

Small-scale tunnel test for blast performance

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Abstract. The data reported here provide a validation of a small-scale tunnel test as a tool to guide the optimization of new explosives for blast performance in tunnels. The small-scale arrangement consisted of a 2-g booster and 10-g sample mounted at the closed end of a 127-mm diameter by 4.6-m long steel tube with pressure transducers along its length. The three performance characteristics considered were peak pressure, initial energy release, and impulse. The relative performance from five explosives was compared to that from a 1.16-m diameter by 30-m long tunnel that used 2.27-kg samples. The peak pressure values didn't correlate between the tunnels. Partial impulse for the explosives did rank similarly. The initial energy release was determined from a one-dimensional point-source analysis, which nearly tracked with impulse suggesting additional energy released further down the tunnel for some explosives. This test is a viable tool for optimizing compositional variations for blast performance in target scenarios of similar geometry.

1. Introduction

A small-scale tunnel test was implemented as a more efficient way of evaluating the performance of explosive compositions than the large scale testing currently used [1]. The arrangement consisted of a 2-g booster and 10-g sample in the closed end of a 127-mm diameter by 4.6-m long steel tube with pressure transducers along its length. Performance was based on three criteria: peak pressure, energy release, and impulse. The assessment of five explosives for the small-scale tunnel favorably compared to the results from a 1.16-m diameter by 30-m long tunnel that used 2.27-kg samples [2].

The performance (peak pressure, impulse, energy) of explosives is determined by several factors including the amount of explosive ingredients, the ingredients in the formulation, the boosting mechanism, and the environment in which the explosive is detonated. Tests in small scale that predict large scale effects are attractive to reduce costs and time in selecting explosive formulations. However predicting performance effects in larger scales from performance values in smaller scale tests is not straightforward. Scaling of free-field blasts are discussed in the literature [3], along with scaling tunnels with free-field [4] and other tunnels [5].

2. Experimental Arrangement

2.1. Small-Scale Tunnel

Tests were carried out in a steel tunnel with a 127-mm inner diameter, 12.7-mm wall thickness, and 4.6-m length, as shown in Figure 1. The diameter was chosen to limit the mixing with air. For a hypothetical sample with 3.0 grams of aluminum, 3.5 tunnel diameters are required to combust all of the aluminum, assuming only aerobic combustion with the oxygen in the tunnel. This length of air is comparable to a larger tunnel with a 900-kg charge. The full length provides over ten times the air



needed to burn 3.0 grams of aluminum. A length-to-diameter ratio of at least one was desired for the sample, and with a sample diameter of 19.1 mm this worked out to be between 19.1 and 25.4 mm for a 10-gram sample depending on the sample's density. A steel holder surrounded the charge with 28.6-mm of steel, which provides high confinement of the sample. The short sample length and high confinement allowed detonation of samples with critical diameters over 19.1 mm. The holders had a conical booster charge of 2-grams of a plastic-bonded explosive pressed into them. Samples were inserted on one side of the booster and an exploding bridge wire detonator on the other. The charge holder was bolted into the source section of the tunnel. Coiled around the outer diameter of the source section was a length of rubber sheeting. The sheeting reduced the inner diameter to approximately 88.9 cm. The sheeting served two purposes: lessen the damage from fragments on the source section and minimize the shock input on the steel wall. The source section assembly was then bolted onto the end of the tunnel with a plastic ring in between it and the tunnel. The plastic ring both limited the shock in the steel wall transmitted to the tunnel and aided in keeping charge holder fragments from entering the tunnel. The other end of the tunnel remained open. Because of the design, almost all of the energy was directed down the tunnel with minimal mechanical or thermal energy losses.

Pressure was measured at 305-mm intervals starting at 610-mm from the face of the charge holder along the length of the tunnel, as shown in figure 1. Eleven PCB series 113 piezoelectric transducers were used in each test. In reference [1], the gauges were mounted directly into the tunnel, which led to a high mortality rate for the gauges and noise in the signals. In this test series, the gauges were mounted in PVC adapters to isolate them from the steel walls of the tunnel. The annulus of PVC around each gauge was about 50% of the gauge diameter.

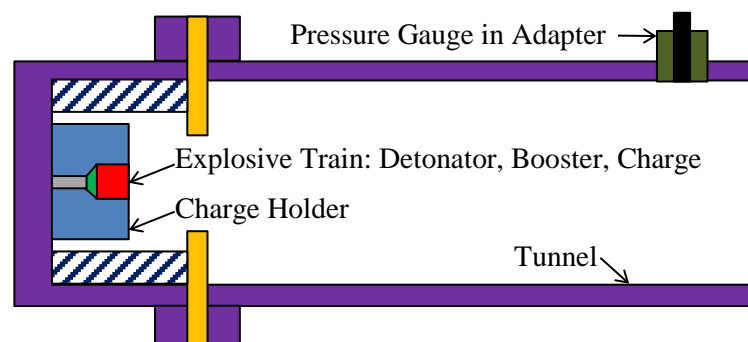


Figure 1. Experimental Setup.

