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Investigating a 140 dB threshold model for peak pressure level from C4 detonations

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Far-field acoustical characterization of blast wave propagation from explosives is often carried out using relatively small shot sizes (less than 1 kg). This paper describes a series of eleven Composition C4 detonations, with shot charge mass varying from 13.6 kg to 54.4 kg (30 to 120 lbs.) that were recently measured at the Big Explosives Experimental Facility (BEEF) at the Nevada National Security Site. Pressure waveform data were recorded at up to nine different stations, ranging from 23 m to 2.7 km from the blast origin, with some angular variation. As part of examining blast overpressure decay with distance and comparing with literature, the data were analyzed from the context of human safety regulations. To provide improved guidance for BEEF personnel working distances, an empirical model equation was developed for the distance, as a function of shot size, at which the peak pressure level drops below 140 dB. A preliminary investigation into peak level variability due to wind was also conducted.

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1. BACKGROUND

This paper describes a series of eleven Composition C4 detonations, varying charge mass from 12.6 kg to 54.4 kg (30 lb. to 120 lb.) that were measured at the Big Explosives Experimental Facility (BEEF) at the Nevada National Security Site. These measurements were analyzed to better define the distance at which a given detonation's peak pressure level drops below 140 dB (re 20 μPa); i.e.: the safe distance for an observer without hearing protection. MIL-STD-1474E[1] requires "peak-pressure levels of impulsive noises less than 140 dBP, at the ear (protected or unprotected), at all personnel locations during normal operations." Figure 1 shows one of the measured shots, labeled with the level recorded on the visible microphone (located 19 m away from the blast). The peak level, 188 dB, is well above the safe level. However, observers would not be located this close to the blast, so one goal of this paper is to find the distance from the detonation at which these unsafe levels persist to provide improved guidance for BEEF personnel.

Figure 1. Image of 02/16/21 120 lb. C4 shot with measured peak level labeled (located at 19m from blast).

Another goal of this paper is to provide benchmark data for comparison against historical models. These models predict peak pressure levels for a given distance. Since any given blast may vary in size, the models use Hopkinson's scaling[2]:

$$\boldsymbol{\lambda} \approx \boldsymbol{R}/(\sqrt[3]{\boldsymbol{W}})$$

In the above formula, R is the distance in meters and W is the charge mass in kilograms of TNT. Hopkinson's scaling divides the distance by the cubic root of the detonation size, resulting in $\boldsymbol{\lambda}$. This $\boldsymbol{\lambda}$ value provides a relative 'distance' that should be consistent for any blast, regardless of size.

A variety of models have been developed to predict peak pressure levels from yield scaled distance, each with its own methodology and each developed over a given range of distances. Figure 2 shows a comparison of several example models. The historical models are taken from a 1981 report by Pater[3]. These are the Schomer[4] (derived from 5 lb. C4 detonations at 2-15 miles), Swisdak[5] (a best fit for TNT data), Reed[6] (derived from the assumed slope for nuclear and chemical weapons), and BRL[7] (an empirical model derived from 273 measurements) models. Each is plotted only over the λ range it was developed for. Also included are two predictions from the Department of Defense Explosives Safety Board (DDESB)[8] and Lorenz[9] models for 30 lb. shots, provided by Los Alamos National Laboratory. In this paper, the Schomer[4], Swisdak[5], and Reed[6] models were emphasized for comparison to measured data. Details on these models and scaling distance by yield are covered in the section on Peak Level Decay. The other models are shown in Figure 2 for comparison but were not used for additional analysis.

