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A Brief History of Shaped Charges

by William Walters

ARL-RP-232 **December 2008**

A reprint of the keynote paper from the *24th International Symposium on Ballistics*, vol. 1, pp. 3–10, New Orleans, LA, 22–26 September 2008.

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14. ABSTRACT

This report provides an overview of the history of shaped charge development by consolidating earlier write-ups from several investigators [1–5]. The intent is to educate a new generation of researchers who are not familiar with this material. Most of these documents are now either out of print or hard to find. Since most of these publications originated in the 1980s to early 1990s, a few additions were made based on the discovery of new historical material. The report begins with the early work (prior to the invention of the detonator) and continues to the present. This report chronicles the works of the early researchers, notably Munroe, von Foerster, Newman, Mohaupt, Thomanek, and others.

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A Brief History of Shaped Charges

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This paper provides an overview of the history of shaped charge development by consolidating earlier write-ups from several investigators [1–5]. The intent is to educate a new generation of researchers who are not familiar with this material. Most of these documents are now either out of print or hard to find. Since most of these publications originated in the 1980s to early 1990s, a few additions were made based on the discovery of new historical material. The paper begins with the early work (prior to the invention of the detonator) and continues to the present. This paper chronicles the works of the early researchers, notably Munroe, von Foerster, Newman, Mohaupt, Thomanek, and others.

This brief overview of the development of shaped charges begins with a definition of a shaped charge. In the opinion of the author, a shaped charge is defined as a cylinder of explosive with a hollow cavity at the end opposite the initiation train. If the cavity does not contain a liner, it is referred to as a hollow charge or an unlined-cavity charge. If the cavity contains a liner made from a metal, an alloy, glass, ceramic, wood, or another material, the device is termed a shaped charge or cumulative charge (in the former Soviet Union) or Hohlladung (in Germany). The liner geometry may be conical, hemispherical, parabolic, or any arcuate device. If the liner is "bow shaped" it is called an explosively formed penetrator (EFP). Thus, an EFP also called a self-forging fragment, ballistic disk, P-charge projectile, or Miznay-Schardin device, is also a shaped charge. Shaped charges with conical liners, hemispherical liners, or bow-shaped liners all collapse and form jets and/or slugs in a different manner. Of course, the formed penetrators experience some overlap, i.e., a shaped charge with a truncated hemispherical liner or a shaped charge with a wide angle conical liner may look like an EFP. Walters and Zukas [1] illustrate the formation of shaped charges with various liner geometries and Held, see [1], shows that for conical liners with an apex angle of 150° or greater and for liner wall thicknesses of 1–5% of the liner diameter, the penetrator does not form a slug, but all the liner material flows as a single EFP like penetrator. Also, for very narrow angle conical liners, with very thick walls (an extruded liner), the penetrator resembles the jet from an EFP [1]. Thus, the liner wall thickness profile is critical in terms of discerning the shape of the penetrator.

The term “hollow charge” was apparently coined by A. Marshall in 1920 and the term “shaped charge” was coined in the U.S. during World War II [5].

The petard may have been a forerunner of the shaped charge and was known from the earliest days of gunpowder [5]. The petard consisted of a hood or bell-shaped container with a planar rim at the open end to be applied to the face of the structure to be blasted, and was filled with gunpowder which was set off from the apex end.

The earliest cited reference to the unlined-cavity charge was attributed to Franz von Baader in 1792. F. von Baader focused the energy of an explosive blast using a hollow charge. However, his experiments utilized black powder which is not capable of detonation. Thus, our shaped-charge history will begin after the invention of the detonator by Alfred Nobel in 1867.

The first demonstration of the hollow cavity effect for high explosives was achieved by von Foerster in 1883. G. Bloem of Dusseldorf patented a shell for detonating caps that resemble a shaped charge with a hemispherical liner. This was perhaps the first shaped charge, i.e., utilizing a lined cavity.

