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Technical Report ARMET-TR-18025

WEARABLE BLAST GAUGE COMPARISON TO PENCIL GAUGES IN THE U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER CULVERT TEST FACILITY

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14. ABSTRACT

Wireless pressure gauges pose an advantage to recording blast overpressure in testing scenarios. They also could provide metrics for monitoring Soldier health when exposed to blast events. Before the data recorded by these gauges can be evaluated though, it needs to be validated against accepted means of data collection. In this case, pencil gauges were used to provide the validating pressure curve and the wireless gauges were compared to that data. The wireless gauges were evaluated at three orientations to the blast origin and multiple distances away from the blast origin as well.

15. SUBJECT TERMS

Blast overpressure Wireless blast pressure Wearable blast gauge Air shock Pencil gauge Culvert Confined space

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CONTENT

FIGURES

FIGURES
(continued)

INTRODUCTION

The use of gauges to measure pressure is critical to understanding the forces acting on a structure and fluid dynamics. The standard for accurate measurement of pressure generated from blasts has been properly oriented pencil gauges. Although this type of pressure gauge is widely used, it is often difficult to obtain accurate data due to the sensitivity of proper orientation to incident waves, the noise induced from movement of lengthy wires, and gauge failure. With the introduction of wireless blast gauges, the difficulty and issues that arise due to wired gauges can be relieved.

This has led to investigations being done to evaluate new wireless wearable sensors made by the company BlackBox Biometrics (B3)—Rochester, NY that can measure and record blast overpressure and acceleration. Generation 6 sensors were mounted in a variety of locations and orientations in order to compare their readings to that of conventional pencil gauges in a confined blast environment used to simulate subterranean blast events. It was unclear if or how the wire mesh dome on the front of the sensor would affect the pressure reading, depending on the orientation of the gauge relative to the origin of the blast.

METHOD

Blast Gauges

This test used generation 6 blast gauges that were obtained from the Program Management Office of Soldier Protection Systems. Each gauge has a shelf life of approximately four years. The gauges were initialized the day before the test and set up using the structure mounted option so that they would not go to sleep. Each gauge is capable of holding 12 events worth of data before it needs to be cleared. Figure 1 is an image of the pressure gauge taken off the BlackBox biometric website. These gauges are capable of measuring pressure from 0.5 to 110 psi with a resolution of 0.5 psi. The data these gauges recorded was compared to data recorded by PCB model 137B24B gauges with a LeCroy Waverunner 104MXi oscilloscope.

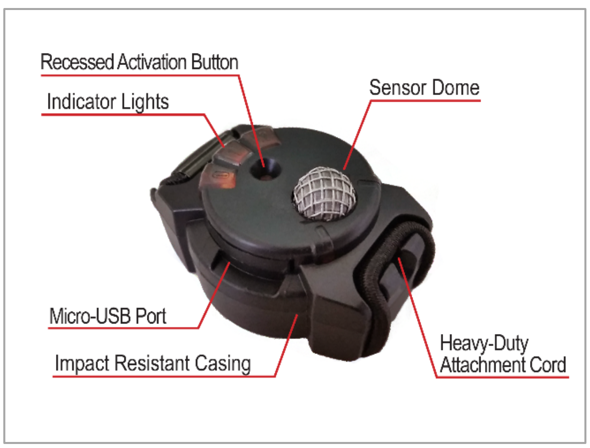
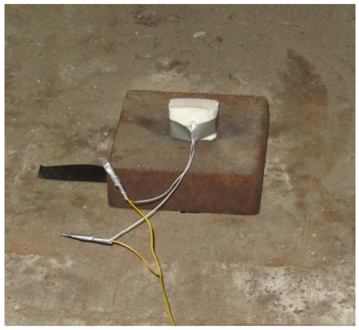


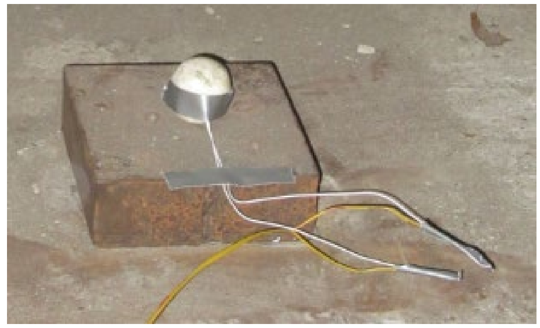
Figure 1
Diagram of the wearable blast gauge used in this work

Explosive Source

The explosive used in this experiment was C4. Nine shots were performed at The Combat Capabilities Development Command Armaments Center (CCDC AC) at Picatinny Arsenal, NJ. The shots were broken up into three sets of three shots. The first set used 1/8th of a block of C4 (0.15625 lb.) cut from the original block and still in its rectangular shape. The second set of shots used 1/8th of a block of C4 but was worked into a spherical shape. The final set used 1/16th of a block of C4 (0.078125 lb.) cut from the original block and still in its rectangular shape. For every shot, the detonator was placed in the C4 facing the closed off end of the culvert. The setup is shown in figures 2, 3, and 4.



