Rifle Recoil Studies

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Introduction

The disturbance of recoil in firing a target rifle is a major accuracy concern for rifle builders as well as being a major physiological concern for riflemen. We will explore the technical aspects of quantifying rifle recoil here and leave the study of riflestock design, shooting positions, and "flinching" problems to others. Even technical recoil is a complicated enough subject to justify separate study. In other articles, we have addressed rifle designs developed to shoot accurately while handling recoil.

We will first study the ***forces*** involved in recoil, making use of *Newton's Third Law of Motion*:

"For every action there is an equal and opposite reaction."

Then we will make use of the principle of "*conservation of momentum*" to find the rearward ***recoil velocity*** of the rifle at the moment of bullet exit from the muzzle. We will also develop expressions for calculating the ***kinetic energy*** of the recoiling rifle. Considering the rifle and loaded round to constitute a "closed system," we can also find the distance that the rifle must have recoiled at the moment of bullet exit by understanding that the center of mass of the system must remain fixed throughout the firing process if no external forces are applied to the system (that is, if the rifle is fired in "free recoil"). We will show how the rifle and the bullet react to the short-term "impulse" forces produced by the combustion of the powder.

In the course of these studies we will examine the rifle recoil increases due to accelerating a portion of the powder charge and due to the "rocket effect" of powder products jetting from the muzzle after bullet exit. We will address the physics of "felt recoil" and the recoil-moderating effects of attaching a sound suppressor or muzzle brake.

Free Recoil Forces

The net force accelerating the bullet at any instant in time while the bullet is within the rifle's barrel must be *exactly matched* by an instantaneous recoil force acting upon the entire rifle. Before the bullet starts moving, *no* recoil force can act on the rifle, regardless of the pressure in the chamber. The force required to engrave the rifling into the bullet's surface (a "one time" starting force of about **700 pounds**) and the force of sliding friction between the bullet and the bore (about **80 pounds**, or **2 percent** of the bullet's **4,200-pound** maximum driving force) are simply deducted from the force accelerating the bullet, and do not cause any separate recoil effects on the rifle. Clearly, the engraving and friction forces both always act to pull the rifle barrel *forward* by amounts *exactly offsetting* their respective portions of the much greater *rearward* push against the inside of the case head due to chamber pressure. For all we can tell externally, the situation is as if there were no engraving or friction forces and the chamber pressure curve were slightly lower than its actual values over the pressure cycle. Only the force causing *movement* of the bullet causes the *recoil force* on the rifle. This is in accordance with *Newton's First and Second Laws of Motion*.

As a brief aside, consider the "recoil" of the rifle due to the striker flinging itself forward within the bolt under its own spring force after it has been released by the sear. For about the **0.002 seconds** of its "lock time," the bolt body is hauling rearward on the rifle's action with a force of about **24 pounds**. But then, the firing pin crashes into the primer anvil and gives back about **240 pounds** of forward push for about **0.0002 seconds** of impact duration. Note that the two "impulses," or *forces applied multiplied by the time durations of their applications*, are the same **0.048 pound-seconds** in each direction and, thus, cancel each other exactly. This perfect cancellation of the impulses is why we do not usually worry too much about recoil effects on the rifle due to striker motion. We know from physics that these impulses *must cancel exactly* (even if the numbers cited are only approximate, and, indeed, even when the firing pin is stopped inside the bolt as in "dry firing") because the rifle's bolt action is a "closed system," with nothing entering or leaving it and with *no net external forces* acting upon it beyond trigger pull during its "lock time." We know that an *impulse* causes a *proportional change in the momentum* of its affected object (from *Newton's Second Law*), and that the momentum of the rifle is **zero**, both before trigger release and after striker fall (from the *First Law of Motion*). Try measuring the recoil of your benchrest rifle during dry firing, if you have reason to doubt this.

In our recurring example of firing a **168-grain** *Sierra MatchKing* bullet at **2,600 feet/second** from our **10-pound** bolt-action target rifle chambered in *308 Winchester*, we can readily calculate the peak force available to accelerate the bullet. We know that this peak force $\mathbf{F_P}$ occurs right after bullet engraving when both the peak chamber pressure and pressure against the base of the slowly-moving bullet $\mathbf{P_B}$ are about the same **57,400 pounds per square inch (psi)**. The cross-sectional area of the bore $\mathbf{A_B}$ for our example rifle is **0.0735 square inches**, so the force on the base of the bullet is:

$$\mathbf{F_P = P_B * A_B}, \text{ or}$$

$$\mathbf{F_P = \underline{4{,}200 \text{ pounds}}},$$

where

$$\mathbf{P_B = 57{,}400 \text{ psi}}, \text{ and}$$

$$\mathbf{A_B = (\pi/4)*(0.306 \text{ inches})^2}$$

$$\mathbf{A_B = 0.0735 \text{ square inches.}}$$

By Newton's Third Law of Motion, this peak force $\mathbf{F_P}$ ***on the bullet's base must be <u>exactly</u> the peak recoil force on the target rifle***. Fortunately for our intrepid rifleman, this great **4,200-pound** peak force exists only for an imperceptibly brief period of time. But the very size of this peak recoil force tells us why it is usually a bad idea to fire a hard-kicking rifle while bracing the buttstock against a solid object. You could easily crack or break your riflestock in so doing. Knowing that this recoil force relationship is based directly on *Newton's Third Law* equips you to win the occasional bet with a shooting buddy. Bet that one can switch to firing heavier bullets at the same peak chamber pressure *without increasing the peak recoil force* of the rifle. [However counterintuitive it might seem, the weight of the bullet does *not* appear in this expression for ***peak recoil force*** on the rifle. However, the peak recoil force *does* increase significantly if we move to firing a *larger caliber* rifle.]

