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AUTHOR(S) I. B. Akst, M-8

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

# HEAT OF DETONATION, THE CYLINDER TEST, AND PERFORMANCE MUNITIONS

**Irving B. Akst**
**Los Alamos National Laboratory**
**Los Alamos, New Mexico**

Heats of detonation of CHNO explosives correlate well with copper cylinder test expansion data. The detonation products/calorimetry data can be used to estimate performance in the cylinder test, in munitions, and for new molecules or mixtures of explosives before these are made. Confidence in the accuracy of the performance estimates is presently limited by large deviations of a few materials from the regression predictions; but these same deviations, as in the insensitive explosive DINGU and the low carbon systems, appear to be sources of information useful for detonation and explosives research. The performance correlations are functions more of the detonation products and thermochemical energy than they are of the familiar parameters of detonation pressure and velocity, and the predictions are closer to a regression line on average than are those provided by CJ calculations. The prediction computations are simple but the measurements (detonation calorimetry/products and cylinder experiments) are not.

## INTRODUCTION

A hypothesis that heat of detonation has a primary effect on the performance of explosives and munitions is certainly neither new nor arcane. But heat of detonation is not a quantity which has been measured extensively. Heats of deflagration and explosion were measured fairly frequently in the past, but few of those data have been used or generated recently. Heat of combustion is usually measured for a new explosive, often for the determination of the heat of formation. At the same time, quite a few explosives performance measurements historically have been very direct and often narrow, as in, say, arena tests of a munition of intended application, or they have been quite indirect, as in the determination of CJ parameters. Now there is a body of data on heats and products of detonation and a body of data on performance in a form that is more widely relatable to munitions applications. These are detonation calorimetry (1) and the copper cylinder test (2). In this work, these bodies of data are used to test the hypothesis, point out its importance, and derive useful information for the relationships established between the two sets of data.

One of the areas that might produce useful information has to do with the insensitive explosives. The current interest in them and the rather low performance produced by two of these (TATB and NQ)--in spite of their reasonably high calculated CJ pressure and measurements of detonation velocity and pressure--suggested that some other detonation condition or parameter is as important as CJ pressure, or more so for the performance of such explosives. Both of these explosives (or formulations very rich in them) have calculated and measured CJ parameters not too different from Comp B, which has cylinder energy 32-37% higher than TNT, depending on the

expansion (V/Vo of 2 to 11), and detonation pressure about 35% higher than TNT. But the TATB and NQ cylinder energies are not much different from those of TNT: 15 to 7% for TATB, 12% to approximately 0% for NQ, at the same expansions.

Kamlet (3) wondered whether, for some reason, insensitive explosives were not reaching the infinite-medium steady-state condition. He also suggested that the trouble with NQ (poor performance) was the low Q (heat of detonation), and that no formulation very rich in NQ or other low-Q explosives would have high performance (of the type herein, see below).

The heat of detonation (Q, in calories or kilocalories per gram) is considered herein to be the thermochemical energy produced during detonation and usable for the work to be done by the explosive. Q or Qv (volumetric heat of detonation, $\rho Q$, where $\rho$ is density) would seem from first principles--energy conservation--to be a primary parameter of an explosive, upon which all physical reaction and performance depends. Therefore it should be useful to compare this parameter with other explosive parameters, and it seemed it would be especially useful to do so with respect to performance data relevant to munitions.

Performance is defined herein as the metal-propelling ability of an explosive, as quantified by the "standard" expanding copper cylinder test (2), because the test produces information of direct use in munitions and itself resembles a number of them in form. These include shells and bombs, which are similar to the test in geometry (end-initiated internally loaded cylinders), in metal mass to explosive charge ratios, and in terms of the length of time over which the explosive energy and products are applied to the metal. The last two factors would include some shaped charges.

Thus we considered it worthwhile to examine a range of explosives, especially to include other apparently insensitive ones such as DINGU and NTO, regarding Q and performance, to characterize these and try to generalize the phenomena.

