Aug. 13, 1963 T. C. POULTER 3,100,445

SHAPED CHARGE AND METHOD OF FIRING THE SAME

Filed Jan. 14, 1959 2 Sheets-Sheet 1

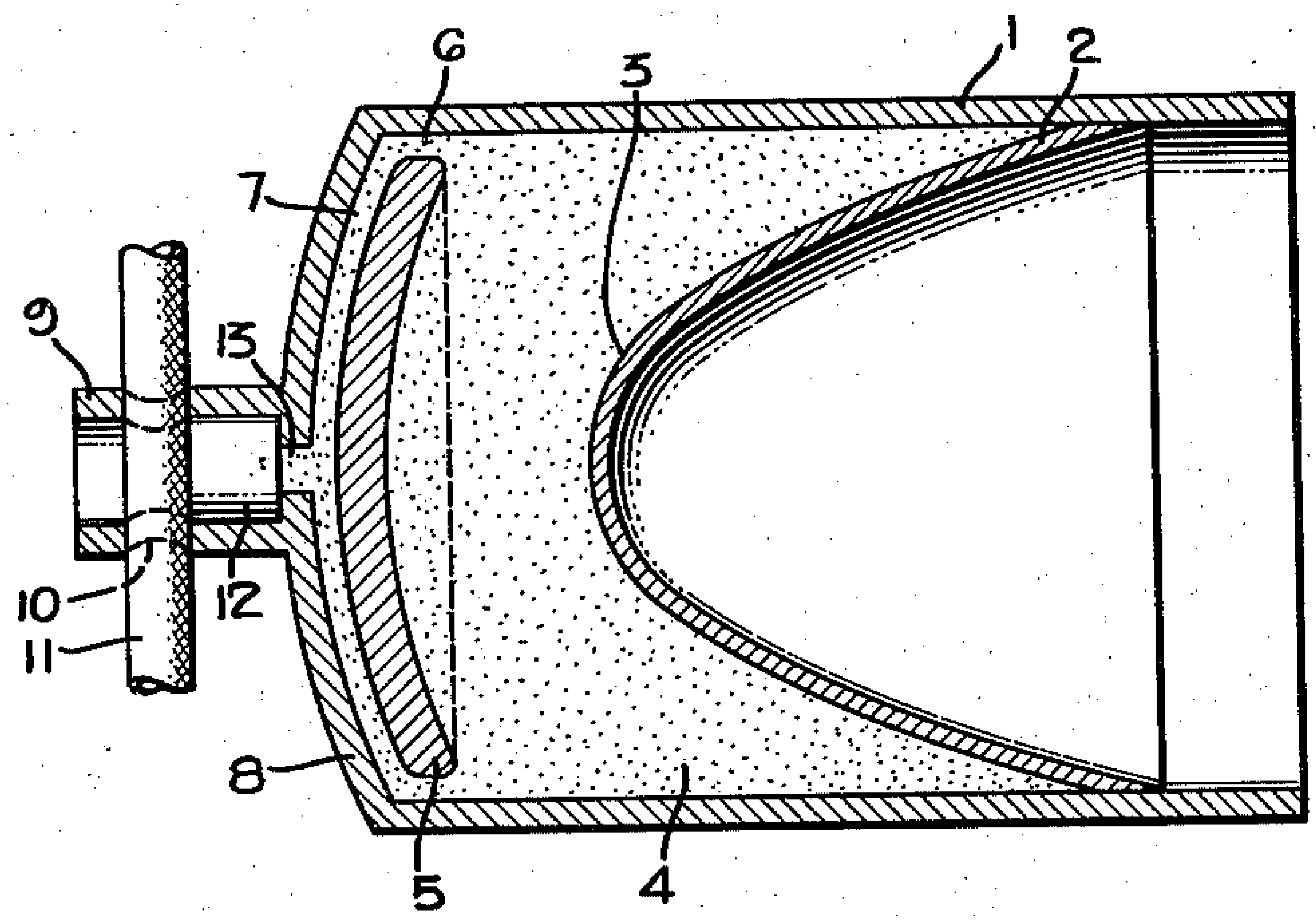

FIG. 1.

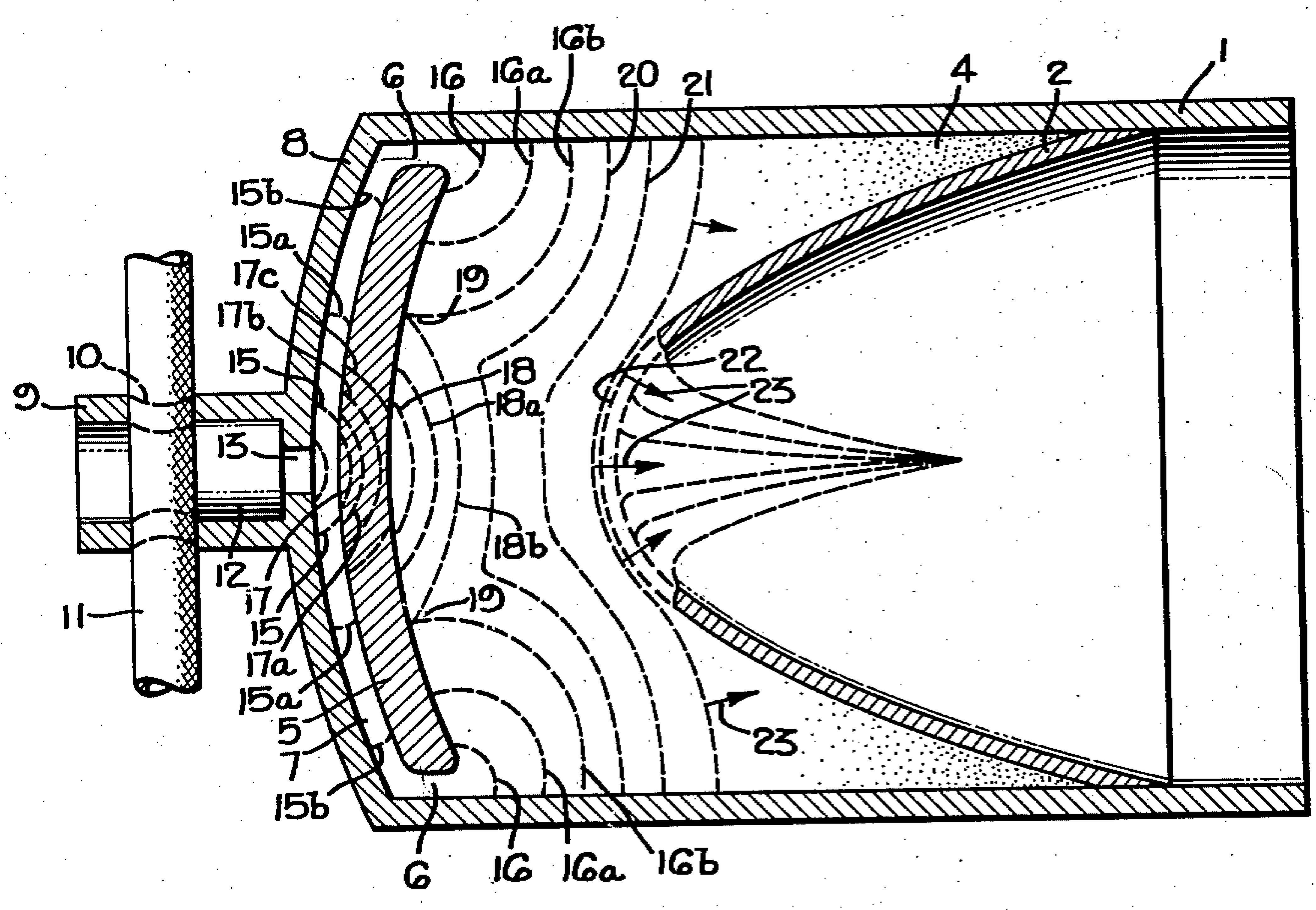

FIG. 2.

