# U S ARMY WEAPONS COMMAND
# RESEARCH & ENGINEERING DIRECTORATE
# SMALL ARMS SYSTEMS LABORATORY

# TECHNICAL NOTES

## SMALL ARMS WEAPONS DESIGN

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Lecture Series

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## I Introduction

The topics discussed in this manuscript were included in a series of lectures conducted by Mr. John G. Rocha, formerly of Weapons Development Branch, Research and Engineering Division, of the Springfield Armory. The lecture series was given at Rock Island Arsenal, Rock Island, Illinois during the period October 1967 - March 1968. Preparation of these lectures was directed toward assisting ordnance engineers of the newly formed Small Arms Research Branch of Rock Island Arsenal in becoming knowledgeable as to ordnance design practices commonly known at Springfield Armory.

A number of selected ordnance design publications and tests were used as source data, and is noted in the bibliography, as well as other recommended reading. In addition to the published source material, available in most ordnance engineering libraries, observations made during Mr. Rocha's 15 years experience as ordnance design engineer at Springfield Armory are included throughout the manuscript.

Included in the lecture series, following a historical resume, are topics on interior and exterior ballistics, systems of weapon operation, stresses, dynamics, kinematics of mechanisms, and topics peculiar to ordnance engineering, such as headspace, recoil forces, links, magazines, and evaluation of time-displacement curves.

Emphasis is placed upon the coordination required between weapon design and ammunition design agencies since the weapon system demands that each group be cognizant of weapon/ammunition interface areas. In addition, this writer feels that any new weapon design, or weapon system reflecting a quantum increase in firepower, must depend upon increased effectiveness of ammunition. Rare exceptions are the externally powered high rate of fire machine guns that increase volume of fire per installation. Advances in future weapon effectiveness may well be triggered by improvements or new concepts in ammunition design. Therefore, again, the weapon designer should be knowledgeable of all the facets of ammunition design including chemistry, ballistics, and thermodynamics, as well as cartridge case and projectile design. "Ballistics" includes interior, exterior, and terminal, or wound, ballistics. In an ordnance organization, only one or two engineers will be thoroughly familiar with any phases of these allied sciences, and will function as a consultant to the section on the particular topic in question.

The material discussed in these lectures should be of interest, and informative to all levels of a small arms design section; but further specialized data on each topic will be left to the initiative of the user, since ordnance engineering is a viable science, and new discoveries are constantly outdating the status quo.

## II Historical

Ever since the caveman used a club or rock as the first weapons, man has continued to improve the design of his weapons, often with the hope that the new weapon developed would end all wars and bring peace for all mankind.

As an example, in 1704, a French engineer named Chaumette devised a new approach to solving the problem of loading a rifle from the breech quickly and effectively. A presentation model of this weapon had the following inscription engraved on the Barrel:

> "La Chaumette has made this terrible gun. All its patrons will be blessed for it is the means of ending war and establishing the Golden Age."

Doctor Richard Gatling interrupted his medical practice during the 1860's to develop his famous multiple barrel weapon, which principles are still prominent today. He confided to his associates that his weapon would put an end to all wars and bring peace to the world. Unfortunately, he was mistaken, because the development of any new weapon spurs the development of a counterpart.

Historically, Past Is Prologue, and this is significant in many weapon designs. A prodigious number of weapon mechanisms have been introduced in the past that failed, but would be adaptable to future weapon designs if the principles are correctly applied. This is because of the many advances made in metallurgy, new alloys, new production techniques, and propellants. For example, the hexagonal bored rifle (Whitworth) of over 100 years ago is being re-introduced in the U.S. in 1968 (commercially) as rifling "without lands or grooves".

### Development of Military Cartridge Case

Friar Bacon was one of the first Europeans to develop a successful formula for gunpowder. At this time, practitioners of the art were more concerned with the noise and flash produced, and observed that confinement of the charge accelerated pressure build-up, but it did not occur to them that this pressure could be utilized to propel shot. This activity started about the year 1250. Another monk, Berthold Schwartz, used gun powder in the period of 1290 - 1350. He experimented with heating sulphur, saltpeter, mercury, and charcoal, attempting to convert mercury to silver, and succeeded in flattening himself and the laboratory in several explosions before he understood the principles of propulsion. The Chinese also used black powder, in the 6th to 10th centuries, but only for ceremonial and demonstrative purposes.

Mechanical art in various forms dictated the course of warfare thereafter. The first weapons were cannon (from the Latin "CANNA") because of their reed-like construction, and the first projectiles were, not balls, but arrows.

For the next few centries, ignition systems were the principal design keys. Initially, the gunner had to ignite the powder through a blow-hole on top of the barrel, so that he could not aim at the same time. Accuracy, then, was only accidental. The touch-hole was moved from the top to the right side of the barrel. A little ledge, or pan, was added beneath it to hold the priming powder and thus make ignition more certain. A hinged cover was added to protect it from the weather. Barrels were lengthened, stocks were shortened and the general contours of a modern gun began to appear. Most important was the development of a wick, or match, together with a device for holding it. This was a twisted rope dipped in saltpeter and spirits of wine, so that it burned slowly, as a punk; thus the shooter did not have to stay near the campfire to ignite his weapon. Thus mobility was improved.

The complete gun-lock, stock, and barrel, appeared with the match lock, which was a spring-loaded device that brought the match into the priming mix when the trigger was pulled.

Bullets developed slowly. Hand cannon fired not only lead, but also stone, iron, steel, brass, copper, and tin missiles as well. As this was an age of experimentation in ballistics, there were also cylindrical, pyramidal, rectangular, and barrel shaped bullets. Arrows were also popular, even silver buttons on one historic occasion. By 1600, the lead ball was universally used. The match lock, despite its limitations remained in usage until the 1700's. About that time, wheel-locks were devised, which worked as simply as the cigarette lighter works; that is, friction between a serrated wheel and pyrite produced sparks to ignite powder in the pan.

The first known reference to a cartridge was by Leonardo da Vinci about 1500, a simple tube of rolled paper, each holding powder for one shot. The gunner simply bit off one end, poured a little powder in the pan and the rest down the barrel. The ball followed, and the paper as a wad. Rate of fire thus improved.

Then came a whole group of ignition systems that produced sparks by striking flint against steel. This improved maintenance, as the wheel-lock mechanisms were complex. The flint-lock, or snap haunce, mechanism was simple. The classic flint-lock mechanism was designed in France in the early 1600's and carried on for at least two centuries, the most noted being the British Brown Bess and the French Charleville. At this time firing rate was about 4 SPM.

The flintlock mechanism also made the pocket pistol really practical.

One big improvement by Henry Nock, was the plenum (or pre-ignition) chamber, to speed ignition, improve maintenance, and improve ballistics.

A clergyman, Alexander Forsyth ushered in the modern era with the first successful percussion lock. This was the turning point in the history of firearms, as it provided the basic theory for all future developments in ignition, including the modern metallic cartridge.

Forsyth's hobby of hunting led him to his remarkable discoveries. He noticed that many of the wild birds escaped his fire by diving the instant they saw sparks or flash from his lock. The ensuing hesitation in ignition was all they needed. He set about to re-develop the firearm in the late 1700's to remedy this inefficient ignition system. New substances being experimented with at that time were called fulminates, or salts produced by dissolving metals in acids. When struck, they exploded violently. After much experimenting, Forsyth succeeded in 1805 in directing the priming charge into the bore. With the help of James Watt, he patented his discoveries. Many variations of his principles led to the percussion cap. This cap was placed on hollow steel nipple, and, when struck, directed a flash into the bore.

The origin of rifling dates back to the early 1500's. Longitudinal grooves were cut in the bore to collect powder residue. When someone spiralled the grooves to increase their length, accuracy improved to everyone's surprise. When tight-fitting projectiles were used, this led to problems in loading, until greased patches were introduced. This also helped clean the bore.

However, with improved accuracy, speed of loading was sacrificed, by the time taken to drive the bullet down the bore in loading. A French army captain, Claude Minie, refined the shape of some experimental hollow-based bullets in 1849 so that, via a iron cup, the projectile skirt expanded into the rifling. Hence the "Minie Ball" was born and proved to be highly effective during the (so-called) Civil War.

Soon afterward, in 1855, an American dentist, Edward Maynard, developed a tape primer, similar to the common children's "caps" in roll form for toy pistols. Hence, a method for speeding the reloading of the ignition system was devised. It soon became clear that it was easier to load a gun at the breech rather than putting a charge of powder, ball, and wadding down the bore, particularly when lying down, confined or under combat stress.

Breech loading had been experimented with for several centuries dating back to the early 1500's when shield-type pistols, of necessity, were breech loaders, using an iron tube similar to the modern cartridge case. Firing was by a match-lock.

The first important breech-loading military weapon was French, and utilized a threaded breech plug perpendicular to the bore, which did not fall free, and was thus easy to load. (1720's)

A large number of gun enthusiasts proceeded to develop a prodigious number of breech loading variations, but powder fouling, gas leakage, and endurance limited any success for well over a century. Finally, Pauly, a Swiss inventor, initiated the concept of using the ammunition as the key to breech-loading design, in 1812, when he used a cartridge with a rimmed head of soft metal, to obturate the propellant gases. These cases had paper bodies with brass heads, like common shotgun shells. One of his technicians, Johann von Dreyse, became one of the most historic figures in the development of breechloaders, as the inventor of the bolt action rifle with the "needle gun" principle of ignition. The basic principle was that of a priming compound in a hollow at the base of the bullet. The primer was detonated by a long firing pin that pierced the powder charge.

With this gun, the Prussians dispatched the Danes quickly, and the Austrians in only 7 weeks, in 1866. Additional developments were made to shorten and strengthen the firing pin, which proved to be a problem in erosion and endurance.

Christian Sharps made another important contribution with his lever action carbine. He utilized a separate-disc priming mechanism that automatically positioned a primer over the nipple for each shot. This weapon was prominent in the Civil War, as well as in pioneering and settling the West. It was the last of the important combustible case weapons. Cartridges were made of paper, linen, rubber, metal foil, and sheet metal, in a variety of breech mechanisms. The basic problem of all breech-loaders was the same: that of obtaining a quick-acting gastight seal in a mechanism that could function for a follow-on shot.

The pin-fire type of cartridge was briefly successful, but proved to be fragile, and prone to accidental firing. From the side-firing pin-fire followed the teat fire and the rim-fire, which was limited to low-powered cartridges, because the metal had to be hard enough to support the chamber pressure, yet soft enough to be easily indented by the hammer or firing pin. The center-fire cartridge eliminated this limitation. In this, a primer pellet is crushed by the striker against a rigid anvil, with vents leading into the main charge. Two important types, by Col. Berdan, U.S., and by Col. Boxer, U.K. were developed and have been essentially unchanged in 100 years.

The 1873 Springfield .45-70 trap-door model was simply a means of converting stock-piles of muzzle loaders into breech loaders. One problem proved to be in tight extraction after prolonged firing due to thermal expansion of the breech end of the barrel.

During this period, in the U.S. and U.K., 120 actions and 50 cartridges were considered in a search for most acceptable mechanism, attesting to the variety of inventions produced in the 1870's, following introduction of the modern metallic case.

In 1889 Alfred Nobel invented "smokeless" powder, Vielle of France developed the ballistics theories, and the age of high performance weapon systems was born.

## The United States Light Rifle Program

This section is a resume of the activity, generally at Springfield Armory, directed at satisfying the User's requirement for a lightweight automatic shoulder weapon. This requirement was a natural follow-on to the semi-automatic (8 round) M1 rifle which gave the U.S. a significant advantage over other countries that were armed with bolt action rifles.

Modifications to the M1 system were initiated in 1944 as the Springfield Armory T20 series and the Remington Arms T22 series. These developments included use of 20 - round box-type magazines selective five with semiautomatic fire on "closed bolt" and full automatic fire on "open bolt". ("Open bolt" means that the bolt is held in the full recoil position between firing bursts.) (This is done to minimize the danger of a cook-off, the inadvertent firing of a cartridge caused by the cartridge being in contact with a hot chamber. Ingition is by conduction of heat through the brass case and into the propellant. The primer is not struck!) Eventually the requirement for the "open bolt" sear was deleted.

Experiments also included use of cut-off and expansion gas systems, muzzle brakes, compensators, bipods, and a number of minor items.

The initiation of the formal light rifle program was featured by a shorter cartridge, the T65 series, which eventually was developed into the 7.62mm NATO standard cartridge. The Cal. 30-06 cartridge (used in the bolt-action Springfield '03 as well as the BAR and the M1 rifle) is 3.33 inches long, while the NATO cartridge is 2.80 inches long.

One of the first rifles to take advantage of the shorter cartridge was the T25 rifle, a Springfield Armory design. It featured a tip-up bolt lock not unlike the BAR lock, an expansion gas system, and an inline butt-stock to facilitate control in automatic fire. User preference in styling dictated redevelopment of this model as the T47, with a conventional drop-stock.

