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ANFO CYLINDER TESTS*

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Cylinder test data is reported for commercially available prilled ANFO (ammonium-nitrate/fuel-oil) at 0.93 g/cc density and ambient temperature. The tests were four-inch inner diameter, with wall-thickness and length scaled from the standard one-inch test (0.4 inch and 48 inch, respectively). The wall expansion was measured with a rotating mirror streak camera and the velocity was measured by fine-wire pin switches, in the standard manner. The wall expansion trajectory is much smoother than for conventional explosives, which show a pronounced jump-off with subsequent ring-up. This observation is consistent with a broadened detonation shock in the granular bed. The data is analyzed for equation-of-state information and JWL parameters are given.

INTRODUCTION

The cylinder test has long been the principal method for obtaining equation-of-state (EOS) parameters for high explosive (HE) detonation products. It involves recording the detonation velocity and wall trajectory of a copper tube filled with an explosive sample, and detonated at one end. The standard tube is 1-inch internal diameter, 0.1-inch wall, and 12 inches long. This diameter is sufficiently large compared to the reaction zone of many HE's that the detonation is essentially planer. The tube length is adequate to ensure that steady flow is achieved during the measurement, while the wall thickness strikes a reasonable balance between maintaining tube integrity and spatial resolution[1].

For non-ideal explosives such as ANFO, the standard cylinder is too small compared to the reaction zone, and must be scaled up accordingly. Previous ANFO cylinder tests[2] were conducted at diameters up to 292.1 mm (11.5 inches). It was reported that a test diameter of 101.6 mm (4 inches) was the minimum size to scale favorably with the large cylinder test; yet, very large field experiments[3] yielded somewhat higher detonation velocities and pressures than even the largest cylinder test. Thus for ANFO it appears that no practically fieldable test is truly "large enough"; rather, there is some schedule of diminishing returns as the size is increased.

The physical origin of this effect is a long reaction tail that is sampled in a different way depending on device size and geometry. It is a very difficult problem to handle computationally; it requires a fully reactive calculation, for which a sufficiently large cylinder test can at best provide a sufficiently accurate end state (product EOS).

ANFO is also non-ideal in other ways. Persson and Brower[4,5] characterized several varieties of commericial ammonium nitrate prills and found substantial variations in performance and product composition. They attributed this to variations in porosity and pore size distribution in prills obtained from different sources. Thus, differences may be expected in otherwise identical experiments using ANFO from different sources.

In this paper we report the results of two nominally identical 4-inch diameter cylinder tests performed on a large ANFO batch, which we reblended to assure homogeneity and uniform performance throughout. This was done to ensure consistency with other work reported here[6], and also to test shot-to-shot reproducibility.

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EXPERIMENTAL

The experimental configuration is shown schematically in Fig. 1. The streak camera is placed with the slit perpendicular to the tube, looking directly into an explosively-driven argon flash. The explosive is detonated at the top, and the cylinder expands as the wave travels down it. This closes the pin switches, and an image is recorded on the streak camera as the tube expands across the slit plane. Different sized tests are geometrically similar in all respects. Thus the present 4-inch tests had a 0.4-inch wall thickness, and were 48 inches long.

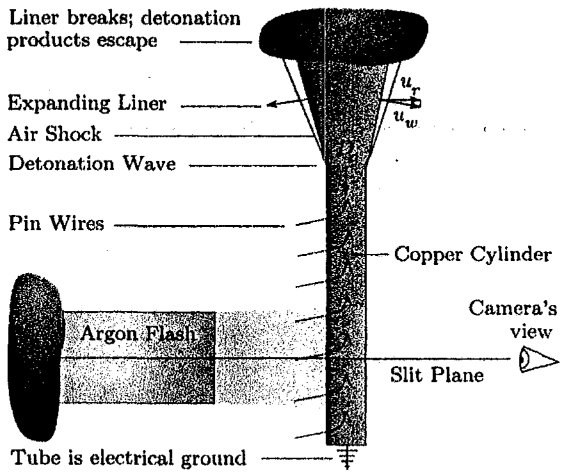

FIGURE 1. Schematic diagram of the Cylinder Test.

It is essential to carefully control copper parameters or the tube will break prematurely. We used Alloy 101 copper (the highest commercial purity), following standard practice for the 1-inch test. Micrographs of tube samples showed that the grain size was about 50 μm (or about 200 grains through the thickness), and that the material was essentially in an annealed state as wrought. Hence, heat treating was not required. Despite the granular composition of ANFO, the tube achieved full expansion without breaking.

The ANFO was composed of explosive-grade prills and 6 wt.% diesel fuel. It was purchased from Titan Energy, Lot #30SE99C.

The tube was loaded in stages, or "lifts." Using approximately 20 lifts per cylinder yielded lift heights and masses that could be conveniently measured to good accuracy. We obtained bulk densities of 0.936 $\pm$ 0.002 g/cm^3 and 0.925 $\pm$ 0.002 g/cm^3. A two-inch thick CompB booster was placed at the top of the tube and initiated with an SE-1 detonator. We aligned the slit with the tube 16 inches from the bottom. This dimension was also scaled from the one-inch test. It is far enough from the booster to ensure that a steady structure has been achieved, yet far enough from the other end that reflected waves don't perturb the measurement. Assembly details for the standard 1-inch LANL cylinder test are given in a recent report[7].

