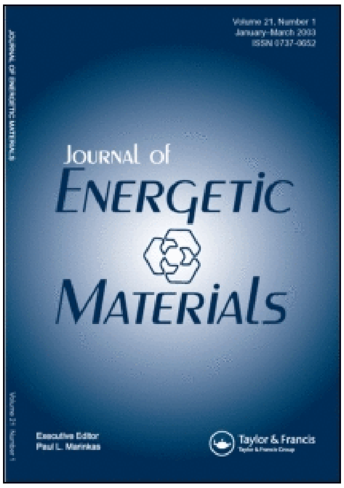

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# On underwater detonations, 1. A new method for predicting the CJ detonation pressure of explosives

R. Gill[a]; L. Asaoka[a]; E. Baroody[a]
[a] Syntnesis and Formulations Branch, Kll Naval Surface Weapons Center Indian Head, Maryland

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# ON UNDERWATER DETONATIONS, I. A NEW METHOD FOR PREDICTING THE CJ DETONATION PRESSURE OF EXPLOSIVES

R. Gill, L. Asaoka and E. Baroody
Synthesis and Formulations Branch, R11
Naval Surface Weapons Center
Indian Head, Maryland 20640

## ABSTRACT

The experimental detonation pressure of explosives has been found to correlate reasonably well with the theoretical specific impulse and density of these compositions. Two data sets were subjected to linear regression analysis, giving a number of possible correlations; however, the equation containing Isp x $\text{Density}^2$, a Kamlet-Jacobs like term, was found to show the best relationship for predicting, today's plastic bonded explosives. The complete equation is:

$$P_{\text{exptl}} = 44.4\ (\text{Isp} \times \text{Density}^2) - 21$$

## INTRODUCTION

Explosives being developed for military use in recent years have consisted of polymeric binder matrices, filled with energetic ingredients. The multi-component, non-homogeneous compositions which have been and are being developed, especially those containing metal powders, have non-ideal detonation properties (an ideal explosive is one that can be described adequately by the steady-state theory)(1). The Kamlet-Jacobs (KJ)(2) simplified computation method can predict the detonation properties of ideal explosives, but cannot always predict those of the less ideal ones, and it offers little possibility of being used to accurately predict the properties of metallized compositions. (Underwater explosives containing metal powders are of special interest to the Navy due to their potential target damage enhancement.)

The authors of this paper, propellant-oriented chemists, who in recent years became more involved in explosive development, have observed the

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remarkable similarity between the thermodynamic properties needed to calculate the performance characteristics of propellants and those of explosives. This similarity is especially evident between the Phi term ($\phi$) in the Kamlet-Jacobs equation and the specific impulse (Isp) in the propellant calculations. Therefore, it appeared reasonable to examine the suitability of using specific impulse (Isp), which is easily obtained from the PEP(3)* computer code, to correlate the detonation properties of explosives. This paper reports the results of our study into the relationship between Isp and detonation pressure. Later papers will describe how Isp is related to detonation velocity and to cylinder energy. We hope to eventually use the Isp calculations for predicting the explosive performance of metallized compositions. (PEP computer calculations have been used for many years by propellant formulators to obtain rocket performance parameters of metallized propellants.)

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*See appendix for an explanation of the PEP code and a sample printout.

## DETONATION CALCULATIONS

The Kamlet-Jacob (KJ) equation accurately predicts the measured detonation pressure for a large number of explosive compounds. The KJ equation is given by:(2)

$$P_{CJ}=K\phi\rho_0^{\,2}$$

where

$K = 15.58$

$\phi = N(MW)^{1/2}(Q)^{1/2}$ = phi

$\rho_0$ = loading density of explosive, g/cc

$P_{CJ}$ = Chapman-Jouguet Detonation Pressure in Kilobars

N = number of moles of gas from one gram of explosive

MW = average molecular weight of gases produced during explosion

Q = heat of detonation in cal/g, calculated using the $H_2O/CO_2$ arbitrary

First, we wanted to see if the Isp could be directly substituted for the phi in the equation: $P_{(exptl)}$ = phi x density$^2$.

Using the $P_{(exptl)}$, phi, and density data presented in Table 1 (this data is from the original paper by Kamlet and Dickinson published in 1968(4) and is composed mostly of pressed and melt-cast ideal explosives), and the Isp of the compositions calculated from the PEP code; the phi x density$^2$, and the Isp x density$^2$ of a number of explosives were plotted against their respective experimental detonation pressures (see Figures 1 and 2). A linear regression analysis of the data gave the results shown in Table 2.

A very good correlation was observed for both relationships, although the KJ equation gave a slightly better $R^2$-correlation coefficient and standard error. The validity of using the Isp in place of the phi for determining detonation pressure was now clearly demonstrated.

Next, we wanted to find out if the exponent of 1 on the Isp and the exponent of 2 on the density gave the best fit to data. This time the linear regression analysis was conducted on the data in Table 1, using an equation of the form $\ln P_{(\mathrm{exptl})} = N \ln (\mathrm{Isp}) + M \ln (\mathrm{Density}) + \mathrm{intercept}$. The results presented below

$N = 1.51 \pm 0.18 \qquad M = 1.95 \pm 0.11$

indicate that the exponents should be approximately 1.5 for Isp and 2.0 for density.

A similar linear regression analysis was then conducted on another data set. This data was obtained from the LLNL (Explosives Handbook(5) and is shown in Table 3. Like Table 1, Table 3 is composed of some pressed and melt-cast explosives; but unlike Table 1, it also contains a number of plastic-bonded compositions (PBXs). (PBXs are representative of todays' state-of-the-art military explosives).

These exponents were found to be quite different:

$N = 0.93 \pm 0.21 \qquad M = 2.25 \pm 0.11$

The Table 3 data-set indicates that the exponent of the Isp is approximately 1.0 and the exponent of the density is approximately 2.25.

