Measurement of In-Bore Set-Back Pressure on Projectile Warheads Using Hard-Wire Telemetry

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ABSTRACT

High Explosive setback has always been a matter of concern for projectile designers. In order to set inspection criteria and establish realistic laboratory sensitivity tests, it was desired to measure the actual setback pressure experienced by projectiles during launch. Described in detail is a simple inexpensive hard-wire measurement system used to obtain inbore setback pressures in a projectile filled with High Explosive. Examples of actual data obtained are shown and an analysis of the results is briefly discussed.

INTRODUCTION

In the Army’s arsenal of weapons are many high explosive filled projectiles. These projectiles are launched from guns with propelling charges that accelerate them to very high levels. The setback loads experienced by the explosives are substantial and care must to taken in the design to insure that critical levels are not exceeded. If defects are present in the explosive, then it may become more sensitive to the loading conditions. It is therefore necessary to set definite explosive inspection criteria to insure that the probability of an inbore premature is no greater than one in a million. Laboratory tests have been designed and/or proposed that supposedly measure the sensitivity of the explosive with conditions that simulate the various launch conditions.\(^{(1-2)}\) In the laboratory large samples can be inexpensively tested to give a good statistical base. However no laboratory test can exactly duplicate all the conditions found during launch.

Defects in explosive fills can be introduced at the time of loading but with proper inspection these projectiles can be rejected. However perfectly good explosive fills can become defective because of the vary nature of the material. For example, with cast explosives such as TNT or composition B the coefficient of expansion is many times greater than that of the metal projectile so that during storage a temperature cycling may occur and produce cracks or separations that were not there at the load plant. Rough
handling may also produce similar defects. The mechanical properties of the explosive may also be altered by variations in the purity of the components or particle size.

Attempts have been made to model the explosive during setback.\(^3-4\) The predictions were found to vary widely depending on the exact mechanical properties i.e. yield strength, coefficient of friction, and degree of bonding to the walls. Early measurements during launch were taken using inert simulants and a direct hard wire system.\(^5\) The results showed a setback pressure roughly one half the hydrostatic pressure (\(\rho gh\), \(\rho = \text{wt density, g = acceleration in g's, h = column heights}\).) While some properties of explosives such as density, and perhaps yield strength may be duplicated with inert simulant it may still behave quite differently than the real thing even without a chemical reaction. It was desirable therefore to test the setback load with real explosive in a real environment. Even more desirable was to compare the results of good fill to that with defects where a finite probability greater than \(10^{-6}\) of a premature existed. A testing program was developed to measure the setback pressure in a 155MM M549 projectile filled with composition B. A modest number of tests were required for each condition and always the possibility of a blow existed. It was required to have a cheap and expendable measurement system. Also since a premature would also destroy a very expensive weapon system an expendable gun (ramp gun) developed at Yuma Proving Ground was used to fire the tests.

**THE MEASUREMENT SYSTEM**

In order to measure the explosive setback pressure it was desired to go to projectile accelerations that occurred when the maximum propelling charge was used. A direct hardwire system where the sensor leads go directly out the gun tube to other instrumentation would not give results that included the peak acceleration. A method using a single wire similar to that described by Craig\(^6\) offered the possibility of obtaining data for the total inbore travel.

The M549 rocket assisted projectile was chosen as the test vehicle. Since in this type projectile the warhead is separate from the rocket motor to which the rotating band is attached, it would allow:

a. Easier stress analysis since the loads in the projectile wall are relatively small.
b. Instrumentation to be housed in the rocket motor area.
c. No intrusion into the explosive compartment which might introduce an unknown hazard.
d. A minimum of modifications.
The system shown in figure 1 consisted of:

1. The sensor - a diaphragm machined in the base of the warhead.
2. The electronics - a potted “hockey-puck” housed in the rocket motor.
3. Two external leads - one for power, one for signal, epoxied in a groove along the cylindrical portion of the warhead and epoxied to the outer wall beyond the bourlett.
4. The collector cup assembly - which housed two 9-volt alkaline batteries used to power the circuit.
5. A single bare wire that carries the signal out the gun tube - the rotating band was used as a return.