## EXPERIMENTAL

The field of explosives for which both detonation calorimetry and cylinder tests have been done is rather small, with a fair number of those being similar or mixtures of monomoleculars studied individually. For example, there are a number of plastic-bonded pressed explosives rich in HMX, with fluorocarbon binders. It seemed best to examine as large a range of explosives as feasible, in terms of Q and performance, but limited to comparable species, that is, monomolecular ideal CHNO concentrated compounds (without additives such as aluminum or large amounts of non explosives). These would be likely to have as near an unconfounded CJ state and as usual an adiabatic expansion coefficient (gamma) and detonation temperature as possible. Furthermore, there should be limited use of similar materials to have as appropriately weighted regression as possible. The explosives for the base set were selected on that basis; there are 15 in all, with a range of power from NM to HMX. Unfortunately, for neither DINGU nor NTO has Q been measured yet, nor has a body of NQ data been published; but they are important to the study, with cylinder tests having been done, and are included. Three intermoleculars, one HNO, and two CNOs were added to the

base set to explore further the correlation, and there is an interesting set of formulations showing effects from aluminum (Table III).

The best (and essentially the only) readily available source of a sufficient quantity of modern, accurate products and heat of detonation data is the work of Ornellas at LLNL (1). However, Volk has been making products measurements recently (4), calculating heat of detonation from the products. This can yield good energy quantities, as is evident from Ornellas' work, in the usually close agreement of the energy calculated from the products and that obtained calorimetrically. Overall, the precision and accuracy of Ornellas' Q measurements are about 1%.

There are few other published data. Some of Volk's experiments are in the manner suggested by the author and carried out at LLNL (5)--that is, using a large sphere with a thin atmosphere of noble gas to slow and dilute the products, thus preventing re-equilibration through shock at the container walls, without the need for massive confinement of the explosive to carry off the energy kinetically. Los Alamos made a few measurements some time ago (6), and Pantex began to make such measurements (7), while NSWC/WOL has made some too (8).

All the thermochemical energy data listed as measured in Table I are taken from Ref. 1. The "ΔH detonation, Experimental" values are normalized, where necessary, to the energy with water as a gas. This is because in the cases of interest (metal-moving military munitions), that is the state which is germane, condensation to liquid being too slow and too late to influence performance. The normalization was done by subtracting 10.5 kcal/mol of water, the difference between -68.3 and -57.8 kcal/mol as the heats of formation of liquid and gaseous water. Although DINGU has not had Q measured, the formulation X-0432 is listed as such because it has 43% TNT, for which Q is known, and the calculated value was used for the DINGU contribution. Calculated gravimetric heat of detonation used heats of formation in (9) or for DINGU and NTO as reported (10), -42.3 kcal/mol and -28 kcal/mol, respectively.

The calculation for Q used the convention of burning hydrogen to water to the limit of oxygen or hydrogen, then carbon to the dioxide, to the limit of oxygen or carbon. Because of the thesis concerning an effect of structure on products and energy (see Results and Discussion, below), calculations were also made for DINGU and NTO, in which half a mole of carbon monoxide would be produced for each carbonyl, before the dioxide.

Polymer binders were estimated to be 20% energetic (because most have fluorine), hydrocarbons (Comp C-4) inert, and the PBX-9404 binder 50% energetic, for the nitrocellulose.

Volumetric heat of detonation, Qv, was calculated as a maximum from the measured Q (where available, calculated Q where not) and the theoretical maximum density (TMD) of the compound or mixture. Qv was also calculated as the specific energy of the explosive in its cylinder test, Qcyl, by using the density of the charge in the test rather than TMD. It is this last value, Qcyl, that was used in the correlations.

For Table I, detonation velccities and detonation pressures were calculated by the Kamlet-Jacobs short method (11), because that method is suited to the sample set of "comparable species" defined above (monomolecular ideal CHNO compounds). Also, it seems to afford rather even treatment of samples, perhaps more so than some more complex codes with various equations of state. In Table II and Table III, detonation pressures were calculated from the experimental densities and detonation velocities, and an assumed constant adiabatic expansion coefficient ($\gamma$) of 2.8, a value which yields, on average, pressures consistent with KSM calculations and a fair number of reported pressures.