A linear regression analysis was then conducted on the relationships as determined from the ln-ln analyses of data from both Tables 1 and 3. Table 4 shows these results. Indeed, the term $\mathrm{Isp}^{1.5} \times \mathrm{density}^{2.0}$ did correlate as well as the $\mathrm{Phi} \times \mathrm{density}^2$ with the experimental detonation pressures given in Table 1. But it showed the poorest correlation for the LLNL data in

Table 3. On the other hand, the term $Isp^{1.0}$ $density^{2.25}$ gave the best correlation with the data in Table 3, but gave the least correlation for the data from Table 1. Because all these terms correlated reasonably well with the experimental detonation pressure ($R^2$>0.95), and since Isp x $density^2$ was an acceptable compromise between the two sets of exponents, the exponents 1 and 2 were chosen. Also, because Table 1 contained mostly ideal explosive compositions, while Table 3 contained many less ideal compositions, e.g. PBX-explosives formed from energetic solids and binder ingredient; this equation was selected as more representative of today's state-of-the-art composite compositions. Thus, the equation for calculating the detonation pressure from the Isp x $density^2$ function was derived from the data in Table 3.

$$P_{(exptl)} = 44.4\ Isp \times density^2 - 21$$

The validity of this relationship can be better demonstrated by plotting the various variables against the experimental detonation pressures given in Table 3. The four plots (Figures 3, 4, 5 and 6) show the Isp, density, Isp x density, and the Isp x $density^2$, respectively, as a function of the detonation pressure. Figure 3 demonstrates that the Isp alone showed some correlation. Figure 4 shows that the density alone gave a much better correlation but the data is quite scattered. In Figure 5, where the term Isp x density is used, we see a significant improvement in the correlation, although LX-17, which has a large density and a relatively small Isp, is still far from the line. Figure 6 shows the result of using Isp x $density^2$. In this plot, all the compositions are reasonably close to the least squares line and exhibit a $R^2$-correlation coefficient of 0.984.

The Isp correlation works well, although the PEP computer code uses the assumption that the products are ideal gases, and the Isp calculation is based on rocket motor pressure conditions (expansion from 1000 to 14.7 psi). Gases at the very high pressures of a Chapman-Jouguet (CJ) detonation are not considered ideal, but Fickett and Davis(6) state: "Little is known about the properties of gases in the neighborhood of the CJ point of liquid and solid explosives."

## CONCLUSION

A novel method has been found to predict the Chapman-Jouguet detonation pressure: using the theoretical rocket performance calculations from the PEP computer code. This method has been shown to agree with the earlier work of KJ for ideal explosives. The correlation obtained through the use of the PEP code have been extended to composite explosives, e.g. binders filled with solid explosive particulate material.

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## GLOSSARY

| Designation | |
|---|---|
| BTF | Benzo-tris [1,2,5]-oxadiazole-1,4,7-trioxide |
| Comp B | RDX/TNT/WAX (63/36/1) |
| Cyclotol | RDX/TNT (75/25) |
| EDNA | Ethylene Dinitramine, (1,2-di-(nitramino)ethane) |
| FEFO | 1,1'-[Methylene-bis-(Oxy)]-Bis-[2-fluoro-2,2-dinitroethane] |
| HMX | Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine |
| LX-04 | HMX/Viton A (85/15) |
| LX-10 | HMX/Viton A (95/5) |
| LX-14 | HMX/Estane (95.5/4.5) |
| LX-17 | TATB/KEL-F 900 (92.5/7.5) |
| NG | 1,2,3-Propanetriol trinitrate |
| NM | Nitromethane |
| Octol | HMX/TNT (75/25) |
| PBX-9010 | RDX/KEL-F (90/10) |
| PBX-9011 | HMX/Estane (90/10) |
| PBX 9404 | HMX/NC/CEF (94/3/3) |
| Pentolite | PETN/TNT (50/50) |
| PETN | 2,2-Bis[(Nitroxy)methyl]-1,3-propanediol dinitrate (Pentaerythritol tetranitrate) |
| RDX | Hexahydro-1,3,5-trinitro-1,3,5-triazine |
| TATB | 2,4,6-Trinitro-1,3,5-benzenetriamine |
| TETRYL | N-Methyl-N,2,4,6-tetranitrobenzenamine |
| TNB | 1,3,5-Trinitrobenzene |
| TNM | Tetranitromethane |
| TNT | 2-Methyl-1,3,5-trinitrobenzene |
| CEF | Tris-b-chloroethylphosphate |
| Estane | Polyurethane solution system from B. F. Goodrich Co. |
| KEL-F | Chlorotrifluoroethylene/vinylidine fluoride copolymer (3/1) from 3M Company |
| Viton A | Vinylidine fluoride/hexafluoropropylene copolymer (60/40) from DuPont Chemical Co. |

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# APPENDIX: THE PEP CODE

The Propellant Evaluation Program (PEP) was developed by D.R. Cruise of Naval Weapons Center, China Lake. It assumes that the gases are ideal. The products are calculated using a free energy minimization technique. First, the enthalpy is calculated for the propellant at 1000 psi, then the propellant is burned and the gases expanded to 14.7 psi. The enthalpy is again calculated for the gases at this lower pressure. This difference in the two enthalpies is proportional to the work done by the expanding gases and is expressed as the specific impulse, ISP. The following information is needed to run the PEP:

1. heat of formation of each ingredient

2. atomic formula of each ingredient

3. composition of propellant or explosive

A sample calculation is given for the explosive LX-04, which is composed of 85% HMX and 15% Viton A.

```
               LX04                  H     C     N     O     F

HMX                                .008 .004 .008 .0080.0000        85.000        61.     .0687
VITON A                            .004 .0050.0000.000 .0070        15.000     -1801.     .0650
0GRAM ATOM AMOUNTS FOR PROPELLANT WEIGHT OF  100.000                                   1.0000
0   (H )       (C )       (N )       (O )       (F )
  2.576587  1.548873  2.295963  2.295963   .521159

  T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY   CP/CV    GAS   RT/V
 2898. 4757.   68.02  1000.00   -21.87   245.98  1.2584  4.260  15.970

   1.33953 CO       1.14743 N2         .52993 H2O        .52104 HF
    .48452 H2        .20926 CO2        .01979 H          .00661 HO
  1.00E-03 NO     1.70E-04 O        1.17E-04 F        7.55E-05 O2
  4.33E-05 NH3    3.63E-05 CHO      3.36E-05 CNH

  T(K)  T(F)  P(ATM)   P(PSI) ENTHALPY  ENTROPY   CP/CV    GAS   RT/V
 1205. 1710.    1.00    14.70   -91.31   245.98  1.3006  4.246    .236

   1.14797 N2       1.14265 CO         .68672 H2         .52116 HF
    .40620 CO2       .34091 H2O        .00003 NH3        .00002 CH4

0HYPOTHESIS  IMPULSE  GAMMA  THR. T  THR. P    CF   ISP*  OPT EX  EXH V   RHO-ISP
0  FROZEN     243.8  1.2807   2541.   37.36  1.575          7.63  7843.     459.3
  SHIFTING    245.8  1.2512   2577.   37.73  1.569  196.0   7.81  7910.     463.3

0BOOST VELOCITIES FOR PROPELLANT DENSITY OF  .06808  (S.G. OF  1.884
```