**SENSOR**

Prior to loading, the projectiles were instrumented, as shown in Figure 1. The diaphragm was nominally 1 inch (25.4mm) in diameter by 0.2 inch (5.1mm) thick. A full bridge diaphragm strain gage was bonded to the bottom of the “hole” for the diaphragm using a room temperature curing strain gage adhesive capable of withstanding the temperature encountered during the loading operation. Each electronic circuit was matched to a certain projectile. A calibration was performed by hydrostatically pressurizing each projectile with its circuitry. Table 1 shows the results of a linear curve fit of the calibration data and the peak-to-peak amplitude of the square wave generated by the electronic package.

**TABLE 1**

*Calibration Data Curve Fit Results*

(1 PSI = $6.89 \times 10^3$ Pa)

<table>
<thead>
<tr>
<th>Proj.No.</th>
<th>PSI/Volt</th>
<th>Sq.Wave P-P PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20300</td>
<td>10560</td>
</tr>
<tr>
<td>2</td>
<td>19635</td>
<td>10156</td>
</tr>
<tr>
<td>3</td>
<td>21384</td>
<td>11013</td>
</tr>
<tr>
<td>4</td>
<td>21452</td>
<td>11691</td>
</tr>
<tr>
<td>5</td>
<td>20524</td>
<td>10775</td>
</tr>
<tr>
<td>6</td>
<td>19334</td>
<td>10054</td>
</tr>
<tr>
<td>7</td>
<td>19824</td>
<td>10507</td>
</tr>
<tr>
<td>8</td>
<td>19772</td>
<td>10380</td>
</tr>
<tr>
<td>9</td>
<td>20038</td>
<td>10520</td>
</tr>
<tr>
<td>10</td>
<td>18845</td>
<td>9800</td>
</tr>
<tr>
<td>11</td>
<td>20300</td>
<td>10560</td>
</tr>
<tr>
<td>12</td>
<td>19-914</td>
<td>10355</td>
</tr>
</tbody>
</table>
CIRCUIT

The circuit, shown schematically in Figure 2, was previously tested to 15,000 g’s in a 5" air gun with spin. When activated by a battery with voltage greater than 12 volts, but less than 24 volts, it will produce a 1 KHz square wave with a nominal 0.5v peak-to-peak amplitude. This square wave is accomplished by switching a calibration resistor across one leg of the transducer circuit. This improvement over previously used circuits allows a constant evaluation of the electronics during launch, i.e., the circuit is being calibrated electrically every 0.5m sec. Power is supplied by two 9 volt alkaline batteries housed in the collector cup assembly, Figure 3. The voltage regulator part of the circuit stores enough energy to power the circuit well beyond the time from first motion to exit. Any problem with the power or amplifiers would be exhibited by a radical change in the square wave amplitude.

LOADING & ASSEMBLY

The H.E. loading was performed at ARRADCOM. While the same loading procedure was followed on all ten Comp B filled projectiles, five of the warheads were prepared by coating the inside with a silicone grease (exact composition unknown). The purpose of the grease was to eliminate adhesion to the walls in that group. All warheads were weighed before loading and after the fuze cavity drilling to give the weight of H.E. Table II gives these weights as well as the total weight at time of firing.

<table>
<thead>
<tr>
<th>Rnd #</th>
<th>Empty Wt (lbs)</th>
<th>Loaded Wt (lbs)</th>
<th>Wt.of Fill (lb)</th>
<th>As Fired Wt.(lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(lubed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>39.00</td>
<td>55.50</td>
<td>16.50</td>
<td>94.6</td>
</tr>
<tr>
<td>2</td>
<td>38.70</td>
<td>55.40</td>
<td>16.70</td>
<td>93.4</td>
</tr>
<tr>
<td>3</td>
<td>38.70</td>
<td>55.40</td>
<td>16.70</td>
<td>94.1</td>
</tr>
<tr>
<td>4</td>
<td>38.80</td>
<td>55.40</td>
<td>16.60</td>
<td>94.0</td>
</tr>
<tr>
<td>5</td>
<td>39.00</td>
<td>55.50</td>
<td>16.50</td>
<td>94.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Non-Lubed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>39.10</td>
<td>55.70</td>
<td>16.60</td>
<td>94.9</td>
</tr>
<tr>
<td>7</td>
<td>38.90</td>
<td>55.50</td>
<td>16.60</td>
<td>94.4</td>
</tr>
<tr>
<td>8</td>
<td>39.10</td>
<td>55.80</td>
<td>16.70</td>
<td>95.1</td>
</tr>
<tr>
<td>9</td>
<td>38.90</td>
<td>55.60</td>
<td>16.70</td>
<td>94.8</td>
</tr>
<tr>
<td>10</td>
<td>38.90</td>
<td>55.50</td>
<td>16.60</td>
<td>94.3</td>
</tr>
</tbody>
</table>

