housing or sheath and the cavity liner may be of one homogeneous material. Specific applications often dictate the two components be of different materials. Cavity liners are most often made of copper, lead, silver, and aluminum. Their primary purpose is to supply a source of heavy molecules that can be accelerated toward the target by the high pressure and shock waves generated by the high or secondary explosive core. RDX, PETN, HNS, and DIPAM (see Chapter 2) are the most often used core explosives. Upon impact with the target, these high-velocity molecules transfer tremendous amounts of kinetic energy to the target, causing it to deform. Comparative tests have shown that when all other parameters are equal, the performance of a shaped charge can be increased or decreased by increasing or decreasing the density of the liner material. Liner material preferences will be reviewed with specific shaped-charge applications. The included angle of the cavity liner varies between 45 and 90 degrees and it too is dependent upon the shaped-charge application. The interaction of the cavity liner's wall thickness, wall taper, and radius of the apex all affect performance.

The distribution of the explosive energy, as stated earlier, is essentially perpendicular from the surface of the explosive. Figure 5-4 details the energy distribution along the periphery of the simplified shaped charge. As illustrated here, even with the increased efficiency of the shaped charge, the majority of the explosive energy is wasted. Several unique shaped-charge

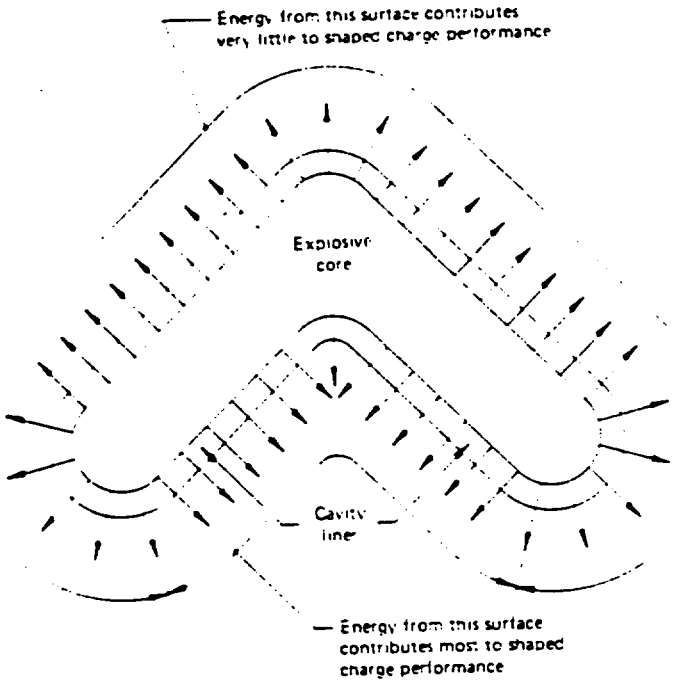

FIG. 5-4. Simplified shaped charge explosive energy distribution.

applications have made use of this apparently wasted energy and will be discussed later in this chapter.

The explosive phenomenon is generally described as the interaction of the detonation (rapid decomposition) products and cavity liner material emanating at high velocity from a shaped charge as the explosive detonates. The detonation releases large quantities of gas almost instantaneously under extreme pressure—as much as several millions of pounds per square inch or square centimeter. The shock waves emanating from the lower portion of a shaped charge converge at a point on the charge centerline and cause an extreme concentration of pressure along the axis of convergence as shown in Figure 5-5. These directed shock waves, together with the products of explosive decomposition and the metal molecules from the cavity liner, form the primary target cutting action—the jet.

Deformation of the target material begins within 1 microsecond (1 one-millionth of a second) after the passage of the detonation front. The shock waves produced by the expanding gases and the cavity liner material emanating from the lower portion of the shaped charge are converging, a jet of high velocity (in excess of 20,000 feet [6,100 meters] per second) cavity liner molecules is forming and penetration of the target is beginning. In Figure 5-6, the jet is fully developed and deformation of the target is well underway. The extent of this deformation is as follows: When a shaped

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charge is detonated on a metal target, the jet exerts an extremely concentrated force over a very small area. This force causes the metal to be pushed out of the way of the advancing jet by plastic flow. The resulting deformation is called "penetration." On a thin plate, however, the performance of the shaped charge depends not only on the cavity liner material and the intense, directed shock waves to erode the target, but also on the rapidly expanding gases to physically dislocate and fracture it. The shock waves, when reflected from the surface opposite the penetration, can also cause spalling (dislodged metal flakes) from that surface. The total effect is termed "cutting." Shaped charges consistently cut targets of greater thickness than they can penetrate.

