Recoil Reduction Using Propellant Gas

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Rarefaction wave gun (RAVEN) propulsion has renewed interest in the fundamental limits of recoil reduction attainable by redirecting propellant gases rearward from a gun without compromising the projectile propulsion. Traditionally, this has only been achievable through the use of muzzle brakes. RAVEN's unique ability tap into the internal energy of propellant gases that are not gainfully employed to propel the projectile may be considered analogous to efforts to mechanically close the muzzle of a gun at shot exit to drive all of the propellant gases through a muzzle brake. The recoil reduction potential for RAVEN and current technology muzzle brakes will be extrapolated across viable gas gun velocities using simple empirical relationships. The quantitative findings of this parametric study must be considered to provide perspective as opposed to true predictions because of the extrapolated nature of the study; particularly at higher muzzle velocities.

INTRODUCTION

RAVEN propulsion has been proposed as a radical departure from current closed breech guns to dramatically reduce recoil momentum and heat transfer to future guns [1, 2]. It is based on the simple premise that a rarefaction wave can travel no faster than the combined gas and sonic velocities through which it propagates. Thus, a gun system designed to vent the breech end of the chamber after the bullet has begun its travel down the bore would release a forward traveling rarefaction wave. Compromise of the projectile propulsion could only occur after the rarefaction wave front was able to reach the base of the bullet. Surprisingly, it has been shown that the rarefaction wave released by venting the back of the chamber of a current 120mm tank gun firing an M829A2 will not reach the bullet prior to shot exit if the release occurs after the bullet has traversed only one fourth of the launcher travel [2]. The time delay between venting and the rarefaction wave front reaching the base of the bullet and muzzle simultaneously is estimated to be 2.5 ms. During this period of concurrent venting and projectile propulsion, half of the propellant gas may be exhausted rearward out an expansion nozzle to negate some portion of the recoil momentum initially imparted to the gun. The hastened blow down of such a launcher will be rearwards, drawing fresh air into the muzzle upon its completion. It has been estimated that such a launcher will eliminate three quarters of the closed breech recoil momentum and reduce the heat transfer to the bore substantially [2].

SPECIFIC IMPULSE OF GUN PROPELLANT GASES AFTER PROPELLING A PROJECTILE

In the following analysis it will be assumed that the gas constant is specific to the propellant gas. Thus:

Eq. (1) $\quad R = R_u / mm$

Using SI units, R_u is equal to 8,314 J/kmol/K. The molecular mass, *mm*, of common propellants is near 25 kg/kmol.

It is worth noting the specific heat for constant pressure minus the specific heat for constant volume is equal to the gas constant. [3, Eq. (5.27)] Thus, the specific heats may be related to the gas constant and ratio of specific heats as [3, Eq.s (7.30-31)]:

Eq. (2) $\quad \gamma = C_p / C_v$

Eq. (3) $\quad C_v = R/(\gamma - 1)$

Eq. (4) $\quad C_p = \gamma R/(\gamma - 1)$

This application of perfect gas theory to interior ballistics must be considered an approximation whose validity often falls into question but never the less is employed in interior ballistic analysis. [4, pp. 1.2, 1.15] Until experimentally validated, analysis based on these assumptions should be considered an estimate that provides perspective; however, that traditional interior ballistics has employed these assumptions lends a strong precedent.

The internal energy of the propellant after the burn is commonly computed via the gas constant multiplied by the adiabatic flame temperature divided by the ratio of specific heats minus one. The terms in the numerator are typically known as the propellant "force" [3, Eq. (1-6)] while the energy release per mass unit of propellant is termed the specific energy or propellant potential [3, pp. 1.15] or the heat of explosion [6, pp. 84].

