An Evaluation of
Gas Systems for the AR15 / M16 Platform

by

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Variable	Units	Description
A_{bore}	in^2	cross sectional area of the rifle barrel bore
A_p	in^2	area of the piston
CR	--	Corner ratio
C_v	$(ft/s)^2/K$	specific heat of the gas at constant volume
d_{bore}	in	diameter of the rifle barrel bore
E_h	lbf-ft	heat loss to the barrel
F_{ef}	lbf	engraving force
F_p	lbf	force of the combustion gas on the piston
g	ft/s^2	acceleration due to gravity
I_{pr}	$lbm\text{-}in^2$	moment of inertia of the projectile
m_c	lbm	mass of the charge
m_{bc}	lbm	mass of the bolt carrier
m_{gun}	lbm	mass of the gun
m_{pr}	lbm	mass of the projectile
P_B	psi	breech / chamber pressure
P_{bp}	psi	pressure at the base of the projectile
P_{cv}	psi	pressure in the piston cavity
P_{ef}	psi	pressure to cause engraving of the projectile
Q	lbf-ft	total heat input to the system from the propellant
R	--	rifling rate of turn
T	K	temperature of the gas
T_A	K	adiabatic flame temperature of the gas
T_S	K	temperature of un-burnt propellant

Variable	Units	Description
U	lbf-ft	change in the internal energy of the system
v_{pr}	ft/s	velocity of the projectile
v_{bc}	ft/s	velocity of bolt carrier
v_c	ft/s	velocity of the charge
v_{gun}	ft/s	velocity of the gun
v_m	ft/s	velocity of the projectile at the muzzle
V_0	in^3	initial empty chamber volume
W_c	lbf-ft	linear kinetic energy of the propellant
W_{ef}	lbf-ft	engraving force of the projectile
W_{gun}	lbf-ft	linear kinetic energy of the gun
W_{pr}	lbf-ft	linear kinetic energy of the projectile
W_{prr}	lbf-ft	rotational kinetic energy of the projectile
W_c	lbf-ft	kinetic energy of the propellant gas
W_{tot}	lbf-ft	total work done by the system
x	in	distance down the barrel
x_m	in	distance at the muzzle
x_p	in	distance traveled by the bolt carrier
z_i	--	fraction of remaining web of the powder grain
δ	--	Pidduck-Kent constant

ABSTRACT

Since the 1950's, the AR15 / M16 rifle platform has been a novel design intended to be an improvement the weight and accuracy of legacy military rifles. This was accomplished in part to a re-invented design of the gas system that operates the action (firing and reloading mechanism) of the rifle. The flaw of the design is partly due to fouling caused by residue from the hot gases blown through the action, which can result in malfunction. Retrofit kits have been made available that replace the gas tube with a short stroke piston system in order to achieve similar reliability to rifles such as the AK-47. Many of these kits are available in the commercial market and are being evaluated for adaptation into the United States military forces. Gas piston systems and their benefits have not been fully accepted by either the military or civilian markets. This paper will evaluate the differences in the function of each system. Also, input and reaction forces on the bolt carrier group will be summarized for several common barrel lengths.

1. INTRODUCTION

The focus of this report is to summarize and evaluate the operation of and benefits and issues with internal and external gas piston systems available for the AR15 / M16 platform. The history and design of the original rifle will be investigated to understand the reason for its conception. A description of the rifle and its working components will be outlined including a summary of the function of the baseline internal gas system. A comparison of other commercially available external gas systems will be completed and summarized versus the internal gas system. Calculations will then be performed in order to estimate piston pressure from prior studies. These pressures will be used to generate input and reaction forces on the bolt carrier (the major moving component). Finally, with an understanding of the operation of each system, a conclusion will be made as to whether the external piston system fills a true need or serves only as an alternate configuration.

1.1. The History of the AR15 Platform

The historical fame, success and overall reliability of weapons such as the Automat Kalashnikov 1947 has captured the attention of the United States military, gun enthusiasts and the media alike. The AK-47, being one of the many varieties of piston driven semi-/fully automatic weapons, was designed with looser fitting parts and a stout piston drive system to enhance the reliability of the gun in any operating environment and under any condition. One of the flaws in the AK-47 design was the very design itself. The loose fitting parts and large reciprocating mass of the piston system, Figure 1, results in a decrease in accuracy and muzzle rise (1). Muzzle rise is an event that occurs where the end of the barrel is forced upward and off of the target by the dynamic forces during the firing of the rifle.

In the late 1950's the small arms manufacturing company, ArmaLite, produced an innovative new firearm called the AR-10 under the direction of the chief designer, Eugene Stoner. Similar to other automatically reloading rifles, the action (or firing and reloading mechanism) of the rifle was initiated by combustion gas pressure tapped from the barrel. The AK-47, known as one of the most widely used, reliable rifles in the world, utilizes this design. Yet, where other rifles typically employ a short or long stroke piston system located above the barrel to unlock the bolt, the AR-10 design used a more lightweight configuration, see Figure 1. Stoner's rifle employed a straight line action from the barrel through the bolt group and into the stock (2). This novel design carried through to the creation of the military M16 and civilian AR15versions available today. An obvious difference between the size of the AK-47 and M16/AR15 piston systems is indicative of the lightweight nature of the AR-10 design.

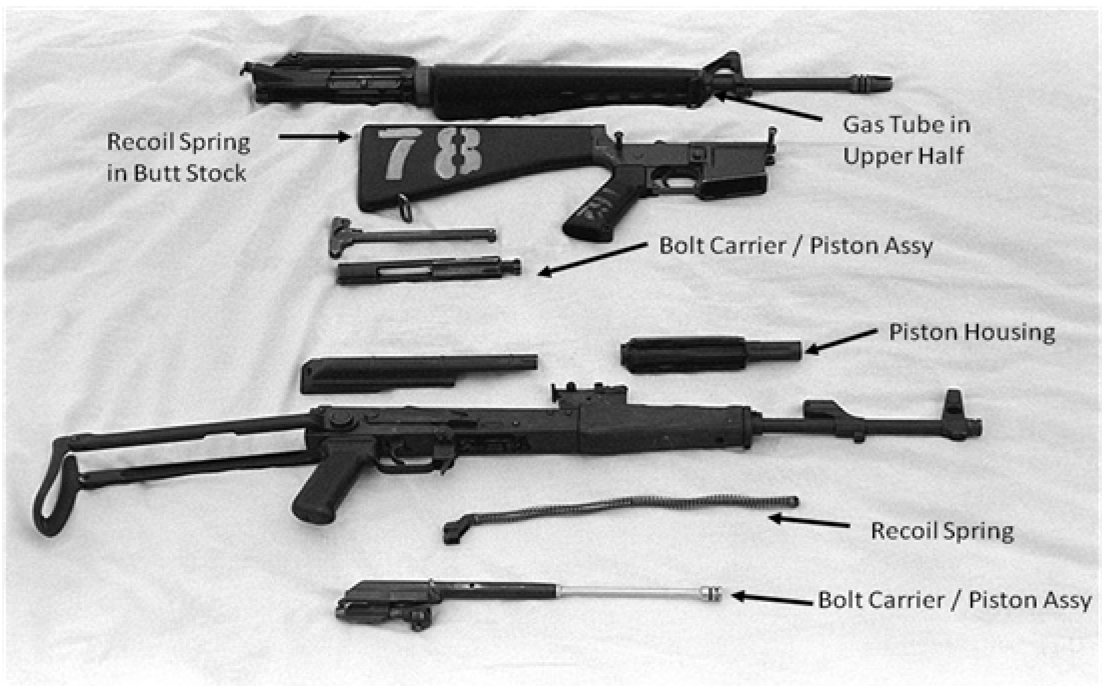

Figure 1: A United States M-16A1 rifle (top) compared to a Soviet Union AK rifle (bottom). The two rifles are disassembled into groups. (3)

The AR10 design differed in that it directed gas down a tube to a piston system located within the bolt carrier group, called direct impingement operation. This design greatly improved the accuracy of the weapon due to a centered, lower mass of moving components. Unfortunately, the AR-10 and its children designs, the military M16 and civilian AR15, suffer from fouling due to the hot gases injected into the action, which over time can result in malfunctions. (2)

1.2. A Description of the Rifle

The AR15 platform was constructed from lightweight materials in order to reduce the overall load carried by soldiers in the battlefield. The rifle was designed with two major sub-assemblies: the lower half and the upper the half (reference Figure 2). The lower half consists of a forged 7075-T6 aluminum frame that houses the trigger assembly and firing pin hammer. Attached to the aft end of the lower is the pistol grip and composite plastic stock. The stock contains the recoil buffer system consisting of an aluminum tube, recoil spring, and tungsten buffer weight.

Figure 2: Picture of the Major Assemblies and Components in an AR15

The upper half of the rifle consists of a forged 7075-T6 aluminum frame that houses the bolt carrier group and attaches to the barrel assembly. The bolt carrier group includes a steel bolt carrier which houses the bolt and firing pin, shown in Figure 3. The bolt is made of Carpenter 158 steel that is shot peened, magnetic particle inspected, and high pressure tested. Atop of the bolt carrier is a gas key, the function of which will be described later. A cam pin passes through the bolt and follows a track in the bolt carrier. The cam pin is what allows the bolt to rotate into the locking lugs on the barrel extension. The cam pin also locks the bolt in the unlocked position via a rail in the upper receiver while the action is cycling.

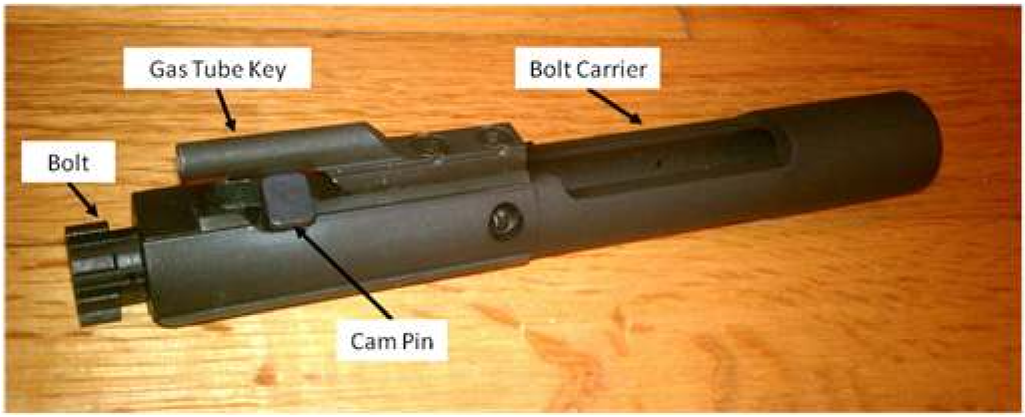

Figure 3: Major Components in the Bolt Carrier Group Assembly

The barrel assembly major components consist of the barrel, receiver extension, barrel nut, gas block, gas tube, and hand guard. The receiver extension attaches to the end of the barrel and as previously mentioned contains the locking lugs that hold the bolt in place during firing. The barrel nut fastens the barrel and extension to the upper receiver. The gas block sits over the gas port in the barrel and allows the flow of gas through the gas tube back to the gas key, shown in Figure 4. Hand guards surround the barrel and gas tube serving as protection from the hot components and protection to the gas system.

