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The Miniaturization and Reproducibility of the Cylinder Expansion Test

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THE MINIATURIZATION AND REPRODUCIBILITY OF THE CYLINDER EXPANSION TEST

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Abstract. The cylinder test (aka cylinder expansion or Cylex test) is a standard way to measure the Gurney velocity and determine the JWL coefficients of an explosive and has been utilized by the explosives community for many years. More recently, early time shock information has been found to be useful in examining the early pressure-time history during the expansion of the cylinder. Work in the area of nanoenergetics has prompted Air Force researchers to develop a miniaturized version of the Cylex test, for materials with a sufficiently small critical diameter, to reduce the cost and quantity of material required for the test. This paper discusses the development of a half-inch diameter version of the Cylex test. A measurement systems analysis of the new miniaturized and the standard one-inch test has been performed using the liquid explosive PLX (nitromethane sensitized with ethylene diamine). The resulting velocity and displacement profiles obtained from the streak records were compared to Photo Doppler Velocimetry (PDV) measurements as well as CTH hydrocode simulations. Measurements of the Gurney value for both diameter tests were in agreement and yielded a similar level of variability of 1%-4%.

Keywords: Cylex, Cylinder Expansion Test, Photo Doppler Velocimetry PDV, hydrocode, CTH
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INTRODUCTION

The cylinder test (herein called the Cylex test) is a method that measures an explosive's ability to accelerate metal and is the standard means for determining the Gurney velocity [1-2] and coefficients for the Jones-Wilkins-Lee (JWL) equation of state [3-4] for an explosive. The Gurney equations are a set of mathematical formulas used in explosives engineering to determine the capability of a detonating explosive to accelerate a surrounding layer of inert material. The Gurney velocity can then be used to estimate fragment velocities, for example. The JWL equation of state (EoS) is used extensively to model explosive detonation, and requires a set of material-specific coefficients which can be determined directly from a Cylex test. Tests typically use copper cylinders of either one- or two-inch internal diameter with a length of approximately 10”-12”.

The standard one-inch test requires 154 cm^3 of energetic material in order to completely fill the copper cylinder, corresponding to a mass of 250—350 grams for a typical formulation. While a trivial quantity for conventional materials, this required volume can make the test prohibitively expensive to examine new energetic materials. With the rapid discovery of new classes of energetic materials (*e.g.* nanoenergetics, ionic liquids, and other research explosives), it is becoming increasingly important to have a way to quickly evaluate the performance-related properties such as EoS, Gurney velocity, and metal acceleration at a smaller scale to alleviate the expense of scale-up.

With this trend in mind, we have investigated the viability of utilizing a half-inch variant of the cylinder test. This miniaturized version of the standard test utilizes a half-inch inner diameter copper tube and requires one-eighth the amount of material (19.3 cm^3 or 30-40 grams) of the one-inch test, making it more appropriate for testing new energetic materials. This paper discusses our efforts to validate the miniaturized test by performing a measurement systems analysis on both the half- and one-inch tests using the liquid explosive PLX (nitromethane sensitized with 5% (by wt) ethylene diamine). In addition to analyzing the velocity and displacement profiles obtained from the streak records we examined the results of Photo Doppler Velocimetry (PDV) measurements and CTH hydrocode simulations.

EXPERIMENTAL PROCEDURE

Eight one-inch and fifteen half-inch Cylex tests were conducted using the standard Cylex test configuration [5] in a randomized order over a period of 14 days. The liquid explosive PLX was used in each of the tests and was chosen in order to minimize the effect of voids and irreproducibility associated with filling the narrow cylinders. In addition to the streak record measurements of the cylinder wall expansion, hydrocode simulations of both half- and one-inch tests and PDV measurements on a single half-inch test were performed. The resulting variabilities in velocity at two, seven, and ten volume expansions were extracted for both the left and right hand side of the cylinder and compared to the literature value for the Gurney velocity of nitromethane, 2.41 mm/μsec. [6]

Cylinder Test Details

The standard one-inch test consists of a fully annealed, oxygen-free high-conductivity (OFHC) copper tube with a 1.000 inch inner diameter (ID) and a wall thickness of 0.100 inch. The miniaturized test used tubes made from the same copper material with a 0.500 inch ID and a 0.050 inch wall thickness. Identical setups were used in each test.

