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EFFECT OF INCREASE IN STARTING PRESSURE ON EFFICIENCY AND VELOCITY OF CALIBER 0.30 WEAPONS

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Abstract

The effect of increasing the initial pressure is studied theoretically. No improvement in muzzle velocity of a caliber 0.30 gun is found. Under some circumstances, the efficiency may be improved, but only at the expense of muzzle velocity.

1. AUTHORITY: This study was authorized by letter O.O. 471/1464.

2. OBJECT: The object of the present report is to determine the theoretical effect on muzzle velocity and efficiency of small arms, of increasing the starting pressure by crimping the cartridge case into the cannelure. A specific example will be given for the caliber 0.30 Gun M1903, firing the Bullet, Ball M2.

3. GENERAL DIFFERENTIAL EQUATION: The interior ballistics will be determined by means of Edmund Röggla's differential equation:*

$$\dddot{\eta} = \frac{B\varphi(\eta)\ddot{\eta}^{r} - \gamma\dot{\eta}\ddot{\eta}}{\eta} \qquad (1)$$

* "Neue Diagramme für die Angewandte Innere Ballistik, Theorie und Beispiele", Edmund Röggla, Pilsen (1930).

where

B is a parameter,

η the expansion ratio for the free volume,

$\varphi(\eta)$ the form function,

r the exponent of the pressure in the rate of burning law,

γ the coefficient of adiabatic expansion.

4. PARAMETER B: The parameter B is defined by the formula:

$$B = (\gamma - 1)n'\sigma\, bO_o\, (gA^2/p')^{1-r} v_o^{\,r-2} \qquad (2)$$

Where

n' is the specific energy of the powder,

σ the density of the powder,

b the coefficient in the rate of burning law,

O_o the initial surface of the powder grains,

g the acceleration due to gravity,

A the cross sectional area of the bore,

p' the modified projectile weight,

v_o the initial free volume.

Although the specific energy may be estimated approximately, it is customarily determined so as to agree with the observed maximum pressure and muzzle velocity for a given gun, projectile, and charge. If the shape of the grain is unchanged, the initial surface is proportional to the charge and inversely proportional to the web thickness. If

c is the charge,

p the projectile weight,

R the weight of the gun and recoiling parts,

n the pitch of rifling,

μ the coefficient of friction,

the modified charge is

$$c' = \frac{R + c/2}{R + p + c} c$$

and the modified projectile weight is

$$p' = p \left[1 + 0.6(\pi/n)\ (\mu + \pi/n)\right] + c'/3.$$

If C is the chamber volume, the initial free volume is

$$v_o = C - c/\sigma\ .$$

5. FORM FUNCTION: The rate of regression of the surface of the grains depends on the form of the powder grains. In general, this is variable, and is expressed as a function of the expansion ratio, $\varphi(\eta)$. For single perforated powders, the surface at the end of combustion is about 0.9 of the initial surface; so, for convenience, the form function is assumed constant and equal to 1.

6. VELOCITY OF COMBUSTION: The linear velocity of combustion is assumed to be described by the expression bP^r, where P is the pressure. Hence, b is the linear burning rate at unit pressure: its value will not be needed for our purpose. The exponent r is assumed to have its mean empirical value 0.7, according to Röggla.

7. ADIABATIC EXPANSION: After the powder is completely consumed, the expansion is assumed to progress adiabatically. The coefficient γ is taken as 1.20.

8. SPECIFIC DIFFERENTIAL EQUATION: If

u is the travel of the projectile at any point, the corresponding free volume is

$$v = v_o + Au.$$

Then the expansion ratio, to which we have been referring, is

$$\eta = v/v_o\ .$$

This can be evaluated by a triple integration of the equation:

$$\dddot{\eta} = \frac{B\ddot{\eta}^{0.7} - 1.2\dot{\eta}\ddot{\eta}}{\eta} \qquad (3)$$

for any desired value of B.

9. PRESSURE: The pressure is proportional to the acceleration, and therefore to the second derivative of the expansion ratio. If p' is expressed in lb., v_o in in^3, g in ft/sec^2, and A in in^2, the pressure in lb/in may be determined by the formula:

$$P = \frac{p' v_o}{12g A^2} \ddot{\eta}. \qquad (4)$$

In particular, the maximum pressure corresponds to the maximum value of η. Then, the third derivative vanishes, and

$$B = 1.2\dot{\eta} \ddot{\eta}^{0.3} \qquad (5)$$

10. INITIAL CONDITIONS: It follows from the definition of the expansion ratio that the integration of the differential equation should start with the conditions:

$$\eta_o = 1, \dot{\eta}_o = 0, \ddot{\eta}_o = \frac{12g A2P_o}{p' v_o},$$

where P_o is the starting pressure. We shall take $P_o = 14{,}000$ lb/in^2 in our calculations, and compare the results with those obtained from Röggla's charts, where

$$P_o = 0.0435 P_{max}$$

if P_{max} is the maximum pressure.

