Propellant Selection & A General Description of the Interior Ballistic Event

By Jeff Siewert

Selecting an appropriate propellant for a particular application depends on the following factors:

- Peak Operating Chamber Pressure
- Expansion Ratio of the firearm
- Propellant charge mass / projectile mass ratio

The peak operating chamber pressure is determined by the gun mechanism (geometry and materials) and the case structure (also geometry and materials, but including case material hardness). The peak operating chamber pressure influences the propellant selection because the rate of propellant consumption is limited by peak pressure. The burn rate of the propellant is given by Vieilles's burn rate equation:

$$r_i = b(\overline{P})^{\alpha}$$

Equation 1: Burn Rate Equation

Where:

r_i = burn rate in in/sec or mm/sec
b = burn rate coefficient
P = instantaneous space mean pressure
α = burn rate exponent

If a system is designed to operate at low peak pressures, like a shotgun or a handgun, a propellant grain with a small "web" dimension (e.g. high surface area to grain volume ratio) must be chosen if propellant needs to be completely consumed while the projectile is in the tube. The "web" of a propellant grain is the smallest dimension required to be burned to completely consume the propellant grain.

If the burn rate coefficient and burn rate exponent are held constant in Equation 1 (e.g. a given propellant has been selected), the only way to make the propellant burn faster (e.g. more inches/sec) is to increase the pressure, and if the weapon has a low peak pressure limit, the powder web must be selected accordingly. Complete combustion of the propellant while the projectile is in-bore aids velocity consistency, reduces flash at shot exit, and aids in gun reliability because there are no unburned powder remnants around to impede the function of the gun mechanism. For guns operating at low pressures, a flake geometry provides small web with a large surface area, helping to ensure the grain is completely consumed while the shot is still in the barrel. Figure 1 shows a comparison of surface area to volume ratio for various propellant geometries.

Figure 1 is a plot of the surface area-to-volume ratio of common small caliber propellants as a function of web size in their "as-made" condition. Flake powders, ball powders and single perf (tubular) powders are shown, along with a C4 offering. Interestingly, the various geometry categories can be "grouped" fairly easily, each geometry has a fairly specific initial surface area / volume ratio according to their web.

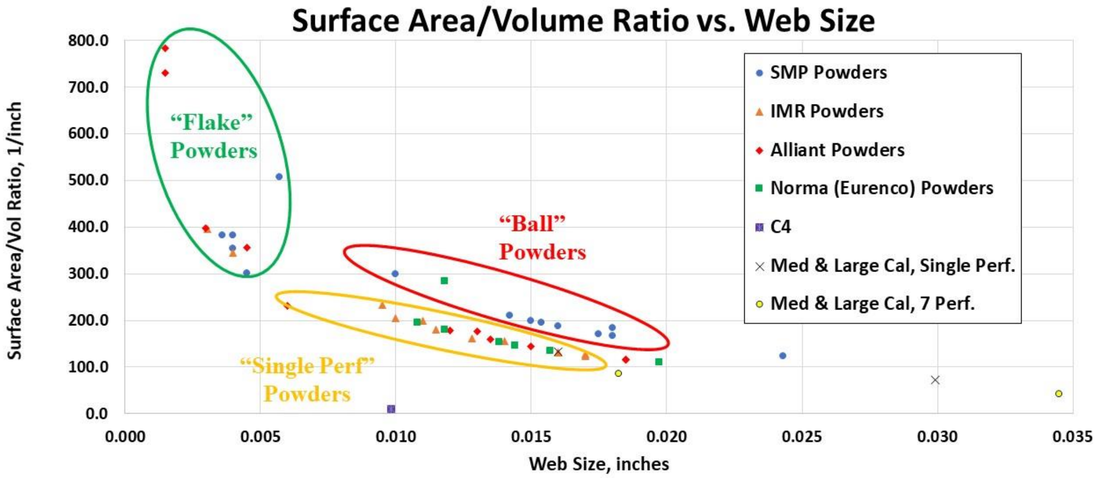


Figure 1: Propellant Grain Surface Area/Volume Ratio vs. Web Size

Figure 1 only indicates the geometric properties of the propellant grains, it doesn't indicate anything about the level of deterrents that might be applied to the propellant grains. Deterrents delay the combustion of the underlying propellant layers, which would seem to be counter-productive if the goal is to maximize muzzle velocity at a given peak pressure. However, to maximize muzzle velocity, the bullet travel at peak pressure must be pushed down-bore as far as possible, while simultaneously pulling in the bullet travel at propellant "all burnt". Adding deterrent to the propellant surface does the following to help maximize muzzle velocity:

- Pushing the travel at peak pressure down-bore creates the largest possible reservoir of gas at the designed maximum pressure. This maximizes the area under the base pressure vs. travel curve, pushing the muzzle velocity as high as possible.