The unlined shaped charge was rediscovered by Charles Munroe of the Naval Torpedo Station, Newport, RI in 1888. Munroe popularized the hollow charge concept with several publications. In one of his famous experiments, Munroe detonated blocks of explosive in contact with a steel plate. The explosive charge had the initials USN (United States Navy) inscribed on the charge opposite the initiation point. The initials were reproduced on the steel plate. This is known as explosive engraving and von Foerster conducted similar experiments. Munroe further observed that when a cavity was formed in a cylinder of explosive, opposite the point of initiation, the depth of the crater produced in the steel target increased. In other words, a deeper cavity could be formed in a steel plate using a smaller amount of explosive. The increase in penetration resulted from the focusing of the detonation products by the hollow cavity.

One of the first lined shaped charges (or perhaps the first shaped charge if we discounted Bloem) may be due to Munroe. This device consisted of a tin can with sticks of dynamite tied around and on top of it, with the open end of the tin can pointing downward. It was able to punch a hole through the top of a steel safe. In this case, the tin can served as the liner.

Early German reference to the hollow cavity effect, after von Foerster and Bloem, occurred in 1911–1912 patents in the United Kingdom (U.K.) and Germany by Westfalische Anhaltische Sprengstoff Actien Gesellschaft (WASAG). The WASAG patents clearly demonstrated the unlined-cavity effect and the lined shaped-charge effect. Also, M. Neumann in 1911 and E. Neumann in 1914 (who are often confused in the literature) demonstrated the unlined-cavity effect. M. Neumann shows a greater penetration into a steel plate from a cylinder of explosive with a hollow, conical cavity (247 g of Trinitrotoluol) than from a solid cylinder (310 g of Trinitrotoluol). This clearly illustrates what is known in the U.S. and U.K. as the Munroe effect and in Germany as the Neuman effect. The depth of the crater in the target is increased by utilizing a lined shaped charge and the penetration can be further increased by displacing the shaped charge some optimal distance from the target.

To illustrate this effect, in Germany in 1941 a hollow cavity charge, a lined cavity charge, and a lined cavity charge detonated at a certain standoff distance above an armor plate were compared. The target plate was ship armor steel and the explosive mixture was 50% TNT and 50% cyclonite. The hollow cavity was a hemisphere with a cylindrical extension at its base equal to one-half of the diameter of the cavity (D). The liner was made of iron. The explosive contour was of the same geometry as the cavity, and the explosive thickness at the base of the liner was 0.15 times the cavity diameter. For the unlined hollow charge, the penetration (P) = 0.4 D at zero standoff. For the lined cavity, P = 0.7 D at zero standoff and P = 1.2 D for standoffs between 0.5 and 1.5 D. For the iron-lined shaped charge, D represents the inside diameter of the liner. These formulas are not universal laws, but they illustrate the increase in penetration in going from hollow charges, to lined cavity charges, to lined cavity charges with a nonzero standoff distance.

Sukharevskii was the first known Soviet to investigate the shaped-charge effect in 1925–1926. The first Italian paper on the shaped-charge effect was by Lodati in 1932. Schardin reviewed his work and reported that Lodati did not contribute anything new to the field. The French research on the shaped charge concept dates to 1891 where Lepidi conducted studies with a 155-mm shell which was essentially a shaped charge with a cylindrical liner. The final construction of the shell failed due to trouble with the initiation system. Due to the use of an inadequate time-fuze device, a gun exploded, and the experiments were halted and forgotten.

The U.K. contributions to the field of shaped charges includes the numerous contributions of Evans, Ubbelohde, Taylor, Tuck, Mott, Hill, Pack, and others [4]. In the U.S., the contributions of Watson on percussion fuzes and Wood on self-forging fragments (now called EFP's) were significant. The Watson percussion fuzes, patented in 1925, used a parabola-shaped booster charge with a metal lined hemispherical cavity or "arched shield" to intensify the effect of the booster charge. Watson stated that the lined cavity effect required only one-fifth to one-sixth as much explosive as an unlined booster, and the lined cavity charge would function over a considerable air gap. This fuze was, in effect, a detonator using the shaped-charge principle. R. W. Wood of Johns Hopkins University described what is known today as an EFP. R. Eichelberger, the former director of the U.S. Army Ballistics Research Laboratory (BRL), credited Wood with recognizing the enhancement obtained by metal-lined shaped charges. Also, Payman and Woodhead of the U.K. discussed jets from a cavity in the ends of detonators in 1937. They attributed this jetting process to the Munroe effect.