TABLE II
Weights of M549 - Empty, Loaded, as Fired (1 lb = 4.448n)
After loading and assembly, the projectiles were x-rayed in two orthogonal planes and examined. No significant defects were observed in any of the projectiles.

The final assembly of the projectiles after loading involved screwing on the rocket motor with all wires attached. The procedure required that first the diaphragm hole be sealed off so that an air cavity remained. In the assembly, the rocket motor was backed off a number of turns equal to the number of threads and then connected. After the motor was torqued, circuit functioning was checked. In two cases, the circuit failed because wires were torn loose. If the circuit passed, the remaining volume of the rocket motor was filled with epoxy potting through a hole just below the joint in the motor side wall. To insure that the assembly procedure did not affect the gage and circuit sensitivity, projectiles filled with water were fired as a functional performance check. Projectile No. 12 was fired at ARRADCOM, and No. 11 was fired at Yuma Proving Ground (YPG). Both showed a setback pressure equal to \( \rho gh \) within the measurement error.

In general, the signal is transmitted up a single (#22 millistrand 60/40 tinned copper) bare wire which is pulled taut in the center of the tube from the collector cup to the muzzle. The gun tube is used as a signal return. This signal, along with the output from pressure gages, timing signals, etc., are recorded on FM-Analog tape in an instrumentation van or bunker several hundred feet away. It is therefore, essential to have only the gun tube as common (electrically) or a serious noise problem from ground loops will occur.

At YPG, isolation generators were used to power all circuits, after projectile 11 was fired. At ARRADCOM, the instrumentation could not be isolated, and some small ground loop noise was present. Other noise is introduced in the signal when the collector cup wire breaks and then remakes. Experience has shown that breaks usually occur when the speed exceeds 1000 ft/sec (305 m/sec). Therefore, the break/make action happens very rapidly and will exhibit itself as high amplitude, short duration spikes on the data. Since the signal wire is on the outside of the warhead, it is possible, if the circumstances are right, that the wire could be either cut or shorted to ground. This is usually fatal to the operation and the signal will cease.

**INSTRUMENTATION & DATA ANALYSIS**

The instrumentation at YPG consisted of the following channels:

a. Setback pressure signal  
b. Breech pressure  
c. Forward chamber pressure  
d. Differential pressure
e. IRIG B timing signal
f. Firing pulse (time \( t = 0 \))

The signals were recorded on a wide-band Group I instrumentation tape recorder at 60 ips (40 KHz frequency response). Since the analog tape was to be digitized in YPG’s Ballistic Trailer electrical calibrations prior to the test were recorded in their required format. For the setback pressure signal, a special procedure had to be developed. The self-calibrating square wave could not be read by the digital program.

To overcome this, the setback channel was amplified so that the top of the wave was at zero volts and the bottom at -1.0 volts, and a dc step calibration was manually inserted on the tape during the calibration cycle (typically 10 sec before the firing pulse). A one volt signal was set equal to 10,000 Psi (68.9 M Pa) in all tests.

