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Recoil Elimination For High Velocity Guns —An Analysis of Alternatives

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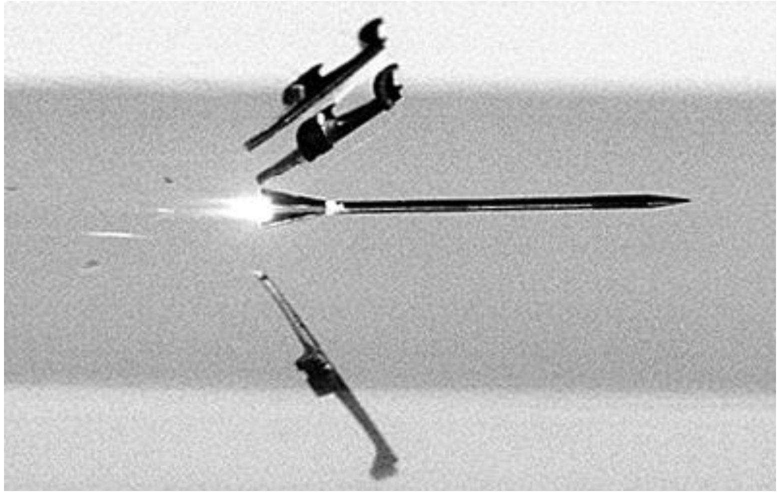
High Velocity Anti-Armor Rounds



An image of sabot separation from a high velocity long rod penetrator [1].

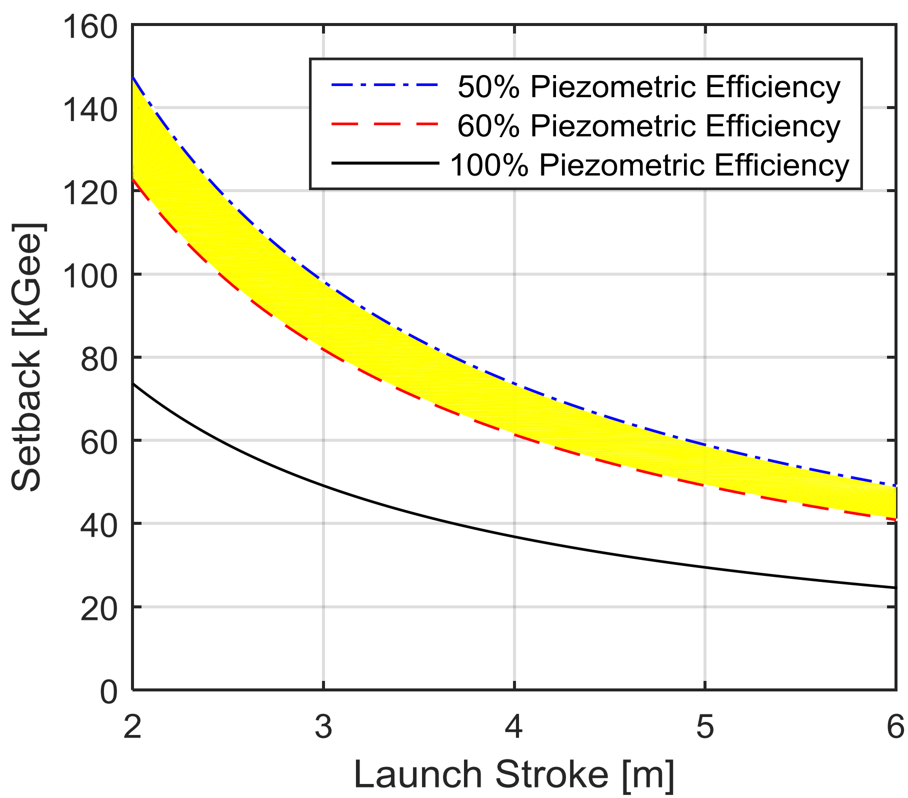
- The current anti armor defeat mechanism of choice is the kinetic energy long rod penetrator. Always smaller in diameter than the bore, discarding sabots are used to fit the rod to the bore and transfer the bore pressure to accelerate the projectile.
- The 25mm M919, 30mm MK268, 105mm M900, and 120mm M829 series are all fielded examples with muzzle velocities approaching that of the fastest round in the inventory, the M865 120mm Mach five (1,700 m/s) target practice round [2].
- Achieving full velocity at the muzzle, such rounds may be used for close combat.
- The launch of such rounds is typically accompanied by significant recoil momentum. The objective of this presentation is to consider methods to fully eliminate recoil for hypersonic (Mack five and up) launch.