These early studies of the shaped charge concept, although interesting, had little application until the pre-World War II era. The lined cavity shaped-charge research accelerated tremendously between 1935 and 1950 due primarily to World War II, and the application of shaped charge development during this time frame is somewhat ambiguous in that the British, Germans, and Americans all have made significant claims to the early development of modern lined cavity charges.

The discoverers of the modern shaped charge were Franz Rudolf Thomanek for Germany and Henry Hans Mohaupt for the U.K. and the U.S. Thomanek and Mohaupt independently perfected the hollow charge concept and developed the first effective lined cavity shaped-charge penetrators. Thomanek's early work dates from 1935 to 1939.

Thomanek claimed discovery of the hollow charge lining effect on 4 February 1938. Thomanek's colleagues were von Huttern and Brandmayer. Thomanek presented an account of his shaped-charge studies in his development of hollow charges summary table starting with the 1883 work of von Foerster and ending in 1941. Thomanek [see 1] states that he was employed at the Air Force Research Institute Herman Goering at Braunschweig. Before entering this employ, he submitted a collection of all his prior inventions. Among other things, he suggested evacuating the cavity in the explosive charge, doing this either by directly pumping out a finished projectile, or by inserting a vacuum body into the cavity. Furthermore, the general idea was presented of firing an anti-tank projectile from the shoulder. Until May 1938, he conducted studies on hollow charges for the Air Force, especially tests with the evacuated cavity.

From 1 June 1938, he worked for the Ballistic Institute of the Air Force Academy, Gatow. In accordance with information given by Professor Schardin, he was not allowed to evaluate test results outside of the institute or to have access to patent records without written permission. At the instigation of Professor Schardin and against his own previously formed opinion concerning the effect of the vacuum, Thomanek also worked on tests since 1937 independent of Braunschweig. It was determined here that the liner without a vacuum, in respect to penetration, gave the same increase of effect as the corresponding evacuated liner. Thomanek left the institute on 31 May 1939. On 10 May 1940, hollow charges were used with resounding success at Eben Emael, Belgium.

Mohaupt independently developed and introduced the shaped-charge concept to the U.S. Mohaupt's earliest patent claimed a date of 9 November 1939. He used liner cavity charges to design practical military devices ranging from rifle grenades, to mortars, to 100-mm-diameter artillery projectiles. These devices were test fired at the Swiss Army Proving Ground at Thun, at Mohaupt's laboratory, and at the French Naval Artillery Proving Ground at Gavre. A U.K. commission investigated Mohaupt's device and upon payment of a fee later witnessed test firings. The British officers witnessing the tests surmised that Mohaupt was using the Neumann principle and dropped negotiations because the price was too high [5].

As a result of the Mohaupt demonstration, however, the British reconsidered whether the shaped-charge effect could be introduced into service munitions. The early studies concentrated on a shaped-charge rifle grenade. After about a year's development, it was introduced into British Service in November 1940 as the No. 68 grenade. Thus, the British were equipped with the world's first hollow-charge, anti-tank rifle grenade [5]. The British test results were sent to Washington and negotiations began with Mohaupt. Before divulging any details, he demanded $25,000, which the U.S. Army Ordnance Department did not want to spend. The matter was dropped until Mohaupt came to Washington in 1940 and arranged for a demonstration at Aberdeen Proving Ground (APG), MD. The U.S. Army and Navy recommended acquisition of rights of the invention [5].