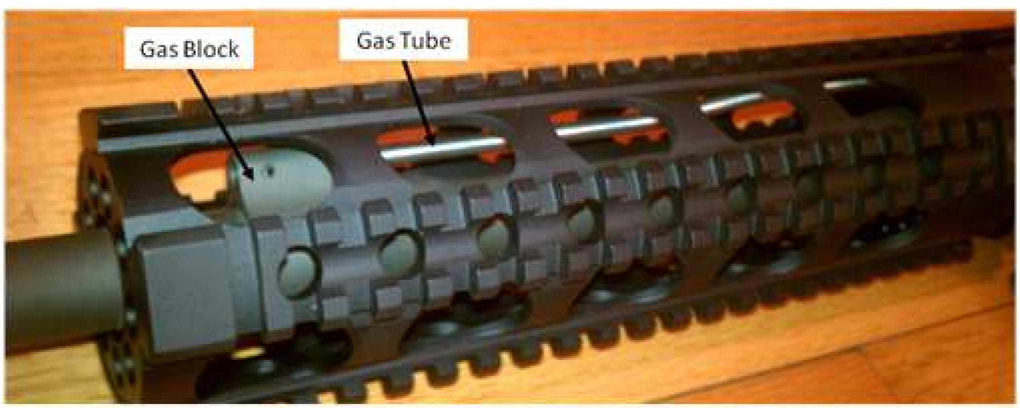

Figure 4: Detailed View of the Gas Block and Tube

Barrel lengths can vary depending on the desired function of the weapon. Longer barrels are for long range engagement, whereas shorter barrels serve a better purpose in close quarters battle (CQB). A long range barrel is typically 18 to 24 inches. Shorter rifles will have 10.5 to 16 inch barrels. A sample of three different rifle barrel lengths can be seen below in Figure 5. Notice also the varying location of the gas port as indicated by the arrow. The gas systems are adjusted to accommodate the rifle length. Short gas systems are referred to as carbine length. Mid-length systems are also available for similar barrel lengths as carbine systems. Full (rifle) length systems are the longest. In most rifles the gas block and front sight are combined to form a single multi-function component.

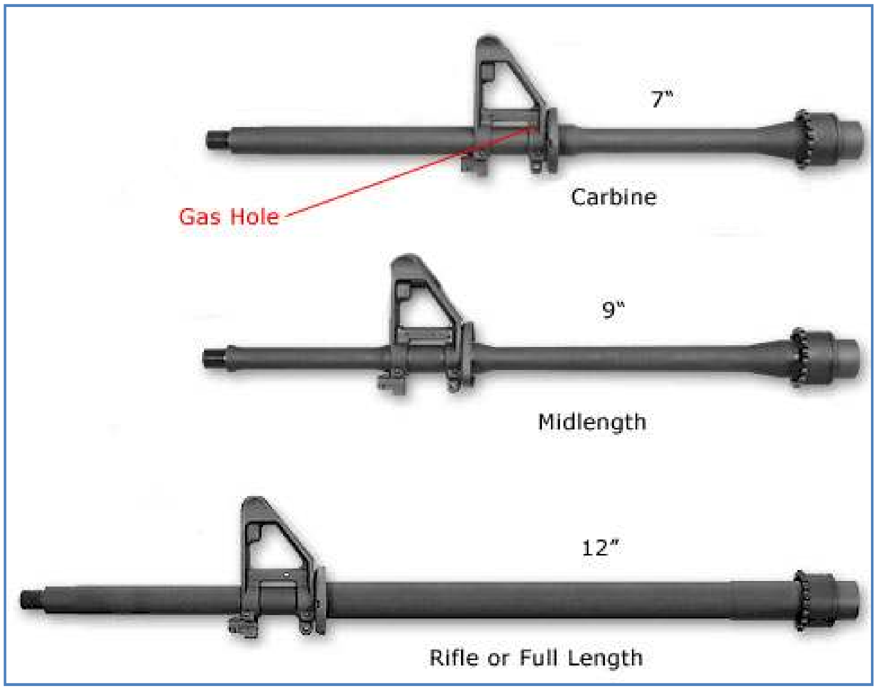

Figure 5: Some Typical Gas Port Locations for Varying Barrel Lengths (4)

1.3. A Questionable Failure Mode

Recently, the fouling issue has spawned the design of both drop-in upgrades and completely new upper receiver systems employing piston systems in an attempt to eliminate fouling and achieve an AK-47-like reliability. This is a controversial topic in both civilian and military forums. Proponents of the direct impingement design and the new piston designs have expressed concern over the benefits and reliability of each system. One such concern is uneven loading acting on the bolt group of the piston driven systems, especially when applied to rifles with shorter barrel lengths.

The pressures generated during the combustion of cartridge powder can exceed 50 kpsi in the breech of an AR15 style rifle using standard rounds. This pressure is required to deform the bullet enough to force it into the rifling of the barrel. As the bullet travels down the barrel the pressure decreases until the bullet leaves the muzzle of the gun. Depending on the length of the barrel and the location of the pressure port, the barrel pressure will vary directly behind the bullet. The function of the pressure port is to provide a metered amount of highly pressurized gas to the gas or piston system. This pressure will provide enough force to activate the bolt carrier group, which allows the action to cycle and the round to be ejected.

The timing of the action is critical to the operation of the weapon, especially in fully automatic mode (over 700 rounds per minute). Interruption of the cycling process can be caused by a poorly cleaned/maintained weapon, under/over-powered ammunition, an improperly sized barrel gas port, or an incorrect buffer weight. Other issues occur in short barrel weapons due to high barrel pressure at the gas port location causing a more violent cycling of the action. When any of these issues arises, problems such as short stroking (not cycling long enough to engage the next round in the magazine) or part failure can occur. In Figure 6, three common failure mechanisms are shown. Failure to extract occurs when the bolt carrier force is large enough that the bolt is unable to grip the cartridge. This causes a jam when the next round is fed into the existing round in the barrel. Forced extraction occurs when the bolt carrier force is large enough that the cartridge casing is pulled out of the barrel when the barrel is still pressurized. In this case the cartridge casing can fail with a portion of the casing stuck in the barrel. This failure is hard to fix since both the new round and the old casing can get stuck in the barrel. Failure to feed occurs when there is insufficient force to cycle the action and the bolt is unable to strip a new round from the magazine. In military applications any of these scenarios can result in life or death situations.

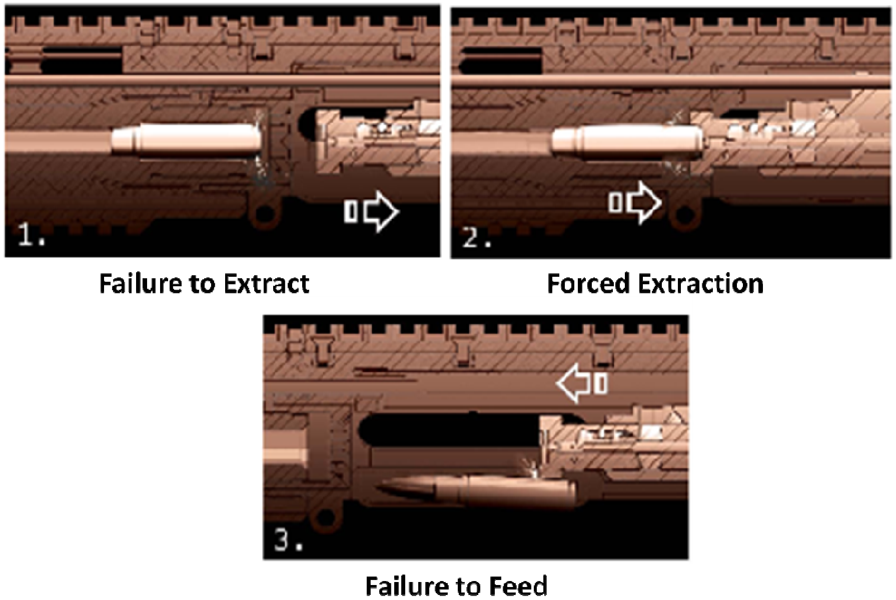

Figure 6: Typical Operational Failures of the AR15 Action (5)

The introduction of gas piston systems to the AR15 platform was intended to drastically reduce or eliminate cycling failures due to improper cleaning or maintenance of the rifle. Fouling in the action is caused by the accumulation of residues from the hot gases, which can attract dirt and other foreign particles. Fouling in the action is typical with the direct impingement gas system. The gas piston system relocates the gases to a drive mechanism above the barrel and outside of the action. Several past piston retrofit designs are available in the consumer market. Some gas piston systems can also better regulate variation in barrel pressure due to adjustment features at the gas block.

The concern with gas piston systems is that the method in which the loads are imparted to the bolt carrier group is not consistent with the original design intent. In direct impingement gas systems, the gases flow along a gas tube from the barrel through a gas key attached to the bolt carrier and into the bolt carrier group, where the gas exerts pressure directly onto the carrier and bolt in line with the rifle bore. In gas piston systems, a piston and rod assembly replaces the gas tube. The rod strikes a feature on the bolt carrier, which replaces the gas key. The off center high load causes the bolt carrier to tilt. Carrier tilt is more prevalent with poorly manufactured and loose tolerance components.

2. COMPARING PISTON SYSTEMS

The following section will explore the inner workings of both direct impingement and gas- piston operated systems. For each system, a description will be provided of the gas system components noting similarities and differences between the two. Also, the functional details involved in cycling the action of the rifle will be explained. For the gas-piston system description, several typical design variants will be used to explain features and operation, which are largely the same among all piston kits. Throughout this evaluation, the use of the terms AR15 and M16 are generally considered to be interchangeable.

2.1. The Direct Impingement (Internal Piston) System

As previously mentioned, the action of the AR15 rifle is operated via combustion gases tapped from the barrel. The following section will explain more about the details of the direct impingement system. After the round enters the chamber and the trigger is pulled, combustion gas forces the bullet out of the casing and into the rifling of the barrel. At this time the casing walls expand and the locking lugs of the bolt engage those in the barrel extension. The pressure inside the casing rises until the bullet is deformed and starts to travel down the barrel. As the volume in the barrel behind the bullet increases and the powder combusts, the pressure will subside until the bullet eventually exits the muzzle. Before the bullet leaves the muzzle, the bullet and combustion gas pass the gas port. At this time, the gas port allows a metered amount of gas into the gas block, which in turn allows the gas to flow back through the gas tube and into the bolt carrier via the gas key. The location and size of the gas port is dependent on the barrel length. Enough gas pressure must exist in the bolt carrier prior to the bullet exiting the barrel in order to cycle the action. A schematic of the gas system is shown in Figure 7 and a detailed section view of the gas port is shown in Figure 8. (6)

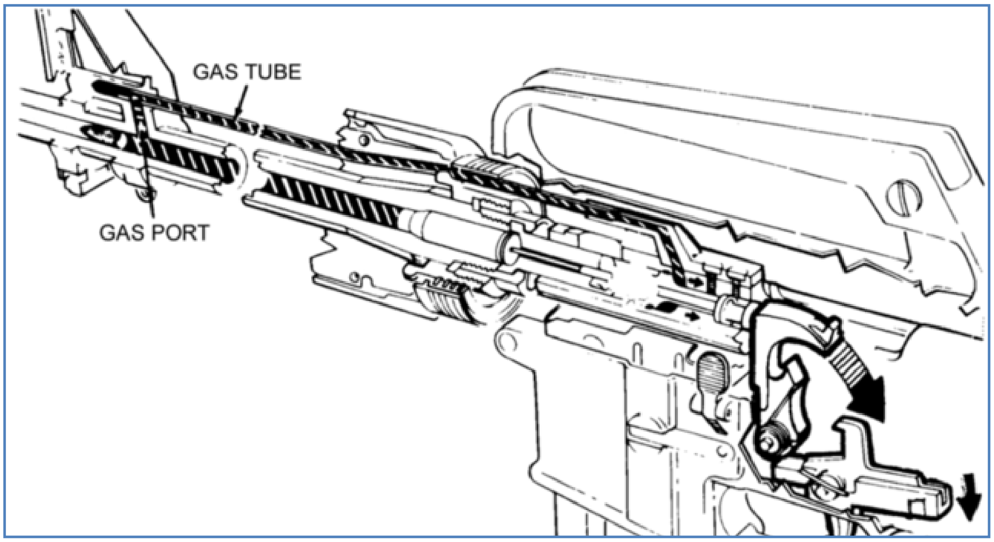

Figure 7: Diagram Showing the Gas Pathway in a DI System (7)