High Velocity Guns

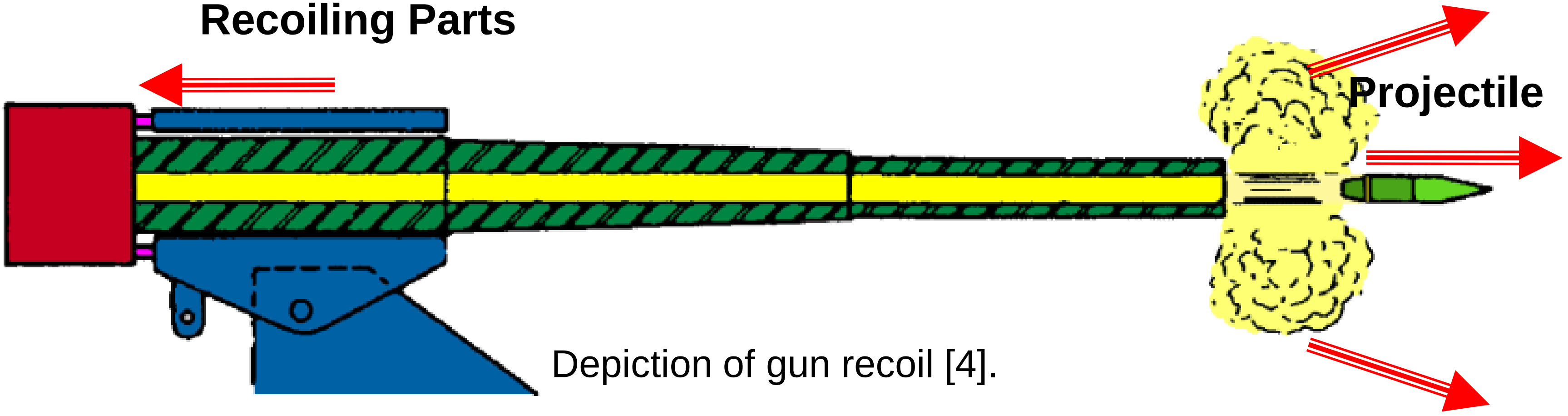
- A critical trait of high velocity launch is the relation between setback acceleration and launcher length.
- An ideal launch at a constant maximum setback acceleration to Mach 5 (1,700 m/s) may be related to launch stroke as:

$$a = \frac{v^2}{2L}$$

- The average acceleration in most guns is 50%-60% of the maximum with this ratio called the piezometric efficiency [3].
- Operating pressures on the order of 500 MPa (70 ksi) are used to achieve such high speed launch [2].
- For a given launch stroke, increasing bore diameter may relax pressure, but more energy is then wasted on larger sabots.



Basics of Recoil Momentum



Depiction of gun recoil [4].

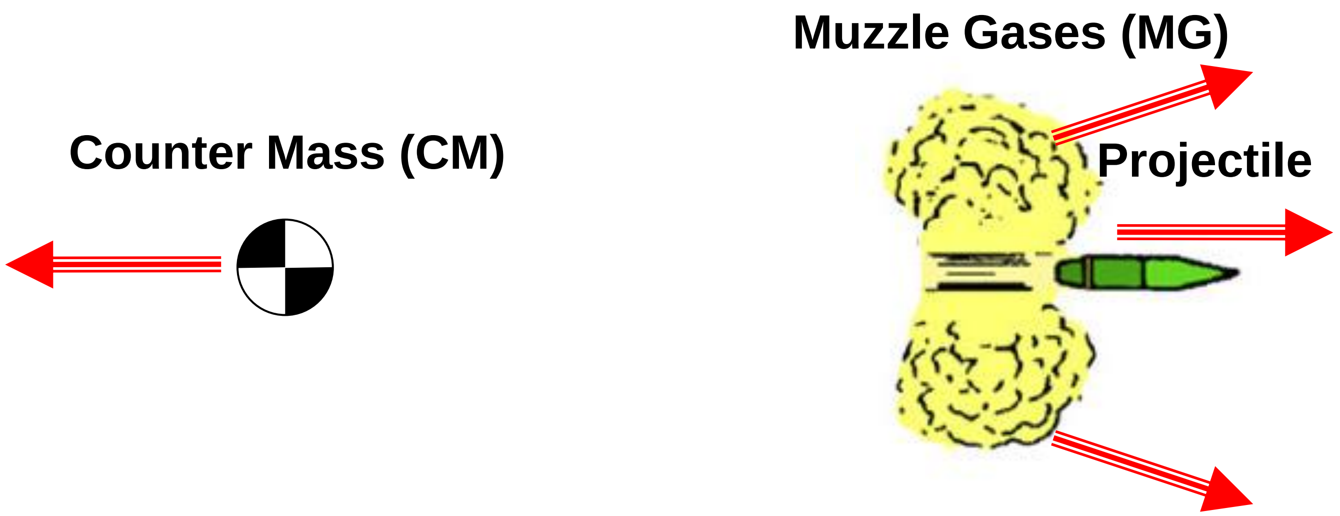
Conservation of Momentum

Momentum Imparted to Projectile and Propellant Gases must be Equal and Opposite to That Imparted to a Freely Recoiling Cannon.

$$m_{gun} \times v_{gun} + m_{charge} \times v_{charge} + m_{projo} \times v_{projo} = 0$$

