MECHANICS OF PROJECTILES IN FLIGHT

BY

PATTI CANADA

A THESIS SUBMITTED FOR THE DEGREE OF

BACHELOR OF SCIENCE

MECHANICAL ENGINEERING COURSE

The University of Tennessee

1936

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MECHANICS OF PROJECTILES IN FLIGHT

Introduction

The word "Projectile" means, in the general usage, a body projected by an exterior force, and continuing in motion by its own inertia. In the technical sense it refers to a missile from a firearm. In this thesis the term "Projectile" is used in the latter sense.

The purpose of this thesis is to develop a theory of the motion of projectiles from basic considerations of Mechanics. Wherever applicable, basic equations of mechanics of motion will be taken and from them the theoretical values of pressure, velocity, trajectory, wind deflection, and time of flight will be computed. Then such constants will be developed as to modify these formulas so that they will give results comparable to test results and to such emperical formulas as are used by the manufacturers of firearms.

MECHANICS OF PROJECTILES IN FLIGHT

Part I

DESCRIPTION OF A CARTRIDGE

The complete cartridge consists of four distinct parts; the case, made from brass plate, stamped and drawn to size; the bullet, either lead or jacketed with an alloy; the primer, which is a brass cup with a priming explosive within; and last, the powder, which is inside of the case and which is kept in the case by the bullet.

The projectile is the bullet. To project the bullet the primer is struck and this ignites the powder. The gases given off expand and force the bullet out through the barrel into space by virture of the pressure thus created.

Powder Space and Combustion

The cartridge is designed to hold a certain amount of powder and a certain amount of air space for best results. Some powders are very dense and do not require much space; others, being less dense, require more. In rifle cartridges, cases are made large and bullets are small in diameter. This is because the bullets are to be expelled at high velocities and require relatively large amounts of powder. In revolver cartridges the use of large bullets and small powder space is now considered standard. This is because revolvers are not made to withstand high pressures; therefore, large bullets at low velocities are used in order to obtain penetration.

If powder is burned in the open air there is no explosion,

but when it is confined to a relatively small space the gases will expand and cause an instantaneous combustion. This is due to the fact that the gases given off will have no place to escape. The powder capacity of a cartridge case must be correct in size for the proper charge of an existing and suitable powder which will give the muzzle velocity desired within the limit of the permissable working pressure of the firearm, and also within the limit of proper burning pressure of the powder.

In bolt-action rifles of high-power, this pressure may be as much as 50,000 pounds per square inch. The cartridge case must be built to withstand this pressure else it might rupture in the rifle causing injuries to the shooter. In the case of revolver cases the pressure seldom exceeds 15,000 pounds per square inch which is a comparatively low pressure. Powder also has low pressure limits, which means that below a certain pressure they will not burn clearly or completely, and the projectile will not take any definite flight.

Bullet Design and Weight

Modern high powered bullets are jacketed with gilding metal or lubaloy. Gilding metal is an alloy of 90% copper and 10% zinc. Lubaloy is a gilding metal with 1% tin added.

For best accuracy bullets should be of such length and shape that at least one caliber of their length can be inserted within the neck of the case, and one caliber length is outside the case to permit centering of the bullet by

the throat of the chamber.

The best bullet is one with a flat base; boatail bullets are of no advantage in rifles. Theoretically, boatail bullets give less pressure, have higher muzzle velocity with the same pressure and have higher remaining velocity. But these advantages are summed up against their disadvantages, which are more barrel erosion and wear. Also they have to be made with more care in order to assure as good accuracy as with flat base bullets.

Primer Design and Its Effect on Accuracy

Primers are very important in the accuracy of the projectile as they ignite the powder. They may be divided into rifle and revolver primers; into corrosive and non-corrosive, and mercuric and non-mercuric. Rifle primers are necessarily harder than revolver primers because they must withstand greater pressures. They maybe corrosive or non-corrosive and mercuric or non-mercuric. In case one wishes to reload the brass cases again, the primer should be both non-corrosive and non-mercuric since the case must be kept clean and non-brittle. The same is true for primers in revolver cartridges. When primers are intended for use in revolver cartridges they are made soft so that the hammer will not have to strike a hard blow to cause ignition.

PART 2

INTERIOR BALLISTICS

Interior ballistics is the scienc of projectiles in motion while in the barrel from which it is being projected. This includes the time from when the firing pin strikes the primer until the bullet leaves the muzzle. When the firing pin strikes the primer, the priming composition ignites, and in an instant sets the powder to burning. In a firearm the powder isconfined in a very small space in the base of the cartridge behind the bullet; and the only way the gases of combustion can expand is to push the bullet along the barrel.

The cartridge case capity is of great importance as it governs the amount of pressure the gases of combustion will generate in order to drive the projectile forward through the barrel. This pressure exerts itself equally in all directions. Since the walls of the case are confined by the chamber and the gas can escape in no way except by pushing the bullet foward through the barrel, the bullet is forced from the firearm.

The pressure and velocities may be found comparatively easily and quickly by experiments in the laboratory. Velocities are found by having velocity meters along the barrel at regular intervals. These meters are similiar to water meters and automatically record the velocity of the bullet as it

passes through the barrel. The pressure is also automatically recorded by meters, but they are not placed at regular intervals. Near the chamber they are placed close together. While near the muzzle they are placed farther apart. The calculation of these pressures and velocities is a long slow process, which will be explained in detail in the following pages. The results obtained theoretically and actually will be compared in the tables and curves that follow.

