LA-6677-MS
Informal Report

UC-45

Issued: February 1977

High-Explosive Performance Tests

by

W. C. Davis

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy $3.50 Microfiche $3.00

HIGH-EXPLOSIVE PERFORMANCE TESTS

by

W. C. Davis

ABSTRACT

Performance tests for high explosives are widely used, but little understood. Selected tests are discussed and compared, and the influence of initial density on apparent performance explored. The available test results indicate that differences between two explosives of about 2 or 3% can be resolved in the common tests. They also show, at least for common explosives, that there is little or no inversion of ordering in performance between tests which sample the high-pressure part of the isentrope, and those which sample the low-pressure part. Inversions can be found when two tests which differ markedly in dependence upon initial density are compared.

INTRODUCTION

A performance figure of merit for high explosives seems to be an intuitively obvious concept. At the Los Alamos Scientific Laboratory (LASL) it is (or should be) an index which orders explosives according to the amount of useful energy each delivers in an implosion system. Oddly enough, there is no generally accepted performance figure of merit, and there is little agreement about how to obtain one. The problem is not as simple as it appears at first glance.

In this report no solution is presented or even proposed. It contains only an attempt to point out some of the difficulties. Two questions in particular are addressed. First, how can the correlation between a performance test and an implosion system be maximized, and second, what is the least resolvable difference in performance that can be distinguished by the several performance tests now in use? The answer to the first question seems to be that one must be very careful and think very hard about the test and the system; more understanding of their relationship is needed. The second is easier and there are many good data to use for comparison; if the explosives are much alike in both density and composition the tests will distinguish differences down to about 2%, and if the explosives are much different, one could be easily fooled.

THE UTOPIAN SOLUTION

If we had a hydrodynamic equation of state for each explosive, and computer simulation for any proposed system which would give an accurate and detailed description of the motion of every point, there would be no need for a figure of merit, or for performance tests except for those experiments needed to determine the equation of state. Any system could be designed in detail to any required degree of accuracy using the explosive with the best performance for that system. Some sort of screening tests to obtain an approximate equation of state cheaply and quickly for new explosives to see whether they are of possible interest would replace the performance test.

At the present time, we do not have accurate equations of state for explosives, partly because we do not have the necessary computer simulation to interpret the experiments. And part of the reason the computer simulation is inaccurate is that there are many small, poorly understood effects in explosives caused by the finite reaction time (buildup of initiation, interaction smoothing, size-and-time-dependence of the detonation, edge effects, etc.) so the computer code does not have the necessary physical processes described properly.

DENSITY EFFECTS ON PERFORMANCE TESTS

The geometry of a performance test or of a proposed system has a strong influence on the transfer of energy from explosive to metal. To illustrate this influence, let us consider a performance test, the cylinder test, which is a copper tube with explosive in it, and a simple explosive system, a flat copper plate with explosive on one side of it. Both the test and the system can be easily treated using the Gurney model to obtain the final velocity of the metal. In this model, the metal is considered incompressible, and the material velocity in the explosive is taken as a linear function of distance at all times, so the necessary integrals can be performed. An excellent review of the model and its applications is given by Kennedy,[1] and the model has been tested against more accurate calculations for several cases by Hoskin et al.[2] The simplicity of the results of the Gurney model make it ideal for an illustration such as we need here, and its accuracy is remarkably good.

The final square of the velocity for the cylinder wall is

$$v^2 = 2E/(M/C + 1/2) \quad ,$$

where E is the effective energy/gram of the explosive and is about 70% of the enthalpy of detonation, M is the metal mass/unit length, and C is the explosive mass/unit length of the tube. The square of the velocity of the flat metal plate is

$$v^2 = 2E/\{[(1 + 2M/C)^3 + 1]/[6(1 + M/C)] + M/C\} \quad ,$$

where the symbols have the same meaning except that M and C are for unit area. These formulas and others are given by Kennedy.[1]

Let the tube be a standard cylinder test with inner and outer radii in the ratio 5 to 6, and let the plate system have the metal-to-explosive thicknesses in the ratio 0.265, with the explosive at density 1.53 g/cm^3. (This might be RDX/void 85/15 volume percent.) Substitution into the formulas shows that the metal velocities for cylinder wall and flat plate are equal.