Recoilless Operation

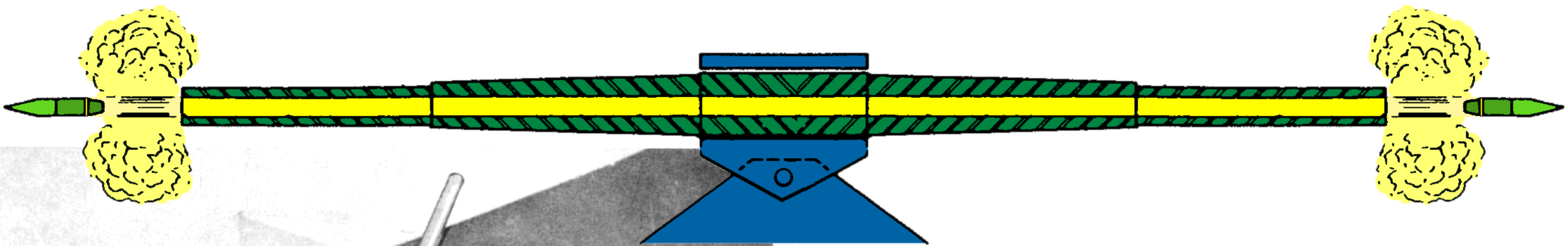
- For recoilless operation, their can be no net momentum applied to the launcher.
- With the projectile and gas exiting forward, this implies some form of counter mass must be expelled rearwards.



$$m_{CM} \times v_{CM} + m_{MG} \times v_{MG} + m_{projo} \times v_{projo} = 0$$

1) The Davis Gun

- The first known implementation of a recoilless gun was the Davis gun that fired two projectiles of equal caliber in opposite directions from a common chamber [5].
- Known as a Davis mass, the rearward directed projectile can be solid, liquid or powder. It need not be the same weight as the projectile.



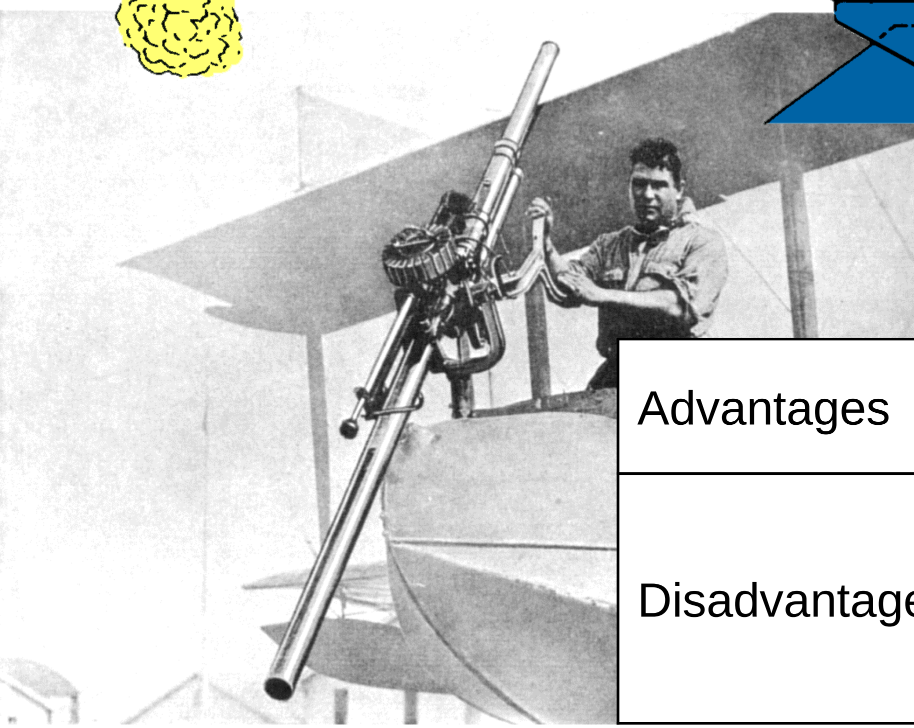
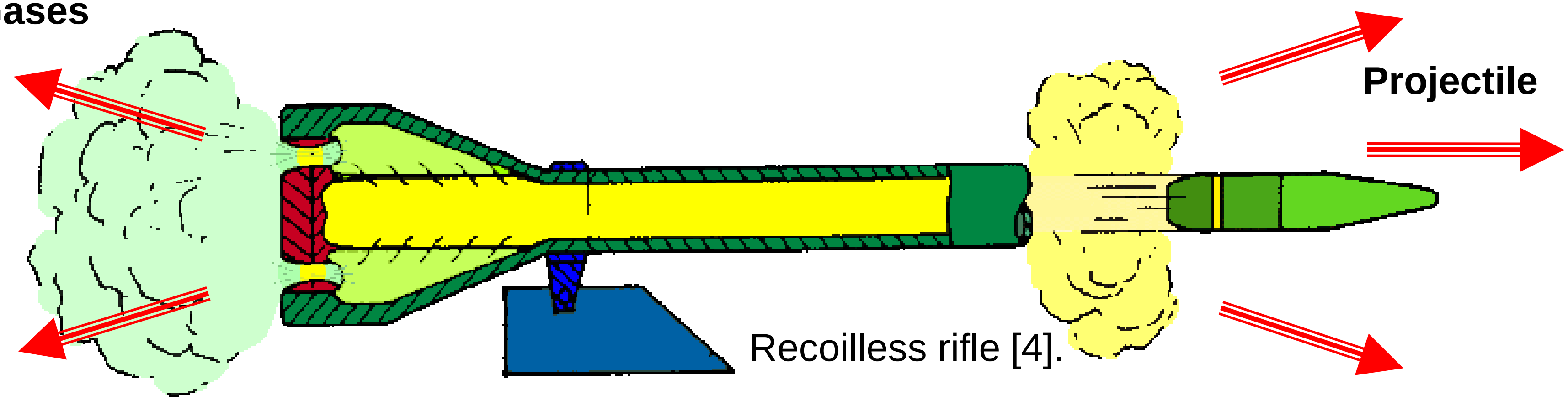