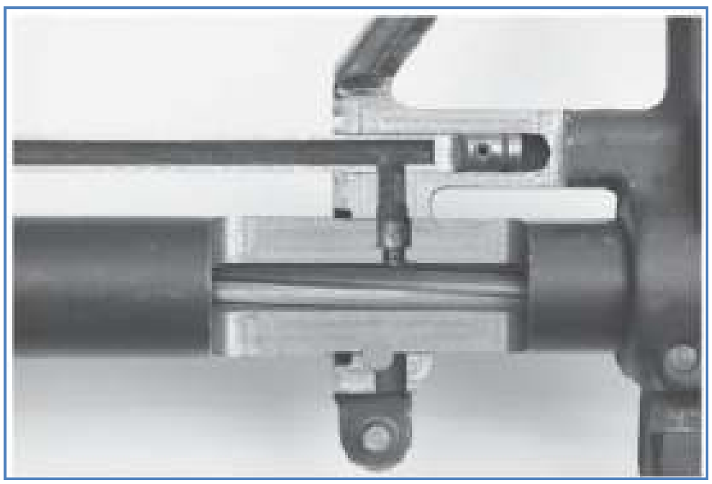

Figure 8: Cross Section of the Barrel, Gas Port & Gas Tube (8)

As the gas enters the bolt carrier from the gas key, it fills a cavity between the bolt and the back side of the carrier. The bolt gas rings seal the gas in the chamber while the bolt is locked. This is shown by the top view in Figure 9. As the pressure builds in the cavity, the gas acts on the back of the carrier forcing it away from the bolt. This motion forces the bolt to unlock and the gas key to separate from the tube. The unlocked carrier position can be seen in the bottom view of Figure 9. From this point forward the momentum of the carrier forces the bolt carrier group into the buffer tube compressing the spring. The rest of the reloading action is not relevant to the evaluation at hand and will be neglected. Further information can be found in the references.

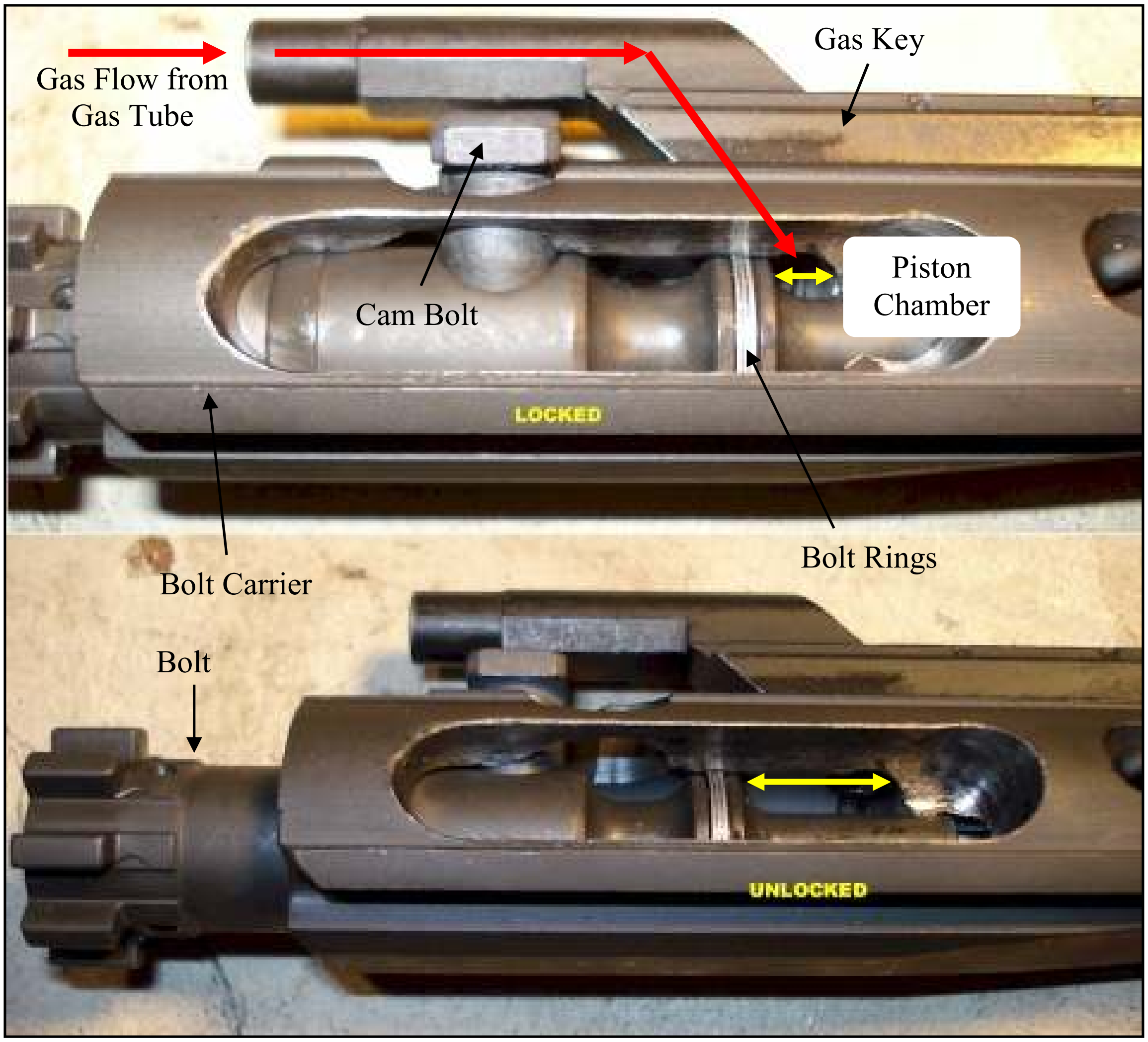

Figure 9: View of the Bolt Carrier Group Gas Piston (9)

It is interesting to note that there is in fact a piston system internal to the bolt carrier group. This shows that a piston in some form or another is essential to the operation of a gas operated rifle. The next section will cover the different types of external pistons that have been developed to combat the fouling issue.

2.2. External Gas-Piston Systems

The above study of the direct impingement system has shown that a piston is in fact a critical component to the action of the standard AR15. Unfortunately, as has been previously mentioned, the gases used to operate said piston cause fouling within the action of the rifle. As a result, several manufacturers have attempted to address reliability concerns due to the fouling by moving the piston operation and gases to an external location on the rifle. These systems generally consist of short stroking rods that contact a modified bolt carrier. Below, several variants of the external piston configuration will be described.

The basic design of an external gas piston system is comprised of relatively few extra components. The simplest of the systems are true retrofit kits that require a modified gas block, piston rod and modified bolt carrier. An example of this type of system is the Adams Arms piston conversion kit shown in Figure 10. In this system, gas passes through the barrel gas port and into the gas block. The gas block contains an adjustable knob for controlling the gas flow using pre-set flow restricting holes that are aligned over the barrel gas port. The knob is part of the metal cylinder that feeds into the cup of the drive rod. The cup is designed to exhaust the combustion gas as the drive rod moves. The drive rod extends along the barrel and through a guide sleeve into the upper receiver. A spring wraps around the drive rod to help decelerate the rod and limit the total stroke. The spring also restores the drive rod to its original position to make it ready for the next round. Another similar configuration exists in the Land Warfare Resource Corporation International (LWRCI) system shown in Figure 11. (10) (11)

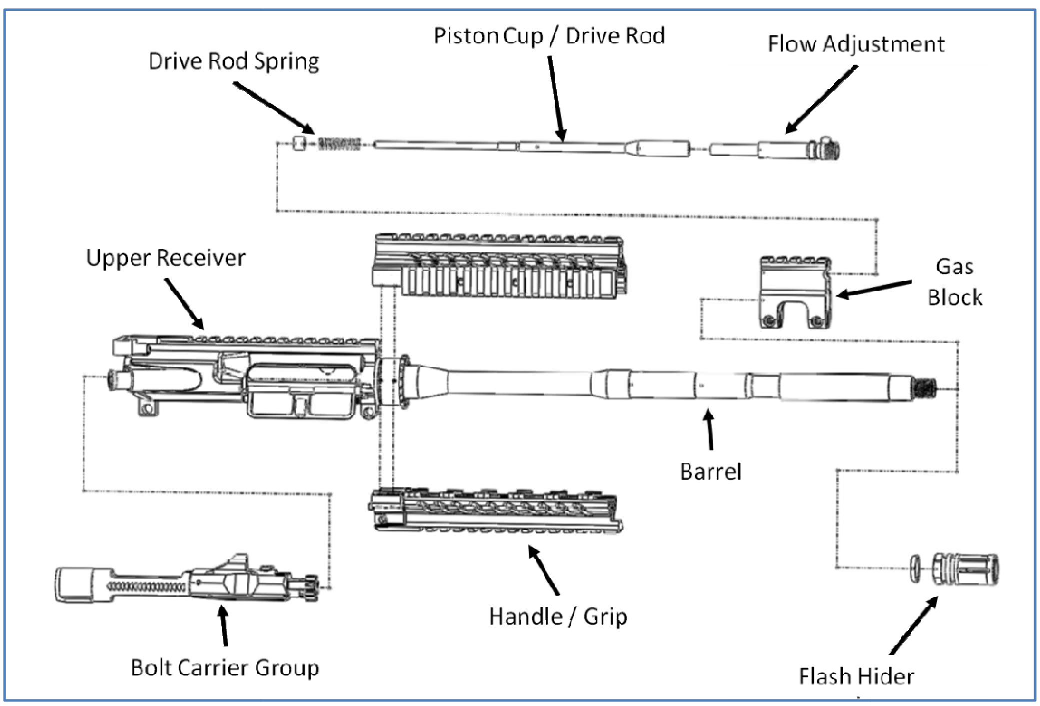

Figure 10: Adams Arms Piston Conversion Kit (10)

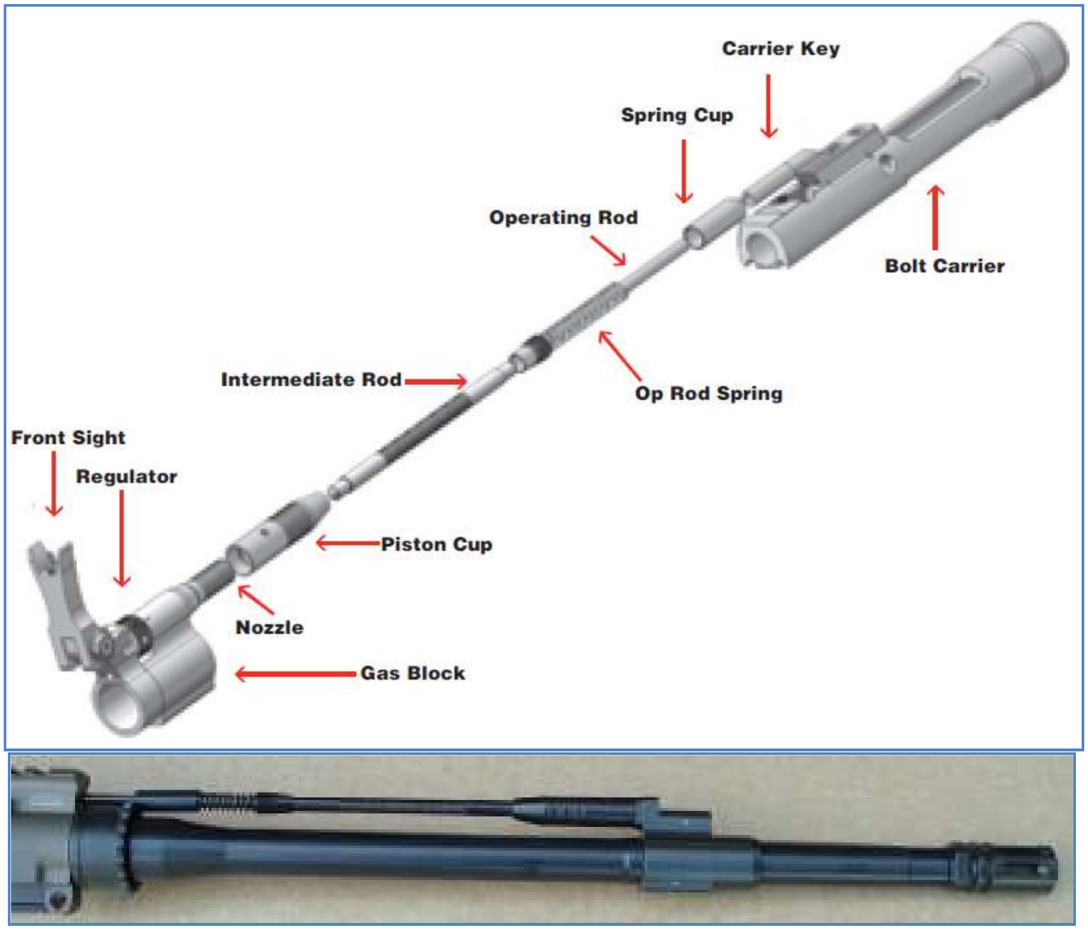

Figure 11: LWRCI Piston System Components (11)