The penetration action of a shaped charge is affected by a number of factors: the explosive used is of great importance; and while the depth of penetration is indicated to be more closely related to the detonating pressure than the rate of detonation, in general, the greater effect is produced by the explosive having the greater rate (velocity) of detonation. Very little effect is produced by explosives having rates of detonation of 15,000 feet (4,570 meters) per second or less.

Comparative tests with cavity liners of different metals give results that indicate, in general, the depth of penetration is greater with metal of higher density. However, liner ductility also plays a major role in penetration.

The standoff distance, or distance between the target and the base of the shaped charge required for maximum penetration effect, varies with the

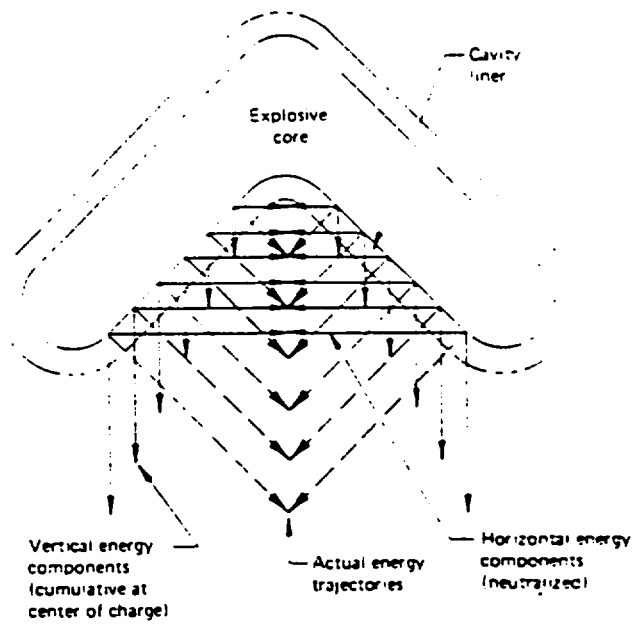

FIG. 5-5. Resolution of simplified shaped charge cavity energy.

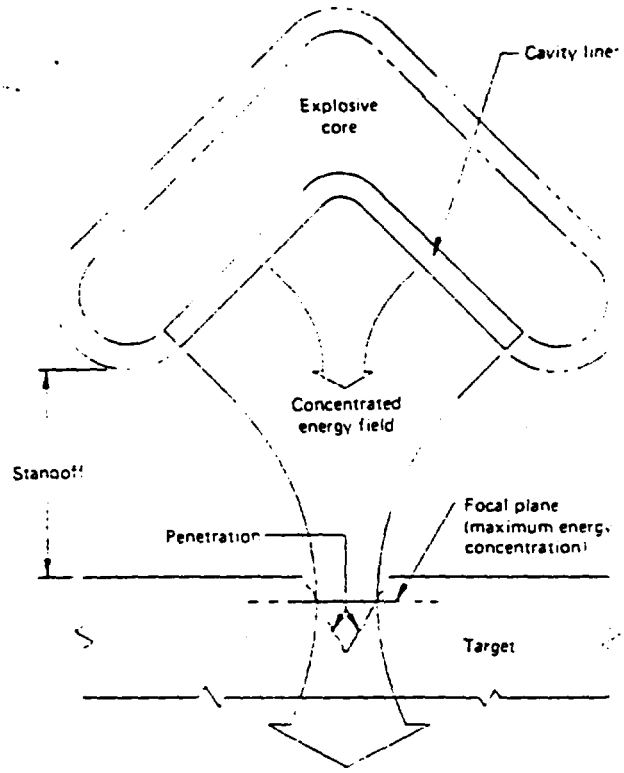

FIG. 5-6. Simplified shaped charge with optimum standoff for maximum target penetration.

metal used as a cavity liner. With a given liner, there is a given optimum standoff distance above and below which less penetration effect is obtained. As stated previously, the jet is the penetrating agent, and as standoff distance is increased, there is more time in which the jet can be extended. However, after a certain standoff distance, the jet has a tendency to break up both axially and radially.

