DISCUSSION OF FIRE OUT OF BATTERY TEST RESULTS

Matthew Tedesche [1] , Robert Durocher [1] , Michael Gully [1]

(1) Benet Laboratories
AMSTA-AR-CCB-DE
Watervliet, NY 12189-4050

Abstract:

The U.S. Army's vision of it's future is a lighter faster more lethal fighting force. The U.S. Army's Future Combat Systems Multi-Role Fighting Vehicle is an example of the application of this vision. In order to combine a lighter faster vehicle with a more lethal weapon system, non-conventional recoil methods will need to be considered. Currently a recoil system called FOOB or fire out of battery is being experimented with. This report will include an explanation of how this recoil system works and results attained from a series of testes performed with a FOOB system. Lessons learned from these tests and how they apply to the design of a FCS Multi-Role Vehicle weapon system will be discussed.

Introduction

The vision of the future U.S. army involves a lighter faster more lethal combat system. In harmony with this vision, a combat vehicle that will meet these requirements is currently in development. This "multi-role" combat vehicle will weigh less than 20 tons and be able to fit in the cargo bay of the Army's C130 transport aircraft. The lightweight and compact design will give this vehicle the advantage of rapid deploy ability compared to the Army's current main battle tank. Although this vehicle will not have the same level of armor as the Abrams, it's lethality will come from its speed, and the range and accuracy of it's main weapon system. With the ability to fire a variety of guided and unguided ammo, this vehicle will be capable of both direct and indirect target engagement. The ability to fire ammo that is up to 30% greater impulse than what is currently be fired from the Abrams main battle tank will give this vehicle the ability to engage and defeat heavily armored vehicles with lethality. However it is this same ability that will present the greatest design challenge in the development of this vehicle, and perhaps one of the greatest challenges in the development of any armored vehicle in modern warfare.

Ogorkiewicz Ratio [1], Round Impulse/Vehicle Mass, is often used when analyzing recoil effects on fighting vehicles, a ratio of 900 N*sec/M. ton is recommended as an upper design limit. The following table, (table #1) is a comparison of Ogorkiewicz Ratio for a number of armored vehicles designed in the later half of the twentieth century compared to the FSC vehicle design concept.

Table#1 [2]

Vehicle	Mass (metric Tons)	Main Weapon	Round	Impulse, Lbf*sec / N*sec	Ogorkiewicz Ratio N*sec/ M.ton
FCS Vehicle	18.15	105 mm	FCS Case Telescoping	8200 / 36,475	2010 N*s/M.ton
M8 AGS L.T. (1995)	18	105 mm	M-490 KE Tactical	4700 / 20,906	1161 N*s/M.ton
LAV-105 (1988)	13.86	105 mm	M-490 KE Tactical	4700 / 20,906	1500 N*s/M.ton
M1A1(1988)	57.15	120 mm	M-829 KE Tactical	6100 / 27,134	475 N*sec/M.ton
M1 (1984)	54.54	105 mm	M-490 KE Tactical	4700 / 20,906	384 N*sec/M.ton
M 60 (1960)	52.167	105 mm	M-490 KE Tactical	4701 / 20,906	400 N*sec/M.ton
M551 (Sheridan)	15.85	152 MM		3700 / 16650	1050 N*sec/M.ton

Although the LAV-105 has an Ogorkiewicz Ratio of 1500, it was never fully tested or type classified. The M8 armored gun system was fully tested and type classified. This vehicle (although not in production) is probably the closest in design to the FCS vehicle concept and its Ogorkiewicz Ratio is only half of what the FSC vehicle will be.

So we are challenged with the question of how to mount a cannon that fires an 8200 Lb*Sec round on a vehicle with out exceeding the total vehicle weight of 20 tons, while maintaining vehicle stability and relative crew comfort when the weapon is fired. In order to do this we are forced to look at non-traditional recoil systems for the solution.

Currently Benet' Laboratories is investigating and experimenting with a recoil concept called fire out of battery, or FOOB. In a FOOB system the recoiling mass is accelerated over some fixed length to a speed equal to half the maximum of what it would be if fired from a stationary position with a given round impulse. Then at the desired position the gun is fired and it recoils back at half the speed it would during conventional firing. Therefore the net change in momentum is the same for both conventional and Fire out of Battery, as it should be due to the same impulse being imparted to each system for a given round. However the recoil velocity in a Fire out of Battery system never gets above half the conventional firing velocity. The recoil force is a function of the recoil velocity squared, (equations 1-3). This means for any given recoil length and mass, a FOOB system will require one quarter the force required by a conventional system in order to start and stop the recoiling mass.