Another critical component to a successful external gas piston system is the modified bolt carrier. The design of these piston systems rely on the drive rod passing through the gas tube hole in the upper receiver. From here, the only practical means of actuating the bolt carrier is at the location of the gas key. Unfortunately, the design of the gas key is not practicable for accepting the end of the drive rod. The bolt carrier needs a feature that provides a contact area for the drive piston. Since the gas key is fastened onto the carrier, removal and replacement of the key with a more functional component was the first design iteration for many systems. Eventually, most systems adopted an integral boss on the top of the carrier. Refer to Figure 12 for the integral boss location.

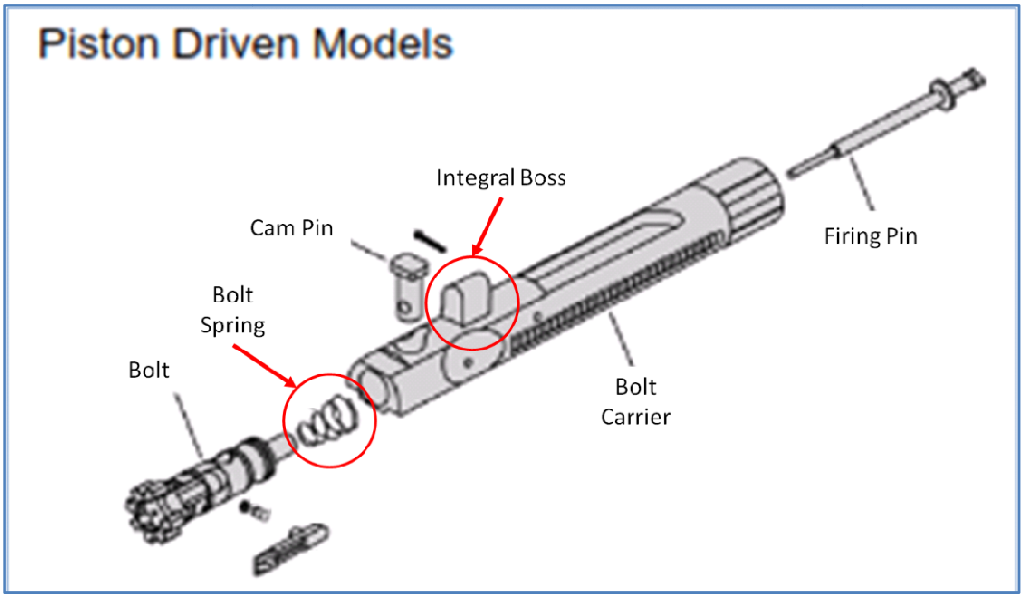

Figure 12: Typical Bolt Carrier Group for a Gas Piston Configuration (12)

An additional modification to the bolt carrier group is to remove the bolt gas rings and install a spring between the bolt and the internal stop in the carrier. In a direct impingement system, the bolt gas rings are necessary to center the bolt in the carrier and provide a sealed cavity for the gases to expand. Yet, in an external gas piston system, the gas rings are unnecessary so they are removed. The spring provides a similar centering effect on the bolt which prevents uneven wear on the cam bolt. The spring can be seen at the back side of the bolt in Figure 12. (12)

The Patriot Ordinance Factory, Inc. (POF-USA) external piston system eliminates the spring and cup configuration of the drive rod as well as the spring on the bolt. As seen in Figure 14 and Figure 13, integral to the gas block is an extended tube with a bushing at the end to guide the narrow drive rod. The drive rod is pushed by a piston that floats between the gas regulator and drive rod. Holes on the underside of the gas block tube release the combustion gas as the piston passes down the cylinder. In this system the drive rod is intended to travel with the bolt carrier group until arrested by the bushing in the gas block tube. The buffer spring slows the whole piston and bolt carrier group assembly and restores it back to the pre-firing position. (13)

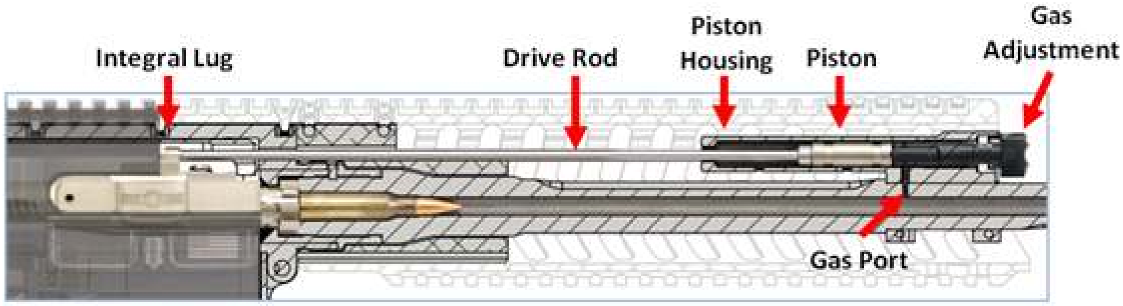

Figure 13: Patriot Ordnance Factory, Inc. Gas Piston System (5)

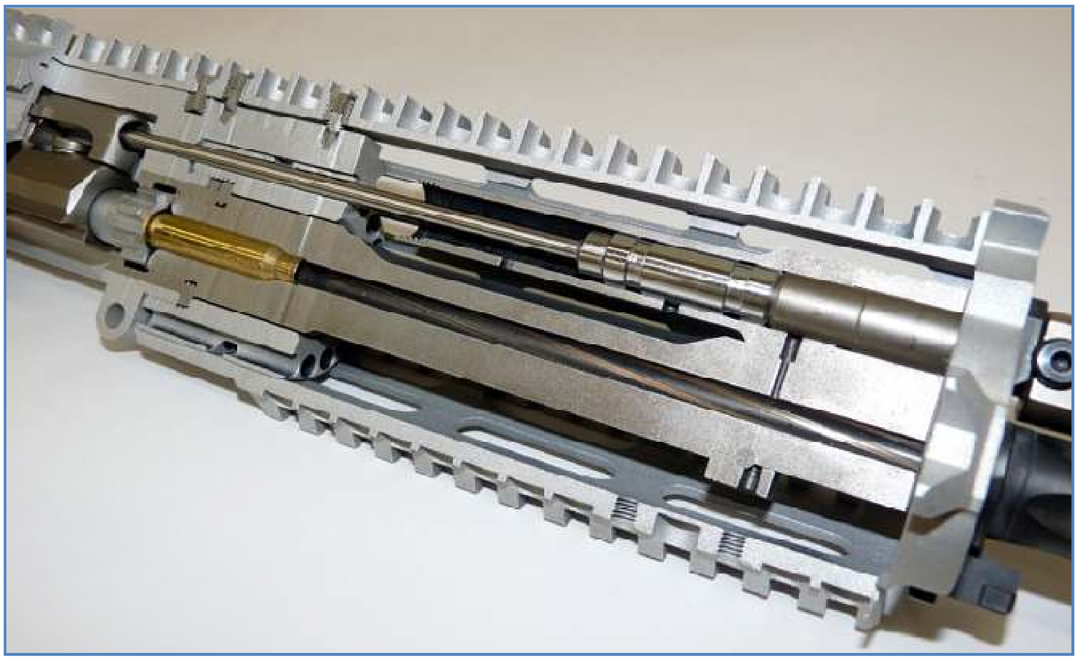

Figure 14: POF-USA P416 Tactical Rifle Piston System (13)

The Primary Weapons System (PWS) external piston setup is a more unique arrangement. This system uses a completely modified upper assembly, shown in Figure 15. The gas block has an integral tube similar to the POF-USA system. The drive rod is segmented and attaches to the top of the bolt carrier. This creates a modular assembly comprising the charging handle, bolt carrier group and the piston rod. In this system, the extra mass of the piston assembly travels with the bolt carrier. The bolt is also modified to accept a dedicated spring. (14)

Figure 15: Primary Weapons System Piston Variant (14)

2.3. Summary of Differences

Both the direct impingement and external piston operated designs utilize many similar components in the action of the rifle. Only components specifically related to the gas system tend to vary. As previously mentioned, a direct impingement gas system consists of the gas block, gas tube, gas key, and a bolt with gas rings. Also, the direct impingement system functions via gases expanding within a cavity created by the bolt carrier and bolt. An external gas piston system uses modified, redesigned or replaced components that remove the piston system from the action and locate it over the barrel. Differing components typically include the gas block, drive rod assembly, upper receiver, barrel nut, and bolt carrier. The bolt is also usually modified by removing the gas rings and replacing them with a spring. A summary of the various components required for each system type discussed above can be seen in Table 1.

Table 1 Configuration Summary of Piston Components

Description	Direct Impingement	Adams Arms	LWRC	POF-USA	Primary Weapons System
Use	Standard	Retro-Fit	Retro-Fit	Retro-Fit	Custom
Piston Location	Internal	External	External	External	External
Gas Venting	Action	Gas Block	Gas Block	Gas Block	Gas Block
Gas Block	Simple	Adjustable	Adjustable	Adjustable	Adjustable
Gas Tube	Yes	N/a	N/a	N/a	N/a
Drive Rod	N/a	Multi-piece Nozzle / Cup + Spring	Multi-piece Nozzle / Cup + Spring	Piston + Drive Rod	Segmented Rod
Upper Receiver	Standard	+ Bushing	+ Bushing	+ Bushing	Custom
Barrel Nut	Standard	Standard	Standard	Custom	Custom
Bolt	Standard	+ Spring	+ Spring	Standard	Modified + Spring
Gas Rings	Standard	Removed	Removed	Removed	Removed
Bolt Carrier & Gas Key	Standard	Custom Lug	Custom Lug	Custom Lug	Keyed Drive Rod

2.4. Implications to System Durability

The original direct impingement design in the AR15 uses an internal gas operated piston. This design dumps hot gases into the action of the rifle. Eventually, carbon build-up and other contaminants mix with available moisture and/or lubricant impeding the moving components in the action. The hot gas also has been known to cause premature failure in small components during excessive/extended firing. The proposed solution to this issue is to remove the hot gas from the action by incorporating an external piston system. Each external piston system configuration and material application has been designed to maximize reliability and wear resistance.