Cylinder performance data (Table II) are from tests done at Livermore (12), Pantex (13), Eglin AFB (14), and Los Alamos (15), in inner diameters (i.d.s) of 25.4, 50.8, or 101.6 mm--chosen to be well above unconfined failure diameter. The "standard" or usual configuration was used, that is, full copper wall thickness of 1/10 the copper tube ID, with the sample length 6, 9 or 12 times the i.d. Initiation was by means of a plane wave lens and pad of Comp B of the HE diameter (i.d.) and thickness one-half the ID, outboard of the tube. Detonation velocity was measured in all the tests over nearly the full sample length, while the radial copper wall motion was measured shadow graphically by streak camera, with the slit about 5 or more diameters downstream from the initiated sample surface. Various analyses were used, from polynomials to power functions and splines, and derivatives thereof; all seem essentially equal, and the overall precision of the measurements is about 1%.

Data are scaled to the 25.4-mm-diameter test, that is, the radial wall distances and times have been divided by the ratio of the diameter of the test to 25.4. Typically, the wall motion could be followed accurately from at least 5 mm to 30 mm or farther (scaled to 25.4-mm diameter) radially from the static position. Scaled distances of 6, 19 and 30 mm are equivalent to internal volume expansion ratios (of the tube and products), V/Vo, of about 2, 7, and 11. These are points customarily reported, although most tests have been analyzed for each millimeter of motion. Some data on wall acceleration are also available from second derivatives of the r,t curves, but there is of course more error, and no pattern germane to the aim of this study seemed to emerge.

Both the detonation calorimetry experiments and the cylinder test principally measure energy, the former thermally and the latter kinetically. The relationships between the two should be readily quantifiable, if the experiments are reasonably precise and accurate, because both are efficient. With heats of detonation and squares of copper wall velocities as the principal variables, linear regression was carried out. The correlation coefficients and line parameters are given in Table IV.

## RESULTS AND DISCUSSION

The principal correlations to look for should be causatively correct ones to test the hypothesis that the chemical energy of the detonation reaction has the primary effect on performance in the cylinder test, and some munitions, through energy conservation. The cylinder performance parameter is the copper wall kinetic energy. The prime correlation has the thermochemical energy Qcyl as the independent variable and the square of the wall velocity at V/Vo = 11 as the dependent variable. The expansion

V/Vo = 11 is the main one used, because it is the largest one accurately measured; it represents the most efficient use of the explosive, nearest to free flight and the Gurney "final velocity" energy. The sample set best suited to test the thesis was defined above as having essentially only monomolecular ideal concentrated CHNO compounds. The hypothesis also requires a 0,0 origin. Therefore 0,0 was added to the data to form the base set. Correlations at different expansions and with variations of the sample set--adding, deleting, or modifying data points--were also calculated to test effects, as were some using other variables such as detonation pressure.

As Table IV shows, the correlation coefficient testing the main hypothesis is high, with r being nearly 0.98 for the base set using the principal variables as stated above. This supports the hypothesis well and suggests that one might profitably do more detonation heat tests and use the data and the correlation for predictive and other practical purposes such as designing explosives and doing research on detonation phenomena. The coefficients are over 0.97 at the lesser expansions V/Vo = 7 and 2. Also, the latter perhaps is a little surprising because one might expect velocities at such low expansion to be more responsive to detonation pressure.

The good fits also reflect well on the experimental quality, that is, the accuracy, or at least the precision, of the measurements. Noise and scatter might be expected to result from the usual experimental errors, exacerbated by those of time, place and investigator, error generated by derivatives (wall velocity) and roundoffs (e.g., squaring a rounded-off velocity). While it is important that the data and fits are good, deviations from the regression are also important as they are the measure of uncertainty in predictions one would like to use the correlations for, and some may be sources of new information. As Table V shows, the deviations are reasonably small, with exceptions: the one or two data points with large deviations from the regression line decrease the correlation coefficient, but more importantly, they may indeed be sources of information. One would like to think they are not just statistical "flukes" or bad data, but that they are caused by real differences in the materials and phenomena

The most deviant points, the only really large deviations in the original sample set, are those for the 94/6 wt%DINGU plastic-bonded explosive (X-0420) at -18% in energy from the regression line, and the 57/43 wt% DINGU/TNT mix (X-0432) at -13%, as may be seen in Table V. The correlation coefficient for the base set with the DINGU points deleted is very high, above 0.99. Recall that Q has not been measured for DINGU . Therefore, its Qcyl was from calculated Q. This may be a cause of at least part of the large deviations, because all the calculated Qs but one are higher than measured Q's by various amounts, as may be seen in Table I.