Velocity pins consisted of 4-mil diameter varnished copper wires, bent in a check mark shape and taped to the tube in equal intervals, with points facing the oncoming detonation. The locations of the pin tips were then measured using a dial caliper. When the detonation passes, the shock-accelerated tube surface crushes the insulation and fires an electrical circuit.

Streak camera measurements used a LANL Winslow-Davis combination camera writing at $\approx$0.5 mm/μs. The argon flash was a box 4 feet long, lined with DetaSheet on its top and bottom inner surfaces, to produce a flash of $\approx$150 μs duration. The both sides of the film record were digitized using an optical comparator.

DATA PROCESSING

The detonation velocity D_0 is the slope of a linear fit to the pin switch x-t points. We assume the measurement uncertainty to be the standard error due to random scatter about the line.

The streak camera measures radial wall expansion versus time at a fixed axial position, for both sides of the tube. When the motion of the two sides is digitized and overlaid, there is generally systematic deviation beyond experimental scatter. The culprit is tilt—due to slit misalignment, detonation wave skew, or some combination of the two. A linear tilt correction provides an exact correction for the first cause, and a sensible correction for the second. It generally reconciles the sides to within random scatter.

The following equation[8] provides a nearly ideal smooth fit through cylinder expansion data: it cuts symmetrically through shock ring-up at early time, and follows the data to within experimental noise at late time:

$$E(t) \equiv R(t) - R_0 = \frac{v_\infty \, t \, g(t)}{\frac{2 v_\infty}{a_0} g'(0) + g(t)}, \quad (1)$$

where R_0 is the initial outer tube radius, a_0 is the initial radial acceleration of the smooth fit, v_∞ is the asymptotic radial velocity, and

$$g(t) = (1+t)^\sigma - 1, \quad (2)$$

where σ is a fitting parameter. Because we seek a smooth fit through the shock ring-up, Eq. 1 is allowed a virtual origin t_0 as an additional fitting parameter. Once the other parameters are determined t_0 may be dropped—except in situations where the data and fit are overlaid directly.

The tilt-corrected expansion data for one of the two shots is shown in Fig. 2, together with the 10× fit residuals. The standard deviation in fit residuals is 175 μm. In contrast to Cylinder tests on conventional explosives, there is no definite jump-off point. The reason is evidently that the effective detonation shock thickness is a few prills, which is of order the wall thickness.

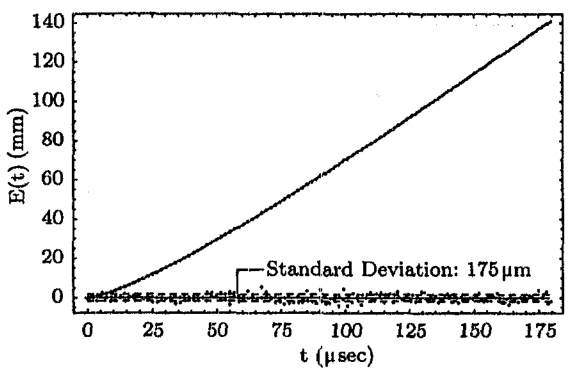

FIGURE 2. Tilt-corrected wall expansion data for Shot#AC88-3926, with analytic fit and 10x fit residuals.

The standard Cylinder test performance metrics are *Cylinder Energy*, E_{19}, and *Gurney Energy*, G_{19}. The subscript indicates that both are evaluated at $E = 19$ mm for the 1-inch test. E_{19} is the radial component of liner kinetic energy per unit liner mass, i.e.,

$$E_{19} \equiv \left. \frac{v_r^2}{2} \right|_{R-R_0=19mm}. \quad (3)$$

G_{19} is the kinetic energy of the HE products plus the liner, per unit mass HE, obtained from the cylindrical Gurney approximation[9],

$$G_{19} \equiv E_{19} \left[\frac{1}{2} + \frac{\rho_w}{\rho_0} \left(\left(\frac{R_0}{r_0} \right)^2 - 1 \right) \right], \quad (4)$$

where ρ_w and ρ_0 are the wall and initial HE densities, respectively, and r_0 is the initial inner tube radius. Neither E_{19} nor G_{19} use D_0, but only the differentiated fit to Eqs. 1 & 2 and, in the case of G_{19}, initial densities and dimensions.

To scale performance metrics from larger tests to match those obtained from the standard 1-inch test, one must make the following scaling argument. If R_0 is sufficiently large compared to the reaction zone thickness then: 1) D_0 is virtually independent of test size and 2) all tube shapes are equivalent when expressed in the dimensionless coordinate system $\tilde{R} = R/R_0$, $\tilde{z} = z/R_0$. Since the flow is steady, $z = D_0 t$. Dividing both sides by R_0 gives the corresponding dimensionless time: $\tilde{t} = (D_0/R_0)t$. Consequently, dimensionless velocities scale as $\tilde{v} = v/D_0$.