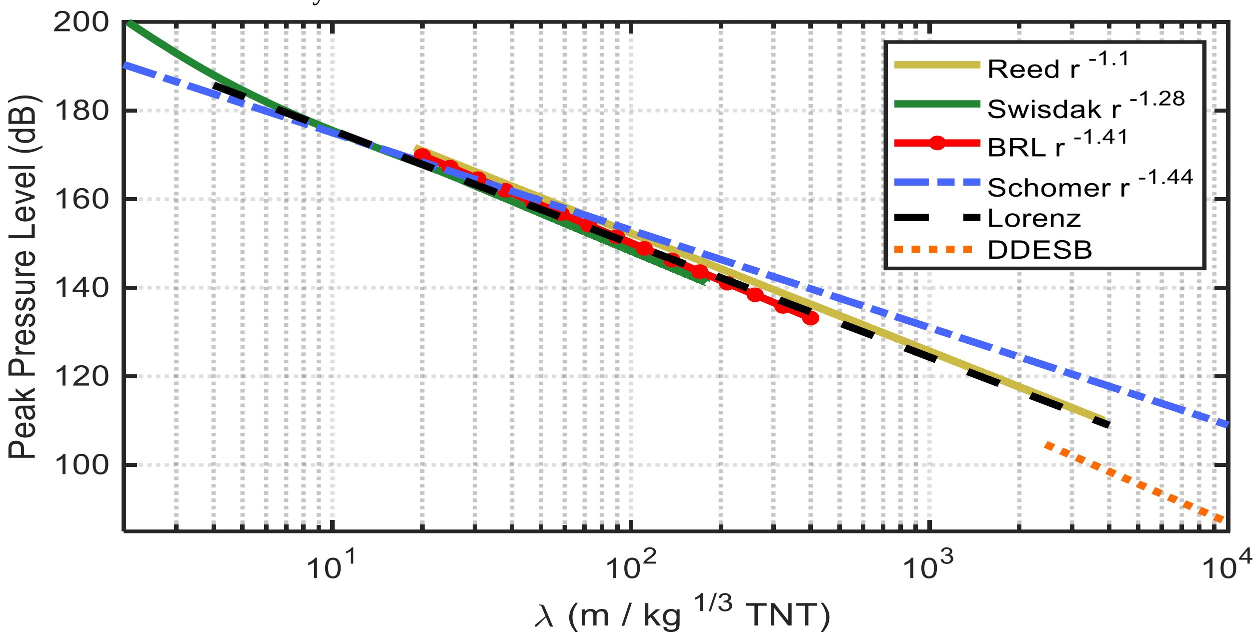

Figure 2. Comparison of shock decay models plotted over their respective ranges of development.

2. DATA COLLECTION

A. MEASUREMENT LOCATIONS

To collect data on the C4 detonations, eight data acquisition systems - Portable Units for Measuring Acoustics (PUMA) - were initially set up. These were labeled P01 to P08. The first six were placed along a radial to the east of Ground Zero (GZ), with the closest sensors 15m away from GZ and the farthest at 1km. Meanwhile P07 and P08 were placed to the north and south of ground zero, approximately the same distance as P05 (610m) and P06 (1.0km), respectively. After the first two shots, an additional manned station was added roughly along the same radial as P01 through P06, but farther away at 2.7km. This was labeled P09. P01's sensors were spread across 4 different locations near GZ, resulting in a total of 12 locations. The layout of the PUMA locations can be seen in Figure 3.

Figure 3. PUMA locations extending east from GZ with P07 and P08 to the north and south of GZ.

B. EQUIPMENT

I. PRESSURE SENSORS

The sensors at each station varied in sensitivity, according to proximity to GZ. The closest sensors (P01 and P02) were Dytran and PCB piezoresistive pressure transducers. Past 30m, various 6.35mm (¼”) diameter microphones were used (46BD, 46BE, and 46BG), all made by GRAS. When PUMA 09 was added, a 12.7mm (½”) GRAS 46AO microphone was set up. Twice each day, GRAS 42AG field calibrators were used to test each microphone. The resulting deviations in calibrated levels were less than 0.3 dB. Examples of pressure sensor stands are shown in Figure 4.