Another Springfield Armory development was the T28 light rifle, which featured a modification of a German conceived breech mechanism, extensive use of stampings, and an inline buttstock, also to assist in control of automatic fire. The locking rollers lock the bolt to the barrel extension, as typified in the German MG42, the Spanish CETME, and the current German G3 rifle. However, these European models are engineered to utilize a retarded blowback principle of operation to cycle the weapon. This does not allow a reserve of power in the event of firing under adverse conditions, so the T28 rifle was developed with positively locked rollers and a gas system of operation to power the bolt carrier.

The T44 series of weapons was basically a continuation of the T20 series of M1 rifle modifications. Eventually, this model (T44E4) was standardized as the M14 rifle.

The T31 rifle was an experimental model designed by John Garand which was characterized by an inline stock, "bull pup" configuration, a pistol grip in front of the 20- round box magazine, and a number of unconventional promising features. These included, among others, a simple leaf-type driving spring, a firing mechanism that utilized only a short stroke of the operating rod, and a gas-operated barrel cooling system. If this weapon had been continued in development, it could well have minimized the necessity for use of the M16E1 rifle. Of course, this is a speculative statement, but it demonstrates how "timing" in the introduction of a novel weapon is important. The User must be prepared to accept a seemingly unconventional item. User preference in styling "feel" (balance), sighting geometries, and other intuitive qualities cannot be technically measured.

The T35, T36, and T37 models were interim phases between the T20 and T44 series.

The T48 rifle was the Belgian FN entry in the competition for selection of a NATO rifle. It was also chambered for the T65E3 cartridge, as was all of the models in the preceding paragraphs. A pilot line of 500 models was manufactured in the U.S. by H.&R., in order to measure adaptability of the design to U.S. production and inspection techniques. Selection of the standard U.S. rifle was eventually based upon a series of U.S. User tests.

A series of feasibility studies for an advanced weapon system evolved as the "Salvo" concept. This was based upon the observations made under combat conditions of the shooters level of ability, or inability, to hit his target. There are many facets to this problem, but it can best be summarized as effort to improve "hit probability". Weapon developments centered about test fixtures using multiple barrels, for simultaneous, or ripple-fire multiple shots per trigger pull. The SPIW rifle program is one generation of this concept study. The 7.62mm Duplex cartridge is one result of this program.

The SPIW system is a shoulder weapon that fires a lightweight flechette projectile saboted in a smooth-bore 5.56mm barrel. The firing mechanism is designed to permit single-shot semi-automatic, high-rate three-round-burst semi-automatic, or full automatic fire. The lecture on "Dynamics or Automatic Rifles" will demonstrate that the high-rate three-round-burst is optimum commensurate with controllability and hit probability.

Studies of liquid propellant rifle systems are discussed in an ensueing chapter.

An additional rifle development was the Springfield Infantry Rifle, designated as "S.I.R." This was a lightweight, compact, Cal. .224 automatic rifle that was designed to incorporate the best features of all of the infantry rifles developed to date, and using a lightweight cartridge that preceded the present 5.56mm round used in the M16E1. This program was also derivative of the "Salvo" concept.

Designers, or principal engineers, of the weapons disclosed in this chapter are as follows:

| | |
|---|---|
| T20 series | John C. Garand |
| T25 | E.M. Harvey |
| T28 | C. A. Moore |
| T44 | L. S. Corbett |
| T31 | John C. Garand |
| SPIW | R. H. Colby |
| S.I.R. | A.J. Lizza |

An excellent description of U.S. standard machine guns is given in Smith & Smith's eighth edition of "Small Arms of the World" as well as in G.M. Chinn's Vols I - IV of "The Machine Gun".

## Caseless Ammunition

Now after the 100 year period since cartridge cases were introduced, efforts are being made to eliminate them, taking advantage of the growth of other technologies, such as metallurgy and chemistry.

In chemistry, new forms of caseless ammunition have been developed, such as a solid molded propellant containing the projectile and a combustible percussion primer. In metallurgy, new and improved materials may lead to successful methods of obturation, the reduction of heat transfer, and elimination of erosion and cook-off.

What are the advantages of this new facet of ordnance design? Essentially, they are as follows:

1. COST - The price of a cartridge case is approximately one half of the cost of a complete round. Eliminating the case should cut ammunition cost in half. (However, note development effort required to realize this)

2. WEIGHT - The weight of a brass case is approximately one half of the weight of the complete round.

3. BULK - The molded caseless cartridge is approximately 25% shorter than the cased ammunition.

4. ELIMINATION of spent cases that clutter the compartment of a vehicle, particularly larger caliber weapons.

5. Possible simplification of gun mechanism, such as eliminating close tolerance headspace dimensions.

6. Critical cartridge brass material will not be required.

The weight and bulk factor are especially attractive from a logistics and installation point of view.

For example, in comparing the 7.62mm NATO cartridge with a comparable 7.62mm caseless round (of comparable ballistics), the Nato round weighs 390 grains and has a storage volume of .85 cubic inches, while the caseless round weighs 196 grains and has a storage volume of .64 cubic inches. The effect of this is that an infantryman's ammunition load (220 rounds) is reduced from 15 lb. to 8.7 lb., or, if the same combat load is used, the caseless ammunition complement is increased to 430 rounds.

For armament installations, the advantages are particularly attractive. In helicopters, as in all aircraft and most vehicles, weight and space are at a premium. A typical installation, the M6 Armament Subsystem, (Quad 7.62mm M60C machine guns) carries 6000 rounds, with a weighting of 390 lb. and a volume of 3 cubic feet. Caseless ammunition would weigh 190 lb. and have a volume of 1.95 cubic feet. If the same system weight is held, the ammunition complement could increase from 6000 rounds to 11,500 rounds.

So much for the prospects, but now what are the problems? This is where the present and future development effort is concentrated, and is generally as follows:

1. COST - Establish production techniques so that ultimate mass production at low cost will be realized.

2. CONFIGURATION - The proper size and shape of caseless ammunition commensurate with the following:

   a. Production techniques and control

   b. Weapon design (close coord. req'd)

   c. Ballistic efficiency

   d. Feeding, storage, and handling

3. OBTURATION - Chamber, bolt, firing pin

4. COOK-OFF (Cartridge case had functioned as insulator)

5. EROSION and fouling

6. MISFIRE extraction

7. COATINGS against moisture

8. STRENGTH to support handling & feeding (durability)

Of the above problem areas, obturation, or the sealing of the high pressure gases from excessive leakage, is expected to be the most articulate if endurance is expected. That is, a self-acting durable seal for an automatic weapon will not be merely a close-tolerance fitted component, because prolonged firing will cause thermal expansion of components to varying levels.

Some relief from the wide scope of problem areas inherent in a caseless system may be realized by using a partially combustible cartridge case. This is done in the 105 mm howitzer and 105 mm gun area. In this, a stub brass shell is used, in order to provide obturation, ease of extraction, etc. etc. A significant reduction in cartridge brass is realized, being approximately 85%, rather than the 100% of completely caseless ammunition.

## Liquid Propellant Systems

Approximately 10 - 12 years ago a considerable amount of work was done in exploring the feasibility of utilizing liquid propellants in small arms. The range of programs was quite extensive, and enveloped a number of applications and philosophies. Initially, it was held to be promising for ship-board installation, where the propellant bulk could be stored in remote areas, and pumped to the weapons. This concept then was applied to tank guns, then interest grew in the small arms field.

There are two general categories of liquid propellant systems: the monopropellants and the bi-propellants. In the bi-propellants two separate liquids, a fuel and an oxidizer, are pumped into a chamber where hypergolic action causes ignition and burning. No primer or igniter is used. Monopropellants are single fuel systems, with ignition by separate means, such as spark, primer, compression, glow-plug, etc.

The advantages of a liquid propellant system are generally as follows:

1. Greater impetus per pound of propellant for liquid (over solid propellant) systems.

2. Sharp reduction in pressure peak through control of pressure-time interior ballistics.

3. Hyper-velocities possible (over 5000 fps projectile).

4. Reduced heat transfer to barrel and chamber.

5. Cleaner burning (no fouling).

6. Reduced erosion.

7. Elimination of cartridge brass.

8. High capacity weapon systems may be realized.

9. Reduced smoke and flash.

10. Reduced recoil peak loads (inherent with item 2 above).

11. Remote storage of propellant (for vehicular installations) to save space in gunner's compartment, and for safety.

12.. High firing rates possible in certain weapon designs.

During the course of development, it was realized that the high impetus propellants were extremely corrosive and unstable. Erratic pressure peaks and erratic ignition & burning ensued, until eventually the bulk of effort was directed toward monopropellant systems in which the propellant was a mixture of hydrazine, hydrazine nitrate, and water. (approx 70-25-5) A typical bi-propellant combination would be Red Fuming Nitric Acid and Hydrogen Peroxide, for example, there being a wide range of propellants considered.

Two philosophies in the liquid monopropellant field centered about the control of the pumping, or chamber-filling, process. One was a constant-pressure theory, the other a constant-volume theory.

In the constant-pressure system, the chamber was filled until a definite liquid pressure of the full chamber was attained. Here, as firing progressed, any change in bullet seat would change bullet position, increasing the propellant volume, causing a change in interior ballistics.

In the constant-volume system, a definite, measured amount of liquid was pumped into the chamber. As firing progressed, any change in bullet seat would cause ullage, or an amount of air, in the chamber, which caused erratic ignition and uncontrolled interior ballistics performance.

In general, the following problem areas remain unsolved and constituted the principle R & D effort;

1. Obturation, both at low (fill) pressure and high (burning) pressure

2. Ignition

   a. Erratic

   b. Energy source for spark

3. Purging system after misfire

4. Pumping

   a. Cavitation

   b. Pre-ignition

   c. Leakage

5. Erratic chamber pressures

6. Poor low temperature characteristics of propellants.

## III Supporting Sciences

This section reviews some of the fundamentals of interior and exterior ballistics, recoil forces, and dynamics of automatic rifles from a mathematical, rather than hardware, perspective.

It is felt that design engineers should be knowledgeable of the sciences that affect their product.

Much of the data indicated here may be corroborated by test fixture firings, since the results are limited to specific calibers, weights, velocities, and other characteristics. These fields are constantly in need of revision because the formulae involved are limited to the specific conditions of the tests observed. This is one of the reasons that the science of ordnance engineering is so fascinating.

### Interior Ballistics

An understanding of the fundamentals of interior ballistics is essential for the weapon design engineer. This is because the development of pressure in the chamber and bore affects the weapon, operating system, and is a basic weapon/ammunition interface area. The weapon designer should be prepared to make positive recommendations as to ballistics parameters when a new weapon system is being specified, or is in a state of development.

The following are examples of weapon/ammunition interface areas that requires knowledge of interior ballistics by the weapon designer.

a. Headspace limits,

b. Timing breech opening,

c. Development of stresses on barrel bolt lugs and breech ring,

d. Rifling twist,

e. Barrel and chamber erosion,

f. Gas pressure at orifice (for gas operated weapons),

g. Gas pressure at muzzle (for recoil operated weapons) for design of muzzle booster,

h. Construction of primer to prevent primer puncture and/or cup flow,

i. Construction of cartridge case to prevent case splitting,

j. Reduction of smoke and flash, as well as various products, and

k. Ballistic stability at temperature extremes.

A diagram of a typical Cal. .30 pressure travel curve is analysed and illustrates pressure and velocity with respect to bullet travel.

This typical cartridge fires a 150 grain projectile at a muzzle velocity of 2700 feet/second. Quite simply, the formula for projectile muzzle energy is: $E = WV^2/2g$.