Equation # 1

$$\int_0^L F dx = \int_0^V mv dv$$

Equation # 2

$$FL = \frac{1}{2} mV^2$$

Equation # 3

$$F = \frac{1}{2} MV^2 / L$$

- M=Recoiling Mass
- L= Recoil Length
- V = Recoil Velocity imparted by round impulse

Testing Goals

A series of two FOOB tests were performed. One test was conducted in October of 2000 at the Write Malta Corporation's test facilities in Malta NY. Another test was conducted in February 2001, in cooperation with United Defense L.P. at the Aberdeen Testing Center, Aberdeen Proving Grounds, Aberdeen Maryland.

Showing recoil force reduction via Fire Out of Battery and acquiring data that could be analyzed to gain insight into the dynamics of a FOOB recoil system was the major goal of the first series of test. The effects of round ignition delay time variation on FOOB, which has been identified as one of the most influential variables, was to be studied during both series of tests and will be discussed subsequently. During the second series of tests, a new and much more precise ignition technology, provided by United Defense L.P., was introduced and studied. The effects of this technology will subsequently be discussed also.

Hardware

A 105 mm M-35 cannon was modified in order enable it to fire out of battery. The original gas springs that are used to recover after standard recoil, with a compression ratio of about 2.25, were used as actuators. A basic mechanical latch that could catch and release the gun was fixed to the gun mount structure and actuated pneumatically. A position sensor was used to determine and record the gun position during operation in real time. A sensor with a very fast response time would need to be used, as the accelerations of the gun during recoil would be as high as 40 to 50 gees. It was determined that a sensor called a Tempo-Sonic device would meet the requirement. This device uses a permanent magnet fixed to the gun and a guide rail on the mount structure. The position of the magnet is calculated by circuitry in the device. This signal is then sent to a comparator circuit, which would send a firing signal to the gun when the gun was in the predetermined position. The gun would then recoil back and if possible be caught and latched back to its original position by the latching mechanism. Although the actual hardware used in the test was not optimal in many ways, it was felt that there would be valuable lessons learned in the process of making the system function even at a sub optimal level.

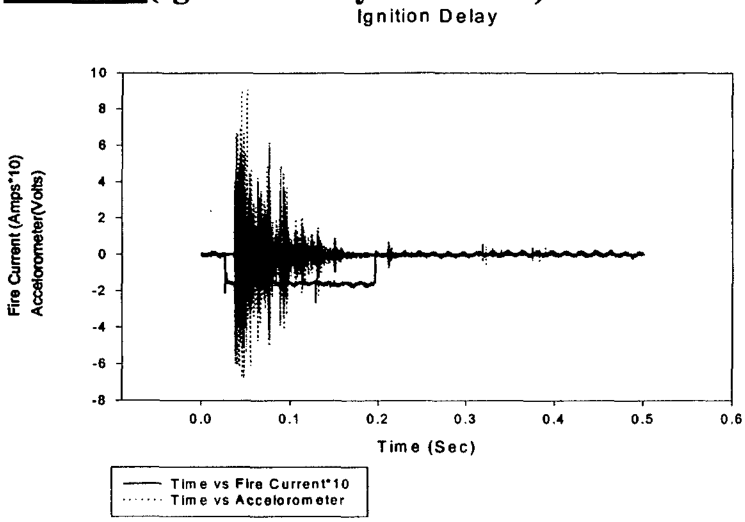
Test Results

Determining Average Ignition Delay Times

The timing of round ignition may be the most crucial factor in the successful operation of a FOOB system. In all ammunition there is a delay between the time when current is sent to the primer and round ignition. This delay is caused by the thermal-chemical reaction time of the primer and propellant. This delay time will vary with round type, batch, and lot. During testing these times were observed to be on the order of 10 to 30 milliseconds. While these times may be virtually undetectable to the eye, and were certainly acceptable for conventional systems, they can make a difference of inches in the position of a gun being accelerated in a FOOB recoil system. This is not acceptable considering control of the ignition position should ideally be a quarter-inch at most. If the average delay time is known it can be factored in to the firing circuit, however the ignition delay time variation will have a significant effect on the performance of FOOB.

During the testing conducted in Malta, NY the M-724 105 mm round was used. By fixing an accelerometer to the breech and comparing its output to the fire current signal during conventional firing, we were able to determine the ignition delay time for each round fired. Figure#1 shows the fire current, (show as the negative rectangular signal) and accelerometer output compared on the same time reference. Table #2 shows statistical data for the M-724 round, based on six of these tests.