Image of Davis gun [6].

Advantages	Can achieve almost any gun launch velocity with good accuracy. No motion.
Disadvantages	Double length. Double weight of gun and cartridge. Complex to load. Significant rearward danger. Long chamber may be prone to ignition waves.

2) Recoilless Rifle

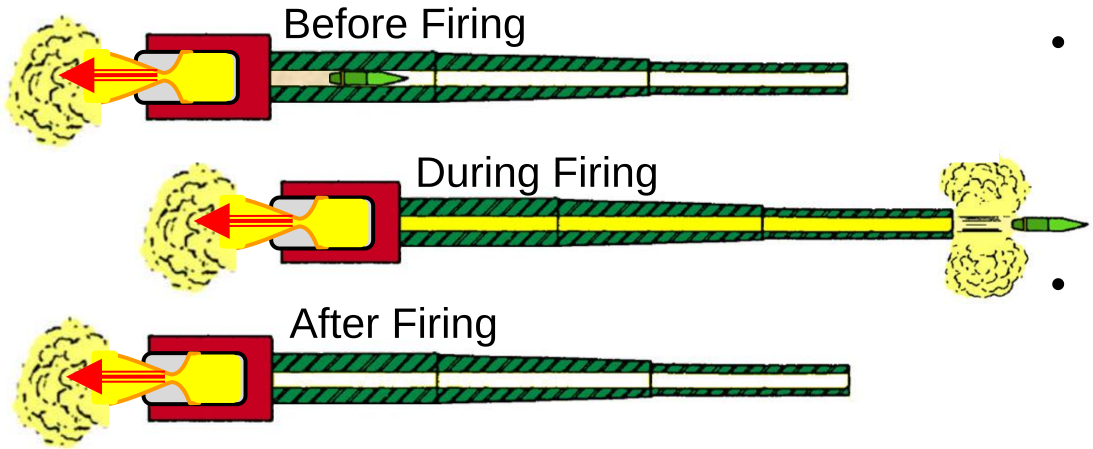


Recoilless rifle [4].

75mm M20 recoilless rifle in action [7].

Advantages	Simple. No recoil motion.
Disadvantages	Loss of ballistic efficiency relative to closed breech guns. Significant back blast danger. Throat erosion is anticipated to worsen if achieving high velocities.