Theoretically, this pressure may be obtained by means of derivation of a series of formulas. The velocity given to a projectile and the burning of the powder are directly proportional to the gas pressure. By taking small intervals and assuming P_1 and P_2 as the pressures at the beginning and end respectively it follows that:

$$\frac{P_1 + P_2}{2} = P_a \text{ average pressure-time interval}$$

Since $$F\,T = M\,V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

In which:

F= force in pounds
M= Mass in slugs
T= time in seconds

and

$$F = P_a\,A$$

also

$$M = \frac{W}{G}$$

W= weight in pounds
G= acceleration in feet per second per second

By substition into (1):

$$P\,A\,dt = \frac{W}{G}\,dv \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Therefore the velocity added during the time interval is :

$$dv = \frac{G\,A\,P}{W}\,C\,C'\,dt$$

In which:

C= a constant to correct for friction

C'=a constant for correcting P to pounds per sq.inch
dt= time of interval in seconds
A_b= area of bore
W= weight of projectile in pounds
P_e= effective pressure in tons per square inch

If V is the initial velocity in feet per second of the interval, the distance moved by the projectile during the time interval is:

$$V_1 = \frac{dv}{2}$$

During this same time interval the amount of powder burnt is equal to:

$$dr = R\ K\ P\ dt$$

In which:

dr= reduction in grains of powder
R = ratio of reduction per ton, per second
K= ratio of the average pressure to P_e

Having found the powder burnt, one may now find the weight of the powder burnt during this time interval.

$$P_a = \frac{\frac{T\ V}{237\ A_T}}{\frac{1}{D} - \frac{V_o}{1000}}$$

(Derived from gas laws, see Thermodynamics, by Goodenough.)

P_a = Pressure assuming no heat loss
A_T = atmospheres in tons per square inch
D= loading density of powder burnt
V_o = the volume of gas given off by one grain of powder

In order to correct for the heat loss by conduction and by friction the formulas were obtained from physics (Physics by Duff and Lewis.)

$$P = P\left[1 + \frac{3}{C}\frac{T1/3}{2330}\right]$$

This is the formula which corrects for conduction loss, In which:

P_c = P_a cooled by conduction
T = time of interval
C_1 = weight fo powder burnt in pounds

The following is also true:

$$\frac{Q_2}{Q_1} = \frac{T_2}{T_1}\frac{C_2}{C_1}$$ (Thermodymics, by Goodenough)

In which:

Q_1 = calories at T_1 degrees
C_1 = average specific heat of the gas between T_1 and T_2
Q_2 = calories at T_2 degrees
C_2 = average specific heat of the gas from T_2 and T_1

Therefore:

$$\frac{Q_2 T_1 C_1}{Q_1} = \frac{T_2 C_2 Q_1}{T_1 C_1}$$

$$\frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2 C_2/C_1}{T_2} - \frac{dq}{Q_1} \quad \text{.....(3)}$$

dq = loss, in calories
T = absolute temperature of the gas

But for any stage in the expansion:

$$\frac{P_2}{P_1} = \frac{T_2}{T_1}$$

Therefore:

$$\frac{P_1 - P_2}{P_1} = \frac{T_1 - T_2}{P_1} = \frac{dp}{P_1} \quad \text{.....(4)}$$

In which:

dp = loss of pressure due to $T_1 - T_2$

Combining equation (3) and (4) gives:

$$\frac{t_1}{T_1}\frac{dq}{Q_1} = \frac{t_1 - t_2 C_2/C_1}{T_1} = \frac{dp}{P_1}\frac{t_1 - t_2 C_2/C_1}{t_1 - t_2}$$

Let

$$F = \frac{t_1}{T_1}\frac{t_1 - t_2}{t_1 - t_2 C_2/C_1}$$

Therefore:

$$\frac{dp}{P_o} = F\frac{dq}{Q_o}$$

F has been found to be constant and equal to 0.8 for temperatures from 1000° to 3330° C.

Therefore:

$$\int\frac{dp}{P_o} - 0.8\int\frac{dq}{Q_o}$$

In which:

dp = change in pressure
dq = change in calories
P_o = initial pressure
Q_o = initial calories

The time the bullet is in the barrel is rather easily calculated since the velocity at the muzzle is found by experiments. One method is to have a platium wire across the muzzle of the firearm which is broken as the bullet touches it. This is attached to an instrument which records the time taken for the bullet to travel from the chamber to the muzzle. There is another wire attached to the trigger of the gun which records the instant the bullet left the chamber.

According to the laws of mechanics the velocity that will be caused by any force acting on a movable object for one second is equal to the force in pounds, divided by the mass of the object.

Since:

$$M V = F T$$

In which:

M= mass in slugs
V= velocity in feet per second
F= force in pounds
T= time in seconds

It can be stated that:

$$V = \frac{F\,dt}{M}$$

But the friction losses are:

$$C P \int f\,ds$$

Therefore the actual velocity is:

$$V = F \int \frac{dt}{M} - C P \int f\,ds$$

In which:

dt = interval of time
C = constant

P = pressure in tons per square inch
f = friction factor
ds = space through which the force is acting

Comparing theoretical and actual values of pressures and velocities computed by the above formula, the following tables are prepared.

TABLE NO. 1

(Taken from actual experiments for Volume-Pressure and Space Velocity Curves.)