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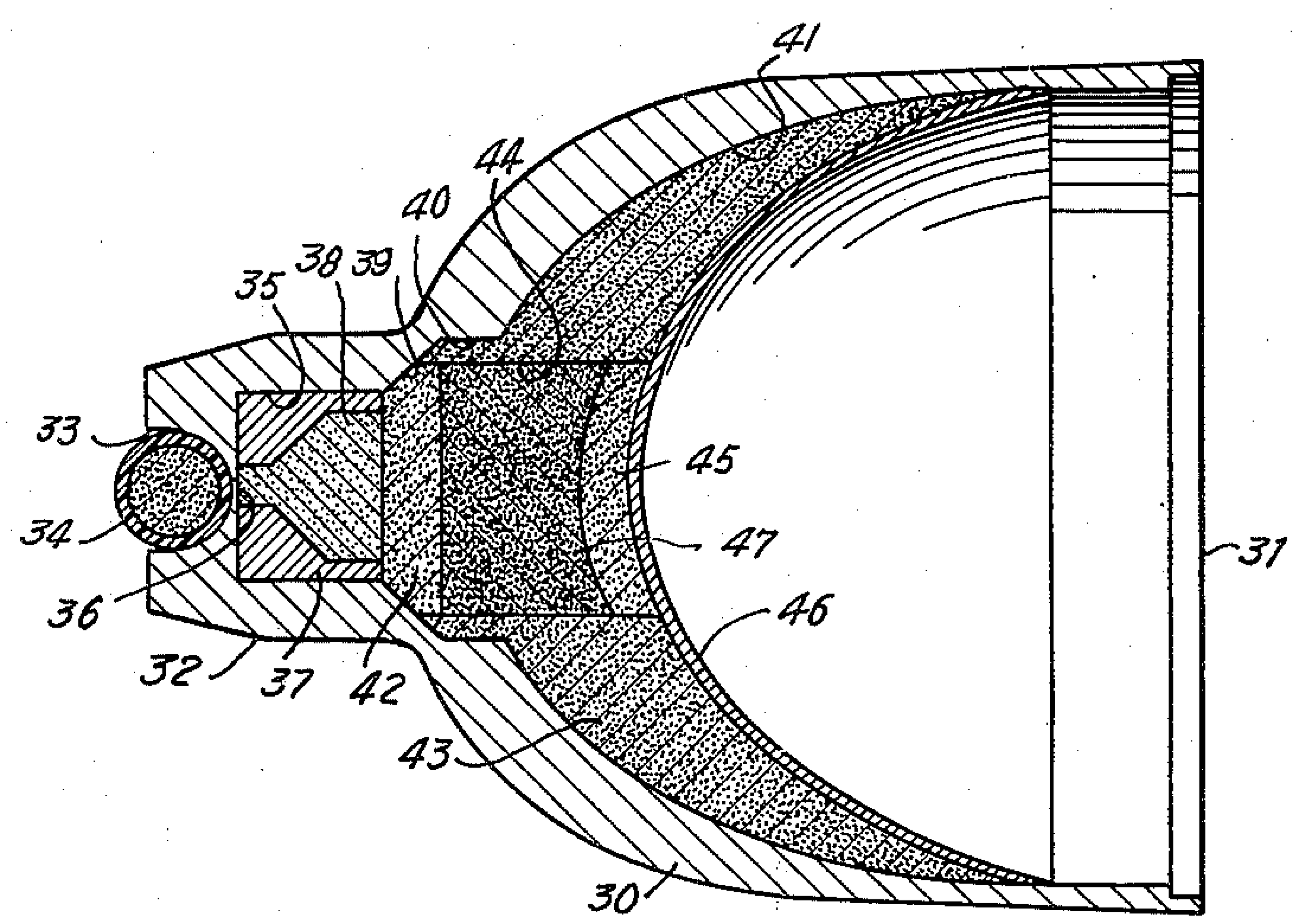

Fig. 3

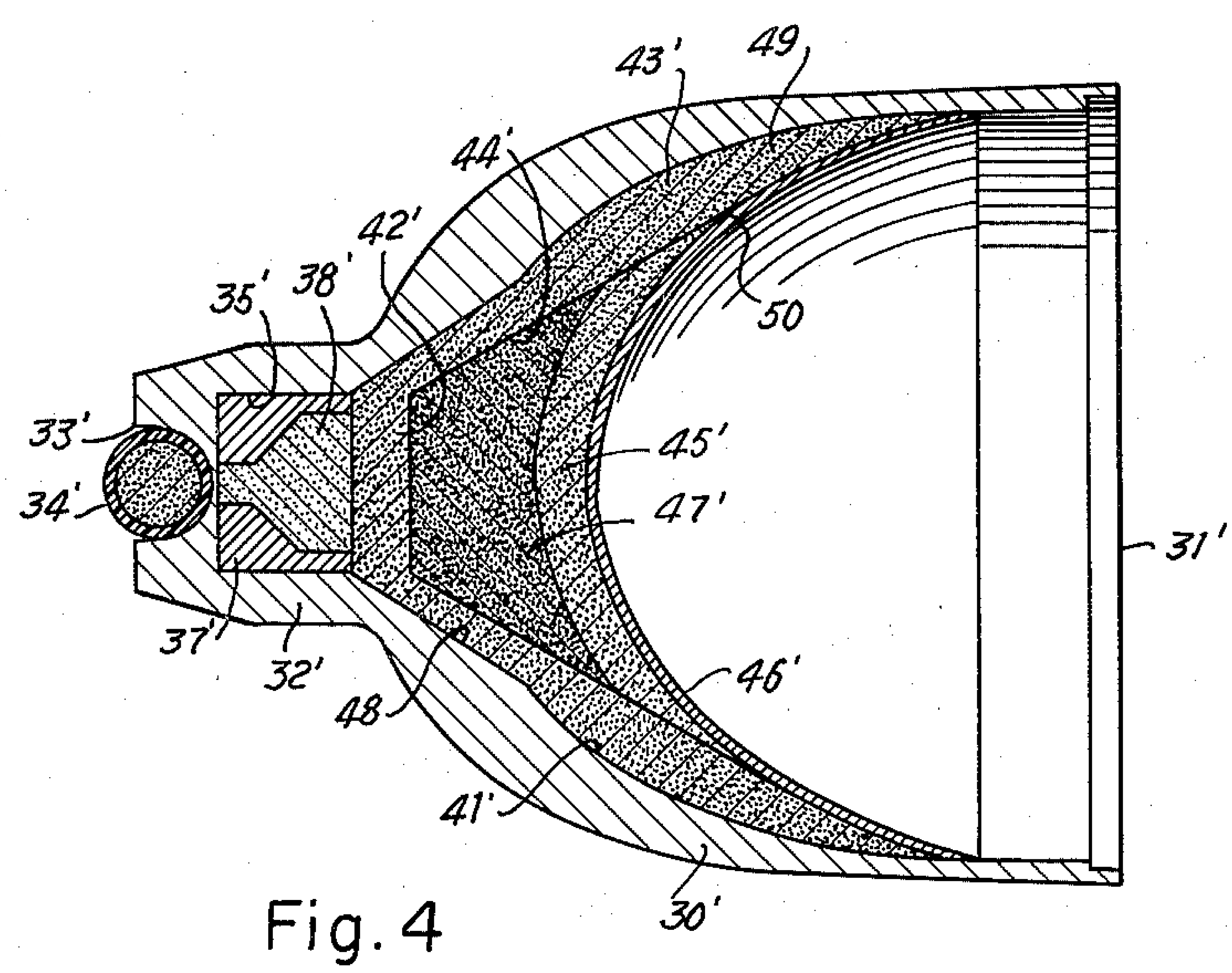

Fig. 4

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3,100,445

SHAPED CHARGE AND METHOD OF FIRING THE SAME

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16 Claims. (Cl. 102—24)

This application is a continuation-in-part of my copending application Serial No. 439,564, filed June 28, 1954, for "Shaped Charge," now abandoned.

This invention relates generally to explosive devices and is directed particularly to improvements in shaped charges. The term "shaped charge," as used herein and as generally employed in the art of explosives, designates a charge of high explosive having a cavity in its forward end which is lined with a layer of inert material. The liner may be metallic, such as copper, steel, cast iron, aluminum or lead, or may be of glass or other non-metallic material. The cavity and liner are usually conical, hemispherical, or conforming to other surfaces of revolution about the longitudinal axis of the charge. Provision is made for initiating detonation of the charge on its axis at its rearward end.

Upon detonation of a conventional shaped charge, a detonation front advances through the charge in the direction of its major axis and impinges on the liner. By virtue of the extremely high particle velocities and pressures prevailing in the detonation front, the major portion of the liner is dynamically extruded in a pencil-like jet along the charge axis at extremely high velocity.

Because of the great penetrating power of this high-velocity jet, many applications, both military and industrial, of the shaped charge have been developed. An outstanding example of an industrial application is in the perforation of well casing and subterranean formations surrounding oil, gas and water wells.

Since its original development as a military weapon, the shaped charge has been the subject of extensive research, both analytical and experimental. For the most part, experimental research has been confined to cut-and-try procedures, and analytical research has been confined to the study of experimental data and the development of theories of the mechanism of jet formation which are consistent with and attempt to explain such data. Many conflicting and erroneous theories and explanations of the mechanism of jet formation have been advanced.

The mechanism of jet formation from a lined hollow charge is very complex, and there is probably no single explanation that will explain all of the experimental results to the exclusion of all other proposed mechanisms. The most widely publicized mechanism is referred to as the hydrodynamic flow mechanism (Journal of Applied Physics, 19, 563, 1948). There are extensive experimental results to substantiate at least two other mechanisms (plastic deformation and brittle fracture) so that when one considers that it is possible to have the formation of the jet follow any one of three mechanisms, plus all possible combinations of these, it is not surprising that much confusion has resulted.

The problem is further complicated by the fact that there are no independent variables.

It is generally recognized that the size, shape and composition and thickness of case surrounding it, the shape, thickness, and composition of the liner, stand-off distance, method of detonation of the charge, shaping of the detonation front, and the angle that the detonation front makes with the surface of the liner are all known to materially affect the performance of shaped charges.

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There is, however, not a single one of these variables which can be considered to be an independent variable. On the contrary, the changing of any one of them changes an unknown number of the others, usually by an undetermined amount, so that without a rather clear understanding of the detonation process and the possible mechanisms of jet formation, it is impossible to predict the performance of a new design of shaped charge. It is not surprising, therefore, that most of the development work to date has been conducted on a cut-and-try basis with usually very discouraging and inconclusive results.