After digitizing, the data was plotted in a format that would allow a relatively easy analysis by hand. An example of a data set for Tube Rnd 1053 (test rnd #10) is shown in Figures 4-6. The first step in the data analysis is to reconstruct the chopped setback signal to give a “continuous curve”. This is done by adding a value equal to the peak-to-peak amplitude to the lowest portion of the signal every other 1/2 m sec. Graphically, this is done by overlaying a copy of the same data curve but translating it one square wave amplitude along the vertical axis and then tracing in the missing portions of the curve. Figure 7 shows the result plotted along with the chamber pressure. The next step is to relate either chamber or breech pressure to the acceleration of the projectile. A review of the data showed some difficulties associated with the forward chamber pressure gage, therefore, the breech pressure was used. The acceleration is given by:

\[
\text{Acceleration (G's)} = \frac{(\text{Base Pressure} - \text{Resistance Pressure}) \times \text{Area}}{\text{Projectile Weight}}
\]

Where base pressure at peak can be approximated by:

\[
\text{BASE PRESSURE} = \text{BREECH PRESS} \times \frac{1}{\left[1 + \frac{\text{CHG. WT.}}{2 \times \text{Proj. WT.}}\right]}
\]

In reality, the forward chamber gage exactly measures the base pressure for the first inch or so of travel because it is located very near the position where the base is seated. If the two traces are superimposed (or the Diff. pressure curves examined), it can be seen that there is a point where the two curves just begin to depart. Therefore, a modified base pressure approximation was used, i.e., base pressure equals breech pressure until 25% of peak pressure is reached, from 25% to 100% of peak pressure it follows a linear relation so that at full pressure the previous approximation is reached. The new base pressure relationship is shown in Figure 8. The other factor affecting the acceleration is resistance
pressure - an effective pressure that accounts for friction. In high zone firings and worn tubes, this effective pressure is considered to be relatively low. In reality, the resistance is the greatest in the first few inches of travel and then falls off to a relatively constant value. Here the effective resistance pressure was chosen to be 2000 PSI (13.78 MPa).

In order to certify the veracity of the data collected for the H.E. projectiles, the water filled test Rnd 12 fired at ARRADCOM was analyzed in detail. Figure 9 shows a copy of the raw data as recorded. The upper trace is the setback pressure signal and the lower trace the breech pressure. Figure 10 shows a plot of the setback pressure vs. breech pressure. The plot and straight line fit were obtained from a H.P. 85 linear regression curve fit routine. Figure 11 shows the plot of both \( \rho gh \) and setback pressure vs. \( g \)’s using the approximation method previously explained. The slope of \( \rho gh \) is 0.648 PSI/G (4.46 K Pa/G), while the measured response was 0.695 PSI/G (4.79 K Pa/G). The two values are within 7% of each other. Referring again to Figure 9, one can see that the signal line width is about 10% of the square wave amplitude Therefore, the measured result and the theoretical prediction are within the measurement uncertainty.

In all, 10 H.E. filled rounds were fired at YPG. Data from two test rounds were lost, caused by human error. Each of the remaining rounds was analyzed in the same manner as the water filled test Rnd # 12. Data representative of the remaining tests are shown in figures 12 and 13. Figure 14 shows the combined plot of the setback pressure vs. \( g \)’s for the lubed and non-lubed groups. Table III gives a listing of the individual slopes measured.

### TABLE III
Setback vs. Acceleration Slope

<table>
<thead>
<tr>
<th>Test Rnd</th>
<th>Tube Rnd</th>
<th>Slope PSI/G’ s(KPa/G)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1053</td>
<td>.208 (1.43)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1054</td>
<td>.182 (1.25)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1055</td>
<td>.147(1.01)</td>
<td>Non-Lubed</td>
</tr>
<tr>
<td>7</td>
<td>1056</td>
<td>Lost</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1057</td>
<td>.105(.72)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>.160(1.10)</td>
<td>Slope of all measured points</td>
</tr>
<tr>
<td>5</td>
<td>1058</td>
<td>.176(1.21)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1059</td>
<td>.334(2.30)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1060</td>
<td>Lost</td>
<td>Lubed</td>
</tr>
<tr>
<td>2</td>
<td>1061</td>
<td>.090(.62)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1062</td>
<td>.142(.98)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>.226(1.56)</td>
<td>Slope of all measured points</td>
</tr>
</tbody>
</table>
Rather than take the average of the 4 slopes, the slope using all the points in each group was calculated. It can be observed that each individual test follows a linear relationship with acceleration to the max of 10,000 G’s. Looking at the two plots of all the points in the group, it can be seen that there is a slight but not significant difference between the lubed and non-lubed groups. Each group of 4 tests has one test that is different from the rest. Eliminating each outlier would make the results look more consistent. It is, however, felt that the differences observed are real differences associated with the individuality of the fill in each projectile. In most cases, the measured setback pressure around 10,000 g’s did not exceed 2500 PSI (17.2 M Pa). In only one case (Tube Rnd 1059) did the setback pressure reach 3500 PSI (24.1 M Pa).