11. REDUCED ENERGY OF CHARGE: The total energy content of the powder is n'c. Part of this is used in producing the energy of recoil. The remainder is n'c'. This is reduced to the scale of Röggla's charts by means of the relation:

$$E_r = 120 n'c/v_o P_{max}$$

where E_r is the reduced energy, n'c is expressed in ft.lb., v_o in in^3, and P_{max} in lb/in^2.

12. REDUCED WORK: The work is defined as

$$W = \int_{v_o}^{v} P\, dv.$$

If W is expressed in ft.lb., the reduced work is

$$W_r = 120W/V_o P_{max}.$$

Substituting the derivatives of the expansion ratio in these expressions, we obtain:

$$W_r = \frac{10}{\ddot{\eta}_{max}} \int_o^t \ddot{\eta}\dot{\eta}dt.$$

13. REDUCED INTERNAL ENERGY: The internal energy of the gas is

$$U = \frac{Pv}{\gamma-1} .$$

Substituting the expansion ratio and its second derivative, and reducing to the desired scale, we obtain the reduced internal energy:

$$U_r = \frac{50\ \eta\ddot{\eta}}{\ddot{\eta}_{max}}$$

14. COMPLETION OF COMBUSTION: Let the subscript $_v$ denote the point where the powder is completely consumed. The expansion ratio η_v is determined by the condition:

$$U_{rv} = E_r - W_{rv} .$$

15. MUZZLE VELOCITY: After the powder is consumed, providing this occurs before the bullet reaches the muzzle, the expansion is assumed to be adiabatic. Then, if v_e, denotes the final free volume, the final reduced work is

$$W_{re} = E_r - U_{rv}\eta_v^{.2} \ \ v_o^{.2}v_e^{-.2}.$$

Now, if g is expressed in ft/sec^2, v_o in in^3, P_{max} in lb/in^2, and p' in lb., the muzzle velocity in ft/sec may be found by the formula:

$$V = (gW_{re}v_oP_{max}/60p')^{1/2} \qquad (6)$$

16. DATA: As a basis of our calculations, we shall use the results obtained from 30 rounds of caliber 0.30 ammunition, containing the 150 grains ball M2 bullet and 49.6 grains of IMR powder, DP lot 1764 of 1940 (cylindrical, single-perforated), fired from the M1903 Gun.

The ratio of maximum pressure to copper gage pressure is assumed to be 1.07*. The data are as follows:

Web thickness	0.0123 in.
Form function	1.0
Specific gravity (approx.)	1.58
Charge	.007,086 lb
Projectile weight	.021,43 lb
Weight of gun	8.69 lb
Cross-sectional area of bore	.071,86 in^2
Travel (total)	21.697 in
Chamber capacity	.2766 in^3
Pitch of rifling	100/3 cal/rev
Coef. of friction (approx.)	.125
Copper gage pressure	37,050 lb/in^2
Maximum pressure	39,650 lb/in^2
Instrumental velocity	2640 ft/sec
Muzzle velocity	2734 ft/sec

17. SPECIFIC ENERGY: By assuming a series of values of the reduced energy and finding the final reduced work, we can find the reduced energy which will produce the reduced work corresponding to the observed data, under Röggla's assumptions. Thus, the specific energy n' was found to be 1,304,000 ft. The initial pressure in this case is 1,725 lb/in^2.

18. EFFICIENCY: The total energy content of the powder is n'c, where c is the charge in lb. The kinetic energy of the projectile at the

* J. R. Lane, "Time-pressure relationships produced by nitrocellulose and nitroglycerine powders in caliber .30 ammunition", APG, BRL Report No. 75.

muzzle is $pV^2/2g$, where p is the projectile weight, V is the muzzle velocity, and g is the gravitational acceleration. In the present problem, the value of p is given in paragraph 16; in order to agree with Röggla, we assume that 2g = 64.37 ft/sec^2. The efficiency is defined as the ratio of the muzzle energy to the powder energy.

19. MAXIMUM PRESSURE: We shall assume a copper gage pressure of 49,000 lb/in^2, which is the highest that the caliber 0.30 gun is designed to stand with safety. Using the empirical ratio mentioned in paragraph 16, we find that the corresponding true maximum pressure is about 52,400 lb/in^2.