- Smaller web powders burn out earlier in the projectile in-bore travel. For a given peak pressure, deterred propellants can be made to have a smaller web dimension. By delaying maximum burn rate until achieving peak pressure, the travel at propellant "all-burnt" is reduced, and the generated gases have as much time/travel to operate on the projectile. The system is not expending energy accelerating unburned propellant grains down bore. This improves resulting combustion efficiency, maximizing muzzle velocity

Figure 2 shows a cross section schematic and photograph of a "Ball" propellant grain showing the deterrent coating applied to the exterior of the grain.

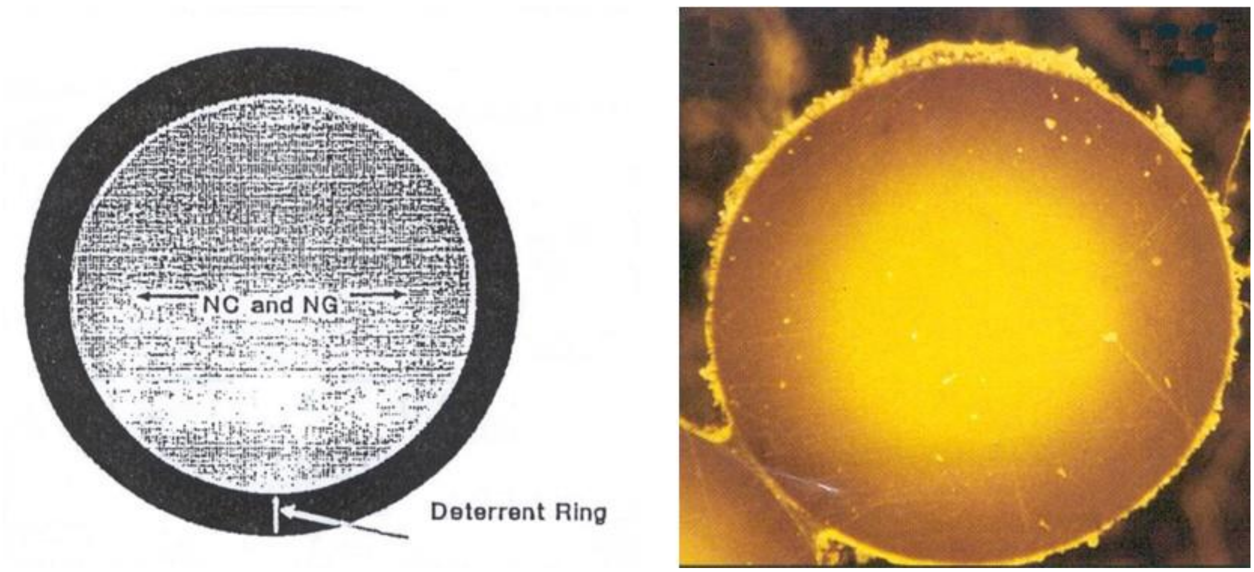


Figure 2: Cross Section of "Ball" Propellant Grain Showing Deterrent Layer

The next factor in determining muzzle velocity, the expansion ratio of a gun, is analogous to the compression ratio of a car engine. The expansion ratio of a gun is the ratio of the volume of the barrel plus the chamber, divided by the chamber volume. For small caliber applications, depending on the length of the bullet, the depth the bullet extends into the case past the case mouth, and of course the internal geometry of the cartridge case, the reloader has the capability to modify the chamber volume a bit. Of course, as the bullet is seated more deeply into the case, the chamber volume is reduced, and as a result, the in-bore travel distance is increased when firing in a given barrel. Pistols usually have fairly high expansion ratios, not because the barrels are so long, but because the chamber volume is typically quite small. Table 1 lists the interior ballistic characteristics of common small caliber systems.