Figure#1 (Ignition Delay Time-Test)



Table#2

Round	Ignition Delay Time	
1	11ms	Average=9.33 ms
2	7.25 ms	St. Dev. =1.65 ms
3	8.875 ms	
4	8.875 ms	
5	8 ms	
6	12 ms	

Using this method we calculated an average delay time of 9.3 milliseconds with a standard deviation of 1.65 milliseconds. It is note worthy however that all the ammunition we used came from the same lot which could mean that the consistency in ignition delay time from round to round was better than what a tank crew may see in their ammo store.

During the testing conducted at Aberdeen Test Center the M-490 105mm round was used. United Defense L.P provided a study of the ignition delay time of this round using both conventional primers and their ETC (electro thermal chemical) ignition system. ETC uses a controlled high current pulse to form and inject plasma into the propellant. Table #3 shows statistical data for the M-490 round. T2 times are synonymous for ignition delay time.

Table #3

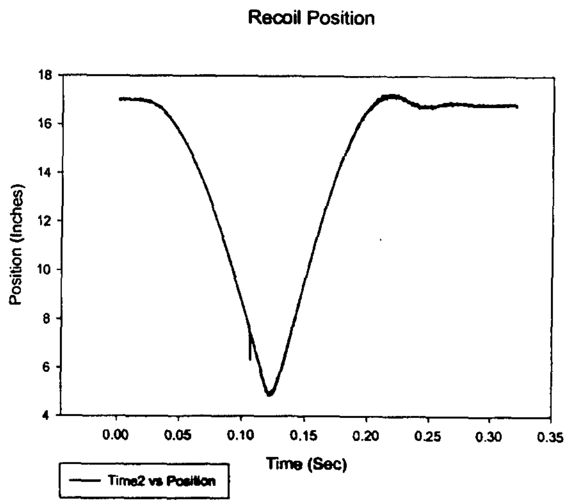
Ignition Type	Convention	ETC
Number of shots	10	7
Velocity	1192 m/s	1208 m/s
T2 Time	31.4 ms	4.69 ms
T2 Sigma	4.85 ms	0.170 ms

As seen in table 3, ETC ignition produces a much quicker ignition and even more importantly, a significant reduction in ignition delay time variation. The effects of this technology will be discussed later in this paper.

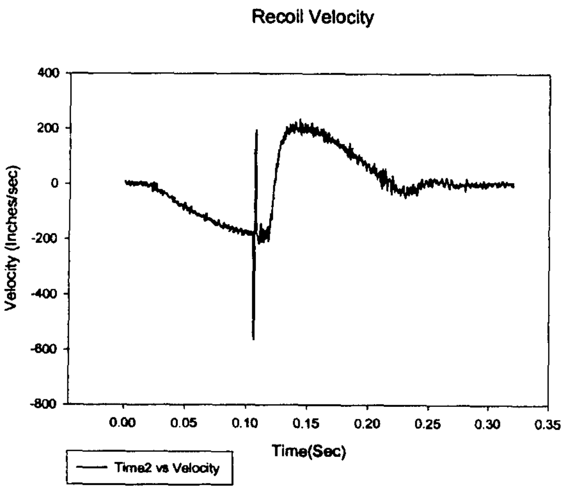
The following figures, figure 2, figure 3 and figure 4 show typical examples of some of the results attained from these tests. In figure 2 we see a characteristic Fire Out of Battery motion profile. The gun starts at about 17 inches out of battery and goes forward to about four and a half inches out of battery before it starts to recoil back. It is then successfully capture by the latching mechanism. The entire cycle takes under 200 milliseconds.

Figure 3 is a velocity profile for the same cycle. Note that the velocity before ignition and after ignition is the same, about 190 inches per second, giving a symmetric curve about the halfway point of the cycle. The spike seen in both plots at about 10 milliseconds is the EM interference of the firing current.

<u>Figure #2</u> (Recoil Position)



<u>Figure#3</u>(Recoil Velocity)



Figure#4(Recoil Force)