Eq. (5) $$U_o = m_c C_v T_o = m_c \frac{RT_o}{(\gamma - 1)}$$

Regardless of the ultimate motion of the gases, internal energy of the gas will be expended on kinetic energy imparted to the projectile and heat transfer to the cannon walls and base of the projectile. Corner has argued that heat transfer to the gun may be reasonably assumed proportional to the muzzle energy with heat transfer rarely more than 30% of the muzzle energy [5, pp. 141]. It has been estimated that RAVEN will reduce net heat transfer by one third [2]. Assuming heat transfer to be about 20% of the muzzle energy, these combined energies (six fifths of the muzzle energy) may be removed from the heat of explosion.

Eq. (6) $$U_1 = m_c \frac{RT_o}{(\gamma - 1)} - \frac{3}{5} m_p v_p^2 = m_c C_v T_1 = m_c \frac{R}{(\gamma - 1)} T_1$$

One may consider the remaining energy in Eq. (6) to be the energy of the propellant gases following shot exit if the muzzle of the gun were corked behind the bullet and all of the gases were to come to rest adiabatically. The temperature of these gases, T_1, is of interest and may be computed as:

Eq. (7) $$T_1 = T_o - \left(\frac{3}{5} m_p v_p^2\right) \Big/ (m_c C_v) = T_o - \frac{3(\gamma - 1)}{5R}\left(\frac{m_p}{m_c}\right) v_p^2$$

This temperature will be used as an approximation to compute the reservoir gas energy and enthalpy available to drive the gases through a de Laval nozzle.

The relationship between gas flow through a nozzle is based on the first law of thermodynamics as expressed via the Bernoulli equation. Neglecting gravitational forces as small, the change in kinetic energy of the gases may be directly related to the change in enthalpy [3, Eq. (14.21)]. The enthalpy, like the internal energy, is a function only of temperature. Using ideal gas assumptions [3, Eq. (5.29)] we arrive at:

Eq. (8) $$H_1 = m_c C_p T_1 = m_c \frac{\gamma R}{(\gamma - 1)}\left(T_o - \frac{3(\gamma - 1)}{5R}\left(\frac{m_p}{m_c}\right) v_p^2\right) = m_c\left(\frac{\gamma R}{\gamma - 1}\right) T_o - \frac{3}{5}\gamma m_p v_p^2$$

Using Bernoulli's equation, the kinetic energy of the propellant gases exhausted from the gun system will decrement the enthalpy [3, Eq. 14.21].

Eq. (9) $$H_2 + \frac{1}{2} m_c v_c^2 = H_1$$

The temperature of the gases as they depart the nozzle, T_2, is related to the magnitude of the exhaust velocity and is of interest:

Eq. (10) $$v_c = \sqrt{\frac{2}{m_c} m_c C_p (T_1 - T_2)} = \sqrt{2\left(\frac{\gamma R}{\gamma - 1}\right)(T_1 - T_2)}$$

If the gun were to discharge into a vacuum through an arbitrarily large nozzle, the gases would theoretically cool to absolute zero if elements of reality such as condensation of the gas into a liquid would not occur. Setting T_2 to zero constitutes an upper bound on the exhaust velocity magnitude. Doing this in Eq. (10) results in the accepted value for this thought exercise [7, Eq. (6.10)].

Exactly how much the gas cools and is accelerated is a function of the nozzle design. It is well known that guns have ample gas energy and pressure to meet the requirements for de Laval nozzle design to reach the sonic velocity at the throat through the vast majority of the gas discharge event [3, pp. 2.48]. (For common propellants, the ratio of atmospheric (discharge) pressure to chamber pressure need only be 0.55 [5, pp. 248].)

Heat conduction and other loss factors within the nozzle are also assumed negligible. [3, pp. 2.48] Empirical evidence supports that nozzle inefficiencies only detract from the theoretical values by a few percent [5, pp. 248]. Further, the effect of co-volume on thrust is considered small and is also neglected [3, pp. 2.49]. Corner has quantified an upper bound for the co-volume effect to be 6.5% for reasonable guns [5, pp. 251].

