ARL-TN-1245 ● APR 2025

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REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED START DATE	END DATE
April 2025	Technical Note	7 July 2024	12 Mar 2025

4. TITLE AND SUBTITLE
Assessing the Accuracy of Microphone Measurements of Small-Scale Height-of-Burst Explosive Charges

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Elliot R. Wainwright, Amee L. Polk, Dakota Scott, Ronnie Thompson, Ray Sparks, Will Sickles, Eugene Summers, Richard Benjamin, and Steven W. Dean

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM Army Research Laboratory ATTN: FCDD-RLA-WA Aberdeen Proving Ground, MD 21005	ARL-TN-1245

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In this work, the pressure profile of height-of-burst detonations from three sizes of spherical C-4 charges (17, 54, and 152 g, corresponding to TNT equivalent scaled distances of approximately 14.8, 10.1, and 7.1 kg/m$^{1/3}$, respectively) were measured using laboratory-grade pressure-field microphones. We assessed the time of arrival, peak pressure, and pressure decay behavior as a function of charge mass and compared experimental results with tabulated Kingery-Bulmash and Conventional Weapons (ConWep) data, in addition to simulations performed in the fast-running code, BlastX. In particular, we found excellent agreement between BlastX predictions and measured times of arrival of the shock wave, when these are combined with known gauge distance, all other values of the incident pressure wave can be derived. We highlight the advantages of these microphones over traditional piezoelectric pencil probe gauges for blast measurements—in particular, the variable sensitivity allowing for high-fidelity measurements across a wide range of scaled distances and utility for smaller events such as microscale shock waves.

15. SUBJECT TERMS
blast wave scaling, acoustic measurements, microphones, explosive pressure, Weapons Sciences

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	17

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
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STANDARD FORM 298 (REV. 5/2020)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

We thank Drs. Jennifer Gottfried and Kevin McNesby (both from DEVCOM Army Research Laboratory) for their insightful conversations.

1. Introduction

The pressure field generated by the passage of a blast wave—itself created by the rapid release of energy within a small volume—has been the subject of study for decades.[1–3] Microphones have been used to analyze blast waves generated by events as large as 10,000 lb net explosive weight (NEW) of Composition C-4[4] to hundreds of gram charges[5,6] to small sub-joule pulses of nanosecond lasers.[7,8] Loubeau et al.[5] established minimum rise times that could be reasonably achieved using microphones with 0.57-kg C-4 charges at scaled distances of TNT equivalence from approximately 27.1–108.6 m/kg$^{1/3}$. Similarly, Gabrielson[6] presents a thorough discussion of the effect of baffling (i.e., embedding the microphone into a circular disk), orientation, and approaches for postprocessing and digital correction filters for similar microphones using both 0.57-kg C-4 charges at a scaled distance of TNT equivalence of approximately 54.3 m/kg$^{1/3}$ and idealized 1D shock tube experiments. Larger-scale experiments using larger-diameter microphones at smaller-scaled distances have also been reported by Sorrell et al.[9]

We seek to validate similar measures with small pressure-field microphones to lower-scaled distance values less than 15 m/kg$^{1/3}$, which are commonly used for novel material testing and development prior to scale-up. In this study, we characterize the efficacy of small pressure-field microphones as a blast wave diagnostic for increasing masses of spherical explosive charges. We compare the resultant pressure and time-of-arrival profiles to both tabulated data (e.g., Kingery-Bulmash [K-B][10,11]) and other fast running codes such as the Conventional Weapons (ConWep) code (see other use cases[12,13]) and BlastX (U.S. Army Engineer Research and Development Center).

2. Experimental Approach

This experiment used a high-fidelity 3.125-mm (1/8-inch) pressure-field microphone (Brüel & Kjær, Type 4138-A-015) and a conditioning amplifier (Type 2670, 316 µV/Pa, 200-V polarization) connected to a digital oscilloscope (PicoScope 4824A, 1-MHz sampling rate). Three masses of spherical C-4 charges (17, 54, and 152 g) were detonated at a nominal standoff of 4.235 m from the microphones at a height-of-burst of 1.5 m above the steel blast pad. These masses correspond to TNT equivalent scaled distances of approximately 14.8, 10.1, and 7.1 kg/m$^{1/3}$, respectively. The charges were suspended using destructible media (i.e., foam and cardboard) and were detonated top-down with an exploding bridgewire detonator (Teledyne, RP-83). At least three shots were conducted at each charge mass. The oscilloscope was triggered simultaneously with the opening of current flow to the detonator. The microphones were oriented at 90° (i.e., side-on or incident pressure) with respect to the incoming shock and upward with respect to the ground with the tip height aligned with the center of the charge. Unlike the previously referenced works, the protective mesh tip of the microphone was kept in place and much of the microphone body was placed within a 6.35-mm-steel tube, exposing less than 25 mm of the microphone tip. A schematic of the experimental configuration is shown in Figure 1. The microphones come precalibrated in terms of frequency to pressure (decibel [dB]) response, with an advertised open circuit sensitivity of approximately –60 dB at 100 mV/Pa.