Standard cutting data are usually derived under optimum conditions and usually tested against only one or two standard materials such as aluminum or steel. Data published by this empirical method can only be used as an approximation in selecting the proper size shaped charge to sever or penetrate a particular target. Other target parameters such as homogeneity, temper or hardness, direction of grain, and backup material, in conjunction with other shaped-charge parameters such as voids in the explosive, non-uniform compacting of explosive, and unsymmetrical geometry of the chevron, can affect the total performance of a particular shaped charge with a specific target. Only through rigorous manufacturing quality assurance and controls and thorough testing can an optimized, reliable shaped charge be configured (see Chapter 8).

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Table 5-1. Geom
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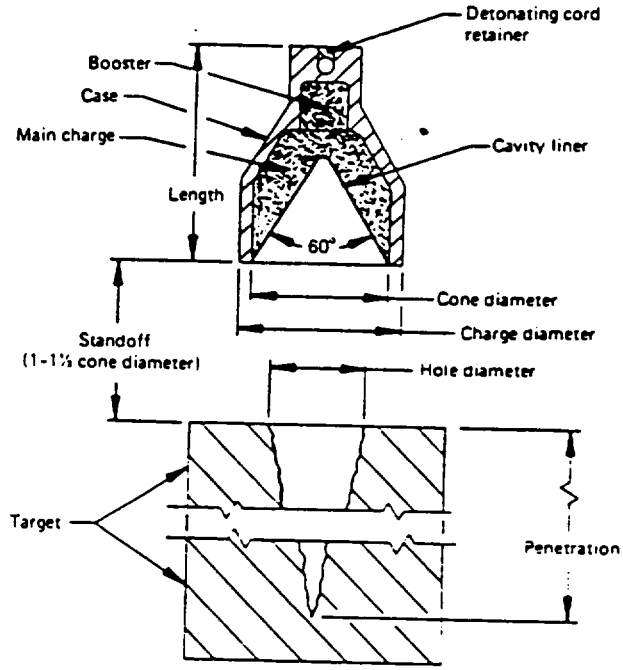
*Performance in milc

CONICAL SHAPED CHARGE (CSC)

A conical shaped charge is, as the name implies, a body of revolution rotated around the axis of symmetry. Table 5–1 illustrates a typical CSC and tabulates the geometric characteristics and performance capabilities for a family of

Table 5-1. Geometric, Weight, and Performance Characteristics of Conical Shaped Charges



Copper cavity liner, RDX explosive

Shaped charge number	Explosive weight, g	Gross weight, g	Approximate OD, in	Approximate overall length, in	Penetration, in*	Hole diameter, in*
1	1.1	20	0.63	0.93	0.75	0.20
2	3.7	48	1.00	1.32	2.00	0.30
3	8.5	96	1.61	1.74	2.50	0.40
4	15.5	152	1.90	2.09	3.21	0.46
5	19.0	189	2.00	2.25	3.40	0.52
6	11.5	106	1.62	1.75	4.60	0.31
7	20.0	205	2.06	2.35	5.50	0.37
8	414.5	743	3.50	6.00	14.0	1.75

*Performance in mild steel

charges. The explosive material used in these CSCs is granular RDX (see Chapter 2) compressed into the case under pressure in excess of 15,000 pounds per square inch (1,055 kilograms per square centimeter). The tremendous amount of explosive energy released and focused by the CSC configuration is emphasized by the last entry in the table: Into a mild steel target a hole 1.75 inches (44.5 millimeters) in diameter with a penetration of 14 inches (356 millimeters). Users of these or slightly modified CSCs are the oceanographic industry for cable cutters, armed forces for demolition, construction contractors for drilling aids, and the steel industry for tapping open-hearth furnaces. The oil industry's application for perforating oil well casing is simplified in the illustration of Figure 5-7. By lowering a detector into a well casing, geologists are able to locate oil deposits in stratum at considerable distances from the casing itself. The problem of tapping into

