# An Overview of the Shaped Charge Concept

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## 1. Executive Summary

The collapse, formation, growth, and penetration of a jet from a shaped charge liner results in extremely high strains (>10), strain rates ($10^7$/s), hydrostatic pressures (up to 200 GPa), and surface temperatures (500-600 C). The tip velocity of the jet usually exceeds Mach 25 in air. However, the flow velocity during the collapse process must remain subsonic (with respect to the liner bulk speed of sound) during the jet collapse process to guarantee that the jet is coherent. This paper describes the shaped charge concept and presents the many applications of shaped charges. Finally, several topics of current research in the shaped charge field are discussed.

## 2. Introduction

A cylinder of explosive with a hollow cavity in one end and a detonator at the opposite end is known as a hollow charge. The hollow cavity, which may assume almost any axis-symmetric geometric shape such as a hemisphere, cone, ellipse, tulip, trumpet, dual angle cone, pyramid, or the like, causes the gaseous products formed from the initiation of the explosive at the end of the cylinder opposite the hollow cavity to focus the energy of the detonation products. The focusing of the detonation products creates an intense localized force. This concentrated force, when directed against a metal plate, is capable of creating a deeper cavity than a cylinder of explosive without a hollow cavity, even though more explosive is available in the latter case. This phenomenon is known in the U. S. and Britain as the Munroe effect and in Europe as the von Foerster or Neumann effect. Von Foerster was the true discoverer of the modern hollow charge.

If the hollow cavity is lined with a thin layer of metal, plastic, ceramic, or similar materials, the liner forms a jet when the explosive charge is detonated. Upon initiation, a spherical wave propagates outward from the point of initiation for the basic case of a single point initiated charge, initiated along the axis of symmetry. This high pressure wave moves at a very high velocity, typically around 8 km/s. As the detonation wave engulfs the lined cavity, the liner material is accelerated under the high detonation pressure, collapsing the liner. During this process, for a typical conical liner, the liner material is driven to very violent distortions over very short time intervals (microseconds) at strain rates of $10^4$ to $10^7$ /s. Maximum strains greater than 10 can be readily achieved

since superimposed on the deformation are very large hydrostatic pressures (peak pressures of approximately 200 GPa ( 30 million psi), decaying to an average of approximately 20 GPa).  The collapse of the liner material on the centerline forces a portion of the liner to flow in the form of a jet where the jet tip velocity can travel in excess of  10 km/s ( 22,370 mph).  The conical liner collapses progressively from apex to base under point initiation of the high explosive.  A portion of the liner flows into a compact slug (sometimes called a carrot), which is the large massive portion at the rear of the jet.  Slugs constitute 80 to 85% of the jet mass and typically travel at about 1 km/s.  The pressures generated during the liner collapse far exceed the yield strength of the liner material and thus the liner behaves approximately as an inviscid, incompressible fluid!

Due to the presence of a velocity gradient, the jet will stretch until it fractures into a column of particles.  Jet breakup or particulation occurs at the peal penetration.  Once the jet has particulated, the individual particles are no longer perfectly aligned and usually result in side wall collisions with the previously formed crater and do not act to increase the penetration depth.  Thus, the total length of the jet does not contribute to the penetration process. That is, the rearward jet particles never reach the crater bottom.  For this reason, it is advantageous to design shaped charges in which the resulting jets remain continuous as long as possible in order to increase the long standoff performance.  The standoff is the distance between the front of the shaped charge (the liner base) and the target.

When this extremely energetic jet strikes a metal plate, a deep cavity is formed, exceeding that caused by a hollow charge without a liner.  Peak pressures in the metal plate of 100-200 GPa are generated, decaying to an average of 10-20 GPa.  Average temperatures of 20-50 % of the melt temperature of the target material and average strains of 0.1 to 0.5 are common.  The jet surface temperature is around 500-600 C for a copper jet.  Localized temperatures and strains at the jet tip can be even higher.  The penetration process occurs at strain rates of $10^6$  to $10^7$/s.  The cavity produced in the metal plate due to this jet-target interaction is due not so much to a thermal effect but to the lateral displacement of the target armor by the tremendous pressures created.  The target material is actually pushed aside or compressed and the penetration is accomplished with no change in the target mass, neglecting any impact injecta or vaporization of the front plate and neglecting any spall from the rear surface of the target.  Thus, with due consideration to the caveats mentioned above, a perforated plate weights the same as the pre-impact or virgin plate!

The cavity formed becomes deeper yet when the explosive charge containing the liner is removed some distance away from the plate.  There is an optimum standoff distance which varies with the liner and charge design.  Devices of this nature are called lined cavity charges or shaped charges.