2.2. Large Scale Tunnel

A similar experimental series was conducted in a larger tunnel constructed at Fort AP Hill [2]. This tunnel had a 1.16-m inner diameter and a 30.5-m length. The charges were 2.27-kg with a 102-mm diameter. They were initiated with an exploding bridge wire detonator and a 381-g pentolite booster. The charges were placed 4.27 m into the tunnel with the direction of detonation towards the other end, 26.2 m away. The near end of the tunnel remained open, whereas there was a small room attached to the other end. Kulite HKS-375 pressure gauges were located at distances of 2.74, 8.84, 14.9, 17.1, and 19.2 m away from the charge. Many explosive compositions were tested in the Fort AP Hill tunnel but five have been selected for comparison to our data.

3. Explosive Formulations

Five plastic-bonded, cast-cured explosives were selected from the earlier tunnel study and tested in the Small-Scale Tunnel. One charge was only nitramine and a binder. Two other compositions contained varying amounts of aluminum in addition to the nitramine and binder. The final two compositions contained an oxidizer as well as the aluminum, nitramine, and binder. All were cut from larger slabs to ensure uniform samples. Explosive are named A-E for this open forum and are the same A-E reported by Lee and Felts for a small-scale chamber tests [6].

4. Data Reduction

Three different metrics were used to evaluate the data. The first was peak pressure of the blast wave. In order to avoid high-frequency noise, the peak pressure was chosen using a smoothing operation performed on the data in the same manner the data for the larger tunnel was handled. The second was the partial impulse. This is the integration of the pressure-time trace for a determined amount of time. A time of 1.5 ms was used for the small-scale tunnel and 8.7 ms was used for the larger tunnel. The data for peak pressure and partial impulse was compared from the 19.2-m location in the larger tunnel to the 2.134-m location in the small-scale tunnel in accordance with cube-root scaling [3]. The 8.84-m location of the larger tunnel was compared with the 3.34-m location in the small tunnel based on linear scaling from references [4,5]. Data was normalized for comparison between the two tunnels and ranked according to the small-scale tunnel. The error bars represent the normalized maximum and minimum values.

Energy release, the third metric, for each explosive was calculated from point source blast theory. For a linear one-dimensional geometry, the source is actually a plane instead of a point. For the small-scale tunnel, planarity is likely achieved within two tunnel diameters, based on a simple geometric expansion from the end of the charge. Estimates of early time energy release were made using a time of arrival analysis. The first gauge location used in the analysis was 610-mm from the charge. Therefore, it is expected that this analysis captures energy from the detonation and early post detonation reactions between added fuels and the products and possibly from some mixing with the air before the planar wave was achieved. There would be enhanced mixing with the air in this time period, opposed to a charge that was the entire diameter of the tunnel. The time of arrival of the blast wave at a number of distances from the charge can be related to the energy released by a sample. This relationship has been derived by several individuals [7-10], although they all used different assumptions. In their formalisms, both Sedov [9] and Harris [10] assumed the mass of gas swept over by the shock wave is much greater than the mass of the explosive charge. In the small-scale tunnel, the air has a mass of 4.6 grams per foot and the charge is 12 grams, so that assumption is not valid until after 10 feet down our tunnel. Freiwald [8] revised the relation to include the source mass but still assumed an identical ratio of specific heats for both the explosive products and the undisturbed air. Hutchens [7] modified the relationship further to use different ratios of specific heats for the explosive products and the undisturbed air. Time of arrival predicted from these four models was plotted against a set of data obtained for a 12-gram charge of the booster explosive in Figure 2. In the models, a theoretical energy of 5.37 kJ/g was used for the booster explosive, which was obtained from the Cheetah thermochemical code [11]. The best fit was the model developed by Hutchens:

$$R(t) = \frac{1}{K_2} \left[\left(\frac{3}{2} K_2 \sqrt{E_0} t + K_1^{3/2} \right)^{2/3} - K_1 \right] \quad (1)$$

$$\text{with } K_1 = \frac{2A\rho_s R_s}{(\gamma_g + 1)^2}, \text{ and} \quad (2)$$