NOTE: Sample Calculation:
(English to metric)

$$245.8 \ \frac{\text{lb sec}}{\text{lb mass}} \times \frac{9.807}{1000} = 2.410 \ \frac{\text{N sec}}{\text{g}}$$

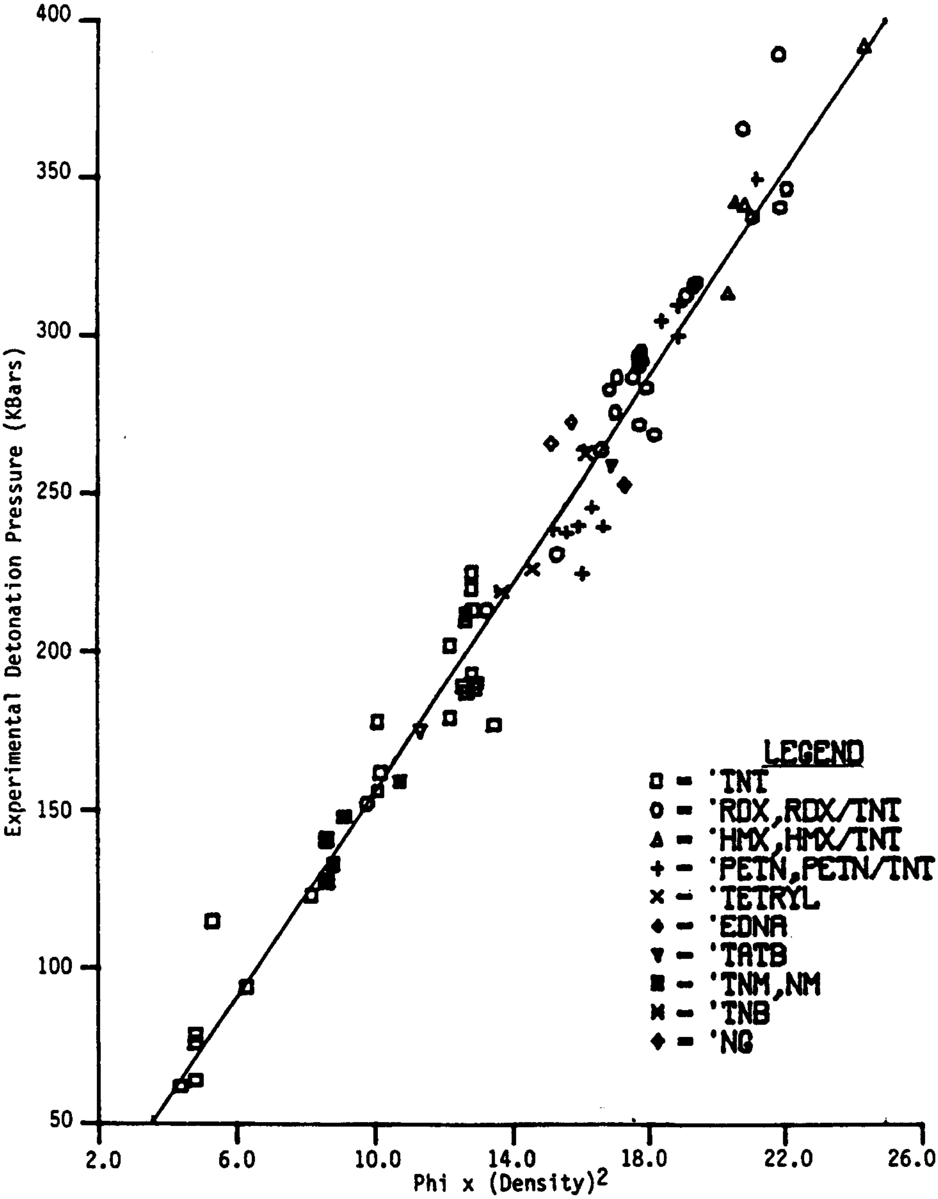

FIGURE 1.
Experimental Detonation Pressure Vs. Phi x (Density)$^2$

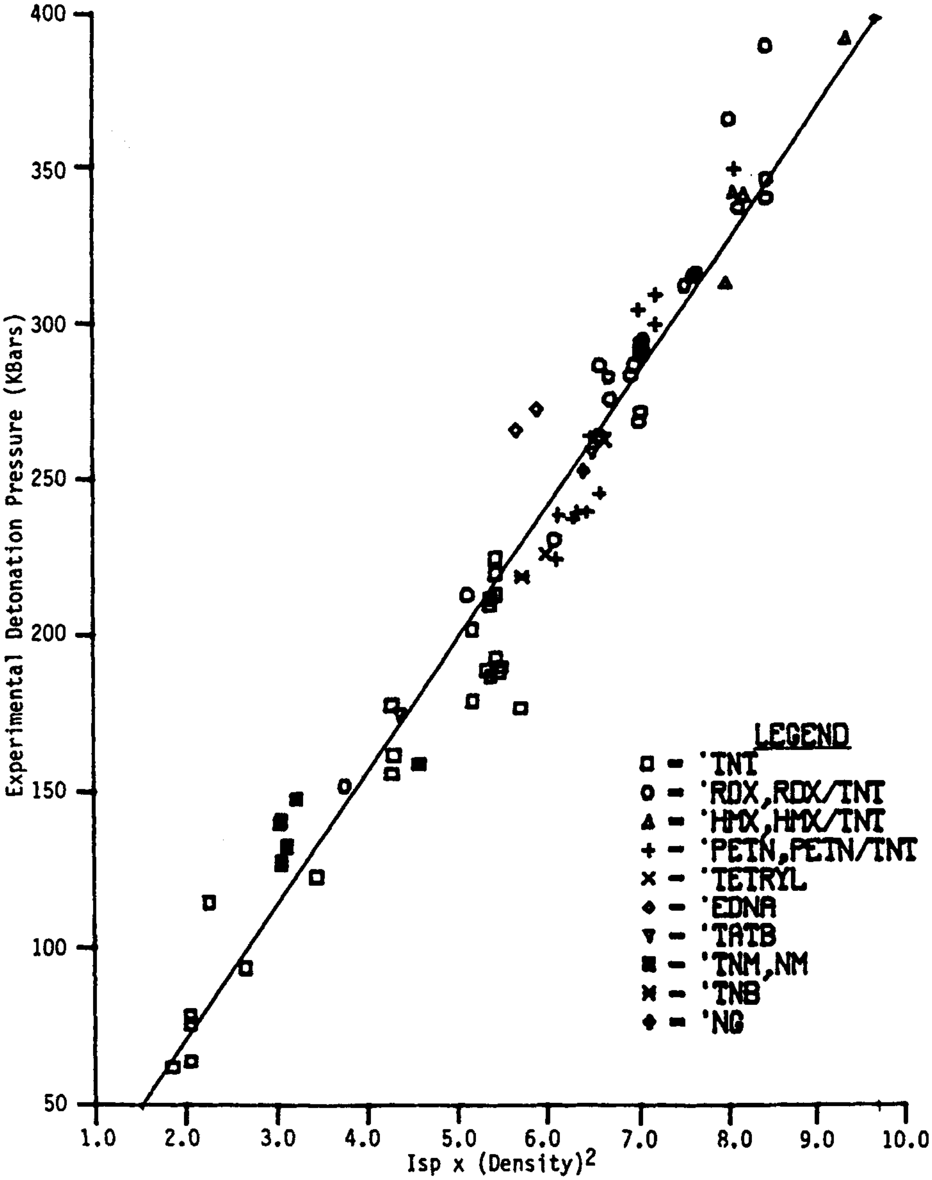

FIGURE 2.
Experimental Detonation Pressure Vs. Isp x (Density)$^2$

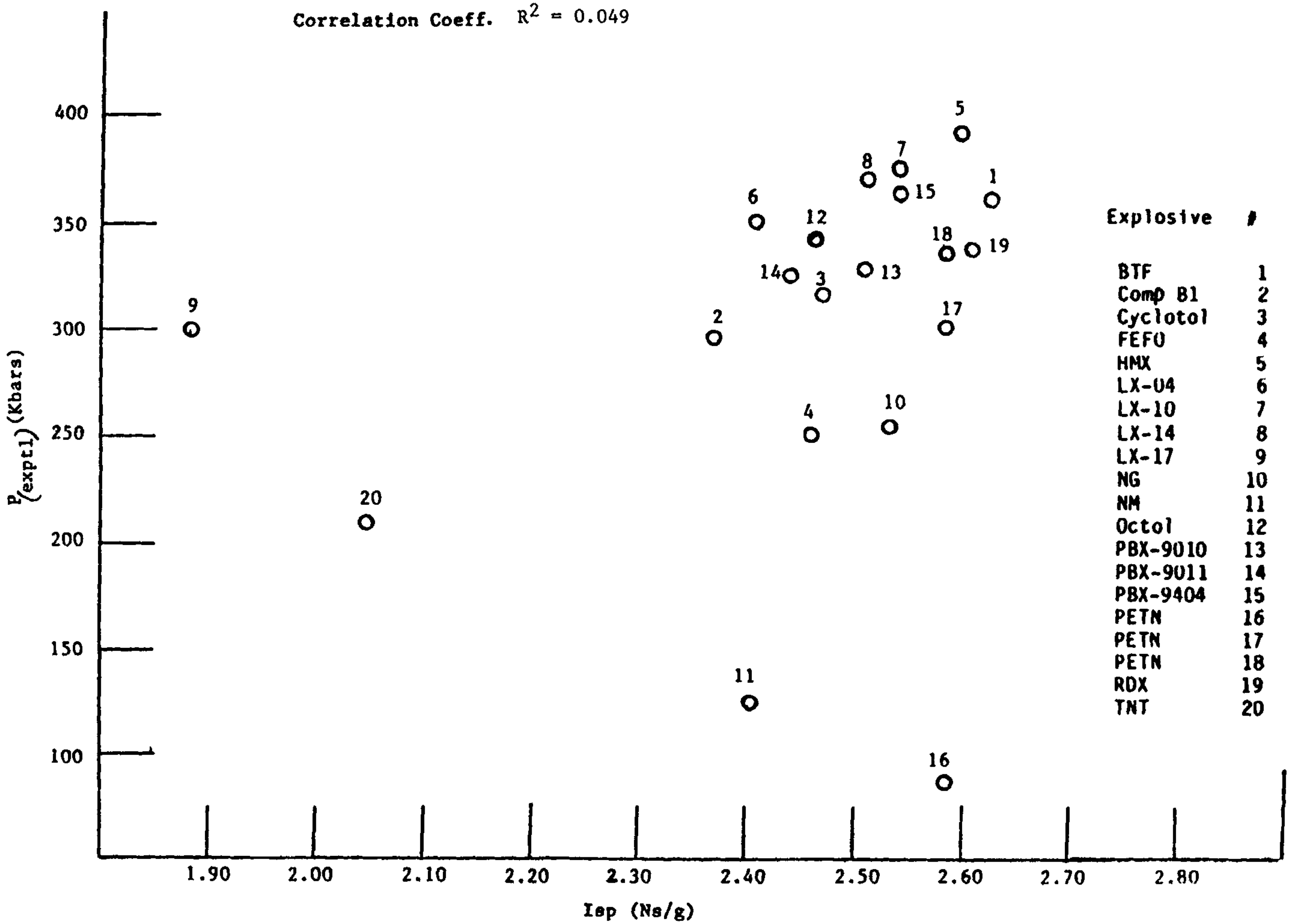

FIGURE 3.