The curious fact then came to light that the essential features of this munition had already been offered to the Ordnance Department by Nevil Hopkins, an American inventor. The Ordnance Technical Department had rejected Hopkins' design of a bomb built with a shaped charge because it was not a new idea, citing the WASAG patent of 1911. A few months later, the technical staff learned what the British had already guessed earlier, that Mohaupt's "secret" was no secret. With this knowledge, the Army was able to conclude a contract with Mohaupt at a lower price [5]. The U.S. accepted the program, classified it, and thus excluded Mohaupt from the program but produced the 2.36-in high explosive anti-tank (HEAT) machine gun grenade and the 75- and 105-mm HEAT artillery projectiles in 1941. Later, the machine gun grenade was modified to include a rocket motor and a shoulder launcher and became the bazooka. The bazooka was first used by the U.K. in North Africa in 1941. Incidentally, Leslie Skinner, formerly of APG, has been called the father of the bazooka.

Allied researchers entered Germany near the end of World War II to study and recover German technology. They discovered flash x-rays showing the collapse and formation of shaped charges with conical and hemispherical liners. Various other liner geometries were studied, including helmet-shaped liners, bottle-shaped liners, and ellipsoidal liners. The effect of varying the cone angle, wall thickness, and standoff distance was studied for various shaped charges. Also, the effect of tapering the liner with respect to thickness was studied. The Germans concluded that 60/40 cyclotol (a RDX-TNT mixture) was the optimum explosive fill for shaped charges, and aluminized explosives provided no additional advantage. The liner materials studied were steel, sintered iron, copper, aluminum, and zinc. It was realized that copper was the best liner material, but due to the shortage of copper in Germany, zinc liners were used instead. Other studies involved standoff distance effects, explosive lenses, wave shaping, and hemispherical liners. One study concluded that the hemisphere was an effective shaped-charge liner geometry (actually a hemisphere with a cylindrical extension on its equator).

Other designs included the Schwere Hohlladung or heavy shaped charge (SHL). The SHL 500 was a 65-cm-diameter shaped charge used against light ships. The SHL 1000 was apparently an improvement to the SHL 500. The largest SHL of this series was called the Beethoven and had a diameter of 180 cm with 5000 kg of explosive. The Beethoven was designed for use against ships and ground fortifications and was the forerunner of the MISTEL (mistletoe) I and MISTEL II. The MISTEL concept used a fighter aircraft mounted piggyback on the top of a large bomber aircraft. The unmanned bomber carried the MISTEL warhead in its nose. The warhead consisted of a 2-m-diameter, wide-angle, conical-shaped charge. It is speculated that the liner had a 120° apex angle, was about 30 mm thick, and made of either aluminum or mild steel. The warhead weighed 3500 kg with an explosive weight of 1720 kg. The fighter pilot flew the combination to the target, aimed it, released it, then returned to his base. The Germans developed this device near the end of World War II, and most were captured intact.

The Germans were also instrumental in transferring shaped charge technology to the Japanese. There is no evidence of hollow charge research in Japan before May 1942. At that time, two German officers, Col. Paul Niemueller and Maj. Walter Merkel, provided Japan with data and samples of the German 30- and 40-mm hollow charge rifle grenades. The Japanese officials involved were Lt. Col. Yoshitaka, the Japanese liaison officer for the Germans and Col. A. Kobayashu, an explosives expert in Tokyo. Other notable Japanese researchers were Futagami, Naruse, Nasu, Nagaoka, Nakiyama, and Lt. Gen. Kan. The shaped charges were presented as a highly secret and valuable project, and the Germans and Japanese continued to exchange shaped-charge data until the cessation of hostilities in 1945. Also, the Japanese instigated a research and development program of their own, and additional shaped-charge designs were received from Germany. These designs included the panzerfaust and the MISTEL. From the MISTEL, the Japanese developed the large SAKURA Bombs I and II for kamikaze plane attacks against warships.