Scaling between sizes requires similarity, i.e., comparison at equal values of the dimensionless variable(s). Noting further that D_0 must be size-independent for scaling to hold, one concludes that times and distances both scale with the test size, and velocities are unaffected. Thus "E_{19}" is obtained from a 4-inch test by using the measured radial velocity evaluated at $E = 76$ mm.

The detonation velocity, wall expansion fitting parameters, and performance metrics (scaled to 1-inch diameter) are listed for both tests in Table 1. The two agree to within a few percent.

TABLE 1. Fit and Performance Parameters

Parameter	Unit	Shot1	Shot2
Shot #	—	AC88-3926	AC88-3927
R_0	mm	60.96	60.96
ρ_0	g/cm^3	0.936	0.925
D_0	mm/μs	4.062	4.258
a_0	mm/μs^2	0.1412	0.1545
v_∞	mm/μs	1.065	1.220
σ	—	0.6376	0.5394
E_{19}	kJ/g	0.373	0.383
G_{19}	kJ/g	1.753	1.821

EOS ANALYSIS

We now compute JWL parameters, necessarily assuming that the 4-inch test is large enough compared to the reaction zone that the detonation is nearly Chapman-Jouguet ($D_0 \approx D_{cj}$). Expansion then follows the *principal isentrope*, the empirical JWL expression for which is

$$P_s(V) = A e^{-R_1 V} + B e^{-R_2 V} + \frac{C}{V^{1+\omega}}, \qquad (5)$$

where $V = v/v_0$ and v is specific volume, with v_0 the initial value. The other quantities are fitting parameters, of which only ω—the ideal gas Grüneisen gamma—has physical significance.

The internal energy on $P_s(V)$ is obtained by integrating the pressure using the isentropic relation $P_s(V) = -\mathrm{d}E_s/\mathrm{d}V$, where $E \equiv e/v_0$. The functions $(V, P_s(V), E_s(V))$ then define the principal isentropic curve in EOS space. The $e(P, v)$ EOS *surface* can be approximated in the neighborhood of the principle isentrope by a linear (Mie-Grüneisen) expansion away from it. JWL further assumes that Grüneisen gamma is equal to ω everywhere. This is not really true; rather, it is a convenience that allows the EOS surface to be approximated from cylinder test data alone.

There are two basic strategies by which JWL parameters have been inferred. The most robust calculates the cylinder wall expansion by hydrocode, iterating on the JWL parameters until satisfactory agreement is achieved. The other comprises various simplified methods, which appeal to hydrocode calculations for validation.

Our method employs elements of both strategies; it is a simplified, quasi-analytic calculation of the cylinder test that *explicitly* generates the isentrope. (In fact, this method was first proposed by G.I. Taylor in 1941, some 20 years prior to JWL and the cylinder test.[10]) The present implementation is a refinement of that outlined in Ref. 8. Taylor's method generates a numerical isentrope, to which JWL must be fit. This is a straightforward nonlinear least squares optimization subject to thermodynamic constraints.

Our JWL, inferred from both cylinder tests combined (using average values $D_0 = 4.160$ mm/μs and $\rho_0 = 0.931$ g/cm^3), has parameters: $P_{cj} = 5.150$ GPa, $V_{cj} = 0.6802$, $A = 49.46$ GPa, $B = 1.891$ GPa, $C = 0.4776$ GPa, $R_1 = 3.907$, $R_2 = 1.118$, $\omega = 1/3$, and $E_0 = 2.484$ kJ/cm^3 (E_0 being the energy of detonation computed from the product Hugoniot). It is plotted in Fig. 3 along with three curves derived from the 11.5-inch test of Ref. 2, and a BKW Cheetah[11] calculation. Our JWL has a total energy slightly below Ref. 2; moreover, energy is released *later* in our expansion, our curve falling below at high pressures and above at low pressures. This behavior suggests that flow reaction persists during our measurement. The Cheetah JWL assumes that reactions go to equilibrium, and has about 25% more energy than Ref. 2. This suggests that reaction also persists at 11.5-inch diameter—and perhaps for all laboratory-scale configurations.

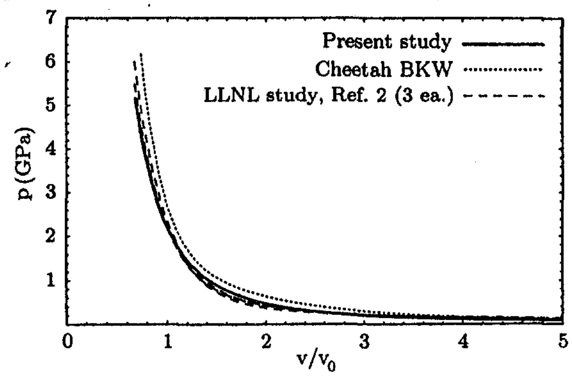

FIGURE 3. JWL expansion isentropes.

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