(a)
Unworked



(b)
Worked

Figure 2
C4 test setup

Figure 3
Detonator facing the bulkhead

Figure 4
Detonator placement for each shot

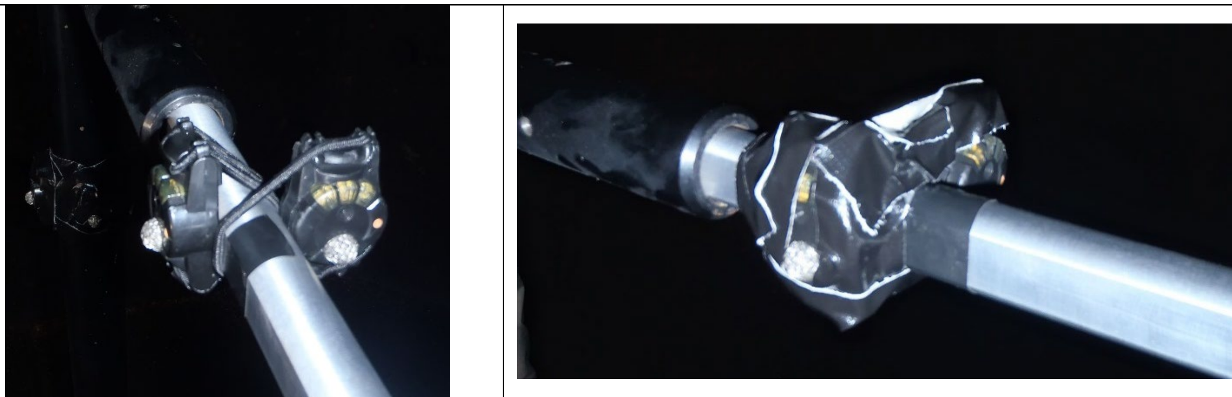
Test Stand Arrangement

The first gauge stand was positioned so that the upright post with the cluster of sensors was mounted to was 5 ft away from the C4. The following three stands were each placed against the one in front of it. The pencil gauges were set in the stands such that their sensing element was 1 foot away from the upright post. This allowed for recording pressures every foot from 4 to 11 ft away from the blast origin. The test setup is shown in figure 5.

Figure 5
Top down diagram of stand arrangement (left), gauge stand setup in culvert (middle) and view from open end of the culvert (right)

Wireless Gauge Mounting Scheme

As with the previous blast chamber test (ref.1), two wireless gauges were mounted to the pencil gauge as close to the sensing element as possible. One gauge was positioned orthogonally to the blast origin and the other was positioned transversely to the blast origin. The elastic band supplied with each gauge was used to attach it to the pencil gauge and high strength adhesive tape was also used to ensure the sensors were not blown off of the pencil gauge by the blast event. The setup is shown in figure 6.



(a) (b)

Figure 6
Two wearable sensors mounted to a pencil gauge

Each upright portion of the pencil gauge stand was also set up with three wearable gauges. As with those mounted to the pencil gauge, one was oriented with the sensing element aimed in the direction of the blast origin and another was oriented transversely to the origin of the blast. A third gauge was also mounted to the stand that was oriented at some angle between those two (approximately 45 deg). A piece of foam was cut to support the gauge at this angle and high strength adhesive tape was used to secure this gauge cluster in place as seen in figure 7. The gauges on the first stand were mounted 7 in. from the topmost surface of the stand and those on the remaining three stands were mounted 12 in. from the topmost surface of each stand, respectively. These heights allowed the gauges to be higher than the stand in front of them to minimize the influence by the stand in front of it. Since the height of each cluster was different on each stand, none of the clusters were directly in line with the blast origin.

Figure 7
Pencil gauge stand upright mounting scheme

The wearable gauges mounted to the vertical tube were approximately 12 in. away from the pencil gauge sensing elements and the distance between vertical tubes was 12 in.

Predicted Response

The Hopkinson scaling laws were used to predict the incident shock pressure. These equations were taken from Kenneth Graham's air shock class taught at CCDC AC at Picatinny Arsenal. The equation for chemical sourced air shock is given in the following equation.

$$p^0/P_a = \frac{797.7\left[1+\left(\frac{Z}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{Z}{0.048}\right)^2}\sqrt{1+\left(\frac{Z}{0.32}\right)^2}\sqrt{1+\left(\frac{Z}{1.35}\right)^2}} \quad (1)$$

Where Z is the equivalent charge weight of the C4 modified by the charge weight scaling factor (1.37) (ref. 2). This equation was used to come up with nominal incident overpressure ranging between 15.53 and 2.23 psi for the 4 to 11-ft standoff distances for 1/8th of a block of C4. This equation was also used to come up with nominal incident overpressure ranging between 9.32 and 1.60 psi for the 4 to 11-ft standoff distances for 1/16th of a block of C4.