The only other deviations of size in the base set are about -6% for TNT and about +6% for HMX and its close relative PBX 9404. A rather anomalous deviation outside of the correlation is the very large one in NM, where the measured Q is more than 20% below the calculated value. There were some other interesting deviations in explosives outside of the base set, discussed below.

The Qs for DINGU and NTO were recalculated based on the supposition that structure has an effect on the products, hence the energy produced. It was assumed that a carbonyl structure predisposes the set of products to contain more CO and less

$CO_2$ than it otherwise would have in a system with the same elemental composition but with oxygens on nitrogen, for example. The idea that structure affects detonation characteristics is expressed well in Rothstein and Petersen's work (16), in which they show high correlation of detonation velocity with composition and structure alone, without numbers for heat of formation or density (although of course those are also functions of structure) or CJ calculations. In that work, they assign oxygen use values which vary with the structure, for example subtracting 0.4 oxygens per carbonyl available for the calculational factor F. I arbitrarily assumed, for exploratory purposes, that there would be 1/2 mol CO + 1/4 mol $CO_2$ per carbonyl oxygen, rather than 1/2 mol $CO_2$ as in the dioxide assumption. This would put energy 10.35 kcal below the dioxide assumption, for each such occurrence. In NTO there is one carbonyl, and in DINGU there are two.

The DINGU recalculations (for X-0420 and X-0432) reduce the Qcyls to 1845 and 1810 cal/cm$^3$. These fit the regression line better, reducing the deviations (defined below) from -18% and -13% to -13% and -11%. However, they do not raise the correlation coefficient r to the value deleting the DINGU points.

The recalculated NTO does not fit the line as well as the original NTO, the deviation changing from -2.7 to +6.3%.

The relatively poorer correlation of detonation pressure with performance may be a reflection of the anomalous situation regarding insensitive explosives: all four (NQ, TATB, DINGU, and NTO) have cylinder test performance significantly lower than one would expect from the detonation pressures of and experience with the usual "sensitive" military explosives. In those rich in RDX or HMX, the correlation of performance with detonation pressure is good. However, much of the study and use has been in fast-response systems, i.e. those having thin metal (low metal mass to HE charge ratios) or short flight ranges before detonation products expand greatly or escape. Those applications, where free flight occurs quickly, are no doubt more responsive to the single point (CJ) or narrow expansion range on the isentrope than is the cylinder test, which responds to much more of the area under the PV curve, as do many munitions.

The standard high-powered explosives also have high Q, however, so they too fit the correlations between Q and metal-moving performance--providing, as implied in the previous paragraph, that the metal to be moved is sufficiently massive and retentive of the explosive's detonation produces and energy. Although P must be related to Q in some way, the correlation coefficient is not very high (r = 0.91 to 0.92) due, no doubt, to factors other than Q and the limited accuracy or precision of the P calculations and measurements.

There are a few explosives outside the base set that widen the field, having had both Q and cylinder performance measured. These are an HNO intermolecular (hydrazine/hydrazine nitrate, RX-23-AA), two CNOs (BTF and HNB), and two CHNO intermoleculars (EAR and AN/ADNT (17) along with the parent monomolecular ADNT). Adding these to the base set does not reduce the fit much, with the coefficient r still being over 0.97 at V/Vo = 11. There are interesting deviations. HNB falls below the

base set line about 9% in energy), the very high performance notwithstanding. BTF is almost on the line (-3%), but recall that HMX is +6%.