What remains is the geometric expansion ratio of the nozzle from the throat to the exit plane. The relationship between expansion ratio and Mach number is provided below [3, Eq. (14.46)]:

Eq. (11) $$\frac{A}{A^*}=\frac{1}{M}\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)/2(\gamma-1)}$$

The resulting relationship between Mach number at exit and the expansion ratio from the throat is shown in Fig 1 for two different ratios of specific heat that are common for gun propellants.

Perspective on reasonable area ratios for large caliber guns may be gained by looking at the cross-sectional area of current breech rings as compared to the bore area. This ratio is approximately 15.5 and 18.5 for the 105mm M35 and 120mm XM291 guns respectively. If one were to incorporate a modestly larger expansion nozzle, say 50% larger in diameter than the breech ring, while venting through a throat of bore area, the expansion ratio would be 40, and result in an exit Mach number of nearly four. The later analysis is not particularly sensitive to this number, so four will be used.

The temperature of the gases exhausting out the reservoir may be related to the Mach number as below [3, Eq. 14.37d]:

Eq. (12) $$\frac{T_1}{T_2}=1+\frac{(\gamma-1)}{2}M^2$$

Recalling the derivation of the reservoir temperature in Eq. (7), the temperature of the gases as the exit the expansion nozzle may be computed as follows:

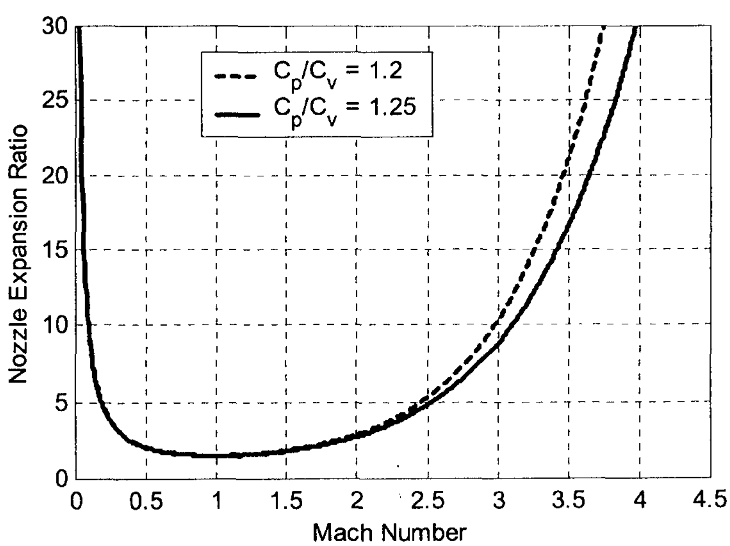

Fig 1. Nozzle expansion ratio required to achieve a given Mach number for common propellant gases.

$$\text{Eq. (13)} \quad T_2 = \left[T_o - \frac{3(\gamma-1)}{5R}\left(\frac{m_p}{m_c}\right)v_p^2\right] \Big/ \left[1+\frac{(\gamma-1)}{2}M^2\right]$$

More directly, Eq. (12) may be used to compute the temperature difference within Eq. (10):

$$\text{Eq. (14)} \quad T_1 - T_2 = \left(\frac{(\gamma-1)}{2}M^2\right)T_2 = \left(\frac{(\gamma-1)}{2}M^2\right)\frac{\left[T_o - \frac{3(\gamma-1)}{5R}\left(\frac{m_p}{m_c}\right)v_p^2\right]}{\left[1+\frac{(\gamma-1)}{2}M^2\right]}$$

The magnitude of the exhaust velocity may be computed by inserting the results of Eq. (14) into Eq. (10) and simplifying:

$$\text{Eq. (15)} \quad v_c = \sqrt{\frac{\left(\gamma R M^2\right)\left[T_o - \frac{3(\gamma-1)}{5R}\left(\frac{m_p}{m_c}\right)v_p^2\right]}{\left[1+\frac{(\gamma-1)}{2}M^2\right]}}$$

It may be seen that the effect of the energy imparted to the projectile and the approximation for heat transfer to the gun and projectile may be interpreted as a decrement on the adiabatic flame temperature.