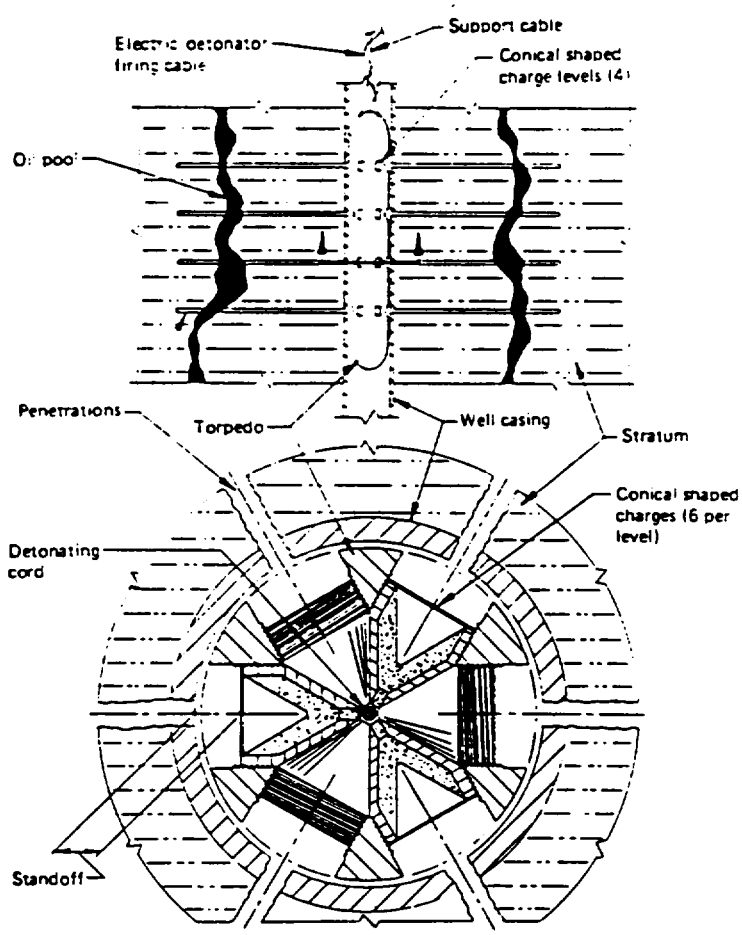


FIG. 5-7. Oil-well casing and stratum penetrators.

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the adjacent oil pools without the added time and expense of drilling another well is resolved by inserting a "torpedo" into the casing and lowering it to the level of the oil pool(s). The torpedo consists of several levels of CDCs. The illustration depicts four levels with six CDCs per level. Torpedoes with twelve levels and twelve CDCs per level have been used. The torpedo is attached to a cable with a bridle at one end. An electric firing cable is entwined around the support cable and terminates at a detonator at the top of the torpedo. The detonator detonates a string of detonating cord (see Chapter 4) that traverses the length of the torpedo. As can be seen in the section, the detonating cord is located at the hub of the six radially oriented CSCs. The detonating cord simplifies the detonation of twenty-four CDCs with a single detonator.

When detonated, the CDCs penetrate not only the well casing but also the surrounding stratum for a considerable distance. Penetrations of several hundred inches (nearly a thousand centimeters) are not uncommon in Berea sandstone (a common oil-bearing stratum). Penetration is primarily dependent on the number of conical-shaped charges nestled into each level of the torpedo, the inside diameter of the well casing, thickness of the casing, casing material, number of concentric casings (up to four is not unusual), and the composition of the oil-bearing stratum. After the CSCs have penetrated the oil pool, the oil will immediately flow into the voids of the penetrations and through the holes in the casings. When inside the casing the oil is easily pumped to the surface.

Torpedoes have been built with a single CSC at each level. Obviously, a single charge designed to the full diameter of the torpedo will have greater penetration than multiple CSCs designed within the same diameter. To preclude the necessity of radial orientation of the torpedo with a single CSC at each level, a different radial orientation of each CSC is employed at each level.