To develop a set of rules for the design of an effective lined shaped charge based on so many interdependent variables would, of course, be impossible. A fundamental study of the detonation process and the mechanism whereby a metal liner is given its velocity when an explosive in contact with it is detonated, was therefore undertaken. In this manner a few least common denominators have been obtained which provide some useful design parameters.

From this it has been possible to evaluate the relations between the shape of the detonation front and the detonation velocity, and the relation between the detonation velocity and the detonation pressure. Still further studies of the detonation process permit an evaluation of the factors controlling the duration of the pressure associated with the detonation process. This pressure and its duration provide a means of determining the impulse imparted to the liner. This, coupled with the design of the liner, provides a means for determining the direction and velocity of the motion imparted to the various elements of the liner. Thus, it has been possible to better understand the complexity of jet formation and its control, which has resulted in the invention and development of a basic design of a shaped charge having vastly improved performance characteristics.

In the usual cut-and-try procedure there has been but little, if any, basic information on which to arrive at a modification of the construction of a charge, nor was there any basis for knowing whether the change in performance was a result of the variable which was intentionally changed or whether one of the dependent variables dominated any change there may have been in performance. It was therefore a matter of changing an unknown number of variables by an indeterminate amount to produce an accumulative effect that may be positive or negative.

From a knowledge of jet penetration it is possible to specify certain desirable properties of a jet and, with this as a basis, to establish many of the requirements for a jet-producing mechanism and through that to an effective charge design.

For good performance, the material in the jet should be concentrated in to a compact, straight line of high velocity, high density material. There should be a maximum range in material velocity in the jet consistent with its having the highest attainable material velocity at the forward end of the jet, and decreasing at a reasonably uniform rate over the length of the jet to the minimum velocity that will produce effective penetration.

The necessity for this spread in jet velocity is to permit each element of the jet to complete its penetration of the target before the following element strikes the target.

Other things being equal, an increase in velocity of the forward end of the jet will increase the penetration of the jet. This is a very important factor since the percentage in penetration greatly exceeds the increase in jet velocity necessary to produce it.

It is entirely possible that an increase in the average velocity of the material in the jet may reduce the penetration if that increase in velocity occurs primarily at the after-portion of the jet. In such a case each element of the jet would be striking the target before the preceding element had completed its penetration, and the piling-up effect may cause a large decrease in depth of penetration of as much as 75 percent, with only a minor increase in hole diameter. The extent to which the after-end of the jet can have its velocity increased is determined by the ability of each preceding element to complete its penetration. In order to obtain maximum penetration, the forward end of the jet should have the maximum obtainable velocity and each successive element should have the maximum velocity consistent with permitting the preceding element to complete its maximum penetration of the target before the succeeding element strikes.

With such specifications set up for an effective jet, it then becomes a matter of selecting the mechanism of jet formation and the charge design which will best lend itself to the production of such a jet.

While it is possible to design a lined shaped charge operating by a mechanism of jet formation whereby the high velocity forward end of the jet originates from the base of the liner, such a design does not permit taking advantage certain novel features of the present invention.

From experimentation in which a conventional charge was modified in such manner as to increase the velocity of the after end of the jet by only a small amount, it was found that an appreciable decrease in penetration resulted. From this it was obvious that if any appreciable increase in penetration was to be accomplished, it would have to be through an increase in the velocity of the forward end of the jet. This meant devising techniques for increasing the velocity imparted to the metal of the apex of the liner.

Numerous attempts have been made to do this by means of peripheral detonation of the charge with generally unsatisfactory results, either because of the requirement of an excessive quantity of explosive or, if the quantity of explosive were reduced, because the meeting of the converging detonation front over the apex of the liner would blast a hole through the liner along its axis and disrupt its normal jet formation. It is my discovery, however, that if the inert barrier by which peripheral detonation is generated is so constructed as to permit a delayed detonation to occur through its central portion, then instead of the converging peripheral detonation front meeting at the center and blasting a hole through the apex of the liner, it will meet the delayed expanding detonation front in a circular area generally surrounding the apex of the liner and a generally spherical concave detonation front is developed which envelopes the apex of the liner in a pressure manyfold the sum of the pressures in the two detonation fronts.

Thus the forward end of the jet acquires a velocity far in excess of that produced by the conventional expanding spherical detonation front produced by single-point initiation.

Due to the more nearly normal angle of approach of the peripherally generated detonation front over the central portion of the liner, the velocity over the central portion of the jet will be correspondingly increased. This will therefore permit an increase in the after portion of the jet, and hence the ratio of explosive to metal around the base of the liner can be increased over and above that which is permissible with the single-point-initiated charge.

I have discovered that my invention provides another very important advantage in that merely by a small shift in position of the apex of the liner closer to or farther away from the inert barrier, the diameter of the hole produced by the jet from this charge can be varied over a several-fold range, the maximum size hole being produced with the liner at the proper distance to cause the detonation front to conform in curvature to that of the liner apex.

A general object of the invention is therefore to provide an improved shaped charge the performance of which is characterized by more effective utilization of the energy available in the explosive than has heretofore been possible.

Another object of the invention is to provide an improved shaped charge which, upon detonation, produces a jet of higher overall velocity than has heretofore been attained.

A further object of the invention is to provide an improved shaped charge which not only produces a higher velocity jet than heretofore, but which is so designed that the velocity of successive elements of the jet is distributed over a range of velocities sufficiently wide to permit each element of the jet to most effectively expend its energy in effecting penetration of the target before the next succeeding element strikes the target.

Another object of the invention is to provide a shaped charge wherein the shape of the detonation front is altered in a predetermined manner by a body of inert material embedded in the explosive charge.

Yet another object of the invention is to provide a shaped charge wherein the size and shape of the hole produced in a target may be predetermined solely by the relative positions of certain of the charge components.

Another object of the invention is to provide a shaped charge incorporating a body of inert material embedded in the explosive charge, and wherein the size and shape of the hole produced in a target may be varied in predetermined manner by varying the distance between the inert body and the liner.

A still further object of the invention is to provide a shaped charge wherein, upon detonation, a detonation front is developed in the explosive which is characterized by a central concave front and a peripheral or annular convex front.

Still another object of the invention is to provide a shaped charge incorporating means for developing, upon detonation, a central detonation front and an initially separate and distinct peripheral detonation front, the time and space relation of the two fronts being such that they merge into a composite front having a concave central portion characterized by extremely high order pressure and particle velocity.

Yet another object of the invention is to provide a shaped charge wherein the optimum stand-off distance from the base of the liner to the target is substantially less than with charges heretofore developed.

Still another object of the invention is to provide a shaped charge wherein the mechanism of jet formation is such that the degree of interdependence of the various parameters of the charge is substantially less than in charges heretofore developed.

A still further object of the invention is to provide a shaped charge wherein the usual slug or "carrot" may, if desired, be substantially eliminated.

Another object of the invention is to provide a shaped charge incorporating a body of explosively active substance embedded in the explosive charge as a means for providing a peripheral high-order detonation and a central low-order detonation.

Yet another object of the invention is to provide a method of firing an explosive charge, particularly a shaped charge.

Generally speaking, based on my studies of detonation phenomena, I have discovered and developed an arrangement and procedure or technique whereby a detonation front of abnormally high pressure and velocity can be developed in the explosive charge rearwardly of the liner, with the central portion of the front being concave and conforming in shape very closely to that of the apex portion of the liner. This is accomplished by developing a combined peripheral detonation front and central detonation front in predetermined time and space relation to each other and to the apex portion of the liner. The merging of these detonation fronts produces a composite front in which the pressure and the detonation velocity greatly exceed the sum of the individual pressures and velocities of the two fronts. Not only is it possible to "tailor" the shape of this composite front to conform substantially to liner apices of different curvatures, but it is also possible with my improved charge design to produce a wide range of target hole sizes with the same liner shape, by the simple expedient of slight changes in the position of the liner, involving merely a slight change in loading technique.

In general, the invention includes a method of firing a detonating explosive charge having in a face thereof an outwardly opening cavity the walls of which are defined by a surface of revolution about an axis, the cavity having sidewalls converging to the rear, the charge being capable of sustaining low-order detonation and high-order detonation therein, and the cavity being lined with a liner, which method includes the following steps: initiating a low-order detonation in said charge in a zone coaxial with the axis and spaced inwardly from the inner end of the cavity; and initiating a high-order detonation in and throughout an annular zone in the charge, which zone is located in a plane normal to the axis, is spaced inwardly from the inner end of the cavity, is positioned symmetrically about the axis, and is disposed around the zone of initiation of low-order detonation, the initiation of the high-order detonation being performed in predetermined time relation to the initiation of the low-order detonation to cause the detonation waves resulting from the initiations to merge in a zone located in the charge between the zones of initiation and the cavity to form a composite detonation wave that attacks the liner.