To lend perspective on this it is known that the projectile velocity may be estimated as 1,500 m/s multiplied by the root of the ratio of charge to projectile mass where this ratio is nearly unity. (This relationship will be employed later and referenced in Eq. (17).) Using this approximate relationship the projectile to charge mass ratio of Eq. (15) and the ratio of charge to projectile mass used to estimate the square of the velocity cancel. Assuming representative gas properties similar to JA2 with a molecular weight of 25 Kg/kmol and a ratio of specific heats of 1.225 the temperature decrement may be estimated to be 913 K. For the representative case at hand, using a propellant with an adiabatic flame temperature of 3,400K and a Mach four nozzle, the velocity is 2.4 km/s. This is about 400m/s slower than it would be without the energy lost to the projectile propulsion and heat transfer, which indicates a lack of strong sensitivity to the energy lost to gun propulsion. (For those who prefer specific impulse expressed as momentum per unit weight, 2.4 km/s = 2.4 kN*s/Kg => 245 lb*s/lb = 245 s.)

The result of Eq. (15) constitutes the purpose of this derivation. It represents a realistic upper bound on the specific impulse that could possibly be attained from the propellant gases used to propel a bullet out a gun with out regard to the mechanism used to achieve it. This upper bound is relevant for any RAVEN launcher as well as any clever muzzle brake devices that would obstruct the bore at the muzzle following shot exit. It is also a valid upper bound for recoil amplifiers (nozzle's at the muzzle used to increase recoil momentum imparted to the gun, occasionally used for recoil operated automatic weapons.) We may now say with confidence using Eq. (15) that the net rearward recoil imparted to any gun will be bracketed as follows:

$$\text{Eq. (16)} \quad m_p v_p + m_c v_c < net\ rearward\ recoil < m_p v_p - m_c v_c$$

The left side corresponds to a recoil amplifier ejecting gases forward and the right side to recoil abatement that ejects gases rearward. The left side corresponds to the greatest rearward momentum that could be imparted to the gun. The right side corresponds to the least rearward momentum. For current high performance kinetic energy rounds, there exists sufficient specific impulse in the propellant gases to completely negate the rearward momentum imparted by the projectile and generate a net forward momentum. Accessing the specific impulse of the propellant gas to encroach upon recoillessness with little if any compromise in projectile propulsion is the intent behind RAVEN.

A PARAMETRIC STUDY

To lend perspective on recoil momentum, a parametric study will consider the momentum imparted to a gun as a function of the muzzle velocity. It will be assumed that virtually no degradation in projectile propulsion will be tolerated. Therefore, schemes such as prior recoilless rifles [7] or achieving recoil reduction through large muzzle brakes employed by guns of low expansion ratio with large charge to propellant mass ratio rounds [5, pp. 391] will not be considered.

A simple and reasonably accurate empirical relationship to determine muzzle velocity as a function of the charge to projectile mass ratio for fielded guns has been published by Ogorkiewicz. [8, Eq. 4.8]

$$\text{Eq. (17)} \quad v_p = (1{,}500m/s)\left(\frac{m_c}{m_p}\right)^{0.45}$$

The approximation is depicted in Fig 2 for various charge to projectile mass ratios. Included are real performance points largely drawn from Stiefel [9] with the inclusion of a current 120mm M829A2 round. A similar relationship has been made by Schmidt [10] that is within 5% agreement over most of the ratios and within 2% for high-speed rounds.