20. CHARGE: If the differential equation (3) is integrated numerically, with an assumed value of the parameter B and the initial conditions stated in paragraph 10, the maximum value of η can be found by interpolation. Then, with the assumed value of the maximum pressure and the given value of the cross sectional area, the product $p'v_o$ can be calculated by formula (4). Since the modified projectile weight p' and the initial free volume v_o are both functions of the charge c, the corresponding charge can easily be determined.

21. WEB THICKNESS: If r = 0.7 and the initial surface of the powder grain O_o is taken as proportional to c/w where w is the web thickness, formula (2) shows that B is proportional to

$$cw^{-1}(p')^{-0.3}v_o^{-1.3}, \text{ \underline{ceteris paribus}.}$$

With the data of paragraph 16, it was found by formula (5) and Röggla's charts that B = 1,059,500. Since all factors are known in this case, the factor of proportionality can be found. Therefore, the web thickness corresponding to any B and c can be determined by the above proportionality.

22. EXAMPLES WITH LOW INITIAL PRESSURE:

a. Tables I and II give the data and results respectively for a series of examples. In all these, the maximum pressure is 52,400 lb/in^2. We shall first consider three cases in which the results were obtained from Röggla's charts. For these, the initial pressure is 2,280 lb/in^2. The ratio c/w satisfies his pressure formula, together with the data of paragraph 16.

b. In the first example, a charge of 0.007,750 lb is assumed. It follows that the web thickness is 0.01125 in. The muzzle velocity is 2953 ft/sec. Consequently, the muzzle energy is 2903 ft.lb, the total powder energy is 10,106 ft.lb, and the efficiency is 0.2873.

c. For case 2, the web thickness is assumed to be 0.0123 in, which is that of lot 1764. The charge required to give the desired maximum pressure is 0.008,204 lb. This increases the muzzle velocity to 2998 ft/sec. The muzzle energy is now 2992 ft.lb. the powder energy is 10,667 ft.lb, and the efficiency is lowered to 0.2805.

d. The highest muzzle velocity obtainable under these conditions was found to be 3074 ft/sec. This can be obtained with 0.009,500 lb of powder with a web thickness of 0.0158 in. The muzzle energy is now 3146 ft.lb, but the powder energy is 12,388 ft.lb, so the efficiency is only 0.2540.

23. EXAMPLES WITH HIGH INITIAL PRESSURE:

a. In the remaining examples, the results were obtained from trajectories calculated by integrating equation (3) numerically, with a series of values of B and the initial conditions stated in paragraph 10. The initial pressure is 14,000 lb/in^2 in these cases.

b. In cases 4, 5, and 6, the assumed values of B are 1,000,000, 1,100,000, and 1,200,000 respectively. The corresponding charges are 0.004,943, 0.006,119, and 0.007,092 lb, and the web thicknesses are 0.0069, 0.0090, and 0.0109 in. The respective muzzle velocities are 2464, 2707 and 2866 ft/sec, giving muzzle energies of 2021, 2439 and 2734 ft.lb. The powder energies are 6,446, 7,979, and 9,248 ft.lb, so the efficiencies are higher than those of the previous cases, the muzzle velocities are lower.

c. In order to use powder lot 1764, with a web thickness of 0.0123 in., it was found necessary to take B = 1,280,000, which corresponds to a charge of 0.007,750 lb. The muzzle velocity for this case is 2948 ft/sec, the muzzle energy is 2893 ft.lb, the powder energy is 10,106 ft.lb, and the efficiency is 0.2863. The charge is the same as for case 1, where the initial pressure is low; the muzzle velocity, and consequently the efficiency, is just a little less in the present case. The web thickness is the same as for case 2: the muzzle velocity and the charge are both considerably less, but the efficiency is greater.

d. It is evident from the preceding that a larger charge will give a higher muzzle velocity under the present conditions. Therefore, four more trajectories were computed with successive increments of 80,000 in B. As indicated in Table I for cases 8 to 11, the charges range from 0.008,332 to 0.009,673 lb, and the web thicknesses from 0.0137 to 0.0174. Table II shows that the muzzle velocities for these cases are 3002, 3034, 3047, and 3041 ft/sec. respectively, but the efficiency decreases to 0.2441.

e. By interpolation of the results of the last four cases, it was found that the highest muzzle velocity obtainable under the present conditions is 3048 ft/sec. The corresponding value of B is 1,536,000, the charge is 0.009,353 lb, and the web thickness is 0.0164 in. The resulting muzzle energy is 3093 ft.lb, the powder energy is 12,196 ft.lb, and the efficiency is 0.2536. Comparing these results, which pertain to an initial pressure of 14,000 lb/in^2, to those of case 3, which is the optimum for an initial pressure of 2,280 lb/in^2, we see that the increase in initial pressure causes a decrease of 26 ft/sec. in muzzle velocity, with a decrease of 0.000,147 lb. in the charge so that the efficiency is practically the same.

