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# THE SHAPED CHARGE CONCEPT
## PART III. APPLICATIONS OF SHAPED CHARGES

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
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This article is the third and final part of a three part series on hollow charges and shaped charges. This section describes the various and sundry applications of shaped charges.

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## 1. APPLICATIONS

Shaped charges are extremely useful when an intense, localized force is required for the purpose of piercing a barrier. A primary application is in the military arena including torpedos, missiles, high explosive anti-tank (HEAT) rounds including hand held (bazooka type) rounds, gun launched rounds (e.g., rifle grenades), cannon launched rounds, and various bombs. The targets are armors, bunkers, concrete or geological fortifications, and vehicles. Attacks against aircraft and spacecraft are possible. Underwater applications (torpedos) are possible with the design such that water does not enter the hollow charge area. In fact, most warheads of the type described above contain an ogive to cover the liner. This ogive acts as an aerodynamic (or hydrodynamic) shield while the projectile is in flight. It can provide a housing for impact fuzes or guidance, stability, and control electronics, and it provides a built-in standoff designed to aid performance. Recall that the standoff is the distance from the base of the charge (or liner) to the target in question. Figure 1 (Mohaupt 1966) and Figure 2 show an old HEAT artillery projectile.

The largest known shaped charge was a modification of the Beethoven or SHL (Schwere Hohlladung or heavy shaped charge) called the MISTEL. The SHL charges and the Beethoven were discussed in Part 2. The MISTEL (mistletoe) concept used a fighter aircraft mounted piggyback on the top of a large bomber aircraft. The unmanned bomber carried the MISTEL warhead in its nose. The warhead consisted of a 2-m diameter, wide angle, conical shaped charge. It is speculated that the liner had a 120° apex angle, was about 30 mm thick, and made of either mild steel or aluminum. The warhead weighed 3,500 kg with an explosive weight of 1,720 kg (D. R. Kennedy 1983; Coles and Rickson 1977). The fighter pilot flew the combination to the target, aimed it, released it, then returned to his base. The Germans developed this device near the end of World War II and most of them were captured intact.

However, as mentioned earlier, the MISTEL technology was made available to the Japanese. The Japanese developed the SAKURA bomb which was 1.6 m in diameter. The design and characteristics are given in Figure 3. The SAKURA bombs were used for kamikaze attacks against warships.

A shaped charge with an aluminum liner was used in an attempt to place certain identifiable man-made materials into orbit. According to D. R. Kennedy (1983), a 35° included angle aluminum shaped charge was installed on a multistage rocket assembly. The craft was fired into near-space and the warhead was detonated in an attempt to project hypervelocity fragments into earth orbit. These tests were conducted at Holloman Air Force Base in 1955-56.

Along the same line, S. K. Golaski, formerly of the U.S. Army Ballistic Research Laboratory (BRL), and in conjunction with the former Defense Division of the Firestone Tire and Rubber Company, developed shaped charge meteor simulators for NASA (Woodall and Clark 1966; FTRC 1968). The objectives of these studies were to obtain the luminous efficiency of a meteor-like body of known mass, composition, and speed during re-entry into the earths' atmosphere. The luminous efficiency is the percent of kinetic energy of the body which is converted into visible light as observed by photographic study of the visible re-entry tail. The study was designed to obtain the required mass, composition, and speed from pellets generated by a specific shaped charge design flown on a solid state propellant vehicle. The vehicle was used to achieve the necessary velocities. Nickel and iron were the shaped charge liner materials. The rocket engines were designed to carry the shaped charge liner above the atmosphere, turn, and allow the detonated shaped charge to accelerate at hypervelocity through the earths' atmosphere (re-entry). The intent was to simulate a body (meteor) re-entering the earths' atmosphere. A specialized shaped charge liner design was required along with a specialized bi-explosive waveshaping device (FTRC 1968).