In addition to captured U.S. and U.K. ammunition, and the information received from Germany, the Japanese did considerable independent research on shaped charges. This research included gas flow and gas velocity from an unlined hollow charge; the jet velocity from a lined hollow charge; penetration versus standoff distance studies; hollow charge liner geometries varying from conical to hemispherical caps; various liner materials including mild steel, copper, aluminum, zinc, asbestos, molded Bakelite, tin, and paper; recovery of jet particles in sand; and dynamic (missile) effects. The Japanese preferred laminated liners (three to seven sheets) over a single, homogeneous liner of the same thickness. The Japanese also concluded that a hole in the apex of a conical or hemispherical liner was desirable. Also, the size of this hole was critical, an optimal value for the apex hole diameter being 1/10 of the warhead charge diameter. (The wall thickness was taken as 1/25 of the charge diameter and the liner diameter was taken to be 4/5 of the charge diameter for both conical and hemispherical liners.) The optimal cone apex angle was determined to be between 35° and 50°. The optimal open apex diameter was concluded to be 3/16 of the charge diameter for this warhead.

Tapered liners were designed based on the 30–40-mm German rifle grenades. They used 19° conical steel liners tapered from 0.5 mm at the apex to 1.0 mm at the base. Other projectiles used constant wall thickness, laminated liners. The Japanese also developed 18- and 21-in-diameter torpedoes using a tapered wall with a 45° conical steel shaped-charge liner with an open apex.

Other Japanese studies related to detonation physics and methods of focusing the gas flow, calculation of the target hole volume and penetration, penetration of concrete targets, and the recovery of jet particles by reducing the explosive power (mixing dynamite with starch to reduce the “strength” of the dynamite), and capturing the jet in sand.

The explosive charges used in their research were spherical and formed from the arcs of two circles. Thus, the cross section of the charge looked like a new moon, quarter moon, and so on, depending on the two radii used. Cylindrical, tapered, and boat-tailed explosive geometries were also studied as well as the effect of the high-explosive head height and the length-to-diameter ratio of the charge. In fact, the height of the charge was varied from one-half of a charge diameter to 6 charge diameters. A charge height of 1.5–2 charge diameters was concluded to be optimal for a 80-mm-diameter charge with a 64-mm-diameter soft iron, hemispherical liner and with a 2.5-mm-thick wall.

Futagami tested two-dimensional charges, i.e., a flat, disk-shaped charge confined between two lead plates. Tests of this nature were used to evaluate various liner geometries, cone apex angles, liner wall thickness effects, and the effect of the diameter of the open apex region. All of these effects, including standoff distance studies, were also investigated with three-dimensional shaped charges. Futagami also studied bimetallic liners of soft iron and copper (the iron was in contact with the explosive). The Japanese also observed that a cavity between the liner and the explosive reduces the penetration capability of the warhead.

The Japanese antitank shells, although not as effective as those developed by the Allies or the Germans, were used effectively in Burma. Other Japanese inventions included the suicidal "Lunge" mine, which was in fact a shaped charge with a wooden handle used as an antitank weapon [2].

The U.K. conducted research in the shaped area in the 1940s with studies by Tuck, Monro, Evans, Ubbelohde, Leonard-Jones, Devonshire, and Andrew. Many liner materials were studied including Cadmium.

Shaped-charge development, based on the early work of Mohaupt, was continued in the U.S. by the DuPont Company, the Hunter Manufacturing Company, the Dobbins Manufacturing Company, the Hercules Powder Company, the Atlas Powder Company, and the Corning Glass Company. Research was conducted by DuPont and the Eastern Laboratory at Gibbstown, NJ. Demolition charges such as the M1, M2A3, M3, M3A, and others, were tested at APG in 1942 and developed by the corporations already cited.

In addition to the fundamental studies performed in 1941 at the Eastern Laboratory (DuPont), parallel studies were undertaken by the Eastern Laboratory and Division 8, National Defense Research Committee (NDRC), Bruceton, PA. The chief NDRC scientists were G. Kistiakowsky, D. MacDougall, S. Jacobs, and G. Messerly.