As shown in the following plots, the Hopkinson scaling law prediction, which was used for comparison of the recorded magnitudes to the expected value, predicted lower magnitudes than recorded by the gauges. This was not a correct assumption to use since the Hopkinson scaling law prediction is made for an open air blast. As this test was performed in a confined space and the explosive was detonated on the ground, a scaling factor of 1.8 times the open air prediction was used for comparison (ref. 3)

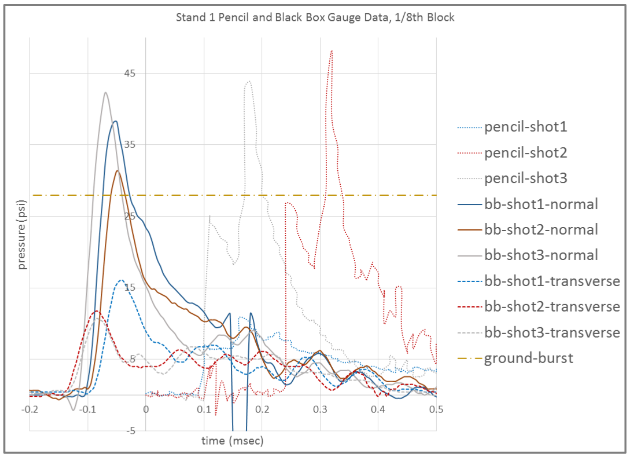
RESULTS

Shot Sequence

This test series consisted of three groups of three shots. Shots 1 to 3 were performed with 1/8th of a block of C4. The explosive was cut from a larger block and remained in its original shape. Shots 4 through 6 were also performed with 1/8th of a block of C4. However, for these three shots, the explosive was worked by hand and formed into a spherical shape. Shots 7 through 9 were performed with 1/16th of a block of C4. The explosive was cut from a larger block and remained in its original shape. During shot 1, no data was received from the pencil gauge mounted on the stand furthest from the blast origin. A second gauge wire was substituted before the second shot. During shot 2, no data was received from the pencil gauge mounted furthest from the blast origin again and this gauge was considered dead.

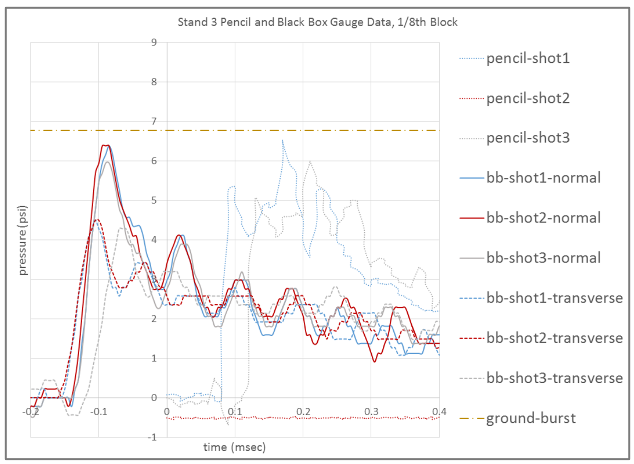
Shot Results Comparing Wearable Gauges to Pencil Gauges

The pencil gauges recorded two peaks on the rise of the first pressure spike in the majority of the shots in this test. Overall, the wearable sensors mounted normal to the origin of blast were consistent and recorded magnitudes close to the pencil gauge readings. The traces are shown in figures 8 through 10.