Detailed discussions of the shaped charge concept and an extensive list of sources (too numerous to list here) are available elsewhere, e. g., [1], [2], [3], [4].  This concept is not well understood by people outside the warhead community.  For example, the jet is not a "cutting plasma", it is not a liquefied or molten metal jet, the cone does not impact the

armor intact, the jet temperature is not 20,000 C, and the density of the jet is not several times that of steel, and the jet does not burn its way through armor, as reported in many newspaper, TV, and even semi-technical journal articles.  Some confusion may arise due to the fact that shaped charge devices are sometimes called HEAT rounds.  HEAT is an acronym for High Explosive Anti-Tank and does not relate to thermal effects [4].

The purpose of the remainder of this paper is to discuss the application of shaped charges and to highlight a few topics in modern shaped charge research.

## 3. Applications of Shaped Charges

Shaped charges are extremely useful when an intense, highly localized force is required for the purpose of piercing a barrier.  The shaped charge is employed for assorted peaceful purposes in the petroleum industry.  In fact, the oil well industry is the major user of shaped charges.  Corporations such as Schlumberger, Halliburton, Baker Atlas and others manufacture and shoot millions of shaped charges a year, all over the world. In the oil well industry, large diameter, but extremely short, lined shaped charges are used to penetrate various geological formations to increase the flow of oil. Increasing the flow of oil, natural gas, or the like, is necessary since it costs about a million dollars per mile to drill oil wells.  Oil well completion tasks present extremely difficult design problems due to the minimal amount of allowable space available in the well, the short standoff distances required, the fact that multiple charges must not interfere with each other, the debris must be controlled, and the hostile environment within the well.

Another application is in the military arena including torpedoes, missiles, high explosive anti-tank (HEAT) rounds including hand held (bazooka type) rounds, gun launched rounds (e.g., rifle grenades), cannon launched rounds, and various bombs. The targets are armors, bunkers, concrete or geological fortifications, and vehicles. Attacks against aircraft and spacecraft are possible. Underwater applications (torpedoes) are possible.  A torpedo is essentially a shaped charge designed to function under water.

The largest known shaped charge was the German MISTEL. The MISTEL (mistletoe) concept used a fighter aircraft mounted piggyback on the top of a large bomber aircraft. The unmanned bomber carried the MISTEL warhead in its nose. The warhead consisted of a 2-meter diameter, wide-angle, conical shaped charge. The warhead weighed 3,500 kg with an explosive weight of 1,720 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 of them were captured intact. The Japanese used a scaled version of the MISTEL, called the SAKURA bomb, for kamikaze attacks against warships.

Zwicky, see [1], proposed the use of a shaped charge as a method of producing artificial meteorites in 1947. He proposed launching a hypervelocity shaped charge on a V-2 rocket to exceed the earth's escape velocity and thus create an artificial meteorite. Since the shaped charge liner could be fabricated from nickel, iron, or other metals, one could observe the signature of say, nickel or iron, entering the Earth's atmosphere. Also, the hypervelocity jet particles could be tracked to study hypersonic aerodynamic effects. In addition, the experiment could be designed to allow the jet to impact a heavenly body,

such as the moon. A spectroscopic analysis of the impact flashes would reveal the elementary chemical constituents of the moon's surface. Shaped charges were used to simulate micro meteorite impact on spacecraft.

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

Also, spin compensated liners may be used, especially when associated with spinning warhead applications. Gun fired projectiles are spun in flight to provide aerodynamic stability. Spin compensation (i.e., causing the jet to spin enough and in the right direction to compensate for the spin of the warhead) may be achieved by metallurgical spin compensation or by the use of fluted liners. Metallurgical spin compensation is achieved by introducing anisotropies or residual stresses into the liner during the fabrication process in order to provide rotation of the jet. Fluted liners contain raised ridges (or panels which are offset with respect to the normal to a radius) either on the outside or the inside surface of the liner. The flutes allow the jet to form with a given angular momentum to compensate for the rotation of the warhead in flight.

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

Another application of shaped charges is in demolition work. This area has both military and industrial application. Buildings, bridges, railroad tracks, aircraft runways, and other structures are the common demolition targets. The shaped charge principle is also used in construction work to break, crack, or drill holes in rock. A technique known as mudcapping is sometimes used to break rock and usually utilizes an unlined hollow charge. Shaped charges have also been used in construction as earth movers, in tunneling, or to assist in well drilling.