3) Closed Breech Recoilless

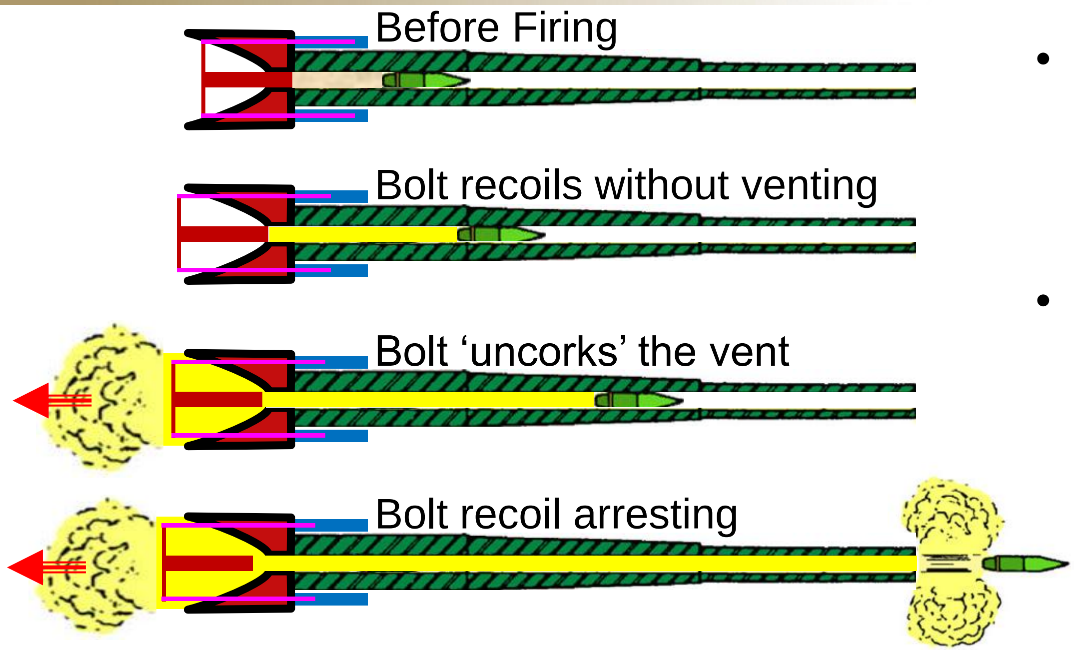


- The concept of using an impulse generator to eliminate gun recoil has been considered for airborne artillery [8].
- The impulse generator is a rocket motor coupled to the breech of the cannon.

- Rather than seeking to cancel recoil momentum as it is generated, the lower pressure motor is sized to produce less thrust for a longer duration to eliminate recoil.
- Depicted above is the “fire out of battery” approach that imparts forward momentum to the cannon prior to firing and fully arrests remaining cannon recoil after firing.

Advantages	Reduced rocket motor pressure and blast pressures. Recoil elimination is decoupled from propulsion allowing high velocity launch.
Disadvantages	Inefficiency relative to closed breech gun. Complex. Requires exceptionally reliable ignition of both the rocket and gun charge. Mounting for recoil motion.

4) Rarefaction Wave Gun [5]



- Intentional venting (by a blow back bolt) of a gun chamber causes a dramatic loss of chamber pressure and produces thrust.
- The pressure loss (rarefaction) wave can only travel as fast as sound wave.

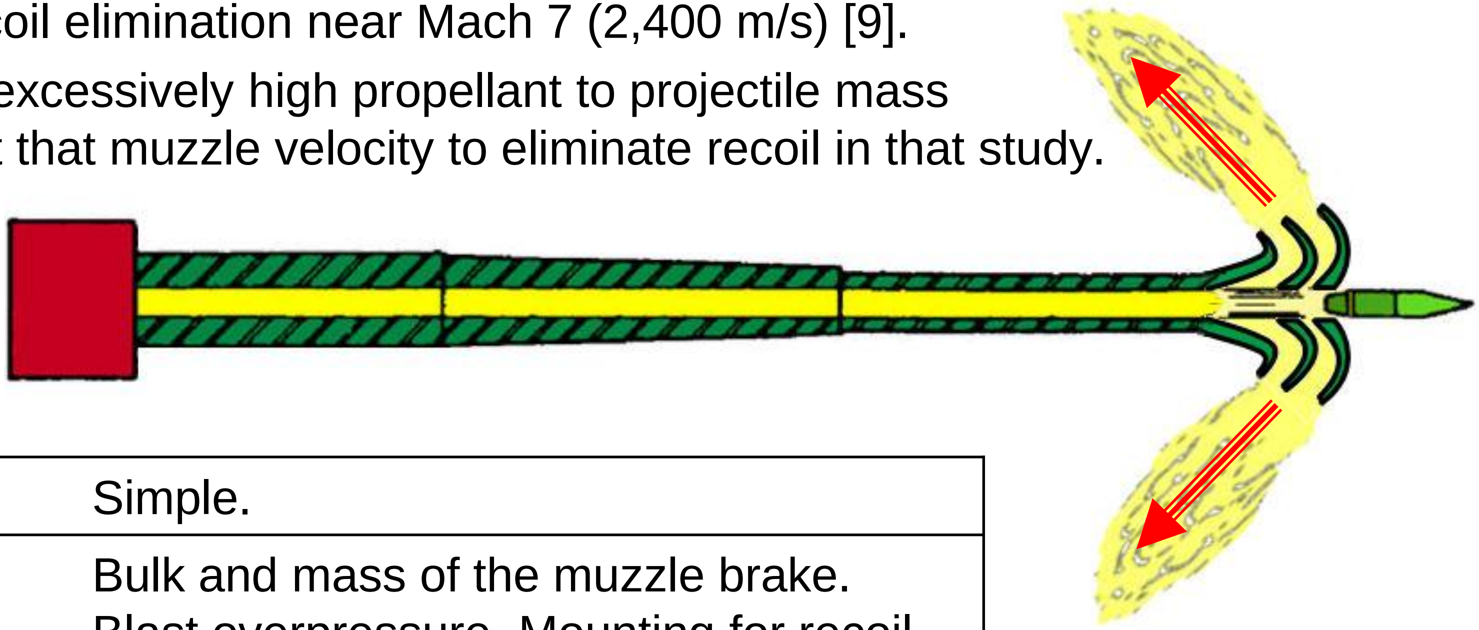
Bullet propulsion and loss of ballistic efficiency can only occur after the wave reaches the bullet.