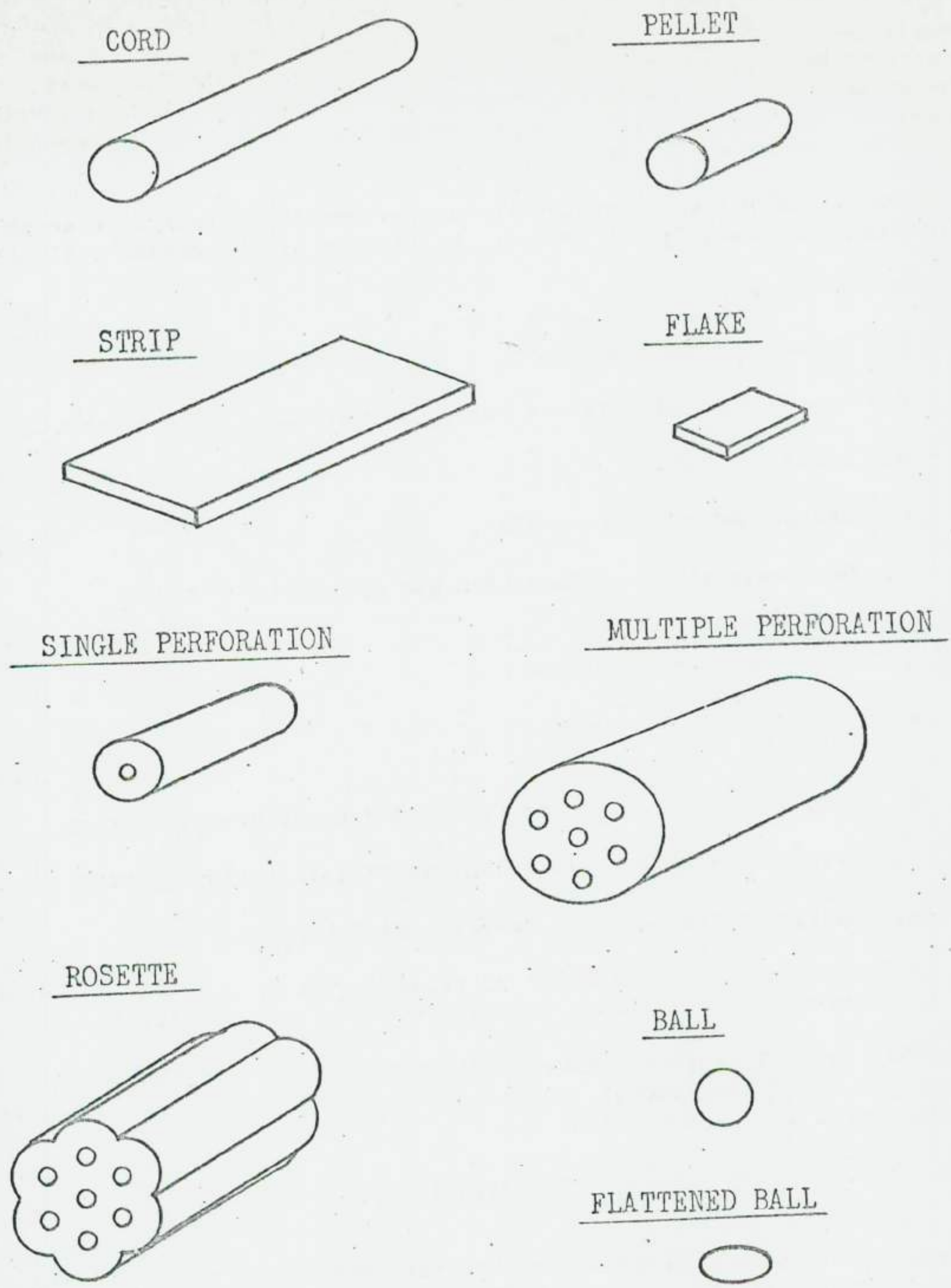
$$E = \frac{150 \times 2700^2}{7000 \times 64.4} = 2420 \text{ ft. lb.}$$

Correlate this with integration of the pressure-travel curve: That is, the area under the curve multiplied by the bore area is equal to the energy developed.

Travel scale 1/4" = 1" (typical)

Ref.: Hatcher's Notebook by J.S. Hatcher, Chapter on Interior Ballisti

## COMMON POWDER TYPES for SMALL ARMS




NOTE: The pressure the propellant develops varies inversely with the thickness of propellant grain.

Pressure scale 1/4" = 5000 psi.

each square = $1/16''^2$ = 5000 in. lb./in.$^2$

Count of squares = 78 (use of grid)

$78 \times 5000 = 390{,}000$ in. lb./in.$^2$

Bore area = $\pi/4 \ .308^2 = .0745$ in.$^2$

Energy = $390{,}000 \times .0745 = 29000$ in. lb.

.E = 2,420 ft. lb. Therefore, the data correlates.

The identical procedure is utilized with a pressure-time curve, in which the unit is lb.-sec., or a measure of impulse.

Note that if a heavier projectile were used, which would result in increased muzzle energy, or a more powerful charge were used to increase velocity, then the area under the curve would have to increase proportionately. Since barrel travel is constant, then the pressure would have to increase. This is one penalty that is paid for packing more propellant into the cartridge case.

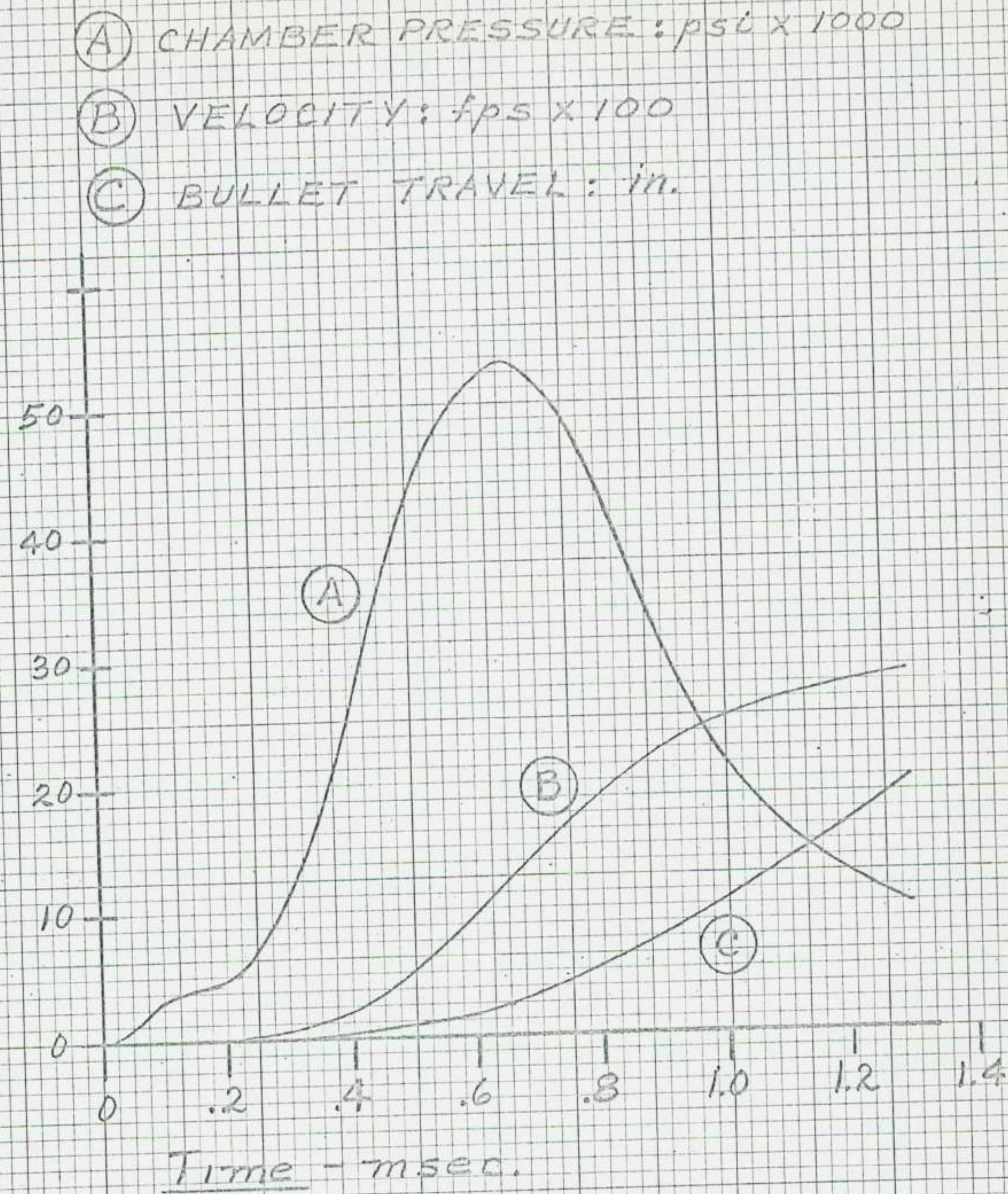
At times attempts have been made to alter the shape of the pressure curve, so that a lower peak, acting for a longer time, would result in reduced weight of locking mechanism barrel, etc. but there are limits to the effect of such a change.

The development of pressure in the weapon is also controlled by simply changing the chemical composition of the powder or by changing its form. The pressure the propellant develops varies inversely as the thickness of the propellant web. Smokeless powders are most commonly used, being a double-based composition of nitrocellulose (gun cotton) and nitroglycerine. When completely decomposed, nitrocellulose yields $CO_2$, $CO$, $H_2O$, $N_2$, and nitroglycerine yields $CO_2$, $H_2O$, $N_2$, and $O_2$. The exploding temperature of both materials is about 180°C. -200°C.

Note that the propellant contains its own oxygen.

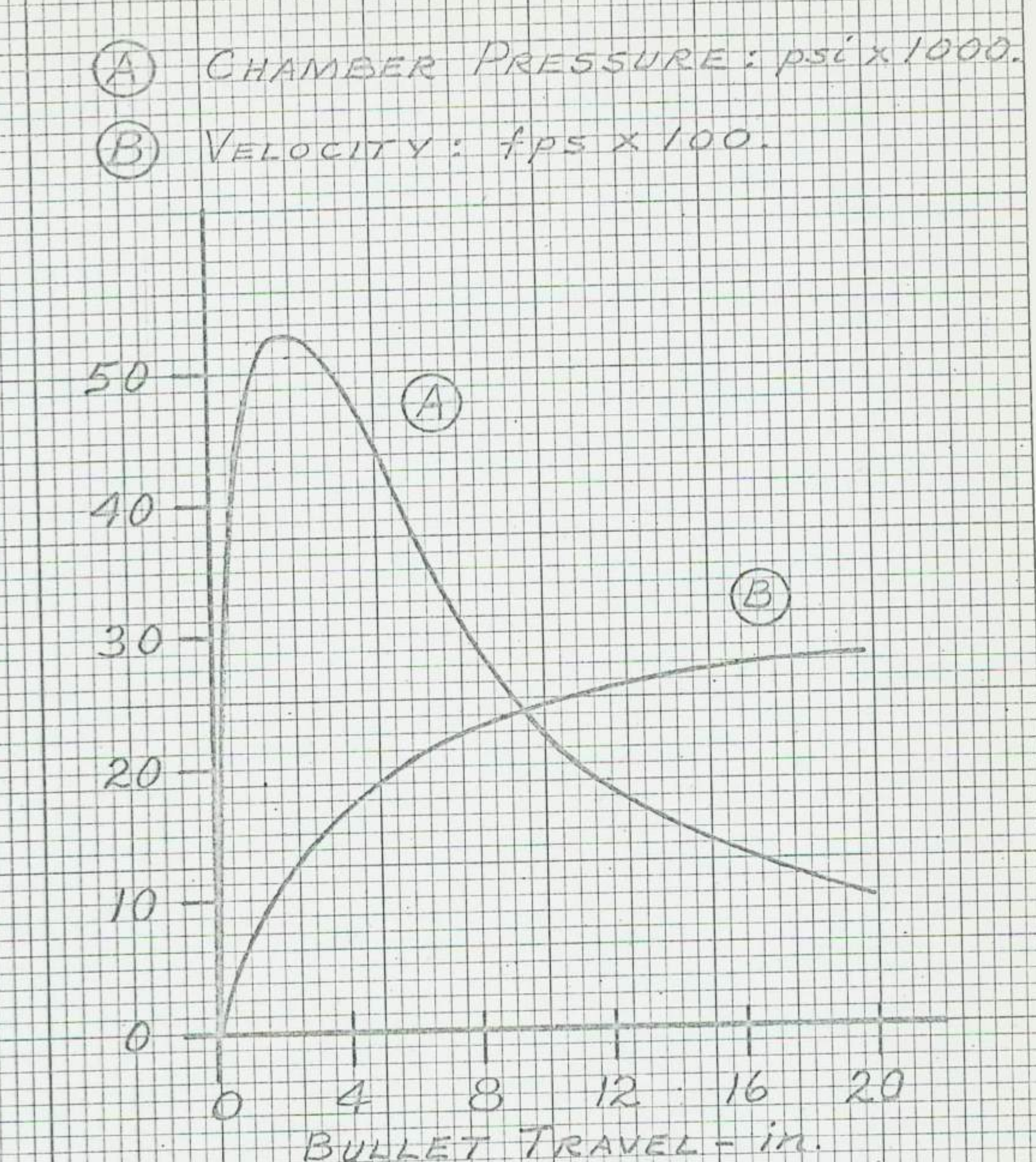
A material advantage of smokeless powder over the old black powder is the fact that it burns in parallel layers. Therefore, by appropriate shaping, the burning rate, and thus the rate of pressure increase, may be controlled.

Moisture must also be controlled in nitrocellulose powders. A change in moisture content of ± 1% changes the muzzle velocity by ∓ 12 fps and the gas pressure by ∓ 750 psi.