The primary use of the peak recoil force value is in calculating (for example) the peak recoil force $\mathbf{F_S}$ trying to shear off the scope mounting bases from the receiver or to damage the optical scope sight. By finding the weight ratio of the **1.5-pound** scope system $\mathbf{W_S}$ to the whole rifle's weight ($\mathbf{W_R}$ **= 10 pounds**), we can calculate this *proportion* of the peak recoil force (**4,200 pounds**) and find the peak shearing force $\mathbf{F_S}$ on the scope base mountings to be **630 pounds**:

$$\mathbf{F_S = (W_S/W_R)*P_B*A_B = \underline{630\ pounds}}.$$

Perhaps more meaningful to the shooter, is the *average force* $\mathbf{F_{AV}}$ over the brief *time period* during which the bullet is moving up the barrel. The *momentum* $\mathbf{p_B}$ of our example **168-grain** bullet on exit from the muzzle at **2,600 feet/second** is:

$$\mathbf{p_B = m_B*V_B = [(168/7000)/32.16]*2600}$$

$$\mathbf{= \underline{1.94\ pound\text{-}seconds}.}$$

[Here, we are dividing the bullet's *weight* in grains by **7,000 grains/pound** to find its weight in pounds, and dividing this weight by the acceleration of gravity **g** (**32.16 feet per second per second**) to find its *mass* $\mathbf{m_B}$.]

By the muzzle velocity $\mathbf{V_B}$, I mean here the speed of the bullet *immediately on exit from the muzzle*, neither after the bullet has been accelerated another two percent, or so, by the subsequent muzzle blast, nor as it might be chronographed several yards downrange.

This *net change in the bullet's momentum* (from **zero** at rest) $\mathbf{\Delta p_B}$ has to match the *impulse* ($\mathbf{F_{AV}*\Delta t}$) given to it during its trip up the barrel:

$$\mathbf{F_{AV}*\Delta t = \Delta p_B = m_B*V_B = 1.94\ pound\text{-}seconds.}$$

[Here, I am adopting the standard short-hand notation from physics of using the Greek capital letter "**Δ**" to mean "change in" whatever symbol follows it.]

The time interval $\mathbf{\Delta t}$, during which the bullet is accelerating, is about **0.0011 seconds;** so the average force $\mathbf{F_{AV}}$ driving the bullet (averaged over the time interval $\mathbf{\Delta t}$) is just:

$$\mathbf{F_{AV} = \Delta p_B\ /\ \Delta t = (1.94)/(0.0011) = 1{,}760\ pounds}.$$

As a point of interest, if we multiply the *momentum* of the bullet (**1.94 pound-seconds** on exit from the muzzle) again by *half of its muzzle velocity*, we would have the *bullet's kinetic energy* $\mathbf{KE_B}$ at the muzzle**:**

$$\mathbf{KE_B = (1/2)*m_B*V_B^2}$$

$$\mathbf{KE_B = (V_B/2)*(m_B*V_B)}$$

$$\mathbf{KE_B = (1300)*(1.94) = 2{,}520\ foot\text{-}pounds}.$$

Free Recoil Velocity

From the principle of "***conservation of momentum***," we can state that the *total momentum* **p** of the rifle and its loaded round (as a system) must be the same *constant* value *before*, *during*, and *after* firing until external forces take effect. We can also conveniently assign this total momentum **p** the constant value of **zero** since everything is stationary before firing. Then, we can simply ratio the *bullet's weight* W_B to the *rifle's weight* W_R and find this proportion of the *bullet's muzzle velocity* V_B in order to calculate the *recoil velocity* V_R of the rifle:

$$\mathbf{p = (W_R/g)*V_R - (W_B/g)*V_B = 0.0}, \text{ or}$$

$$\mathbf{V_R = (W_B/W_R)*V_B}$$

$$\mathbf{V_R = [(168/7000)/10]*2600}$$

$$\mathbf{V_R = 6.24\ feet/second}.$$

This would be all there is to the matter if accelerating the bullet up the bore were all that was going on, but that is not quite the case here. The rifle has also ***accelerated a portion of the powder charge*** of IMR-4064 powder (weighing $\mathbf{W_P = 44.0}$ **grains** in this example). We can account for this effect by adding an *empirically determined* **50 percent** of the *weight of the charge* to the bullet weight, and recalculating the recoil velocity of our rifle. In fact, often a portion of the burning powder mass actually adheres to the base of the moving bullet as it travels up the barrel. Our adjusted recoil velocity is now:

$$\mathbf{V_R = [(W_B + 0.50*W_P)/W_R]*V_B}$$

$$\mathbf{V_R = [((168 + 22)/7000)/10]*2600}$$

$$\mathbf{V_R = 7.06\ feet/second.}$$

But, ***there is yet a third effect at work*** increasing the recoil velocity of our target rifle. Just after the bullet cleared the muzzle, whatever gas pressure remained in the bore and chamber vented itself into the atmosphere as a forward-firing, high-velocity jet of hot gasses (at about **6,000 degrees** Fahrenheit) and powder particles in various stages of burning. The gas pressure at the muzzle upon bullet exit can easily be **12,000 psi**, or more, for high-pressure cartridges, using slower-burning powders, and fired from shorter-barreled rifles. On the other hand, a 12-gauge shotgun shell might have only **2,000 psi** of pressure remaining when the shot wading clears the choke of a **32-inch** barrel. Maj. Gen. J. S. Hatcher reports in *Hatcher's Notebook*, Stackpole, 1947, that for WWII-vintage .30-06 military (and similar) rifles, we should use a value of **4,700 feet/second** for the *effective* velocity V_P of the escaping powder gasses. Now, our expression for the *recoil velocity* of our very similar rifle becomes:

$$\mathbf{V_R = [W_B/W_R]*V_B + [W_P/W_R]*V_P}$$

$$\mathbf{V_R = [(168/7000)/10]*2600 + [(44/7000)/10]*4700}$$

$$\mathbf{V_R = \underline{9.19\ feet/second}.}$$

Note that this effective powder exit velocity V_P of **4,700 feet/second** *includes* the effect of accelerating the powder moving up the bore before bullet exit (as above) as well as the jetting-out of the full charge-weight of ejecta from the muzzle behind the bullet. The total mass of the ejected gasses and particles should equal the mass of the original powder charge.

At this fully adjusted recoil velocity, the *recoil momentum* of the rifle $\mathbf{p_R}$ is found by multiplying its mass $\mathbf{m_R}$ by its recoil velocity $\mathbf{V_R}$:

$$\mathbf{p_R = m_R * V_R = (W_R/g) * V_R = (10\ pounds/g) * (9.19\ feet/second)}$$

$$\mathbf{p_R = \underline{2.86\ pound\text{-}seconds}.}$$

We know from the principle of "conservation of momentum," that this rearward momentum $\mathbf{p_R}$ of the recoiling rifle must equal the sum of the forward momentum of the bullet $\mathbf{p_B}$ (**1.94 pound-seconds**) and the total forward momentum of the powder products $\mathbf{p_P}$, or **0.92 pound-seconds**:

$$\mathbf{p_P = [(44.0\ grains/7000)/g] * 4700\ fps = \underline{0.92\ pound\text{-}seconds}}.$$

And, our example **10-pound** rifle would have a *kinetic energy of recoil* $\mathbf{KE_R}$ of:

$$\mathbf{KE_R = [W_R/(2*g)]*V_R^2}$$

$$\mathbf{KE_R = (5/32.16)*(9.19)^2}$$

$$\mathbf{KE_R = \underline{13.1\ foot\text{-}pounds}.}$$

If our **10-pound** rifle were dropped butt-first from a height **h** of **15.8 inches**, it would impact at this same velocity of **9.19 feet/second**, and with the same **13.1 foot-pounds** of kinetic energy:

$$\mathbf{h = [V_R^2/(2*g)]*12\ inches/foot = 15.8\ inches}.$$

Also, let me emphasize here that the *impingement* of the jet of hot gasses from the muzzle upon the base of the bullet during (typically) its first **15 calibers** of flight distance *does not* increase the recoil velocity of the rifle $\mathbf{V_R}$ under *any* conditions. This jet *does* speed along the bullet about **50 feet per second** faster than its spin rate would indicate, but this occurrence *cannot* somehow cause an extra push-back against the muzzle.

An alternate formulation is sometimes used for convenience in handling the powder ejection problem. The weight of the powder charge $\mathbf{W_P}$ is increased by a factor that normally varies between **1.0** and **2.0** that would be necessary to adjust the recoil momentum if the powder products *had all been ejected at the muzzle velocity of the bullet* $\mathbf{V_B}$. Hatcher recommends a factor of **1.75** for rifles chambered for .30-06 class cartridges, but we would need to use a factor of **1.81** here because of our unusually low muzzle velocity from this **21.75-inch**-barreled target rifle:

$$\mathbf{V_R = [(W_B + 1.81*W_P)/W_R]*V_B}$$

$$\mathbf{V_R = \underline{9.19\ feet/second}.}$$

A factor of only **1.25** would have been appropriate in this formulation for the long-barreled 12-gauge trap gun mentioned earlier.