- For many guns, venting when the bullet has only traveled one fourth to one third of its launch stroke does not slow the bullet.
- At high enough velocities it is recoilless without slowing the bullet. At lower velocities, early venting may eliminate recoil with minimum loss of efficiency.

Advantages	Maximum ballistic efficiency. Minimum blast energy. Recoil thrust and firing robustly coupled. Reduced bore heating and erosion.
Disadvantages	Complex. Mounting for recoil motion. Primary recoil arresting of heavy blow-back bolt.

5) Muzzle Brakes

- If made large enough in size, and when firing a projectile with enough propellant, it is possible to achieve recoilless operation using muzzle brakes.
- A 2001 study by Schmidt of ARL in comparing railguns and propellant guns estimated recoil elimination near Mach 7 (2,400 m/s) [9].
- Required an excessively high propellant to projectile mass ratio of five at that muzzle velocity to eliminate recoil in that study.



Advantages	Simple.
Disadvantages	Bulk and mass of the muzzle brake. Blast overpressure. Mounting for recoil motion. The need for very high propellant to projectile mass ratios results in reduced efficiency at lower velocities relative to a normal gun.

6) In-Bore Rocket

- Although not strictly a gun, an in-bore rocket engineered to burn-out prior to muzzle exit is rather gun-like. An early variant was the Goddard gun [5].
- The launch tube is straight with a constant diameter. The rearward discharge of the rocket gases produces forward acceleration to satisfy action and reaction.
- Hybrid designs expelling a liquid “Davis mass” exhaust have been demonstrated.

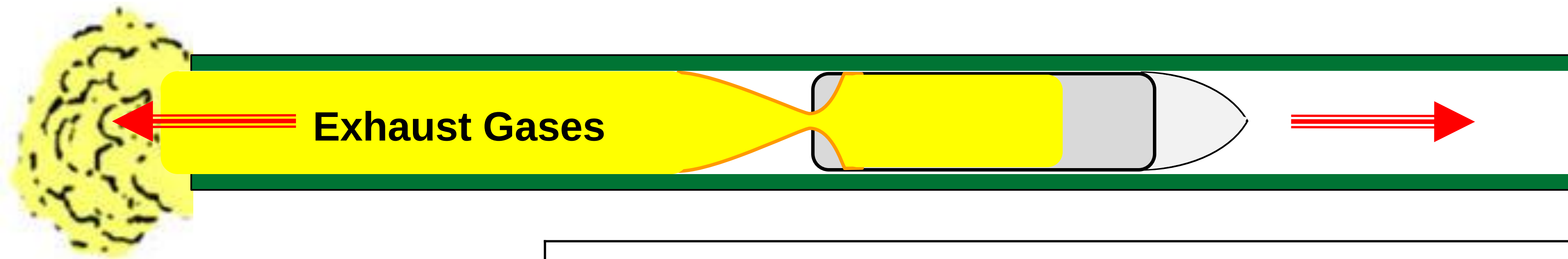



Image of Goddard gun [5].

Advantages	Simple. For very high velocities, rocket efficiency may exceed gun launch efficiency. No launcher recoil motion.
Disadvantages	The need to burn out prior to muzzle exit requires excessive rocket motor pressure and acceleration to achieve high velocity. Results in heavy parasitic motor mass. Back blast danger.

Davis and recoilless analysis

For a baseline, the M865 120mm round may be used.

M865 and 120mm Gun Parameters		
v	1,700 m/s	Muzzle velocity [2]
m_p	5.5 Kg	Projectile mass [2]
m_c	7.2 Kg	M14 Propellant mass [2]
m_T	17.0 Kg	Total cartridge mass [2]
P_c	480 MPa	Max pressure [2]
L	5.3 m	Length of M256 [10]

1. Davis Gun:
   - A Davis gun employing a double cartridge would use twice as much propellant and drive a parasitic Davis mass. This reflects a poor ballistic efficiency. Applied to launch the M865 it would employ a 10.6 meter long barrel (twice that of the M256).
2. Recoilless Rifle:
   - Using a prior performance curve fit (Eq 3.3-1 of [5]) and extrapolating from highest prior art velocities of 500 m/s reaches a maximum velocity of 1,100 m/s. This makes a 1,700 m/s firing apparently infeasible.
   - Published results for the Mauser RMK 30 recoilless auto-cannon claim a muzzle velocity of 1,200m/s without listing propellant consumption [11]. This would imply the above extrapolation is inaccurate. Nevertheless, excessive propellant consumption and throat erosion is anticipated at 1,700m/s.