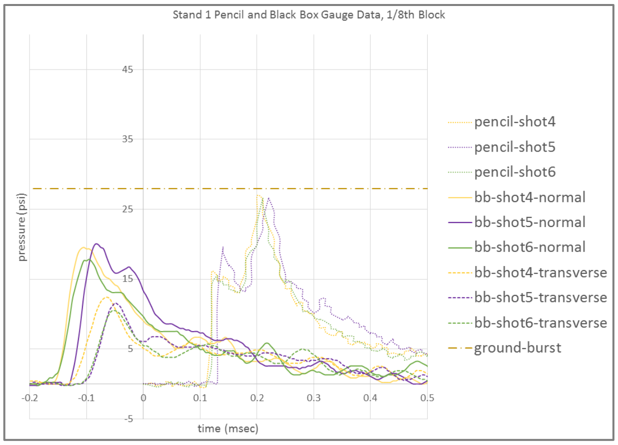
(a)
Stand 1

(b)
Stand 2

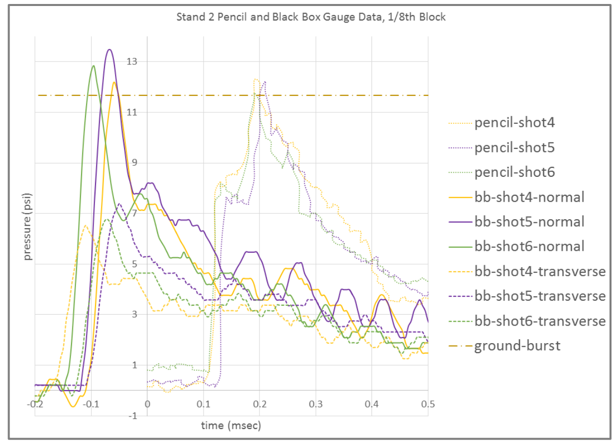


(c)
Stand 3

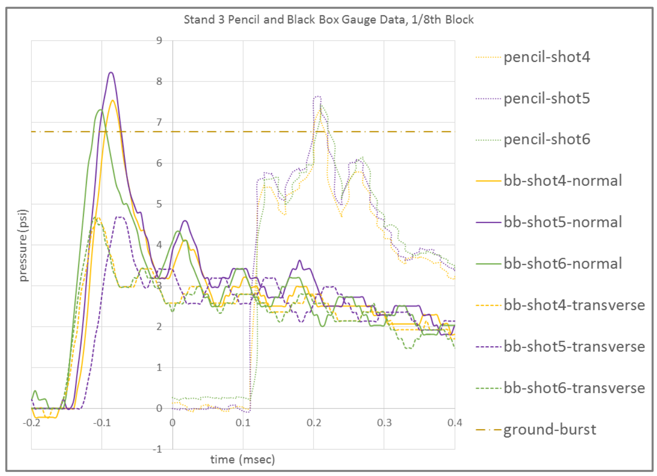
Figure 8
Pencil versus wearable gauge data for shots 1 through 3



(a)
Stand 1

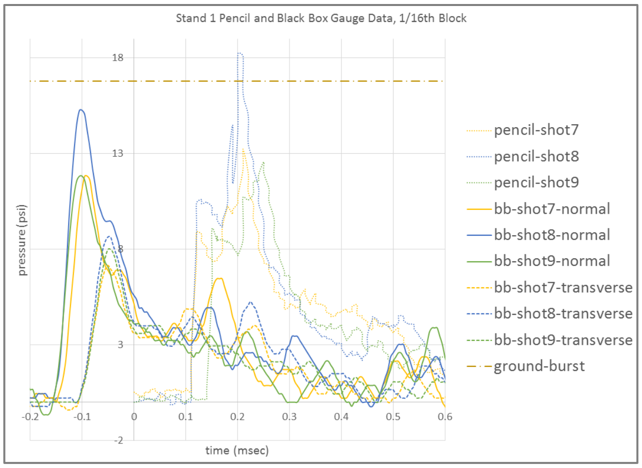


(b)
Stand 2

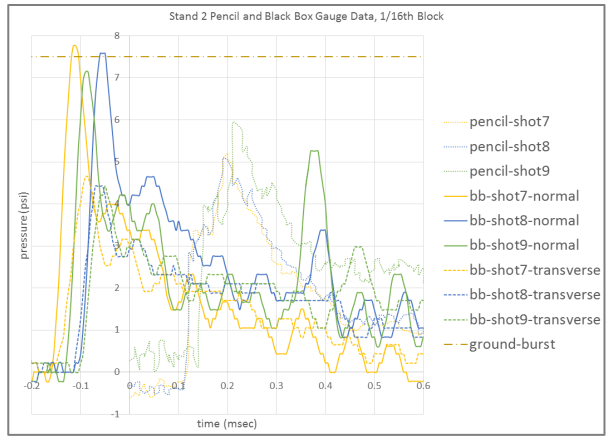


(c)
Stand 3

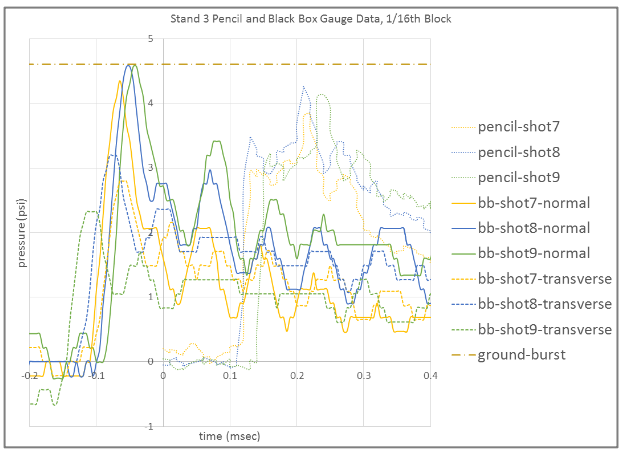
Figure 9
Pencil versus wearable gauge data for shots 4 through 6



