

The Diameter Effect in Bullseye Powder

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Detonation velocity as a function of charge diameter is reported for Alliant Bullseye powder. Results are compared to mixtures of ammonium nitrate and aluminum, and ammonium nitrate and fuel oil. Additionally, measurements of free surface velocity of flyers in contact with detonating Bullseye are presented and results are used to construct a JWL equation of state.

I. INTRODUCTION

The failure diameter, or radius (R_f), is a fundamental property of an explosive, and is defined as the charge diameter, below which, steady-state detonation cannot occur. It is typically determined by detonating a series of cylinders of explosive of varying diameters, while measuring the detonation velocity. As the charge diameter increases, the detonation velocity will also increase, until a specific dimension (R_f), after which the velocity will remain constant with further increase in diameter. The failure diameter is a function of the physical state of the explosive (e.g., density, temperature, etc.) and confinement. It is essential to know R_f because it directly affects explosive performance, is illustrative of non-ideal behavior and is an indicator of reaction zone thickness. Campbell and Engelke [1] were the first to publish a coherent correlation between the failure diameter of an explosive and its detonation velocity. They emphasized that while their treatment was phenomenological, it

could give hints to dominant mechanisms. They also provided a fitting form that provides a way to interpolate between data sets.

The Jones-Wilkins-Lee (JWL) equation of state (EOS) is used to describe the performance of an explosive after detonation has occurred. An accurate determination of the EOS is required if reliable predictions of explosive performance are to be obtained from numerical calculations. Generally, JWL constants are determined from observing the expansion of a copper cylinder as the detonation proceeds past that point. However, matching the acceleration of a flyer plate from the surface of a detonating explosive can also be used to calibrate the EOS. While not as precise, the technique proved adequate for present purposes.

Alliant Bullseye powder is a double-base propellant (NC/NG/other, 58/40/2) that is very useful in the study of explosive behavior and has been used as a model system for equation of state studies. The nitrocellulose is nitrated to a level of 13.25%.

II. EXPERIMENTAL

Mild steel tubes (see TABLE I) were cut to length and packed with Bullseye by pouring and tapping the tube to consolidate the powder.

TABLE I. Tube measurements

OD (inch)	ID (inch)	Wall Thickness (inch)
2	1.87	0.065
1	0.93	0.035
$\frac{3}{4}$	0.68	0.035
$\frac{5}{8}$	0.555	0.035
$\frac{1}{2}$	0.43	0.035
$\frac{3}{8}$	0.305	0.035
$\frac{1}{4}$	0.18	0.035
$\frac{3}{16}$	0.118	0.035

Piezoelectric pins from Dynasen were placed into a plastic mount and recessed from the tube surface by approximately 1 mm as shown in

Figure 1.