TYPICAL INTERIOR BALLISTIC DATA

7.62 mm NATO (BALL)




INTERIOR BALLISTICS DATA

PRESSURE & VELOCITY VS. TRAVEL

7.62 mm NATO (BALL)

Temperature change also changes gas pressure and velocity accordingly. The propellant is ignited by the primer charge, either fulminate of mercury or lead azide, so that a large flame is created by adding a very surface-rich powder, so that practically all the powder grains begin to burn at the same time. The rate of burning is a function of the pressure of confinement. The speed of reaction increases with increasing pressure until a pressure and temperature maximum is reached, producing an explosion. Loading density, therefore, is an important value in internal ballistics. Loading density is the ratio of propellant charge to chamber cavity volume, in grams per C.C.

Improper selection of propellant chemistry could result in a high temperature increase at concentrated points in the propellant mass, causing a pressure wave to emanate, that travels through the powder mass in a shock wave, creating a detonation.

In order to guarantee consistent burning from round to round, and thus consistent pressure development, the chamber density should not exceed a maximum value, which depends upon the burning heat of the powder used. The loading density, therefore affects uniformity of weapon performance.

Development of formulae on Internal Ballistics has been principally through the efforts of Vielle (France), Cranz (Germany), and Charbonnier (France).

The burning temperature of nitrocellulose powder will peak, in a typical weapon, at 3000°F, with the temperature at the muzzle exit of 2000°K.

It has been proved mathematically that the maximum attainable muzzle velocity of a projectile, using nitrocellulose powder is 9100 fps. This considers 36% of the charge transformed into muzzle energy of the projectile and charge. This figure is only of academic interest, because it requires extremely high charge to mass ratios. "Charge to mass ratio" is merely the propellant weight/ projectile weight, and for small arms varies from .3 to .4. Higher propellant loads are inefficient, causing temperature and barrel erosion values to accelerate.

A typical variation of muzzle velocity with powder temperature change is as follows:

| Temp. degrees F. | Velocity |
|---|---|
| 0 | 2631 |
| 10 | 2641 |
| 20 | 2648 |
| 30 | 2657 |
| 40 | 2668 |
| 50 | 2682 |

| Temp. degrees F. | Velocity |
|---|---|
| 60 | 2700 |
| 70 | 2722 |
| 80 | 2750 |
| 90 | 2784 |
| 100 | 2827 |

Five general equations are commonly used in the development of interior ballistics theory. These are:

1. Equation of state of propellant gases
2. Equation of energy
3. Equation or motion
4. Burning rate equation
5. Form function

The equation of state is used to develop the equation of energy, which in turn is a statement of how the energy released by propellant combustion is distributed during weapon operation. The equation of motion is the solution of forces due to the gas pressure accelerating the projectile.

The burning rate equation determines the rate at which new gas is being generated in the gun by the combustion in the charge. This rate is a function of the pressure of burning, and the area of the reacting surface. If this surface is not constant, it is necessary to introduce the form function to account for effect of the charging burning surface on the rate of generation of gas in the gun.

A detailed discussion of each equation of energy is given in "Interior Ballistics of Guns", AMC Pamphlet #706-150, dated Feb. 1965, Chapter 2.

It should be pointed out that a general theory of gun barrel erosion has not been formulated because the erosion rate decreases as the gun is used due to changes in the interior ballistics resulting from the erosion. A number of general theories have been evolved one of which assumes that, due to roughness, the surface melts only locally, so that erosion is at "hot spots", that shift about on the surface.

## Black Powder

Black powder was commonly used as the sole propellant in guns up to the end of the 19th centry, when they were replaced by the nitrocellulose powders.

Being the original "gunpowder" since the 13th centry, it is a mixture of 75% sodium nitrate (saltpeter) 15% charcoal, and 10% sulphur. It has consistently proved to be an undesirable propellant for the following reasons:

1. It burns incompletely, leaving large amounts of residue in the bore.
2. It creates high temperatures locally when burning, causing rapid erosion of the bore.
3. It creates large billows of black smoke.
4. It tends to detonate, developing a high reaction speed that is incontrollable.
5. It must be stored in airtight containers, since it deteriorates when exposed to moisture. Deterioration causes unstable burning.
6. It is highly responsive to friction, shock, and sparks.
7. Black powder dust is highly dangerous.

However, it is used as either a primer or igniter for boosting propellant charges.

Rifling Twist

In specifying rifling twist, the most common practice is to follow prior art, either military or commercial for the same projectile form and weight. Increasing projectile weight causes the projectile to tend toward being unstable unless the twist is sharp enough. Therefore, the twist required varies with the projectile weight.

The torque developed by the rifling in providing rotational acceleration is given by the formula:

$$\text{Torque} = Fd/2 = 2\, AX\, \pi^2\, pd/NW$$

F = Rotating force

d = Caliber

$A_x$ = Axial moment of inertia (grains-in$^2$)

p = pressure

N = Twist (calibers/turn)

W = Bullet weight

$A_x = cWd^2$

C = .11 for conventional projectile accordingly, $F = \frac{4cd^2\pi^2 p}{N}$

Gain twist is employed to gradually accelerate the projectile to the required spin rate. The gain twist exit angle is equal to the helical angle of conventional straight twist required for a comparable projectile.

The projectile jacket is a composition of 90% copper and 10% zinc.

## Distribution of Energy

For a typical conventional weapon, the energy developed by the propellant, assuming complete combustion, may be distributed generally as follows:

| | |
|---|---|
| Projectile forward motion | 32.00% |
| Projectile rotation | .14 |
| Projectile friction | 2.17 |
| Weapon recoil | .12 |
| Propellant gas motion | 3.14 |
| Heat loss to gun and projectile | 20.17 |
| Latent heat losses in propellant gases | 42.26 |
| Propellant potential | 100.00 |

One particular example, as measured in the Cal. .30 BAR, is as follows, expressed in terms of calories:

| | | |
|---|---|---|
| Heat to cartridge case | 131. | calories |
| Kinetic Energy of Bullet | 885.3 | " |
| Kinetic Energy of Gases | 569.1 | " |
| Heat to Barrel | 679.9 | " |
| Heat in Gases | 598.6 | " |
| Total | 2863.9 | calories |
| Frictional Heat Loss | 212.0 | " |

## Exterior Ballistics

Exterior ballistics is the study of projectile motion from the muzzle to the target. An understanding of this topic is important to a weapon designer because he should try to promote efficiency in projectile design and effecitveness to the limit of his capacity. That is, a gun designer develops a given weapon to the specifications of minimum weight, maximum reliability and endurance, producing a given velocity to a projectile of a given weight, size, and shape. If the projectile design is of maximum efficiency, the projectile remaining velocity will be high (minimum drag or retardation) and the effective range will be maximized. A gun designer should strive for the maximum effective mileage and penetration at long range of each round fired from his weapon. If the projectile design were lowered in efficiency, then the effective range would be reduced, or effectiveness at the target lowered. Then, in order to increase weapon system effectiveness, a heavier or higher velocity projectile would be specified, resulting in higher pressures, loads, barrel wear, and stresses on the weapon and mount components. Therefore, again, it is most important that close co-ordination be maintained between weapon and ammunition design agencies, as their product is so inter-related, for maximum system effectiveness.

Two important elements of exterior ballistics data are the trajectory and the remaining velocity. The trajectory is the curved path the projectile follows in the air and is a function of gravity and (1) angle of departure, (2) air resistance, (3) shape of the projectile, (4) projectile diameter, and (5) projectile weight. Remaining velocity, of course, is a measure of the projectile velocity at any given range as a function of muzzle velocity and the elements of air resistance that slow the projectile. The remaining projectile energy is then computed, as well as any other function of velocity that effects the lethality of the projectile, as well as other terminal effects.

The study of projectile lethality, or striking energy, is called terminal ballistics, and is a complex study, if all the elements of wound ballistics are to be understood. That is, there is a variety of phenomena that occur when a bullet strikes, and this is a function of projectile velocity, shape, structure, angle of impact, etc., as well as target structure, density, etc., etc. Many of the facets of this subject are not well understood.

The calculation of a trajectory in a vacuum is a common practice in high school physics, but for an accurate treatment, a series of exterior ballistic charts have been prepared that enable anyone to plot trajectories for any cartridge with sufficient accuracy. A typical chart is "Ingalls Ballistic Tables", prepared by personnel of E.I. DuPont De Nemours &Co., Inc. and another is the Speer Ballistic Calculator, slide-rule type of chart. The data is arranged in a series of logarithmic curves (as a slide rule) in order to facilitate the math process.

With these aids, curves of projectile velocity and energy up to 1000 yards can be obtained and compared with each other. It will become apparent how important the "Ballistic Coefficient" is in reducing drag, or velocity retardation, and thus getting more mileage out of the round fired. The ballistic coefficient is, in effect, a measure of the efficiency of the projectile form. The higher the Ballistic coeeficient, ("C"), the better, and vice versa. The value of "C" for the 7.62mm 150 grain boat-tailed projectile is in the order of .4 - .387.

Other common values of "C" are:

| Projectile | "C" |
|---|---|
| .22 Long rifle, 40 gr. | .137 |
| .224-55 gr. SP (flat base) | .209 |
| .223-55 gr. boat-tail | .280 |
| .270 WIN-130 gr. expanding pt. | .496 |
| 30/06 Spfld - 110 gr. | .237 |
| 30/06 Spfld - 150 gr. | .323 |
| 30/06 Spfld - 180 gr. | .560 |
| 7.62mm - 125 gr - M43 (Soviet)) | .31 |
| .45/70 W.C.F. - 405 gr. | .219 |

In general, a bullet with a long, smooth ogive, minimum point diameter, boat-tailed, and high in weight, will have a good ballistic coefficient. The long ogive radius reduces head pressure, and the boat-tail reduces suction at the base.

The ballistic coefficient is calculated as $C = W/id^2$, where

w = projectile weight in lb.

d = projectile diameter in inches

i = coefficient of form.

The coefficient of form depends upon the ratio of the bullet ogive to the bullet diameter and the effect of air resistance on the point. Bullets of different calibers that have the same shape (mere scale-ups) have the same coefficient of form. The tables given in the DuPont charts have been compiled from firing, as well as tabular, data, from several sources; being averaged whenever there were differences.

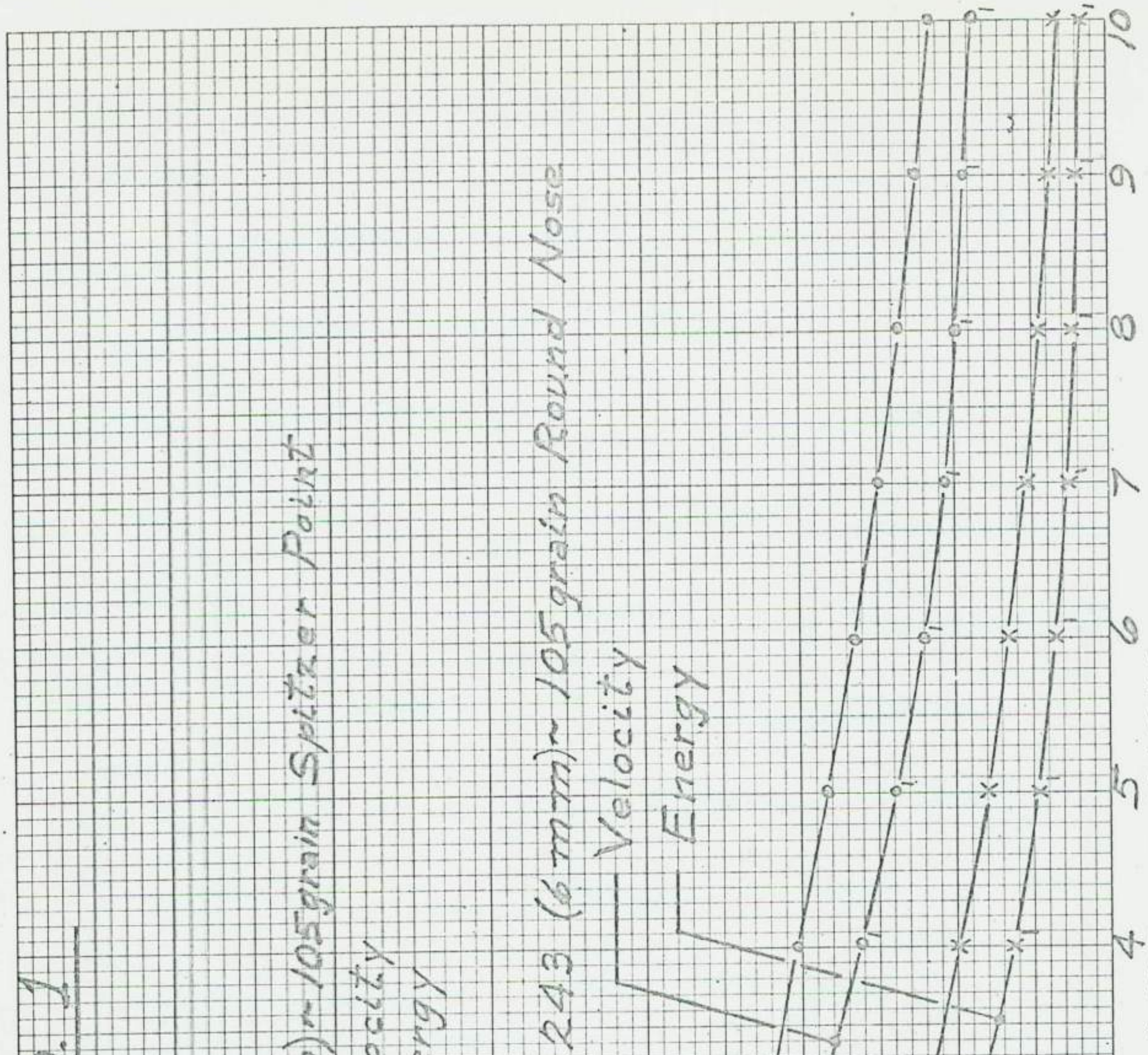


CHART No. 1
.243 (6 mm) - 105 grain Spitzer Point
Velocity
Energy
.243 (6 mm) - 105 grain Round Nose
Velocity
Energy
RANGE IN HUNDREDS OF YARDS
0
1
2
3
4
5
6
7
8
9
10
VELOCITY (FT./SEC. X 1000)
ENERGY (FT. - LB. X 1000)
1
2
3