Experimental Detonation Pressure Versus Isp

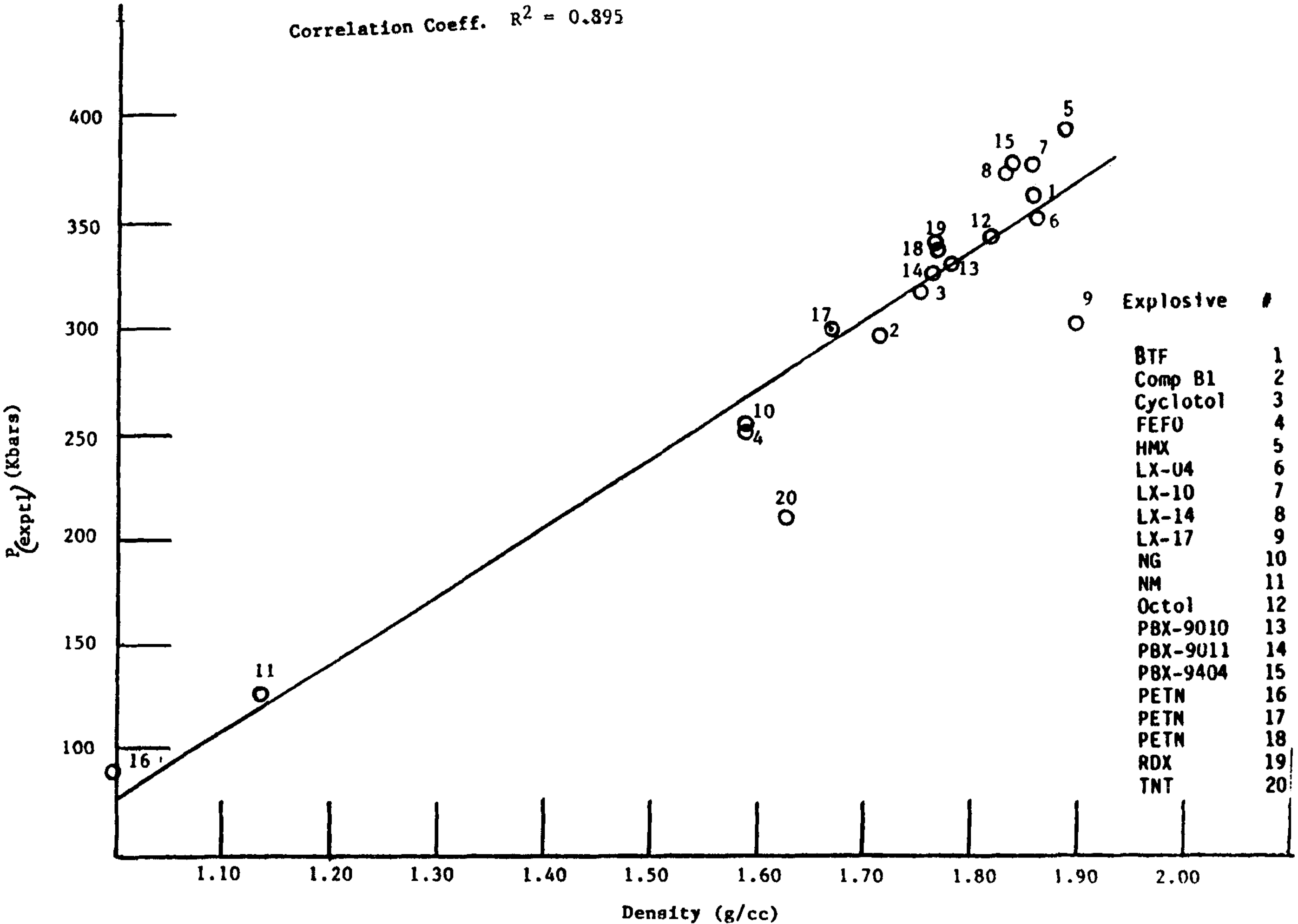

FIGURE 4.