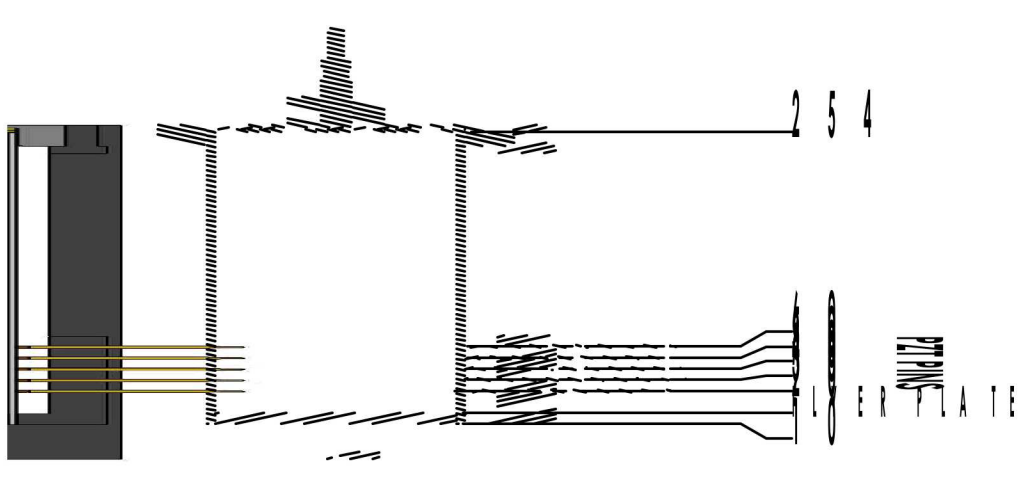


Figure 1. Schematic of tube assembly

Flyer plates were machined to a press-fit and were inserted into the end of the tubes. Two different thicknesses were used; 3 mm and 10 mm. For the larger diameter tubes and thicker flyers, spall was observed after the initial free surface acceleration. Thus, the late-time data for the 10 mm flyers were not used for development of EOS parameters. However, the initial free surface velocities were unaffected.

III. RESULTS

The results from the test series along with the densities of each experiment are shown in TABLE II. The data will be analyzed in the next two sections.

TABLE II. Experimental results

<i>Shot number</i>	<i>Tube OD (in)</i>	<i>Density (g/cc)</i>	<i>Flyer velocity (m/μs)</i>	<i>Detonation velocity (mm/μs)</i>		<i>Shot number</i>	<i>Tube OD (in)</i>	<i>Density (g/cc)</i>	<i>Flyer velocity (mm/μs)</i>	<i>Detonation velocity (mm/μs)</i>
1	2	0.73	895	4.43		14	0.375	0.73	132	3.89
2	1	0.75	489	4.41		15	1	0.74	628 ¹	N/A
3	0.75	0.74	N/A	4.42		16	1	0.74	N/A	N/A
4	0.625	0.75	418	4.40		17	0.25	0.73	N/A	3.22
5	0.5	0.73	209	4.08		18	2	0.73	546	N/A
6	0.375	0.73	113	3.87		19	0.625	0.75	579	4.2
7	2	0.73	524	4.43		20	0.625	0.75	664	4.2
8	1	0.75	478	4.33		21	0.75	0.73	533	4.3
9	0.75	0.75	460	4.31		22	0.75	0.73	585	4.3
10	0.625	0.75	390	4.32		23	1	0.73	684	4.2
11	0.25	0.73	N/A	3.45		24	1	0.73	485	4.4
12	0.1875	0.74	N/A	N/A		25	2	0.72	663	4.6
13	0.5	0.73	269	4.16		26	2	0.72	671	4.5

A. Diameter effect

The diameter effect data from this study are shown in Figure 2, and combined with several other datasets in Figure 3.

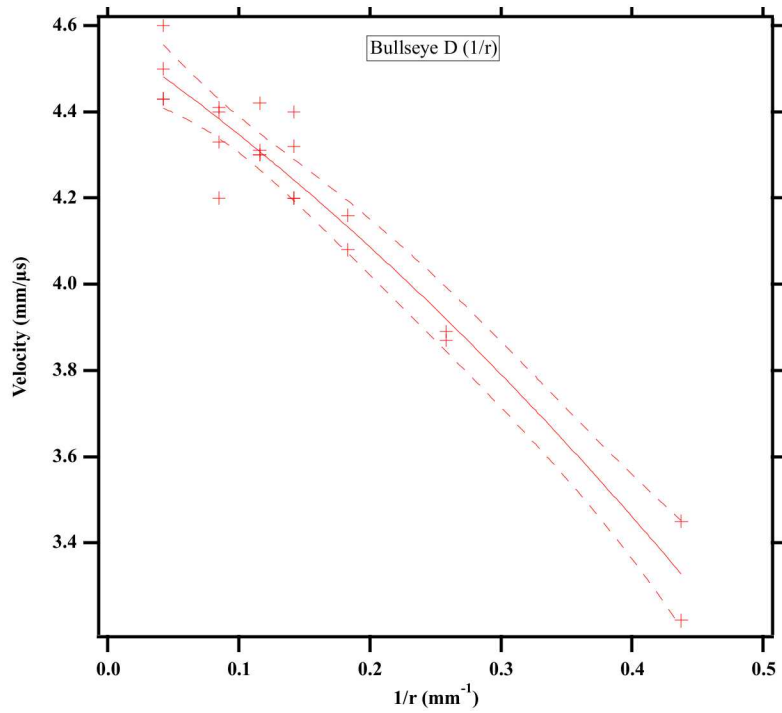


Figure 2. Diameter effect data for Bullseye. Confidence levels of 95% are shown.