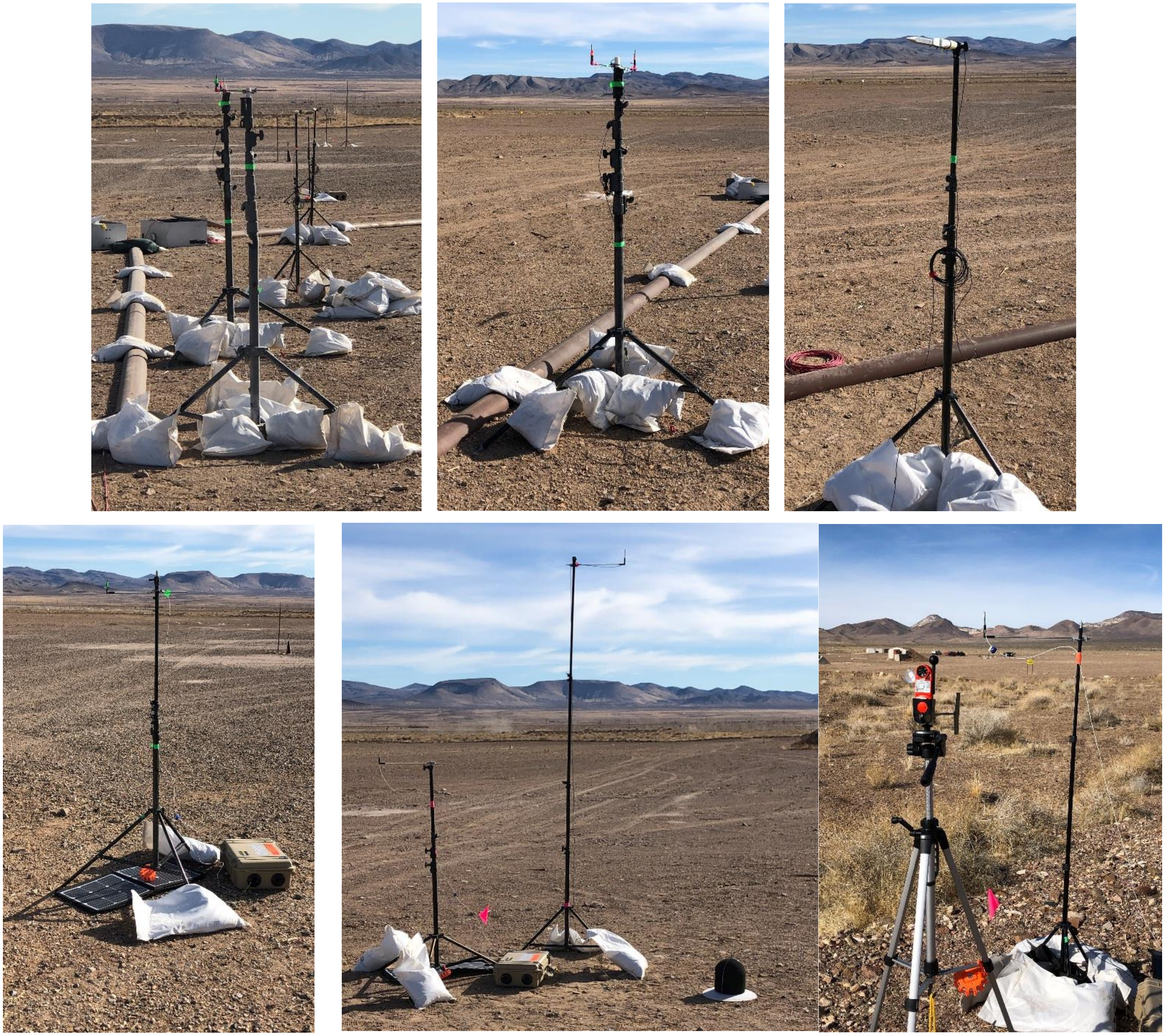

Figure 4. Top left: First few tripods looking out from GZ. Top middle: Tripod, with two sensors, at 19 m. Top right: Tripod at 30 m. Bottom left: PUMA 02 and microphone at 46 m. Bottom middle: PUMA 03 with three microphones. Bottom Right: PUMA 04 at 305 m, including weather station.

II. METEOROLOGY

PUMA 04 and PUMA 06 logged meteorological measurements using Kestrel 4000-series Bluetooth weather meters. Collected data included ambient pressure, temperature, humidity, and wind speed/direction with a temporal resolution of 1s.

III. RECORDING EQUIPMENT

The PUMAs used to measure and record data consisted of a tablet computer, a 24-bit National Instruments data acquisition chassis (NI 9171 or NI 9174) and module (NI 9232 or 9250), and a Masterclock 500 GPS (IRIG-B) time clock. These components were housed in a weatherproof case and powered by a lithium-ion battery. All stations were set to a sampling rate of 102.4 kHz. Recordings were triggered by peak sound pressure level, with a prebuffer of 60 seconds and a total recording length of 180 seconds. Note that some temporary problems (such as a loose battery cable causing the PUMA to shut down or equipment damage due to supersonic shrapnel) prevented proper recordings for some channels for some shots. All equipment was checked after each shot to ensure proper set up and address any resulting damage.

C. DETONATIONS

Using the set-up described above, measurements were made for a total of 11 detonations (or shots) of C4 explosives, though most measuring stations were not yet set up for the first shot (30 lb.). Shot size ranged from 30 lbs. to 120 lbs., with two shots each of the 30 lb. and 90 lb. size, three 120 lb. shots, and four 60 lb. shots. Details on the shot distribution are included in Figure 10 in the Appendix.

Note that the core purpose of these detonations for BEEF was to destroy weapons parts. As a result, some aspects of the shots were not set up identically – different destruction methods, different parts sizes, and different shot heights were used. The effect of the differing shot configurations is uncertain. Additionally, the closest measuring station (PUMA 01) sustained damage from debris and supersonic shrapnel, occasionally leading to data loss. These factors impose some limits on comparisons between shots. One final factor of note was the varying meteorology, with particularly strong winds (~8-10 m/s) during the last four shots (the second 30 lb. shot and all three 120 lb. shots). A preliminary analysis of the effects of wind on measured peak pressure levels can be found in Meteorological Variability.

Figure 5 shows frames from Shot 9, the first of the 120 lb. detonations. Three of the 2 m microphone tripods can be seen in the bottom-right corner of the frame. These frames show the shot was not perfectly symmetrical or hemispherical. This asymmetry was present in all shots.

Figure 5. Four frames from the 02/16/21 120 lb. C4 shot.