Barrel length in inches	Pressure in tons per sq. inch	Velocity in feet per second
1	0.4	10
2	7.0	110
3	17.5	500
4	18.5	900
5	17.5	1300
6	16.0	1500
8	12.25	1800
10	10.00	1900
12	7.50	2100
14	6.25	2200
16	5.00	2300
18	4.20	2350

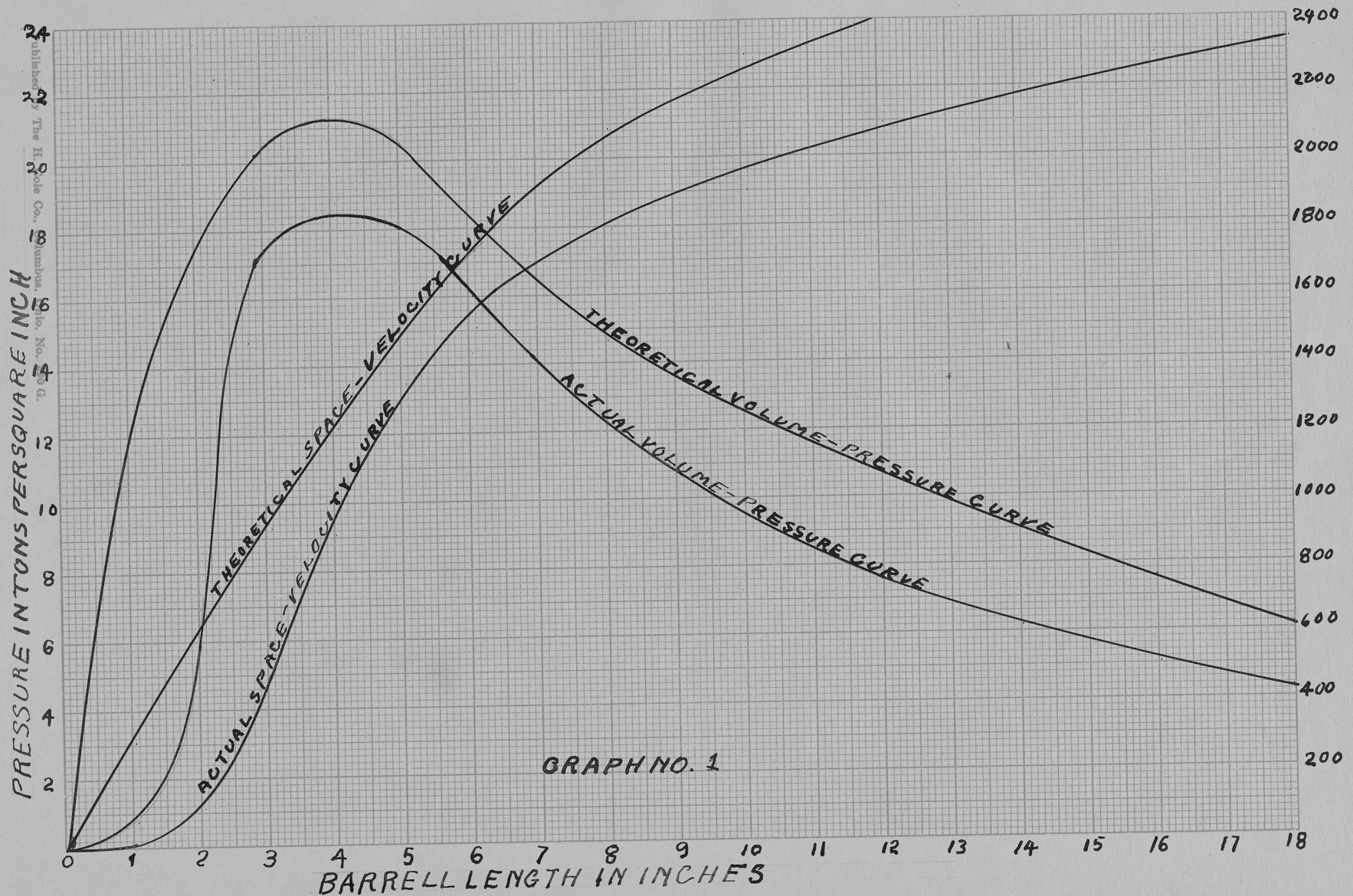
TABLE NO. 2

Barrel length in inches	Pressure in tons per sq. inch	Velocity in feet per second
1	12	300
2	17.80	630
3	20.50	740
4	21.00	1220
5	20.50	1500
6	17.20	1720
8	14.90	2100
10	12.30	2300
12	11.35	2500
14	9.00	
16	7.50	
18	6.00	

(Volume-Pressure and Space-Velocity Table calculated from formula no.5)

The Energy of a Projectile

The energy of a projectile is very important as it determines to a great extent power of the projectile. The



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energy of a projectile may be found mathematically as follows:

$$1/2\ M\ V^2 = \text{Kinetic Energy}$$

In which:

M =mass in pounds
V =velocity in feet per second

In order that this formula may be more useful in finding energies it may be written as follows:

$$1/2\ M\ V^2 = \text{Kinetic Energy in foot pounds}$$

$$\frac{1/2\ M\ V^2}{7000} = \text{K.E.}$$

$$0.000022225\ M.V^2 = \text{K.E.}$$

In which:

M =mass in grains
V = velocity in feet per second

By intergration of the volume-pressure curve the energy may be found from which the velocity of the projectile may be calculated. This intergration gives:

$$P\ ds = \text{work} = U$$

But,

$$U = 1/2\ M\ V^2$$

Thus

$$V^2 = \frac{U}{.5M}$$

$$V = C\ C'\ \frac{U}{.5M}$$

In which:

V= velocity in feet per second
U= work in foot pounds
M= mass in grains
C= friction factor
C'=constant which corrects the pounds to grains

Graph No.2 shows the muzzle velocities both theoretical and actual for barrel lengths of 2,4,6, and 8, inches. Table No.3 compares these values. Actual values were taken from the Ideal Handbook No. 31, published by the Lyman

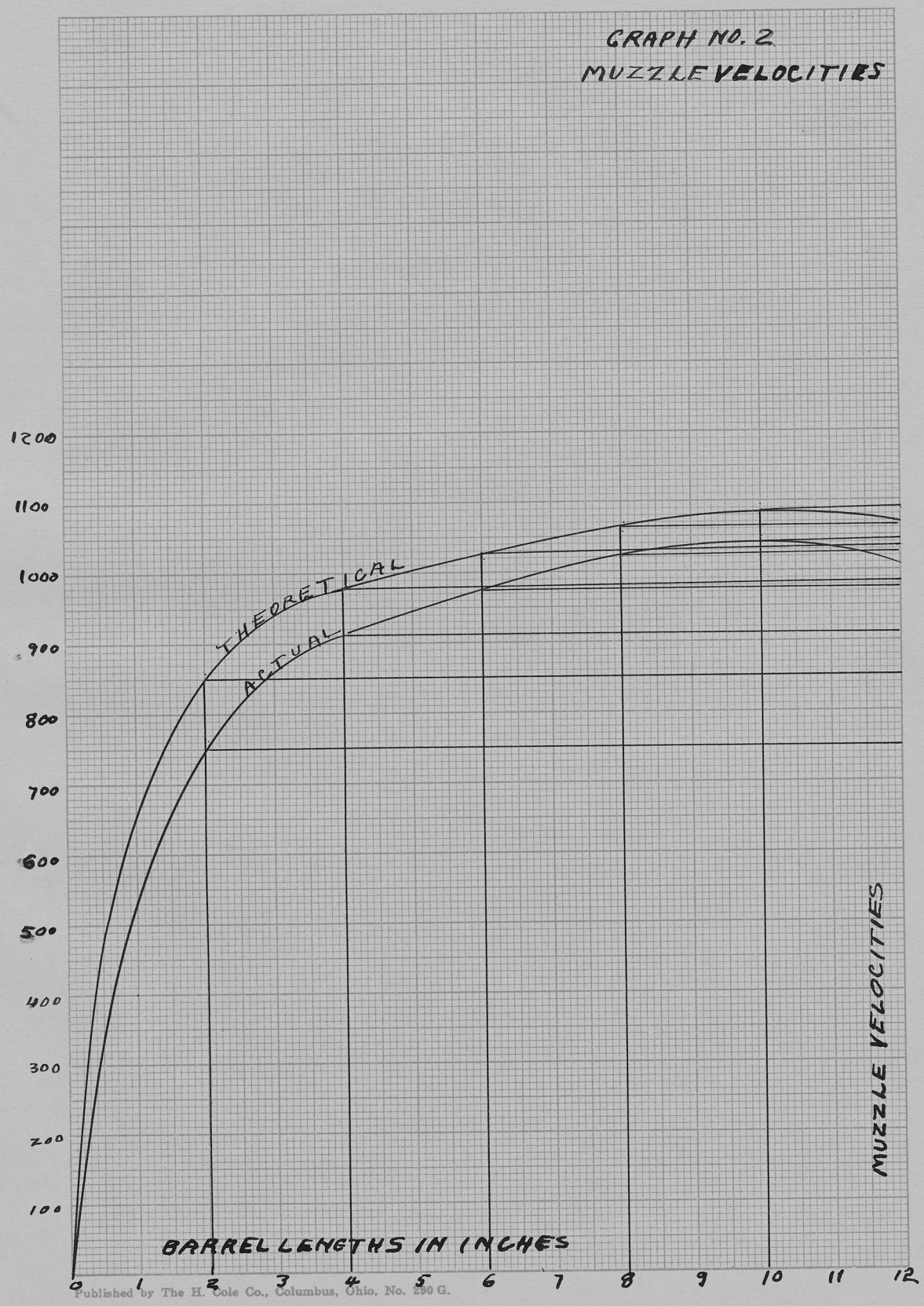
Gunsight Corp.

TABLE NO.3

Barrel lengths	Theoretical Muzzle velocities	Actual Muzzle velocities
2	860	760
4	940	880
6	980	965
8	1020	990

SUMMARY

Interior ballistics deals with the bullet while it is within the firearm. The srength of the primer, the quantity of powder, the rapidity with the powder burns, the fit of the case in the chamber, and the fit of the bullet in the bore, all affect the pressure exerted on the bullet. In turn, this pressure determines the acceleration of the bullet in the bore and consequenly its velocity when it leaves the muzzle. Pressures and velocities at successive points along the bore may be calculated from the formulas derived above, and they may also be found experimentally in the laboratory. Results as calcuated by purely theoretical formulas will agree closely but not exactly with experimental results because of the effect of bore-friction, gas- leakage, and heat conduction by the barrel. The relation between theoretical and experimental results can be observed on Graph No. 1 which is plotted from Tables No. 1 and 2.