$$K_2 = \frac{2A\rho_0[(\gamma_g + 2\gamma_d) - 1]}{(\gamma_g + 1)^2(\gamma_d - 1)}, \quad (3)$$

where R is the distance from the charge, E_0 is the energy released by the charge, A is the cross-sectional area of the tunnel, ρ_s is the density of the explosive charge, R_s is the thickness of the charge if it had cross-sectional area A instead of its actual dimension, ρ_0 is the density of the gas in the tunnel, γ_g and γ_d are the ratio of specific heats for the gas in the tunnel and the explosive products, respectively. A value for air, 1.4, was used for γ_g and γ_d was calculated with Cheetah. The value for γ_d varied non-linearly for each aluminized compositions. Values of γ_d were found for increasing percent reactive aluminum in the Cheetah calculation. The energy release calculated corresponds to a percentage of aluminum reacting initially as the wave becomes planar.

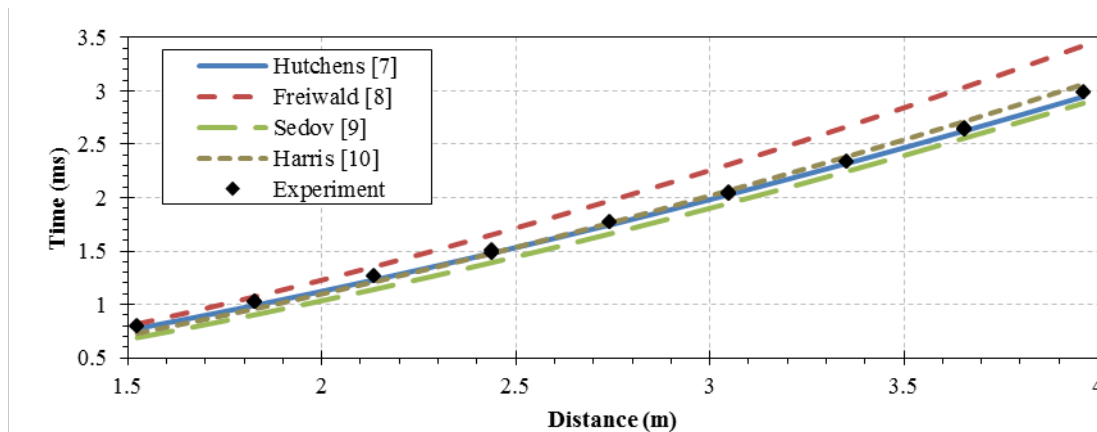


Figure 2. Comparison of experimental time of arrival data for 12 grams of the booster explosive with several theoretical predictions.

For each set of time of arrival data, an energy release was calculated using equation (1). Equation (1) was transformed into a linear equation of the form $y = m \cdot t$, where y is a function of R and m is a function of E_0 . This transformation simplified the fitting procedure. The value calculated represents the early time energy release of the sample. The contribution of the booster explosive was subtracted from the total energy value. Data was then normalized for comparison and the error bars represent the maximum and minimum values.

5. Results

Comparisons of peak pressure for the two tunnels are shown in figure 3 and figure 4. The linear scaling method correlates the rankings better than the cube root method. Only one explosive is out of place with the linear method as opposed to twice that with the other method. The partial impulses measured for both tunnels are compared in figure 5 and figure 6. The ranking for both scaling methods are nearly identical except for the swapping of explosives A and B. The initial energy release of the five explosives is compared in figure 7. The rankings between the tunnels are identical. The larger tunnel produced a narrower range of energy values due to its configuration having the open end behind the charge instead of a solid wall.

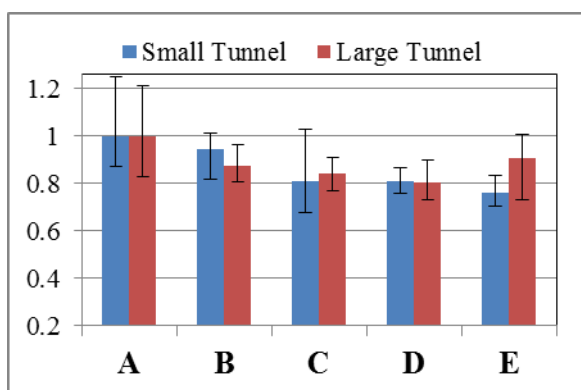


Figure 3. Peak pressure comparison for linear scaling.