One of the major concerns with the external piston systems focuses on the different way in which the loads are applied to the bolt carrier group. In the direct impingement system the loads are applied along the axis of the bolt. This configuration more evenly distributes the loads on the bolt carrier and bolt. In external piston systems, the actuation force is applied to the integral lug at the top of the bolt carrier causing it to tilt within the upper receiver. Tilting of the bolt carrier can cause higher friction loads in an environment within the receiver that already has been shown to be susceptible to operational issues due to friction. Tilting can also cause large contact forces between the steel and aluminum components within the rifle resulting in premature wear or damage. Sectional views of the direct impingement and external piston systems are shown in Figure 16. Yellow arrows indicate the direction of the applied load on the bolt carrier. Green arrows indicate the reaction forces. The red arrow indicates the direction of rotation of the bolt carrier in the receiver of a typical external piston system.

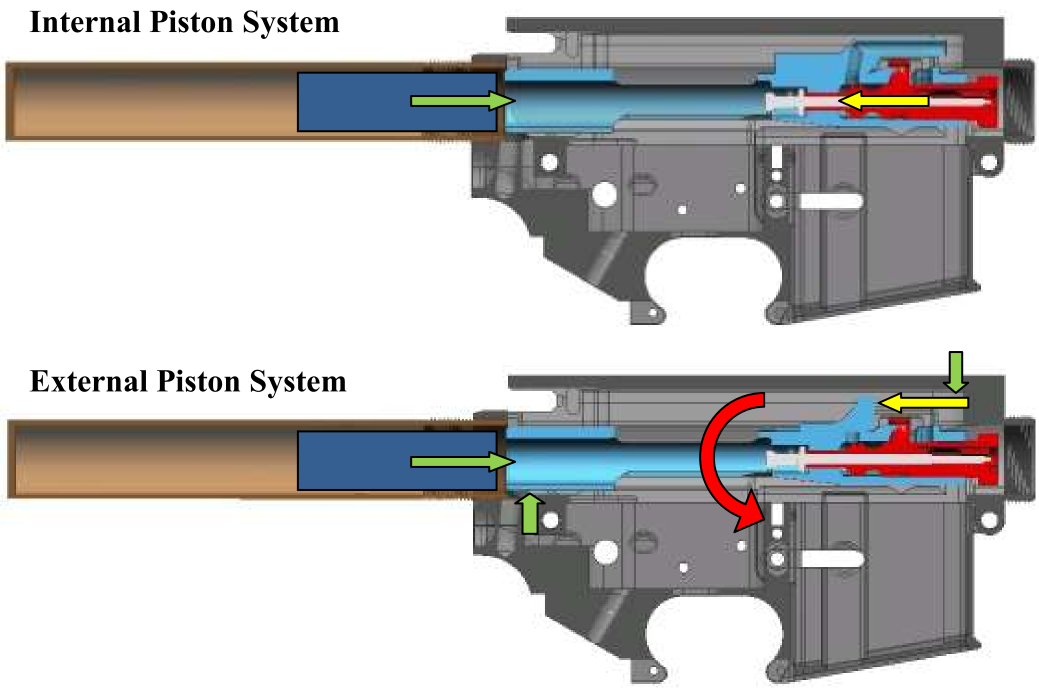

Figure 16: Sectional View of Internal and External Piston Systems with Loading Arrows.

3. METHODOLOGY

The following section will explain the methodology used to calculate the loads imparted on the bolt carrier in the gas system of an AR15. The loads will be used to evaluate the potential functional differences between the direct impingement and external piston systems. Load variation due to changes in barrel and gas system length will also be calculated. The results of these calculations will assist in evaluating the benefits direct impingement versus external gas piston type systems for the AR15 platform.

3.1. Interior Ballistics

Interior ballistics is the study of the pressures and motion of a projectile while in the barrel of a gun. For this study, the pressure in the barrel and the velocity of the projectile are required. Many studies have been completed over the years in an attempt to more fully understand this topic (15). Even the simplest calculations are still quite complex and require specific information about the weapon of interest and the propellant used.

Calculations are based on the rate of evolution of solid propellant into a gaseous phase, which results in a large pressure increase over a short period of time. This pressure forces the projectile into the rifling and accelerates it down the barrel. As the volume behind the projectile increase due to the travel down the barrel, pressure decreases due to polytropic expansion of the gas. Generally, these calculations are used in the design of the barrel of the weapon. A typical view of the pressure, velocity and displacement profiles can be seen in Figure 17 for an M16A1 rifle. With this information, the pressure at any point in the barrel can be determined. In this study, the interior ballistics results are taken from other experimental and theoretical evaluations of the M16 direct impingement system. For a more detailed explanation of calculations involving the development of the data in Figure 17, refer to documents in the Reference section of this report.

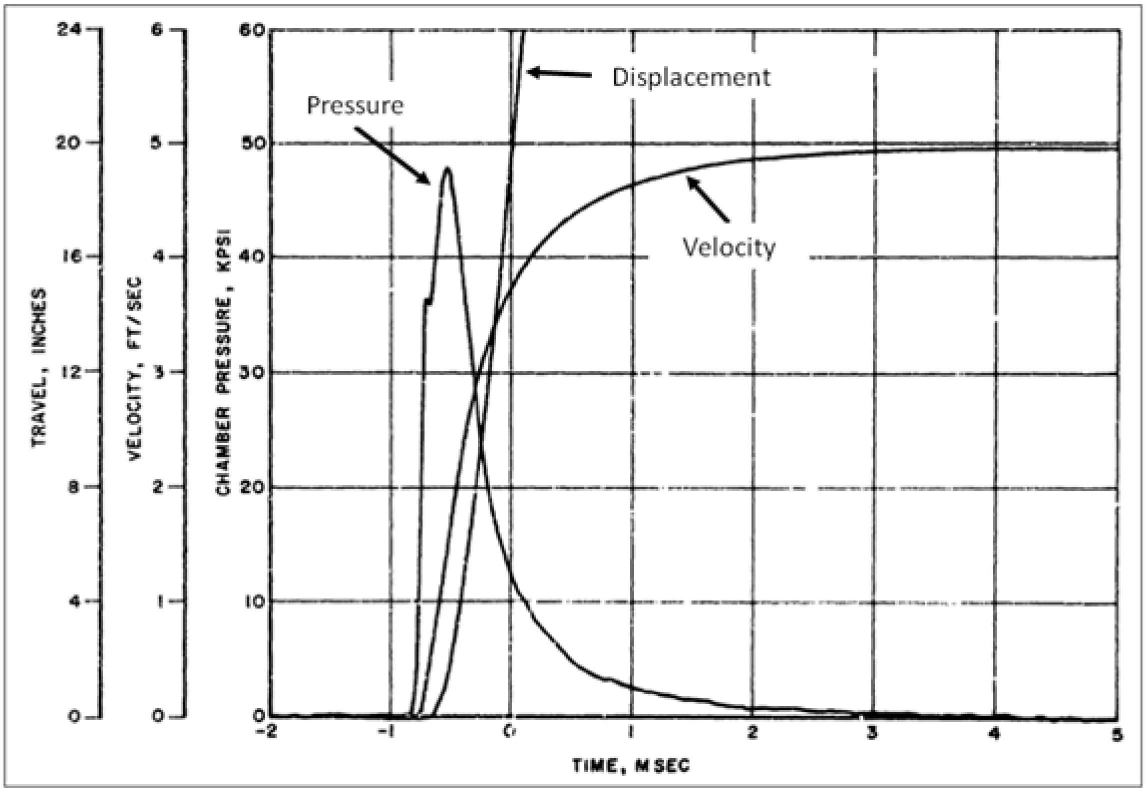

Figure 17: Internal Ballistics of an M16A1 Rifle (16)

From this type of chart the base pressure, or pressure directly behind the projectile, can be determined. In prior studies, a relationship has been made that identifies the base pressure as a function of the chamber pressure (P_B). The Corner Ratio (CR) calculates the base pressure (P_{bp}) as a relation to projectile and charge mass (17).

$$\mathbf{CR} = \left(1 + \frac{1}{2}\frac{m_c}{m_{pr}}\right) \qquad (17) \qquad [1]$$

$$P_{bp} = {P_B}/{CR} \qquad (17) \qquad [2]$$

3.2. Work, Energy, & Momentum

The calculations required to fully evaluate the pressures and temperatures in gas operated weapons are quite complex and are not fully covered in this document. Fortunately, the results from several past technical papers can be referenced from which a fundamental evaluation will be made. The foundations of the calculations used in this paper are the first law of thermodynamics and the law of conservation of momentum. From the First Law of Thermodynamics, change in the internal energy (U) equals the total heat input (Q) to the system and the total work done by the system (W_{tot}) plus losses.

$$\mathbf{U = Q - W_{tot} + \; losses} \qquad [3]$$

where:

$$\mathbf{U = m_c \; z_i \int_0^T Cv \; dT} \qquad (15) \qquad [4]$$

$$\mathbf{Q = m_c \; z_i \int_0^{T_A} Cv \; dT} \qquad (15) \qquad [5]$$

The change in internal energy (U) is equal to the total amount of energy remaining in the gas after all of the work is done and heat losses have been accounted for. The change in internal energy can be estimated based on the mass of the charge (m_c) the fraction of remaining web of the powder grain (z_i) the temperature of the gas (T), and the specific heat of the gas at constant volume (C_v). An assumption made here is that for all cases the solid propellant will be completely burned, or evolved into a gaseous state, prior to exiting the muzzle of the weapon. For this case, the value of z_i is equal to unity, representing 100% of the solid propellant turning to gas. The heat input to the system (Q) is equal to the total energy that is available in the solid propellant. The only difference between the equation for Q and the equation for U is that in the latter, the integral is taken to the adiabatic flame temperature of the gas (T_A).

The work and losses in the system can also be broken down for any point of travel of the projectile in the barrel. The two situations of most interest here are the point just after the projectile passes the gas port in the barrel and the point at which the bolt carrier reaches its maximum velocity prior to the bullet leaving the muzzle. The time between the gas port and the muzzle is the duration in which the combustion gas has the ability to perform work on the actuating piston in the action of the rifle. The total work put into the movement of the bolt carrier must be sufficient to completely cycle the system.

Work and loss components can be estimated from the linear kinetic energy of the projectile (W_{pr}), propellant (W_c), and gun (W_{gun}), the rotational kinetic energy of the projectile from the rifling of the barrel (W_{prr}), the engraving force of the projectile (W_{ef}), and the heat loss to the barrel (E_h).

$$W_{tot} + \textbf{losses} = W_{pr} + W_c + W_{gun} + W_{prr} + W_{ef} + E_h \qquad [6]$$

where:

$$W_{pr} = \tfrac{1}{2}\,\mathbf{m_{pr}}\,\mathbf{v_{pr}}^2 \qquad [7]$$

$$W_c = \tfrac{1}{2}\,\mathbf{m_c}\,\mathbf{v_{pr}}^2 = \frac{\mathbf{m_c v_c}^2}{\mathbf{2g\,\delta}} \qquad (15) \qquad [8]$$

$$W_{gun} = \tfrac{1}{2}\,\mathbf{m_{gun}}\,\mathbf{v_{gun}}^2 \qquad [9]$$

$$W_{prr} = \mathbf{2\,I_{pr}\,R\pi\,v_{pr}}^2 \qquad [10]$$

$$W_{ef} = \mathbf{A_{bore}} \int_0^x \mathbf{P_{ef}}\,\mathbf{dx} = \mathbf{F_{ef}\,x} \qquad [11]$$

$$E_h = \frac{0.38\,d_{bore}^{\,1.5}\left(x_m + \frac{V_0}{A_{bore}}\right)\left(\frac{m_c\,T_A}{m_c} - T_s\right)v_{pr}^2}{\left(1 + \frac{0.6\,d_{bore}^{\,2.175}}{m_c^{\,0.8375}}\right)v_m^2} \qquad (15) \qquad [12]$$

The kinetic energy work components for the projectile, charge and gun are based on the respective masses of the object and their velocities. The projectile and charge velocities are assumed to be the same (v_{pr}) since the charge gases are generally traveling with the projectile as it translates down the length of the barrel. The kinetic energy of the propellant gas can also be estimated from the right hand side of the work equation (W_c), where g is the acceleration due to gravity and δ is the Pidduck-Kent constant (15)(17).