3. DATA AND ANALYSIS

The recorded data was trimmed to 5 seconds, starting 0.5 seconds before the trigger and ending 4.5 seconds after. The resulting files were plotted, and the peak pressure of each waveform was found. An example can be seen in Figure 6.

The waveforms seen in Figure 6 come from Shot 8 (a 30 lb. shot). All are taken from the main radial propagation line and range from 19 m to 2680 m. These examples are demonstrative of several notable features. First, a ballistic shock is visible preceding the main shock in the waveform at 30 m, likely due to a supersonic projectile. The waveforms also show the shape of the shock as it propagates. In particular, the steepness of the shock has notably declined by 610 m, and the shape was already rounded by 305 m. Of particular note is the 1000 m waveform which shows a peak level of only 140.4 dB, nearly below the desired threshold. Finally, the latter recordings – 1000 m and 2680 m – begin to show a secondary minor impulse at the start of each waveform (around .02 s). Looking at other waveforms at the same distance, only some present the secondary impulse, implying its source may be meteorological.

A. PEAK LEVEL DECAY

The first goal of this paper is to determine a distance beyond which the peak pressure level is below 140 dB. Since the detonations varied in size (and many other sizes are used at the BEEF site), the yields need to be scaled to a uniform value. As with the historical models, this was done through Hopkinson's scaling:

$$\boldsymbol{\lambda} \approx \boldsymbol{R} / (\sqrt[3]{\boldsymbol{UEW}})$$

This formula appears slightly different from the earlier version of Hopkinson's scaling. R still represents the distance in meters, but U – a conversion factor for units - and E – a conversion factor for TNT equivalence - have been added to account for differing types of detonations. This modified version of the formula provides the same $\boldsymbol{\lambda}$ without needing to individually convert each shot size into equivalent kg of TNT. In this case, U is the ratio between lb. and kg (0.454) and E is the TNT equivalence of C4 (1.37). Combining these terms and simplifying the equation a bit, we get a new formula:

$$\boldsymbol{\lambda} \approx \boldsymbol{R} / (\mathbf{0.854}\sqrt[3]{\boldsymbol{W}})$$

The peak pressure level data, plotted as a function of $\boldsymbol{\lambda}$, can be seen in Figure 7. The data are relatively close for some scaled distances ($7 < \boldsymbol{\lambda} < 70$), with deviations of less than 4 dB. For any values outside this range, however, discrepancies arise (up to ~10 dB). For peak pressure levels closer than $\boldsymbol{\lambda} = 7$, this is likely due to asymmetry in the near field, as seen in Figure 5. Beyond $\boldsymbol{\lambda} = 70$ (~200-300 m for these shot sizes), the variation is likely due to terrain and meteorological effects.