Also of interest are the large positive deviations, all of them in the low-carbon systems: H/HN +17%, EAR +10%, and AN/ADNT +7%. All three are intermolecular (but seem to behave ideally), high in hydrogen, and zero or low in carbon. AN/ADNT is $CO_2$-balanced, and EAR is nearly so. These three formulations are the only ones having that kind of elemental balance. Although it does not affect the Qcyl or the present result, note that the EAR parent explosive, EDD, is the only one with a measured Q higher than the calculated Q, indicating that the published heat of formation, -156.1 kcal/mol, may be in error.

Differences in detonation characteristics between explosives with mainly hydrogen as a fuel and those with mainly carbon as a fuel would be expected: Carbon-free and low-carbon (hydrogen) systems would produce more moles of gas per gram (or per cubic centimeter if densities are similar) at lower average molecular weight than do carbon-rich systems. Also, one would expect detonation temperatures of high-hydrogen explosives to be lower than those of high-carbon explosives, requiring less time for relaxation into translational kinetic activity. Although not necessarily relevant to the present results (because the specific energy was measured), 50% more energy is obtained, gravimetrically, from gaseous water as a product than from $CO_2$: 3.21 kcal/g (57.8 kcal/mol from water as a gas, molecular weight 18) versus 2.14 kcal/g from $CO_2$ (94/44). Whether more or less energy is realized volumetrically from real materials depends of course on density, heat of formation, etc., and one sees that carbon systems usually produce more net energy volumetrically than do hydrogen systems.

Some of the regressions were recalculated using the base set plus the six points just described, with and without the 0,0 point, and some without the DINGU points. This was done because the biggest deviations in the six explosives are at opposite ends of the line, and line bias by 0,0 or the different set of points might be yielding deviations higher than warranted for those materials. But that is not the case, the deviations being changed little except that HNB is somewhat less deviant and HMX is somewhat more so.

The set of aluminized explosives (Table III) indicates directly--assuming that aluminum simply adds Q--the effect of the explosive's chemical energy on cylinder energy. Replacing about 5% of the HMX by aluminum increases the wall energy by about 5% at V/Vo of 7 and larger. The CJ parameters do not seem to have been much affected, although in the nonaluminized mix, the early wall velocity (hence acceleration and pressure) is higher, as indicated by the shorter flight time to V/Vo = 2. However, the average wall velocity in both the aluminized mixes is equal to or slightly faster than the non-aluminum mix by the time the outer copper wall diameter is a little over 2.5 times the original diameter ($r - ro\sqrt{7}$ at V/Vo = 7).

## CONCLUSIONS

Detonation calorimetry can be both pragmatically and academically useful in the study of explosives and munitions. The correlation with performance in the cylinder test and its correspondence with several kinds of munitions is of practical value, while the study of products and heats should be of academic value in research on detonation.

The large negative deviation of one insensitive explosive (DINGU, approximately 18% below that expected from the correlation) is noted but not explained. Large positive deviations in high-hydrogen explosives (especially the 17% in hydrazine/hydrazine nitrate and 10% in EAR) are also noted.

The detonation pressure or velocity parameters do not predict cylinder test performance as well as the thermochemical energy does.

With some refinement to improve the correlation between calculated and measured Q, performance of new explosives might be reasonably well estimated before they are made. Refinements might include the use of structure or equations of state to predict products and energy.

## GLOSSARY

| | |
|---|---|
| ADNT | ammonium dinitrotriazole |
| AFX-902 | 95/5 NQ/Viton A |
| AN | ammonium nitrate |
| BTF | benzotrifuroxan |
| AN/ADNT | 2/1 moles |
| Comp B | 64/36 RDX/TNT |
| Comp C-4 | 91/9 RDX/organic binder |
| DINGU | dinitroglycolurile |
| EAR | 42.5/42.5/15 EDD/AN/RDX |
| H/HN | 21/79 hydrazine/hydrazine nitrate |
| HNB | hexanitrobenzene |
| NM | nitromethane |

| | |
|---|---|
| NQ | nitroguanidine |
| NTO | nitrotriazolone |
| Octol | 75/25 HMX/TNT |
| PBX 9404 | 94/3/3 HMX/nitrocellulose/chlorethyl phosphate |
| PBX 9502 | 95/5 TATB/Kel-F 800 |
| RX-23-AA | H/HN |
| TMD | Theoretical maximum density |
| X-0420 | 94/5/1 DINGU/Exon/titanate |
| X-0432 | 57/43 DINGU/TNT |