The discovery of petroleum deposits under the sea created the need for many new techniques to recover oil from the new source. Problems connected with drilling platforms, special support vessels, and in many other areas were resolved by modifying techniques used in the standard land recovery methods. The task of laying the pipeline from the floor of the sea to the shore presented a unique problem in many areas, particularly in rock- and coral-encrusted coastal reefs and shoals. These areas quite often are shallow in depth, which precludes the use of deep-draft floating platforms from which to dig a trench for the pipeline to rest protected from the elements and possible entanglement with ships' anchors. In some cases the rock and coral formations are too hard to be economically removed with standard ditching or dredging equipment. One solution to the problem is the classical method of drilling bore-holes in the rock or coral formation, placing an explosive charge in each hole, and blasting to break or crush the dense formation. Needless to say, this is a slow and costly process.

The final solution came with the development of a conical shaped charge

about the size of a small milk can. Instead of filling the CSCs with granular or solid explosives, and transporting them under rigid safety regulations to faraway places where they were needed, a liquid explosive was developed whose constituents can be shipped in separate containers by commercial transport to the using site. As can be seen in Figure 5-8, even when filled with the liquid explosive, more than half of the internal volume of the CSC is void. If placed in water the CSC would float inverted. This anomaly is overcome by placing the base of the CSC in an oversized box and filling the gap with concrete. CSC case segments are often molded plastic and the cavity liner is a deep drawn steel cone. The total assembly weighs approximately 40 to 50 pounds (18.14 to 22.68 kilograms). Handholds are provided in the box to facilitate carrying the CSC on land and maneuvering it into position under water. The stable liquid explosive ingredients are mixed and poured into the case through a hole in the top. The stopper serves a dual purpose—it is also the detonator. To the detonator is attached a length of detonating cord.

Figure 5-9 is a series of pictures of the insensitive liquid explosive chemicals and CSC cases being transported to the using site. There the liquid explosive constituents are mixed; cases are assembled and placed in handling boxes where concrete is poured around the base of the CSC. The liquid explosive is poured into the case and topped with a detonator and a short length of detonating cord (see Chapter 3). Barges are loaded with numerous

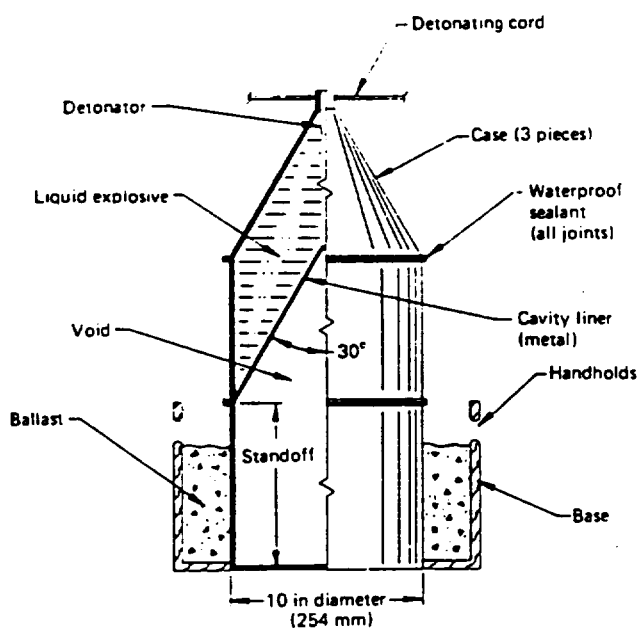

FIG. 5-8. Liquid explosive CSC used in trenching and dredging operations.

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FIG. 5-9. Transporting, filling, positioning, and firing of CSCs for underwater oil pipeline operations. (a) Pallets loaded aboard air freighter. (b) Transporting pallets to using site. (c) Assembling CSCs. (d) Filling CSCs with liquid explosive. (e) Positioning CSCs along trenching line. (f) Detonating cord attached to CSC detonator. (g) Underwater trench being excavated. (h) Final positioning of oil pipe in trench through shoal.

CSCs for transporting to the underwater trenching site. At the trench site, up to several hundred CSCs are placed in rows about 4 feet (1.2 meters) apart on either side and along the centerline of the trench. The short lengths of detonating cord from each of the stationed CSCs are knotted to a longer detonating cord strung the length of the positioned CSCs. Attachment of an electric detonator to the end of the long detonating cords attached to the CSCs completes the trenching preparations. After detonating the CSCs, subsequent dredging is not usually required. The oil pipe is then placed in the trench and the job is complete. The following summary is typical of the underwater CSC trenching operations around the world:

Mexico: Isle DeLobo—Pipeline trench from offshore drilling platform to island storage facility.