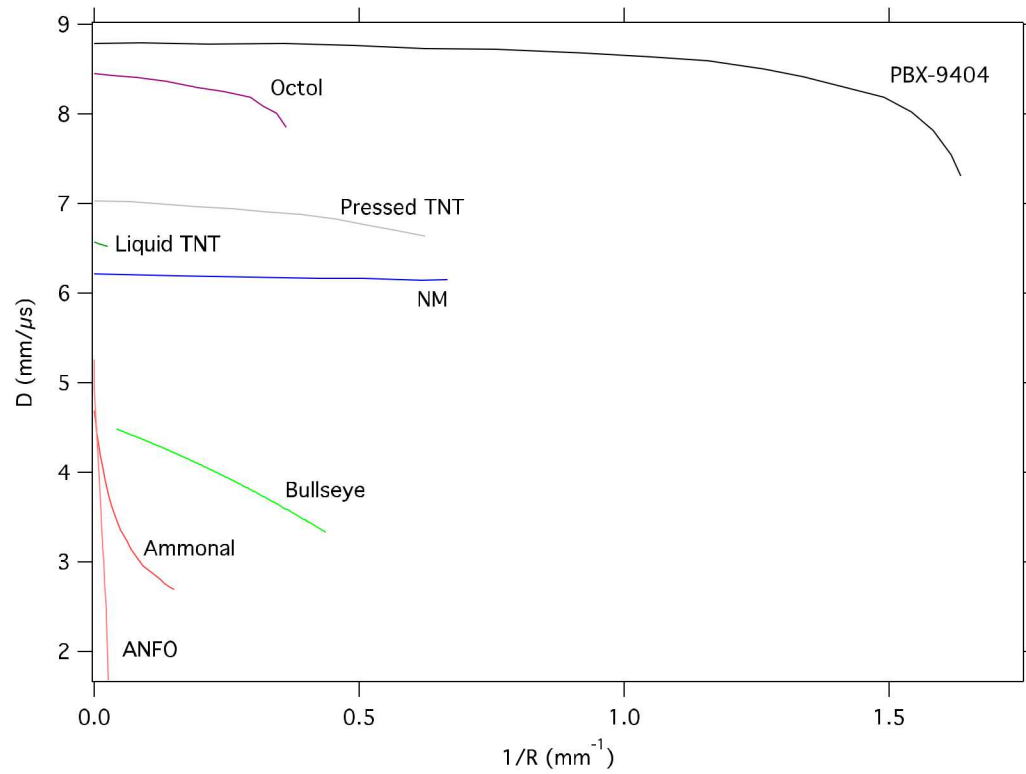


Figure 3. Diameter effect data. Ammonal data taken from [2], ANFO data taken from [3], and remainder from [1].

Campbell and Engelke [1] proposed a fitting function as shown in eq 1.

$$D(R) = D(\infty)\left[1 - \frac{A}{R-R_c}\right] \quad (1)$$

Both the Ammonal and the Bullseye data were fit and the values for the two parameters are found in TABLE III. Campbell and Engelke note that at fixed R_c , the parameter A determines how abruptly the downturn in the curve occurs. Also, if R_c has a value less than zero, the curve is concave rather than convex. From their data, only Nitromethane showed this behavior, whereas Ammonal also demonstrates concavity.