Shaped charges are also used in tapping steel mill furnaces, as a source of earth waves for geophysical prospecting and seismic exploration, mining (surface or underground), quarrying, in salvage operations, boring holes in demolition work, breaking large rocks, and for hypervelocity impact studies. Other applications occur in submarine blasting,

breaking log jams, breaking ice jams, initiating avalanches, timber or tree cutting, the perforation of arctic sea-ice or permafrost, glacier blasting, ice breaking, hole drilling, posthole digging, and underwater demolition.

Shaped charge liners are not always made of glass or metals, e.g., the Naval Proving Ground describes a shaped charge with a liner made of balsa wood. In fact, liners have assumed a multitude of geometric shapes, and have been made from common and exotic metals, alloys, eutectics, ceramics, plastic, paper, rubber, etc.

Another application of the shaped charge is in the internally coned end of certain detonators. This indented, lined cavity acts to concentrate the effect along the axis. In fact, Gustov Bloem in 1886 patented a shell for detonating caps which resembles a shaped charge with a hemispherical liner. Also, the Munroe effect is used to engrave or stencil letters and other designs onto metal plates. Munroe's discoveries date from 1888 and are well documented [1]. Munroe detonated blocks of explosive in contact with steel plates. The explosive charge had the initials U.S.N. (United States Navy) inscribed on the charge opposite the point of initiation. These initials were reproduced on the steel plate. Also, one of the first lined shaped charges was devised by Munroe. This device consisted of a tin can (the liner) with sticks of dynamite tied around and on top of it, with the open end of the tin can pointing downward. It was used to punch a hole through the top of a steel safe.

Linear (wedge-shaped, V-shaped, or W-shaped) shaped charges are used as cutting charges. They generate a ribbon shaped jet used to cut metals and other materials. Commercial cutting charges are available from several sources. For cutting charge applications, it is sometimes advantageous to use homemade cutting charges which can be optimized to the particular problem on hand. Cutting charges and hollow charges are also used as explosive separation devices, as bolt cutters, and for other applications. The shaped charge effect is used on systems for separation, deployment, and safety destruct devices in missiles and spacecraft.

Additional applications relating to explosive metal interactions, which require an understanding of the jet formation phenomena, are explosion welding, explosion cladding, or explosion forming of metal parts.

## 4. Current Research on Shaped Charges

Many efforts have been made over the years to understand the process of jet formation regarding the various modes of jet formation, i.e., formation of jets from conical, hemispherical, and EFP (Explosively Formed Penetrator) liners. The flow near the collision region in the jet formation process for moderate apex angle conical shaped charge liners, i.e., when the liner material splits into a jet-slug flow, can be analyzed by the PER (Pugh-Eichelberger-Rostocker) theory [1]. The PER equations provide a very good prediction for most of the jet parameters for conventional conical liners. With modifications, the PER model can predict jet characteristics for near-conical liners, e.g., trumpet shapes. An analogous analytical model for hemispherical or elliptical liner geometries, for dish shaped (EFP) liners, and for other non-standard geometries (pyramid

shapes, cylindrical shapes, etc.) is needed. The jet collapse and formation process is different for these liner geometries especially regarding the jet-slug partitioning. Also, most metals, except those that are extremely expensive, rare, or toxic, have been tested as shaped charge liner materials. Many alloys have also been tested. With few exceptions, the pure metals out perform the alloys in terms of jet quality and performance (penetration). Jet quality implies a ductile jet, i.e., a jet with smooth, not 'jagged" (or non streamlined) particles that neck gradually prior to breakup. Ductility, or smooth breakup under ambient conditions, does not necessarily imply ductility under the intense dynamic jet conditions, e.g., aluminum. The converse is also true. Molybdenum is brittle at room temperature, but very ductile under the extreme collapse conditions. Why do alloys not perform as well as pure metals (with a few exceptions)? Along these same lines, it is known that fine grain liner materials perform better than coarse grain materials. What is the optimum grain size (for materials other than copper, where fine grain liners perform better than coarse grain liners [5])? What is the preferred grain orientation/texture? What about metal purity? Note that determining the optimal microstructure and mechanical properties for the liner would determine the preferred fabrication method.

The explosive fill used in military shaped charges has progressed from TNT to COMP B to OCTOL (all cast explosives) to a pressed explosive, LX-14. In the near future, CL-20 may be used. Should the grain size of the explosive components be fine or coarse to match the grain size present in the liner? Studies are underway to increase the efficiency of the jetting process and to control (optimize) the explosive-metal interface. Of course, studies are underway to develop insensitive munitions or safer military explosives.

Another area of interest is jet particulation or breakup. Can one predict the necking and fracture process of a hypervelocity jet stretching due to its velocity gradient? If the breakup/necking process can be modeled, perhaps it can be controlled.