	9x19mm	**45 ACP**	**5.56x45mm**	**7.62x51mm**	**338 Lapua**	**12 Ga**
Avg. Pmax, PSI	35000	18000	58000	53000	68000	11500
In-Bore Travel, in.	3.65	4.30	13.20	20.20	26.00	22.00
Bullet Wt., grain	124	230	62.6	148	300	335
PowderChg., Grain	7.0	8.5	25.8	42.0	101.2	45.0
Expansion Ratio	12.8	12.8	5.9	8.4	6.7	44.5
Charge/Mass Ratio	0.06	0.04	0.41	0.28	0.34	0.13

Table 1: Interior Ballistic Characteristics of Various Small Caliber Systems

The charge-to-mass ratio of the system is important to selection of an appropriate propellant because the energy of the system (determined by the amount of powder) limits the attainable muzzle velocity. Since the gun mechanism and cartridge case structure determine the peak pressure limits, the acceleration of the bullet is limited by the peak pressure. To increase the muzzle velocity, an increased case volume is required, providing a higher **average** base pressure to the projectile with the selection of an appropriate propellant. By increasing the case volume, as the bullet moves incrementally down barrel, a smaller pressure decrease results for a given amount of travel. Thus, an increased case volume typically increases the velocity that can be obtained at a fixed peak pressure because of increased energy capacity, provided the propellant can be completely consumed while the projectile is still in-bore.

General Description of the Firing Event

The firing event starts when the shooter pulls the trigger on the firearm. By pressing the trigger, the sear is moved, which holds the spring-loaded hammer in the cocked position, out of the way. The movement of the sear frees the hammer, which swings or slides until it makes contact with the firing pin. The firing pin is rapidly accelerated, moving forward until it contacts the surface of the primer cup (for center fire ammunition). This is when the actual interior ballistic event starts. Depending on the relative mass/energy of the firing pin and the clearances between the cartridge case and the chamber, and whether the bolt face contains a spring-loaded eject pin, the firing pin may move the case forward in the chamber until the shoulder of the case contacts the shoulder of the chamber. If the cartridge mass is sufficiently low and the case is free to move, the firing pin strike can translate the case forward in the chamber until it meets the headspace stop previously described. This forward movement of the case, or the spring loaded eject plunger, causes a gap between the case base and bolt face. For tapered cartridge cases, this forward movement provides minimum radial gap between the case and the chamber. At some point, the case meets resistance with the chamber and the firing pin energy is dumped into deforming the primer cup. The primer mix is pinched between the interior surface of the primer cup (deformed by the impact of the firing pin) and the anvil, and the compression of the primer mix causes it to detonate. The primer mix is converted to hot particles and gas almost instantaneously, and the pressure starts to rise in the primer pocket. If the primer cup is rigidly attached to the case primer pocket via lacquer and crimp, the primer cup cannot move aft relative to the cartridge case as the pressure starts to increase in the primer pocket. If the cup isn't held in place by the belt and suspenders of lacquer and primer pocket crimp, the primer cup moves aft relative to the case as the pressure rises in the primer pocket until the cup hits the bolt face.

As the ignition process proceeds, hot particle filled gas passes thru the flash hole(s) in the case base, transferring the flame front to the propellant bed. At this point the propellant starts to burn due to the contact of the hot particles from the primer gasses coalescing on the exterior surface of the propellant. Primer gases and gases from the burning of the propellant near the primer cause the remainder of the powder to translate in the case, forcing it against the base of the projectile. As the propellant burns, it changes from a solid directly into a gas, causing the pressure to rise in the case. As the pressure in the case increases, the case starts to swell in both length and diameter. Ultimately, the combination of translation of the propellant bed and powder combustion pressure increases to the point where the force on the base of the bullet overcomes the crimp and/or friction of the case mouth restraining the bullet motion, and the bullet is dislodged from the case. Once the projectile overcomes the case retention force and starts to move, the case moves aft axially in response to the unbalanced pressure load acting on the case.

Initially, the pressure in the case continues to rise as the projectile proceeds down the barrel from the gases evolved from propellant burning. Upon attaining a sufficiently high pressure in the case, the case wall deflects outward enough to contact the chamber and case base contacts the bolt face. Once the case wall contacts the chamber and bolt face, the case walls are supported by the strong (typically) steel structure of the firearm, and the case starts transferring thrust aft to the firearm through the chamber walls via contact force and friction between the case body and the chamber.