Recoil Distance at Bullet Exit

If we isolate the loaded rifle by firing it in "free recoil," so that no external forces are applied to any part of the system until after the bullet has exited the muzzle, we can calculate exactly how far backwards the whole rifle would freely recoil while the base of the bullet moved to a point just clear of the muzzle. Actually, short-range benchrest rifles *are* best fired in exactly this manner—except for being supported, front and rear, on sandbags. If we let $\mathbf{D_B}$ represent the distance (**20.0 inches**) traveled by our example **168-grain** bullet (and **50 percent** of the powder charge of **44.0 grains**) to reach the muzzle of our barrel, how far ($\mathbf{D_R}$) will our example **10-pound** target rifle move backward in recoil before the bullet exits its bore? In our "closed system," the center of mass must remain *fixed in one spot* while all of this is going on, so at the instant of bullet exit:

$$\mathbf{(W_R - W_{BP})*D_R = W_{BP}*D_B}$$

where $$\mathbf{W_{BP} = W_B + 0.50*W_P = (168 + 22)/7000 = 0.0271 \text{ pounds}}.$$

Solving for $\mathbf{D_R}$, we have:

$$\mathbf{D_R = [0.0271/9.9729]*20 \text{ inches} = \underline{0.0544 \text{ inches}}}.$$

So, our heavy target rifle only moves back by less than **1/16-inch** at the time of bullet departure. This "free recoil" distance would be *even less* for a **10.5-pound** *IBS Sporter Class* benchrest rifle in *6PPC* firing a **68-grain** bullet using about **28 grains** of powder.

Perceived Recoil of a Rifle

The recoil of the normally supported rifle, whether shoulder fired or bench rested, often occurs in three stages. First, during the **1.5 milliseconds**, or so, while the bullet and powder products are traversing the barrel, from bullet start and ending after the hot powder gasses have jetted from the muzzle, the *accelerating* rifle achieves its *maximum* rearward velocity, momentum, and kinetic energy. The normally supported rifle is usually in "free recoil" during this first stage since it moves a total of only about **0.060 inches** during this brief interval. Second, the rifle usually goes into an indefinite "*coasting*" period, during which its recoil velocity remains essentially constant. Finally, the rifle-butt *collides* with the firer's shoulder producing "felt recoil" in a "partially elastic" collision. With a very "hard hold," one might be able to collapse these stages somewhat—starting with elimination of the coasting phase. The collision itself can be separated into two distinct sub-stages: (1) the shoulder resistance bringing the rifle to a halt, and (2) the rifle rebounding forward at a fraction of its original recoil speed. This rebound fraction is termed the *coefficient of restitution* ($\mathbf{C_R}$) in engineering and probably runs about **20 to 30 percent** in most shooting situations. When dropped from a height of about **16 inches** onto the carpeted concrete floor of my office, a couple of my synthetic-stocked *Remington 700* rifles rebounded to heights of about **4 inches** ($\mathbf{C_R = 0.25}$). The shoulder of the rifleman initially rebounds rearward in a highly variable motion that we need not attempt to calculate here.

We can model the *interaction force* **F** of the collision between the shoulder and the buttstock as being proportional to some "compression distance" ($\mathbf{x - x_0}$), measured between two relatively rigid points on the rifle stock and the firer's shoulder, so that from Hooke's Law:

$$\mathbf{F = k*(x - x_0)}$$

where **k** = Combined "force constant" for recoil pad, clothing and tissue, and

$\mathbf{x_0}$ = Distance measurement at beginning of contact.

Note that, since $\mathbf{x} < \mathbf{x_0}$ after collision begins, the "compression distance" is *inherently negative*, and that the forward-acting restoring force **F** works oppositely to the positive-rearward **x**-dimension.

The ***average force*** $\mathbf{F_{AV}}$ that must be supplied by the firer to bring the recoiling rifle to a halt within the available "stopping distance" is what is ***felt most directly*** as the "kick" of the rifle. The total "recoil resisting impulse" supplied by the shooter (i.e., the product of $\mathbf{F_{AV}}$ and the time interval $\mathbf{\Delta t}$ over which it must be supplied) is also *sensed* by the shooter, but more as the *total setback* of his upper body, rather than directly as pain and suffering. These are my considered opinions as a trained physicist and as a rifleman. We have shown here how to calculate for the free-recoiling rifle: (1) its peak recoil force, (2) its recoil velocity, (3) its recoil momentum, (4) its kinetic energy of recoil, and even (5) its recoil distance at bullet exit. While arguments could be put forward promoting any of these rifle-motion parameters as principle causes of felt recoil, I reckon that "felt recoil" requires the *interaction* of the shooter with the rifle. We will calculate how much "stopping force" must be supplied by the shooter's shoulder to halt the rifle's rearward motion.

When the buttstock comes back rapidly at the rifleman in firing, the "recoil absorbing" padding between the solid gunstock material and the shoulder bones of the shooter spreads out the impact area and lengthens the rifle's "stopping time" slightly. This recoil padding, whether natural or added-on, usually absorbs about $\mathbf{1 - C_R = 0.75}$ of the kinetic recoil energy, or about **10** of the **13 foot-pounds** of kinetic energy of our example rifle. This absorbed energy is mostly dissipated as heat. Any remaining kinetic energy is temporarily stored as potential energy in the system as when compressing a spring. By maximizing the ***area*** of contact, we can reduce the local *force per unit area*, or *contact pressure*, which can cause localized pain and bruising. The *average force* $\mathbf{F_{AV}}$ required to halt this rearward motion is equal to the *recoil momentum* of the rifle divided by the amount of "*stopping time*" $\mathbf{\Delta t}$ over which we can spread-out the process. If we can *double* this time interval $\mathbf{\Delta t}$, we can *halve* the average recoil force $\mathbf{F_{AV}}$ perceived by the shooter as the "kick" of the rifle. We know the *recoil momentum* $\mathbf{p_R}$ of the rifle, but we do not yet know the "stopping time" interval $\mathbf{\Delta t}$ for its interaction with the shoulder of the shooter. So:

$$\mathbf{F_{AV} * \Delta t = \Delta p = p_R = 2.86 \text{ pound-seconds.}}$$

The rifle's ***recoil momentum*** $\mathbf{p_R}$ of **2.86 pounds-seconds** must be reduced to **zero** by our "recoil system," so this value is *also* the size of the "***recoil impulse***" $\mathbf{\Delta p}$ that must be supplied by the shooter.

The usual manner in which we *spread-out* the "stopping time" of the recoiling rifle is to design its "recoil pad," attached to the rear face of the riflestock, so as to provide an *increasing* amount of compression force **F** to slow the rifle as it moves rearward. The greater the "stopping distance" that we can provide, the less will be the *force of recoil* **F**, averaged over that distance $\mathbf{\Delta s}$, that is felt by the shooter. Another way of finding this average force $\mathbf{F_{AV}}$ is to consider the kinetic energy of the recoiling rifle $\mathbf{KE_R}$. If we know the maximum amount of compression distance $\mathbf{\Delta s}$ that the recoil system is designed to utilize in bringing the rifle to a halt, we can calculate the ***amount of work*** needed to be supplied by the shooter to reduce the ***kinetic energy*** of the rearward-moving rifle $\mathbf{KE_R}$ to **zero**. We can calculate the average force $\mathbf{F_{AV}}$ needed from:

$$\mathbf{F_{AV}*\Delta s = \Delta KE} = \mathbf{KE_R = 13.1\ foot\text{-}pounds} \text{ for our example rifle.}$$

[Technical Note: We can *equivalence* the "time averaged" and the "distance averaged" retarding forces $\mathbf{F_{AV}}$ here because we are able to use a *linear force model*, with all that implies.]

If we fired a rifle with its buttstock held against a concrete wall, the stopping distance $\mathbf{\Delta s}$ might be as short as **0.10-inch** with a thin recoil pad, so that the average stopping force would be:

$$\mathbf{F_{AV} = (13.1\ ft\text{-}lbs)/(0.10\ in/12\ in/ft) = 1580\ pounds.}$$

And, the "stopping time" $\mathbf{\Delta t}$ in this case would be:

$$\mathbf{\Delta t = \Delta p_R/F_{AV} = 2.86\ pound\text{-}seconds/1580\ pounds}$$

$$\mathbf{\Delta t = 0.0018\ seconds.}$$

This stopping force-versus-time profile is similar to the impulse originally given to the bullet during its acceleration up the barrel.

Fired from a firm, normal hold, our example target rifle might recoil through a total stopping distance $\mathbf{\Delta s}$ of about **<u>0.60-inch</u>**, producing:

$$\mathbf{F_{AV} = \underline{263\ pounds}.}$$

And the "stopping time" $\mathbf{\Delta t}$ for our recoiling rifle is:

$$\mathbf{\Delta t = 2.86/263 = \underline{0.0109\ seconds}.}$$

Note that a computational *short-cut* is available that holds in each case above:

$$\mathbf{\Delta s/\Delta t = (V_R/2)*(12\ in/ft).}$$

So,

$$\mathbf{\Delta t = \Delta s/[(V_R/2)*(12\ in/ft)]},$$

$$\mathbf{\Delta t = 0.60\ inches/55.2\ inches/second}, \text{ and}$$

$$\mathbf{\Delta t = 0.0109\ seconds.}$$

This exercise illustrates how *felt recoil force* is reduced by an *effective recoil pad* and why we must hold any rifle *consistently* and *firmly* into our shoulder both for target accuracy and to avoid getting a "Weatherby eyebrow" from our scope eyepiece when firing a powerful rifle. The average resistance force $\mathbf{F_{AV}}$ supplied by the shooter must be *consistent* from one shot to the next because its size affects where the rifle barrel is pointed, its rates of motion, and how much it is vibrating at the instant of bullet exit from the muzzle. Any forward direction *rebounding* of the rifle that might occur increases the time interval $\mathbf{\Delta t}$ of application of the recoil-resisting force without increasing the average size of that force $\mathbf{F_{AV}}$. An effective stock design and recoil system can reduce the otherwise perceived "hard kick" of a powerful rifle to a more pleasant "gentle shove."