Now keep the proportions the same, and the energy per unit volume of the explosive the same, but change the explosive density to 2.00 g/cm^3. (This might be RDX/additive 85/15 volume percent with an inert dense additive to bring the density up to 2.) Now the cylinder wall energy is *down* by about 5%, but the plate energy is *up* by about 12%. If one used cylinder test energy as a criterion for the choice of explosive for the flat plate system, without thinking about it carefully or making some numerical studies, he might easily choose the wrong explosive.

This density effect has been studied by Smith[3] in dent plate experiments; his geometry is not exactly like the simple example above but the principle is the same. In the flat plate system the only tamping available is the inertia of the explosive products and their density has a strong effect on energy transfer. In the cylinder the opposite wall provides the tamping and the explosive density is not important, except that motion of the denser products makes some energy unavailable to the tube wall. In Dobratz,[4] Table 8-7, there are some values for corrections to cylinder wall energies for various additives. These values, presumably from experiments, are not consistent with the simple Gurney treatment. They indicate no change in cylinder wall velocity for the density change case considered here. Perhaps more study is needed, but more likely the values given were intended for less drastic modification.

As an example of how the density effect might be misleading, consider a comparison of TNT (1.63

g/cm^3) and X-0219 (1.915 g/cm^3) with PBX-9404. The cylinder test shows that TNT gives its metal 60% of the energy from PBX-9404, and X-0219 gives 61%. Smith's dent test shows that TNT makes 61% as deep a dent as PBX-9404, and X-0219 makes 72% as deep a dent. This difference in the two tests doesn't mean that the cylinder test is right and the dent test wrong; both are right but they are measuring different things. For any given application, one of the tests may be more nearly indicative of performance than the other, depending on the details of the system.

PRESSURE-TIME HISTORIES

In different arrangements of metal and explosive, the main part of the energy transfer takes place at different pressures. The qualitative sketches in Fig. 1 (at the left) show plots of pressure at the interface between explosive products and metal, as a function of time, for an expanding cylinder like a cylinder test, for an imploding cylinder with an annular detonation in explosive surrounding an empty tube, and for a spherical inward detonation of a shell of explosive surrounding a hollow metal shell. In the two implosion cases, the rising pressure at late time is caused by the convergence, and both have a minimum in the pressure. The energy transferred across the interface increases with time, as shown in the sketches at the right; it is of course equal to the time integral of the pressure times the area times the interface velocity, all of which are functions of time. It would be nice to have quantitative data for these curves, but even without it one can see that different parts of the expansion curves are important in different cases. Only in the spherical implosion system is the high-pressure expansion of interest. A good performance test should sample the expansion region of interest for the application.

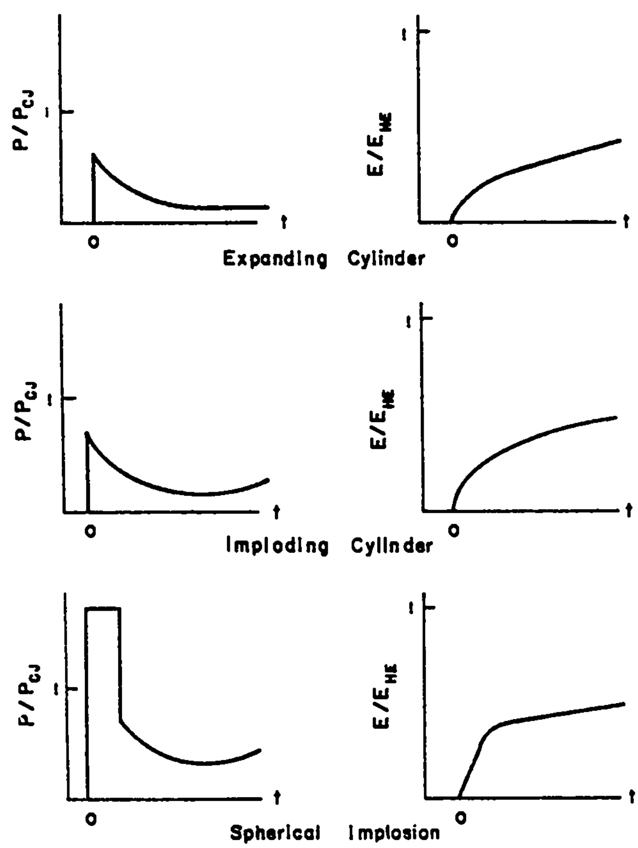

Fig. 1.
Sketch of pressure and energy transfer.