The case wall is thinnest near the case mouth, and gets progressively thicker near the base of the case. This thickness gradient, combined with a strength (hardness) gradient puts the material with the lowest strength at the case mouth and makes the case contact the chamber near the case mouth first, causing the case to seal there early in the combustion process. As the case contacts the chamber wall, the chamber supports the case due to the mechanical stiffness of the barrel or cylinder. At the same time, if the friction between the case wall and the chamber interior is sufficiently low, the case moves aft in the chamber relative to its initial position due to the unbalanced load generated by the release of the bullet from the case mouth, causing the case base to contact the bolt face not long after the bullet leaves the case.

The pressure in the case continues to rise, and the contact between the case wall exterior and the chamber moves from the case mouth aft toward the case base, helping to prevent gas leakage past the case. The case stretches in the radial and hoop direction until it hits the chamber, and along the axis of the case. The stretch along the axis of the case is limited by the coefficient of friction between the case and the chamber forward of the last contact point and the internal case pressure. As the contact point between the case and the chamber moves aft with increasing pressure, progressively more contact area is engaged and more load can be reacted to the chamber in shear through the area of case-chamber contact. The increasing internal pressure and case-chamber contact area increases the axial load carried by the case wall, with maximum axial stretch (and hoop stretch) occurring just aft of where the case wall last touches the chamber. The large combined stretching just aft of the point of last case contact with the chamber wall causes the case wall thinning frequently seen in the aft portion of cases fired multiple times.

The increasing pressure behind the bullet causes the bullet to accelerate down the barrel despite being resisted by the engraving friction forces, increasing the volume of gas behind the bullet. Eventually, the bullet starts moving so fast that the rate of volume change behind the projectile reaches a point where the gas evolved by the burning propellant can’t keep up with the volume increase, causing the chamber pressure to reach a maximum.

From the bullet’s perspective, as the projectile starts moving from its initial position in the cartridge, it moves a short distance and encounters the forcing cone of the firearm, provided we’re not firing in a revolver. Upon encountering the rifling, the exterior of the bullet is plastically deformed, impressing the rifling form on the projectile’s exterior. This engagement causes the projectile to ride the spiral land profile in the bore, making the bullet rotate as it travels down bore. The projectile continues to accelerate as it travels down the barrel, picking up velocity as the propellant gas expands. Velocity continues to increase until the bullet exits the barrel.

Propellant burn continues until the propellant either burns out or the projectile exits the barrel. If there is unburned propellant in the barrel when the bullet exits, a rapid pressure drop occurs in the barrel and extinguishes propellant burn nearly instantly. Figure 3 shows the "before and after" of an artillery propellant grain whose burning was extinguished by the dramatic pressure drop after exiting the barrel.

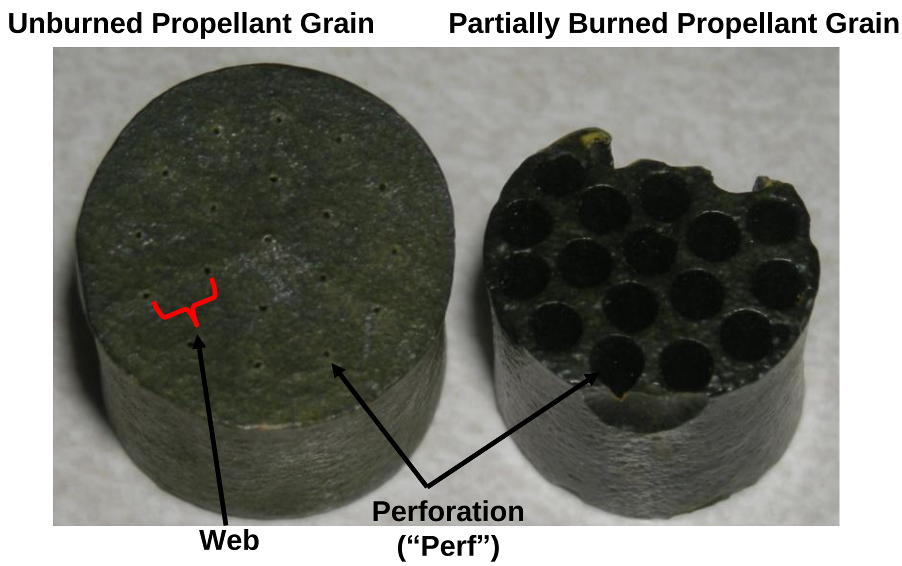


Figure 3: Photo of Unburned and Partially Burned Artillery Propellant Grain

In the photo above, a critical dimension called "web" is shown on the unburned propellant grain. The web is the smallest grain dimension which must be burned for the propellant to be completely consumed. Figure 4 shows propellant grain geometries commonly used for small caliber applications, along with the web for each grain and other important dimensional parameters.