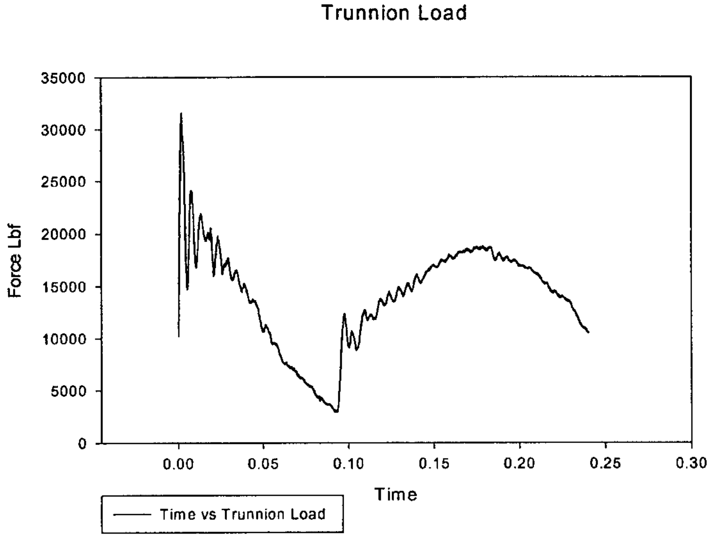
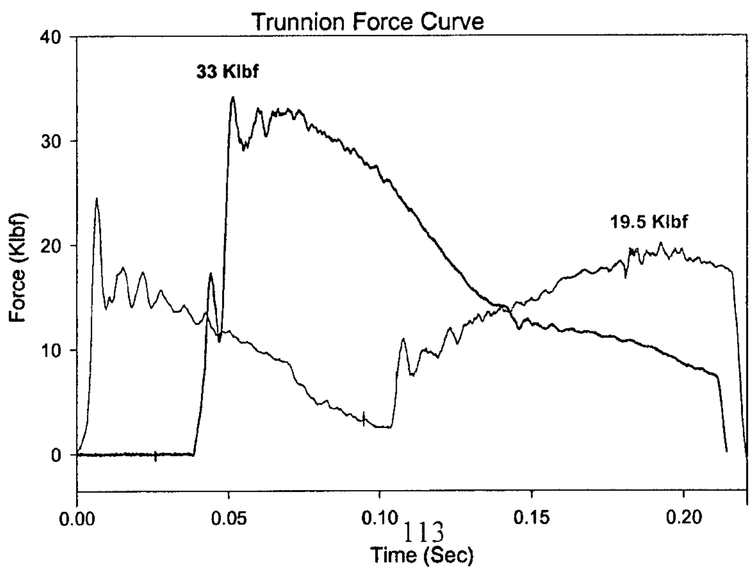


Figure 4 is recoil force time cure for a FOOB cycle. The high frequency oscillations seen in the beginning of the force curve are a result of the dynamic step response of the relatively elastic load cell that connects the gun to the mount and would not be present if the gun were attached directly to the mount. This can be easily understood if we think of this system as a spring, mass, damper system. Compared to the load cells the gun mount will be much more rigid and will have much higher damping properties. Because of the higher damping properties in the gun mount these oscillations will tend to be damped out causing the force curve to lie on the mean value of these oscillations, about 20,000 lbf for this curve.

The theoretical maximum reduction of recoil forces is 75%. In figure 5 we see a comparison of a FOOB firing vs. conventional firing with the same round (M-724). The FOOB force curve has a maximum of about 19.5 thousand lbs force (ignoring the oscillations), and the conventional curve peaks at about 33 thousand lbs force, a 40 % reduction.