Although enhancement of this empirical relationship could be made, it's unaltered fidelity is more than adequate for the current purposes. Although Eq. (17) may appear purely empirical, the square root of the charge to projectile mass ratio can be interpreted as a simple energy balance between the chemical energy of the charge mass and the kinetic energy of the projectile. The difference between the 0.5 and 0.45 power that remains may be considered a velocity dependent efficiency factor that penalizes higher velocities more so than lower ones.

The momentum of closed-breech launch may be broken down into three components corresponding to the projectile momentum, momentum imparted to the gases up to shot exit, and the momentum imparted during the blow-down of the gases after shot exit. The momentum is often termed the impulse of the round and will be denoted by I. Assuming constant gas density along the length of the gas column and a linear propellant gas velocity gradient along the length of bore from rest at the breech to projectile velocity at the base of the projectile at shot exit, the center of mass of the propellant gas may be approximated as traveling at one half the projectile velocity. There exists no simple and accurate formula for the blow-down or post-ejection momentum, I_{BD}, although an approximation will later be made.

Eq. (18) $$I = m_p v_p + m_c (v_p/2) + I_{BD}$$

Maintaining a separation between the gas momentum prior to and after shot exit will facilitate the use of formulae for the momentum reductions afforded by muzzle brakes.

A simple empirical rule for the estimation of the average outflow velocity of all the propellant gases relates the velocity to the sonic velocity of the gases at the muzzle and the projectile velocity. Such empirical estimations cannot be held in high regard, but for the purpose of providing reproducible and easily understood results they are of value. The sonic velocity may be estimated as 1,000 m/s and the resulting velocity computed as below [6, Eq. 64]:

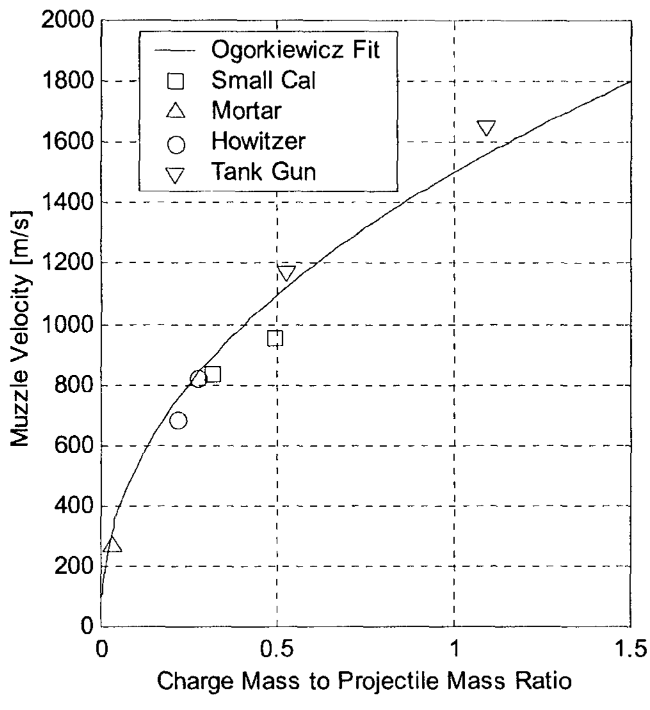

Fig 2. Empirical relationship between charge to projectile mass ratio and muzzle velocity.

Eq. (19) $v_m = m_c\sqrt{(1{,}000m/s)^2 + v_p^2}$

Thus the blow down momentum may be computed as:

Eq. (20) $$I_{BD} = m_c\left(\sqrt{(1{,}000m/s)^2 + v_p^2} - \frac{v_p}{2}\right)$$

There is particular reason to be concerned about the fidelity of Eq. (19) as historically, when such empirically supported relationships were generated, terms of the order of the charge to projectile mass ratio squared were considered small and ignored [5, pp. 365]. For current tank ammo this ratio is near unity and may call into question the results. However, no mention of this historical assumption that would not be valid is included in reference 6.