To ensure that the test series evaluated the inherent variability of the measurement, great care was taken to fill the cylinders and to construct the set-up reproducibly. Each tube was epoxied to a steel plate to form a liquid tight container, and the PLX was poured into the tube to within approximately 0.25 inch of the top of the tube. A piece of Tygon hosing was used as a riser on the half-inch tests to extend the length of the copper cylinder, allowing for easier placement and alignment of the detonator. Both the half- and one-inch tests were initiated using an RP-80 exploding bridge wire detonator (nominally a 0.295 inch diameter by 0.824 inch cylinder) which was centered on the cylinder and submerged approximately 3/8 inch into the PLX.

The time-dependent displacement of the cylinder wall was measured in the standard fashion by recording the backlit silhouette of a horizontal slice of the cylinder viewed through a slit with a Cordin film streak camera. The backlighting in these experiments was cast by an argon candle located approximately one meter behind the cylinder. Kodak TMAX 400 film was used for all of these measurements and the camera's slit width was approximately 100 µm.

Fig. 1 *(left)* shows a typical Cylex streak record. The top 20% of the record contains the static fiducial, which is exposed before the test and is used for spatial calibration of the image. The bottom 80% of the image shows the expansion of

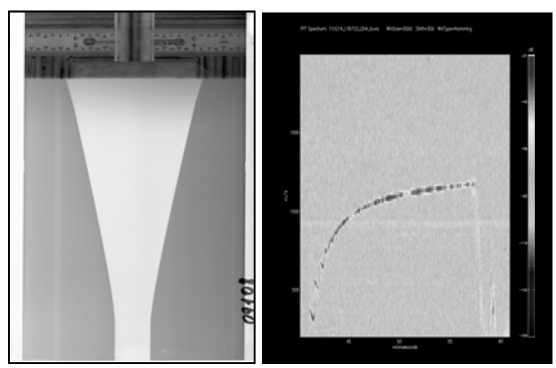

Figure 1. Half-inch test measurements: *(left)* A typical Cylex streak record showing the static fiducial at the top and dynamic cylinder silhouette at the bottom. *(right)* PDV velocity-time trace obtained by taking the Fourier transform of the raw time-intensity.

the cylinder, with time increasing from the bottom to the top of the image.

Given the writing rate of the camera, the image can be converted to a displacement-time representation. Each of the streak records was digitized, calibrated, processed, and analyzed via an automated procedure written in the IGOR Pro software, the details of which have been described thoroughly elsewhere. [7]

In addition to the standard streak records, a PDV [8] measurement was used on a single half-inch test. This was done to examine the compatibility of the technique to the smaller radius of curvature of the cylinder as well as examine the technique's ability to resolve the shorter ring-up period expected in the thinner wall. Fig. 1 (*right*) shows the velocity-time trace obtained by Fourier transforming the raw PDV signal. In principle, the PDV technique has the advantages of measuring the wall velocity directly (as opposed to the displacement observed in the streak image) and in having a higher resolution, but captures data over a shorter time window (only 15 µsec).

Hydrocode Modeling Details

Both the one- and half-inch diameter Cylex tests were simulated using the CTH hydrocode [9]. The simulations were run in two-dimensional, radially-symmetric cylindrical coordinates, with a mesh size of 0.00787 inches and time increments short enough to resolve the shock ringing in the cylinder walls (<0.05 µsec/step). The explosive was simulated using a JWL EoS and a programmed burn model, and the copper cylinder was simulated by the Mie-Grüneissen EoS and a simple yield-strength model. All dimensions of the simulation were identical to those used experimentally. To obtain analogous information to what is observed on a streak record, tracer points were placed on the outer edge of the wall in the simulation to track its position, velocity, and pressure at each time increment.

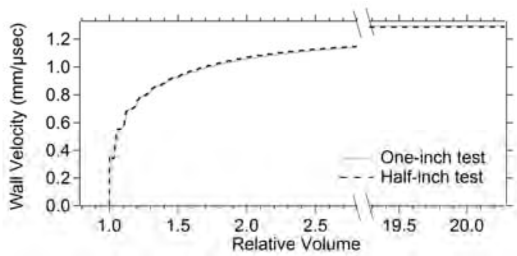

Figure 2. CTH simulations of cylinder wall expansion velocity vs. relative volume expansion for half-inch and one-inch diameter Cylex tests. The results show the theoretical equivalency of the tests across scale.