BlastX simulations were completed using the known ambient conditions on the day of testing (e.g., 95 °F, 14.69 psi); we assume experimental uncertainties of ±0.25 g for each charge mass and a center-to-center positioning uncertainty of ±10 mm between the microphone and charge; however, the latter value may be larger and the former value is smaller than this assumption.

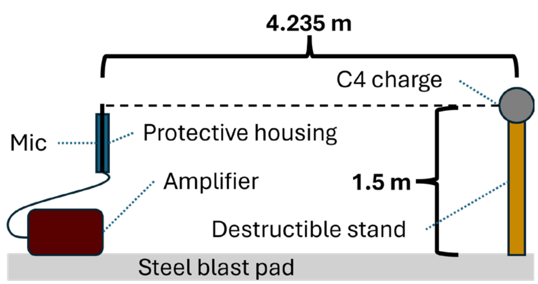

Figure 1. Schematic of experimental configuration.

3. Results

An overlay of the raw experimental data for each charge mass with BlastX calculations under the same nominal conditions is shown in Figure 2; it displays excellent agreement between the microphone measurements and the expected pressure profiles of the primary shock passage. The microphones also accurately track the extended Friedlander decay of the blast wave. The ground reflection is present at later times for all charge masses but is visible for the largest charge mass within Figure 2. The initial overshoot in the measured data over the predicted data is characteristic of a second-order Butterworth filter and is observed and discussed by Gabrielson[6]; a thorough discussion of anti-aliasing, filters, and diffraction effects from the microphones are also discussed in that work and we refer the reader there for additional details. Using an oscilloscope sampling rate of 1 MHz (1 µs per sample) for these experiments, the rise time of the primary shock passage lasts for approximately nine data points, corresponding to a dynamic range of these microphones of at least 2.6 kPa/μs. Pencil pressure gauges (i.e., the “gold standard” for blast testing) have a similar rise time under the same sampling and experimental conditions. Such measurements suggest these microphones can accurately measure large dynamic pressure events.

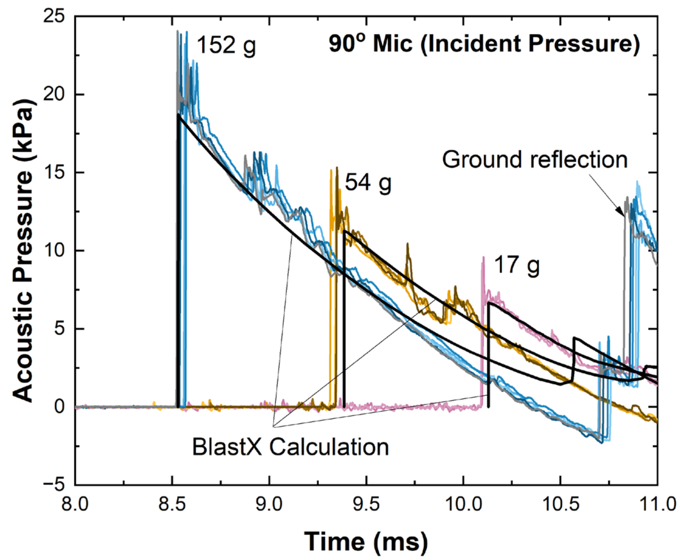

Figure 2. Unfiltered microphone pressure response data, compared with BlastX simulations at nominal conditions and demonstrating good shot-to-shot repeatability and the presence of ground reflections at later times after the passage of the initial shock.