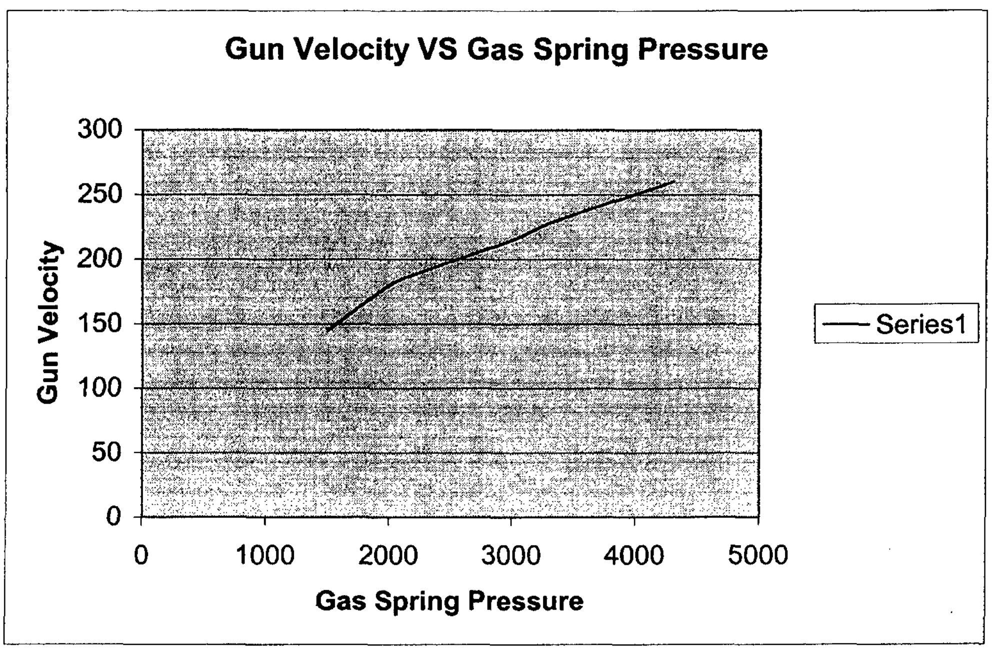
Figure#5



The first question to address is why we see only a 40% reduction, much less than the theoretical maximum reduction. We know the integral of the force time curve is the impulse imparted to the gun by the round. For a constant round impulse or area under the force time curve, we realize that a perfectly rectangular shape will give the lowest peak force for that given area. This assumption is what the maximum theoretical 75% reduction based on, and this is what we would strive for in a final FOOB design. However the gun system that was tested was not optimized and we should not expect this kind of performance from a proof of principal test system.

As we can see in figures 3 and 4 the force curve is far from rectangular due primarily to the high compression ratio of our gas springs. Another factor that contributed to the loss of performance was high levels of system damping. Although it was not possible to exclusively isolate one variable at a time, such as damping, one of the tests we performed did give some indication as to the effects of damping in the system. While performing tests to determine what velocity the gun would achieve under different gas spring pressures we noted significant damping effects. These tests were performed by charging the pneumatic actuators to a specific pressure, and then releasing the gun from its latched position and allowed to travel forward into battery. The velocity achieved after 12 inches of travel was compared for different gas spring pressures. In figure #6 we see a plot of the gun velocity (after 12 inches of travel) vs. initial gas spring pressure, for a number of tests.

Figure#6



As we can see the relation ship is not linear. The shape of the cure indicates that the system is significantly damped. This is not surprising considering this gun system was not original designed for a Fire Out Of Battery recoil configuration. The conventional design of the 105 mm M-35 cannon allows the recoiling mass to slide on a set of greased rails after the gun is fired. While this method is acceptable for conventional recoil, it presents a great deal of inefficiency for FOOB. While system damping helps during the recoiling portion a cycle it will cause system disturbances and variations that will interfere with system repeatability and predictability, which are two essential characteristics for this type of recoil system. Higher levels of uncontrolled damping will also create an unsymmetrical recoil force curve as the direction of damping forces will change to oppose the direction of gun velocity, but the direction of actuator forces will not change. This deviation from the ideal rectangular force curve will reduce efficiency, drive up recoil forces and limit the effectiveness of FOOB.

Although the recoil force reduction was much less than ideal, the reduction achieved was significant considering the system was highly unoptimized. The first goal of testing was to show reduced recoil forces, and that goal was achieved. These tests indicate that a system designed specifically for FOOB will achieve much higher reductions in recoil force. A system that incorporates even a few important design improvements such as actuators that produces a force that is closer to a constant and a reduction of system damping, perhaps through the use of bearing, will achieve reduction much closer to 75%.

Ignition Delay

Analysis of the effects on performance of ignition delay time variation was the second major goal of these tests. The way this analysis was conducted was to tune the system properly and conduct a repeatability series. By analyzing the result of these tests we established a correlation between variations in system performance and ignition delay time variation.

The first tests, conducted in Malta, were based on conventional round ignition methods with the M-724 round. The converted M-35 system used for these tests, had maximum recoil of 13 inches, after which the gun would enter a braking zone, therefore the proper gun speed needed to be achieved around 12 to 12.5 inches of travel. When the accelerating gun passed the specified position the comparator circuit would then send the firing signal. Due to ignition delay this position was somewhere before the 12 inches of maximum travel. Using a computer simulation we found the necessary gun speed, the necessary gas spring pressure to achieve that speed at the correct position, and considering average ignition delay time, the best trigger position. Using these values and about four test firings for fine-tuning, the system was properly tuned. A velocity of about 190 inches per second, a gas spring pressure of about 2,250 psi, and a trigger position of 9.5 inches gave the best performance.

Table#4 shows data collected from Malta test rounds 5 through 10. For these tests the average recoil travel was 12.263 inches, with a standard deviation of .23 inches. The average final recoil position was .346 inches past the latching or starting position, with a standard deviation of .214 inches. The average ignition delay time was 9.758 milliseconds, with a standard deviation of .956 milliseconds.