Suppressor Effects

Some might not realize that among the many beneficial effects of equipping your rifle with a quality "sound suppressor" is the *significant reduction of the net recoil velocity of the rifle*. If, for example, we were to attach securely a typical **2-pound** ($\mathbf{W_S}$), bayonet-mounted, add-on suppressor to its muzzle, the recoil velocity $\mathbf{V_R}$ of our example rifle would be reduced to:

$$\mathbf{V_R = [W_B/(W_R + W_S)]*V_B}$$

$$\mathbf{V_R = [(168/7000)/12]*2600}$$

$\mathbf{V_R}$ = **5.20 feet/second**, a reduction of **43.4 percent.**

And, at this reduced recoil velocity the suppressed rifle would have a kinetic energy $\mathbf{KE_R}$ of:

$$\mathbf{KE_R = [(W_R + W_S) /(2*g)]*V_R^2}$$

$$\mathbf{KE_R = (6/32.16)*(5.200)^2}$$

$\mathbf{KE_R}$ = **5.05 foot-pounds**, a reduction of **61.6 percent.**

As with the use of a muzzle brake, some of these *perceived* reductions in recoil velocity and kinetic energy are produced by a ***time-delayed*** forward (counter-recoil) impulse force acting to offset a portion of the rifle's recoil velocity. Notice also that the main recoil reducing effect in this expression for $\mathbf{V_R}$ is that there is *no* "rocket effect," at all, in this calculation. ***Preventing*** this high-velocity gas discharge is *precisely* what a suppressor is designed to accomplish. The effective suppressor traps most of the powder gasses and particulates, cools them and expands the gasses tremendously, and releases them slowly at low pressure. [The suppressor eventually gets *very hot* in use.] In so doing, the suppressor produces a *forward-acting impulse* pulling forward on the muzzle that *just counteracts* the accelerating of half the charge weight to the muzzle velocity $\mathbf{V_B}$. In fact, not much of the powder combustion product, or even the compressed air column ahead of the bullet, escapes the suppressor at a high velocity.

Adding the suppressor to our target rifle has reduced the recoil velocity and energy levels of the *308 Winchester* rifle to about those we would have experienced if our same heavy-weight target rifle had been chambered in *223 Remington*, instead. A well made and securely attached suppressor should also *enhance* the target accuracy of our rifle by minimizing the effects of vertical-plane, transverse barrel vibrations by serving effectively as an un-tuned "barrel mass." Not only has the hearing-damaging muzzle blast of our example rifle been greatly reduced, of course, but so also have its militarily important muzzle flash and dust signature. The long-range military sniper benefits greatly by using his suppressor to prevent enemy personnel in the vicinity of his distant target from being able to locate his firing position accurately by the arrival one to two seconds after his supersonic bullet of the sound signature of his rifle's muzzle blast. The "sonic boom" (or "crack") of his supersonic bullet is *not* suppressed. The muzzle velocity $\mathbf{V_B}$ of the bullet is not greatly affected by suppressor use. The "muzzle blast" that has been eliminated would only have accelerated the bullet by about **50** extra feet per second beyond the muzzle. An enlightened society should *promote* the use of these beneficial devices in many types of recreational shooting for prevention of hearing damage and reduction in the nuisance of shooting noise, rather than legally *proscribing* their use as devices associated with the "bad guys" in countless inane Hollywood movies.

Muzzle Brake Effects

If, instead, we were to attach securely a well designed muzzle brake, typically weighing about **1.0-pound** (W_{MB}), to our rifle's barrel by threading its muzzle, we could reduce the net recoil velocity V_R of our target rifle, more or less, depending upon the efficiency **e** of the brake's design and the gas pressure available at the muzzle of the rifle:

$$V_R = [W_B/(W_R + W_{MB})]*V_B + (1 - 2*e)*[W_P/(W_R + W_{MB})]*V_P$$

where: V_P = Effective powder gas exit velocity **= 4,700 feet/second**, and

The efficiency **e** of the muzzle brake ranges from **0.0** (no effect) to **1.0** (when all powder gasses are turned around to exit directly toward the rear at the same effective velocity V_P).

[Note that with **e = 0.0** and W_{MB} **= 0.0 pounds,** this expression reduces to the "fully adjusted" equation for V_R of an un-braked rifle.]

An efficiency rating in a range of about **e = 0.40** to **e = 0.60** would be typical for an effective, but relatively small, muzzle brake of current design. The value of V_P would need to be adjusted upward for large magnum rifles using very slow-burning powders, and the efficiency rating might possibly reach about **e = 0.80** for large, maximally gas-reversing, "clam shell" brakes. If we attach a hypothetical muzzle brake to our example target rifle having a high efficiency rating of **e = 0.60**, the recoil velocity would be:

$$V_R = [(168/7000)/(11)]*2600 - 0.20*[(44/7000)/11]*4700 = \underline{5.14 \text{ feet/second}}.$$

This represents a reduction of **44.1 percent** in the perceived recoil velocity compared to the un-braked rifle, but the *sound signature* of our target rifle has been increased to levels not welcomed on many target ranges.

And, at this reduced recoil velocity the muzzle brake equipped rifle would have a kinetic energy KE_R of:

$$KE_R = [(W_R + W_{MB}) /(2*g)]*V_R^2$$

$$KE_R = (5.5/32.16)*(5.14)^2$$

$$KE_R = \underline{4.51 \text{ foot-pounds}}.$$

This **65.7 percent** reduction in the net kinetic energy of recoil is quite impressive, but the noise level emitted from this device requires the wearing of *two sets* of hearing protection by the firer and all nearby personnel.