Other areas of interest are scaling. Typically, shaped charges can be scaled (homologous scaling) over a charge diameter range of about 1.5 inches to 7 inches. For small charges, the precision/tolerance requirements are hard to achieve and the detonation physics involved does not scale. For large charges, the liner metallurgy is harder to control and the explosive loading is more difficult (may have to be done in stages). Are other, not homologous, scaling laws possible?

Efforts are underway to obtain relatively simple analytical formulas to predict penetration explicitly as a function of time to provide fast answers to penetration predictions. The same is true of hole size and hole growth models. These models must be accurate for a multitude of jet-target configurations.

Finally, the jet temperature is in general unknown and its prediction by hydrocodes (large computer codes) is difficult and driven by the constitutive equation and equation of state

used in the calculation.  In a classic experiment von Holle and Trimble, see [1], measured the surface temperature of a copper liner near the tip and concluded the jet surface temperature was around 500 C, as mentioned earlier.  They developed their temperature measurement technique for shocked materials based on two-color infrared radiometry.  However, the use of only two colors (wavelengths) indicates that the measured results are not as accurate as they would be if more colors were obtained.  Also, some uncertainty occurs in the determination of the emissivity.  Experiments such as this should be continued/repeated with better instrumentation.  What is the gradient of temperature, tip to tail, for a shaped charge jet?  Recovered jet particles and slugs indicate regions of at least localized melting.  What is the interior temperature of the jet?  How could one measure this temperature?

## 5. Conclusions

The shaped charge concept, oft misunderstood, was explained along with the prevalent dynamics associated with materials subjected to high pressure, high velocity, high strain, high strain rates, and high temperature.  In addition, the various and sundry applications of the shaped charge principle were elucidated.  Finally, a few, but not all, areas of interest in shaped charge research were briefly discussed.

## 6. References

[1]  Walters, W. P. and Zukas, J. A., *Fundamentals of Shaped Charges,* Wiley, New York, NY, 1989 and soft cover edition (with corrections), CMC Press, Baltimore, MD, 1998.

[2]  Zukas, J. A. (ed.), *High Velocity Impact Dynamics,* Wiley, New York, NY, 1990.

[3]  Walters, W. P., "Application of the Shaped Charge Concept", *Journal of Explosives Engineering,* Vol. 8, No. 5, Jan.-Feb. 1991.

[4]  Kennedy, D. R. "History of the Shaped Charge Effect, the First 100 Years", U. S. Department of Commerce, AD-A220 095, 1983.

[5]  Dante, J. G. and Golaski, S. K., "Micrograin and Amorphous Shaped Charge Liners", *Proceedings of ADPA Bomb and Warhead Section,* White Oak, MD, May 1985.

# An Overview of the Shaped Charge Concept
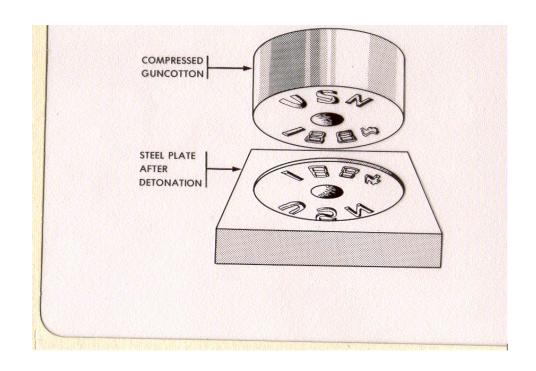
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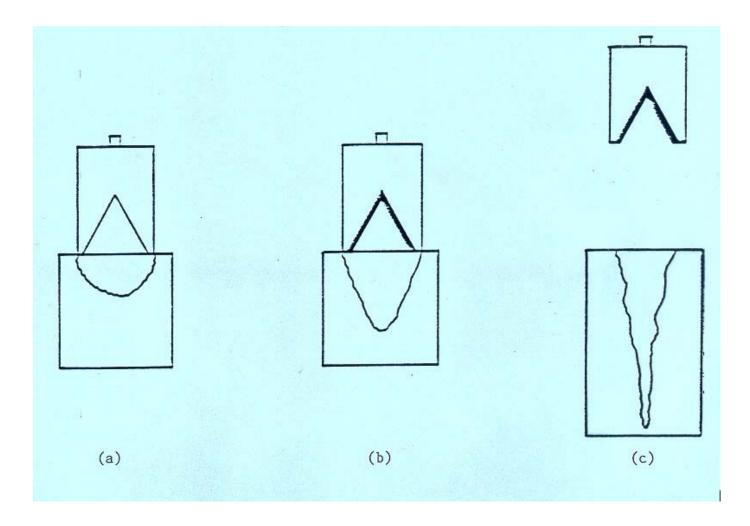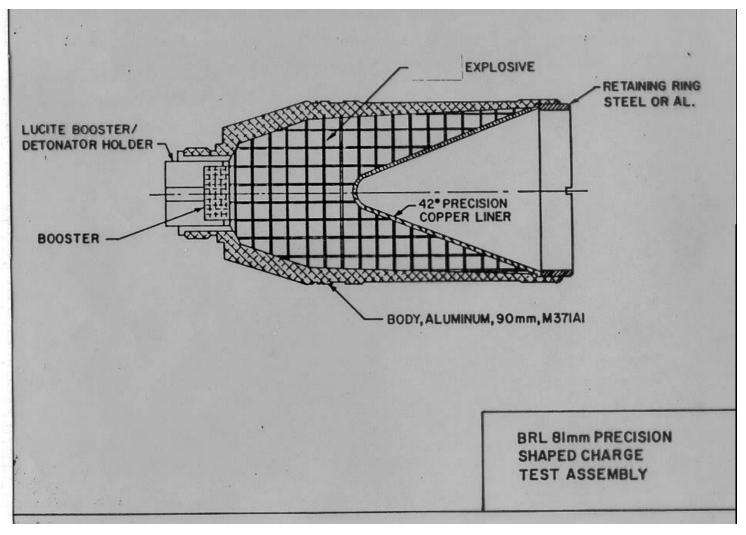
# The Munroe Effect