LEAST DISCERNIBLE DIFFERENCES

A performance test is not needed to find out that TNT is not as good an explosive as PBX-9404. Very simple calculations and very simple tests easily resolve such a large difference. At the other extreme, a performance test cannot be expected to show a difference between two very similar explosives such as PBX-9404 and PBX-9501. The utility of a test or a group of tests is increased as the least discernible difference is decreased. One way to try to estimate the discernible difference is to compare results from different tests for a group of similar explosives.

There are seven HMX and RDX explosives for which a reasonably complete set of performance measurements has been made and which can be compared. The explosives, with their densities and detonation velocities, are listed in the first column of Table I, and the results of the measurements are in the other columns. With the exception of X-0204, which is HMX/Teflon 83/17 wt%, all the explosives are familiar ones; compositions and other properties are readily available.[4] The performance of these explosives is at the high end of the range, and their energies are within about 15% of each other.

Seven measures of performance have been chosen for comparison. Each is discussed in some detail below. The average of the values for one kind of test for the seven explosives has been used as the center

TABLE I

COMPARISON OF PERFORMANCE TEST RESULTS

Explosive Dens Vel	Impl	Cyl 19	Cyl 6	Dent	BKW	u_{fs}	P_{calc}
PBX-9404	1.000	1.620	1.295	0.434	0.114	3.81	36.55
1.844 8.80	+7.96	+8.67	+9.43	+8.08	+5.70	+4.18	+8.46
Octol	0.963	1.535	1.215	0.403	0.108	3.70	33.53
1.813 8.48	+3.96	+2.97	+2.67	+0.36	+0.13	+1.17	−0.50
X-0204	0.931	1.480	1.184	0.420	0.115	3.92	34.65
1.909 8.44	+0.51	−0.72	+0.05	+4.59	+6.62	+7.19	+2.82
LX-04	0.929	1.470	1.170	0.409	1.110	3.73	34.06
1.865 8.46	+0.29	−1.39	−1.13	+1.85	+1.99	+1.99	+1.07
Cyclotol	0.907	1.445	1.140	0.370	0.103	3.52	31.37
1.754 8.30	−2.08	−3.07	−3.67	−7.86	−4.50	−3.75	−6.91
PBX-9010	0.890	1.470	1.160	0.394	0.102	3.57	32.52
1.788 8.37	−3.92	−1.39	−1.98	−1.89	−5.43	−2.38	−3.50
PBX-9011	0.864	1.415	1.120	0.381	0.103	3.35	33.21
1.777 8.50	−6.72	−5.08	−5.36	−5.12	−4.50	−8.40	−1.45
average	0.9263	1.4907	1.1834	0.4016	0.1079	3.657	33.70

for that test, and performance values are given as percentage above or below that average. This normalization makes it possible to compare values from different tests.

The values, the averages, and the percentages are given in Table I, with the percentage listed under the value in the table. Each test has been assigned an error bar; since little is known about the distribution of values for any of the tests, these error bars represent my guess of the effect of experimental error, systematic error, interpretation error, and relevance of the particular test. The results are plotted for the seven explosives in Fig. 2. The abscissa in the plots is just the cardinal number used to denote the test used, in the same order as they appear in the table. The ordinate is the percentage which the explosive is above or below the average for each test.

In Fig. 2 the measurements define a performance band for each explosive. The bands are so wide that, to avoid overlap, it was necessary to make a separate graph for each explosive except the best, PBX-9404, and the poorest, PBX-9011. The ordering of tests on the abscissa indicates their probable relevance to implosion system performance. The left half of the band gives a good idea of explosive performance. For example, PBX-9404 seems to be from 7% to 11% above the average, while Cyclotol may be average to about 6% below. It is clear that a performance index can be obtained from these measurements, but that it has an uncertainty of 2 or 3%.

DESCRIPTION OF TESTS

The principal reason for choosing to compare these seven explosives is that data from a series of spherical implosion shots[5] using them are available. The systems were identical except for the explosive.