Cautionary Warning

Anyone relying on the recoil reductions achievable by using a muzzle brake on a monstrously hard-kicking rifle must be aware that the *full force* of recoil *still happens* with this device—but only for about **1.5 milliseconds**. Only *after* the bullet clears the muzzle (or the gas ports), does the gas-driven counter-recoil force "kick in," so to speak. While the firer feels only the *net* recoil velocity, the rigidly mounted equipment must endure the *full effects* of *both* the rearward and forward-acting forces. Actually, because of the *reversal of force direction* involved, adding a sharp counter-recoil impulse to the firing cycle is *much tougher* on things mechanical (and optical) than if we had just not attempted any reduction in the recoil of the rifle. This warning does *not* apply to the recoil forces that are *prevented* by use of a suppressor.

Muzzle Pressure

The effectiveness of any gas-operated recoil-reducing device such as a muzzle brake must rely upon the availability of suitable gas pressure behind the bullet as it clears the muzzle. This "muzzle pressure" *varies widely* from one rifle and cartridge to the next. If the muzzle pressure for our rifle is not at least **5,000 psi**, a muzzle brake would not be very effective, and we should perhaps consider using a slightly *slower-burning* (more "progressive") powder in that load to increase the *muzzle velocity* of our bullets without increasing the *peak chamber pressure* level. If, on the other hand, our muzzle pressure is above **12,000 psi**, we would probably find that a load using a *faster-burning* powder would be more pleasant to shoot in this particular rifle. A high (or very low) muzzle pressure also indicates a load that should *not* be fired in a gas-operated semi-automatic rifle—especially not in one like an *M1 Garand*, having neither a gas pressure regulator nor a gas pressure adjustment feature.

We need to determine three important auxiliary parameters to learn more about what conditions determine *muzzle pressure*. The first parameter needed is the barrel length **L** (in inches) available for use by the bullet in accelerating to its muzzle velocity. One way to determine this effective length **L** would be to load an ***inert*** round into the chamber and measure, with a cleaning rod, the depth of the loaded bullet's nose below the muzzle crown, and then add the nose-to-rear-of-body length of our bullet (**1.05 inches**) to that distance. The effective length **L** for our example **21.75-inch** 308 rifle barrel is just **20.0 inches**.

The powder chamber volume $\mathbf{Vol_C}$ of the cartridge, the effective bore diameter **D** of the barrel, and the effective bore length **L** of the rifle's barrel, all combine to determine the *gas expansion ratio* $\mathbf{R_{EXP}}$:

$$\mathbf{R_{EXP} = (Vol_C + Vol_B)/Vol_C},$$

where $\mathbf{Vol_C}$ = Volume of the chamber in cubic inches,

$\mathbf{Vol_B}$ = Volume of the bore in cubic inches, and

$$\mathbf{Vol_B = L*(\pi/4)*D^2 = 1.471\ in^3}.$$

[Here, we use **0.306-inch** for the effective bore diameter **D** to account for the volume the rifling grooves, which are three times wider than the lands in our example barrel.]

If we measure the *weight of water* $\mathbf{W_C}$ needed to fill a fired cartridge case to "powder capacity" as **53.0 grains** in this example, we can divide that weight $\mathbf{W_C}$ by the constant value of **252.75** *grains of water per cubic inch of water* to calculate the desired case volume $\mathbf{Vol_C}$ in *cubic inches*:

$$\mathbf{Vol_C = W_C/252.75 = 53/252.75 = 0.210\ in^3.}$$

Now, we can calculate the important *gas expansion ratio* $\mathbf{R_{EXP}}$ to be:

$$\mathbf{R_{EXP} = (0.210 + 1.471)/0.210 = \underline{8.01}}$$

The ratio $\mathbf{R_{PB}}$ of the powder charge weight $\mathbf{W_P}$ to the bullet weight $\mathbf{W_B}$ will also be needed. Since both are usually given in the same weight units (grains in this case), this ratio is easily calculated:

$$\mathbf{R_{PB} = W_P/W_B = 44.0/168 = \underline{0.262}}.$$

But, if we did not yet have a specific load in mind, we could calculate a value for the weight of powder $\mathbf{W_P}$ that could occupy the entire powder capacity as measured in grains of water $\mathbf{W_C}$ by multiplying it by the *specific gravity* of our single-base rifle powders (**0.859**):

$$\mathbf{W_P = W_C*(0.859) = 45.5\ grains.}$$

Using the two ratios, $\mathbf{R_{EXP}}$ and $\mathbf{R_{PB}}$, that we just found, we can enter ***Table I*** below to find the ***approximate muzzle pressure*** for our rifle and ammunition combination. Typically, we will want to interpolate linearly between two successive table entries in each of two adjacent columns surrounding our ratio values, and then linearly interpolate between these values in the row-direction to get the best value. This is called *bi-linear interpolation*, and it is easier to *do* than to describe. It happens that our expansion ratio of **8.01** is so close to the row heading **8.0** that we can just use the values on that row without interpolating vertically. Then, horizontally interpolating **62 percent** of the interval from **6,850 psi** to **7,025 psi** yields the needed result for our example rifle:

Approximate Muzzle Pressure = **6,960 psi.**

This muzzle pressure value means that this load *is suitable* for use in gas-operated semi-automatic rifles, such as the *M1A*, while still providing adequate pressure to operate a muzzle brake effectively.