Table#4 Malta Repeatability Test ResultsM-724 Conventional Primers

Test Round	Ignition Position	Ignition Delay Time	Maximum Travel (Inches)	Final Recoil Position (Inches)	Max. Recoil Fo
#5	9.5 inches	9.25 milliseconds	12.32 inches	.05 inches	19,300 Lbf
#6	9.5 inches	8.9 milliseconds	12.05 inches	-.4 inches	19,400 Lbf
#7	9.5 inches	8.4 milliseconds	11.95 inches	-.6 inches	19,400 Lbf
#8	9.5 inches	10.5 milliseconds	12.17 inches	-.43 inches	19,400 Lbf
#9	9.5 inches	11 milliseconds	12.59 inches	-.5 inches	19,300 Lbf
#10	9.5 inches	10.5 milliseconds	12.5 inches	-.2 inches	19,065 Lbf
Average		**9.758**	**12.263**	**-0.346**	**19310**
St. Deviation		**0.956**	**0.23**	**0.214**	**118**

The second series of tests, conducted in Aberdeen, was based on conventional round ignition methods with the M-490 round. These tests used the same converted M-35 gun system with an additional muzzle brake. Using our dynamic computer simulation and a number of real test rounds to fine tune we found a gas spring charge pressure of about 3350 psi, a gun speed of 230 inches per second and an ignition position 5 inches from release position or 12 inches from battery, gave the best results. Table#5 shows results from 5 FOOB M-490 rounds fired with conventional primers.

Table#5 ATC Repeatability Test Results M-490 Conventional Primers

FOOB Firing Test Data
Test data record for live fire testing

Test date: 3/15/01 Temperature: 55° F Location: Aberdeen Proving Grounds, Barricade 3

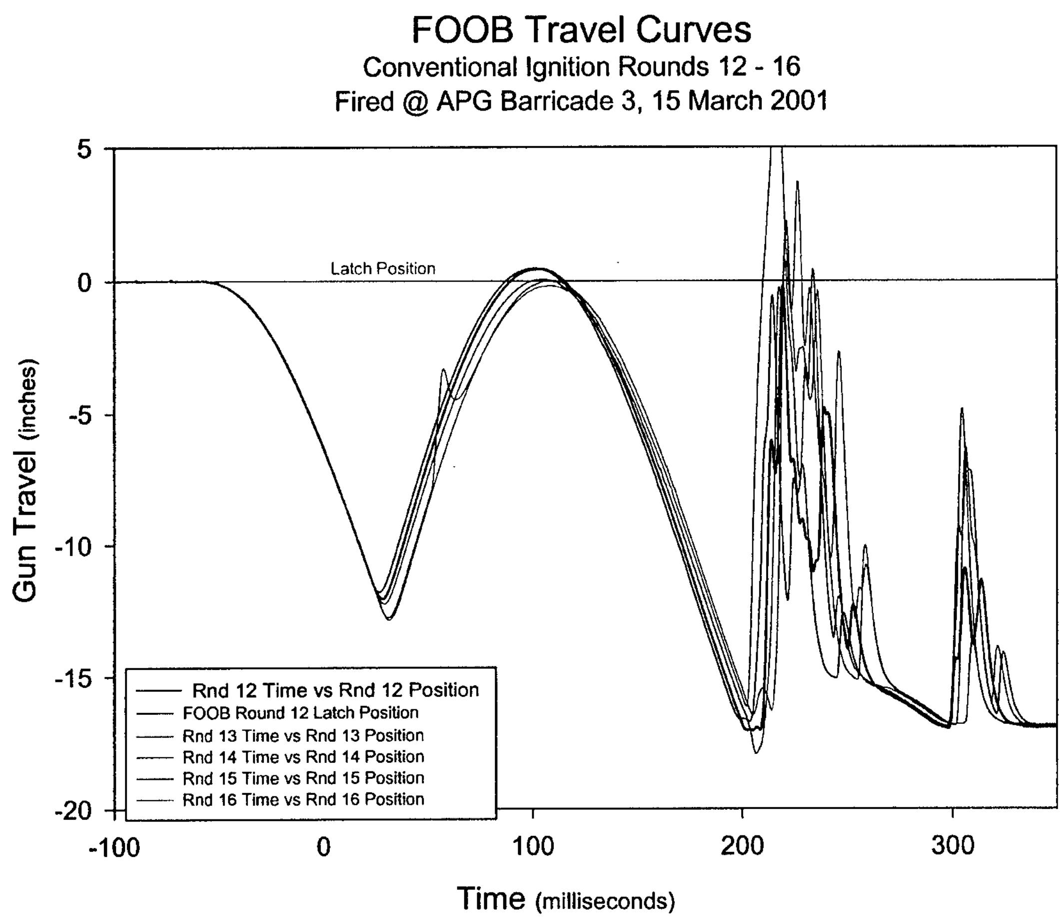
PFN Calibration	**Charge Volts:**	3.7 KV
	Voltage Offset:	
	Adjusted Firing Charge Volts:	