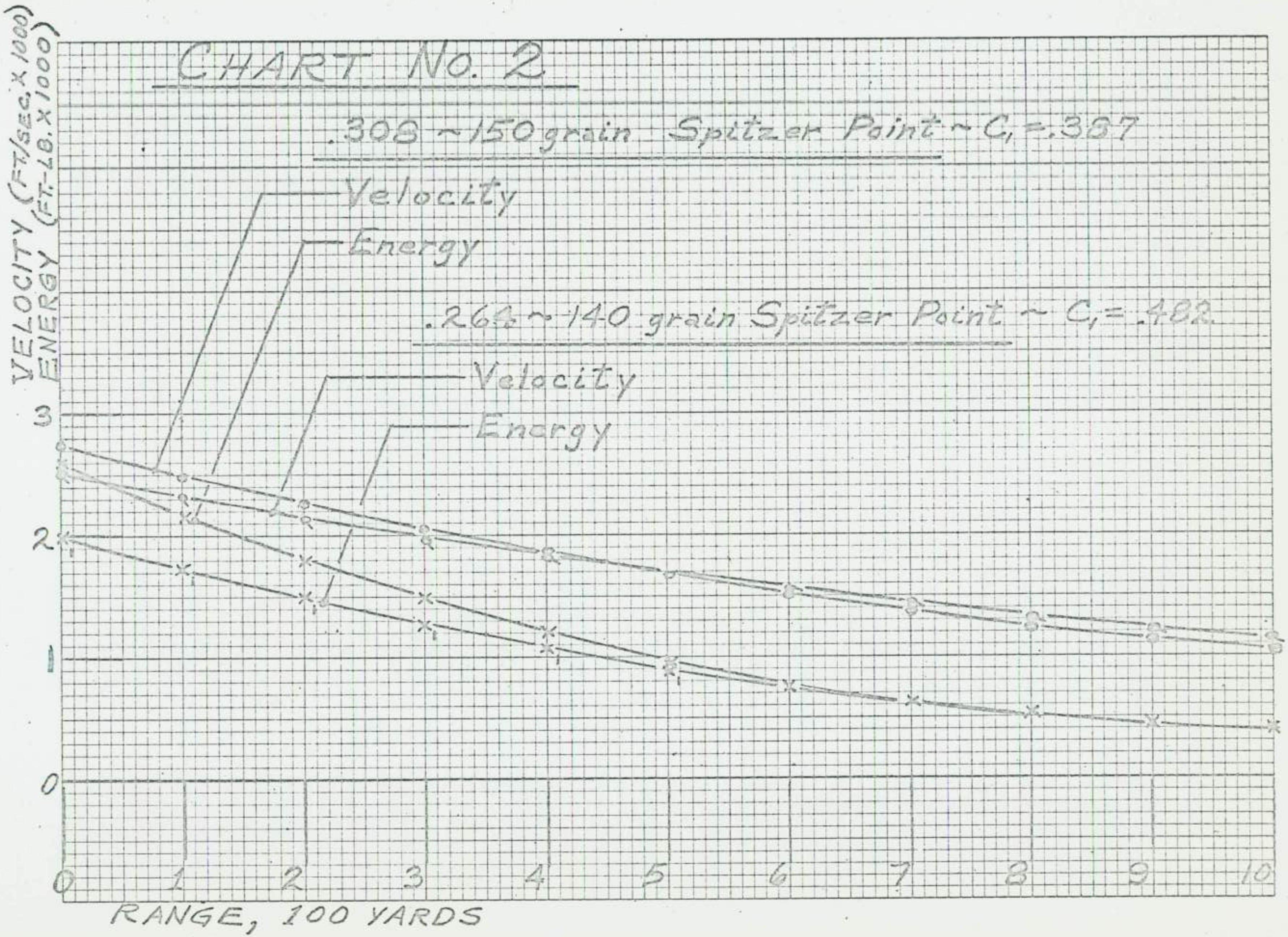


CHART No. 2
.308 ~ 150 grain Spitzer Point ~ C1 = .387
Velocity
Energy
.264 ~ 140 grain Spitzer Point ~ C1 = .482
Velocity
Energy
VELOCITY (FT/SEC. X 1000)
ENERGY (FT-LB. X 1000)
0
1
2
3
0
1
2
3
4
5
6
7
8
9
10
RANGE, 100 YARDS

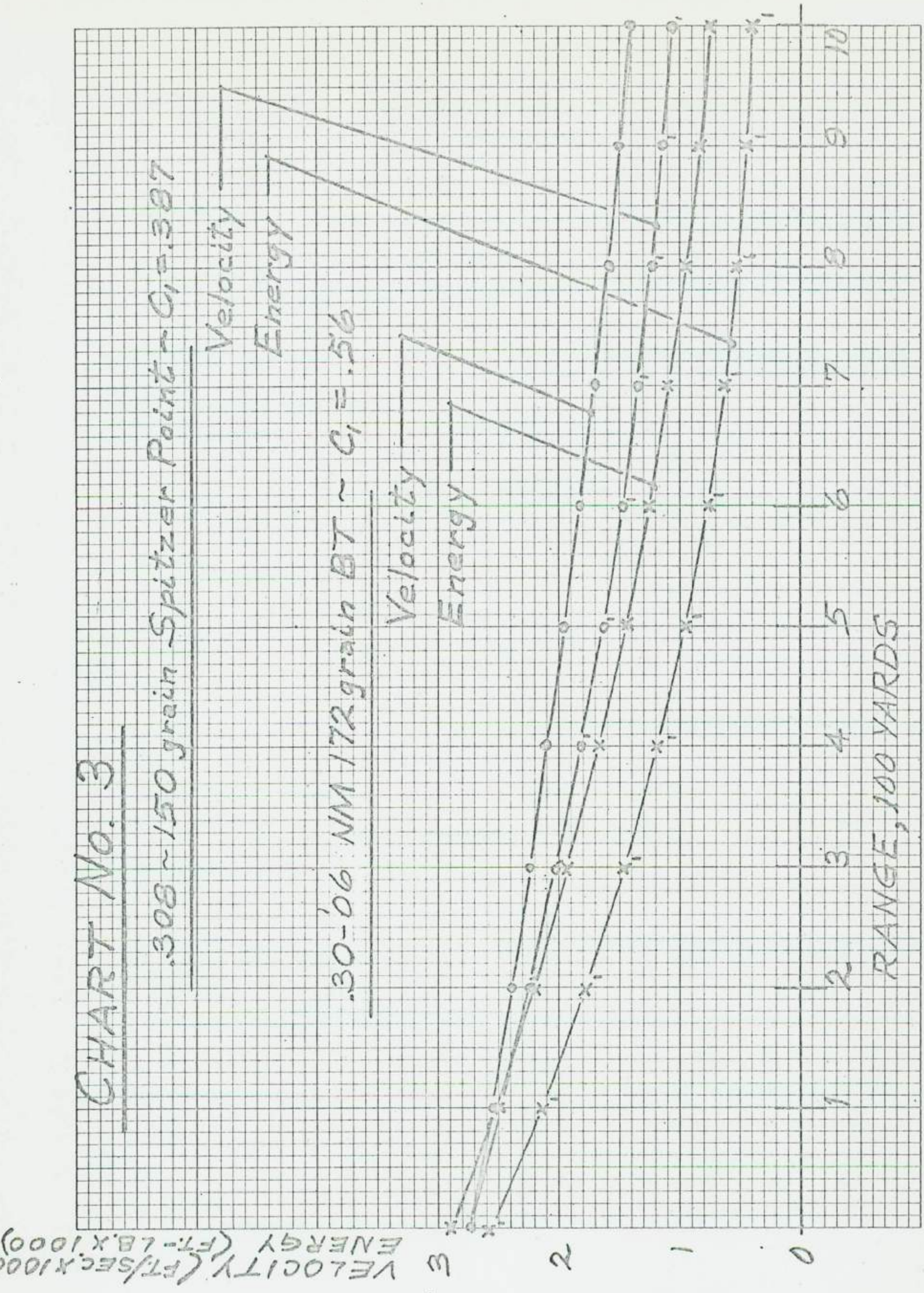


CHART No. 3
.308 ~ 150 grain Spitzer Point ~ C1 = .387
Velocity
Energy
.30-06 NM 172 grain BT ~ C1 = .56
Velocity
Energy
RANGE, 100 YARDS
1
2
3
4
5
6
7
8
9
10
VELOCITY (FT/SEC.x1000)
ENERGY (FT.-LB.x1000)
0
1
2
3

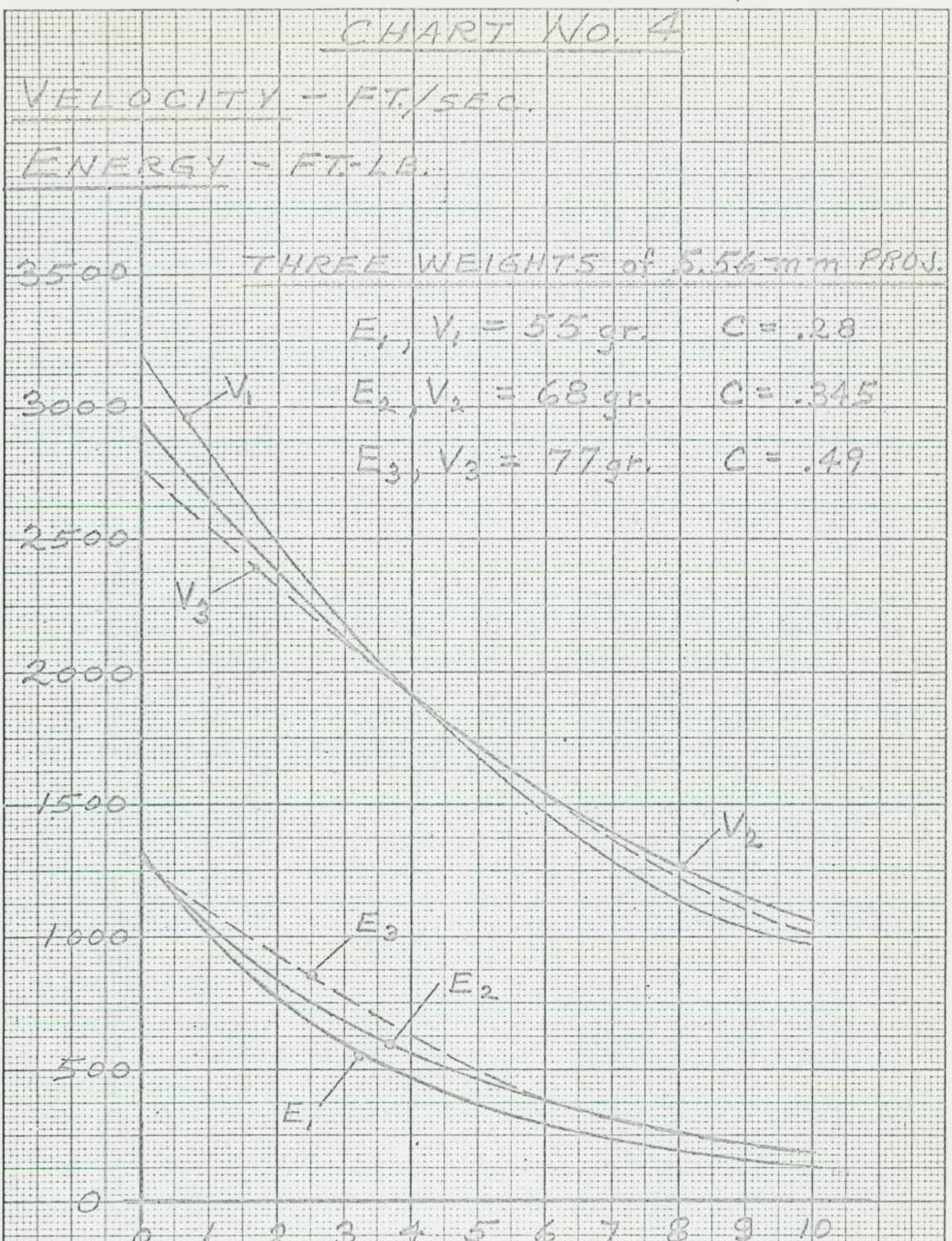


CHART No. 4
VELOCITY - FT./SEC.
ENERGY - FT-LB.
THREE WEIGHTS of 5.56 mm PROJ.
E1, V1 = 55 gr. C = .28
E2, V2 = 68 gr. C = .345
E3, V3 = 77 gr. C = .49
3500
3000
2500
2000
1500
1000
500
0
V1
V3
V2
E3
E2
E1
0 1 2 3 4 5 6 7 8 9 10
RANGE X 100 YD.