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PART 3

EXTERIOR BALLISTICS

Determination of the Path of a Projectile while in Flight

The purpose of all ballistics work is to enable the best results to be calculated from certain dominating factors, namaly, the muzzle velocity, the diameter, weight, shape of the point, and the atmospheric conditions prevailing at the time. If the methods which are adopted enable such a calculation to be made with accuracy it follows that future results can be predicted with equal accuracy.

Theory of a Projectile in Flight

All bodies which fall free would have the same acceleration if it were not for the effect of air resistance. Air resistance is very small in the case of all dense solids falling short distances and may be neglected for the theoretical case. Thus when a body is projected vertically downward with a given velocity, such as V_1 the total velocity may be found by the equation:

$$V_2 = V_1 + gT \qquad (1a)$$

In which,

V_1 = initial velocity
g = acceleration of gravity in feet per second
T = time in seconds
V_2 = velocity at end of T seconds

The air resistance is very noticable where the body is projected over long distances at high velocities and must be taken into account. By introduction of a constant the air resistance may be taken into account ,and formula (1a) may be written as follows:

$$V=(V_1-gT)f.$$

In which the constant f is the friction factor.

The above formula holds true for bodies being projected either up or down vertically but does take into consideration bodies being projected obliquely into the air. When the motion of a body is at an angle with the horizontal, it may be thought of as consisting of two compoents, horizontal and vertical. The vertical velocity is subject to gravity, while the horizontal velocity is constant. This is the theoretical case neglecting air resistance.

Let X = horizontal distance traveled in T seconds
V = velocity in feet per second
T = time in seconds
θ = angle above or below the horizontal from which the body was projected

If X is the horizontal distance covered in T seconds, then:

$$X= V\ T\ \text{cosine}\ \theta$$

Likewise:

$$Y= V\ T\ \text{sine}\ \theta + 1/2\ gt^2$$

Let D = actual distance covered in T seconds

$$D =\sqrt{X^2+ Y^2}$$

By substition:

$$D =\sqrt{(V\ T\ \text{cosine}\ \theta)^2\pm (V\ T\ \text{sine} + 1/2\ gt^2)^2}\quad.....(2a)$$

This gives the theoretical distance when air resistance is neglected. (D is the distance along the trajectory.)

Remaining Velocity

In order to obtain the true velocity of a projectile in still air, certain constants will be introduced to take into consideration the air resistance.

The "unit" form of bullet is evolved by introducing a term known as "Ballistic Coefficient, which is:

$$B = \frac{W}{N D^2}$$

In which,

W= the weight of the bullet in pounds
D= diameter of the bullet in inches
N= form factor
B= Ballistics Coefficient

The form factor N depends upon the shape of the bullet, its steadiness in flight, and the density of the atmosphere. For all practical purposes the steadiness of flight of the projectileand the density of the atmosphere may be considered as constant. N will then vary directly with the shape of the bullet and will be called the "Coefficient of Shape". If all the bullet forms are reduced to one common denominator called the "Ballistic Coefficient" all range velocities can be found irrespective of the actual bullet and the effect of air resistance thus stands out as being applicable to all.

The actual formula for the distance covered may now be computed from formula (2a).

Let, D= distance in feet
T= time in seconds
V= horizontal velocity in feet per second
θ= angle with the horizontal line in degrees

$$D = V T$$

Hence,

$$T = \frac{D}{V}$$

Substituting $\frac{D}{V}$ for T in equation (2a):

$$D = \sqrt{(D \text{ cosine } \theta)^2 + \tfrac{1}{2} g \frac{D}{V})^2}$$

Squaring and reducing, this equation becomes:

$$V^2 = g D^2 \text{ sine } \theta + g^2 D^4$$

$$V^2 = \frac{g^2 D 4}{g D \text{ sine } \theta}$$

$V^2 = g\ D^2 \text{cosecant}\ \theta$
There fore the actual velocity is:

$$V = \sqrt{B\ g\ D^2 \text{cosecant}\ \theta}$$

The actual remaining velocity may now be calculated, and from it the time of flight of the projectile may be found. The following compares the calculated values taken from the tables of the Winchester Handbook, published by the Winchester Repeating Arms Company.

TABLE NO. 4
Calculated Velocities

Caliber	Muzzle Velocity	Remaining Velocity in feet per second				
		50	100	150	250	400 yds.
30.06 220 Gr. Bullet	2400	2350	2200	2150	1900	1730
30.06 180 Gr. Bullet	2700	2625	2510	2420	2210	1940

TABLE NO. 5
Actual Velocities

Caliber						
		50	100	150	250	400 yds.
30.06 220 Gr. Bullet	2400	2335	2185	2100	1925	1625
30.06 180 Gr. Bullet	2700	2590	2500	2410	2200	1900