(a)
Stand 1



(b)
Stand 2

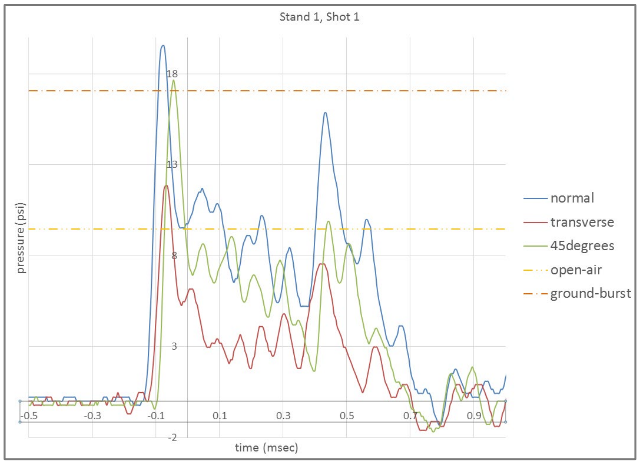


(c)
Stand 3

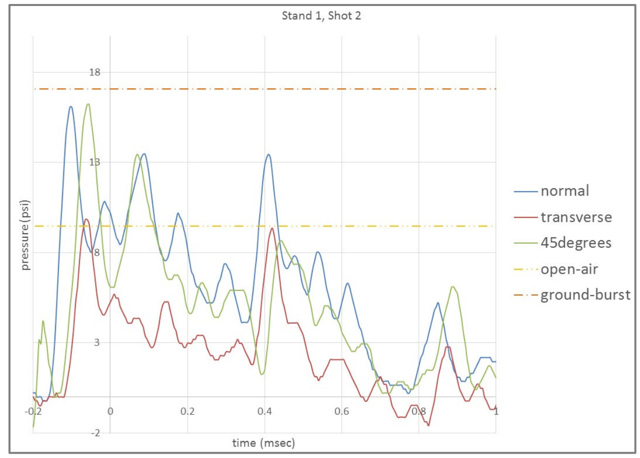
Figure 10
Pencil versus wearable gauge data for shots 7 through 9

Shot Results for Angle Sensitivity of Wearable Gauges

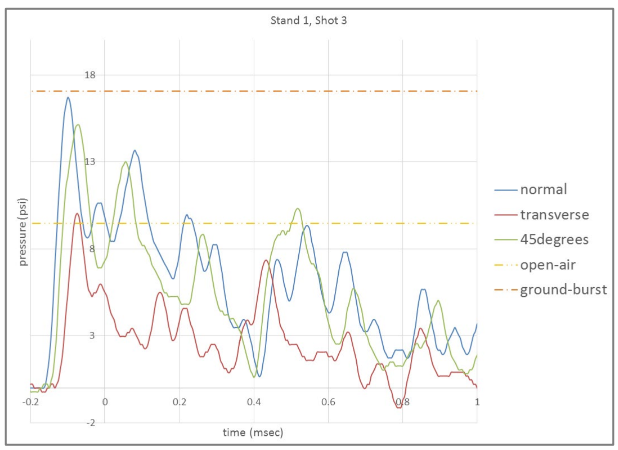
In figures 11 through 14, the blue curve is the normal sensor, the red curve is the transverse sensor, and the green curve is the angled sensor. As expected, the normal gauge read the highest magnitude, the transverse gauge read the lowest, and the angled gauge read somewhere in between. The 45-deg mounted gauge read closer to the orthogonally mounted gauge on stands 1 and 2 and closer to the transversely mounted gauge on stands 3 and 4. The traces are shown in figures 11 through 14. The second pressure peaks that produced pressures higher than the scaling laws are due to the coalescence of the reflected pressure waves from the boundaries of the confined space and can be significantly larger than the incident blast wave.