There are currently two different methods used to predict the performance of muzzle brakes based upon the recoil momentum imparted to guns. Unfortunately, both are termed beta, β. The first method attributed to Oswatitsch relates the recoil reduction to the entire gas momentum imparted during normal launch ($m_c v_m$ using Eq. (19)) [11]. The second method championed by Corner and used here relates the momentum reduction as a ratio of the blow-down momentum. [12, Eq.s 3.37-39] Thus:

Eq. (21) $$I = m_p v_p + m_c(v_p/2) + (1-\beta)I_{BD}$$

Although strictly incorrect, it is often assumed that a physical limit of muzzle brakes is that their performance could not exceed a complete reversal of the entire gas momentum relative to a gun with out a muzzle brake. (This would be an Oswatitsch beta of two.) This belief is analogous to the actual performance limit of impulse bucket design for hydraulic turbines, where the working fluid is incompressible. The potential to expand the gases from the muzzle pressure to atmospheric pressure within a nozzle is what is missing in this limit. Despite the lack of validity to this upper performance limit, design considerations have kept the muzzle brakes of practical weapons substantially below this perceived limit.

Using the theoretical limit of rearward gas velocity attainable from Eq. (15), a theoretical lower bound on the impulse may be derived as below:

Eq. (22) $$I_{LB} = m_p v_p - m_c v_c$$

It is postulated that the performance of RAVEN will be very closely related to the percentage of the charge mass that is ejected out the rear expansion nozzle. This will be termed alpha, α. The utility of a muzzle brake for a RAVEN may be substantial. For lack of a better model, the specific forward impulse imparted to that portion of the propellant gases ejected out the muzzle will be assumed equivalent to the close breech case using Eq. (19). The specific impulse of the portion of the gases ejected out a rearward facing Mach 4 nozzle will be assumed to be that computed using Eq. (15). The use of an aggressive muzzle brake may be anticipated to reduce the specific impulse of the muzzle gases to zero. (Loosely speaking this could be considered a beta of unity.) Actual RAVEN performance may be anticipated to occur between these two limits.

Eq. (23) $$m_p v_p - \alpha m_c v_c < I_{RAVEN} < m_p v_p + (1-\alpha) m_c v_m - \alpha m_c v_c$$

In a manner analogous to the RAVEN impulse, the momentum imparted to a closed breech gun (α = 0%) that may incorporate a muzzle brake may be considered practically limited by a brake that eliminates all gas momentum. Thus:

Eq. (24) $$m_p v_p < I_{Closed\ Breech} < m_p v_p + m_c v_m$$

These results are plotted in Fig 3 for α equal 0%, 50%, 75%, 90%, and 100%. The example used JA2 with a ratio of specific heats of 1.225, a molecular mass of 24.865 Kg/kmol, and an adiabatic flame temperature of 3410K. The dotted lines passing through the close breech field are the impulses for a gun employing a perforated (β = 0.700) brake, single baffle brake (β = 0.910), and a double baffle brake (β = 1.351). The performance of the first is based on the Benet designs for the 105mm EX35 and 155mm XM297 while the later two are found in the literature [12, Table 3-3]. It is worthy to note that the back blast directed at the turret by the perforated muzzle brake on the EX35 tank gun was too aggressive for fielding where the crew was required to be allowed to fire with hatches open and double ear protection. It was therefore removed prior to type classification as the M35. It must also be reiterated, that the empirical relationships employed here must be considered extrapolations, and therefore are meant only to provide perspective.

Independent evaluations of RAVEN firing an M829A1 or M829A2 round from and M256 based gun system indicate that about two thirds of the charge mass will be ejected out the back [2]. This would place the anticipated RAVEN performance between the 50% and 75% regions. The recoil reduction estimates for the analyses is between 66% and 75% for a 1650m/s or so round velocity and no muzzle brake [2]. Examination of the plot confirms that reduction in momentum. Validation of this mix of analytical and empirical analysis by comparison to unvalidated computational fluid dynamic models provides optimism that it is reasonable. However, without experimental validation, this form of validation between models may be considered unsound.