24. CONCLUSION: We have calculated the muzzle velocity and efficiency which would be obtained in a caliber 0.30 Gun M1903, firing a 150 grain bullet, ball M2, with various charges of powder with the same specific energy as that of lot 1764 but with various web thickness, subject to the conditions that the true maximum pressure is 52,400 lb/in^2 and the starting pressure is 2,280 lb/in^2 in some cases and 14,000 lb/in^2 in others. If the same charge is used, the web thickness has to be greater when the initial pressure is higher, and the muzzle velocity is 5 ft/sec. less: the starting pressure is really immaterial. If the same lot of powder is used, the charge has to be smaller when the initial pressure is increased, and the muzzle velocity is 50 ft/sec. less: the lower starting pressure is then better. If the optimum charge and web thickness are used, the higher starting pressure necessitates the use of a smaller charge with a slightly larger web thickness, resulting in a muzzle velocity 26 ft/sec. lower than with the low starting pressure, although the efficiency is practically the same: here again, the lower initial pressure has the advantage. The evidence indicates that increasing the starting pressure, which may be done by crimping the cartridge case into the cannelure, will not augment the muzzle velocity: if the efficiency is improved, the muzzle velocity is lowered. If the powder grains were progressive - i.e., if the burning surface increased - a greater starting pressure might prove to be advantageous; but with single-perforated grains, whose burning surface is here assumed constant although it actually decreases slightly, the present study indicates that an increase in starting pressure would not appreciably improve the results.

25. ACKNOWLEDGMENTS: We express our sincere thanks to Mr. R.H.Kent for his valuable suggestions, and to Miss M.E. Harrington for her lengthy calculations, including the numerical solutions of the differential equation.

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In the calculated trajectories, the initial value of the second derivative of the expansion ratio was assumed to be:

$$\ddot{\eta}_o = 6{,}747{,}000 \text{ per sec}^2.$$

Therefore, the initial pressure was not 14,000 lb/in^2, as stated in the report, but had the values given in the table below, which should be substituted for Table I. Since these pressures are high compared to the normal initial pressure of about 2,280 lb/in^2, the conclusions are qualitatively correct, although some of the numerical results are erroneous.

TABLE I

DATA

Maximum Pressure = 52,400 lb/in^2

Copper Gage Pressure = 49,000 lb/in^2

Case No.	Initial Pressure lb./in	Charge lb.	Web Thickness in.
1	2,280	.007,750	.01125
2	2,280	.008,204	.0123
3	2,280	.009,500	.0158
4	15,010	.004,943	.0069
5	13,610	.006,119	.0090
6	12,410	.007,092	.0109
7	11,580	.007,750	.0123
8	10,830	.008,332	.0137
9	10,180	.008,828	.0150
10	9,580	.009,273	.0162
11	9,050	.009,673	.0174
12	9,480	.009,353	.0164

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TABLE II

RESULTS

Case No.	Muzzle Velocity ft/sec.	Muzzle Energy ft.lb.	Powder Energy ft.lb.	Effi-ciency
1	2953	2903	10,106	.2873
2	2998	2992	10,667	.2805
3	3074	3146	12,388	.2540
4	2464	2021	6,446	.3135
5	2707	2439	7,979	.3057
6	2866	2734	9,248	.2956
7	2948	2893	10,106	.2863
8	3002	3000	10,865	.2761
9	3034	3064	11,512	.2662
10	3047	3091	12,092	.2556
11	3041	3079	12,614	.2441
12	3048	3093	12,196	.2536

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ABSTRACT:

Study was made to determine the theoretical effect on muzzle velocity and efficiency of small arms, of increasing the starting pressure by crimping the cartridge case into the cannelure. Specific example is given for the caliber 0.30 gun M1903, firing the ball M2 bullet. The interior ballistics were determined by means of Edmund Roeggla' s differential equation. No improvement in muzzle velocity of the caliber 0.30 gun was found. Under some circumstances, the efficiency may be improved, but only at tho expense of muzzle velocity.

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