The mass of the gun (m_{gun}) is equal to the sum of the components traveling with the gun at any given time. Prior to the gas port the mass of the gun includes the bolt carrier, spring, and buffer. Between the gas port and the muzzle, the above mention components in the action are moving independently from the main mass of the gun due to the work done on the bolt carrier. The velocity of the gun (v_{gun}) can be calculated by the application of Newton’s Second Law. By the conservation of momentum, the velocity of the gun can be calculated.

$$\mathbf{m_{gun}v_{gun}} + (\mathbf{m_{pr}} + \mathbf{m_c})\mathbf{v_{pr}} = \mathbf{0} \qquad [13]$$

The work done to cause rotation of the projectile as it travels down the barrel is based on the moment of inertia (I_p) and the rifling rate of turn (R), which is 1:7 for a standard rifle.

$$\mathbf{I_p} = \mathbf{m_{pr}\, d_{bore}}^{2} \big/ \mathbf{4} \qquad [14]$$

The work done to force the projectile into the rifling of the barrel is also required. This work can be estimated from experimental data on the force (F_{ef}) required to deform the projectile into the rifling. This force can be shown to be relatively constant along the length of the barrel. Therefore, the work required is simply the product of the engraving force acting on the projectile and the distance that force has moved the projectile down the barrel.

The energy lost to the barrel (E_h) can be estimated from an equation derived and shown in more detail by the resource listed. The calculation shown here will assume that the value of the remaining solid temperature (T_S) is zero since all of the solid will be assumed converted to gas prior to exiting the muzzle at distance x_m. The bore diameter of the rifle (d_{bore}), the empty case/chamber volume (V_0), and the muzzle velocity (v_m) are also used in the above derivation.

When the bullet is at the muzzle, the work and losses equation separates the mass of the bolt carrier from the mass of the gun. As previously mentioned, the kinetic energy imparted to the bolt carrier is the only available energy to cycle the action of the weapon. Variation of this energy due to pressure change will either increase or decrease the force applied to the piston and the bolt carrier velocity (v_{bc}).

$$\mathbf{W_{tot} + losses = W_{pr} + W_c + W_{gun} + W_{bc} + W_{prr} + W_{ef} + E_h} \qquad [15]$$

where:

$$\boldsymbol{W}_{\mathbf{bc}} = \tfrac{1}{2}\,\mathbf{m_{bc}\, v_{bc}}^{2} = \mathbf{F_p x_p} = (\mathbf{P_p A_p})\mathbf{x_p} \qquad [16]$$

Since bolt carrier mass (m_{bc}) and piston area (A_p) are known, and velocity (v_{bc}) and pressure (P_{cv}) can be determined experimentally or theoretically from more advanced calculations in the references (15)(18)(19), a correlation can be established between the work required and the equivalent force on the piston necessary to make the bolt carrier travel a specified distance (x_p).

3.3. Estimating Piston Pressures and Forces

For gas-reloading weapon systems, such as the AR15/M16, the barrel pressure is a necessary piece of information in designing the gas system. The barrel pressure at the gas port dictates the pressure that will be generated in the piston, Figure 18. Yet, there are other parameters of an M16 gas system that also impact the pressure generated in the piston. Gas port diameter is the primary gas system parameter that affects piston pressure. Since the gas port area controls the flow of gas into the system, the diameter must be tuned in for a typical propellant performance and gas system length. This is relatively simple for a single gas system.

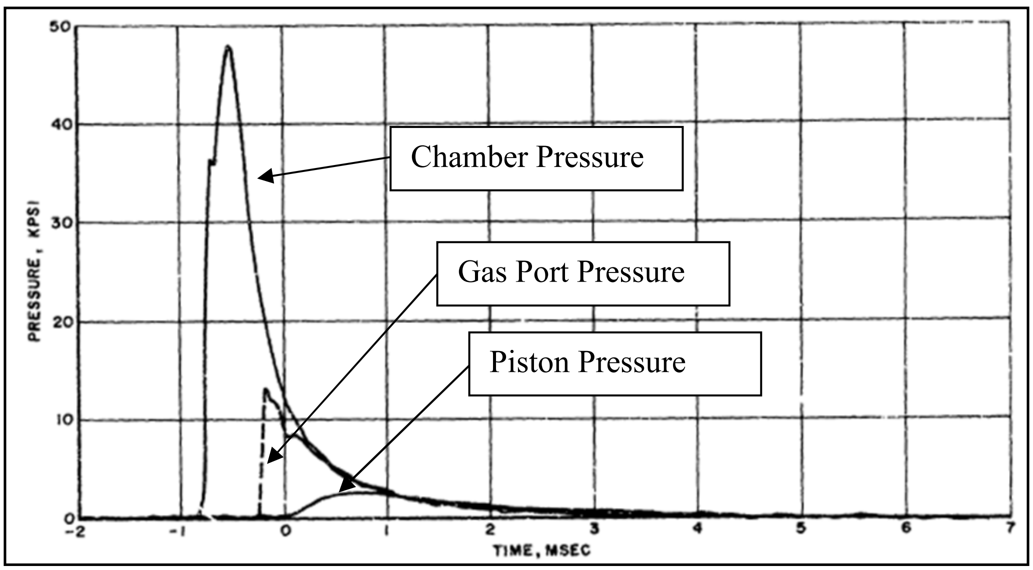

Figure 18: Pressure Profiles of Barrel, Gas Port, and Piston (16)

In a study on the variation of parameters of an M16, it has been shown that the operation of the weapon is greatly affected by the variation of pressure acting on the bolt carrier due to change in port area, Figure 19. A piston cavity pressure of around 4,000 psi will cause internal clashing between the bolt carrier key and the rear of the upper receiver. This high pressure also attempts to prematurely extract the casing and can cause a failure to cycle. If the pressure is too low, the bolt carrier will not have enough energy to complete the reloading cycle. Pressures below 2,000 psi resulted in failures to feed. (16)

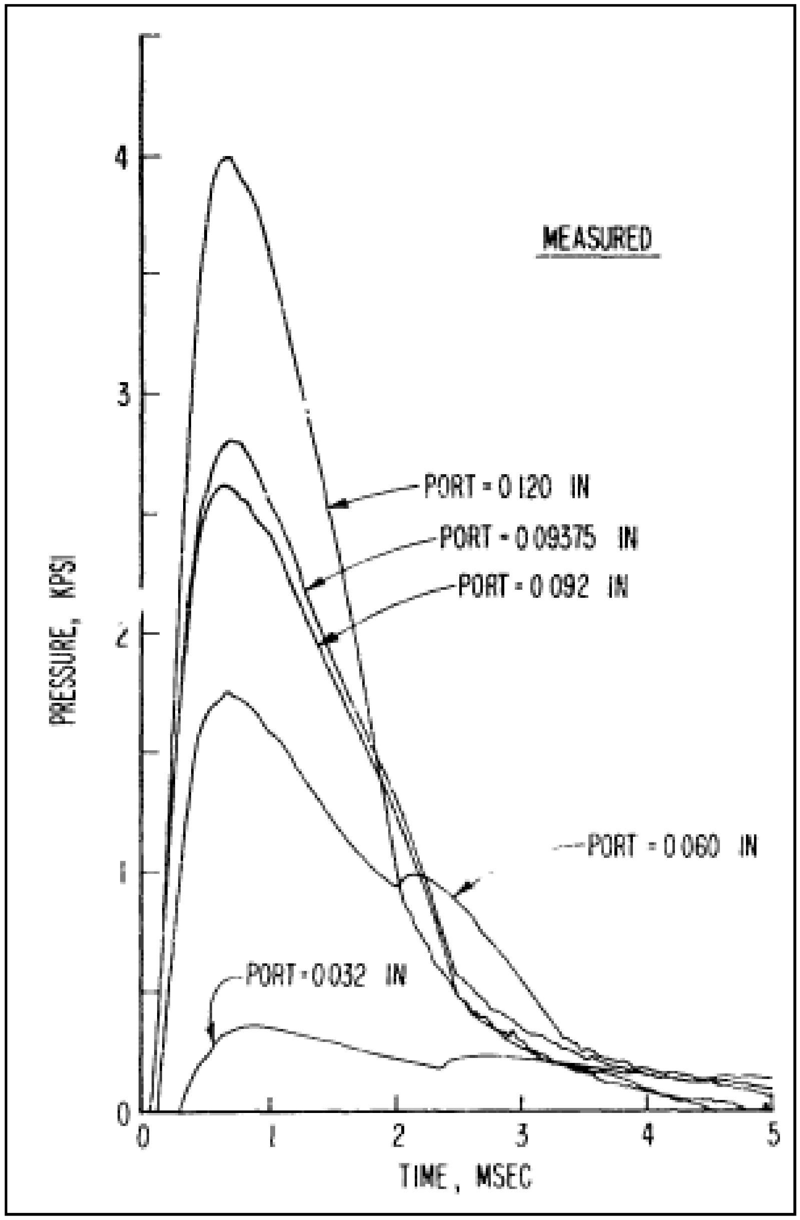

Figure 19: Effect of Gas Port Area on Piston Pressure (16)

Understanding the sensitivity of the gas system to parameters that affect pressure in the piston is crucial. This allows for estimates of the piston pressure based on available internal ballistics results. Also, an assumption made here is that the gas port area is constant for rifle systems of any length. Therefore, an estimate can be made assuming piston pressures are primarily dependent on the input (gas port) pressures. In this study, the piston pressure will be taken as proportional to length of the gas system since the gas port pressures are directly dependent on the barrel pressure at the gas port.

For the external gas piston system, most of the internal components are the same as those used in the direct impingement system. The major difference is the addition of the drive rod, piston/cup and gas block/piston housing. These components are relatively small and light weight compared to other moving components in the weapon. Therefore, the work done by the combustion gases should be similar in magnitude to the work done in a direct impingement system. This makes the comparison between systems much simpler. Despite the difference in pressures generated in internal versus external pistons, the work done for systems of equal barrel length should be the same. The most significant difference between the direct impingement and external piston systems is that the external systems typically have gas feed adjustment capability. The direct impingement gas port hole size and gas system components are generally the same for any length system with the exception of the obvious length change of the gas tube to accommodate the longer barrel.

Once the work and pressure calculations are complete, a table of applied forces can be generated for M16 rifles with different length and different type gas systems. Free body diagrams can then be created for the bolt carrier. Since the motion of the bolt carrier is dynamic in nature, it is helpful to know the location of the center of gravity. With the aid of a CAD program (i.e., UniGraphics NX6), a detailed model of the bolt carrier can be made to determine the best approximation of the center of gravity. This point will be used as a rotation point for any offset forces in the external piston configuration. The resulting reaction loads will then be summarized and compared.

4. RESULTS

The following section will describe the results based on the calculations and relations established in the methodology section of this report. A selection of pressure and velocity data points will be selected from a prior interior ballistics evaluation. Then these inputs will be evolved into work, energy and momentum terms for the time just after the projectile passes the port and as the projectile exits the muzzle. These values will be then used to determine estimates of the pressure within the piston and force acting on the bolt carrier. These calculations will be assumed similar for both the direct impingement and external piston systems. Finally, the free body diagrams of the bolt carrier will be used to evaluate how the input pressure load is reacted by the system.