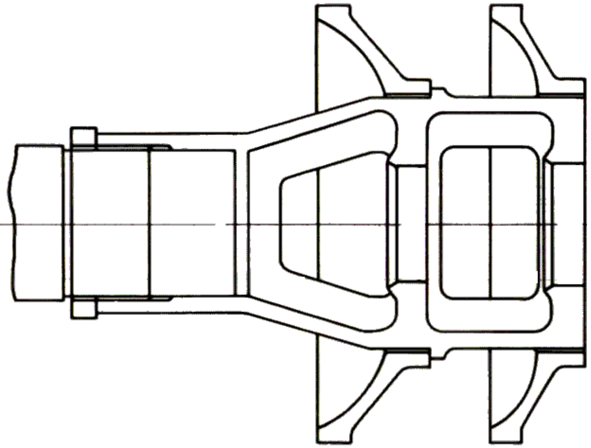
Closed breech recoilless and rarefaction wave gun analysis

3. Closed breech recoilless:
   - The total firing momentum of the baseline M865 is the sum of the projectile and charge mass momentum. The mass averaged propellant gas expulsion velocity may be computed using various methods to be around 2,000 m/s [3].

$$I = m_p v_m + m_p \bar{v}_c = (5.5Kg)(1{,}700m/s) + (7.2Kg)(2{,}000m/s) = 23.8KN*s$$

   - Using a specific impulse estimate of 250 s [12, page 7-7] the jet velocity of the impulse cartridge may be estimated to be 2,450 m/s [12, eq 5-5].
   - Dividing the estimated M865 impulse by this jet velocity estimates a rocket propellant mass of 9.7Kg to eliminate recoil. This is excessive and does not warrant estimating the additional weight of the case for this cartridge.
4. Rarefaction wave gun:
   - Using a methodology very similar to Schmidt [9] rarefaction wave gun recoil was analyzed to predict recoilless operation within ±300 m/s of 1,700 m/s without slowing the projectile [5].
   - Venting somewhat early, and allowing some small loss of ballistic efficiency, will allow assured recoilless operation capability for high velocity launch.

Muzzle brake analysis



5. Prior to Schmidt [9] the question of eliminating recoil using muzzle brakes was analyzed by Corner [13].

- He computed propellant to projectile ratio's required to achieve this feat as a function of muzzle velocity. The highest velocity considered was1,525 m/s. At this speed he estimated a ratio in excess of 8 for a muzzle brake exhibiting a momentum index of 1.8. (This corner index is the ratio of recoil reduction to the blow down recoil. The latter being the additional recoil imparted after shot exit.)

- The brake shown above and below exceed a 1.8 momentum index [14].
- Caution should be exercised. Data for aggressive brakes like this is not known to be available for high velocity launch. The simplified analysis methods known to be useful for lower velocity artillery guns should be considered low fidelity extrapolations for such high velocity applications.

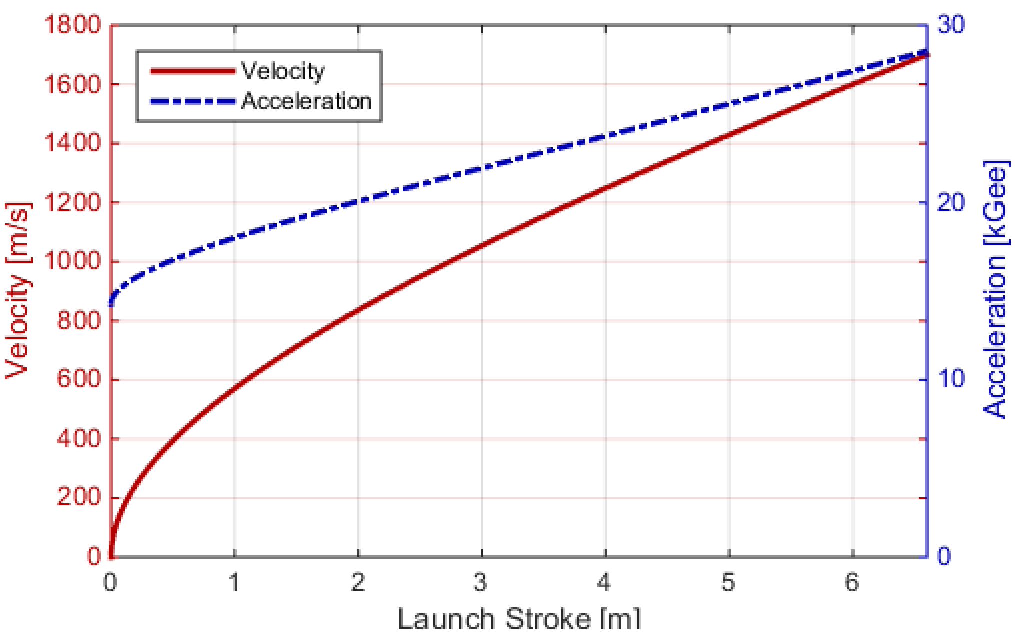
Images of tested 105mm umbrella muzzle brake [14].

In bore rocket analysis

6. The in-bore rocket may be analyzed using ideal rocket equations. A notional constant burn rate rocket for the 120mm M865 provides a benchmark.