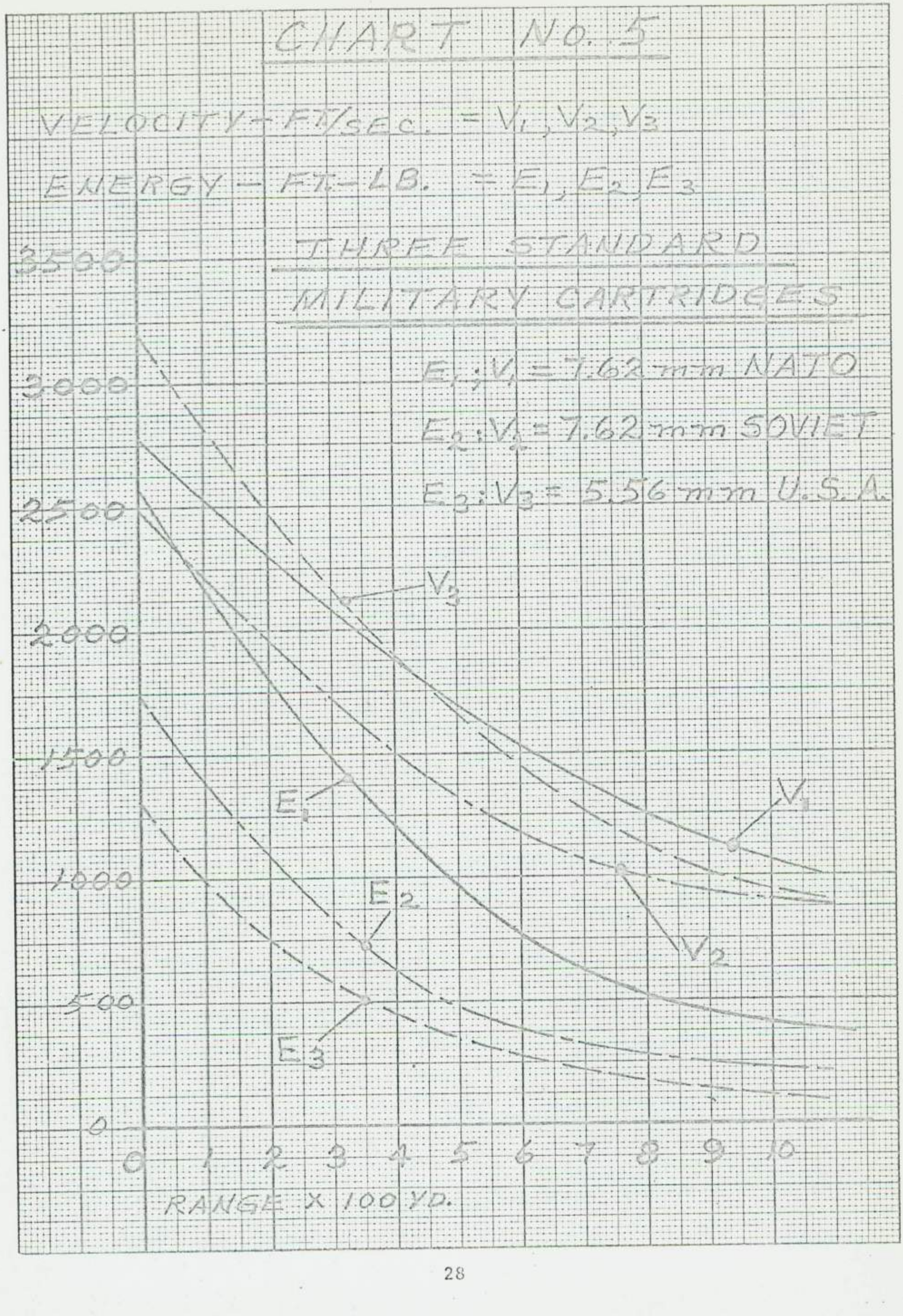


CHART No. 5
VELOCITY - FT/SEC. = V1, V2, V3
ENERGY - FT-LB. = E1, E2, E3
THREE STANDARD
MILITARY CARTRIDGES
E1 ; V1 = 7.62 mm NATO
E2 : V2 = 7.62 mm SOVIET
E3 : V3 = 5.56 mm U.S.A.
3500
3000
2500
2000
1500
1000
500
0
V3
V1
V2
E1
E2
E3
0 1 2 3 4 5 6 7 8 9 10
RANGE X 100 YD.

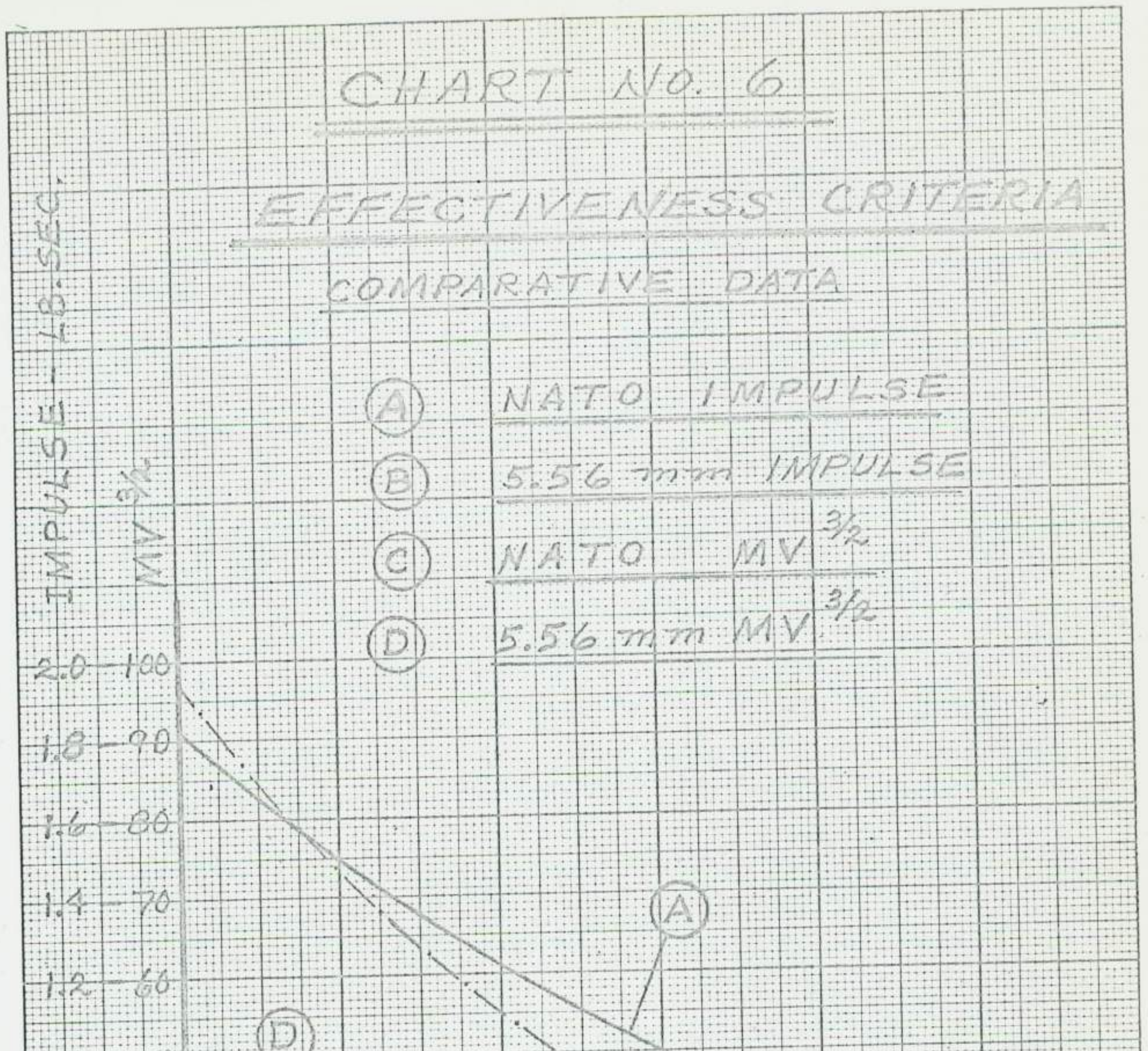


CHART NO. 6
EFFECTIVENESS CRITERIA
COMPARATIVE DATA
(A) NATO IMPULSE
(B) 5.56 mm IMPULSE
(C) NATO MV 3/2
(D) 5.56 mm MV 3/2
IMPULSE - LB-SEC
MV 3/2
2.0 100
1.8 90
1.6 80
1.4 70
1.2 60
1.0 50
.8 40
.6 30
.4 20
.2 10
.1
0 1 2 3 4 5 6 7 8 9 10
RANGE: YARDS X 100
A
C
D
B

In using the DuPont chart for bullet form, match the bullet profile carefully, noting that the sharp points on the diagram are for drafting reference only. The table makes adjustments for the diameter of the hollow point or flat nose.

The charts use a series of vertical reference planes and scales for each of the factors in the equation. Following the step-by-step directions for the given charts, data may be obtained for plotting the curve of remaining velocity up to 1000 yards range; the angle of departure; the time of flight; the maximum height of the trajectory; the angle of fall; wind deflection; and the remaining energy. The charts on the following pages compare the remaining velocities and energies of a number of commercial and military rounds. Note that the comparison of values at the muzzle is not the same as the comparison at, say, 500 or more yards. This is where the ballistic coefficient makes a significant difference.

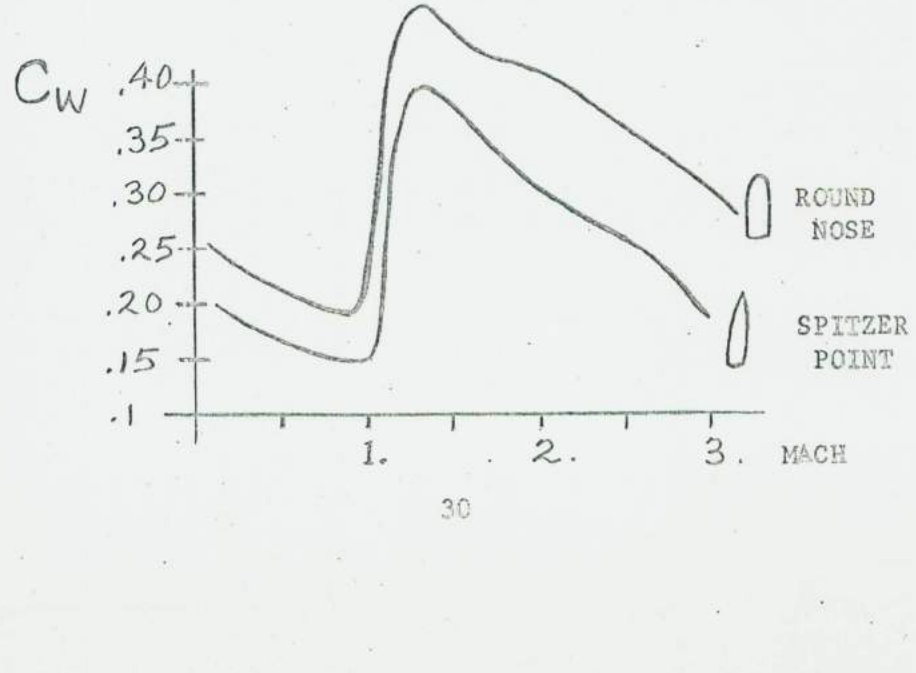
Charts #1, 2, and 3 are related to a following dissertation on "Ballistic Coefficient".