The manner in which the foregoing and other objects may be accomplished will become apparent from the following detailed description of a presently preferred embodiment of the invention, reference being had to the accompanying drawings wherein:

FIGURE 1 is a central longitudinal sectional view of a shaped charge embodying the invention;

FIGURE 2 is an enlarged view similar to FIGURE 1, illustrating successive stages of propagation of the individual detonation fronts, their merger into a single composite front, the progressive change in shape of the composite front and its impingement on the apex portion of the liner;

FIGURE 3 is a longitudinal axial sectional view of another embodiment of a shaped charge in accordance with the invention; and

FIGURE 4 is a longitudinal axial sectional view of a third form of shaped charge embodying the invention.

Referring to FIGURE 1, a charge case **1** is herein shown as cylindrical but may be of any other desired shape symmetrical with respect to the charge axis, and is preferably of metal such as steel, cast iron or aluminum but may if desired be of non-metallic material such as plastic. A liner **2** of copper or other suitable material is mounted in the case in a conventional manner. As shown, the apex portion **3** of the liner is rounded and the side portions of the liner are of gradually decreasing curvature. It will be understood, however, that the specific shape of the liner does not constitute a significant aspect of the instant invention and various other shapes may be employed if desired.

Rearwardly of the liner the case **1** is filled with an explosive **4** having a high detonation rate, such as TNT, Cyclotal, etc. Embedded in the explosive **4** adjacent the rear wall of the case is a barrier **5** of inert material such as steel or other metals or non-metals. The barrier **5** is disposed transversely of the charge and is symmetrical and coaxial with the case and liner. As shown the barrier **5** is of uniform thickness and is preferably in the form of a segment of a sphere, although other shapes which are symmetrical with the axis of the charge may be employed, such as conical, paraboloidal, ellipsoidal, or a flat disc. The diameter or transverse dimension of the barrier is less than the internal diameter of the case **1** thereby providing an annulus **6** of explosive surrounding the periphery of the barrier and joining the bodies of explosive at the forward and rearward sides of the barrier. In order to provide a layer of explosive **7** of uniform thickness between the barrier and the rear wall **8** of the case **1**, the latter is preferably also in the form of a segment of a sphere or of other shape conforming to that of the barrier.

A tubular socket **9** projects from the rear wall of the case **1** in coaxial relation thereto, and is perforated transversely at **10** to receive a length of Primacord **11** or other detonating fuse. A booster pellet **12** is seated in the socket **9** between the Primacord **11** and the rear wall of the case, and is in direct contact with the explosive **7** through an opening **13** in the rear wall **8**, it being understood that the explosive also fills the opening **13**. The opening **13** should be small enough to assure concentricity of the detonation front.

It will be apparent that detonation of the Primacord **11** will detonate the booster **12**, which in turn initiates detonation of the explosive **7** at the opening **13**. Referring to FIGURE 2, the detonation front developed at the opening **13** initially expands spherically until it strikes the rear wall of the barrier **5**, whereupon it is converted into a radially expanding circular front progressing through the layer **7** of explosive, successive positions of the front being indicated at **15**, **15*a*** and **15*b***.

Upon reaching the periphery of the barrier, the detonation front progresses therearound, and forwardly through the annulus **6** of explosive. As it passes the forward peripheral edge of the barrier and enters the main body of explosive **4** it is free to expand both forwardly and radially inwardly toward the axis of the charge. Hence, the forward and inward portion of the front assumes the form of a portion of the surface of a torus, as indicated by the corresponding pairs of arcuate dotted lines **16**, **16*a*** and **16*b***.

Meanwhile the detonation of the explosive in contact with the rear surface of the barrier **5** has generated a shock pulse in the material of the barrier. This shock pulse, initiated at a point on the axis of the charge, progresses forwardly through the barrier as indicated at **17**, **17*a***, **17*b*** and **17*c***, to the forward, concave surface thereof. Also as the detonation front indicated at **15**, **15*a*** and **15*b*** expands through the explosive layer **7**, it rolls along the rear surface of the barrier **5** and generates a radially progressing series of shock pulses in the barrier, which progress forwardly through the barrier.

Whether or not the explosive in contact with the forward surface of the barrier **5** will be detonated by the shock pulse transmitted through the barrier, and whether the detonation is low-order or high-order, depends, generally speaking, on the intensity of the shock pulse as it reaches the forward surface of the barrier and on the sensitivity of the explosive in contact therewith. The intensity of the shock pulse after it passes through the brarier depends on the material of the barrier, the thickness of the central portion thereof, and the thickness of the central portion of the layer **7** of explosive which generates the shock pulse.

By way of example, in tests wherein the explosive used was waxed "RDX," a military form of Cyclonite

$$(CH_2 \cdot N \cdot NO_2)_3$$

it has been determined that with a barrier **5** of steel and with a 1/16 inch thick layer **7** of explosive which is detonated by a booster such as the pellet **12**, if the thickness of the central portion of the barrier is 3/16 inch or greater the explosive in contact with the forward surface will not be detonated by the shock pulse. If the central portion of the barrier is 1/10 inch to 1/8 inch in thickness, the shock pulse transmitted through it will initiate low-order detonation of the explosive at the forward side of the barrier. If the central portion of the barrier is substantially less than 1/10 inch in thickness the shock pulse will initiate high-order detonation of the explosive at the forward side thereof.

On the other hand, from tests with charges in which the type of explosive, the material and thickness of the barrier 5, and the thickness of the layer 7 of explosive were identical with those referred to in the preceding paragraph, but in which the booster pellet 7 was omitted and detonation was initiated directly by Primacord, it was found that the optimum barrier thickness from the standpoint of depth of penetration was 0.059 inch, as compared to 0.10 to 0.125 in the previously mentioned test results. This may be explained by the fact that the booster pellet 12 constitutes in effect an additional thickness of explosive behind the central portion of the barrier. This points up the important influence which the thickness of the explosive exerts on the initial velocity of the shock pulse developed in the barrier.

It is thus apparent that by the selection of a barrier of appropriate material and thickness, or by varying the effective thickness of the explosive behind the barrier, any one of three distinctly different detonation front conditions may be produced in the explosive forwardly of the barrier (*a*) a converging, high-order peripheral detonation front only; or (*b*) a converging, high-order peripheral detonation front and a delayed, expending, low-order central detonation front; or (*c*) a converging, high-order peripheral detonation front and a delayed, expanding, high-order central detonation front.

The respective characteristics of the two distinct types of detonation known as "high-order" and "low-order" detonation are well known to those familiar with explosives and have been delineated in many publications dealing with explosives. A well-known example of such publications is "Detonation in Condensed Explosives," by J. Taylor, Oxford Press, 1952, London, England. An explanation and discussion herein of those phenomena is therefore not deemed necessary.

As has been pointed out previously, a converging peripheral detonation front alone (condition (*a*) above) is not conducive to proper jet formation. The apex of the liner is not the first portion of the liner to be given a velocity as is the case with single-point detonation. Instead, the detonation front first contacts a ring of material farther down on the liner. Since this first contact is normal to the surface, that portion of the liner will be given a high velocity. As the detonation front rolls along the surface of the liner in the direction of the apex, the angle of approach becomes less than 90° and the material is given a lower velocity than the portion of the liner first contacted. This lower-velocity material is projected into the region where the jet is being formed and disturbs the jet formation. However, as the detonation front reaches the apex, it converges and meets at a point. Such a meeting of detonation fronts produces, at that point, a pressure estimated to be in excess of fifty million p.s.i. With such a pressure at a point, a jet of extremely high-velocity material is projected into the zone where the jet proper is being formed, and since the lower velocity material has already been projected into that zone, the collision of the extremely high-velocity material with it tends to disrupt the process of jet formation. Although the process of jet formation proceeds in an orderly manner in the lower portion of the liner, the disturbance in the formation of the apex of the jet has been such as to prevent its superior performance. This interference can be prevented to some extent if the distance between the zone of peripheral initiation and the apex of the liner is increased, which accounts for the belief that in order for peripheral detonation to function properly, an excessive amount of explosive is required.

I have discovered that if conditions are such as to produce a high-order central detonation front and a high-order peripheral detonation front, the collision of two such high-order fronts produces a sharply defined annular zone of extremely high pressure. If the liner be located close enough to the barrier to subject any portion of the liner to the effect of this sharply defined, annular high-pressure zone, there results a marked decrease in the effectiveness of the jet. This is attributed to the sharp boundary-cutting effect of the annular high-pressure zone on the liner, producing a sharp discontinuity in the velocity gradient of the jet. On the other hand, if the liner be located far enough away from the barrier to avoid the sharp boundary-cutting effect of the high-order detonation collision zone, the performance of the charge is strikingly similar to that of a conventional charge having single-point initiation. This indicates that the axial spacing between the liner and the barrier is so great that the intially centrally concave detonation front has been converted to a conventional convex front before it reaches the apex of the liner, and hence that the advantageous effect of the barrier has been dissipated. It therefore appears that less advantageous results are obtained when the parameters of the components of a barrier-type charge are such as to produce central and peripheral detonation fronts which are both of high-order.