CONCLUSIONS

A reasonably well-founded upper limit on the specific impulse remaining in propellant gases that have been employed to fire a bullet out of the gun has been identified. This limit may be used in a manner analogous to the Carnot cycle limit for heat engines to determine the viability of later RAVEN impulse reductions predictions arrived at through computational fluid dynamics (CFD) analysis efforts.

Perspective has been shed on the limits of current technology muzzle brakes to reduce recoil momentum. It was pointed out that the use a moderate performance perforated muzzle brake was considered too aggressive for a tank gun where the crew was to maintain the ability to fire with hatches open and double ear protection.

Prior simulations of RAVEN have indicated that it may vent two thirds of the propellant gas rearward through an expansion nozzle, thus eliminating three fourths of the recoil momentum. This earlier result was placed into a context where it could be considered reasonable, and within the thermodynamic feasibility of interior ballistics.

Estimations of performance of future RAVEN configurations and muzzle brakes may be drawn from simple relationships developed in this work. However, discretion is advised to the extrapolated nature of the predictions. The intent has been to provide perspective.

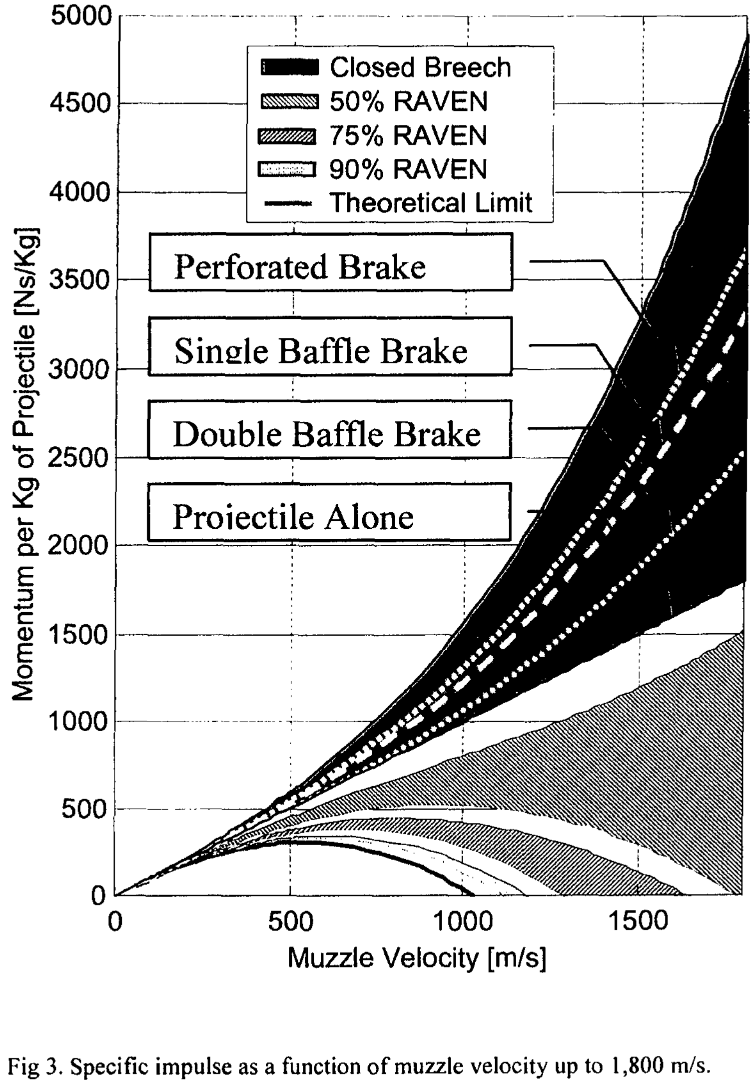

Fig 3. Specific impulse as a function of muzzle velocity up to 1,800 m/s.

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