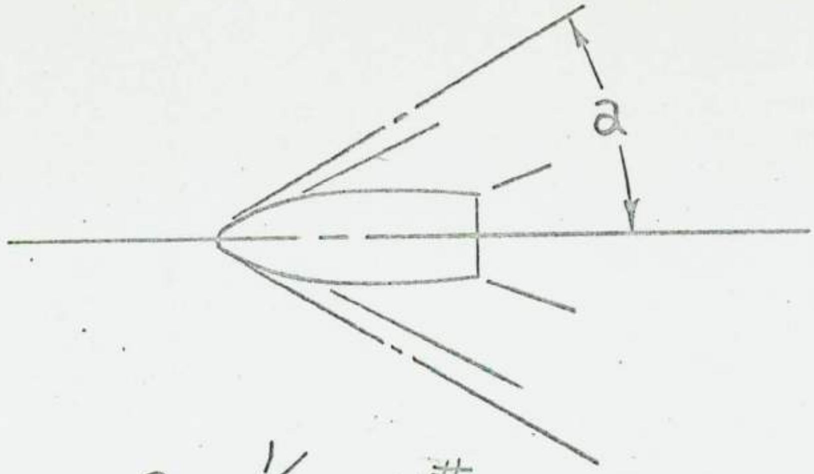
Chart #4 shows the effect of increasing the weight of, for example, a 5.56mm projectile. The resultant change in rate of velocity loss reflects a variation in the remaining energy level over the range of 1000 yards. In chart #5, values of remaining velocity and energy over the range of 1000 yards are shown for the three current military cartridges.

In addition, when the remaining velocities are determined by the use of ballistic tables, a variety of data may be derived, as shown in chart #6. Here, two philosophies of projectile effectiveness are shown in a comparison of the 7.62mm NATO and the 55 grain 5.56mm cartridge.

Remaining impulse and MV 3/2 curves reflect a comparison of these two standard cartridges over the range of 1000 yards.

The coefficient of air resistance as a function of the Mach number is shown as follows: (p. 181 Oerlikon handbook)





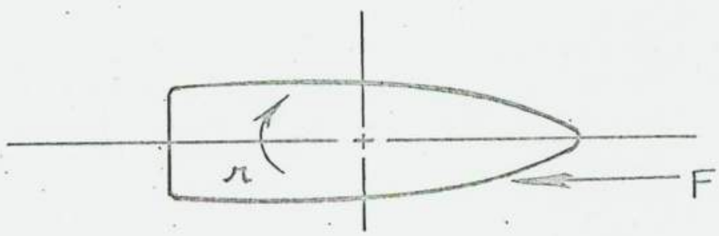

SIN a = 1/MACH #

Spark photogaphic techniques of a projectile in flight permit measurement of the velocity as a function of the Mach number.

The complex nature of the bullet's trajectory is due to the fact that for a spin stabilized projectile, the mass of the projectile is not concentrated at the center of gravity and the projectile does not travel exactly in the direction of its axis, but yaws, oscillating about the tangent of the trajectory. This angle is the angle of precession, and is caused by the air resistance and moment with respect to the center of gravity.

The projectile in flight is stabilized as a gyroscope is; by spin. Such a rotating body possesses an angular momentum that tends to resist forces that act to tilt the spin axis.

In comparing the behavior of a gyroscope, if a force is applied on the head of the projectile, F,




the projectile will turn, not about the horizontal axis, but will precess, or turn, about the vertical axis. This motion is called precession, and is due to the spin imparted by the rifling.

The force causing bullet deflection is not a lateral force against the side of the bullet, but a force applied at some other point on the ogive. There, it will tend to tip the bullet, and gyroscopic precession must result.

With comparable rates of spin, the angular momentum of a short fat bullet is much greater than that of a long thin one of equal weight, and the short fat one accordingly will precess more slowly and deflect less. Thus it will result in less deflection from branches and twigs. This is why round nose bullets have better brush - bucking ability than spitzer - point bullets.

Another familiar phenomenon is called bullet drift. It is well known that bullets tend to curve to the right of the line of sight when fired over long range, assuming a right hand rifling twist. This is also due to the gyroscopic effect. The force opposing gravity, on the ogive area forward of the center of gravity, causes precession to the right, because of the right hand spin. The yaw is the attitude of the projectile with respect to the longitudinal axis.

Likewise, windage will cause the projectile to strike higher or lower, depending upon wind direction. Wind blowing from right to left will cause bullet drift to the left, and at the same time (assuming right hand twist) due to gyroscopic precession, will cause the bullet to strike low.

Wind direction from left to right will conversely cause the bullet to drift to the right, and strike high.

The following informal dissertation on "The Ballistic Coefficient", by this author, again outlines the significant characteristics of the ballistic coefficient. Of particular importance is the comparison of the .264 (6.5mm) and the 7.62mm NATO remaining energies, which are equal from 600 yards to 1000 yards. (Chart #2).

Also significant is the comparison between the NATO round and the Cal. .30 - 172 grain bullet which shows, for example, that the heavier bullet has as much energy at 1000 yards as the NATO has at 650 yards. This is where firepower is improved without paying a penalty in the weapon.

## Ballistic Coefficient

What is it? Very simply, it is a measure of the efficiency of a projectile in flight through the air. If we were firing in a true vacuum, there would be no need to consider a ballistic coefficient, but firing in a true vacuum only occurs in high school textbooks, and the rest of us have to put up with air resistance, which creates frictional resistances and drag. This causes the projectile to steadily lose velocity. The rate at which velocity drops is determined by the Ballistic Coefficient. The higher the value of Ballistic Coefficient, the greater the efficiency of the projectile in flight.

The practical value of studying the Ballistic Coefficient should be apparent to those who seek a flatter trajectory, more impact energy at longer range, and a longer effective range. Instead of cramming more or hotter powder into the chamber to increase energy, which, by the way, adds dangerously higher strains to the barrel, locking lugs, and cartridge case, and shooter should pay closer attention to the bullet weight and shape. These are the factors that determine Ballistic Coefficient. The most efficient projectile would be essentially heavy (some even consider the use of a depleted uranium core) for maximum density, but retain a long smooth ogive (Spitzer point) with minimum flat point, and a boat-tail, to reduce the aft drag, or turbulence. The ideal bullet tip would be pointed, but this is impractical for handling in the magazine, therefore the flat tip diameter should be about one tenth of the caliber.

Other good reasons for paying attention to bullet design for increased effectiveness at longer range, rather than making the chamber hotter, are that, first with increased load, the recoil impulse is higher, loading your shoulder all the more, which also will affect your accuracy, and that higher loads reduce the number of times you can safely reload your cartridge. Also, barrel wear is reduced and the wear and tear on automatic mechanisms is also to be considered.

There are three factors in the standard formula for computing the Ballistic Coefficient and these are weight, bullet diameter, and form factor. The bullet weight divided by the bullet diameter squared is a measure of sectional density, and the higher this is, the better your Ballistic Coefficient. The form factor is a value based on the shape of the projectile. The longer the ogive radius and the smaller the tip flat diameter, the better the form factor. Boat-tailing the projectile also improves form factor.

Now let's look at some practical results of this Ballistic Coefficient in action. For example, study the curves shown in Chart #1, which plot velocity and energy of two different bullets out to 1000 yards. Each bullet is a standard 105 grain 6mm (cal..243) sample with a muzzle velocity of 2964 feet per second. The difference is that one is a round nose bullet with a Ballistic Coefficient of .256, while the other is a spitzer point bullet with a Ballistic Coefficient of .395. Of course, since bullet weights, diameters and muzzle velocities are identical, there is no difference in travel in the bore, since the energy from the expanding gases is identical in each case. After the projectiles leave the muzzle and are free in the air, then the difference in Ballistic Coefficient shows up markedly. Immediately the respective velocity and energy curves begin to separate from their common starting point at the bore, so that eventually, the spitzer point has the same energy at 1000 yards that the round point bullet has at 650 yards. Thus, by picking the spitzer point, you gain 350 yards in range effectiveness. Likewise, with velocity, for example at 600 - 700 yards, the spitzer bullet velocity is 40% greater than the round nose bullet.

This is not a condemnation of round nosed bullets, however. They have their place. The principle advantage of round nose bullets is their stability in brush bucking, when compared to Spitzer point bullets. Therefore, if you are hunting in wooded or brushy terrain, where you target is likely to be at medium or shorter ranges, use round nose bullets. If your hunting range is open country and the target is likely to pop up at longer ranges, then the Spitzer point bullet is recommended.

The criteria for effectiveness shown here is energy. Effects in tumbling and other wound ballistic phenomenon depend upon the portion of the game hit, whether boney, fluid, effectiveness against vital organs, etc., and are so variable that many arguments on this subject have burned the midnight oil, each hunter having a different opinion which naturally is based on his experience and observations. The subject therefore need not be exhausted further in this discussion.

Another interesting effect of an improved ballistic coefficient for a number of projectiles is that their performance is upgraded to the level of higher caliber cartridges at longer ranges. For example, note Chart #2, which compares a (.264) 6.5mm 140 grain bullet having a muzzle velocity of 2500 fps and Ballistic Coefficient of .482 with a (.308) 7.62mm 150 grain bullet having a muzzle velocity of 2740 fps and Ballistic Coefficient of .387. Both bullets are spitzer points. The big difference in Ballistic Coefficient is due to the smaller diameter of the 6.5mm coupled with its weight of 140 grains. This is known as sectional density, which is one reason why lead cores are used.

Looking at the curves, you will see that the 6.5mm muzzle energy is 2000 ft.-lb., while the 7.62 muzzle energy is 2600 ft.-lb. However, because of improved sectional density, or Ballistic Coefficient of the 6.5mm, the energies are equal at about 600 yards. That is, the 6.5mm caught up to the 7.62mm at that range, and equalled it on out to 1100 yards, at least. In fact, at those longer ranges, the 6.5mm remaining velocity is higher than the 7.62mm.

Many of you may recognize the 7.62mm example as the U.S. standard NATO military cartridge. This is true, and points out how the NATO Cartridge may be improved by increasing its Ballistic Coefficient. In fact, this can be done quite simply by substituting another standard 7.62mm projectile, the 172 grain boat-tailed National Match bullet, boasting an impressive Ballistic Coefficient of .56. Of course, a slight adjustment in powder charge is made in order to maintain peak pressure at the same level. That is, increasing bullet weight (without changing powder charge) causes the peak pressure to rise in the chamber. This is because the expanding gases are pushing against a heavier bullet, causing a slightly slower acceleration, or take-off, of the bullet; therefore, if you can imagine you are keeping the lid tighter on a boiling pot, the gas pressure will be higher, therefore either a slower burning powder is used, or a few grains of propellant are lopped off.

Chart #3 shows the vast difference in remaining energies for the two 7.62mm projectiles. For example, the 172 grain N M bullet has the same energy at 1000 yards that the 150 grain NATO has at 600 yards, and the NM energy at 1000 yards is double the NATO energy at 1000 yards. This is particularly advantageous when shooting in open country.

As a curious sidelight, compare the Ballistic Coefficient of the NATO (150 gr.) bullet with the old-time lead ball. The ball, being a sphere, will have a poor form factor, about 1.4 (the Nato is .6), and a corresponding Ballistic Coefficient of .152 times the ball diameter (which makes it easy to compute for all size lead balls). For a .30 cal. ball, the Ballistic Coefficient then is .0455 while the NATO is .387, even though the lead ball will be heavier, weighing in at about 200 grains (NATO, 150 grains).

The obvious result is that the lead ball, while potent at the muzzle, will lose energy very quickly. This is the main reason that shot pellets have such a short effective range of only 60-80 yards.

In summary, then, selection of a more efficiently streamlined bullet, (better surface finish, too, when casting bullets) will pay off more handsomely in striking energy than loading the case with a hotter powder charge. The benefits will also include a shorter time to target, a flatter trajectory, and, therefore, improved accuracy.

## Recoil

"Recoil" is nothing more than an expression of Newton's third law, which states that "for every action there is an equal and opposite reaction". The determination of recoil values is fundamental in ordnance, as it represents a measure of the force produced for each round fired.

The value of "free recoil" is usually considered in calculations of recoil energy. That is, not considering additional masses or resistances such as the shoulder or forearm that, in reality, make recoil "effect" less violent than the "free recoil" calculated. The calculation of free recoil is useful for purposes of comparison of one weapon, or charge, against another.

In fact, and as bourne out by experience, recoil effect or "kick" is lessened by holding the butt firmly against the shoulder. This affects the acceleration of the skeletal frame. Thus the resulting recoil energy is more "enjoyable" if it is a "push" rather than a "blow".

Some authorities place a limit on maximum recoil energy for a military rifle of about 15 foot-pounds. A person can briefly handle double that amount, but the frequency is not expected to approach that which the infantryman will fire. As an extreme, a fifteen pound elephant rifle may commonly have a recoil energy in excess of 50 foot pounds.

Typical recoil energies of several standard weapons are calculated as follows:

a. Recoil energy of Cal. .30 M1 rifle:

Projectile Impulse $=$ 2.3 lb.-sec.

Rifle impulse then $= 2.3 = WV/g$

$V = 2.3 \times 32.2/9 = 8.25$ ft./sec.