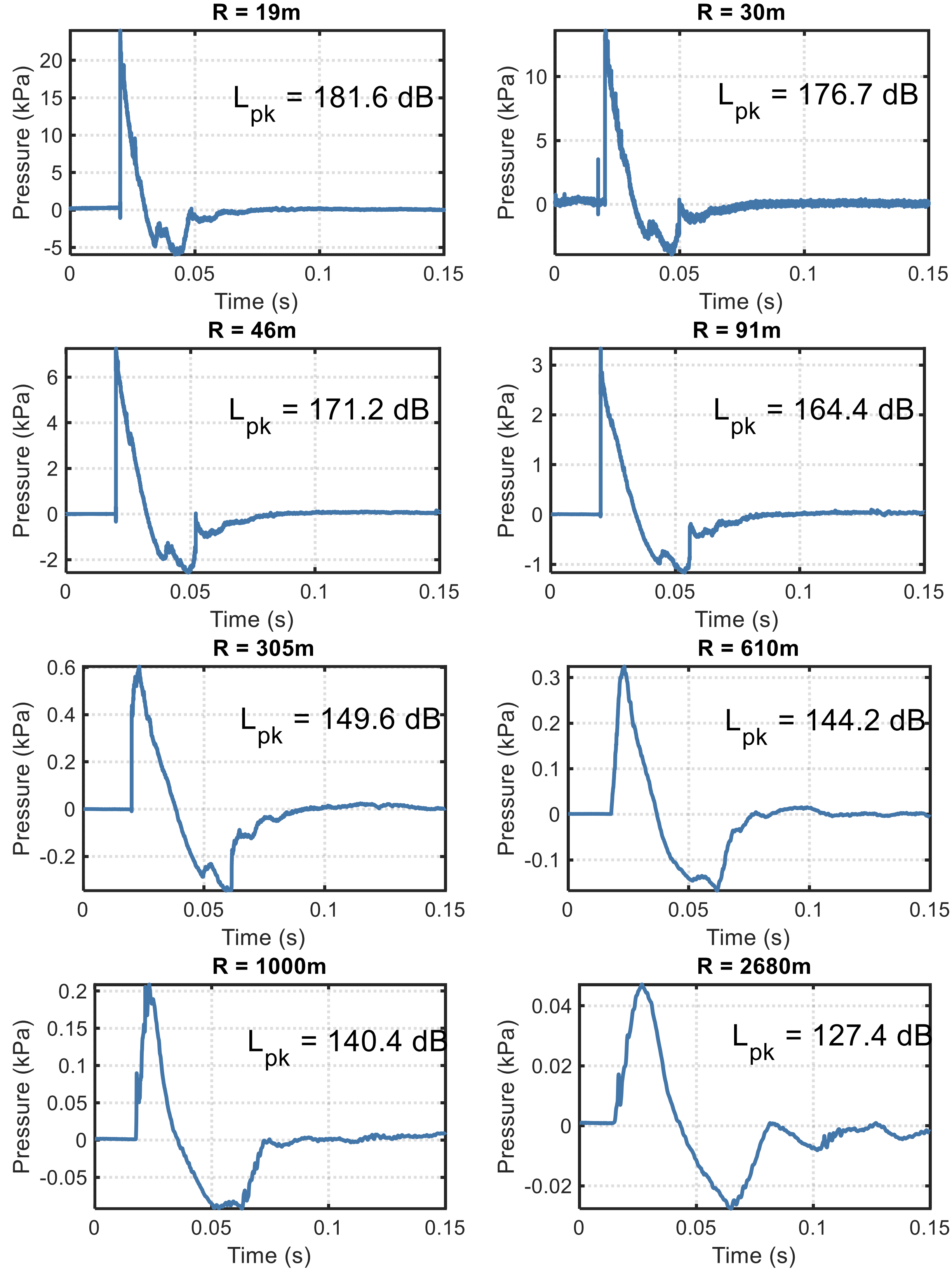

Figure 6. Representative waveforms from Shot 8, which reaches 140 dB at 1 km.

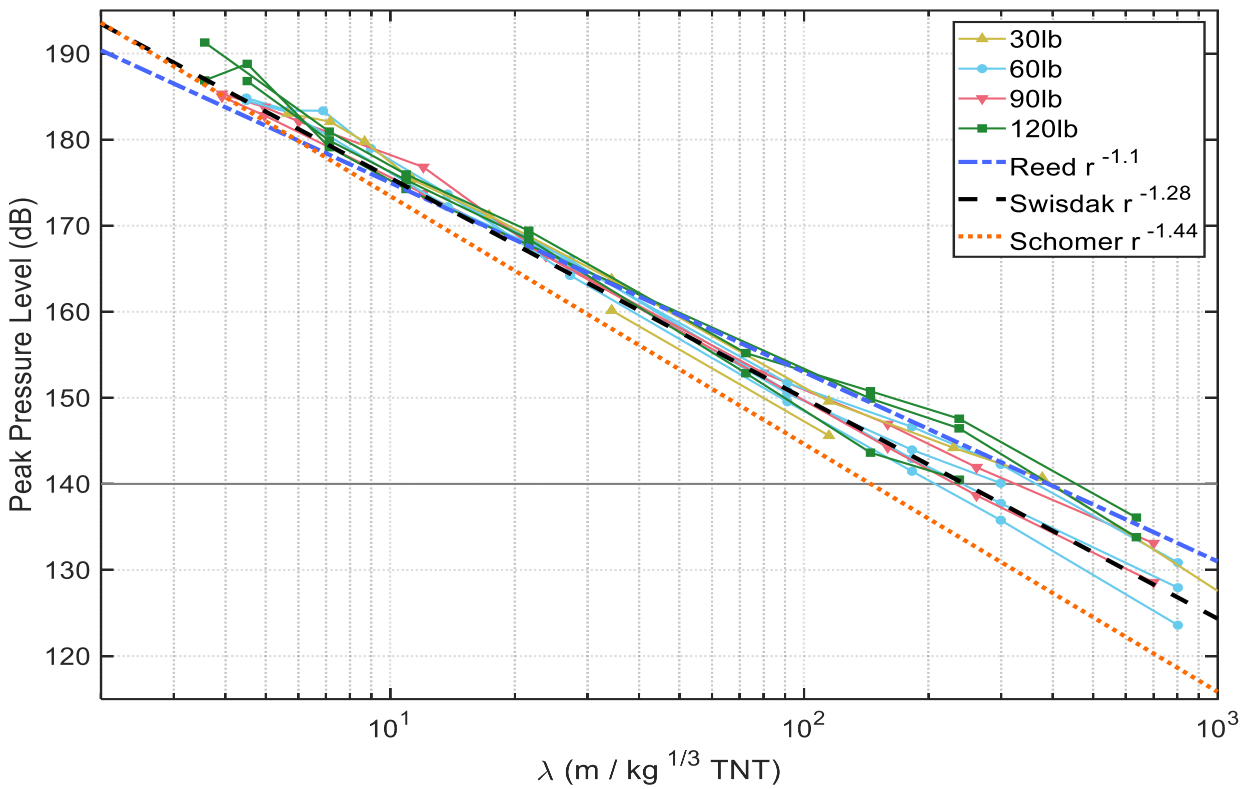

Figure 7. Peak pressure level decay for C4 explosions as a function of yield-scaled normalized distance.