Expansion		Table I. Approximate Muzzle Pressure (psi)						
Ratio		Powder Charge to Bullet Weight Ratio (Rpb)						
Rexp	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
4.0	25,600	26,200	26,800	29,050	31,300	33,500	38,000	0	0
5.0	15,400	16,000	16,600	17,050	17,500	18,000	18,500	19,050	19,600
5.5	13,200	13,675	14,150	14,600	15,050	15,475	15,900	16,350	16,800
6.0	11,000	11,350	11,700	12,150	12,600	12,950	13,300	13,650	14,000
6.5	9,820	10,118	10,415	10,778	11,140	11,495	11,850	12,158	12,465
7.0	8,640	8,885	9,130	9,405	9,680	10,040	10,400	10,665	10,930
7.5	7,745	7,955	8,165	8,383	8,600	8,848	9,095	9,330	9,565
8.0	6,850	7,025	7,200	7,360	7,520	7,655	7,790	7,995	8,200
8.5	6,150	6,378	6,605	6,759	6,913	7,053	7,193	7,387	7,580
9.0	5,450	5,730	6,010	6,158	6,305	6,450	6,595	6,778	6,960
9.5	4,750	5,083	5,415	5,557	5,698	5,848	5,998	6,169	6,320
10.0	4,050	4,435	4,820	4,955	5,090	5,245	5,400	5,560	5,720
10.5	3,883	4,188	4,493	4,617	4,740	4,873	5,005	5,154	5,303
11.0	3,715	3,940	4,165	4,278	4,390	4,500	4,610	4,748	4,885

Table I is from Dave Scovill, as published in *Handloader* and *Rifle* Magazines in 1986. This is an extension of earlier work by Homer S. Powley and William C. Davis. This table is built from data for a *308 Winchester* firing **150-grain** bullets using **46.4 grains** of

IMR-4064, but it should be at least crudely accurate when used with any modern small-arms, and it serves to illustrate the variational patterns. Use of faster powders would *decrease* these muzzle pressures, while a slower powder would *increase* all of these pressures slightly. An internal ballistics program should be utilized if more detailed accuracy is needed for your rifle and cartridge.

Other Approaches to Recoil Reduction

Several "recoil reducing devices" have been marketed for many years, and new ones come and go regularly. We have explained here the principles of operation for the suppressor, the muzzle brake, and the "recoil pad." Another class of add-on devices attaches a mass (weight) to the firearm—usually in the buttstock, forestock or magazine. Sometimes a portion of this added mass is either spring-mounted (forming a simple harmonic oscillator) or free to move back and forth (as with "slosh tubes" partially filled with the dense liquid element mercury). Allowing some movement is intended to spread out the recoil time duration **Δt**, but that effect is *small* because of the small amount of added mass relative to the mass of the gun. A blowback-operated self-loading rifle, or one of the firearms using John M. Browning's original "long recoil" system (such as a *Remington Model 8* or *Browning Auto-5* shotgun), would be a more extreme version of this same recoil principle, but anyone who has fired one of these pioneering Browning-designed guns will likely remember its ***abnormally severe*** felt recoil. Mostly, these add-on devices reduce the rifle's recoil velocity and kinetic energy (but *not* its momentum) by making the rifle *heavier*. They also adversely affect its balance, swing and portability.

Many shooters claim to notice slightly less felt recoil in firing a gas-operated semi-automatic *M1 Garand* rifle, as opposed to using the same .30-06 ammunition in a bolt-action *Model 1903 Springfield* rifle of the same weight. There *is* a small reduction in the recoil momentum of the *M1* when, late in the firing cycle, its operating rod, bolt and empty case are driven rearward by trapped gas pressure. This amount of recoil reduction is about equivalent to the reduction in the *muzzle velocity* of the bullet due to the gas-operation of the *Garand—not really that much*. I never felt that either of these fine old battle rifles, weighing about **8.5** to **9-pound**s, kicked very badly anyway.

Another approach to reducing felt recoil is to design-in (or add-in as a modification) a "recoil energy absorbing" system into the buttstock. These systems *can* and *do* absorb much of the kinetic energy of recoil and greatly reduce felt recoil. [By the way, *every* recoil system—including simply the meaty shoulder—absorbs *all* of the kinetic energy of recoil as it halts the rearward motion of the rifle.] The main impediment to the general use of these recoil systems is the rather long "stopping distance" **Δs** that they require. Many high-magnification scope sights do not provide this much eye relief.

I have recently seen a published review of a novel firearm designed to "redirect the recoil" downward instead of to the rear. This idea directly violates the fundamental principle of "*conservation of momentum*." Maybe our schools no longer teach basic physics. Or perhaps *Newton's First Law of Motion* somehow does not apply if we refuse to recognize it. For my part, I will continue to be guided by "*conservation of momentum*" as a fundamental principle in physics.