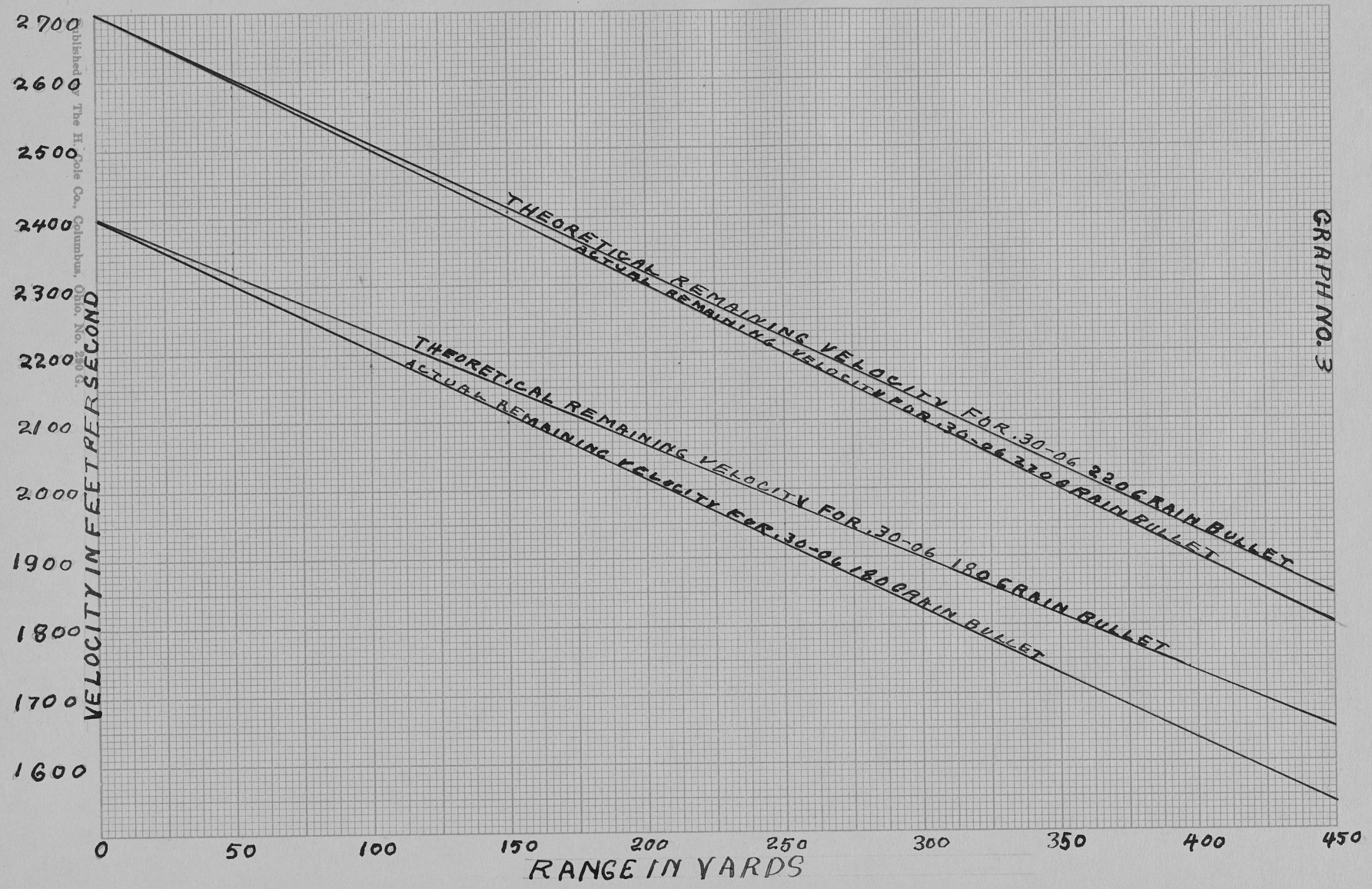
Trajectory of the Projectile in Flight

Let X equal the horizontal distance
Y equal the vertical distance
A equal the acceleration in feet per second per sec.

By definition:

$$A = \frac{V_2 - V_1}{t_2 - t_1} = \frac{dv}{dt} = \frac{d^2x}{dt^2} \text{ or } = \frac{d^2y}{dt^2}$$

$$A = \frac{d^2x}{dt^2} = 0 \qquad A = \frac{d^2y}{dt^2} = -g$$



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$$V_x = \frac{dx}{dt} = C_1 \qquad V_y = \frac{dy}{dt} = -gt + C_3$$

$$x = C_1 t + C_2 \quad \text{.....(1b)}$$

$$y = -\tfrac{1}{2}g t^2 + C_3 t + C_4 \quad \text{.....(2b)}$$

Where;

$C_1 = V_o \cos\theta$
$C_2 = 0$
$C_3 = V_o \sin\theta$
$C_4 = 0$

C= constant of integration
t= time in seconds
V_o= initial velocity

Combining Equations (1b) and (2b) and eliminating t one obtains:

$$y = -\tfrac{1}{2}g\left(\frac{x}{V_o \cos\theta}\right)^2 + V \sin\theta \left(\frac{x}{V_o \cos\theta}\right) \quad \text{...(3b)}$$

Where, $t = \dfrac{x}{V_o \cos\theta}$

Simplifying:

$$y = \tfrac{1}{2}g \left(\frac{x}{V_o \cos\theta}\right)^2 + x \text{ tangent } \theta$$

In order to find the maximum height of the trajectory let $\frac{dy}{dx} = 0$

Hence equation (3b) becomes:

$$H_m = \frac{V_o^2 \sin^2\theta}{2g} = \text{Maximum height Of trajectory}$$

To find the maximum range, let y = 0 and solve for x from equation (3b):

$$R = \frac{V_o^2}{g} \sin 2\theta$$

Taking air resistance into account and substituting B, the Ballistic Coefficient, in Equation (3b):

$$y = x \text{ tangent} - \frac{gx^2}{2 \cos^2\theta}\left(\frac{l_2}{V_o} + \frac{B}{V_o}x\right)$$

But,

$$B = \frac{W}{N D^2}$$

In which:

W = weight of projectile in pounds
N = form factor
D = diameter of projectile in inches

$$Y = x \text{ tangent } \theta - \frac{-gx^2}{2 \text{ cosine}^2\theta}\left[\frac{1}{V_o^2} + \frac{Wx}{N D^2 V_o}\right] \quad \text{.....(4b)}$$

The following table gives the actual trajectory as taken from charts of the writer, and the theoretical trajectory as calculated from equation (4b):

TABLE NO. 6
Trajecties in inches

Yards Range	Actual Trajectory	Theoretical Traj.
10	1.5	2.0
20	2.6	3.0
30	3.6	4.0
40	4.1	4.5
50	4.5	5.0
60	4.4	4.8
70	4.2	4.5
80	3.5	3.8
90	2.3	2.7

Time of Flight

With the velocity and the range known the time of flight of the projectile may be found by integration.