Also included in the above Figure 7 are the aforementioned Schomer[4], Swisdak[5], and Reed[6] models from the Pater[3] report. Each of these models uses the same basic equation for peak pressure as a function of scaled distance: $p_{pk} = C\boldsymbol{\lambda}^{-\boldsymbol{\alpha}}$. In each model, $\boldsymbol{\alpha}$ is a radial decay rate, while C is simply an empirical constant from fitting data. Purely spherical spreading would have a value of $\boldsymbol{\alpha} = -1$ (20 dB/decade), while Rogers[10] and Wright[11] indicate far-field decay of a weak shock displays $\boldsymbol{\alpha} = -1.13$ and $\boldsymbol{\alpha} = -1.14$, respectively. The respective C and $\boldsymbol{\alpha}$ values for each model are listed in Figure 7.

As mentioned, the Reed[6] model has the same decay rate as that assumed for nuclear and chemical weapons explosions in ANSI S2.20-1983[12], which essentially indicates that these blast waves are expected to remain as weak shocks far from the source. Some of the shots approximate the same slope. The Schomer[4] model appears to underestimate most observed data. Since the model is based on data from 5 lb. C4 detonations collected 2 - 15 miles from the explosion, the more rapid decay seen here likely models "old age" shock behavior, where the shock front thickens due to atmospheric absorptive losses being greater than the additional nonlinear propagation effects. The overall predicted levels are too low, but a few detonations have begun to approximate the 28.8 dB/decade roll off seen in this model.

Ultimately, however, the intermediate Swisdak[5] model (-25.6 dB/decade) seems to better approximate the general trend of the data over the measured range. Since this model is a best fit of experimental data from TNT detonations, the observed similarity should be expected.

B. A SAFE THRESHOLD FOR C4

Figure 7 shows the data fit crosses the 140 dB threshold at 210 < $\boldsymbol{\lambda}$ < 450. Since the purpose of this investigation is to find a distance that is sure to be safe, the 450 upper bound is more appropriate. This results in the following determination:

$$\boldsymbol{\lambda} \approx \mathbf{450}\, \boldsymbol{m} \,/\, \sqrt[3]{\boldsymbol{kg\ TNT}}$$

For the shot sizes examined here, this translates to a range of 1.2 km for 30 lb. shots to 1.9 km for 120 lb. shots. BEEF personnel work out of trailers located ~2.7 km away from GZ, which translates to ~350 lb. as the maximum safe shot size (without hearing protection) using the conservative upper limit. However, much of the data appears to agree with the Swisdak[5] model, which corresponds to a bound of $\boldsymbol{\lambda} \approx 240$. This would translate to a maximum shot size of 1000 lbs. Thus, it becomes important to understand the variations in the far-field peak levels, and particularly how meteorology might affect those variations.

IV. METEOROLOGICAL VARIABILITY

While a detailed analysis of meteorological effects is beyond the scope of this investigation, some key factors can be established. One particular factor identified is the wind direction during each shot. To better understand the effects of wind, measurement stations at similar distances - but different directions - are compared.

Two of the PUMAs, P08 and P06 were equidistant from GZ (1 km), but P05 was slightly closer (570 m) than P07 (610 m). To compensate for this, the measured peak level decays along the main radial are used for each shot to slightly adjust the level measured at P05.With each pair of stations, the measured value at the station along the main line (to the East) is subtracted from the diverging station (to the North or South). These differences are then labeled with the prevailing wind direction during the shot, as shown in Figure 8:

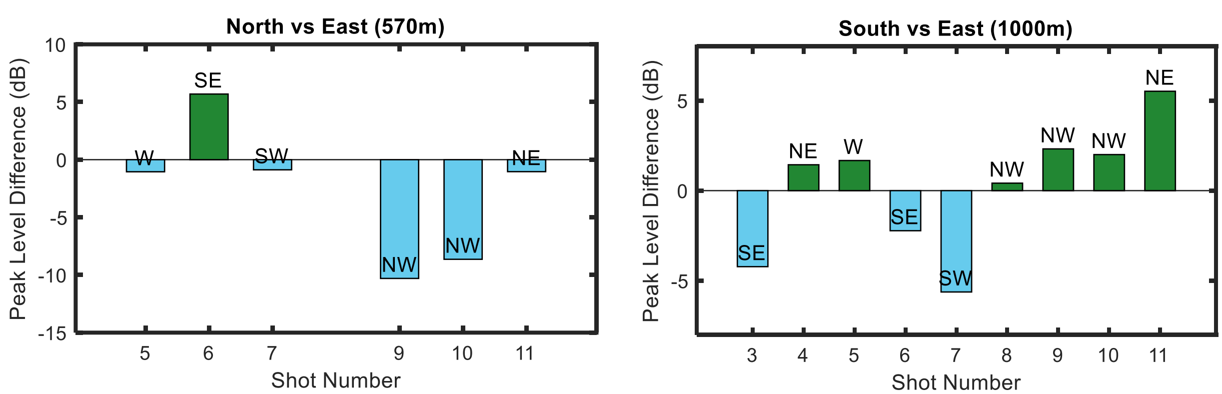

Figure 8. Comparison of PUMA 07 (relative to adjusted PUMA 05) and PUMA 08 (relative to PUMA 06).

Note that the wind direction refers to the direction from which the wind is blowing. Figure 8 only shows the Cardinal and Intermediate directions to provide a brief, qualitative comparison. Whenever the prevailing wind is at least partially northern, P07 decreases relative to the main array and P08 shows an increase. The converse is also true. Said increases/decreases are often significant (3-10 dB).

Additionally, Figure 9 shows a comparison of just the 120 lb. shots without scaling the distance. Shots 9 and 10 both show fairly consistent agreement, but at the 1 km mark there is a ~8 dB difference between either and Shot 11. All three shots had northern winds, but for shots 9 and 10 it came from the northwest (partially along the main line) while for shot 11 it came from the northeast (partially against the main line). This only provides qualitative analysis, but it helps to explain the greater differences seen after $\boldsymbol{\lambda} \approx 70$.

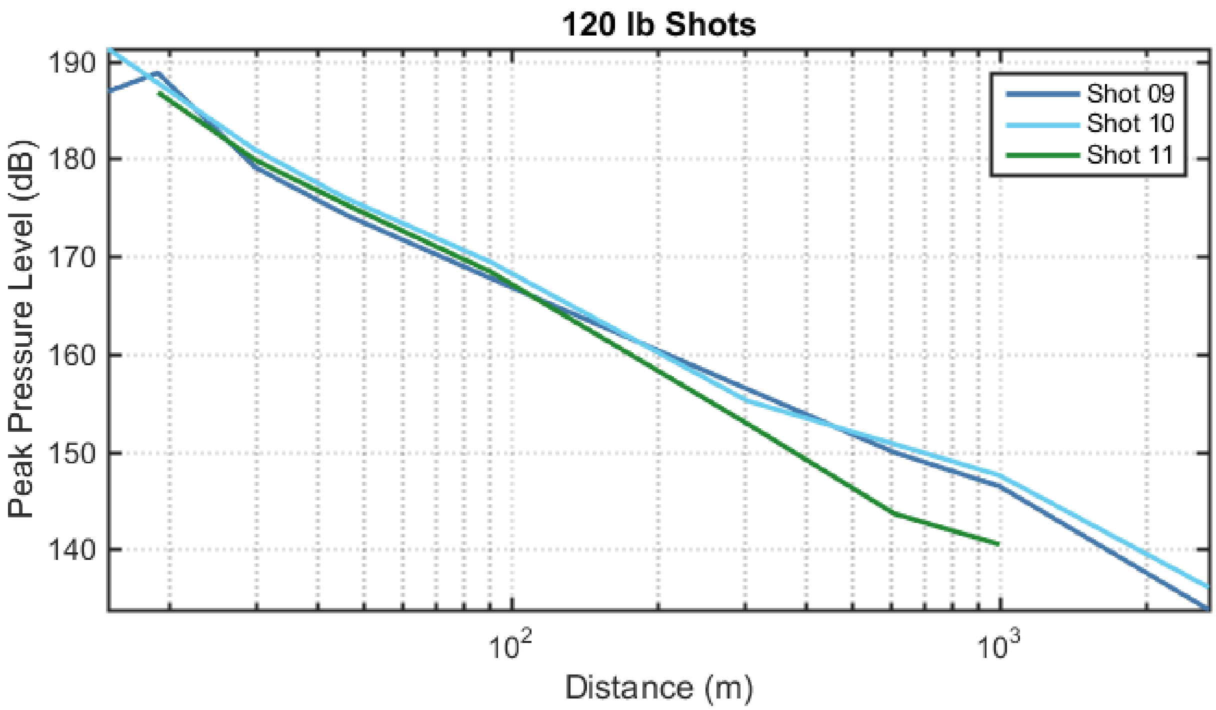

Figure 9. Peak pressure level decay for 120 lb. C4 explosions as a function of distance