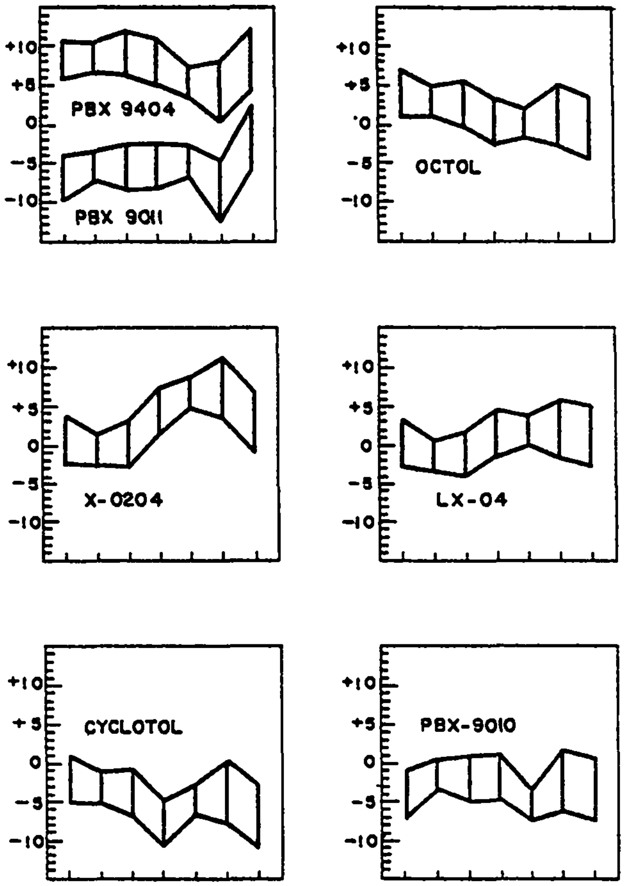

Fig. 2.
Test results.

A shell was collapsed by the explosive, and the position-time history of its inner surface was recorded with a large number of electrical-contactor pins. A least-squares fit to these position-time data was used[6] to get the kinetic energy of the steel near collapse, and these energy values in relative units are listed in the first column of Table I. The experimenters estimate that the precision of these values is ±3%.

The cylinder test is familiar and its detailed description is available.[7,8,9] Most of the data in Table I are from Dobratz.[4] The test is made with a cylinder of explosive 25.4 mm diameter and 305 mm long tightly encased in a copper tube with wall thickness 2.54 mm. The position of the wall as a function of time is measured at a distance of 200 mm from the initiation end of the cylinder, and the results differentiated to obtain velocity. The usual values used are at wall expansions of 6 mm and 19 mm, corresponding to expansion to 2 and 7 times the original volume. The copper is commercial oxygen-free high-conductivity material, and seems to be reasonably reproducible. The velocities at 19 mm are varying only slowly and the position-time fit is good. The velocities are probably reproducible to about 1%, and the energies to 2%. At 6 mm the tube wall is both accelerating and ringing strongly, so the measurements are not as good; 3% error flags have been used for the energy. The units for the values in Table I are kj/g for the energy of the copper wall. Although it has been suggested that the 6- and 19-mm values are not well correlated, $E^{19}/E^{6} = 1.27 - 0.35\ (\rho_0 - 1.80)$ fits the data well. The density correction has not been made in the data presented here. The 19-mm value is listed in column 2 and the 6-mm value in column 3 because of their relative precisions.

The plate-denting test has been described by Smith.[8] It consists of a cylinder of explosive, unconfined, 8 inches long and 1-5/8 inch diameter, stood up on a plate of 1018 cold rolled steel, and detonated at the top. The depth of the resulting dent in the steel is the measured quantity. Smith has shown that the test is reproducible and correlates well with other performance measurements. The correction for explosive density was discussed above. He recommends using steel all from the same lot to remove one source of variations. These inexpensive shots allow good sampling of the distribution. The precision seems to be about ±3%.

A different sort of performance figure can be obtained from Mader's BKW calculations.[10] Fickett[11] has shown, building on work of Jacobs,[12] that a quasistatic cycle for detonating explosive can be defined, and that the maximum work which can be obtained from the explosive is equal to the p-v work down the isentrope through the CJ point to ambient pressure, minus one-half the square of the particle velocity at the CJ point. This value can be obtained from the BKW listings using the relationship

$$\int p\,dv = E^{s}(p_{CJ}) - E^{s}\ (\rho_0) \quad ,$$

where E^{s} is the internal energy on the principal isentrope. The BKW calculations are based upon an assumed equation of state for the explosive products which depends on the explosive composition, and has been calibrated to experimental results by adjusting covolumes of the various molecules. Chemical equilibrium, found by calculating the minimum free energy of the mixture, is assumed to exist. This method, then, combines the initial chemistry of the explosive, the requirement of chemical equilibrium in the products, and some calibration experiments. The Fickett-cycle values are listed under BKW in column 5 of the table; the units are Mbar-cm^3/cm^3. In the plots the error flag for these values is ±2%, which represents a guess to take into account the fact that the tables do not go to ambient pressure but only to about 100 bars, the errors in the method at low pressure, and an estimate of relevance of this total work figure to the problem at hand.