Let,

T = time in seconds
D = distance in feet
V = velocity in feet per second

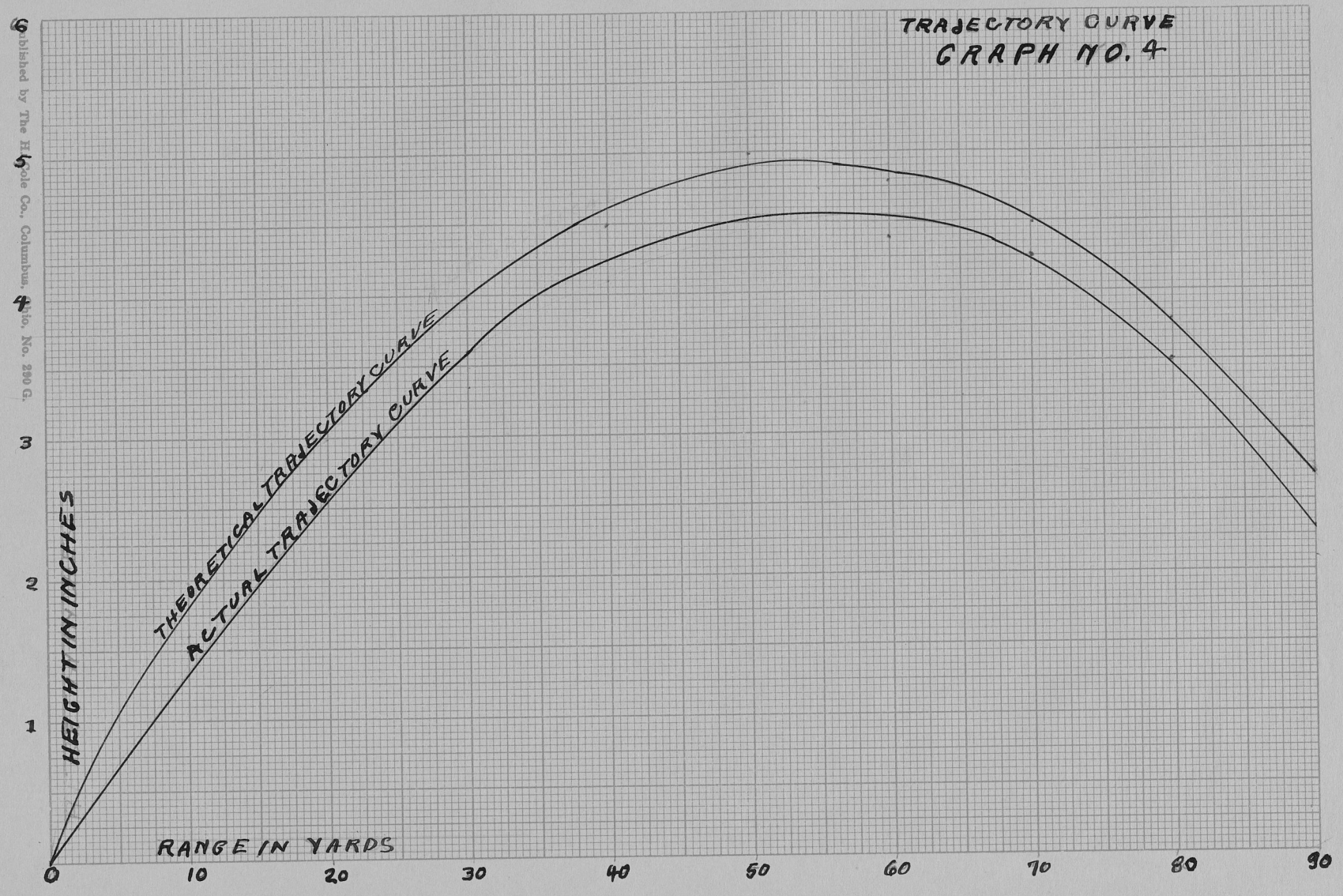
As above:

$$T = \frac{D}{V}$$

$$\Delta t = \frac{D}{V - \frac{\Delta V}{2}} = \frac{D}{V - \frac{\Delta V}{2}}$$