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**Table I**
**Performance Factors**

| Explosive | Density TMD (g/cm$^3$) | D,calc (km/s) | P,calc GPa | Q Calc (cal/g) | Q Maes (cal/g) | Qv Max cal/cm$^3$ | Density exp (g/cm$^3$) | Qcyl (cal/cm$^3$) |
|---|---|---|---|---|---|---|---|---|
| IMX | 1.902 | 9.13 | 38.2 | 1475 | 1365 | 2595 | 1.894 | 2585 |
| PBX 9404 | 1.865 | 9.00 | 36.7 | 1430 | 1325[a] | 2470 | 1.845 | 2445 |
| RDX | 1.806 | 8.83 | 34.6 | 1480 | 1340 | 2420 | --- | --- |
| Comp C-4 | 1.67 | 7.95 | 25.9 | 1360 | 1235 | 2065 | 1.601 | 1975 |
| Comp B | 1.748 | 8.12 | 28.8 | 1410 | 1225 | 2140 | 1.717 | 2105 |
| TNT | 1.654 | 7.01 | 20.7 | 1290 | 1020 | 1685 | 1.630 | 1665 |
| TATB | 1.938 | 7.93 | 29.1 | 1075 | 935 | 1810 | 1.854 | 1735 |
| PBX 9502 | 1.942 | 7.89 | 28.9 | 1030 | 900[a] | 2005 | 1.89 | 1695 |
| NQ | 1.775 | 7.90 | 27.5 | 920 | --- | 1630 | --- | --- |
| AFX-902 | 1.779 | 7.58 | 26.4 | 885 | --- | 1570 | 1.742 | 1540 |
| DINGU | 1.982 | 8.49 | 33.8 | 1125 | --- | 223 | --- | --- |
| K-0420 | 1.93 | 8.31 | 31.9 | 1070 | --- | 2065 | 1.874 | 2000 |
| K-0432 | 1.826 | 7.78 | 27.1 | 1195 | 1080[a] | 1970 | 1.758 | 1900 |
| NTO | 1.93 | 8.05 | 30.0 | 950 | --- | 1,840 | 1.825 | 1735 |
| PETN | 1.78 | 8.73 | 33.5 | 1515 | --- | 2455 | 1.765 | 2435 |
| NM | 1.136 | 6.41 | 13.2 | 1365 | 1075 | 1220 | 1.136 | 1220 |
| EDD | 1.595 | 7.57 | 23.6 | 975 | 990 | 1580 | 1.55 | 1535 |
| Octol | 1.845 | 8.63 | 33.4 | 1435 | 1330 | 2455 | 1.804 | 2400 |
| 00 | | | | | | | | 0 |
| HNB | 2.017 | 9.43 | 42.1 | 1705 | 1665 | 3340 | 1.965 | 3250 |
| EHN | 1.421 | 7.70 | 22.5 | 1285 | 1130 | 1605 | 1.421 | 1605 |
| ADNT | 1.63 | 7.82 | 25.5 | 1195 | 1045 | 1705 | 1.574 | 1645 |
| AN/ADNT | 1.67 | 8.15 | 28.2 | 1075 | 1025 | 1715 | 1.64 | 1680 |
| EAR | 1.678 | 8.16 | 28.3 | 1040 | 1000 | 1675 | 1.617 | 1615 |
| TTF | 1.901 | 8.56 | 33.1 | 1690 | 1410 | 2680 | 1.852 | 2615 |

Measured Q of one component + calculated or estimated other components.