TABLE III. Coefficients from functional fit

Material	R_c	A
Ammonal	-20.5	11.6
Bullseye	0.393	0.5221

These data are fit and compared to other results in Figure 4

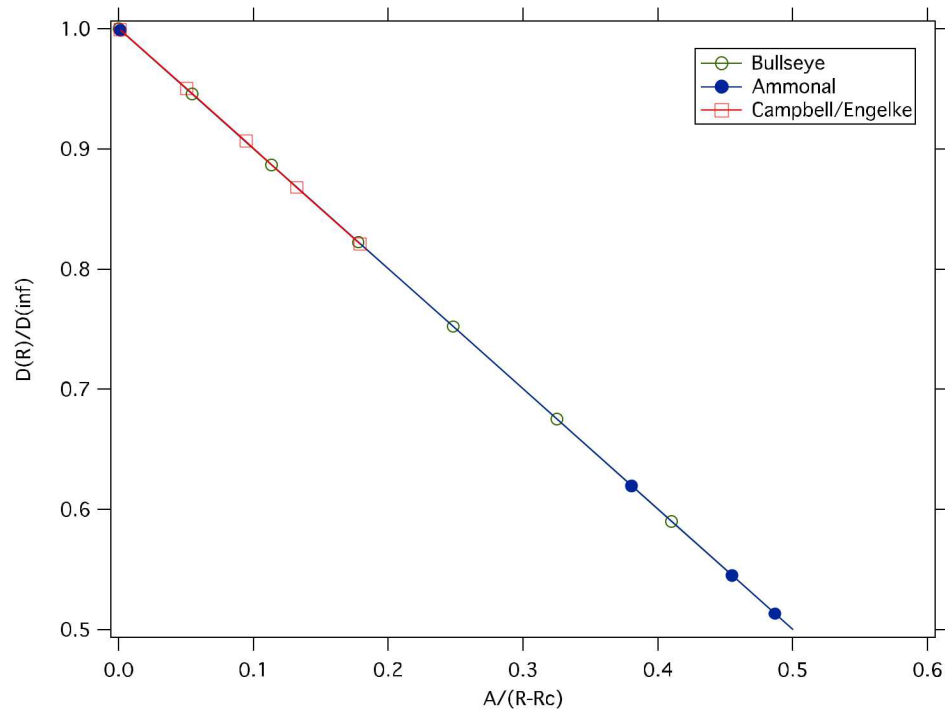


Figure 4. Parameterized fit of 3 data sets.

B. Free surface velocities

The complete set of free surface velocities is shown in Figure 5. The 10 mm flyer data were fit with a quadratic function and the thin flyer data were fit with a linear function. The coefficients are found in TABLE I. The data scatter becomes more pronounced as the tube diameter decreases, which is to be expected.

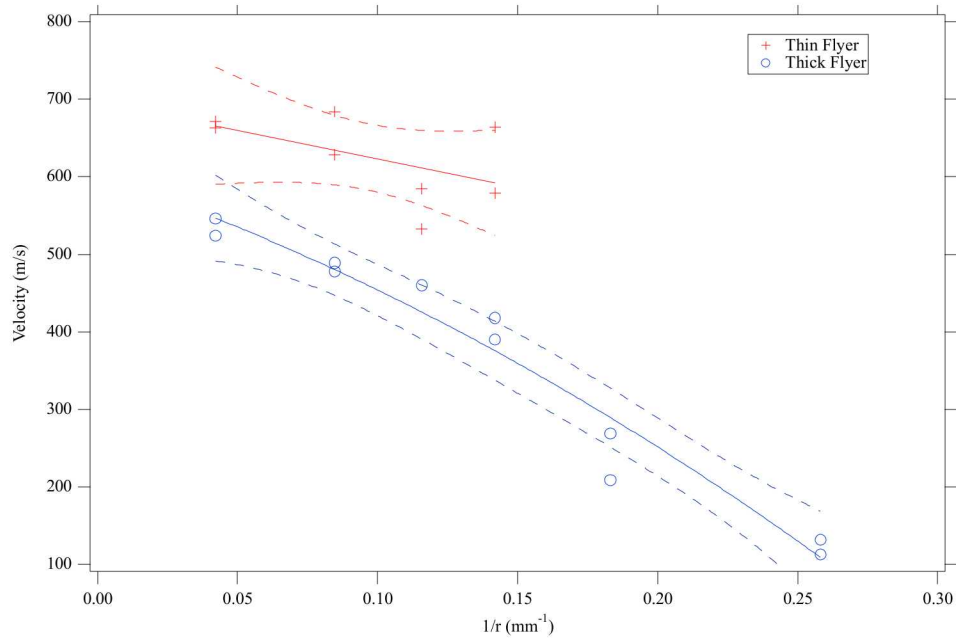


Figure 5. Free surface velocities for thick (10 mm) and thin (3 mm) flyers. Confidence levels of 95% are shown.