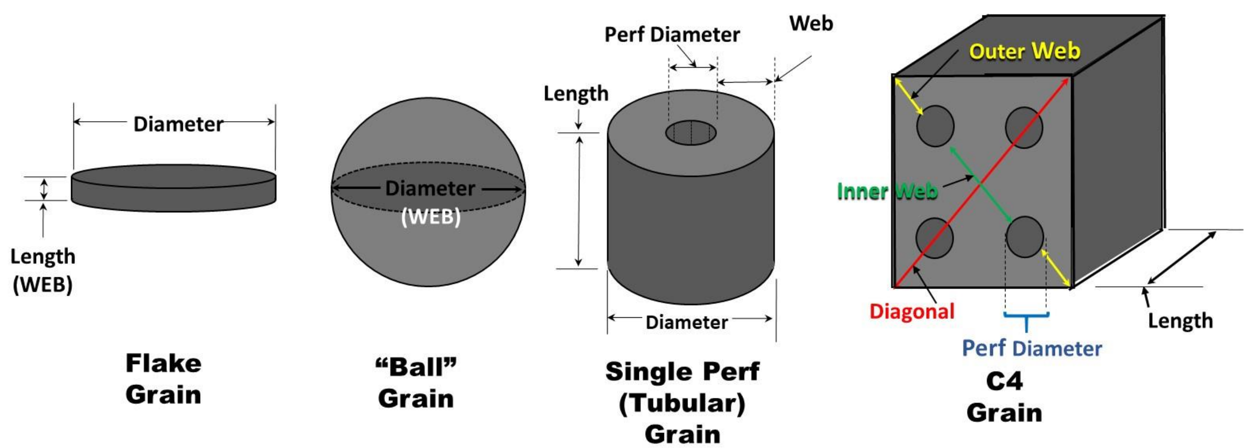


Figure 4: Common Small Caliber Propellant Grain Geometries

Propellant "progressivity" is an important interior ballistics concept: it can be defined as the ability of a propellant to increase its burn rate after the travel at peak pressure has been attained. Figure 5 shows the relative surface area of a propellant grain as a function of depth burnt and propellant grain geometry. On the left-hand side is the initial burning surface, and the far right represents all the propellant is consumed.