# The Monroe Effect
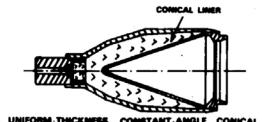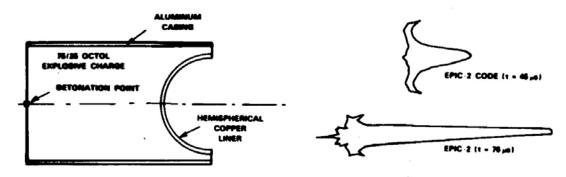


(a)          (b)          (c)

# BRL 81 mm Shaped Charge



EXPLOSIVE

RETAINING RING
STEEL OR AL.

LUCITE BOOSTER/
DETONATOR HOLDER

42° PRECISION
COPPER LINER

BOOSTER

BODY, ALUMINUM, 90mm, M371AI

BRL 81mm PRECISION
SHAPED CHARGE
TEST ASSEMBLY

# Shaped Charge Liner Geometries



a) UNIFORM-THICKNESS, CONSTANT-ANGLE CONICAL LINER DESIGN
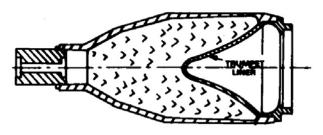
b) UNIFORM-THICKNESS, HEMISPHERICAL LINER DESIGN
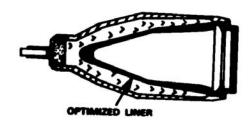
c) UNIFORM-THICKNESS, TRUMPET LINER DESIGN
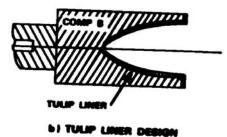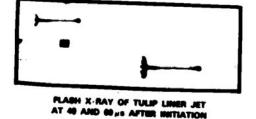
# Shaped Charge Liner Geometries
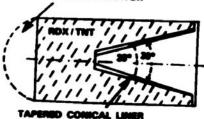