At the same time, E. M. Pugh organized a group at the Carnegie Institute of Technology (CIT). Following the war, CIT took over the NDRC facilities at Bruceton. The Carnegie group employed some outstanding researchers who contributed much of the current shaped charge knowledge. The leaders at CIT were Heine-Geldern, N. Rostoker, E. Pugh, and R. Eichelberger.

In addition to the work at CIT, important postwar contributions to shaped charge research were made by L. Zernow and associates at BRL. Other laboratories making important contributions during this time period were the Naval Ordnance Laboratory, MD (Solem and August), the Naval Ordnance Test Station, CA (Throner, Weinland, Kennedy, Pearson, and Rinehart), Picatinny Arsenal, NJ (Dunkle), the Stanford Research Institute, CA (Poulter), and others.

The shaped-charge principle was clarified and understood as a result of the pioneering flash x-ray photographs taken in the US by Seely and others, and in the U.K. by Tuck. Schumann and Schardin obtained similar flash radiographs in Germany in 1941. It is debatable as to who took the first flash radiograph. Note that flash radiographs (or x-ray photographs) are necessary since ordinary photographs are uninformative due to the smoke and flame associated with the detonation.

Schardin and Thomer published excellent flash radiographs of collapsing shaped charges with hemispherical liners. These x-ray photographs clearly depict the collapse of the hemispherical liner (as it turns inside out from the pole) and illustrates the “pinch-off” effect as the equatorial region of the liner collapses on the jet. The liner was truncated from the equator to remove this pinch-off. These phenomena were rediscovered some 30 years later.

Also, Linschitz and Paul experimentally studied conical lined shaped charges in different stages of collapse. Hand-tamped nitroguanidine of various densities was used as the explosive fill to achieve a partial collapse of the liner. The conical liner was recovered in water after a partial deformation, the degree of liner deformation (or collapse) corresponding to the density of the explosive fill. The recovered liners showed excellent agreement with the flash x-rays. Based on the analysis of the flash x-ray data and the partial collapse studies, analytical models of the collapse of a lined conical shaped charge were developed and verified by Birkhoff, Evans, Tuck, and Pugh, Eichelberger, and Rostoker.

Shaped-charge theory continued to develop during the 1950s, boosted by the Korean War. During this time period, tremendous progress was made toward understanding the phenomena associated with shaped-charge jets. Efforts were made to improve existing shaped-charge warheads and to enhance the overall system performance.

Starting in the 1950s–1960s, significant shaped-charge developments were made possible by the perfection of experimental techniques such as high-speed photography and flash radiography. Other advances stemmed from the development of large computer codes to simulate the collapse, formation, and growth of the jet from a shaped-charge liner. These codes provide, for the most part, excellent descriptions of the formation of the jet.

Currently, shaped-charge research continues in order to devise a successful countermeasure to the advanced armors currently fielded or contemplated. Studies that originated in the 1930s–1950s still continue; notably, torpedo applications of shaped-charge rounds, anti-aircraft rounds, fragmentation rounds, and other devices using shaped charges. Many of these improvements and research activities are well documented, for example, in the present and past symposia on ballistics.

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1	INTRNTL RSRCH ASSOC D ORPHAL 4450 BLACK AVE PLEASANTON CA 94566-6105
1	TELEDYNE RISI INC J VAROSH PO BOX 359 TRACY CA 95378

ABERDEEN PROVING GROUND

33	DIR USARL AMSRD WM J SMITH AMSRD WM M R DOWDING AMSRD WM T P BAKER AMSRD WM TA M BURKINS W GOOCH T HAVEL M KEELE J RUNYEON AMSRD WM TB R EHLERS R BANTON AMSRD WM TC G BOYCE AMSRD ARL SL R COATES

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	T FARRAND S SEGLETES T EHLERS R MUDD K KIMSEY L MAGNESS D SCHEFFLER S SCHRAML B SORENSEN R SUMMERS C WILLIAMS AMSRD ARL WM BC R ANDERSON A TANK W WALTERS (5 CPS) AMSRD ARL WM TD T W BJERKE E RAPACKI M RAFTENBERG