* Indicates data taken from Benet's Tektronix equipment

Shot # / Description	Nitrogen Pressures PSI (after pressurizing system)			Latch Position (" from battery)	Max Recoil (" from battery)	Turn Around Position (" from battery)	Gun Velocity @ 5"	Notes
	Tank		Gun Recoup					
	System	Pump						
Dry Run			500					Dry Run to verify instrumentation
Conventional FOOB Shot 1	2700	2700	3370	16.85	17.27*	4.91*	218*	1st conventional FOOB shot; Ignition-10.54"; T2=20.22mS
Conventional FOOB Shot 2	2500	2500	3370	16.77	16.75*	4.03*	225*	T2 = 23.97mS
Conventional FOOB Shot 3	2200	2250	3360	16.77	16.80*	4.66*	224*	T2 = 21.43mS
Conventional FOOB Shot 4	1950	1900	3370	16.87	17.30*	5.18*	212*	T2 = 19.09mS
Conventional FOOB Shot 5	1700	1400	3380	16.87	16.59*	4.18*	224*	T2 = 23.25mS

Due to the slower ignition delay of the M-490 we needed to send the fire signal to the gun at a position about 2.5 inches closer to the release point of the gun than we did with the M-724 rounds. For the M-490 with conventional primers the average maximum travel was about 12.25 inches or 4.592 inches from battery, with a standard deviation of .484 inches. The average ignition delay time was 21.54 milliseconds with a standard deviation of 2.034 milliseconds. Figure #7 is a superposition of five recoil travel curves, using M-490 conventional primer rounds. The travel cures in figure 7 and 8 represent a FOOB firing were the gun was not latched back to its initial position due to mechanical issues. In a final FOOB design the gun will always be captured at its release position, as seen in figure 2. Both Figures 7 and 8 contain noise introduced by the sensor if shock levels exceeded a threshold.

Figure # 7 Recoil Position VS. Time ATC M-490 Conventional Primers



The third series of tests, which was conducted in Aberdeen, used the M-490 round, and the ETC ignition methods provided by United Defense L.P.. Tuning the system for these tests involved adjusting only the ignition position, as our system was previously tuned for the M-490 round. The ignition position was moved forward to 11 inches, or 6 inches from battery due to the very short ignition delay time achieved by ETC ignition. Table#6 shows results from 5 FOOB rounds fired with ETC primers.

Table#6 ATC Repeatability Test Results M-490 ETC Primers

FOOB Firing Test Data
Test data record for live fire testing

Test date: 3/14/01 Temperature: 55° F Location: Aberdeen Proving Grounds, Barricade 3

PFN Calibration	
Charge Volts:	3.7 KV
Voltage Offset:	570 V
Adjusted Firing Charge Volts:	

* Indicates data taken from Benet's Tektronix equipmen

Shot # / Description	Nitrogen Pressures PSI (after pressurizing system) Tank System	Tank Pump	Gun Recoup	Latch Position (" from battery)	Max Recoil (" from battery)	Turn Around Position (" from battery)	Gun Velocity @ 5"	Notes
Dry Run 1	2200	1400	500	17.25				Low pressure dry run verify elec. sys. & instrumentation
Dry Run 2			500	17.28				ETC dump to calibra
FOOB / ETC Shot 1	1900	1100	3360	16.95	17.58*	3.89*	227*	FOOB/ETC w/relatcl sticking, possible be
FOOB / ETC Shot 2	2500	2800	3380	16.71	??	3.91*	227.1*	Broken fins, incom data (timing issue), velocity
FOOB / ETC Shot 3	2300	2600	3360	16.77	17.39*	3.91*	227.4*	Broken fins, 530 Mpa M/s velocity
FOOB / ETC Shot 4	2000	2300	3350	16.77	17.46*	3.90*	235.4*	Good shot with goo
FOOB / ETC Shot 5	1800	1950	[illegible]	16.77	17.48*	3.88*	227.9*	
FOOB / ETC Shot 6	1500	1400	[illegible]	16.77	17.33*	3.88*	224.9*	
FOOB / ETC Shot 7	1400	900	[illegible]	16.82	17.55*	3.88*	229.2*	

For the M-490 with ETC primers the average maximum travel was about 12.9 inches or 3.89 inches from battery, with a standard deviation of .014 inches. The average ignition delay time was 4.417 milliseconds with a standard deviation of .0822 milliseconds. Figure #8 is a superposition of five recoil travel curves, using M-490 ETC primer rounds.