**Experimental Detonation Pressure Versus Density**

Correlation Coeff. $R^2 = 0.927$

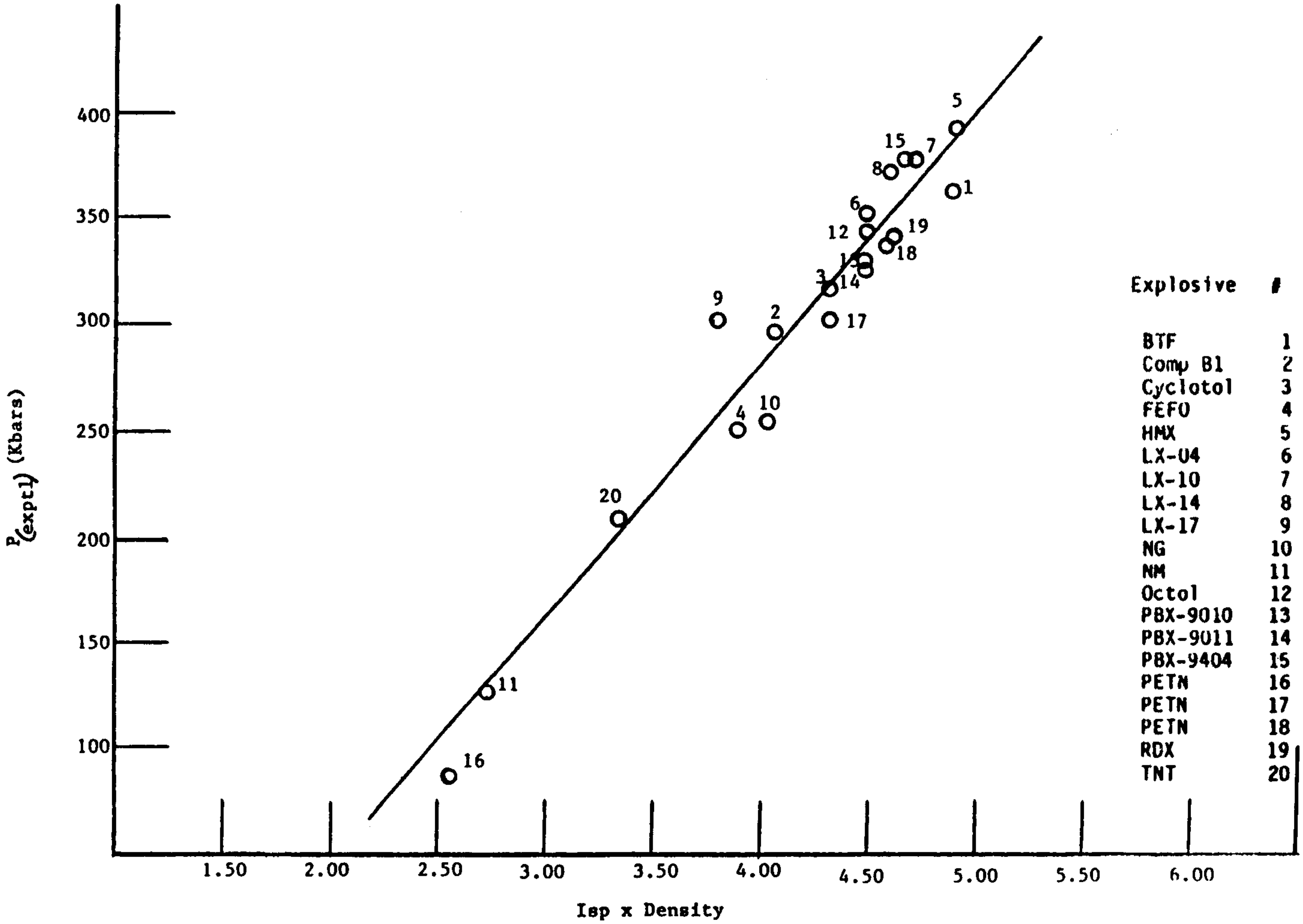

FIGURE 5.
Experimental Detonation Pressure Versus Isp x Density

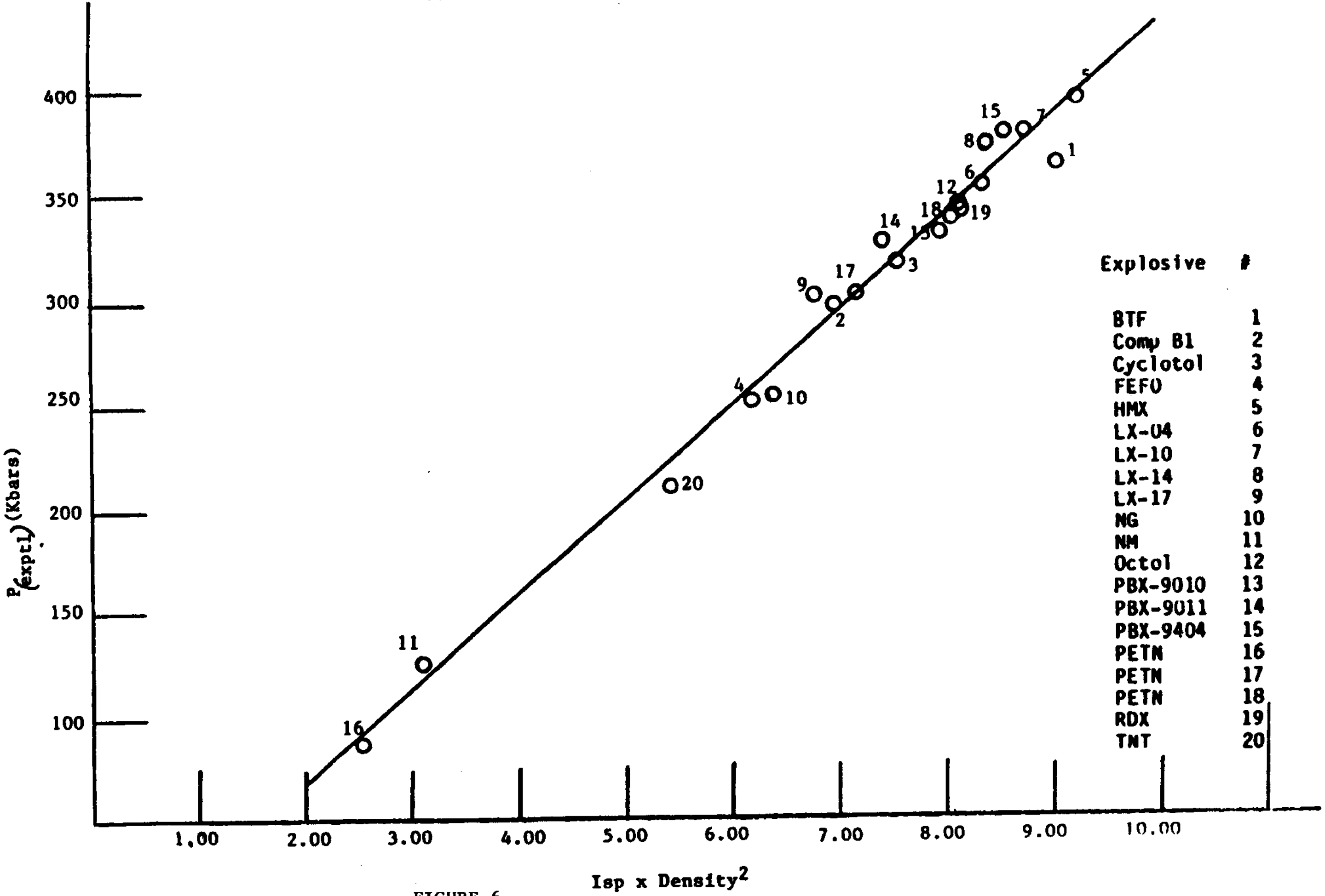

FIGURE 6.

Experimental Detonation Pressure Versus Isp x Density$^2$

TABLE 1
Comparison of Experimental and Calculated Detonation Pressures

| Explosive | Isp* (Ns/g) | Isp x Density$^2$ | $P_{(calc)}$ (Kbars) | $P_{(exptl)}-P_{(calc)}$ (Kbars) | Density** (g/cc) | $P_{(exptl)}$** (Kbars) | Phi** | phi x Density$^2$ | $P_{(KJ)}$ (Kbars) | $P_{(exptl)}-P_{(KJ)}$ (Kbars) |
|---|---|---|---|---|---|---|---|---|---|---|
| TNT | 2.048 | 1.848 | 63 | - 2 | 0.95 | 62.2 | 4.838 | 4.366 | 64 | - 2 |
| | | 2.048 | 72 | 4 | 1.00 | 76.3 | | 4.838 | 72 | 4 |
| | | 2.048 | 72 | 6 | 1.00 | 78.5 | | 4.838 | 72 | 7 |
| | | 5.178 | 206 | -27 | 1.59 | 179.0 | | 12.231 | 193 | -14 |
| | | 2.048 | 72 | - 8 | 1.00 | 64 | | 4.838 | 72 | - 8 |
| | | 2.662 | 99 | - 5 | 1.14 | 94 | | 6.287 | 96 | - 2 |
| | | 3.461 | 133 | -10 | 1.30 | 123 | | 8.176 | 127 | - 4 |
| | | 4.306 | 169 | - 7 | 1.45 | 162 | | 10.172 | 159 | 3 |
| | | 5.178 | 206 | - 4 | 1.59 | 202 | | 12.232 | 193 | 9 |
| | | 5.508 | 229 | -52 | 1.64 | 177 | | 13.012 | 214 | -37 |
| | | 5.481 | 219 | -31 | 1.63 | 188.4 | | 12.949 | 205 | -17 |