Zwicky (1947) proposed the use of a shaped charge as a method of producing artificial meteorites in 1947. He proposed launching a hypervelocity shaped charge on a V-2 rocket to exceed the earth's escape velocity and thus create an artificial meteorite. The hypervelocity jet particles could be tracked to study hypersonic aerodynamic effects. On October 16, 1957, the first particles from a shaped charge jet were successfully launched into an orbit about the sun from an Aerobee rocket at Alamogordo, New Mexico (Zwicky 1962). Actually, three different shaped charge configurations were fired from the Aerobee rocket on October 16, 1957. Also, an experiment was contemplated that would allow the jet to impact a heavenly body, such as the moon. A spectroscopic analysis of the impact flashes would reveal the elementary chemical constituents of the moon's surface. This later experiment, although feasible, was never carried out. Larikov (1958) also discussed jet vaporization upon impact.

Many other specialized shaped charge applications have been pursued by the Departments of Defense of several nations. These specialized designs included confinement or tamping of the explosive fill, varying the geometry or type of explosive used, altering the mode of initiation, using explosive lenses or more than one type of explosive or an explosive/non-explosive barrier or gap, waveshaping or shaping the detonation wave (usually done to insure a uniform wave with a short head height), or varying the standoff distance. Also, significant effects can be achieved by varying the liner material (including the use of non-metals such as glass), varying the liner thickness, increasing the liner diameter, tapering (or causing a gradual wall thickness variation either continuously or discontinuously) or varying the liner geometry. The liner geometry variation may utilize the same basic geometry, e.g., varying the conical apex angle, or may employ a radically different liner configuration. Other useful liner geometries are hemispheres, truncated (from the equator) hemispheres, disc or dish shaped (EFP like) devices, tulips, trumpets, dual angle cones, or a combination of the above such as hemi-cones or tandem devices. In fact, any arcuate device may be used.

Also, spin compensated liners may be used, especially when associated with spinning warhead applications. (Recall the discussion from Schardin [1954] in Part II.) Gun fired projectiles are spun in flight to provide aerodynamic stability. This angular momentum is imparted to the liner and is conserved during the liner collapse process. This leads to a large increase in the angular velocity of the jet so that centrifugal forces, if they exceed the yield strength of the material, can tear the jet apart. Without spin compensation, the jet will exhibit a radial instability (if the spin rate is high enough) and disperse radially, thus reducing the effective penetration capability. Spin compensation (i.e., causing the jet to spin enough and in the right direction to compensate for the spin of the warhead) may be achieved by metallurgical spin compensation or by the use of fluted liners. Metallurgical spin compensation is achieved by introducing anisotropies or residual stresses into the liner during the fabrication process in order to provide rotation of the jet. Fluted liners contain raised ridges (or panels which are offset with respect to the normal to a radius) either on the outside or the inside surface of the liner. A fluted liner with ridges (flutes) on the outside surface is shown in Figure 4. The flutes allow the jet to form with a given angular momentum to compensate for the rotation of the warhead in flight. Weickert (1986) describes fluted liners and spin compensated liners in detail. The Firestone Tire and Rubber Company (1957) published engineering drawings for a 105-mm diameter fluted liner.

A unique shaped charge warhead design was developed by Kennedy and others in 1967 and 1970 as reported by D. R. Kennedy (1983). This particular missile design used a two-stage, tandem liner designed to produce a precursor or pre-jet to remove the guidance and control package located in the ogive of the missile. Otherwise, the main jet would have to penetrate the seeker package at a short (non-optimum) standoff distance. Alignment difficulties in the tandem configuration made it necessary to blend the precursor liner, its standoff tube, and the main conical liner into a single piece. The result was the trumpet design configuration which is used for certain applications today. This design showed improved penetration with a relatively small standard deviation in penetration.

There exists numerous other tales of warhead development, the point being that some of the warhead concepts being pursued today are not original concepts. For example, the tandem warhead concept was first proposed by Tuck (1943) and patented in 1946 by Precoul of France (1946).

Another application of shaped charges is in demolition work. This area has both military and industrial application. Buildings, bridges, and other structures are the common demolition targets. Usually, demolition charges are hand placed. Demolition charges are sometimes constructed and placed in sites using a plastic explosive and a collection of liners. This technique allows for more flexibility and adjustment to the conditions at hand than a collection of fixed charges. Of course, experience on the part of the blaster is required and this technique (the adjustment of the charge to the task) has delayed bulk charge production and research towards this particular application. The shaped charge principle is also used in construction work to break, crack, or drill holes in rock. A technique known as mudcapping is sometimes used to break rock and usually utilizes an unlined hollow charge. Shaped charges have also been used in construction as earth movers, in tunneling, or to assist in well drilling.