(a)
Shot 1

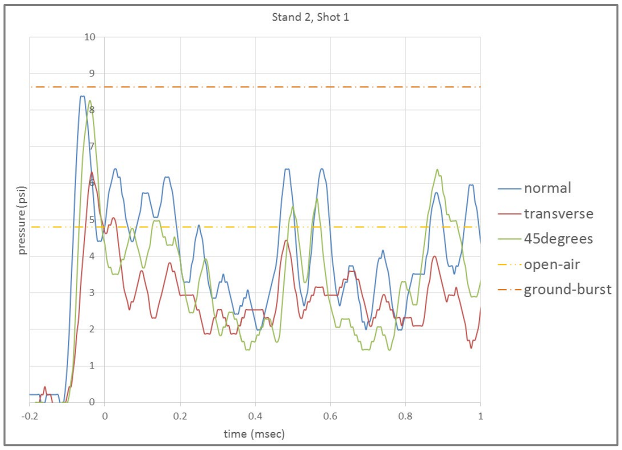


(b)
Shot 2

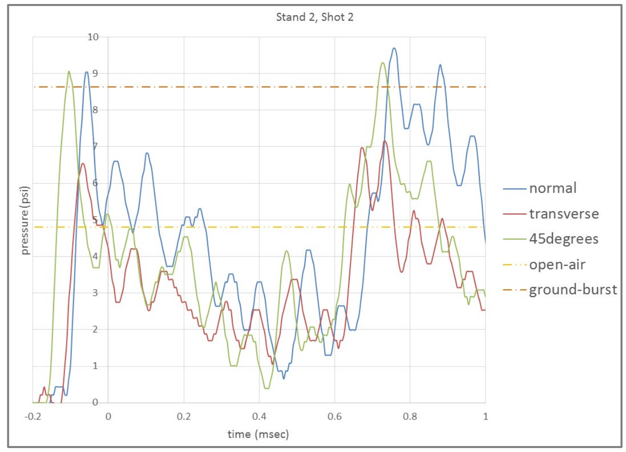


(c)
Shot 3

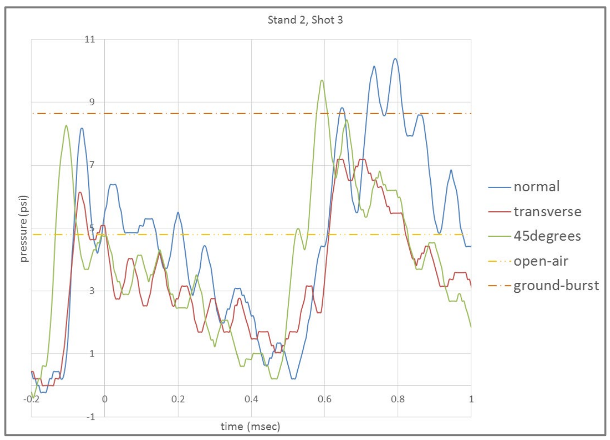
Figure 11
Angle sensitivity of wearable gauge for stand 1



(a)
Shot 1

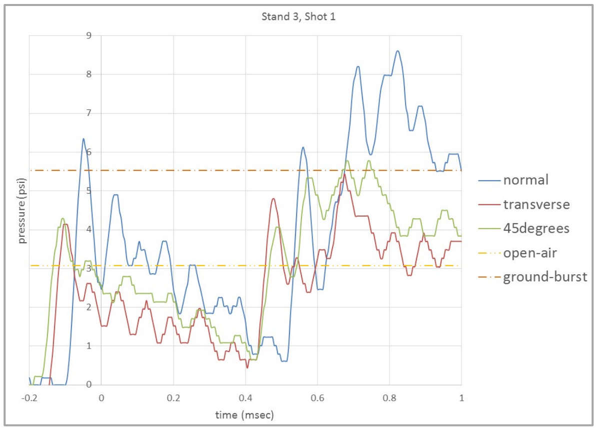


(b)
Shot 2

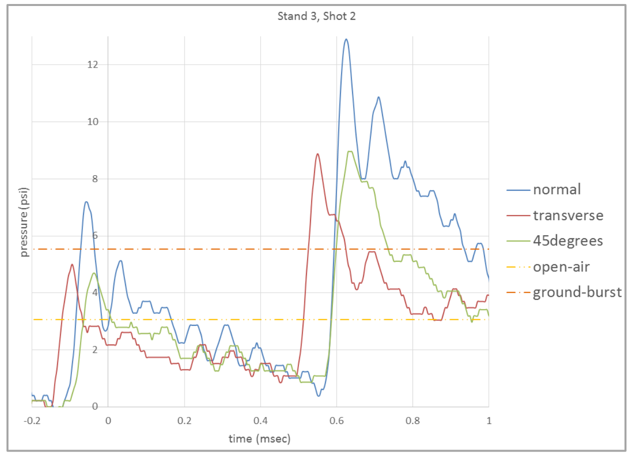


(c)
Shot 3

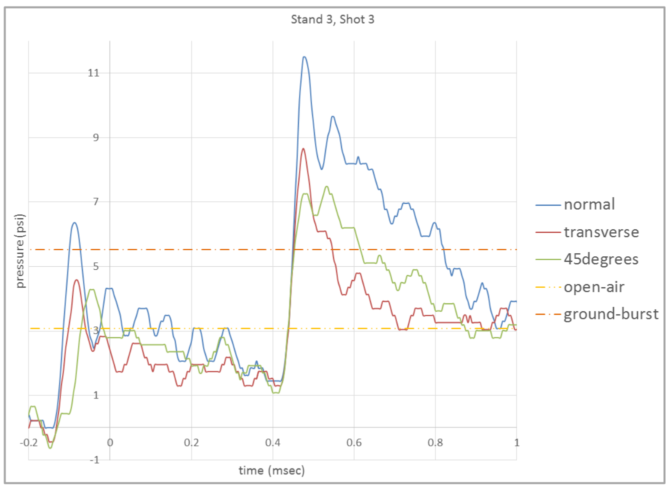
Figure 12
Angle sensitivity of wearable gauge for stand 2