$E = WV^2/2g = 9 \times 68/64.4 = 9.5$ ft. lb.

b. Grenade Launcher M79:

Projectile impulse $= .375 \times 240/32.2$
$= 2.8$ lb.-sec.

Recoil Velocity $= 2.8 \times 32.2/6.5 = Ig/W$
$= 14$ ft./sec.

Recoil Energy $= WV^2/2g = 6.5 \times 194/64.4$
$= 19.6$ ft.-lb.

Often the question is broached as to the amount of rifle motion prior to bullet exit. Taking the common 30'06 rifle as an example, firing a 180 grain match bullet, popular in competitive target shooting in a 24 inch barrel, the solution is easily found. Simply consider the distance the bullet travels as being inversely proportional to the rifle recoil travel as the weights of bullet and rifle.

Consider 1/2 of the propellant charge as traveling with the bullet, since this is true up to the point of muzzle exit.

$$\frac{Sr}{Sp} = \frac{Wp}{Wr}$$

$$\frac{Sr}{24} = \frac{(180 + 25)/7000}{9}$$

$$Sr = .078 \text{ inch}$$

Various methods of measuring recoil are used, the preferred method being to hang the gun on parallel wires, and measuring the velocity of recoil of high speed cameras or other instruments.

This eliminates the use of secondary calculation, which do not correct for certain losses.

In another method, a steel ball is attached to the buttplate and the indentation made in a lead block is measured. (Ala rockwell hardness testing.) This method is good for comparative measurements only.

To calculate recoil data, the basic law of course, is $F = m\,a$. Since $a = v/t$ then $F\,t = mv$. The term "m v" is referred to as the "momentum", or the property of a given mass at a given velocity, while "F t" is the "impulse", or the effect of a given force acting for a given time.

For recoil forces, impulse is equivalent to the average force that would bring the moving body to rest in one second.

There are three vectors contributing to recoil and they are:

(1) Reaction to projectile acceleration

(2) Reaction to propellant motion

(3) Muzzle blast, both gas exit and action on muzzle face.

The first factor is the most important, and while the impulse of the projectile equals the weapon impulse, the energy is a function of velocity squared, therefore, the weapon energy is usually only about 1/200 of the projectile energy.

The effect of the muzzle blast is a function of muzzle pressure. Therefore, shortening the barrel does not reduce recoil, as one may think, since the muzzle velocity is lowered. Rather, recoil will be intensified because of the much higher muzzle pressure, usually quite noticeable. This is equivalent to a rocket thrust. and is determined by the equation:

Thrust = Muzzle pressure X Area X Mass rate of discharge. (This factor is a function of propellant chemistry).

An approximation that compensates for the unknown in muzzle blast equations is the practice of assigning a velocity of 4700 for gas exit velocity. This agrees with dynamometer tests for military small arms.

Thus the formula for recoil velocity of the weapon is approximately $Vw = (WpVp + 4700C)/Ww$

The energy then, $E = \frac{WV^2}{2g}$

The value of weapon impulse in firing is best determined by test firings in Ballistic pendulums or by using a Velocimeter to determine velocity of muzzle gases. It is this variable that limits the accuracy of conventional analysis. For example, the stated formula using a charge velocity of 4700 fps at the exit, is restricted to small arms with a projectile velocity in the range of 2400 - 2800 fps class. Further, the weapon impulse formula may be divided into two phases: First, impulse during projectile travel to the muzzle, and Second, impulse at muzzle exit.

For the first phase, the weapon impulse equals the projectile impulse plus the powder impulse at one half the projectile muzzle velocity, since the powder expands at one half the rate of the projectile velocity.

This formula, then, is:

$$I = Ww\ Vw/g = WpVp/g + 1/2\ WcVp/g$$

$$\text{or, } Vw = Vp\ (Wp + .5Wc)\ /Ww$$

After muzzle exit, additional impulse is realized due to the gas blast.

Extensive experiments indicate that this can be compensated for by increasing the effective mass of the powder charge as follows:

(1) For Shotguns and Revolvers with long barrels:

$Vw\ Ww = Vp\ (Wp + 1.25\ Wc)$

(2) Krag Rifles and shotguns and revolvers with short barrels:

$Vw\ Ww = Vp\ (Wp + 1.5\ Wc)$

(3) M1903 Rifle & M1 Rifle:

$Vw\ Ww = Vp\ (Wp + 1.75\ Wc)$

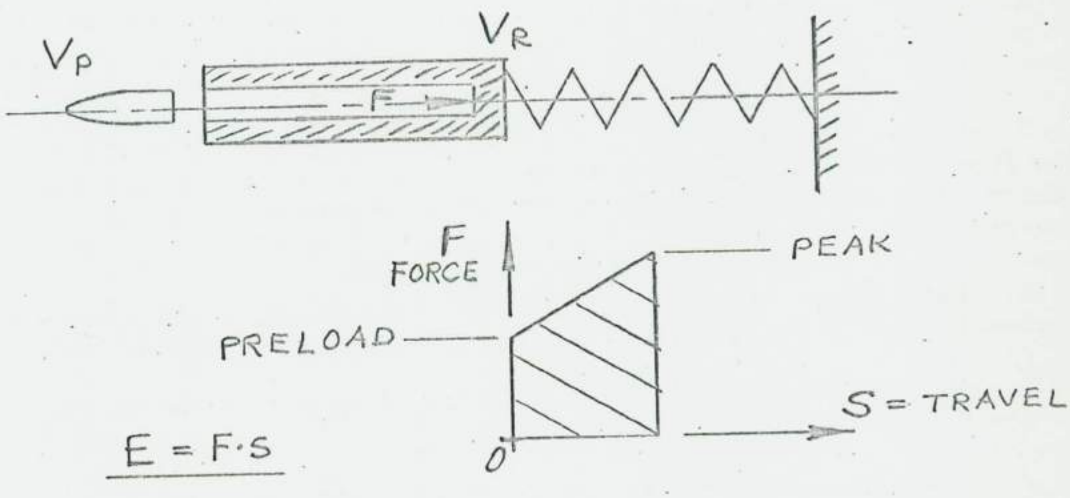
(This is comparable to assigning a charge velocity of 4700 at full charge weight, rather than 1/2 charge)

Pendulum data taken at Springfield Armory show an impulse of 2.51 lb.-sec. for the M14 rifle. This resulted in a constant of 1.05 (V= 2860). (Impulse varied from 2.45 - 2.55)

The mount, or gun support, must react to the recoil energy, and the value of this force depends on the elasticity of the mounting.

The conditions of loading for resilient mounts depend upon the stiffness of the spring; for stiff springs the load is high, while recoil is short, while for softer springs, the load is lower, but a longer permissible recoil travel is required. The weapon rate of fire requirements determine spring rates.

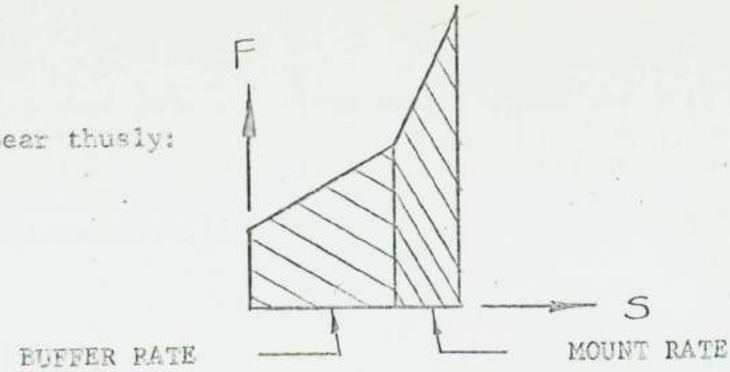
In the following schematic, note that the area under the spring load diagram approximately equals the recoil energy:




Ordinarily recoil systems will have secondary loading diagrams, which may be due to buffers, resilient pads, or the frame work itself.

The diagram would appear thusly:

$$E = \int F \cdot S$$




Therefore, in laying out spring loads for assembled and minimum heights the area under the trapezoidal diagrams should represent the energy of the recoiling mass.

A study of the recoil effects of shoulder fired small arms weapons was conducted at BRL, Aberdeen, Maryland, and the following observations were made:

a. The free recoil momentum and energy of rifles firing AP ammunition were greater than those firing ball ammunition.

b. The average escape velocity (at the muzzle) of the powder gas was less for AP ammunition than it was for ball ammunition. A greater part of the powder energy was apparently transmitted to the AP projectile.

c. Experimental muzzle brakes produced a considerable decrease in the gas escape velocity, while a cone-type flash hider produced an increase.

d. The recoil momentum of the M1 rifle is slightly less than that of a Springfield rifle, most likely due to the escape of gas at the breech on opening.

In another series of tests, a variety of shooters fired the M1 rifle from a standing position, without use of a sling. Measurements of force vs. time and displacement vs. time were made. Results indicate:

a. The average maximum force and velocity on 10 out of 11 men was greater when firing AP ammunition (over ball ammunition).

b. The variation of force and velocity from man to man was relatively large.

c. The maximum velocities are lower than the free recoil velocities in every case. This is due to the shooter's arm and shoulder weight, as well as his resisting force. The effective shoulder weight varies from 3.5 to 5.0 pounds, and neglects the resisting forces.

d. It appears that the way a rifle is held has a greater effect on recoil than the size or build of a rifleman.

Quantitative values were found as follows:

a. Free recoil measurements (five wire pendulum) of M1 Rifle (weight rifle = 9.72 lb.)

(1) Ball ammunition:

| | | |
|---|---|---|
| (Projectile) | $W_p V_p$ = | 58.63 ft. lb./sec. |
| (Charge) | $W_c V_c$ = | 30.77 ft. lb./sec. |
| (Rifle) | $W_r V_r$ = | 89.40 ft. lb./sec. |
| | $V_c$ = | 4270 fps |
| | $V_r$ = | 9.2 fps |
| Rifle | KE = | 12.8 ft.-lb. |

Average Maximum force (11 shooters) = 69.3 lb.
Standard deviation = 3.6 lb.

(2) AP ammunition:

$W_p V_p$ = 64.71 ft. lb./sec.
$W_c V_c$ = 30.07 ft. lb./sec.
$W_r V_r$ = 94.78 ft. lb./sec.
$V_c$ = 4170 fps
$V_r$ = 9.75 fps
$KE_r$ = 14.4 ft.-lb.

Average maximum recoil force = 73.7 lb.
Standard deviation = 3.2 lb.
(Note that $W_pV_p + W_cV_c = W_rV_r$)

## Dynamics of Automatic Rifles

The tactical requirements of a full automatic weapon are quite different than those of a semi-automatic rifle, so a weapon design that seeks to satisfy both functions can only be compromise, at best. (M-14 vs BAR). The BAR, being a heavy automatic rifle, can be held on the target area, whereas the lighter M14, with a dropstock, climbs badly in automatic fire.

When a round is fired, an impulse develops both translational and rotational velocities in the gun. This is not a significant problem in semi-automatic fire, but in full-auto, riflemen have difficulty holding the weapon on the target.

The induced rotational velocity, multipled by the time lapse between shots represents the angular deviation between successive shots. This widens for each round because of the initial velocity input for successive rounds. Therefore, an effective automatic fire program should be limited to short bursts if any degree of accuracy is desired.

With "w" representing angular velocity increments per round, "r" the rate of fire, "n" the number of rounds in a given burst and "θ n" the accumulated deviation for the burst, the following formula is applied:

$$\theta n = 1/2 \frac{w}{r} n (n - 1)$$

Therefore, the deviation varies as the angular velocity increment and inversely as the rate of fire. Therefore, firing rate should be higher for this application. However, if the geometry and weight of the weapon is such that the shooter can be trained to "hold" the rifle on target between rounds, then a lower rate may be desired, as in the BAR.

The "salvo" concept is concerned with the "number of rounds" that are fired into a target area before a significant deviation occurs. This is in line with the "shotgun" concept. Note that the formula contains an $n^2$ factor; therefore, the deviation is accelerating with burst length. As an example, with a firing rate of 600 spm and a "w" per shot of 20 mils per second; the deviation as a function of burst length is as follows:

| Shot No. | Deviation (mils) |
|---|---|
| 1 | 0 (assumed) |
| 2 | 2 |
| 3 | 6 |
| 4 | 12 |
| 5 | 20 |
| 6 | 30 |
| etc. | |

Therefore, a three round burst, as utilized in the SPIW system, would offer short bursts of maximum effectiveness and prevent needless waste of ammunition.

One critical user test is the "quickfire" course, in which the shooter fires at short-range random targets from the hip. Here, rifle profile is important, as noted in tests with the M16 rifle. With the shooter's eye approximately 18 inches above the weapon, the shooter's projected sight line runs from the top of the carrying handle to the muzzle. This creates an optical illusion that cause the bore to be projected at a sharp upward angle, causing the shooter to hit high.