Parameter		Description / Source
L	6.6 m	Upper bound length to the 120mm L55 [10].
v	1,700 m/s	Burn out velocity set to M865 [2].
m_b	5.5 Kg	Burn out mass set to M865 Projo [2]. (Real system would add motor pressure vessel mass.)
I_{sp}	250 s	Propellant specific impulse [12, page 7-7].
v_j	2,450 m/s	Jet velocity [12, eq 5-5].
m_p	5.5 Kg	Required propellant mass [12, eq 5-55].
t_b	8.8 ms	Computed time to burn-out from plot $\int_0^{t_b} v(t)dt = L$.
$\dot{m}_p$	630 Kg/s	Computed constant burn rate (m_p/t_b).
F	1,540 kN	Approximate thrust ($\dot{m}_p * v_j$).

- Computations neglecting motor mass show a favorable charge mass relative to the M865.
- The mass flow and thrust are comparable to a space shuttle main engine [15]. A short launch stroke is not practical. A real motor would be heavy and further increase propellant consumption and thrust.



Analysis of Alternatives

Assessment of the alternatives versus four performance attributes:

Technology	High Speed Launch	High Efficiency	Trainable Weapon (Length)	High Reliability	Figure of Merit
	1-Yes/0-No	1-Yes/0-No	1-Yes/0-No	1-Yes/0-No	
1) Davis Gun	1	0	0	1	50%
2) Recoilless Rifle	0	0	1	1	50%
3) Close Breech Recoilless	1	0	1	0	50%
4) Rarefaction Wave Gun	1	1	1	1	100%
5) Muzzle Brakes	1	0	1	1	75%
6) In-Bore Rocket	1	0	0	1	50%

Conclusions

Six methods to eliminate high speed gun recoil were considered:

1. The Davis gun is simply too bulky both for the weapon and ammo.
2. Recoilless rifles cannot reasonably achieve high velocities. They are inefficient and subject to throat erosion at high pressure.
3. Close breech recoilless has reliability concerns. Also, the separate loading of the impulse cartridge requires additional ammo bulk and complexity.
4. Muzzle brakes can only achieve recoilless operation at excessive charge to projectile mass ratios. At such ratio's muzzle blast would likely be very high.
5. Rarefaction wave gun propulsion is the best technology solution for recoilless high speed launch.
6. In-bore rockets require excessive launch length to achieve high velocities and are not suitable for a trainable high velocity close combat gun.

References

1. Wikipedia, "Armour-Piercing Discarding Sabot," accessed 1 April 2015.
   en.wikipedia.org/wiki/Armour-piercing_discarding_sabot
2. Orbital ATK, “M865 Fact Sheet,” accessed 1 April 2015.
   http://www.orbitalatk.com/defense-systems/armament-systems/120mm/
3. D. Carlucci and S. Jacobson, "Ballistics: Theory and Design of Guns and Ammunition," CRC Press, December 2010.
4. Army Materiel Command, "Engineering Design Handbook: Elements of Armament Engineering: Part 2: Ballistics," AMCP 706-107, September 1963.
   www.dtic.mil/dtic/tr/fulltext/u2/830287.pdf
5. E. Kathe, "Rarefaction Wave Gun Propulsion," Rensselaer Polytechnic Institute, May 2002.
   www.dtic.mil/dtic/tr/fulltext/u2/a435128.pdf
6. Wikipedia, "Davis Gun," accessed 1 April 2015.
   en.wikipedia.org/wiki/Davis_gun
7. Scheinker, Signal Corps Photo #8A/FEC-51-41144, November 1951.
   www.history.army.mil/photos/Korea/kor1951/kor1951.htm
8. T. Redling, "Analysis of a 105mm Closed Breech Gun Design with Recoil Cancellation and a 105mm Davis Type Gun Design," August 1973.
   www.dtic.mil/dtic/tr/fulltext/u2/913702.pdf
9. E. Schmidt, "Comparison of the Recoil of Conventional and Electromagnetic Cannon," Shock and Vibration, v8n3-4, pages 141-145, 2001.
   http://downloads.hindawi.com/journals/sv/2001/590948.pdf
10. Wikipedia, "Rheinmetall 120 mm Gun,” accessed 3 April 2015.
    en.wikipedia.org/wiki/Rheinmetall_120_mm_gun
11. A. Williams, “Rapid Fire,” Airlife Publishing, July 2000.
12. Army Materiel Command, "Engineering Design Handbook: Elements of Aircraft and Missile Propulsion," AMCP 706-285, July 1969.
    www.dtic.mil/dtic/tr/fulltext/u2/861082.pdf
13. J. Corner, "Theory of The Interior Ballistics of Guns," Wiley, 1950.
14. P. Shilstone, "Experimental Muzzle Brakes," within "Gun Blast and Muzzle Brake Symposium," G. Nice, ed., Fort Halstead, UK, Held March 1968, November 1970.
    www.dtic.mil/dtic/tr/fulltext/u2/513629.pdf
15. Aerojet Rocketdyne, “Space Shuttle Main Engine,” accessed 3 April 2015.
    http://www.rocket.com/space-shuttle-main-engine