Data postprocessing can remove overshoot artifacts, as explained by Gabrielson.[6] We applied a time-domain diffraction filter with the MATLAB code presented in that work to our data using the conditions of 3.125-mm microphones with a 1-MHz sampling rate. An overlay of a representative raw data trace and the resultant filtered data using Gabrielson’s approach is shown in Figure 3, which displays good alignment between the two save for the expected removal of the initial pressure overshoot peak. This filter was subsequently applied to all the experimental shot data collected for this study. The smaller, second “overshoot” peak observed for the larger charge masses is likely due to a reflection of the primary shock between the protective microphone tube housing and the microphone body. Further perturbations to the Friedlander decay are due to other test fixtures present in the vicinity of the blast wave, which are not discussed here.

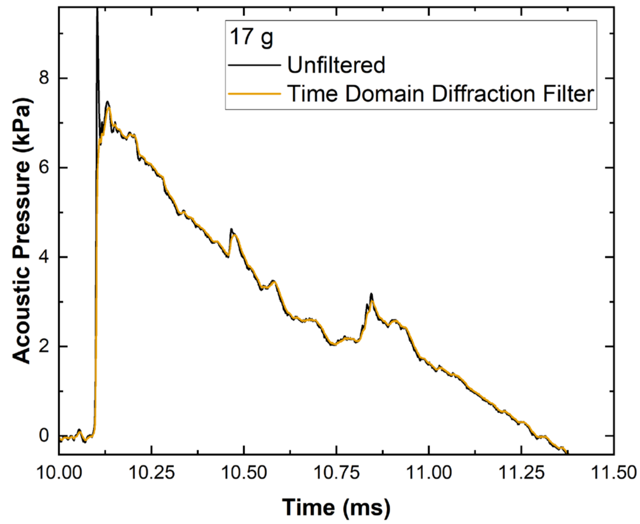

Figure 3. Representative raw pressure data overlaid with the same data with time-domain diffraction filtered applied via the approach presented by Gabrielson.[6]

We compare the filtered response curves to the look-up table and fast-running code models for each of the three charge masses in Figure 4. For the BlastX simulations, we provided an estimate of high and low bounds using a combination of the following: the charge to microphone distance being 10 mm closer and the charge mass being 0.25 g higher; and 10 mm further with a 0.25 g lower charge mass. These cases represent overly strong and weak estimates, respectively, of peak pressure and time of arrival relative to the nominal conditions presented in Figure 3, where the dotted curve arriving sooner is the stronger case and the dotted curve arriving later is the weaker case. These bounds suggest that positioning errors in the charge to microphone distance are a likely reason for offsets between the measured and simulated time of arrival, with a less-significant effect on the peak pressure. The positioning errors are likely greater than that assumed for the simulations (±10 mm). However, the experimental data generally falls within these bounds and generally displays good agreement with the time of arrival, peak pressure, pressure decay profile, etc.

Among these data, the K-B estimate appears to significantly overestimate the strength of the charge (e.g., overestimate the pressure and underestimate the time of arrival), while the opposite case is true for ConWep. Among these comparisons, BlastX provides the best agreement with measured time of arrivals (measured as the first point to exceed 20% of baseline) at 0.01% for the 17-g case (10.091 ms measured vs. 10.09 ms simulated) and 0.1% for the 54-g case (9.343 ms measured vs. 9.354 ms simulated). The 152-g case falls within the estimated bounds. From the time of arrival, and known distance to charge, all other pertinent blast wave information can be appropriately derived—including peak incident pressure, positive phase duration, positive phase impulse, etc.