a) OPTIMIZED LINER DESIGN

OPTIMIZED LINER

COMP B

TULIP LINER

b) TULIP LINER DESIGN

FLASH X-RAY OF TULIP LINER JET
AT 40 AND 60 µs AFTER INITIATION

PLANE WAVE INITIATOR

RDX / TNT
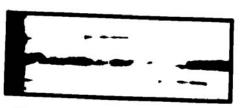
TAPERED CONICAL LINER

c) TAPERED CONICAL LINER DESIGN
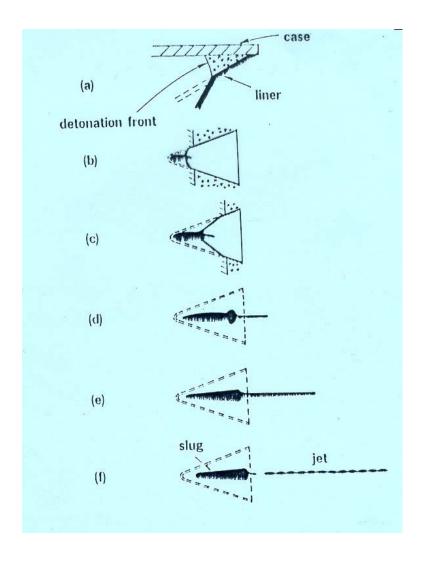
FLASH X-RAY OF TAPERED CONICAL LINER JET
WITH RDX 40/TNT 60 AT 33 AND 43 µs
AFTER INITIATION
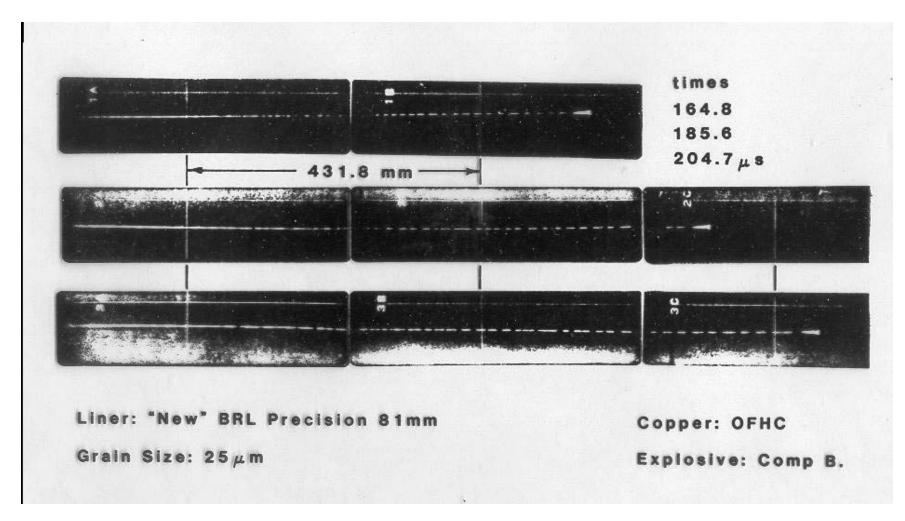
# Calculated Jet Collapse
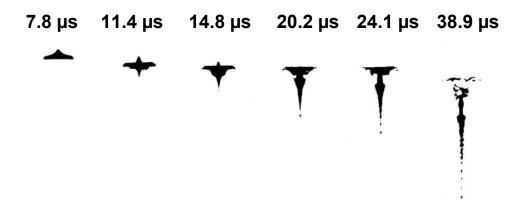
# Experimental Jet Collapse

7.8 µs    11.4 µs    14.8 µs    20.2 µs    24.1 µs    38.9 µs

# Jet From a Conical Liner



times
164.8
185.6
204.7 μs

431.8 mm

Liner: "New" BRL Precision 81mm
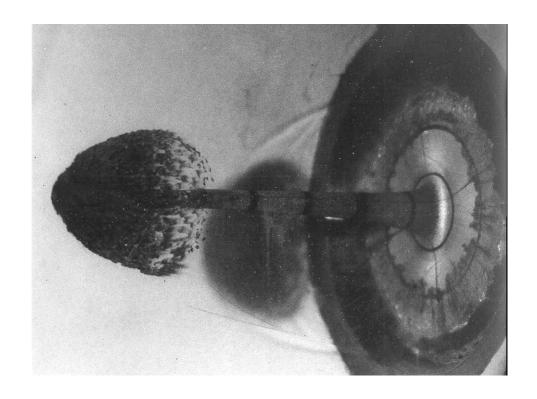
Grain Size: 25 μm

Copper: OFHC

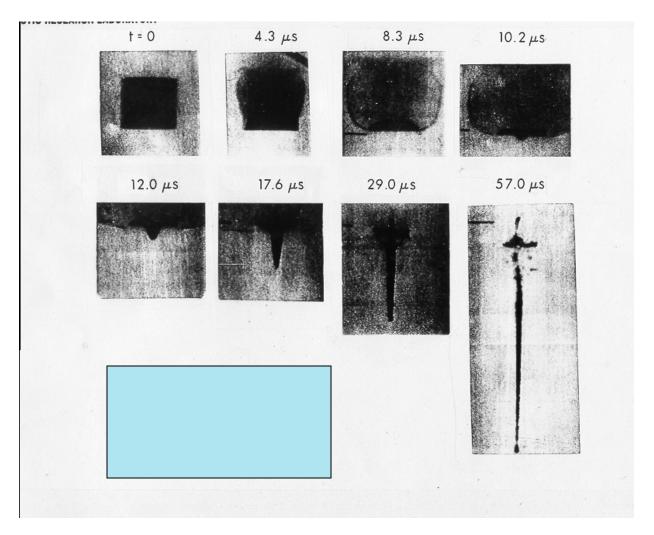Explosive: Comp B.