One of the most important and most significant aspects of my invention is my discovery that with the proper relationship between the type of explosive, the barrier material and thickness, and the thickness of explosive behind the central portion of the barrier to develop a low-order central detonation front and a high-order peripheral detonation front at the forward side of the barrier, marked and unprecedented improvements in charge performance from many standpoints, as well as several other outstanding advantages, can be achieved. These improvements and advantages, which will be explained more in detail hereinafter, are briefly as follows:

(*a*) Greatly increased depth of target penetration and volume of target hole for a given amount of explosive;

(*b*) Wide variation in the cross-sectional area of the target hole by varying only the amount of explosive while maintaining all other components the same;

(*c*) Substantial reduction in the number of parameters which effect performance, making possible the development of a simple equation defining the relationship of the significant parameters;

(*d*) Substantial reduction in optimum stand-off distance (from base of liner to target);

(*e*) Substantial elimination of the usual slug or "carrot."

The mechanism of development of the initially separate, low-order central detonation front and high-order peripheral detonation front, their merger into a composite front having a concave central region, and the progressive change in the contour of this front, will be made clear by reference to FIGURE 2 of the drawing. As shown therein, the dot-and-dash lines **18**, **18*a*** and **18*b*** represent successive positions of the low-order expanding central detonation front initiated by the shock pulse transmitted through the barrier **5**. The meeting of this front with the converging peripheral detonation front, indicated at **16**, **16*a*** and **16*b***, produces a composite front which initially comprises the portions **16*b*** and **18*b***.

The juncture of the central front **18*b*** with the peripheral front **16*b*** initially produces an annular, sharply concave region indicated at **19**, wherein the radius of curvature is very small and the pressure and the particle velocity are considerably higher than at other points on the composite front. Consequently this portion of the front has a greater velocity than the remainder of the front, resulting in a progressive increase in radius of curvature in that region.

It will be observed that the peripheral portion **16*b*** of the initial stage of the composite front is considerably in advance of the central portion **18*b***. This results from the cumulative effect of several time-delays occurring in the generation of the central front **18*b***. The first time lag occurs in imparting velocity to the surface particles of the barrier **5** at the interface with the explosive layer **7**, to generate the shock pulse **17**. Another time-delay is the result of the lower velocity of the shock pulse **17** in comparison with that of the high-order detonation pulse traveling through the explosive around the barrier. The shock pulse velocity in a steel barrier is only about one-fourth that of the detonation pulse. Consequently the successive positions of the shock pulse front indicated at **17**, **17a**, **17b** and **17c** approximately correspond respectively to the positions **15**, **15a**, **15b** and **16** of the detonation front.

Another time-delay occurs in the initiation of detonation of the explosive at the central forward side of the barrier **5** by the shock pulse. Lastly, if the barrier is such as to cause the shock pulse to generate low-order detonation of the explosive, the considerably lower velocity of the low-order detonation pulse will cause an additional time delay. Thus, the location of the low-order detonation front indicated at **18** will correspond in time to that of the shock pulse front indicated at **17c** which, as stated above, corresponds to the location of the peripheral detonation front indicated at **16**. As the front **18** moves successively to the positions **18a** and **18b**, the front **16** moves to the positions **16a** and **16b**.

It will be understood that the aforementioned time-delays are of infinitesimal order, but nevertheless sufficient to cause the formation of a composite front such as **16b**, **18b** having a peripheral portion **16b** in advance of its central portion **18b**.

An important and advantageous characteristic of the meeting of a low-order central detonation front and a high-order peripheral detonation front is that it does not produce a sharply defined, extremely high pressure zone as in the case of the collision of two high-order detonation fronts. Instead of a sharply defined annular zone of extremely high pressure resulting from the collision of a high-order, expanding central detonation front and a high-order, converging peripheral detonation front, which, as stated previously, produces a sharp boundary-cutting effect, the meeting and merging of a low-order central detonation front with a high-order peripheral detonation front produces a zone of considerably lower pressure, distributed over the entire central area of the resulting composite front. This distribution is the result of a merging, as distinguished from a collision, of the two fronts.

As the composite front advances toward the apex of the liner **2**, the concave annular region **19** which joins the central portion with the peripheral portion gradually flattens out and eventually merges with the central and peripheral portions to produce a concave-convex front, as indicated successively at **20** and **21**. At a certain distance forwardly of the barrier **5**, this front has a central concave portion substantially conforming to the curvature of the spherical apex portion of the liner **2**, as indicated at **22**. In the illustrative embodiment the liner is positioned with its apex at the proper distance from the barrier **5** to achieve this conformity. Accordingly, the entire spherical apex portion of the liner is subjected simultaneously to the extremely high pressure and velocity of the concave central portion of the detonation front. A relatively large portion of the liner is therefore concentrated in the forward, maximum velocity portion of the jet. This is in striking contrast to the jet formed by a charge in which detonation is initiated at a single point and the convex detonation front travels along the axis and strikes the apex of the liner. In the latter case only a relatively small amount of the material of the liner is concentrated in the forward, maximum velocity portion of the jet.

Inasmuch as the particle velocity at any point on the detonation front is a maximum in a direction normal to the front at that point, as indicated by the arrows **23**, and inasmuch as in the arrangement shown in FIGURE 2 each point on the central concave spherical portion of the front impinges on the apex of the liner in such normal direction, the maximum velocity is substantially simultaneously imparted to the entire mass of that portion of the liner. As the detonation front advances beyond the last position shown in FIGURE 2, the angle of approach of the front to the side portion of the liner progressively decreases from 90°. Other factors being equal, this serves to reduce the velocity imparted to successive portions of the liner material. Furthermore, the thickness of the explosive, measured normal to the surface of the liner, decreases forwardly and has a further reducing effect on the velocity imparted to successive portions of the liner. The desired velocity gradient along the jet is thus attained, while still providing an average velocity considerably higher than that obtained previously, by virtue of the extremely high velocity of the forward portion of the jet.

By virtue of the higher pressure and velocity of a concave detonation front, as compared to that of a planar or convex front, the curvature of the central concave portion **22** of the front decreases as the front advances beyond the last position shown in FIGURE 2. Hence, if the liner **2** were positioned with its apex farther from the barrier **5** the concave central portion of the front would be of less curvature than that of the apex of the liner at the instant of impingement of the front on the liner apex. Consequently the front would strike the liner first at a point on the axis of the charge, followed by successive impingement over an expanding spherical area of the liner apex.

Conversely, if the liner **2** were positioned closer to the barrier **5** than as shown in FIGURE 2, the curvature of the central concave front would be greater than that of the liner apex and consequently the initial contact of the detonation front with the liner apex would be along a circular concentric path spaced from the axis. In each of these instances the portion of the liner forming the forward portion of the jet would be extruded in a mass of smaller diameter than under the condition shown in FIGURE 2, and a smaller hole would be formed in the target.

It is thus apparent that the target hole size may be varied over a considerable range by the simple expedient of varying the axial distance between the liner and the barrier, and using identical charge components except for a variation in the amount of explosive. This is an important and highly advantageous feature of the instant invention.

The foregoing statements concerning variation of target hole size have been confirmed experimentally. Numerous test have been conducted under simulated oil well conditions, wherein the targets were sections of well casing of .375″ wall thickness, surrounded by aged cement simulating oil-bearing rock formation such as sandstone or limestone. Typical results are shown in Table I below, which shows a comparison of target hole sizes obtained in the well casing with charges which were identical except for variation of the axial distance between the liner and the barrier and a corresponding variation in the amount of explosive.

Table I

Weight of explosive (grams)	Dia. of hole in well casing (inches)	Depth of penetration in formation (inches)	Volume of hole (cu. in.)
15	.462	9.1	3.1
19	.550	9.8	3.67
23	.740	10.65	4.25
26	.437	9.5	2.50
29	.375	9.0	3.00

The charges used in the foregoing and numerous other tests are typical of charges which have been developed embodying the instant invention, and in which emphasis has been placed on the diameter of the hole produced in the target, rather than on obtaining maximum penetration irrespective of hole size. By way of example, structural details of the charges used in the tests referred to above are given as follows:

The case **1** is of standard 1¼ inch I.D. steel tubing of 1/16 inch wall thickness, the rear wall **8** being formed of **11** gage steel plate pressed with a 2¼ inch ball to a 1⅛ inch radius of curvature and welded to the end of the case. The booster socket **9** is welded to the rear wall **8** and is of a suitable size and shape to accommodate the particular type of booster pellet **12** to be used. The barrier **5** is made from circular blanks of 11 gage steel, pressed with a 2 inch ball to a 1 inch radius of curvature. The liner **2**, of copper, has a 50° included angle with an apex radius of curvature on the inside of ½ inch and a uniform wall thickness of 0.030 inch. The O.D. of the base of the liner is about 0.003 inch larger than the I.D. of the case, thus providing an interference fit to hold the liner snugly in position when pressed into the case.

The explosive charge **4** and the layer of explosive **7** rearwardly of the barrier **5** are waxed, granular "RDX" pressed to 10,000 p.s.i. The loading operation is performed in two steps—first, 4 grams of explosive are pressed to form the layer **7**, about 1/16 inch in thickness; the barrier is then inserted and the remainder of the charge is then loaded and pressed. The liner **2** is then pressed into snug contact with the main charge. The quantity of explosive in the main charge **4** will vary in accordance with the target hole size desired, as pointed out hereinabove. In the tests from which the results given in Table I above were obtained, the explosive weights of 15, 19, 23, 26 and 29 grams represent the total amount of explosive including the 4-gram layer **7**.