TABLE IV. Functional fit coefficients for flyers

Coefficient	10 mm flyer	3 mm flyer
K_0	602.94 ± 46.5	696.83 ± 48.5
K_1	1223.1 ± 703	-738.31 ± 471
K_2	$-2670.7 \pm 2.27e+03$	N/A

The complete velocity-time history for the thin flyers is given in Figure 6 and Figure 7. The detonation velocities in the larger tubes show a classic acceleration history, while as the tubes decrease in size the acceleration, after the initial jump, flattens out.

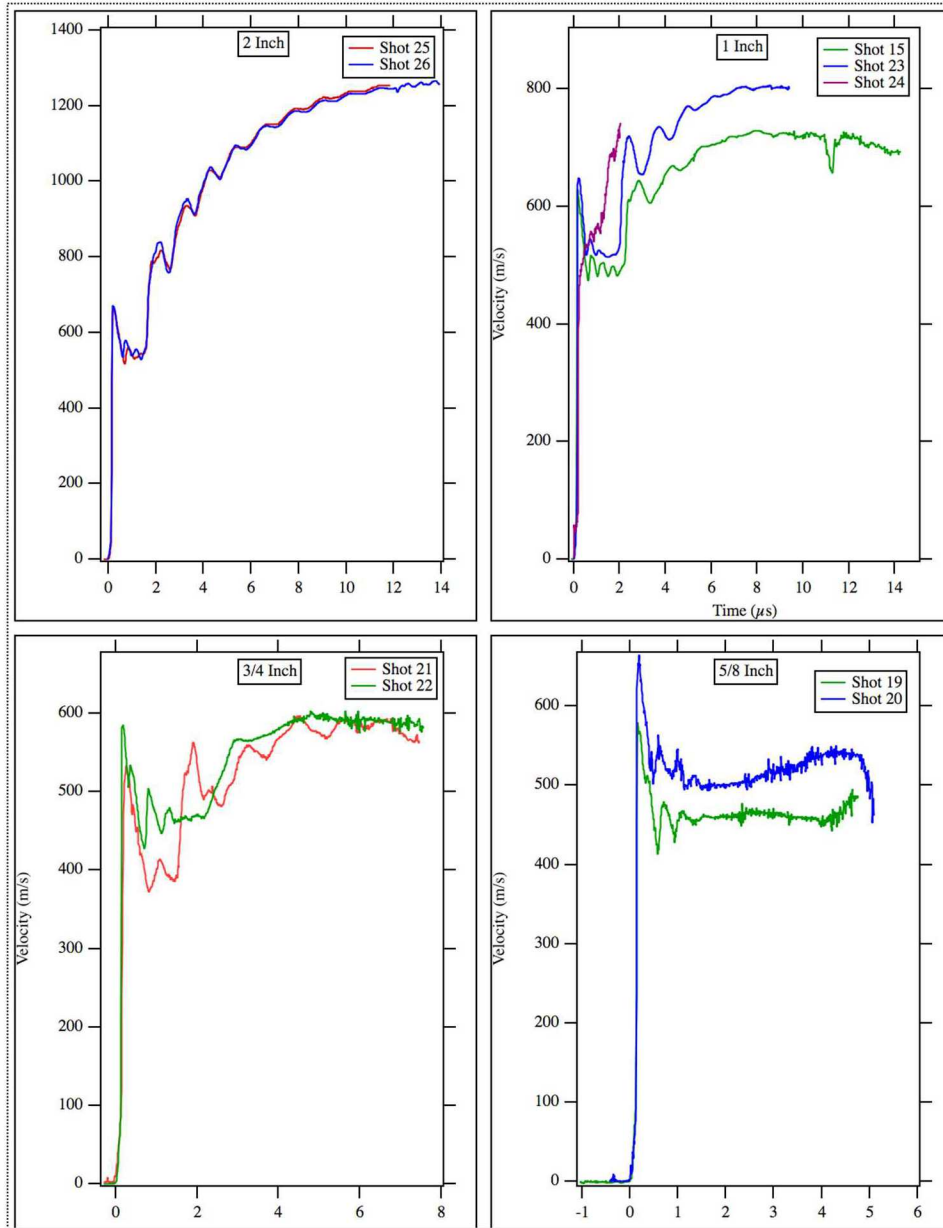


Figure 6. Flyer velocity history for 2-, 1-, 3/4- and 5/8 inch tubes.