The free-surface velocity measurements given in column 6 are the zero-thickness extrapolation of a fit to measured free-surface velocities at various plate thicknesses. The system is a large plane-wave detonation driving a dural plate. The technique has been described by Deal,[18] and most of the values given are from his work. The precision of these results is probably ±2%, but the finite reaction zone causes additional uncertainty in the interpretation, so the error flags are ±4%.

The pressure at the CJ point is given by

$$p_{CJ} = \rho_0 D^2/(\gamma + 1) \quad .$$

The density ρ_0 and the detonation velocity D are known very accurately for these explosives, and an estimate of a value for γ allows us to get an approximate p_{CJ}, which is closely correlated with performance. We know that γ is a function of initial density and take

$$\gamma = 1.8 + 0.6\rho_0 \quad .$$

The values are given in column 7, and the error flag is ±4% to allow for the lack of sophistication of the approach.

SUMMARY

The response of performance test i to explosive j is a number which can be expressed as

$$R_{ij} = R_{ij}\ (\rho_{0j}, E_j, a_{1j}, \ldots, a_{nj}) \quad ,$$

where the a's are coefficients in the hydrodynamic equation of state of the explosive products. (E is of course another constant in the equation of state, but here we give it a special position.) With a very simple approach it was shown that the density enters differently into the responses of performance tests with different geometry. It was suggested, but not demonstrated, that tests with different pressure-time histories would respond differently to changes in the a's, the equation of state coefficients. Finally, it was shown that current results from various performance tests of a group of similar explosives (similar means that the a's are all about the same because the composition is about the same) all seem to be related within a few percent to some poorly defined explosive energy measure.

REFERENCES

1. J. E. Kennedy, "Explosive Output for Driving Metal," in *Behavior and Utilization of Explosives in Engineering Design,* L. Davidson and J. E. Kennedy, Eds., New Mexico Section of the ASME, 1972, p. 109.

2. N. E. Hoskin, J. W. S. Allen, W. A. Bailey, J. W. Lethaby, and I. C. Skidmore, "The Motion of Plates and Cylinders Driven by Detonation Waves at Tangential Incidence," Proc. 4th Symp. (Intern.) on Detonation, ACR-126, 1965, p. 14.

3. L. C. Smith, "On Brisance, and a Plate-Denting Test for the Estimation of Detonation Pressure," Explosivstoffe No. 5, p. 106 and No. 6, p. 130 (1967).

4. Brigitta M. Dobratz, Ed., "Properties of Chemical Explosives and Explosive Simulants," Larwrence Livermore Laboratory report UCRL-51319 (December 15, 1972, rev. July 31, 1974).

5. Unpublished experimental results, Los Alamos Scientific Laboratory Group GMX-4, 1959 to 1966.

6. Unpublished Los Alamos Scientific Laboratory work, Frederick P. Cranston, 1954.

7. J. W. Kury, H. C. Hornig, E. L. Lee, J. L. McDonnel, D. L. Ornellas, M. Finger, F. M. Strange, and M. L. Wilkins, "Metal Acceleration by

Chemical Explosives," Proc. 4th Symp. (Intern) on Detonation, U.S. Office of Naval Research, Washington, DC, report ACR-126 (1965), pp. 3-13.

8. M. Finger, H. C. Hornig, E. L. Lee, and J. W. Kury, "Metal Acceleration by Composite Explosives," Proc. 5th Symposium (Intern.) on Detonation, ACR-184, (1970), p. 137.

9. E. L. Lee, H. C. Hornig, and J. W. Kury, "Adiabatic Expansion of High Explosive Detonation Products," Lawrence Livermore Laboratory report UCRL-50422 (1968).

10. C. L. Mader, "Detonation Properties of Condensed Explosives Computed Using the Becker-Kistiakowsky-Wilson Equation of State," Los Alamos Scientific Laboratory report LA-2900 (1963); and results for X-0204 as a private communication.

11. W. Fickett, "Evaluation of Explosive Performance with a Simple Model; a Test of a Proposed Aluminum System," unpublished LASL work, March 1962.

12. S. J. Jacobs, "Energy of Detonation," NAVORD report 4366, (September 1956).

13. W. E. Deal, J. Chem. Phys. 27, 796 (1957).