4.1. Interior Ballistics

As previously mentioned in the methodology section, the calculations required for determining the interior ballistics of weapons can be quite complicated and are beyond the scope of this report. For the current evaluation, the only information required is a plot of barrel pressure behind the projectile and projectile velocity versus distance traveled down the barrel. A typical plot of the interior ballistics of an AR15 rifle is shown in Figure 20. This plot clearly shows the variation of available pressure at the different gas port locations.

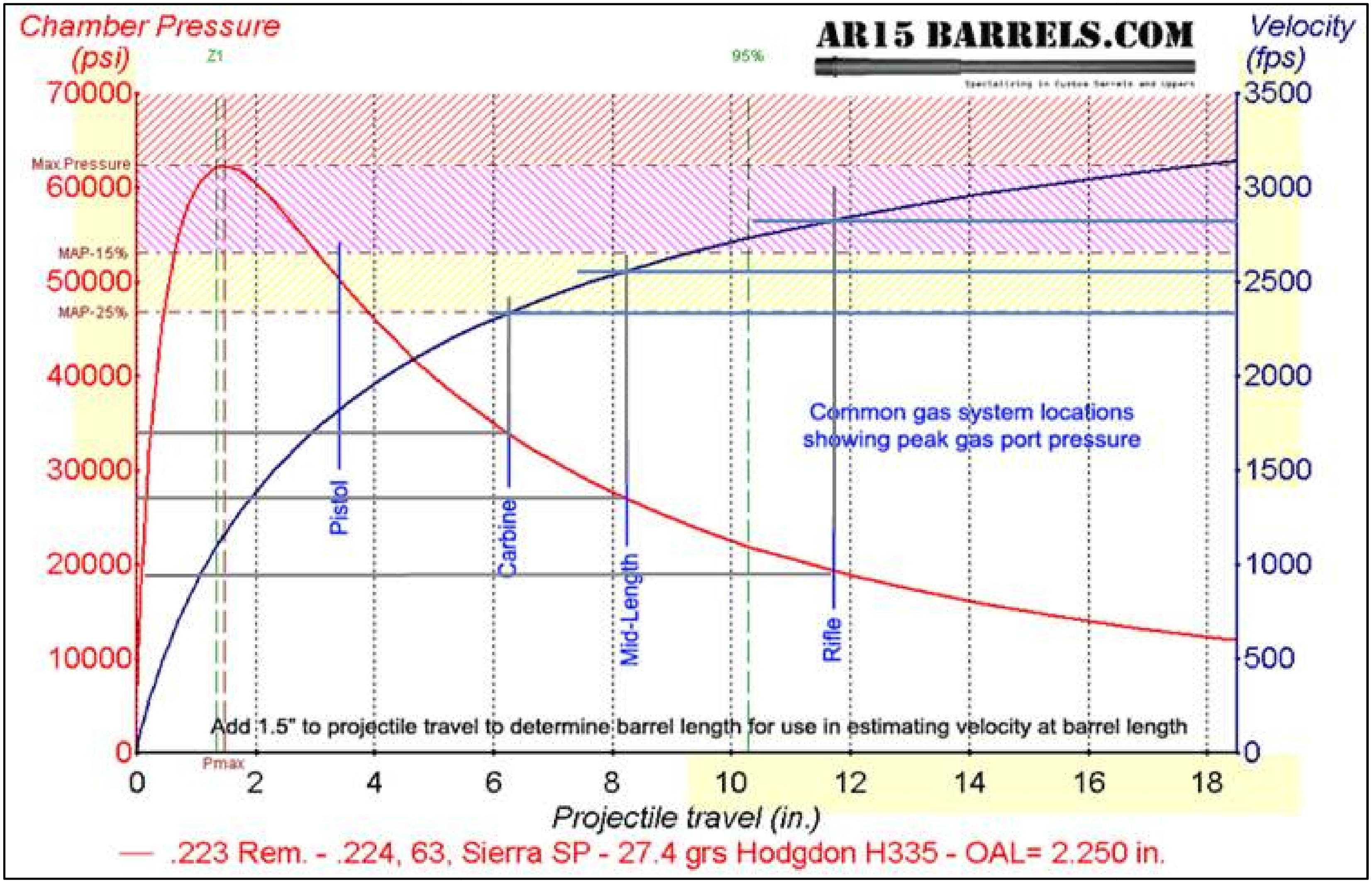

Figure 20: Typical Pressure and Velocity Curves for .223 Caliber Ammunition (6)

Data in the above plot was then summarized in Table 2. For this study, three common rifle lengths were chosen to represent the range of M16 gas systems used by operators today. Shorter pistol systems were discounted from this study as they are not as common. The standard gas system length to the gas port was 7.8, 9.8, and 13.2 inches from one barrel manufacturer for carbine, mid-length, and rifle systems, respectively (6). These gas port locations correlate to 14.5, 16, and 20 inch barrels, respectively. The base pressure, or gas port pressure, increases approximately 35% for the mid-length and 67% for the carbine gas system from the baseline rifle gas system. The calculations at the pressure port describe the pressure behind the projectile at the instant just after the projectile passes the gas port. The calculations for when the projectile is at the muzzle shows the base pressure at the projectile as well as an averaged value for the pressure at the gas port. The pressure at the port is averaged as the pressure drop is almost linear for these short times.

Table 2: Tables of Pressures and Velocity for Different Gas Systems Lengths (6)

CALCULATIONS PROJ. @ PRESSURE PORT						
Lp	7.8	7.8	9.8	13.2	in	Port location
vp	2,372	2,372	2,612	2,891	ft/s	Velocity of projectile
P_B	32,900	32,900	26,507	19,658	psi	Chamber Pressure
Ppb	26,225	26,225	21,129	15,669	psi	Port Pressure
%	167%	167%	135%	100%		
CALCULATIONS PROJ. @ MUZZLE						
Lmuzz	14.5	16	16	20	in	Muzzle location
Vmuzz	2,978	3,064	3,064	3,244	ft/s	Velocity of projectile
P_B	17,831	16,005	16,005	12,466	psi	Chamber Pressure
Ppb	14,213	12,758	12,758	9,937	psi	Base Pressure
Pport	20,219	19,491	16,943	12,803	psi	Average Port Pressure
%	158%	152%	132%	100%		

4.2. Estimating Pressure and Force from Work

For this next section, general system inputs are required. The first set of inputs is the masses of relevant components. The projectile used in this study will be a 55 grain full metal jacketed round similar to the M193 United States 5.56mm military round. The 5.56mm round is similar to the .223 civilian round. Since, most commercial rifle barrels are designed and tested to meet the higher proof testing loads of the 5.56mm round, the selected cartridge choice seems reasonable. The masses of relevant components are summarized in Table 3. In some instances, mass of a component is shown in grains and ponds mass, where one grain is equal to 1/7000 pounds mass.

Table 3: Table of Relevant System Masses

Masses			
mpr	55	grains	mass of the projectile
	0.0079	lbm	
mc	28	grains	mass of charge (gas)
	0.0040	lbm	
mcap	28.5	grains	capacity of casing
mgt	8.7900	lbm	total mass of gun
mbc	0.61	lbm	Mass of bolt carrier
mba	0.13	lbm	Mass of bolt assy
mspef	0.14	lbm	Mass of spring (effective)

The rifle, buffer system and gas system dimensions are also necessary for the determination of work and energy terms. The rifle bore diameter, rifling twist rate, buffer tube and spring dimensions, direct impingement piston area and travel of the bolt carrier to unlock the bolt are listed in Table 4. The twist rate of the rifle is 1:7 or one complete revolution in seven inches of travel. Piston area and bolt carrier travel were physically measured.

Table 4: Tables of the Relevant System Dimensions

General Dimensions			
Dbore	0.223	inch	bore diameter
Abore	0.0391	in^2	Bore Area
TR	0.1429		Twist rate of rifling
Vo	0.113	in^3	Empty Chamber Volume

Buffer / Recoil System			
ksp	2	lbf/in	Buffer spring force constant
Nc	38		Number of coils
Lsp	11.125	inch	Free length of spring
Lb	3.25	inch	Total buffer length
Lbh	0.255	inch	Length of buffer head
Ltube	7.125	inch	Length of buffer tube
xi	3.745	inch	Initial spring compression
xf	7.62	inch	Final spring compression
Ltbc	3.875	in	Total travel of bolt carrier

Gas System Dimensions			
Abc	0.1967	in^2	Area of Piston
Lbc	0.335	in	Travel of Bolt Carrier to disengage the bolt

The gas properties of the propellant were also required in order to determine the energy potential of the solid propellant and the heat loss terms. The specific heat at constant volume (C_v) was taken from a sensitivity study of M16 gas system parameters (18). The adiabatic flame temperature (T_A) and the temperature of the un-burnt solid propellant (T_S) are listed. The value T_S is set to zero assuming that all of the gas has been evolved into gas.

Table 5: List of Gas Properties and Factors (17)

Gas Properties			
Cv	1.49E+04	(ft/s)^2/K	Specific Heat Const Volume
Ta	2855	K	Adiabatic flame temp of gas
Ts	0	K	Temp unburnt solid propellant
Rcorn	1.2545		Corner Ratio
Vba	0.47	in^3	Volume of bolt assy metal

The results of the equations derived in the methodology have been summarized for three different combinations of barrel lengths and gas port locations in Table 6. The effects of barrel length on the total chamber or breech pressure have already been shown in the previous section. As expected, the location of the gas port also directly affects the source pressure for the gas system. The average gas port pressure (P_{port}) is listed as an intermediate pressure for the time period between the gas port and the muzzle. This pressure is the value that is used to determine the relationship between the port pressure and the piston cavity pressure (P_{cv}). The magnitude of the predicted port pressure is consistent with other studies of the M16 gas system (16).

Table 6: Summary of Work, Momentum and Applied Force

CALCULATIONS PROJ. @ MUZZLE						
Lmuzz	14.5	16.0	16.0	20.0	in	Muzzle location
Lp	7.8	7.8	9.8	13.2	in	Port location
Vmuzz	2,978	3,064	3,064	3,244	ft/s	Velocity of projectile
P_B	17,831	16,005	16,005	12,466	psi	Chamber Pressure
Ppb	14,213	12,758	12,758	9,937	psi	Base Pressure
Pport	20,219	19,491	16,943	12,803	psi	Average Port Pressure
%	158%	152%	132%	100%		
Pcv	3,948	3,806	3,308	2,500	psi	Scaled Cavity Pressure
Wbcin	21.7	20.9	18.2	13.7	lbf-ft	Work from pressure & distance traveled
vgun	3.5	3.7	3.7	4.1	ft/s	Velocity of gun
Fbc	**777**	**749**	**651**	**492**	**lbf**	**Force from cavity pressure**
%	158%	152%	132%	100%		% change of force length

An additional data point was taken using a 16 inch barrel with a carbine length gas system. This configuration is a common length due to United States federal laws dictating the length of the rifle barrel must exceed 16 inches. The port pressure for this configuration is slightly lower than the shorter 14.5 inch barrel carbine rifle. Based on the study shown in Figure 19, the estimated pressures indicate that hard clashing can occur between the bolt carrier and the rear inner portion of the upper receiver. Therefore, any small variation within the gas system that decreases the effective cavity pressure to eliminate this issue is beneficial.

The cavity pressure shows up to a 58% increase for the 14.5 inch barrel and 7.8 inch gas system as compared to the rifle length arrangement. The mid-length gas system shows a piston cavity pressure that is almost half that of the carbine system. The resulting forces acting on the bolt carrier also show the same trend. This evaluation confirms that a shorter barrel and gas port location introduces significantly higher loads onto the gas system of the M16 platform.

4.3. Reacting Loads

The gas loads estimated in the previous section can readily be used to generate free body diagrams for the bolt carrier. The time of interest is just before the end of the bolt carrier's stroke just prior to the disengagement of the bolt from the barrel extension. This is the time at which the pressure force is starting to be bled out of the piston cavity via leakage paths designed into the carrier. These leakage paths are required to bleed out the pressure safely to atmosphere.