Fig. 2 shows the simulated cylinder wall velocities for both the half- and one-inch ID models as a function of the relative expansion volume, $v(t)/v(t=0)$, of the explosive. The two velocity profiles are essentially identical out to ten volume expansions, a demonstration of the theoretical equivalency of the one-inch and half-inch tests and simulations across scale.

RESULTS AND DISCUSSION

Fig. 3 shows example CTH and streak record displacement and velocity profiles for both one-inch and half-inch Cylex tests, and PDV data for a half-inch test. The CTH and streak record profiles are in near perfect agreement, aside from a slight deviation in velocity near 3-5 volume expansions (approximately 28 and 30 µs for one- and half-inch tests respectively). The source of the discrepancy has not been identified, but was consistently observed in each of the replicates. Nonetheless, the qualitative agreement indicates the high degree of accuracy in CTH simulations.

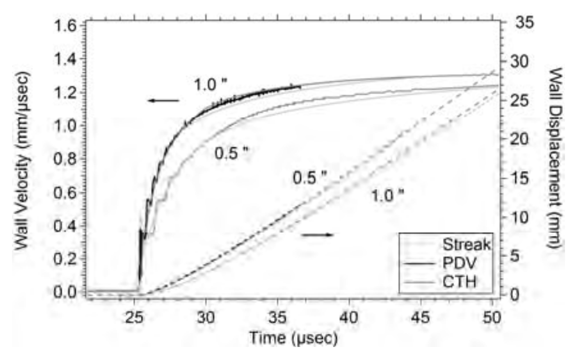

Figure 3. Wall velocity and displacement data for one-inch and half-inch cylex tests, both experimental and CTH hydrocode simulations.

Also in excellent agreement with the streak profiles is the half-inch PDV measurement. In addition to perfectly reproducing the displacement, the reverberations in the copper wall were completely resolved, in contrast to streak data which resolved only the first "pulse." Interestingly, the CTH simulation underestimated the amplitude of these reverberations, a topic that will be investigated further in future tests.

Table 1 summarizes the results of analyzing all of the replicate measurements and comparisons to the CTH and PDV tests, listing the velocities at two, seven, and ten volume expansions as well as the Gurney velocities. The values for the various velocities were statistically indistinguishable. No systematic deviations were observed between the data taken from the right and left side of the streak records, nor were any statistically significant differences observed between the half-inch and one-inch tests. The only notable difference between the two sizes is the approximately four-fold increase in the variability of the half-inch test. However, the uncertainty in velocity is at most 4%, a value which is likely acceptable for most applications.

TABLE 1. Test descriptions, average expansion wall velocities at two, seven, and ten volume expansions, and the calculated Gurney velocity for one- and half-inch Cylex tests. Numbers in parenthesis are the standard deviations of the replicate shot measurements in the last decimal places. Uncertainty in the PDV measurements is due to noise inherent in the single measurement.

Test	# Shots	v_2 (mm/μs)	v_7 (mm/μs)	v_{10} (mm/μs)	v_{Gurney} (mm/μs)
1 inch, right side	8	0.95 (01)	1.19 (01)	1.23 (01)	2.38 (01)
1 inch, left side	8	0.95 (01)	1.19 (01)	1.23 (01)	2.38 (02)
½ inch, right side	15	0.98 (03)	1.19 (05)	1.23 (05)	2.42 (08)
½ inch, left side	15	0.99 (03)	1.21 (04)	1.24 (04)	2.39 (09)
1 inch, CTH	1	0.97	1.21	1.23	2.39
1/2 inch, CTH	1	0.99	1.22	1.25	2.45
½ inch, PDV	1	0.99 (02)	1.21 (05)	(off record)	2.39 (11)

The most important values to compare are the Gurney velocities, which were found to be within the experimental uncertainty of the literature value of (2.41 mm/μsec). Remarkably, both experimental techniques and the CTH simulation agree as well.

CONCLUSIONS

The half-inch Cylex test has been shown to be a viable test for materials with an appropriately small critical diameter. The resulting v_2, v_7, and Gurney velocities were in agreement with the one-inch test within a standard deviation of the average, though the variability in the half-inch test was higher at about ± 4 %. Further, PDV measurements have also been demonstrated to be compatible with the smaller diameter test and have been shown to clearly resolve the early-time, shock-induced features of the cylinder expansion.

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