Figure # 8 Recoil Position VS. Time ATC M-490 ETC Primers

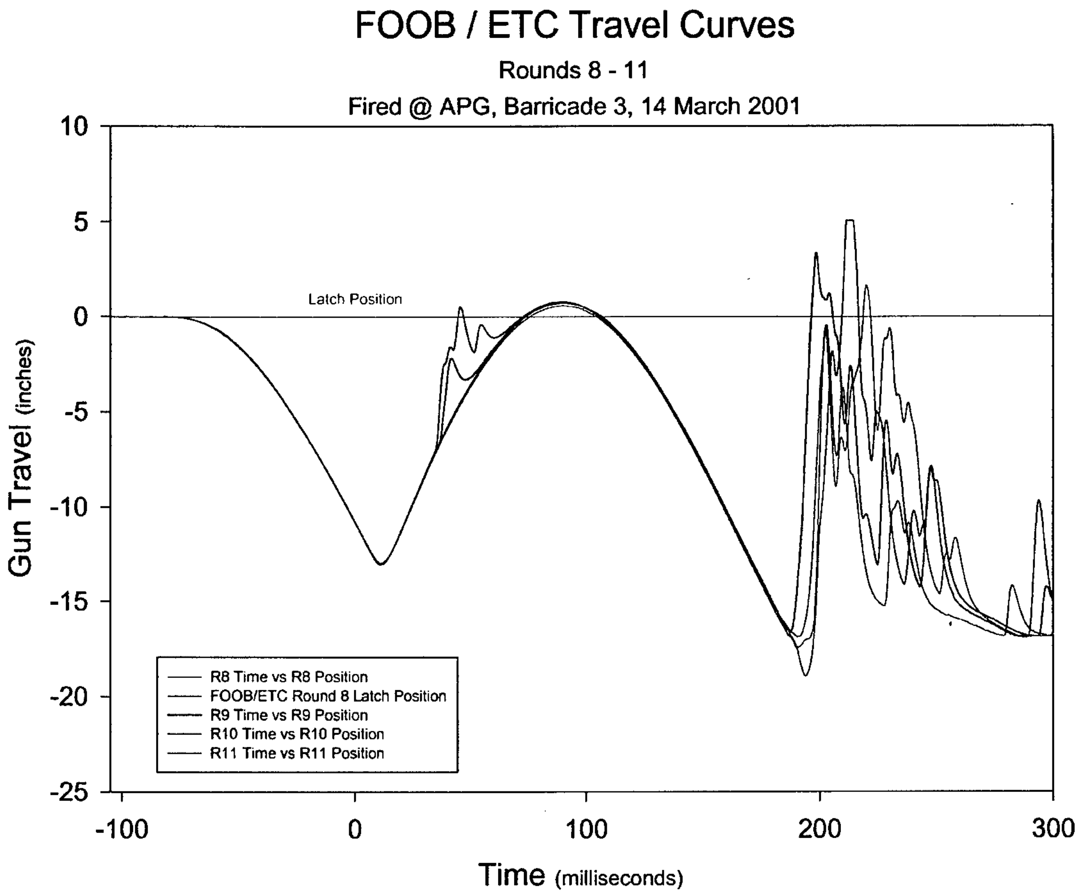


Table 7 compares results from all the tests performed. If a linear regression is performed we can see a correlation of .9274 between ignition time variation and travel length variation. This clearly shows that ignition delay variation has a direct and significant effect on system repeatability and predictability, as would be expected. These results indicate a need for precise ignition timing if a FOOB gun is to be successfully weponized.

Table#7 Test Result Summary

Test	Round	Ignition Method	Maximum Travel	St. Deviation	Ignition Delay	St. Deviation
Malta	M-724	Conventional	12.263	0.23	9.75 ms	.956 ms
ATC	M-490	Conventional	12.25	0.484	21.54	2.034
ATC	M-490	ETC	12.9	0.014	4.417	0.0822
Linear Regression	a=2.0697	b=.4853	Correlation =.92737			

Conclusion

Although the system used in these tests does not represent a design optimized for FOOB, its performance was satisfactory relative to the goals set out before testing. A recoil force reduction of 40% with an inefficient system seems to indicate that force reduction on the order of 55% to 65% should be achievable with a more careful design. The importance of a low a friction system and optimal actuators were indicated by these tests as well. A direct correlation between precise ignition timing and precise system performance was established. All of these lessons will be very useful in the effort to design a weponized FOOB system.

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