(a)
Shot 1

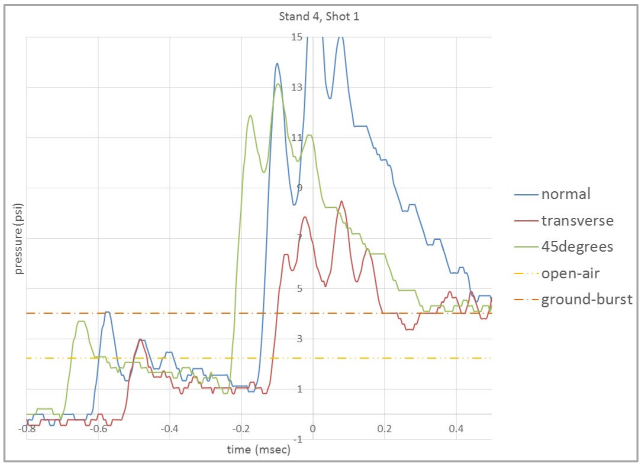


(b)
Shot 2

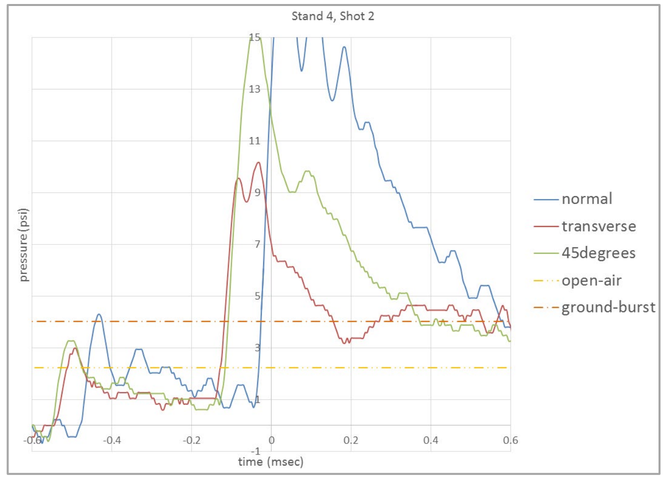


(c)
Shot 3

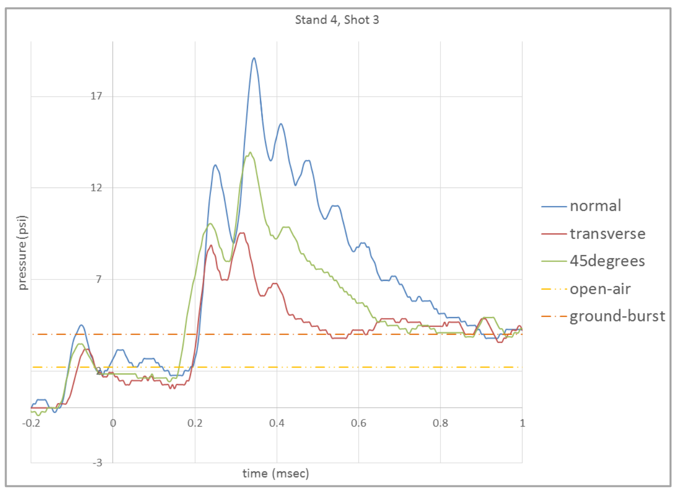
Figure 13
Angle sensitivity of wearable gauge for stand 3



(a)
Shot 1



(b)
Shot 2



(c)
Shot 3

Figure 14
Angle sensitivity of wearable gauge for stand 4

Shot Results Comparing Worked Versus Unworked C4

In figures 15 through 17, shots 1 through 3 are the unworked shots and shots 4 through 6 are the worked shots. The comparison of these shots is not straightforward. The transverse gauges read fairly consistent between all six shots. The normal gauges showed a different trend. For stand 1, the unworked C4 shows higher peak pressure. For stand 2, both worked and unworked C4 produced similar peaks. For stand 3, it was the worked C4 that showed the higher peak pressure.

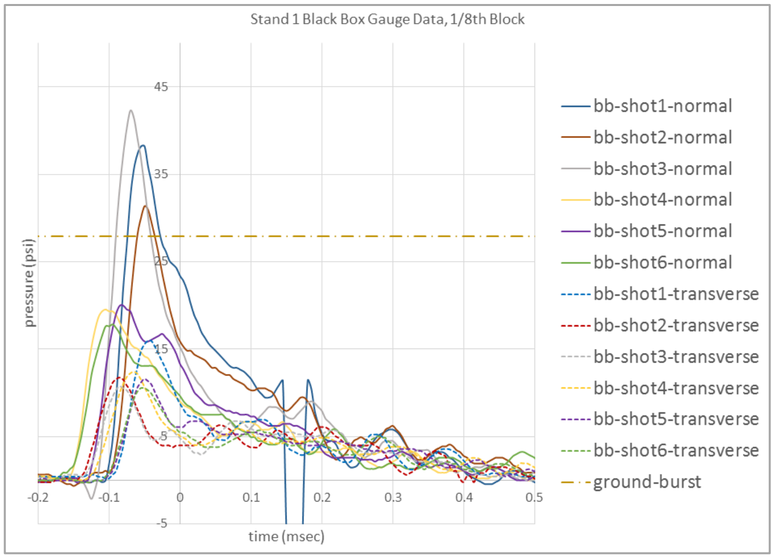


Figure 15
Worked (shots 4 through 6) versus unworked (shots 1 through 3) data for stand 1