From Mechanics:

$$V = V_o^2 + 2AD$$

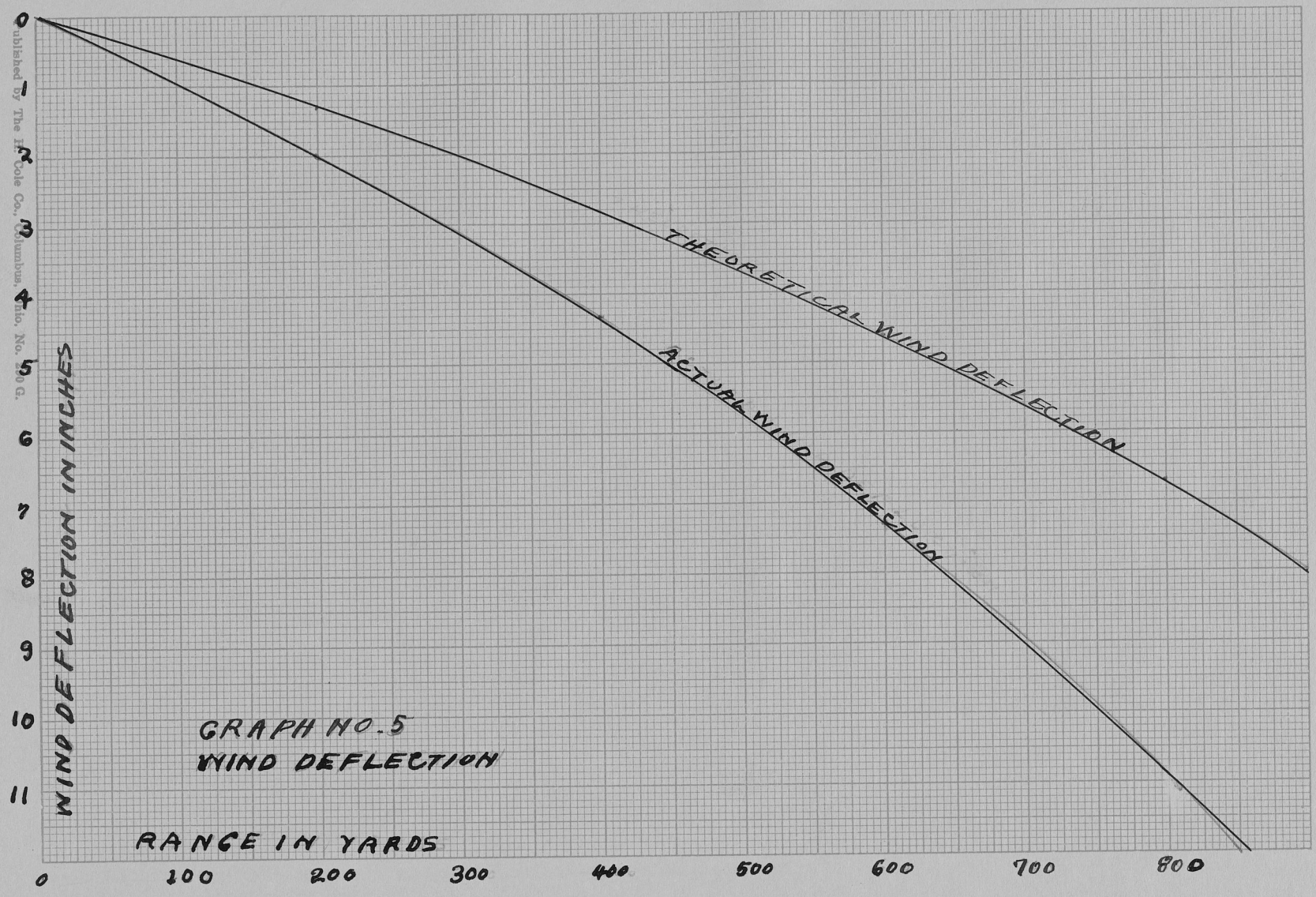


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A = acceleration
V = muzzle velocity

$$\int dt = \int \frac{dD}{V_o^2 - 2AD}$$

$$T = \int \frac{dD}{V_o^2 - 2AD} \quad \ldots\ldots\ldots\



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$$D = \frac{1}{2} \frac{P g}{W} T^2 \quad \text{.....(3d)}$$

Squaring equation (2c) and substuting it in (3d):

$$D = \frac{1}{2} \frac{P g}{W} 1/B^2 \left[\frac{dD}{V_8 - 2 A D} \right]^2$$

This formula gives the theoretical wind deflection for any desired projectile. The following table shows that it gives very good results; and since , in actual practice, the wind velocity can only be determined approximately at best, the accuracy of this formula is entirely satisfactory. Table no. 7 compares the actual and theoretical deflection values of a ten mile cross wind.

TABLE NO. 7

Range in yards	Actual wind deflection in inches	Theoretical Wind deflection
muzzle	0.0	0.0
200	2.0	1.8
400	4.3	4.0
600	7.3	6.8
800	10.9	10.0

SUMMARY

Exterior ballistics treats of the path which a projectile will follow in free flight through the air. This path depends on certain dominating factors, namely; muzzle velocity, bullet diameter, shape of point and atmospheric conidition. The predicition of this path, or trajectory, is neccessary if the motion of the bullet is to be so controlled as to cause the bullet to hit a selected target.This path

can be predicted by the use of the formulas derived above if the dominating factors are known, which they would be in any given case.

CONCLUSION

The writer hopes that this thesis will prove of some value to those desiring a knowledge of the relation between theoretical and actual ballistics, both internal and external. To the best of her knowledge there is no other source of material directly concerning this relation, and yet a knowledge of this relation must be had if theoretical facts are to be applied to actual cases. Other writers have delt with theoretical ballistics and actual ballistics separately; and if use can be made of this thesis as a convenient connecting link between the two, the writer's purpose will have been fulfilled.

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Encyclopaedia Britannica.....Vol. 4

APPROVAL

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Name E. S. Fabian

Title Assistant Professor
Civil Engineering