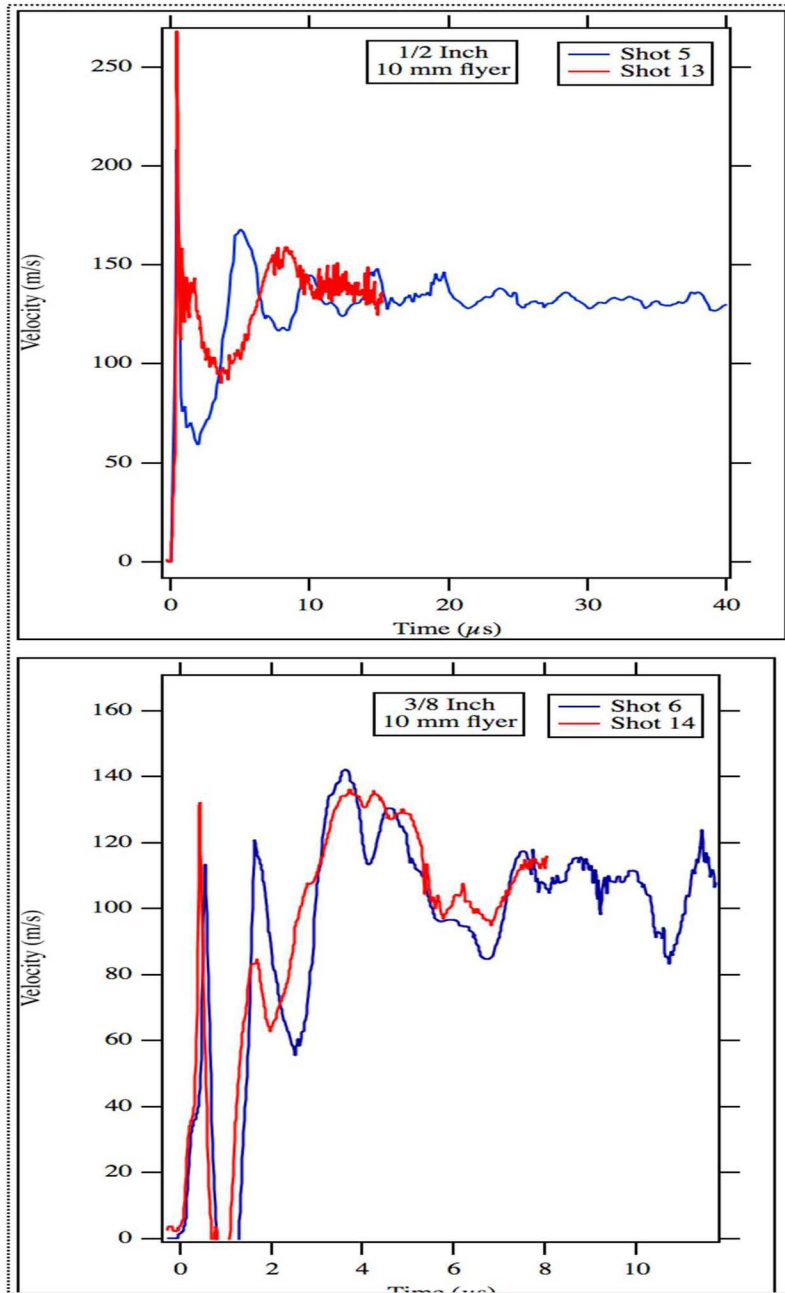


Figure 7. Flyer history for 1/2- and 3/8 inch tubes.