4. CONCLUSION AND OUTLOOK

This series of measurements succeeded in identifying a threshold for scaled distance beyond which peak levels drop below 140 dB: $450\ m\ /\ \sqrt[3]{kg\ TNT}$. Other conclusions are more tentative and qualitative. Existing models were shown to be close to measured data (notably the Reed[6] and Swisdak[5] models) but could be improved and refined with additional data. Additionally, some key questions that could improve physics-based, data-driven models are:

- Given the shapes of the measured waveforms over a significant portion of the range, why does the blast decay faster than ideal shock behavior, with its $r^{-1.1}$ decay rate? (This has been seen clearly in smaller yield gaseous explosions at BYU[13,14]). Is it because of ground interactions or some other physical cause? Although the faster decay in the literature appears to be well established, the physical reasons are unclear and creates a discrepancy between the ANSI standard that assumes weak-shock decay, and other literature.
- What impact did the variations in shot set up have on the measurements?
- What is the quantitative, statistical impact of different wind conditions? Can it be modeled using 2D raytracing?
- Aside from peak level, how are other energy measures (e.g., exposure levels) impacted by shot size, distance, and meteorology?

As part of future work, a new model, with its own C and α values, could be created to better fit the measured data, though additional data would be needed.

ACKNOWLEDGMENT

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APPENDIX A

Figure 10 shows an array of the measured peak pressure levels for each shot at each microphone. The missing channel numbers correspond to the time clocks, which of course have no measured pressure levels. The shown channels are color-coded green, yellow, red, and gray. Gray cells mark channels that were not set up for a particular shot; red cells mark those with corrupted and unusable data, or where data did not properly record at all; yellow cells mark those that still recorded, but had some corruption or other artifacts in the data, making it difficult to extract reliable peak pressure levels; and green cells mark those that had no signs of corruption or other suspicious artifacts. The shot number and the size of each shot is listed across the top, alongside the shot number, and the associated PUMA station are listed along the righthand side.

CH	1-30 lb.	2-60 lb.	3-60 lb.	4-90 lb.	5-90 lb.	6-60 lb.	7-60 lb.	8-30 lb.	9-120 lb.	10-120 lb.	11-120lb.	PUMA #
0		184.8 dB		185.3 dB	185.0 dB		184.5 dB	183.0 dB	186.9 dB	191.3 dB		1
1		183.6 dB		184.4 dB	183.4 dB		183.2 dB	182.1 dB	188.8 dB		186.8 dB	1
2		183.2 dB		183.2 dB	182.3 dB		183.2 dB	174.1 dB	179.1 dB		181.6 dB	1
3		183.4 dB		182.1 dB				179.8 dB				1
4		179.0 dB						176.7 dB				1
6		173.7 dB	173.4 dB	176.8 dB	173.8 dB	173.6 dB	172.2 dB	175.3 dB	179.1 dB	180.9 dB	178.2 dB	2
7								171.2 dB	174.3 dB	176.0 dB	175.3 dB	2
9	159.5 dB	165.8 dB	165.6 dB	166.9 dB	166.5 dB	164.1 dB	164.9 dB	163.0 dB	166.8 dB	168.1 dB	168.1 dB	3
10			166.3 dB	166.1 dB	166.7 dB	164.7 dB	166.6 dB	164.4 dB	167.7 dB		169.0 dB	3
11	160.8 dB	164.8 dB	166.1 dB	166.5 dB	166.3 dB	163.9 dB	165.8 dB	163.9 dB	168.7 dB		168.2 dB	3
13	145.6 dB	150.5 dB	150.8 dB		152.9 dB	149.5 dB	151.7 dB	149.6 dB		155.2 dB	152.9 dB	4
15		144.0 dB	142.9 dB	144.3 dB	147.0 dB	141.5 dB	146.6 dB	144.2 dB	149.9 dB	150.8 dB	143.6 dB	5
17		139.6 dB	137.3 dB	137.9 dB	141.4 dB	135.3 dB	141.7 dB	140.4 dB	145.7 dB	146.8 dB	139.9 dB	6
18		140.6 dB	138.2 dB	139.4 dB	142.5 dB	136.2 dB	142.8 dB	141.1 dB	147.3 dB	148.3 dB	141.1 dB	6
20					146.7 dB	148.2 dB	146.4 dB		141.0 dB	142.7 dB	143.8 dB	7
22			133.5 dB	140.1 dB	143.6 dB	135.7 dB	136.6 dB	141.1 dB	148.8 dB	149.6 dB	146.0 dB	8
24			128.0 dB	128.6 dB	133.1 dB	123.6 dB	130.9 dB	127.4 dB	133.8 dB	136.1 dB		9

Figure 10. Chart of measured peak-levels for each channel and shot.

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