| | | 5.508 | 221 | -31 | 1.64 | 190 | | 13.012 | 206 | -16 |
| | | 5.335 | 213 | -24 | 1.614 | 189 | | 12.603 | 199 | -10 |
| | | 5.375 | 215 | - 5 | 1.62 | 210 | | 12.697 | 201 | 9 |
| | | 5.388 | 215 | -28 | 1.622 | 187.2 | | 12.728 | 201 | -14 |
| | | 5.375 | 215 | - 3 | 1.62 | 212 | | 12.697 | 201 | 11 |
| | | 5.455 | 218 | - 5 | 1.632 | 213 | | 12.886 | 204 | 9 |
| | | 5.441 | 218 | 2 | 1.630 | 220 | | 12.854 | 204 | 16 |
| | | 5.441 | 218 | 7 | 1.63 | 225 | | 12.854 | 204 | 21 |
| | | 5.441 | 218 | -24 | 1.63 | 193 | | 12.854 | 204 | -11 |
| | | 4.276 | 168 | 10 | 1.445 | 178 | | 10.102 | 158 | 20 |
| | | 4.276 | 168 | -11 | 1.445 | 156 | | 10.102 | 158 | - 2 |
| | | 2.262 | 81 | 34 | 1.051 | 115 | | 5.344 | 80 | 35 |
| RDX | 2.611 | 8.152 | 334 | 4 | 1.767 | 338 | 6.784 | 21.182 | 340 | - 2 |
| | | 8.460 | 347 | 43 | 1.80 | 390 | | 21.980 | 353 | 37 |
| | | 8.042 | 329 | 37 | 1.755 | 366 | | 20.895 | 336 | 30 |
| | | 6.601 | 267 | 20 | 1.59 | 287 | | 17.151 | 274 | 13 |
| | | 5.118 | 204 | 9 | 1.40 | 213 | | 13.297 | 211 | 2 |
| | | 3.760 | 146 | 6 | 1.20 | 152 | | 9.769 | 153 | -1 |
| | | 8.460 | 347 | -6 | 1.80 | 341 | | 21.980 | 353 | -12 |
| | | 6.937 | 282 | 2 | 1.63 | 283.7 | | 18.024 | 288 | -5 |
| | | 8.460 | 347 | 8 | 1.80 | 347 | | 21.980 | 356 | -9 |
| | | 7.023 | 285 | -16 | 1.64 | 269 | | 18.246 | 292 | -23 |