# **Early Stages of Jet Formation**

# Collapse of a Hemispherical Liner

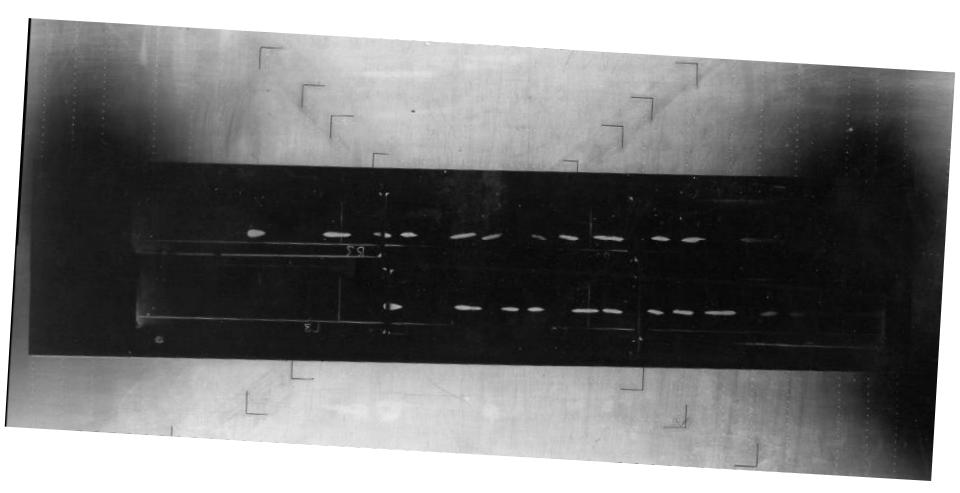# Hemi Jet Free Flight

# **Shaped Charge Characteristics**

- Tip Velocity of > 10 km/s

- Maximum Strains > 10

- Pressure 200 GPa decaying to 20 GPa

- Strain Rates $10^4$-$10^7$ /s

- Jet Temperature 400-500 C

# **Misnomers**

- "On impact, the shaped charge within the round ignites and begins to play a stream of plasma on the target.  Each shaped charge configuration has an optimum distance from the target where the cutting power of the plasma cone is greatest. This detonation distance is established by the length of the warhead tip.  The plasma cone burns through the armor and sprays molten particles into the tank at speeds of 30,000 fps."

# More Misnomers

- "A shaped charge detonates on impact, liquefying metal, which melts the tanks armor."

- "The jet is a high temperature plasma (about 20,000 C)"

- "The jet reaches a density several times that of steel, and the armor becomes plastic and yields whilst the jet torch assists by melting and burning the armor metal"

# The Solution

"There Is No Problem That Can't Be Solved by the Proper Application of High Explosives"

Sign in the office of Dr. J. Carleone,

Vice President, Aerojet Corporation.

# Shaped Charge Applications

Military Targets

Demolition/Construction Work

Aerospace

Oil Well Completion

Steel Mill Furnace Tapping

Glacier Blasting, Tree Cutting, Hole Drilling

Explosive Engraving

Cutting Charges, Safety Destruct Systems

And Many More ....

# More Applications

- Earth  Waves for Geophysical Prospecting and Seismic Exploration
- Mining
- Submarine Blasting
- Ice Breaking
- Breaking Log Jams
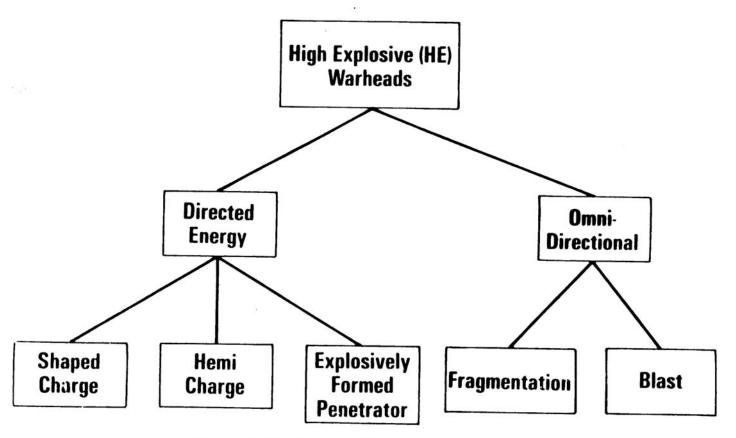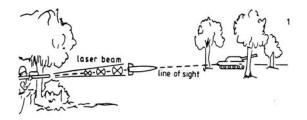- Salamander Blasting
- Coned End of Detonators