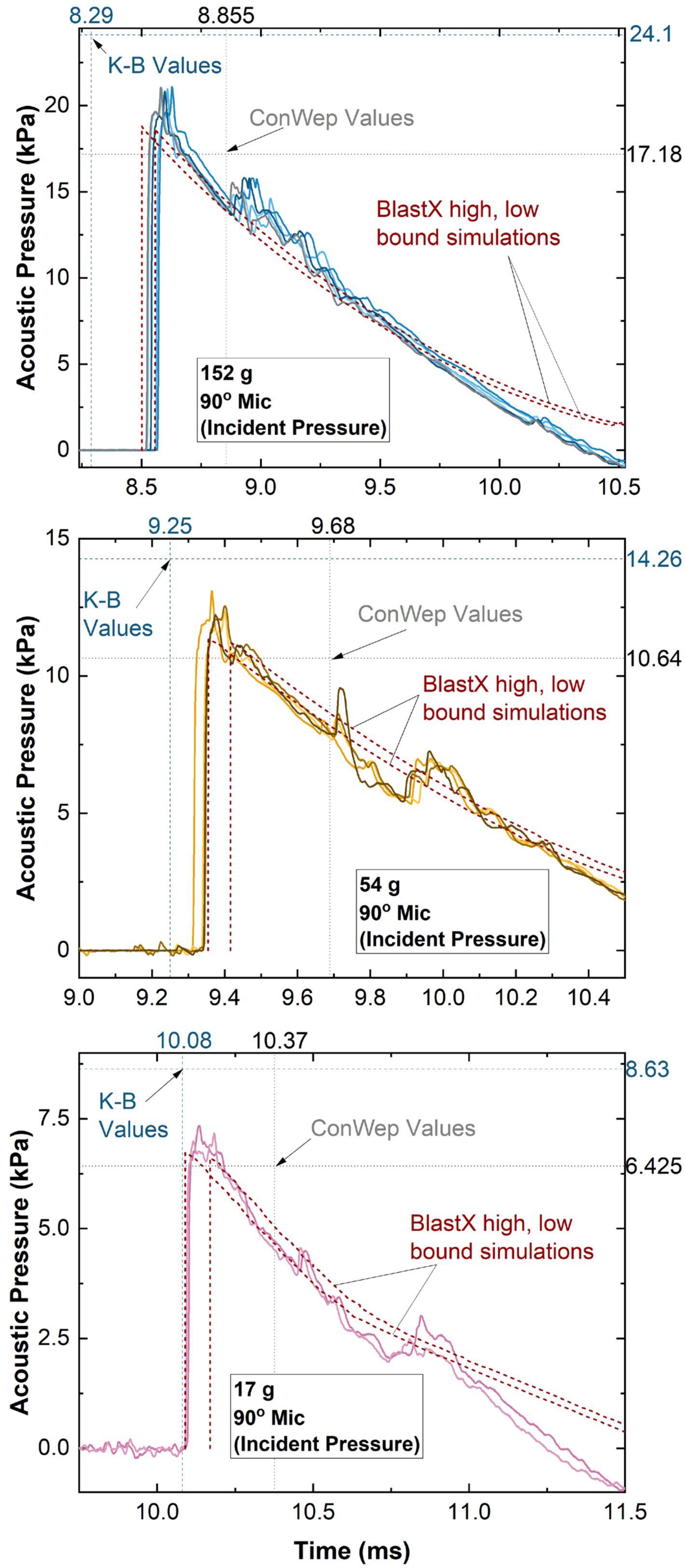

Figure 4. **Time-domain diffraction filtered data for the charges compared with K-B, ConWep, and BlastX predictions for the same event.**

4. Discussion and Conclusion

The data suggests high-fidelity pressure-field microphones are well suited to blast wave characterization and support findings from previous research. Microphones of this type could readily be used for estimation of energetic yields in a variety of experimental configurations including free-field, height-of-burst, etc. One major advantage of using a microphone is the ability to adjust the sensitivity of the instrument in real time. The microphone-plus-amplifier system used in these experiments can be adjusted from 100 μV/Pa to 3.16 V/Pa, in contrast to standard piezoelectric pencil probes commonly used that have a fixed sensitivity (e.g., PCB PiezoTronics, ICP blast pressure pencil probe Model 137B23B at 100 mV/psi or 14.5 μV/Pa). Since higher V/Pa values mean greater sensitivity, in this example this means that when paired with the same sampling diagnostics (oscilloscopes) the microphones range from approximately 6.8 to over 24,000 times as sensitive as the standard pencil probe. This high and adjustable sensitivity allows for the following: 1) the placement of the same diagnostic across a larger-scaled distance space while ensuring measurement accuracy and 2) microphones that can be used for small shock wave events as demonstrated in recent work that uses them to study focused nanosecond laser-generated shocks.[8,14]

The measured time of arrival, peak pressure, and pressure decay profiles using these microphones fall within the bounds of K-B and ConWep look-up values as well as demonstrate excellent agreement with simulations via BlastX.

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List of Symbols, Abbreviations, and Acronyms

1D	one-dimensional
ARL	Army Research Laboratory
ConWep	Conventional Weapons
dB	decibel
DEVCOM	U.S. Army Combat Capabilities Development Command
K-B	Kingery-Bulmash
NEW	net explosive weight
TNT	trinitrotoluene

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