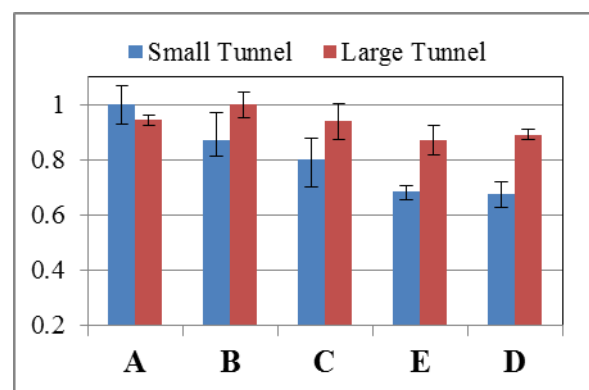


Figure 4. Peak pressure comparison for cube root scaling.

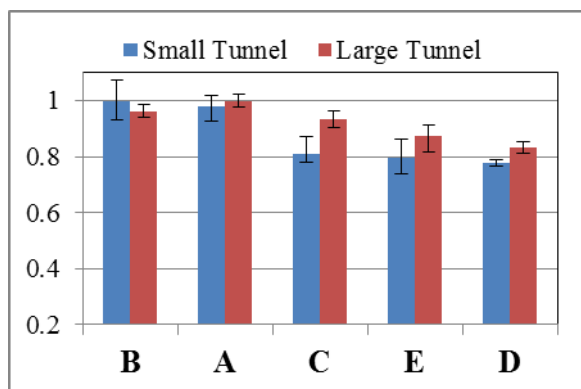


Figure 5. Partial impulse comparison for linear scaling.

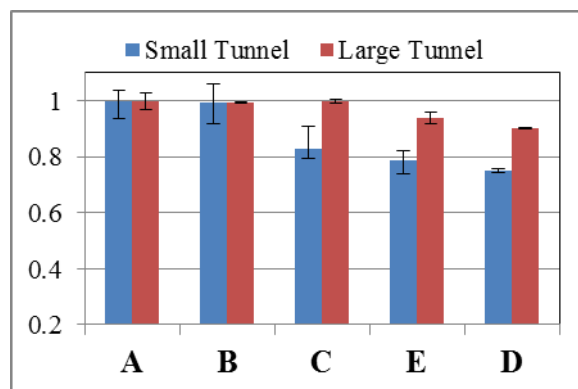


Figure 6. Partial impulse comparison for cube root scaling.

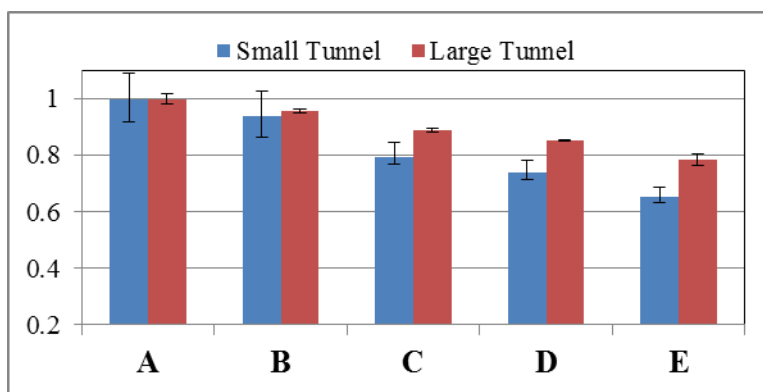


Figure 7. Comparison of initial energy release.

6. Discussion and Conclusions

The relative ranking of the explosives between the small-scale and larger tunnel for linear scaling were preserved with a couple exceptions. For the peak pressure, one explosive was out of place and for partial impulse; the top two explosives were swapped. The cube root scaling method failed for preserving the ranking of peak pressure, but didn't for partial impulse. The relative ranking of the initial energy release calculated for the two tunnels is consistent. The larger tunnel shows less variation in the energy, but this is due to the test geometry. In the larger tunnel, the open end opposite the direction of detonation allows a portion of the energy to be directed away from the pressure gauges and not represented in the measurements made. The energy values calculated for the larger tunnel were lower because of this same fact. The difference in the experimental setup for the two scales is why no attempt has been made to scale the pressure or impulse values using the recording locations. The small-scale tunnel test is a viable tool for screening new explosive materials and formulations before moving on to larger tests.

7. Future Work

One point that needs addressed is modeling of the small-scale tunnel. Modeling would determine how long it takes for a planar blast wave to be achieved and what effect mixing has on the early combustion of metal fuels in the explosive. Modeling would also provide better understanding of the late-time combustion that drives the impulse. The scaling between a linear one-dimensional system, i.e. the small-scale tunnel, and a spherical one-dimensional system, e.g. free-field blasts, needs to be explored, as in reference [4]. The metric of interest here would be impulse as it may not scale well for explosives with both metal fuels and additional oxidizers.

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