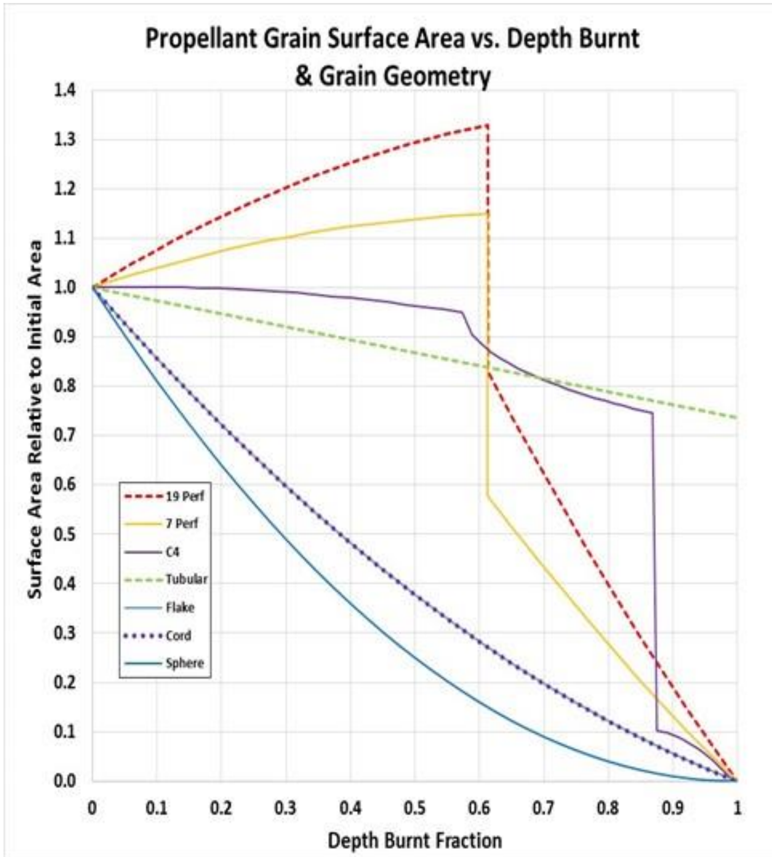


Figure 5: Propellant Grain Surface Area vs. Depth Burnt

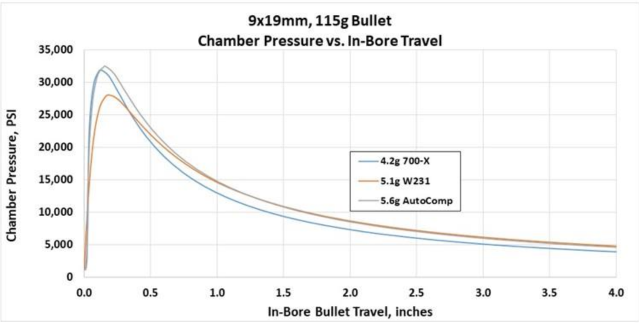
Use of progressive propellants increases muzzle velocity because they increase the average base pressure acting on the bullet after peak pressure (e.g. there is more area under the pressure-travel curve). Propellant with geometry with more perforations than the C4 grain are generally unsuitable for use in small caliber grains due to the rheology of the energetic compounds and physical dimensions required to form the propellant grains.

Selecting a propellant for a given application might involve more than just a financial decision, depending on the particular needs of the customer. Table 2 lists a summary of simulated interior ballistics performance for a 9x19mm cartridge using 3 different propellants. The peak chamber pressure, a critical gun interface parameter, and the muzzle velocity from a pistol with a 4 inch long barrel are listed.

Propellant	Pmax, PSI	MV, FPS
4.2g 700-X	31901	1095
5.1g W231	28096	1159
5.6g AutoComp	32491	1164

Table 2: 9x19mm Interior Ballistics Summary

Figure 6 shows the results of a simulation of a 9x19mm interior ballistics simulation using a lumped parameter interior ballistics code of 3 propellant loads for a 115g projectile. The peak chamber pressures for each of the simulated loads are fairly comparable, and the velocities of the W231 and the AutoComp propellants are fairly comparable (~1160 FPS) but the 700-X muzzle velocity is down considerably (~ 1095 FPS). However, neither the W231 or the AutoComp propellants are completely burned out as shown in the graph on the right-hand side of Figure 6, but the 700-X is almost completely burned out, due to the different burn characteristics of this propellant.



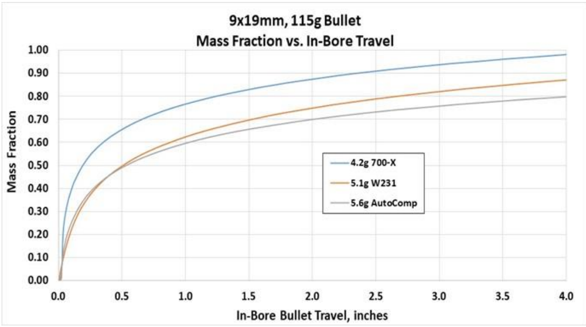


Figure 6: 9x19mm Chamber Pressure and Mass Fraction vs. Projectile In-bore Travel

So, as long as the 1095 FPS muzzle velocity that comes with using 4.2 grains of 700-X propellant will cycle the pistol slide reliably, it would be a preferred choice for night firing or use with a suppressor as very little to no unburned powder exits the barrel. If the cost per pound (kilogram) of propellant is comparable among the powders, the lower charge weight of the 700-X makes it the leading choice among the powders presented.

Conclusion:

The choice of propellant for a particular application depends on:

- Peak Operating Chamber Pressure
- Expansion Ratio of the firearm
- Propellant charge mass / projectile mass ratio

of the weapon system under consideration. Other factors, such as muzzle velocity performance, muzzle flash, temperature consistency, loaded cartridge cost, lot quantities, system function and casualty performance, and other considerations may influence the final choice of propellant for a particular application.