III. MODELING

The Jones-Wilkins-Lee (JWL) equation of state (EOS) is frequently used to describe detonation products of explosives [4]. The modified JWL used in the shock physics code used at Sandia National Laboratories (SNL) is shown in equation 2.

$$\begin{aligned}
 P(\rho, T) &= A \exp(-R_1 v) + B \exp(-R_2 v) + \omega \rho C_v T \\
 E(\rho, T) &= \frac{1}{\rho_0} \left[\frac{A}{R_1} \exp(-R_1 v) + \frac{B}{R_2} \exp(-R_2 v) - \varepsilon_0 \right] + C_v T
 \end{aligned} \tag{2}$$

Where $v = \rho_0 / \rho$, ρ_0 is the initial density of the unreacted explosive. A , B , R_1 , R_2 , ω , and ε_0 are determined for cylinder expansion test data or from thermochemical code calculations.

The JWL used to model the Bullseye for these experiments was calculated using an SNL thermochemical code. The JWL was used in a program burn, and the parameters were

$$\begin{aligned}
 \rho_0 &= 0.72 \text{ g/cc} \\
 A &= 8.24192\text{E}+11 \text{ dynes/cm}^2 \\
 B &= 1.00888\text{E}+10 \text{ dynes/cm}^2 \\
 R_1 &= 4.94820 \\
 R_2 &= 1.19703 \\
 \omega &= 0.294557 \\
 P_{CJ} &= 4.24951\text{E}+10 \text{ dynes/cm}^2 \\
 D_{CJ} &= 4.55403\text{E}+05 \text{ cm/s} \\
 T_{CJ} &= 0.337773 \text{ Ev}
 \end{aligned}$$

As shown in Table II, the measured detonation velocity at large diameter ranged from 4.2 mm/ μ s to 4.6 mm/ μ s. The calculated value of 4.55 mm/ μ s is within this range.

A numerical simulation was then conducted with an SNL hydrocode which assumed a symmetric two-dimensional cylindrical geometry with a mesh size of 200 microns. A planar initiation scheme was used to generate the initial reaction. Figure 8, Figure 9, Figure 10 show the comparison of three experiments with the calculated $v(t)$ profiles. While there

is some variation between the data and the calculations, considering that no manipulation of variables was used to improve the fit, they compare extremely well.

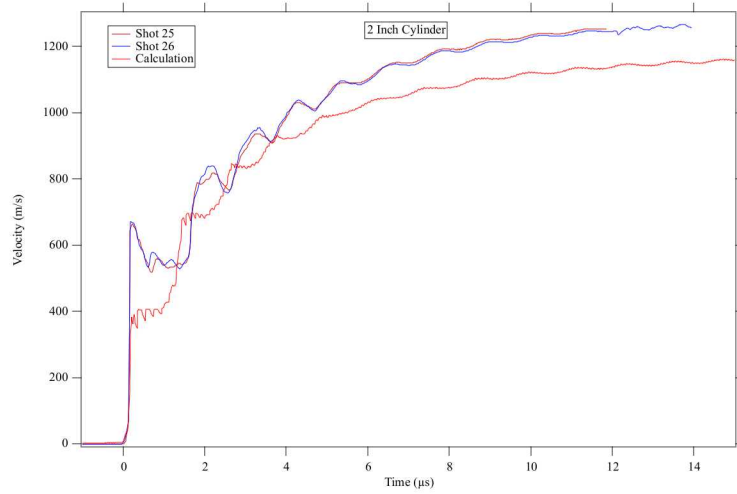


Figure 8. Comparison of model calculation and experimental data for 2 inch cylinder.

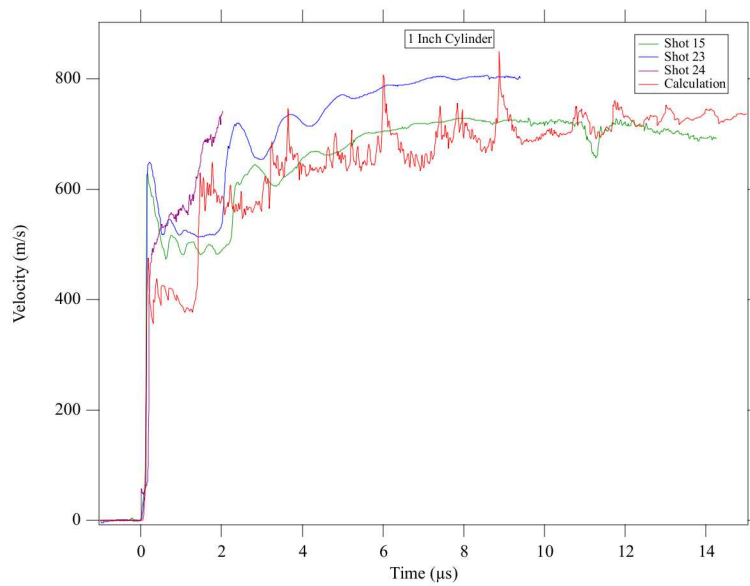


Figure 9. Comparison of model calculation and experimental data for 1 inch cylinder.