The shaped charge has also been employed for assorted peaceful purposes in the petroleum industry (Reinhart and Cocanower 1959; Poulter and Caldwell 1957; Carter 1978; Delacour et al.1958; Lebourg and Hodgson 1952; Lebourg and Bell 1959; Gardiner 1950; Kastrop 1957; Reed and Carr 1950; Anon. 1947; Robinson 1957; McLemore 1946; Box and Meiklejohn 1950; and Pandya 1959). Shaped charges are also used in the steel industry, as a source of earth waves for geophysical prospecting and seismic exploration, mining (surface or underground) (Austin 1959, 1961, 1964; Austin and Pringle 1964), quarrying, in salvage operations, boring holes in demolition work (NAVWEPS 1962), breaking large rocks, and for hypervelocity impact studies (Merendino et al. 1963). Other applications occur in submarine blasting, breaking log jams, breaking ice jams, initiating avalanches, and timber cutting.

Dennis (1966) describes the evaluation of standard and field- fabricated conical and linear shaped charges for felling live, sappy trees of up to 40 inches in diameter. Lined cavity linear shaped charges at a 4- to 10-in standoff and unlined cavity conical shaped charges at zero standoff yielded effective cutting and felling of 18- to 43-in diameter hickory, poplar, and oak trees with significantly less explosive than required for felling by conventional timber cutting techniques. Conventional timber cutting techniques state that the amount of explosive required, P, in pounds of TNT, is

$$P = D^2 / 40,$$

where D is the diameter, or smallest timber dimension, in inches.

Dennis (1966) reports that two unlined cavity conical shaped charges improvised from coffee cans (used as the casing) and 10 pounds of C4 explosive felled trees of up to 34 inches in diameter when detonated in diametric opposition to each other. Larger diameter trees were felled by multiples of 3 to 5 charges detonated symmetically at points one-third to one-fifth the circumference of the trees.

Another application for shaped charges is in tapping steel mill furnaces. The steel mill furnace tapping problem is depicted in Figure 5 (DuPont 1980). The tapping problem requires a means of starting the flow of molten steel once the tap hole has been plugged. Steel mill jet tapping is sometimes called salamander blasting since salamander is the term used to describe the large mass of solidified iron deposited at the base of the blast furnace after it has been in operation for some time. The tap hole is dug out as far as possible and a jet tapper is inserted into the tap hole using a loading pole. A jet tapper is a shaped charge with a conical metal or glass liner. The jet tapper is then detonated, clearing the plug, usually with a high rate of success (DuPont 1980). A commercial jet tapper is illustrated in Figure 6. The shaped charge assembly may be aligned on axis or offset up to 10°, as shown in Figure 6, to reduce the line-of-sight thickness of the plug that must be perforated. The jet tapper assembly is insulated and special detonators are used to withstand the prolonged exposure to high temperatures.

Shaped charge liners are not always made of glass or metals, e.g., Naval Proving Ground (1954) describes a shaped charge with a liner made of balsa wood. The liner consisted of flutes or wedges of balsa wood. The warhead provided a satisfactory method for producing equiaxed fragments. The liner was not satisfactory for producing a rod or a jet. In fact, liners have assumed a multitude of geometric shapes, and have been made from common and exotic metals, alloys, eutectics, ceramics, plastic, paper, rubber, etc.

Another application of the shaped charge is in the internally coned end of certain detonators. This indented, lined cavity acts to concentrate the effect along the axis, recall Bloem (1886).

General references on the Munroe effect and on various shaped charge designs are given by Torrey (1945a, 1945b), Koroiev and Pokrovsky (1944), Carter (1978), Hyatt (1959), Tardif (1956), Byers (1949, 1950), and Pandya (1959). Torrey (1945a) points out that miners have known for a long time that it is advantageous to hollow out the end of a dynamite stick with a jack knife to increase rock breaking ability or to arrange dynamite sticks in a tepee fashion to blow a hole in the ground.