In similar previous tests (tube rnds 1015-1020)\(^7\) using standard Comp B with numerous cracks and voids, much higher setback pressures were observed. The poor quality rounds showed a higher relationship with acceleration .35 to .70 psi/g (2.41 to 4.8 K Pa/G), and a change of slope at measured setback pressures above 8500 PSI (58.6 M Pa). The behavior of the “poor quality” group indicates that the tighter, more densely packed the fill, the more it behaves as an elastic solid supported by the side walls, as well as the base. Theoretical predictions by S. Sadik show that setback pressure increases with decreasing yield strength and decreases with bonding to the side walls. With high quality tight fills, we have essentially a bonded fill for which Sadik calculated a compressive axial stress of 1700 Psi (11.7 M Pa) at 15,930 g’s. The poor quality fills could have been loose (unbonded) or crumbly (low yield in compression) and certainly had long vertical cracks/voids that supply stressfree surfaces in the center of the shell. All of the above will tend to increase the setback pressure at the center of the base.

**CONCLUSION**

In conclusion, it can be stated that the setback pressure from a high quality (no measurable voids or cracks) standard Composition B fill, measured at the center of the base of a M549 warhead, behaves in a linear manner with acceleration to at least 10,000 g’s. The value of this relationship may be as low as .100 Psi/G (.689 K Pa/G) up to .300 Psi/G (2.07 K Pa/G), depending on the exact nature of each individual fill. As the quality of the fill decreases, higher setback pressures are observed, and the relationship with acceleration shows changes in slope. This last series of tests can be considered as firing nearly perfectly filled projectiles. In reality, after handling and temperature cycling, perfectly filled projectiles may become similar to loose, crack laden projectiles and have a setback response approaching that obtained with poor quality fills.

In cases, such as this, where data may vary widely from test to test a substantial number of tests must be performed using expendable telemetry. The self calibrating single channel system used here worked well and cost less than $1000 each including all parts. The
system will reliably give inbore data to exit provided the signal lead from electronics to collector cup is protected.

ACKNOWLEDGEMENTS

The author wishes to thank Mr. Neil Albrecht for his invaluable time and efforts in the design and construction of the electronic circuitry and Mr. Paul Baker for his aid in the design and stress analysis of the collector cup.

REFERENCES


FIG. 1
ASSEMBLED PROJECTILE
GAIN = 100 NOM. (SEE NOTE)

FIG. 2

Universal Amplifier Circuit, Rev. 1
Constant Voltage Excitation
Continuous Switched A/Cal.

FIG. 3
COLLECTOR CUP
FIG. 4

RAW DATA PRESSURE (PSI) VS. TIME (MSEC) RND 1053.
FIG. 5
BREECH PRESSURE RND 1053
FIG. 6

CHAMBER PRESSURE RND 1053
FIG. 7
CHAMBER PRESSURE AND SETBACK OVERLAYERD RND 1053.
FIGURE 8

MODIFIED BASE PRESSURE APPROXIMATION

\[ Y = -0.19X + 1.04 \]

BASE PRESSURE % OF BREECH PRESSURE

BREECH PRESSURE % OF PEAK PRESSURE

\[
Y = \frac{\text{BASE PRESSURE}}{\text{BREECH PRESSURE AT POINT}}
\]

\[
X = \frac{\text{BREECH PRESSURE AT POINT}}{\text{BREECH PRESSURE AT PEAK}}
\]
FIGURE 10

SETBACK VS BREECH PRESSURE
RND 12 WATER FILLED

SLOPE = 0.214
SETBACK VS G'S RND 12
WATER FILLED

SLOPE = 0.695 PSI/G (4.78 KPa/G)
ρGH = 0.648 PSI/G (4.46 KPa/G)

FIGURE 11
FIGURE 12
RAW-DATA PRESSURE (PSI) VS. TIME (MSEC) RND 1059
FIGURE 13
CHAMBER PRESSURE AND SETBACK OVERLAYED RND 1059