It should be pointed out that it is not necessary to directly determine the axial distance between the barrier **5** and the apex of the liner **2**, inasmuch as this distance is relative and is indirectly determined by the amount of explosive in the main charge **4**. It is, however, necessary to determine experimentally the performance data of a charge of a particular design. An important characteristic of shaped charges embodying the instant invention is that by virtue of my newly developed and entirely different mechanism of jet formation, the number of variables which materially affect charge performance, and which are changed by unknown amounts by changing other variables, has been greatly reduced. For example, an anlysis of a large quantity of test data involving identically-designed charges of different sizes has revealed that the ratio of the depth of penetration to the diameter of the charge liner is fairly constant over a reasonably wide range of liner diameters. This ratio, which is an effective criterion of charge performance, may be expressed by:

$$K=P/d \qquad (1)$$

where:

P=depth of penetration of the target;
d=liner diameter; and
K=ratio of depth of penetration to liner diameter.

The weight of explosive in a charge of a given design is proportional to the cube of the diameter of the liner; or

$$W=Cd^3 \qquad (2)$$

or, expressed differently,

$$C=W/d^3 \qquad (3)$$

where:

W=weight of explosive;
C=weight of explosive in a charge whose liner diameter is unity.

By combining Equations 1 and 2, the following equation is derived:

$$W=C(P/K)^3 \qquad (4)$$

It will be apparent that by substituting in Equations 1 and 3 the values W and d of a given charge exemplary of a series of the same design, and the value of P obtained from test firings of such a charge, the values of the constants C and K for that design may be determined. When these values of C and K are substituted in Equation 4 above, one may determine either the penetration which may be expected from a charge of the same design having a weight of explosive W, or the weight of explosive W required to produce a desired penetration.

By the use of the foregoing equations in conjunction with test data from a few types of special-purpose charges of varying designs, it is thus possible to select the proper design for a particular purpose and to calculate the actual charge dimensions for a particular size of the selected design. The determination of the proper amount of explosive required to produce a desired target hole size with a selected design and charge size, if hole size should be a major consideration, can be accomplished by a few simple experiments which involve merely varying the amount of explosive between liner and barrier while using otherwise identical charge components. The effect of such variance within the range of feasible hole sizes is minor.

From the foregoing detailed description of one embodiment of the invention and the accompanying description of the newly developed and proven theories of detonation and of jet formation in a shaped charge, it will be evident that by following these teachings a shaped charge having superior performance characteristics may be produced. Furthermore, by the application of the principles set forth hereinabove to the design of shaped charges for various uses and purposes and to meet various conditions of use, it is possible to "tailor" a charge design for optimum performance under a given set of conditions.

For example, if a large hole is desired, the charge may be designed to provide a relatively large radius of curvature of the liner. Application of the principles of this invention permits the concentration of a large portion of the material of the liner apex in the forward, maximum-velocity portion of the jet. Thus the liner is disposed at the proper distance from the barrier to cause the curvature of the central concave portion of the detonation front to substantially conform to the curvature of the liner apex at the instant of impact of the detonation front on the liner apex. Conversely, should a smaller hole size be desired, a smaller radius of curvature would be utilized, and again in order to attain maximum efficiency the liner would be disposed at a distance from the barrier to permit conformation of the detonation front to the liner apex curvature.

Reference has previously been made to the three distinctly different detonation front conditions produced at the forward side of the barrier, depending on the type of explosive, the material and thickness of the barrier, and the thickness of the explosive behind the central portion of the barrier. In addition to the criterion afforded by the pronounced increase in target penetration when conditions are such as to produce a low-order central detonation front and a high-order peripheral detonation front, another and even more positive and reliable indication is available from test firing of charges from which it can be definitely determined which of the three detonation front conditions was produced. This indication is afforded by an examination of barriers after test firing of the charges.

Inasmuch as the time interval between detonation of the rearward layer **7** of explosive and detonation of the main explosive charge **4** is infinitesimally small, on the order of one micro-second, the forward velocity which would otherwise be imparted to the barrier **5** by detonation of the explosive layer **7** is counteracted and offset by the rearward velocity imparted thereto by detonation of the main charge **4**. Accordingly upon firing the charge the barrier remains practically motionless and, in tests with charges having steel barriers, the barriers can be found in close proximity to the original position of the charge, intact and undamaged by impact on any objects in the vicinity. The physical appearance of the barriers will, however, undergo certain specific and distinguishable changes, depending on which of the three aforementioned detonation front conditions is produced.

Thus, if conditions are such as to produce a high-order central detonation front and a high-order peripheral detonation front, the sharply defined annular zone of extremely high pressure produced by the collision of these two high-order fronts forms a sharply defined circular cut or groove in the forward surface of the barrier close to the periphery thereof. This definitely identifies this condition.

If, however, conditions are such as to produce the preferred combination of a low-order central detonation front and a high-order peripheral detonation front, the distributed zone of moderately higher pressure produced by the merger of these two fronts forms a shallow depression of substantial width in the forward surface of the barrier. Because of the relatively lower velocity of the low-order front, as compared to that of a high-order front, the region of initial meeting of the fronts in this instance is at a shorter distance from the axis than in the case of the collision of high-order central and peripheral fronts. Hence both the location and the form of the indentation or groove provide positive means of distinguishing between the two above-mentioned conditions.

Lastly, if conditions are such as to prevent the development of a central detonation front by shock pulses transmitted forwardly through the barrier, the extremely high pressure developed along the axis of the charge, by the converging of the peripheral front and its meeting at a point on the charge axis, produces a high velocity jet in both directions along the charge axis. The rearwardly directed jet blasts a large hole through the central portion of the barrier, but there is no indication on its forward surface of a collision or merging of detonation fronts, as in the other two cases. This condition can thus be identified.

It has also been stated previously that the optimum stand-off distance (from the base of the liner to the target) of shaped charges embodying the instant invention is substantially less than with charges heretofore developed. This is another result of the different mechanism of jet formation. According to the generally accepted theory of the mechanism of jet formation in a conventional shaped charge having single-point initiation of the main charge, the liner is collapsed radially inwardly upon itself and the forward portion of the jet contains liner particles which are extruded forwardly from the center of the collapsed liner by the extreme inward collapsing pressure. This extrusion of liner material occurs while the collapsed liner is being propelled forwardly at a lower velocity than that of the extruded material, and it is believed to be for this reason that a stand-off approximately equal to the diameter of the charge must be provided in order to permit this mechanism to function properly.

On the other hand, in a charge embodying the instant invention a substantial portion of the liner at the apex end is projected forwardly along the axis at an extremely high initial velocity and, from the start of jet formation, forms the forward portion of the jet. The effective stand-off in this instance might well be measured from a point near the apex of the liner rather than from its base. Hence the stand-off distance from this base of the liner to the target need be merely a small fraction of that required for conventional charges. This is obviously a distinct advantage in uses of shaped charges which impose severe restrictions on the permissible over-all length of the charge plus the stand-off distance.

Yet another important characteristic of shaped charges embodying the instant invention, which is of particular advantage in certain fields of use, is that the usual slug or "carrot" may, if desired, be substantially eliminated. This is believed to be due primarily to the following factors: first, a large portion of the liner, starting at its apex end, is projected into the forward, maximum-velocity portion of the jet and is disintegrated during the process of penetration into the target; secondly, the enhanced velocity gradient along the jet assists in disintegration of the intermediate and base portions of the liner; and lastly, because of the more efficient utilization of the available energy of the explosive by the higher average velocity of the jet and the improved distribution of velocity along the jet, it is possible to use a liner of less wall thickness than is required for optimum performance of a conventional shaped charge, resulting in a reduced amount of residual liner material to form a slug.

The invention embodying a barrier of explosively active substance will now be described with reference to FIGURES 3 and 4.

In general, a shaped explosive charge in accordance with FIGURES 3 and 4 includes a mass of high explosive material capable of sustaining high-order detonation and low-order detonation therein and having a cavity at its forward end. The cavity is lined with a liner of inert material. Means is provided for initiating in the mass of explosive material rearwardly of the liner a peripheral, high-order detonation. Means is also provided for initiating in the mass of explosive material rearwardly of the liner a central, low-order detonation initially separate from and laterally surrounded by the high-order detonation, the low-order detonation initiating means including a body of explosively active substance having its forward face in contact with the mass of high-explosive material. Such body may be formed from an intimate mixture of a finely divided high-explosive material and a finely divided inert diluent therefor. The body is capable of sustaining therein a detonation of an order not greater than low-order. Means is provided for detonating the body of explosively active substance. The loci of initiation of the high-order and low-order detonations in the mass of high-explosive material are positioned with respect to each other, and the liner is shaped and positioned with respect to the loci of initiation, to permit the high-order and low-order detonations that propagate from the loci to merge in part in the mass of explosive material between the loci and the liner to form a composite detonation front that attacks the liner.

The body or barrier of explosively active substance preferably consists of finely divided RDX, Cyclonite, TNT, PETN, or the like to which is added a finely divided inert diluent such as plaster of Paris, salt, powdered glass and the like. Although the inert diluent material preferably is an inorganic non-explosive substance, finely divided non-explosive inert organic substances may also be used. Examples of such organic diluents are powdered synthetic resins.