Table II
Cylinder Test Performance

| Explosive | Density ($g/cm^3$) TMD | Density ($g/cm^3$) Exp | D (km/s) | Pa (GPa) | $V/V_o = 2$ v (km/s) | $V/V_o = 2$ t (μs) | $V/V_o = 7$ v (km/s) | $V/V_o = 7$ t (μs) | $V/V_o = 11$ v (km/s) | $V/V_o = 11$ t (μs) |
|---|---|---|---|---|---|---|---|---|---|---|
| HMX | 1.902 | 1.894 | --- | --- | 1.70 | 4.30 | 1.90 | 11.47 | 1.95 | 17.23 |
| PBX 9404 | 1.865 | 1.845 | 8.782 | 37.4 | 1.61 | 4.49 | 1.83 | 11.93 | 1.90 | 17.80 |
| Comp C-4 | 1.67 | 1.601 | 8.193 | 28.3 | 1.39 | 5.38 | 1.59 | 13.99 | 1.64 | 20.82 |
| Comp B | 1.748 | 1.717 | 7.99 | 28.8 | 1.44 | 5.22 | 1.63 | 13.60 | 1.68 | 20.23 |
| TNT | 1.654 | 1.630 | 6.95 | 20.7 | 1.23 | 6.26 | 1.40 | 16.03 | 1.46 | 23.75 |
| TATB | 1.938 | 1.854 | 7.675 | 28.7 | 1.32 | 5.49 | 1.47 | 14.73 | 1.51 | 22.10 |
| PBX 9502 | 1.942 | 1.89 | 7.57 | 28.5 | 1.31 | 5.50 | 1.46 | 14.79 | 1.49 | 22.24 |
| AFX-902 | 1.779 | 1.742 | 8.344 | 31.9 | 1.30 | 5.58 | 1.42 | 15.04 | 1.47 | 22.69 |
| X-0420 | 1.93 | 1.874 | 7.76 | 29.7 | 1.30 | 5.45 | 1.46 | 14.71 | 1.50 | 22.14 |
| X-0432 | 1.826 | 1.758 | 7.390 | 25.3 | 1.29 | 5.58 | 1.46 | 14.89 | 1.51 | 22.33 |
| NTO | 1.93 | 1.852 | 8.101 | 31.5 | 1.33 | 5.33 | 1.47 | 14.50 | 1.52 | 21.84 |
| PETN | 1.78 | 1.765 | 8.277 | 31.8 | 1.58 | 4.78 | 1.78 | 12.44 | 1.84 | 18.49 |
| NM | 1.136 | 1.136 | 6.285 | 11.8 | 1.05 | 7.51 | 1.24 | 18.65 | 1.27 | 27.37 |
| EDD | 1.595 | 1.55 | 7.55 | 23.3 | 1.29 | --- | 1.44 | --- | 1.47 | --- |
| Octol | 1.845 | 1.804 | 8.48 | 34.1 | 1.56 | 4.72 | 1.75 | 12.48 | 1.80 | 18.68 |
| (O) | | | | | | | | | | 0 |
| HNB | 2.017 | 1.965 | 9.335 | 45.1 | 1.71 | 4.29 | 1.92 | 11.31 | 2.04 | 16.82 |
| HHN | 1.421 | 1.421 | 8.645 | 27.9 | 1.36 | 5.45 | 1.54 | 14.24 | 1.60 | 21.24 |
| ADNT | 1.63 | 1.574 | 7.868 | 25.6 | 1.30 | 5.68 | 1.49 | 14.80 | 1.53 | 22.05 |
| AN/ADNT | 1.67 | 1.64 | 7.890 | 26.9 | 1.37 | 5.29 | 1.53 | 15.14 | 1.57 | est.--- |
| EAR | 1.678 | 1.617 | 8.17 | 28.4 | 1.36 | 5.32 | 1.51 | 14.20 | 1.56 | 21.36 |
| BTF | 1.901 | 1.852 | 8.485 | 35.1 | 1.59 | 4.61 | 1.80 | 12.05 | 1.88 | 17.93 |

[a]Calculated from experimental density, measured D, and 2.8 for $\gamma$.