# The Warhead Family
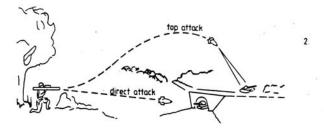


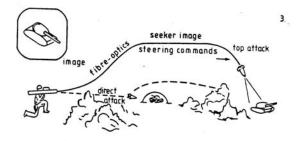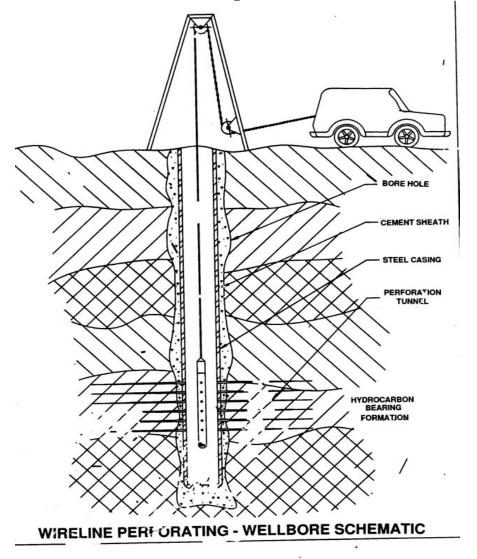Figure 1-1. The Family of High-Explosive Warheads.

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# Anti-Armor



The medium-range weapon can be guided onto the target by means of a laser beam (laser beam rider) as in no. 1. The fire & forget principle, on the other hand, gives more freedom to the gunner. In concept 2 this is realized by means of a lock-on before launch via an infrared image of the target on a socalled focal plane array semiconductor sensor. Direct attack and top-attack are optional, the latter having greater kill probability. If a fibre optic link with the weapon is maintained the gunner can still intervene during the flight (no. 3).

# Oil Well Completion Methods



WIRELINE PERFORATING - WELLBORE SCHEMATIC

# Current Research Topics

- Jet formation and growth models for non-conical liner geometries

- Liner Material Studies—Alloys?

- Liner metallurgy—Grain Size, Texture

- Jet Particulation

- Control of HE—Grain Size, HE-Liner interface
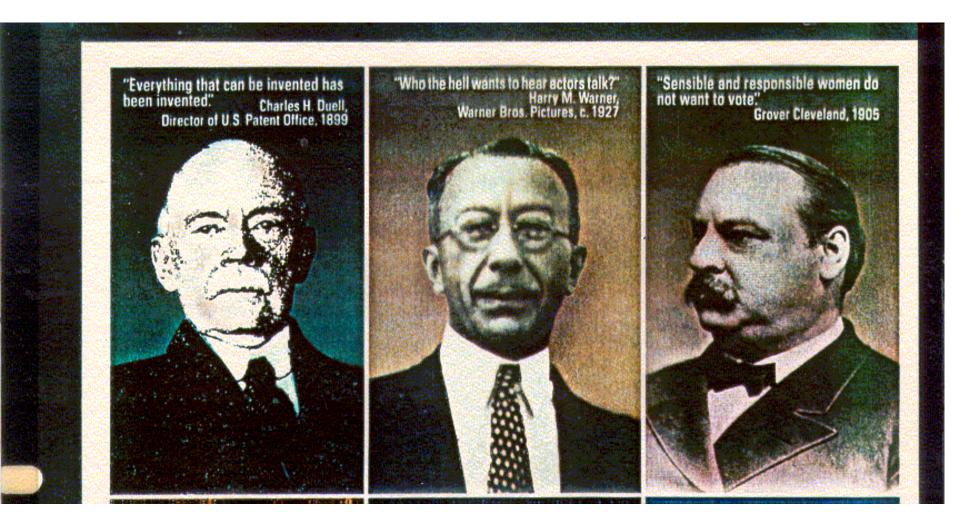
# Current Research Topics (Continued)

- Scaling ?

- Penetration/ Hole Growth Analytical Models

- Jet Temperature– Experimentally and Numerically

# The future isn't what it used to be



"Everything that can be invented has been invented." Charles H. Duell, Director of U.S. Patent Office, 1899

"Who the hell wants to hear actors talk?" Harry M. Warner, Warner Bros. Pictures, c. 1927

"Sensible and responsible women do not want to vote." Grover Cleveland, 1905

# The future



"There is no likelihood man can ever tap the power of the atom."
Robert Millikan, Nobel Prize in Physics, 1923

"Heavier than air flying machines are impossible."
Lord Kelvin, President, Royal Society, c. 1895

"Ruth made a big mistake when he gave up pitching."
Tris Speaker, 1921