The mixture of high-explosive and diluent may be compacted in a die to produce a self-supporting body of the desired shape that is inserted in the shaped charge during loading.

The barrier of explosively active substance is characterized by an ability to sustain therein a detonation of an order not exceeding low-order. The proportions of high-explosive material and diluent required to produce a body of this nature will depend upon a number of factors such as the particular high-explosive material and the particular diluent employed. Particle size and degree of compaction of the body will also influence the order of the detonation that the body can sustain.

In a general way, the shaped charge structures of FIGURES 3 and 4 are similar to the shaped charge structure of FIGURES 1 and 2. Each has a barrier of solid material embedded in the main charge of explosive between the booster and the cavity liner. It will be noted, however, that the explosively active barriers are relatively thicker in the axial direction than the inert steel barrier. It appears that the detonation front traveling forwardly through the explosively active barrier advances at a faster rate than the shock pulse in the inert steel barrier. Consequently, an explosively active barrier must be relatively thicker than a steel barrier to achieve a delay time that is comparable to the delay time effected by a steel barrier in the initiation of a central low-order detonation in the main explosive charge at the forward face of the barrier.

The explosively active barrier is initiated at the rear by the booster or that portion of the main explosive charge situated immediately rearwardly of the barrier. The nature of the barrier is such that it is initiated low-order. It is capable of propagating only a low-order detonation forwardly therethrough. The detonation should not develop into a high-order detonation nor degenerate into a detonation that has insufficient energy when it reaches the front face of the barrier to initiate a low-order detonation in the main charge of explosive at the forward side of the barrier. Of course, the detonation should not die out in the barrier. The detonation traveling forwardly through the explosively active barrier should reach the front face thereof with only sufficient intensity to initiate a central low-order detonation in the main charge of explosive at the front of the barrier.

As in the case of the inert metal barrier described hereinbefore, the explosively active barrier of the invention has a transverse configuration effective to cause the high-order detonation initiated in the main charge rearwardly of the barrier to travel outwardly through the main charge around the barrier and to appear at the front of the barrier as a peripheral high-order detonation that laterally surrounds the central low-order detonation. Such peripheral high-order detonation converges radially inwardly to meet and merge with the central low-order detonation to provide a single composite detonation front that impinges upon the liner. The central portion of the combined detonation front has an extremely high energy that is much greater than the energy of a conventional high-order detonation front.

The principles of the invention will now be described with greater particularity with reference to FIGURE 3.

The shaped explosive charge perforating unit shown in axial sectional view in FIGURE 3 is in the form of a body of revolution about the horizontal axis. It has a case 30 that is cup-shaped and has an open front end 31. Projecting axially rearwardly of the case is an integral boss 32 providing at the rear thereof a transverse fuse slot 33 through which is passed a conventional detonating fuse 34, such as a Primacord fuse.

The interior of the boss has a forwardly opening cylindrical booster recess 35 separated from the fuse groove 33 by a thin wall 36. The case may be die cast from zinc-base or aluminum-base alloy, or it may be formed of other suitable material such as cast iron or synthetic resin.

Seated within the recess 35 is a cylindrical booster cup 37 containing a booster charge 38. The booster charge may be composed of compressed powdered Cyclonite or other appropriate booster explosive. The rear of the booster is in contact with the thin wall 36 through which it is initiated centrally when the fuse 34 is detonated. At the front end, the booster charge is in detonating relation to the forwardly positioned explosive components of the charge unit.

Immediately in front of the recess 35 is an enlarged recess having a forwardly flaring, conical wall section 39 and a cylindrical wall section 40. A cup-shaped forwardly flaring curved wall 41 adjoins the cylindrical wall section 40 and terminates adjacent the open front end 31 of the charge case.

The main explosive charge consists of three increments. One of these, the base increment 42, is in the form of a disc seated against the front of the booster. The second, an annular increment 43, has an axial cylindrical hole 44 therein, in the rear of which the front portion of the base increment is received. The third, or forward central main charge increment 45, is in the form of a spherical section that is received in the forward end of the cylindrical hole 44. The sides of the annular increment 43 conform to the inner walls of the case as shown in FIGURE 3. The forward faces of the annular increment 43 and the central increment 45 define the shaped charge cavity into which is fitted a liner 46, preferably formed of copper or other conventional liner material. The apex portion of the liner is generally spherical and symmetrical with respect to the longitudinal axis of the charge, and the side walls of the liner have a lesser curvature than the apex portion. The basal rim of the liner engages the interior of the case 30 with an interference fit. The explosive material forming the three increments 42, 43 and 45 is waxed RDX containing 91% RDX and 9% wax.

Fitted in the cylindrical hole 44 of the annular main charge increment 43 is a cylindrical barrier 47. The front face of the barrier conforms to and is in contact with the rear face of the central increment 45 of the main charge, while the rear face of the barrier conforms to and is in contact with the front face of the base increment 42. The sides of the barrier are in contact with the side walls of the hole 44.

The barrier 47 is formed from a pressed mixture of 10% finely divided RDX and 90% finely divided plaster of Paris.

Loading of the shaped explosive charge unit of FIGURE 3 may be accomplished as follows. Initially, a charge of waxed RDX is pressed into the case 30 using a punch having a face of the size and configuration of the rear surface of the liner 46, such charge completely filling the booster recess 35 as well as the enlarged cavity 39, 40 and the interior of the case between the wall 41 and the end of the punch. Such initial pressing is done with a force less than that to be applied in a later stage when the liner is pressed into the case. The punch is withdrawn and the initially pressed charge is drilled to provide the cylindrical hole 44, and to remove explosive from the booster recess 35.

A booster cartridge is then inserted into the recess 35.

In a separate die, having a cylindrical cavity with a diameter equal to the diameter of the hole 44 and a bottom conforming in shape to the shape of the rear portion of the base increment 42, is pressed a sandwich element, including the base increment 42, the barrier 47 and the central increment 45. The pressure used is approximately equal to the pressure used in forming the initial charge in the case 30. The separately pressed sandwich element provides a preform which is inserted in the hole 44 of the annular increment 43. The loading procedure is completed by pressing the liner 46 into the assembly to consolidate the explosive components to final form.

In firing the device of FIGURE 3, the fuse 34 is detonated by a conventional blasting cap (not shown). Detonation of the fuse effects high-order detonation of the booster charge 38 through the thin wall 36. A high-order detonation front travels symmetrically forwardly through the booster charge 38 and initiates a high-order detonation in the base increment 42 of the main charge. The high-order detonation front travels to the outer periphery of the increment 42 to initiate high-order detonation at the rear of the annular increment 43 of the main charge. The annular high-order detonation front travels forwardly through the increment 43 outside of the barrier 47 and, when it reaches the forward edge of the barrier, turns inwardly around the forward edge to converge in the central increment 45 toward the axis. The annular high-order detonation front also advances through the annular increment 43 toward the side wall of the liner 46.

Meanwhile, when the high-order detonation front advancing forwardly through the base increment 42 strikes the rear face of the barrier 47, it initiates in the latter a low-order detonation front that travels forwardly through the barrier at low-order rate. When the low order detonation emeges from the front face of the barrier and enters the main charge increment 45, it initiates therein a central low-order detonation.

Although the path of the high-order detonation around the barrier is substantially longer than the path of the low-order detonation through the barrier, the high-order detonation reaches the increment 45 before the central low-order detonation front initiated therein has had time to expand outside of the increment. The fact that the velocity of the high-order detonation is greater than the velocity of the low-order detonation accounts for this. The converging high-order detonation and the diverging central low-order detonation merge in the increment 45. Thus, there is created in the increment 45 a central zone of intense explosive energy resulting from the merging of the low-order and high-order detonation fronts. The extremely high energy explosion of the central zone blasts the apex portion of the liner 46 forwardly and toward the axis of the charge to form the leading element of the penetrating jet. Such leading element has extremely high velocity.

Impingement of the high-order detonation front in the annular increment 43 against the sides of the liner successively and smoothly feeds the jet with a flow of liner particles of ever decreasing velocity. Thus, the jet formed upon detonation of the unit of FIGURE 3 has a leading element containing a concentrated portion of the liner material moving a high velocity and a slower moving trailing portion containing material from the sides of the liner. The velocities of the elements of the trailing portion of the jet decrease from front to rear.

Referring to FIGURE 4, the shaped explosive charge perforating unit shown therein is similar to the unit shown in FIGURE 3, but differs from that of FIGURE 3 primarily in the shape of the barrier. The barrier of the unit of FIGURE 4 takes the form of a truncated conical body with the larger base facing forwardly and being concave, whereas the barrier of the unit of FIGURE 3 is a cylinder having a concave front face.

As seen in FIGURE 4, the perforating unit has a case 30′ that is outwardly the same as the case 30. It has an axial boss 32′ providing a fuse slot 33′ at the rear. A detonating fuse 34′ is seated in the slot. A booster cartridge, consisting of a cup 37′ containing a booster charge 38′ is fitted in a booster recess 35′. In front of the booster recess, the inner wall 48, which has a conical surface, flares forwardly and merges with the curved wall 41′, the latter being similar to the curved wall 41 of the unit of FIGURE 3.