Trench specifications: Width—Depth—Length—Feet (Meters) 14—6—2,300 (4.2—1.83—701) Operation completed in 4 days.

Egypt: El Alamain—Pipeline trench from mainland to offshore tanker loading facility.

Trench specifications: Width—Depth—Length—Feet (Meters) 16.5—6.5—1,-650 (5—2—503) Operation completed in 10 days.

Iran: Kharg Island—Pipeline trench from mainland to island storage facility.

Trench specifications: Width—Depth—Length—Feet (Meters) 40—8 to 14—3,050 (12.2—2.4 to 4.3—930) Operation completed in 25 days.

Trucial States: Jebel Dhanna—Pipeline trench from mainland to offshore tanker loading facility.

Trench specifications: Width—Depth—Length—Feet (Meters) 6—8—2,500 (1.8—2.4—762) Operation completed in 7 days.

Alaska: Cook Inlet—Pipeline trench from offshore platform to mainland.

Trench specifications: Width—Depth—Length—Feet (Meters) 4–7–2,500 (1.2–2.1–762) Operation completed in 4 days.

The same types of CSCs used in the above trenching operations can also be used in harbor and river dredging. Here the CSCs are placed in a checkerboard pattern, laced together with detonating cord, and detonated.

When solid rocket motors (SRMs) are launched, the capability must be provided to terminate the mission due to some malfunction of an onboard system, i.e., guidance, thermal control, etc. Unlike liquid propellant rockets, the SRMs cannot be shut down once they are ignited. If the SRM is of the type that has an open hole through its entire length, the propellant burns from the inside radially outwards over the entire length of the SRM. A simple method of terminating the thrust is to fire several conical shaped charges (by radio command) through the forward closeout dome of the SRM. The burning propellant will then exhaust through these forward holes,

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Some SRMs, however, don't burn radially their entire length. They burn from their aft end forward over the entire inside diameter of the rocket. Terminating the thrust of these SRMs necessitates reliable rocket igniters as well as conical-shaped charges. A dual-purpose CSC is shown in Figure 5-10 that includes a cylindrical exothermic pellet built into its base. The cylindrical geometry of the exothermic pellet allows the jet of the CSC to pass through its center after which it penetrates the forward dome of the SRM. The tail of the jet then ignites the pellet as it is pulled inside the dome of the SRM. Once inside, the burning pellet, 3,000°F (1,649°C) smears through the exposed SRM propellant—igniting it. Neutralizing thrust from the forward dome of SRMs is usually short-lived. The cylindrical walls will most often rupture a few seconds after the thrust termination CSCs have penetrated the SRM's dome due to internal overpressure.

LINEAR SHAPED CHARGE (LSC)

In cross section, the linear shaped charge has many similarities to the conical-shaped charge with the main exception being the included angle of the cavity liner. Where the cavity angle of the CSC was shown to be approximately 60 degrees (see Table 5-1), the included angle of the LSC cavity liner is nearly 90 degrees. LSCs are generally fabricated in lengths up to 12 feet (3.66 meters) with explosive core loading up to 3,200 grains per foot (680 grams

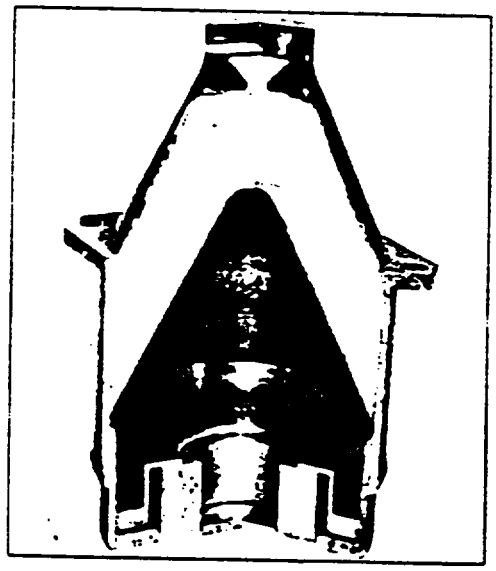

FIG. 5-10. Cutaway of SRM thrust termination CSC with exothermic pellet.