Also, Cook (1948) used the original Munroe effect to engrave or stencil letters and other designs onto metal plates.

Other examples are in the oil well industry where large diameter, but extremely short, lined shaped charges are used to penetrate various geological formations to increase the flow of oil. Oil well perforation problems present extremely difficult design problems due to the minimal amount of allowable space available in the well, the short standoff distances required, and the hostile environment within the well (Reinhart and Cocanower 1959).

The commercial use of the shaped charge in perforating oil wells was made public by McLemore in 1946. Box and Meiklejohn (1950) and Lawrence (1947) also refer to investigations in the use of shaped charges for perforating oil wells. Lawrence also discussed the use of shaped charges to fragment rocks and boulders. The use of shaped charges for oil well completion was reported by Poulter and Caldwell (1957), Carter (1978), Delacour, et al. (1958), Lebourg and Hodgson (1952), Lebourg and Bell (1959), Gardiner (1950), Kastrop (1957) Byers (1949, 1950), Reed and Carr (1950), Anon. (1947), Robinson (1957), McLemore (1946), Box and Meiklejohn (1950), and Reinhart and Cocanower (1959).

The oil well perforating industry has designed several unique shaped charge devices. Because of the available space and to minimize damage to the well casing and to prevent interference between neighboring charges, these devices contain a relatively small amount of explosive. (Usually, several shaped charges are fired simultaneously.) The shaped charges used in the oil well industry contain conical liners, hemispherical liners, truncated conical liners, parabolic liners, and trumpet shaped liners. Reed and Carr (1950), Robinson (1957), Box and Meiklejohn (1950), and Byers (1949, 1950) discuss technical aspects of oil well perforating charges.

Well perforator cones usually have an apex angle of 45° to about 60°. The smaller angle increases penetration, but the hole size is small. The larger cones tend to create a tapered hole which hinders fluid flow. In addition, the interrelationship of wall thickness, wall taper, and the radius at the apex of the cone (i.e., round or pointed apex) all affect performance. If the wall is too thick, penetration will decrease and there may be a hole-plugging slug. If the wall is too thin, the slug mass can be greatly reduced, but the jet mass will also decrease and lower the performance. Delacour, et al. (1958) explains the use of bimetallic liners to eliminate the carrot or slug formation.

Thus, efforts have been made to design shaped charges which are slugless or non-carrot forming. (In the oil well industry the slug of a shaped charge jet is termed a carrot). About 90% of the material that must be perforated consists of the cement well annulus and the rock formation. The problem is further complicated by the short standoff distances available (since the space is limited), the hostile environment (caustic and with temperatures in excess of 500° F), and the fact that the charges may have to remain in this hostile environment for several hours before they are detonated. Reed and Carr (1950) discuss the formation and penetration of oil well perforation charges as a function of the pressure and temperature of the environment. The short standoff distance available is critical since the jet must have time and hence distance to form. Also, an optimal standoff exists to achieve maximum penetration. This optimal standoff is usually greater than three charge diameters and these standoff distances are simply not available to the oil well perforator designer.

The first jet penetrators for oil well applications used glass liners. The glass lined shaped charges made large holes, but the penetration depth was inadequate. Later shaped charge liner designs used steel, copper, zinc, lead, and combinations or alloys of these metals, particularly, copper and zinc.

One slugless liner design (in addition to the work of Delacour, et al. [1958]) used two cones press-fit together. The inner cone (on the air side) was copper and was approximately one-half of the composite cone wall thickness. Theoretically, this part of the liner forms the jet. The outer cone (on the explosive side) was made of a low melting point metal such as zinc or lead, which has little or no tendency to form a slug. However, some of the outer cone material enters the jet. Slugless charges are also made using a conical liner made entirely of an alloy of zinc. Ultimately, bimetallic designs using lead or zinc alloys on the outside and copper on the inside were found to minimize the slug or carrot size without an appreciable loss in performance. The correct dimensions of each material and of the overall liner were determined experimentally. Slugless liners are also formed by preforming finely divided copper particles into molds followed by a sintering process. Another technique of slug elimination uses powdered copper, but does not sinter or even bond the particles in forming the liner. Standard powder metallurgy techniques are also used.