The main charge 49 has a base section 42′ formed integrally with the annular portion 43′, the latter extending forwardly along the side walls of the case to meet the side walls of the liner 46′. The main charge provides a truncated conical cavity 44′ that flares forwardly to meet the liner along a circular line of intersection 50.

The main charge also includes a spherically shaped forward central main charge increment 45′ in contact with that portion of the liner encompassed by the circular line of intersection 50. The sides of the increment 45′ are in contact with the annular portion 43′ of the main charge.

Filling the space between the generally spherical rear surface of the main charge increment 45′ and the walls of the conical cavity 44′ is a barrier 47′. This barrier is formed from an explosively active composition like that from which the barrier 47 is made.

The perforating unit of FIGURE 4 may be loaded in a manner analogous to that described hereinbefore with reference to FIGURE 3. First the booster cartridge 37′, 38′ is inserted in the booster recess 35′. Thereafter, the main charge 49 is pressed into the charge case, the conical cavity 44′ being formed by an extension on the press punch. The barrier 47′ and central main charge increment 45′ are prepressed together to approximately the desired form and the element so prepared is inserted in the cavity 44′. Thereafter, the liner 46′ is pressed into the case, sufficient pressure being applied to consolidate the explosive components of the charge unit.

In the embodiment of the invention shown in FIGURE 4, the booster charge may be pure RDX, the annular portion 43′ and the central increment 45′ of the main charge may be waxed RDX, and the barrier may be a consolidated mixture of finely divided RDX and plaster of Paris.

One particular perforating unit as shown in FIGURE 4 has an over-all length of 2.187″ as measured from the rear face of the boss 32′ to the open front end of the case, and an inside diameter of 1.698″ at the base of the liner 46′. The base section 42′ and the annular portion 43′ are formed from 17.5 grams of an explosive composition consisting of 91% RDX and 9% wax. The central increment 45′ is formed from 1.5 grams of explosive composition consisting of 91% RDX and 9% wax. The barrier 47′ is formed from 4.1 grams of a mixture consisting of 20% RDX and 80% plaster of Paris.

This perforating unit, when fired against a standard steel-faced, cement filled target with the open front end of the perforating unit placed against the steel face of the target, made an entrance hole of 7/16″ diameter in the steel face of the target and penetrated through the steel and into the cement a total distance of 9¼″.

In a similar firing test employing the same type target and the same type perforating unit, but wherein the composition of the barrier was 30% RDX and 70% plaster of Paris, the entrance hole was 7/16″ in diameter and the depth of penetration was 8¾″.

In a third and similar test, employing a perforating unit wherein the composition of the barrier was 40% RDX and 60% plaster of Paris, the entrance hole meassure 9/16″ x 5/8″ and the depth of penetration was 9″.

In each of the foregoing three tests, no carrot was found in the hole.

Measurements were made of the detonation velocities in several explosive pellets like the barrier 47′ of FIGURE 4, the composition of the pellets being varied. Portions of RDX, having a detonation velocity of 8.1 millimeters per microsecond, were diluted with varying percentages of plaster of Paris and the mixtures used to form the pellets. The measured velocities were found to be as follows:

Pellet composition, percent RDX:	Detonation velocity, mm./sec.
10	3.78
20	4.43
30	5.65
40	6.62

In the type of charge tested, the composition of the barrier may be varied between 10% RDX with 90% plaster of Paris and 50% RDX with 50% plaster of Paris to produce perforations having approximately the dimensions set forth in the foregoing description of the tests.

Comparing the barrier 47′ with the barrier 47, the former has a slightly greater axial thickness and a somewhat greater breadth at the front than does the latter. The mechanism of central low-order and peripheral high-order detonation is analogous, in the increment 45′ of FIGURE 4, to that which occurs in the increment 45 of FIGURE 3. However, in the case of the perforating unit of FIGURE 4, the zone of very high explosive energy that is produced by the merging of the high-order and low-order detonations is somewhat broader than that occurring in the perforating unit of FIGURE 3.

While there have been illustrated and described herein three embodiments of the present invention, it will be apparent to those skilled in the art that various modifications and changes in the shape, material and relative positions of the various components may be made without departing from the essence of the invention. It is intended to cover herein all such modifications and changes as come within the true scope and spirit of the appended claims.

I claim:

1. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly of said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least an axially symmetrical central portion of substantial lateral extent of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

2. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly of said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

3. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means, and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

4. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid metal barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

5. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid steel barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

6. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation there-

in, said charge having a front end and a rear end opposite said front end and being in the form of a body of revolution about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid, disk-shaped barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer periphery of said charge, said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

7. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being in the form of a body of revolution about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid, disk-shaped barrier of steel symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer periphery of said charge, said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

8. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being in the form of a body of revolution about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid, substantially uniformly thick, disk-shaped barrier of metal having a spherical curvature symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer periphery of said charge, said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

9. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier comprising an explosive substance capable of sustaining therein a detonation of an order not greater than low-order, and said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

10. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier comprising an intimate mixture of a finely divided high-explosive substance and a finely divided inert diluent therefor in proportions to render said barrier capable of sustaining therein a detonation of an order not greater than low-order, and said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

11. A shaped explosive charge device comprising: a

charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier comprising an intimate mixture of finely divided Cyclonite and finely divided plaster of Paris in proportions to render said barrier capable of sustaining therein a detonation of an order not greater than low-order, and said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

12. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity, said liner having a rearwardly convex, substantially spherical, apex portion that extends across a wide central area of said charge and side portions extending forwardly and outwardly from said apex portion; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly of said cavity and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least an axially symmetrical central portion of substantial lateral extent of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

13. A shaped explosive charge device comprising: a charge of detonating explosive materal capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being symmetrical about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity, said liner having a rearwardly convex, substantially spherical, apex portion that extends across a wide central area of said charge and side portions of gradually decreasing curvature extending forwardly and outwardly from said apex portion; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a barrier symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly of said cavity, and spaced forwardly from said initiating means and inwardly from the outer surface of said charge, said barrier having a substantially greater width than its axial thickness and having the characteristics throughout at least an axially symmetrical central portion of substantial lateral extent of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

14. A shaped explosive charge device comprising: a charge of detonating explosive material capable of sustaining high-order detonation and low-order detonation therein, said charge having a front end and a rear end opposite said front end and being in the form of a body of revolution about a longitudinal axis extending between said ends, said charge providing a cavity in its front end symmetrical about said axis, said cavity having sidewalls converging to the rear; a liner of inert material lining said cavity, said liner having a rearwardly convex, substantially spherical, apex portion that extends across a wide central area of said charge and side portions of gradually decreasing curvature extending forwardly and outwardly from said apex portion; means for initiating high-order detonation in said charge at the rear end thereof and symmetrically of said axis; and a solid, substantially uniformly thick, disk-shaped barrier of metal having a spherical curvature symmetrical about said axis embedded in said charge, all portions of said barrier being positioned rearwardly from said cavity and spaced forwardly from said initiating means and inwardly from the outer periphery of said charge, said barrier having the characteristics throughout at least substantially its entire width of blocking transmission of high-order detonation-initiating energy forwardly therethrough and transmitting low-order detonation-initiating energy forwardly therethrough to initiate a low-order detonation in the explosive material on the forward side of said barrier in response to high-order detonation of the explosive material at the rear of said barrier, said low-order detonation and the high-order detonation that travels forwardly around the periphery of said barrier merging in the explosive material between said barrier and the rear end of said liner to form a composite detonation wave that attacks said liner.

15. The method of firing a detonating explosive charge having in a face thereof an outwardly opening cavity symmetrical about an axis, said cavity having sidewalls converging to the rear, said charge being capable of sustaining low-order detonation and high-order detonation therein, and said cavity being lined with a liner, which method comprises the following steps;

(a) initiating a low-order detonation in said charge in a zone symmetrical with said axis and spaced inwardly from the inner end of said cavity; and

(b) initiating a high-order detonation in and throughout a second zone in said charge, which zone is located in a plane transverse to said axis, is spaced inwardly from the inner end of said cavity, is positioned symmetrically about said axis, and is disposed around said zone of initiation of low-order detonation, the initiation of said high-order detonation being performed in predetermined time relation to the initation of said low-order detonation to cause the detonation waves resulting from said initiations to merge in a zone located in said charge between said zones of initiation and said cavity to form a composite detonation wave that attacks said liner.

16. The method of firing a detonating explosive charge having in a face thereof an outwardly opening cavity the walls of which are defined by a surface of revolution about an axis, said cavity having sidewalls converging to the rear, said charge being capable of sustaining low-order detonation and high-order detonation therein, and said cavity being lined with a liner, which method comprises the following steps:

(*a*) initiating a low-order detonation in said charge in a zone coaxial with said axis and spaced inwardly from the inner end of said cavity; and

(*b*) initiating a high-order detonation in and throughout an annular zone in said charge, which zone is located in a plane normal to said axis, is spaced inwardly from the inner end of said cavity, is positioned symmetrically about said axis, and is disposed around said zone of initiation of low-order detonation, the initiation of said high-order detonation being

performed in predetermined time relation to the initiation of said low-order detonation to cause the detonation waves resulting from said initiations to merge in a zone located in said charge between said zones of initiation and said cavity to form a composite detonation wave that attacks said liner.

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