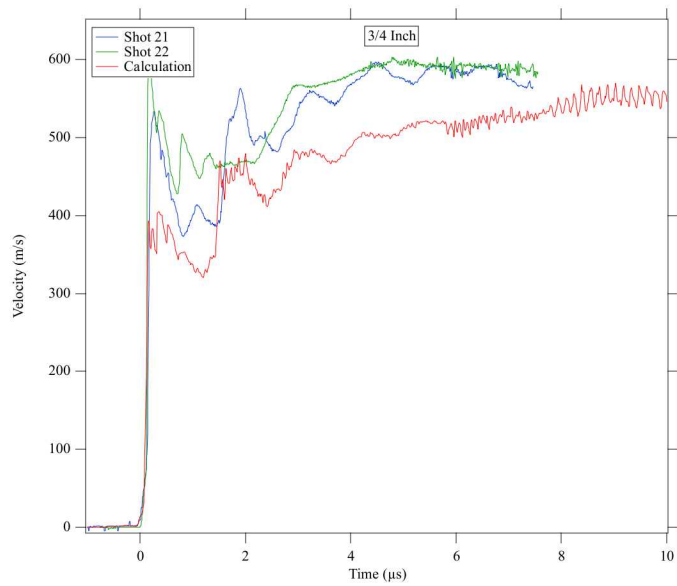


Figure 10. Comparison of model calculation and experimental data for 3/4 inch cylinder.

Finally, Figure 11 shows the calculated final velocity compared to the measured velocity for the experiments with 3 mm flyers, along with an exponential fit to the experimental data.

The fit represents the data well, even at small diameters.

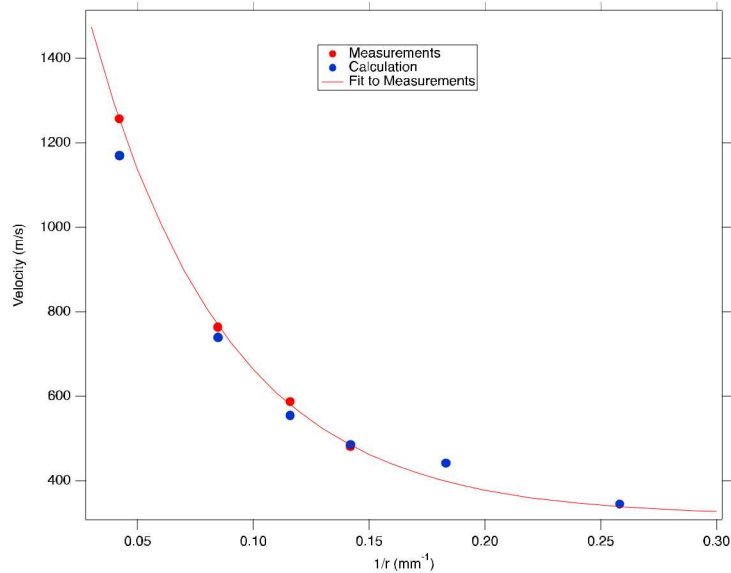


Figure 11. Comparison of experimental measurements to calculation of final flyer velocity. Experimental data were fit with an exponential.

IV. CONCLUSIONS

A complete set of data that demonstrates the D ($1/r$) behavior of Bullseye propellant has been reported. Comparisons were made with both ideal and non-ideal explosives and standard fits to the data were accomplished. Additionally, JWL parameters were generated, and flyer plate velocity histories were calculated that compare favorably with the experimentally-measured data. These data will be of use to those desiring to improve explosive initiation and reactive shock physics models.

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