Table III

ALUMINIZED EXPLOSIVE, 50.8-mm CYLINDER TESTS[a]

| | Density g/cm$^3$ | | D | Pb | V/Vo = 2 | | V/Vo = 7 | | V/Vo = 11 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | TMI | Expt'd | km/s | GPa | v(km/s) | t(μs) | v(km/s) | t(μs) | v(km/s) | t(μs) |
| 80.0/20[c] | 1.85 | 1.85 | 8.32 | 33.7 | 1.51 | 4.80 | 1.70 | 12.75 | 1.76 | 19.08 |
| 76.4/20 | 1.883 | 1.868 | 8.28 | 33.7 | 1.51 | 4.83 | 1.74 | 12.73 | 1.80 | 18.97 |
| 72.8/20 | 1.905 | 1.90 | 8.23 | 33.9 | 1.51 | 4.90 | 1.75 | 12.72 | 1.80 | 18.91 |

a. Courtesy H. G. Adolph, White Oak Laboratory, NSWC, and Group M-8, LANL.

b. Calculated from $\rho_0 D$ and $\gamma = 2.8$.

c. Wt% HMX/aluminum/fluorinated binder.

## TABLE IV
## CORRELATIONS

| Sample | Variables | | | Coefficients | |
|---|---|---|---|---|---|
| Set | Independent | Dependent | Fig. r | Slope | Y-intercept |
| 1 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 1.1 | 0.979 | 1.42 $(km/s)^2$/kcal/g | -0.134 $(km/s)^2$ |
| 1 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 7 | 0.978 | 1.33 | -0.122 |
| 1 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 2 | 0.975 | 1.05 | -0.100 |
| 2 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 1.1 | 0.960 | 1.54 | -0.367 |
| 3 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 1.1 | 0.993 | 1.44 | -0.121 |
| 4 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 1.1 | 0.988 | 1.44 | -0.143 |
| 5 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 1.1 | 0.974 | 1.34 | +0.097 |
| 6 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 1.1 | 0.985 | 1.34 | -0.084 |
| 6 | $Q_{cyl}$ (cal/g) | $v^2$ at $V/V_O$ = 2 | 0.963 | 0.95 | +0.097 |
| 1 | $Q_{cyl}$ (cal/g) | $P_{expl}$ (GPa) | 0.909 | 14.2 GPa/kcal/g | 1.01 GPa |
| 5 | $Q_{cyl}$ (cal/g) | $P_{expl}$ (GPa) | 0.917 | 13.2 | 3.19 |
| 1 | $P_{expl}$ (GPa) | $v^2$ at $V/V_O$ = 2 | 0.929 | 0.0613 $(km/s)^2$/GPa | 0.138 $(km/s)^2$ |
| 5 | $P_{expl}$ (GPa) | $v^2$ at $V/V_O$ = 2 | 0.943 | 0.0626 | 0.117 |
| 5 | $P_{expl}$ (GPa) | $v^2$ at $V/V_O$ = 1.1 | 0.923 | 0.0858 | 0.134 |

Sample sets:

1. Base set, 15 explosives, Tables I and II.
2. Base set, less 0.0.
3. Base set, less DINGU points
4. Base set, with DINGU points using CO calculation.
5. Full set, base plus additional 6 points
6. Full set, less DINGU points

## TABLE V
## DEVIATIONS

$$\text{Relative deviation} = \frac{100\,\Delta v_{11}^2}{\text{line } v_{11}^2}, \text{ in percent.}$$

where $\Delta v_{11}^2 = \exp v_{11}^2 \cdot \text{line } v_{11}^2$ and

where the line[a] is $v_{11}^2 = 1.44 Q_{cyl} - 0.121$

and $v_{11}$ is velocity at $V/V_0 = 11$.

| | | | | | |
|---|---|---|---|---|---|
| HMX | +5.7 | AFX 902 | +3.2 | Octol | -2.8 |
| PBX 9404 | +6.3 | X-0420 (DINGU) | -18.4 | HNB | -8.7 |
| Comp C-4 | -1.1 | X-0432 (DINGU/TNT) | -12.7 | RX-23-AA (H/HN) | +17.0 |
| Comp B | -2.9 | NTO | -2.7 | ADNT | +4.3 |
| TNT | -6.2 | PETN | +0.1 | AN/ADNT | +7.4 |
| TATB | -4.0 | NM | -1.2 | EAR | +10.5 |
| PBX 9502 | -4.2 | EDD | +3.6 | BTF | -2.9 |

[a]Highest r, average slope and intercept: Sample set 3 (Table IV).