TABLE 1 (Cont)

| Explosive | Isp* (Ns/g) | Isp x Density$^2$ | $P_{(calc)}$ (Kbars) | $P_{(exptl)}-P_{(calc)}$ (Kbars) | Density** (g/cc) | $P_{(exptl)}$** (Kbars) | Phi** | phi x Density$^2$ | $P_{(KJ)}$ (Kbars) | $P_{(exptl)}-P_{(KJ)}$ (Kbars) |
|---|---|---|---|---|---|---|---|---|---|---|
| HMX | 2.601 | 9.390 | 387 | 6 | 1.90 | 393 | 6.772 | 24.447 | 394 | -1 |
| Tetryl | 2.305 | 6.005 | 242 | -15 | 1.614 | 226.4 | 5.615 | 14.627 | 233 | -6 |
| | | 6.661 | 270 | - 7 | 1.70 | 263 | | 16.227 | 259 | 4 |
| PETN | 2.586 | 6.117 | 247 | -22 | 1.538 | 224.7 | 6.805 | 16.097 | 257 | -32 |
| | | 6.358 | 257 | -17 | 1.568 | 239.9 | | 16.731 | 267 | -27 |
| | | 7.212 | 294 | 16 | 1.67 | 310 | | 18.978 | 304 | 6 |
| | | 7.212 | 294 | 6 | 1.67 | 300 | | 18.978 | 304 | - 4 |
| | | 8.102 | 332 | 18 | 1.77 | 350 | | 21.319 | 343 | 7 |
| | | 7.023 | 285 | 20 | 1.648 | 305 | | 18.428 | 296 | 9 |
| RDX/TNT | | | | | | | | | | |
| 50/50 | 2.301 | 6.090 | 246 | -14 | 1.627 | 231.1 | 5.806 | 15.369 | 245 | -14 |
| 60/40 | 2.373 | 6.603 | 267 | - 3 | 1.668 | 264.1 | 5.992 | 16.671 | 266 | - 2 |
| | | 6.698 | 272 | 11 | 1.680 | 283 | | 16.912 | 270 | 13 |
| | | 6.980 | 284 | 3 | 1.715 | 287 | | 17.624 | 282 | 5 |
| 64/36 | 2.401 | 7.078 | 288 | 7 | 1.717 | 295 | 6.063 | 17.874 | 286 | 9 |
| | | 7.053 | 287 | 6 | 1.714 | 293 | | 17.812 | 285 | 8 |
| | | 7.053 | 287 | -15 | 1.714 | 272 | | 17.812 | 285 | -13 |
| | | 7.053 | 287 | 4 | 1.714 | 290.4 | | 17.812 | 285 | 5 |
| | | 7.045 | 286 | 8 | 1.713 | 294 | | 17.791 | 285 | 9 |
| 65/35 | 2.408 | 7.081 | 288 | 4 | 1.715 | 292 | 6.086 | 17.900 | 286 | 6 |
| 75/25 | 2.472 | 6.714 | 272 | 4 | 1.648 | 276 | 6.292 | 17.088 | 273 | 3 |
| 77/23 | 2.485 | 7.550 | 308 | 5 | 1.743 | 313 | 6.319 | 19.197 | 308 | 5 |
| | | 7.628 | 311 | 5 | 1.752 | 316 | | 19.396 | 311 | 5 |
| 78/22 | 2.491 | 7.672 | 313 | 4 | 1.755 | 317 | 6.331 | 19.500 | 313 | 4 |
| HMX/TNT | | | | | | | | | | |
| 75/25 | 2.463 | 8.007 | 328 | -14 | 1.803 | 314 | 6.288 | 20.441 | 328 | -14 |
| 76.7/23.3 | 2.474 | 8.096 | 331 | 12 | 1.809 | 343 | 6.310 | 20.649 | 332 | 11 |
| 77.6/22.4 | 2.479 | 8.220 | 337 | 5 | 1.821 | 342 | 6.321 | 20.961 | 337 | 5 |
| EDNA | 2.421 | 5.683 | 228 | 38 | 1.532 | 266 | 6.473 | 15.192 | 242 | 24 |
| | | 5.908 | 238 | 35 | 1.562 | 273 | | 15.793 | 252 | 21 |