Linear (wedge-shaped, V-shaped, or W-shaped) shaped charges are used as cutting charges. They generate a ribbon-shaped jet used to cut metals and other materials. Commerical cutting charges are available from several sources. For cutting charge applications, it is sometimes advantageous to use homemade cutting charges which can be optimized to the particular problem on hand. Cutting charges and hollow charges are also used as explosive separation devices, as bolt cutters, and for other applications. The shaped charge effect is used on systems for separation, deployment, and safety destruct devices in missiles and spacecraft (Naval Bureau of Ordnance 1946; Cox 1964; Soper 1964; Sewell 1965). Garcia (1967), Brown (1969), and Sewell (1965) provide additional information on the linear cutting charge concept. Leidel (1978) discusses the design of an annular, or circular, cutting charge.

An interesting paper by J. M. Jones (1971) discusses the perforation of artic sea-ice by large, demolition-type, shaped charges. Jones and the U.S. Army Field Manual FM 5-25 (1971) describe the characteristics of three demolition charges (the M2A4 and M3A1 demolition charges and the No. 1, 6-in Mk3, a British designed demolition charge) currently in service and lists their approximate penetration capability into various targets. Also, Schardin (1954) discussed the use of shaped charges for glacier blasting and Mellor (1987) discussed ice breaking. Pandya (1959) reported on several shaped charge applications including underwater demolition.

General references on application are found in Kennedy (1983), Cook (1958), E. I. du Pont (1980), Bawn and Rotter (1956), Hyatt (1959), Austin (1959), and Pandya (1959). Certain specific applications of interest are found in Cook (1948) on engraving; Torrey (1945a, 1945b) on a review of shaped charge weapons of WW II; Huttl (1946) on underground blasting; Clark (1947) and Clark and Bruckner (1947) on concrete fragmentation; Lawrence (1947), Austin and Pringle (1964), and Austin (1959, 1961, 1964), on boulder breaking, drilling, and seismic exploration; Draper, et al. (1948) and Tardif (1956) on drilling; and Davidson and Westwater (1949), Davis (1953), Huttl (1946), and Tardif (1956) on cratering and boulder breaking. Overviews on application of shaped charges are available in Murphy (1983) and Baum, et al. (1949). Hyatt (1959) discusses hole drilling, post hole digging and underwater demolition via shaped charges. Byers (1949, 1950) presents novel shaped charge designs for mining, hole drilling, and boulder blasting. McPherson (1947) discusses mining applications and mudcapping.

Extensive studies are currently underway in cratering (earth removal), boulder breaking, and penetration of concrete and geological formations at several installations, notably the Waterways Experimental Station, Vicksburg, Mississippi. The demolition and cratering work performed at the Waterways Experimental Station is too extensive to cover here, but their studies cover many of the applications cited earlier. See Joachim (1983) as one example.

Extensive studies are also currently underway in the design of lined shaped charges for torpedo warheads (Merendino and West 1960). This work is also too extensive to cover here.

Additional applications relating to explosive metal interactions (Walters and Zukas 1989), and which require an understanding of the jet formation phenomena, are explosion welding, explosion cladding, or explosion forming of metal parts. The principles of explosive welding are beyond the scope of this paper. Basically, the technique involves using explosives to form bimetallic or trimetallic parts. A tremendous savings in material usage is thus possible because a thin layer, of an often costly material, can be applied to a cheaper, load bearing substrate. The thin noble and expensive material is usually used to provide an inert or corrosion resistance barrier to the substrate material. Applications occur in chemical vessels, heat exchangers, desalination plant piping, and other areas where caustic environments exist. With explosive welding techniques, even metallurgically incompatible metals and immiscible metal combinations can be bonded, as well as compatible metal systems. Mechanical Engineering (1978), Reinhart and Pearson (1963), and Blazynski (1983) provide an excellent introduction to the various aspects of explosion welding.