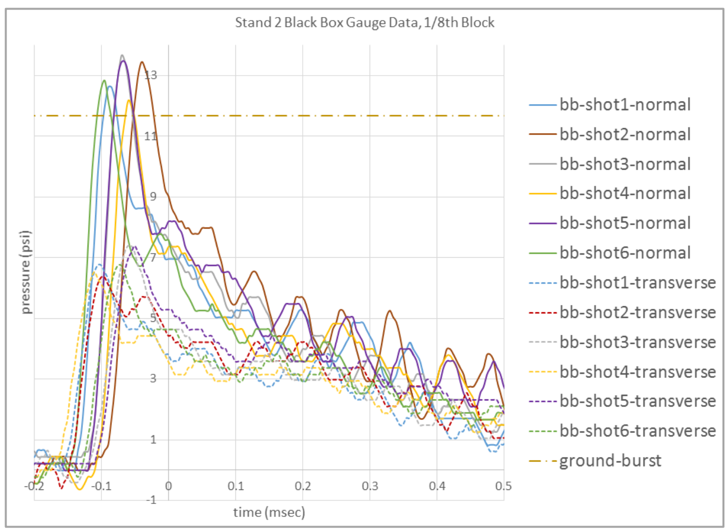


Figure 16
Worked (shots 4 through 6) versus unworked (shots 1 through 3) data for stand 2

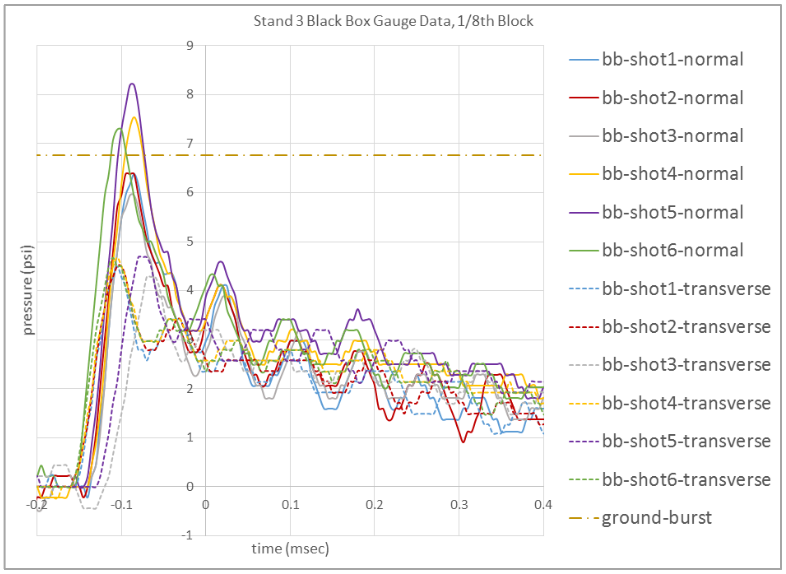


Figure 17
Worked (shots 4 through 6) versus unworked (shots 1 through 3) data for stand 3

DISCUSSION

The data from the cluster of gauges mounted near the pencil gauge sensor suggests that those mounted in a normal orientation to the blast origin are the correct way to mount these wearable gauges. The scaling law predictions, once corrected for ground burst effects, seem to confirm the dependence on gauge orientation with respect to blast origin. These observations illustrate the point that gauge orientation and blast location need to be known when evaluating recorded pressure data. While it is feasible to control the orientation of the wearable gauges in a testing environment, this sensitivity to the angle of impact raises the question of how one would interpret the data if this gauge cluster was worn in a real-life scenario where the origin of blast (in the air versus on the ground and also proximity) may not be as well documented. Due to the orientation dependence for the documentation of pressure on a subject, a minimum of five gauges should be worn with orientations facing front, back, both sides, and up.

CONCLUSIONS

The wearable gauges produced data for all of the shots performed in this test series. The same cannot be said for the pencil gauges, suggesting that the wearable gauges are more reliable/durable. In addition, the results were much more consistent with the wearable blast gauges compared to the pencil gauge readings from shot to shot. The wearable blast gauges measured the incident overpressure (not reflected) closest to the analytical prediction when the gauge was oriented orthogonally to the explosive source. The transverse gauges data was noticeably lower in magnitude. The 45-deg orientation varied in between the other two. This could have been due to the angle, which was intended to be 45 deg, varying from shot to shot since this was not tightly measured or controlled or perhaps the dynamics of the confined blast wave affected the pressure. A computational fluid dynamic analysis would be beneficial to look at the shock dynamics both along the culvert and inside the dome covering the sensor on the gauge. Future testing needs to look at modifying the gauge to reduce dependency on shock angle of attack and if these gauges are intended to be worn by Soldiers.

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3. "A Manual for the Prediction of Blast and Fragment Loading on Structures," DOE/TIC-11268, page 13.

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