Since the reloading gas operated system in an M16 is accelerated at a very high rate, the system will be treated as a dynamic analysis. The firing rate of a fully automatic can be around 750 rounds per minute. Over the very short cycling time, the applied load will act on the locations indicated in the free body diagrams in Figure 21 and Figure 22. The input loads are indicated by green arrows, the reacting loads are yellow, and the center of gravity (CG) of the bolt carrier is the yellow circle.

For the internal gas system, the input load is acting along the z-axis of the rifle and the CG is only a short distance from the axis. The reacting loads in the internal system are well balanced and any rotation or tilting of the bolt carrier is minimal. This result is in accordance with the expectations for the original design of the weapon. For the external gas piston system, a necessary assumption is that the necessary input load to cycle the weapon is the same as that required for a rifle length internal piston system. Therefore any extra load would be unnecessary to the system and could only be detrimental. The exception is that external piston systems are not always directly subjected to gas port pressures. Some of the gas systems have designs that allow adjustment to optimize the performance of the piston system for a given barrel length, gas port location or projectile round/charge.

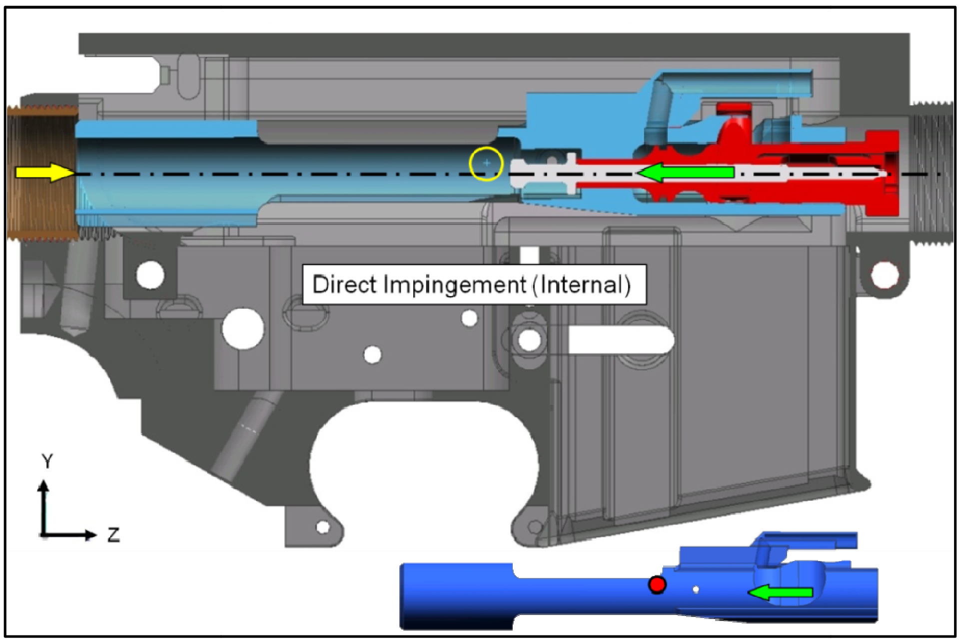

Figure 21: Free Body Diagrams of Loads on the Bolt Carrier (Internal Piston)

The design of the bolt carrier for the external system has the input load offset 0.785 inches from the z-axis of the weapon. This is the same location as the gas tube in the internal piston system. The difference is that the load is applied at the contact face of the boss. For this system, the large magnitude of the offset load creates significant tilting of the bolt carrier within the upper receiver. Reaction loads, indicated by the yellow arrows in Figure 22, are indeterminate.

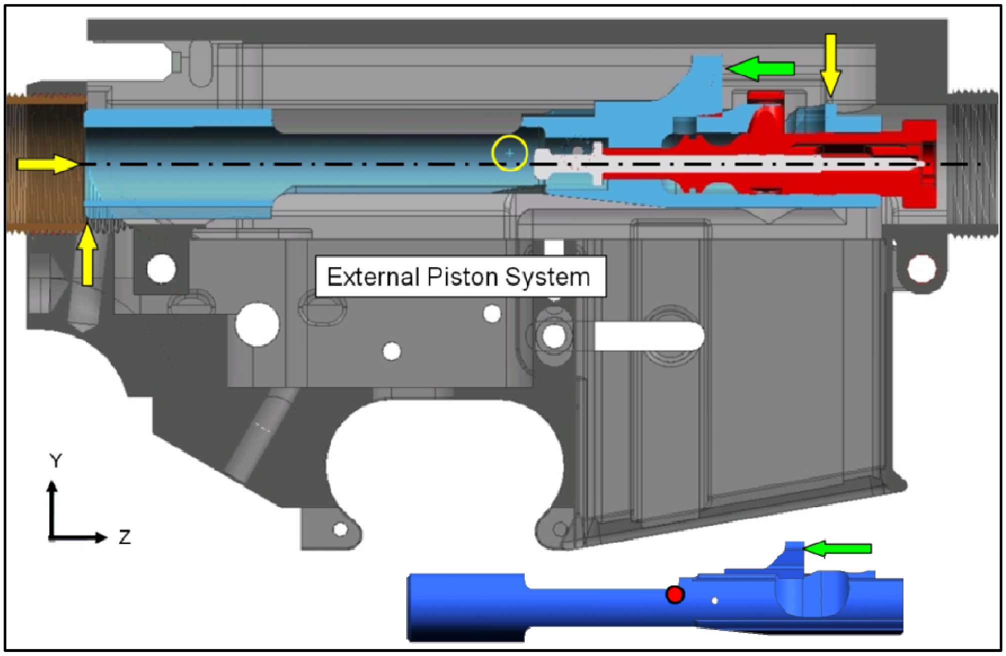

Figure 22: Free Body Diagrams of Loads on the Bolt Carrier (External Piston)

Therefore, in order to estimate the worst case loading, two points of contact were evaluated. The first point was at the end of the bolt carrier near the buffer tube. The second point of contact is taken to be the forward end of the bolt carrier close to the bolt. The reaction loads are summarized in Table 7 for both the internal and external gas piston systems. The values for the input gas force (F_{bc}), the axial reaction force (F_{btz}), and the buffer tube (F_{bty}) and bolt end (F_{bty2}) tilting forces are included for review. The loads for either contact case are significantly larger than those for the internal gas piston system.

Table 7: Summary Table of Forces from the Free body Diagram

INPUTS					
Lp	7.8	7.8	9.8	13.2	Port location
Lmuzz	14.5	16	16	20	Muzzle location
Fbc	-777	-749	-651	-492	Gas Force
Internal Piston Reaction Forces					
Fbtz	777	749	651	492	Axial Force
Fbty	20	19	16	12	Tilt Force @ Tube
External Piston Reaction Forces					
Fbtz	777	749	651	492	Axial Force
Fbty	161	155	135	102	Tilt Force @ Tube
Fbty2	672	648	563	426	Tilt Force @ Bolt

5. CONCLUSIONS

After reviewing the history and reliability of the AR15 / M16, the need for a more reliable action is clearly warranted. Claims of field failures, from extraction/feeding issues to jamming and cycling problems, have endangered soldiers on the battlefield and frustrated enthusiasts at the range. Generally, these failures are related to the requirement for strict cleaning and lubrication regimens in order to ensure proper function of the rifle. Other concerns are related to the configurations that use either shorter barrels or shorter gas systems. These short rifles were shown to exhibit pressure estimates up to 58% higher than the baseline rifle. This extra load explains the extra wear and damage that can occur in the shorter rifles. In an attempt to facilitate a solution to these problems and improve the baseline design, retro-fit external piston designs similar to that employed in the reliable AK-47 have been introduced into the market.

These designs promote an improvement in reliability as the hot combustion gases are removed from the action of the rifle and instead work at a remote location above the barrel. The residue from the hot gases no longer accumulates on the moving components in the action. Specially designed external piston arrangements require less maintenance and cleaning. Improving the service interval requirements provides a major benefit to soldiers that may not have the ability or opportunity to thoroughly clean their rifle. Also, the design of the external gas piston system is less susceptible to build up of other contaminants in extreme environments.

Opponents of the external piston designs claim that the upgrade is not necessary. Proper lubrication and cleaning can be minimal without failures that may have been typical in the past. Also, the offset loading of the bolt carrier causes higher friction loads between the carrier and the inside of the upper receiver. The larger internal loads can cause premature wear and failure of components over time. Even in the larger rifle length external piston gas systems the predicted loads are larger by a factor of ten. Therefore, despite the ability of some external piston systems to regulate pressure into the gas system, the baseline loads are still significantly higher.

The above methodology provides a simple path to understanding the variation in internal piston cavity pressures for M16 gas systems of various lengths. A recommendation for future work would be to evaluate more accurate piston cavity pressures for both internal and external piston systems. The studies performed in the reference section provide a more detailed analysis. These calculations should also be applied to the individual external gas systems in order to more fully differentiate the benefits or issues with each.

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APPENDIX

Below is the complete set of work and energy terms calculated when the projectile is at the muzzle and the pressure stops actuating the piston.

CALCULATIONS PROJ. @ MUZZLE						
Lmuzz	14.5	16	16	20	in	Muzzle location
Vmuzz	2,978	3,064	3,064	3,244	ft/s	Velocity of projectile
P_B	17,831	16,005	16,005	12,466	psi	Chamber Pressure
Ppb	14,213	12,758	12,758	9,937	psi	Base Pressure
Pport	20,219	19,491	16,943	12,803	psi	Average Port Pressure
%	158%	152%	132%	100%		
Pcv	3,948	3,806	3,308	2,500	psi	Scaled Cavity Pressure
Wbcin	21.7	20.9	18.2	13.7	lbf-ft	Work from pressure & distance traveled
vbc	8.4	8.3	7.7	6.7	ft/s	Velocity Estimate
Momentum Terms						
Mpr,c	35.3	36.3	36.3	38.5	lbm-ft/s	Momentum of projectile and charge
mbf	0.19	0.19	0.26	0.33	lbm	Mass of buffer weight
Mbc	7.1	7.0	7.1	6.6	lbm-ft/s	Momentum of carrier, buffer & spring
Mgt	28.2	29.4	29.3	31.9	lbm-ft/s	Momentum of gun
vgun	3.5	3.7	3.7	4.1	ft/s	Velocity of gun
Fbc	**777**	**749**	**651**	**492**	**lbf**	**Force from cavity pressure**
%	158%	152%	132%	100%		% change of force length
Work/Energy Terms						
Q	**169,587**	**169,587**	**169,587**	**169,587**	**lbf-ft**	**Total Energy Released by Gas**
Wpr	34,840	36,882	36,882	41,342	lbf-ft	Work projectile motion down the barrel
Wprr	389	412	412	461	lbf-ft	Rotational energy of projectile
Wc	174	184	184	206	lbf-ft	KE of unburnt gas/solid
Eh	1984	2155	2155	2612	lbf-ft	Heat Loss to gun
Wef	544	600	600	750	lbf-ft	Work from engraving resistive force
Wspun	0.01	0.01	0.01	0.01	lbf-ft	Work to slightly compress spring
Wbcin	22	21	18	14	lbf-ft	Work estimate from force
Wgun	55	60	61	73	lbf-ft	KE of gun
Wtot	**38,008**	**40,313**	**40,311**	**45,459**	**lbf-ft**	**Total Work done by the System**
U	**131,578**	**129,272**	**129,274**	**124,127**	**lbf-ft**	**Remaining Energy in Gas**
Tg	**2,215**	**2,176**	**2,176**	**2,090**	**K**	**Temperature of Gas**
	1,757	**1,718**	**1,718**	**1,632**	**F**	