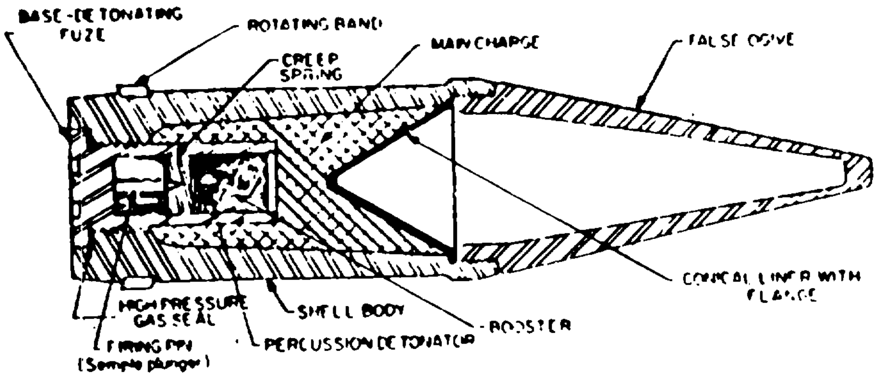


Figure 1. High Explosive Anti-tank Artillery Projectile (HEAT) (Mohaupt 1966).

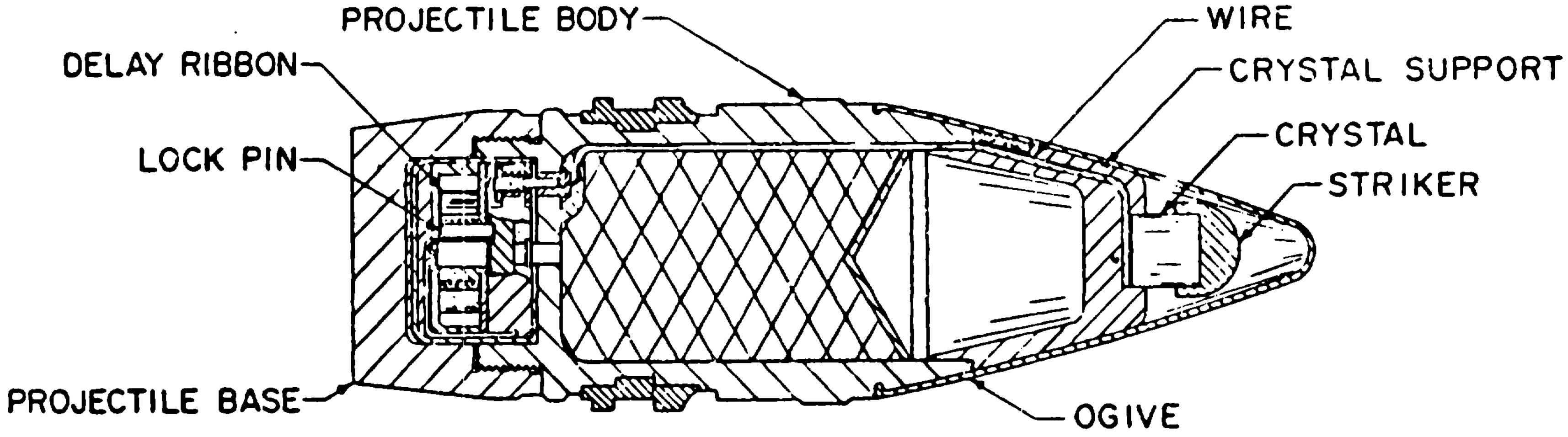


Figure 2. HEAT (High Explosive Anti-tank) Projectile (Walters and Zukas 1989).