## TABLE 1 (Cont)

| Explosive | Isp* (Ns/g) | Isp Density$^2$ | $P_{(calc)}$ (Kbars) | $P_{(exptl)}-P_{(calc)}$ (Kbars) | Density** (g/cc) | $P_{(exptl)}$** (Kbars) | Phi** | phi x Density$^2$ | $P_{(KJ)}$ (Kbars) | $P_{(exptl)}-P_{(KJ)}$ (Kbars) |
|---|---|---|---|---|---|---|---|---|---|---|
| PETN/TNT | | | | | | | | | | |
| 50/50 | 2.332 | 6.504 | 263 | 1 | 1.670 | 264 | 5.796 | 16.164 | 258 | 6 |
| | | 6.598 | 267 | -21 | 1.682 | 246 | | 16.398 | 262 | -16 |
| 45/55 | 2.294 | 6.451 | 261 | -20 | 1.677 | 240 | 5.680 | 15.974 | 255 | -15 |
| 40/60 | 2.253 | 6.305 | 255 | -16 | 1.673 | 238 | 5.586 | 15.635 | 249 | -11 |
| 35/65 | 2.210 | 6.150 | 248 | - 9 | 1.668 | 239 | 5.492 | 15.280 | 243 | - 4 |
| NM | 2.405 | 3.060 | 116 | 25 | 1.128 | 141 | 6.767 | 8.610 | 134 | 7 |
| | | 3.060 | 116 | 11 | 1.128 | 127 | | 8.610 | 134 | - 7 |
| | | 3.060 | 116 | 12 | 1.128 | 128 | | 8.610 | 134 | - 6 |
| | | 3.043 | 115 | 25 | 1.125 | 140 | | 8.564 | 133 | 7 |
| | | 3.125 | 118 | 15 | 1.14 | 133 | | 8.794 | 137 | - 4 |
| | | 3.230 | 123 | 25 | 1.159 | 148 | | 9.090 | 142 | 6 |
| TATB | 1.913 | 6.527 | 264 | -5 | 1.847 | 259 | 4.976 | 16.975 | 271 | -12 |
| | | 4.363 | 171 | 4 | 1.51 | 175 | | 11.346 | 179 | - 4 |
| TNB | 2.132 | 5.734 | 230 | -11 | 1.64 | 219 | 5.105 | 13.730 | 218 | 1 |
| TNM | 1.701 | 4.574 | 180 | -21 | 1.64 | 159 | 4.007 | 12.302 | 169 | -10 |
| NG | 2.535 | 6.425 | 260 | - 7 | 1.592 | 253 | 6.837 | 16.284 | 277 | -24 |
| STD error of estimate = | | | | 18 | | | | | | 14 |

*Calculations from PEP code
**Data from KJ Paper (ref. 4)

# TABLE 2
## Linear Regression Analysis of Data

| x variable | Y variable | Intercept | Slope | $R^{2**}$ | Std Error (Kbars) |
|---|---|---|---|---|---|
| phi x density$^2$ | $P_{(exptl)}$ | -8 ± 10* | 16.42 ± 0.68 | 0.969 | 14 |
| Isp x Density$^2$ | $P_{(exptl)}$ | -15 ± 14* | 42.8 ± 2.2 | 0.951 | 18 |

* Least-square value of the coefficient ± its standard error

** $R^2$ = correlation coefficient squared

### TABLE 3
### Explosive Parameters

| Explosive | # | Isp* (Ns/g) | Density** (g/cc) | $P_{(exptl)}$** (Kbars) | Isp x Density | Isp x Density$^2$ | $P_{(calc)}$ (Kbars) | $P_{(exptl)} - P_{(calc)}$ (Kbars) |
|---|---|---|---|---|---|---|---|---|
| BTF | 1 | 2.632 | 1.859 | 360 | 4.893 | 9.096 | 383 | -23 |
| Comp B1 | 2 | 2.372 | 1.717 | 295 | 4.073 | 6.993 | 289 | 6 |
| Cyclotol | 3 | 2.472 | 1.752 | 316 | 4.331 | 7.588 | 316 | 0 |
| FEFO | 4 | 2.461 | 1.59 | 250 | 3.913 | 6.222 | 255 | - 5 |
| HMX | 5 | 2.601 | 1.89 | 390 | 4.916 | 9.291 | 392 | - 2 |
| LX-04 | 6 | 2.411 | 1.865 | 350 | 4.497 | 8.386 | 351 | - 1 |
| LX-10 | 7 | 2.544 | 1.860 | 375 | 4.732 | 8.801 | 370 | 5 |
| LX-14 | 8 | 2.514 | 1.833 | 370 | 4.608 | 8.447 | 354 | 16 |
| LX-17 | 9 | 1.884 | 1.900 | 300 | 3.580 | 6.801 | 281 | 19 |
| NG | 10 | 2.535 | 1.59 | 253 | 4.031 | 6.409 | 264 | -11 |
| NM | 11 | 2.405 | 1.135 | 125 | 2.730 | 3.098 | 117 | 8 |
| Octol | 12 | 2.463 | 1.821 | 342 | 4.485 | 8.167 | 342 | 0 |
| PBX-9010 | 13 | 2.510 | 1.783 | 328 | 4.475 | 7.980 | 333 | - 5 |
| PBX-9011 | 14 | 2.391 | 1.765 | 324 | 4.485 | 7.449 | 310 | -14 |
| PBX-9404 | 15 | 2.544 | 1.840 | 375 | 4.681 | 8.613 | 361 | -14 |
| PETN | 16 | 2.586 | 0.99 | 87 | 2.560 | 2.535 | 92 | - 5 |
| PETN | 17 | 2.586 | 1.67 | 300 | 4.319 | 7.212 | 299 | - 1 |
| PETN | 18 | 2.586 | 1.77 | 335 | 4.577 | 8.102 | 339 | - 4 |
| RDX | 19 | 2.611 | 1.767 | 338 | 4.614 | 8.152 | 341 | - 3 |
| TNT | 20 | 2.048 | 1.630 | 210 | 3.338 | 5.441 | 221 | -11 |

*PEP code calculation
**LLNL Explosive Handbook Data (ref. 5)

## TABLE 4
### Results of Regression Analysis

| | Intercept* | Slope* | $R^2$ | STD Error | |
|---|---|---|---|---|---|
| Isp x $Density^2$ | -15 ± 14 | 42.8 ± 2.2 | 0.951 | 18 | Table 1 data |
| $Isp^{3/2}$ x $Density^2$ | 4 ± 10 | 25.8 ± 1.1 | 0.966 | 15 | |
| Isp x $Density^{2.25}$ | 3 ± 13 | 35.1 ± 1.9 | 0.947 | 18 | |
| Phi x $Density^2$ | -8 ± 10 | 16.42 ± 0.68 | 0.969 | 14 | |
| a. Isp x $Density^2$ | -21 ± 21 | 44.4 ± 2.8 | 0.984 | 10 | Table 3 data |
| $Isp^{3/2}$ x $Density^2$ | 1 ± 34 | 26.4 ± 2.9 | 0.954 | 18 | |
| Isp x $Density^{2.25}$ | 2 ± 18 | 36.0 ± 2.1 | 0.986 | 10 | |

*95% Confidence level

Note a: This expression was selected from the data set that was more representative of today's state-of-the-art composite PBX explosives.