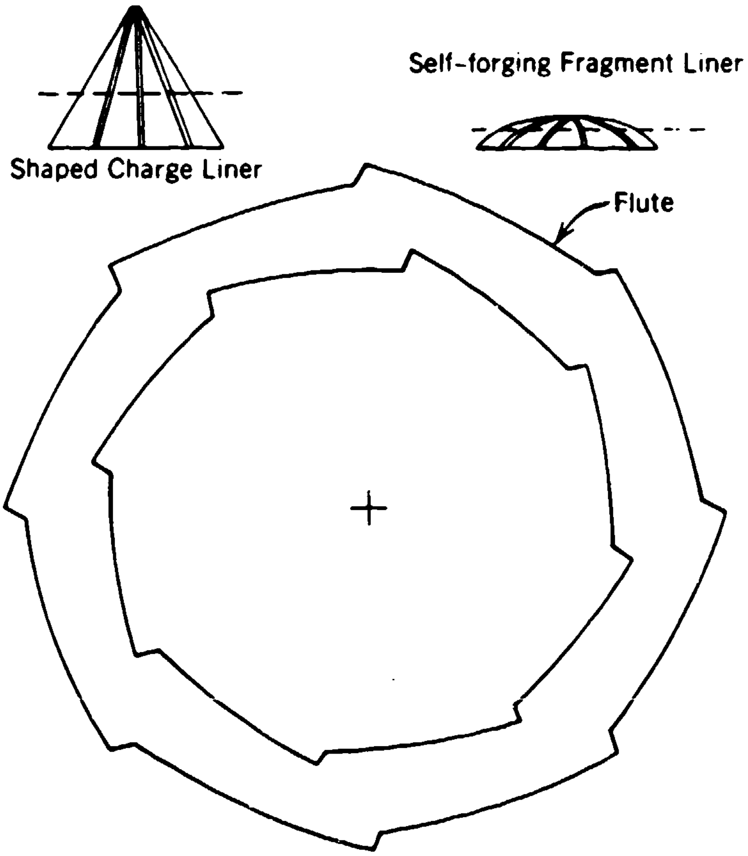


Figure 4b. Fluted Liner Cross Section (Walters and Zukas 1989).

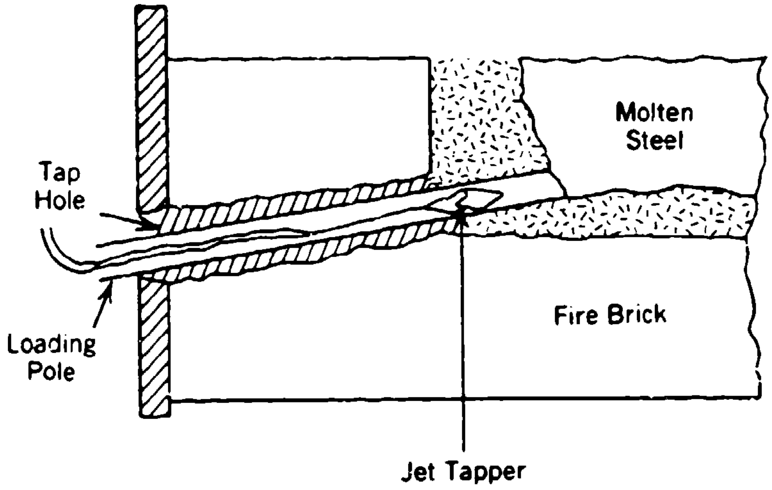
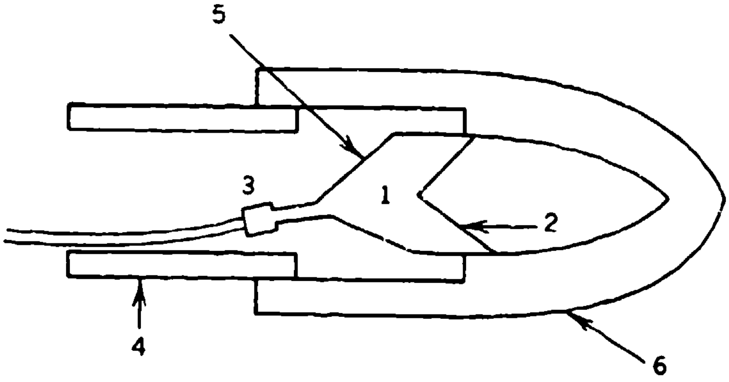


Figure 5. Steel Mill Furnace Tapping (Dupont 1980).



1. Explosive
2. Copper Conical Liner
3. Electric Blasting Cap
4. Loading Pole
5. Plastic Case
6. Insulating Ogive

Figure 6. The Offset Jet Tapper Charge (Dupont 1980).

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