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Hugoniot Equations of State of Several Unreacted Explosives

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Plane shock-wave compressions and an optical method were used to obtain the unreacted equations of state of 11 explosives and propellants for pressures up to 90 kbar. Measurements of the transit times of weak shock waves (~100 bar) yielded longitudinal sound-wave velocities.

I. INTRODUCTION

THE dynamic pressure–volume relations, or Rankine–Hugoniot curves, of many solids and several liquids have been measured in recent years. However, fewer data are known for explosives and propellants, because when shocked they readily undergo violent chemical decomposition. This behavior, though, is an important reason for obtaining such data. Any quantitative measurements of shock parameters, used to determine hazards from burning or detonation, require knowing the shock Hugoniot of the unreacted explosive or propellant.

In 1958, Majowicz and Jacobs[1] derived unreacted pressure–volume data from shock experiments using explosive wedges. Their data and the results of Garn[2] are perhaps the first Hugoniot measurements of unreacted explosive materials. Garn's data are for liquid TNT from 44 to 110 kbar, where chemical reaction begins. Ilyukhin *et al.*[3] give shock-wave compression results from 57 to 139 kbar for cast TNT, also pressed RDX and liquid nitromethane.

In this paper[4] we give the experimentally determined dynamic pressure–volume relations for 11 explosives and propellants. These materials (Table I) include several pure (CHON) explosives[5] and some plastic-bonded and aluminized mixtures. The pressure–volume relations are derived from optical measurements of the shock-wave and particle velocities. It is assumed that any chemical reaction which began during the shock transit time (<1 μsec) was too small to affect the compression results. Finally, we give the results of extrapolating the shock-wave and particle-velocity data to obtain the so-called von Neumann spike pressure.[6]

[1] J. M. Majowicz and S. J. Jacobs, Bull. Am. Phys. Soc., Ser. II **3,** 293 (1958).
[2] W. B. Garn, J. Chem. Phys. **30,** 819 (1958).
[3] V. S. Ilyukhin, P. F. Pokhil, O. K. Rozanov, and N. S. Shvedova, Soviet Phys.—Doklady **5,** 337 (1960) [Dokl. Akad. Nauk SSSR **131,** 793 (1960)].
[4] This work includes additional results from experiments reported at the International Conference on Sensitivity and Hazards of Explosives, London, 1–3 October 1963.
[5] Explosives composed of carbon, hydrogen, oxygen, and nitrogen only. These materials are pressed except as noted.
[6] J. von Neumann, OSRD Report No. 549 (1942).

II. EXPERIMENTAL METHOD

Dynamic pressure–volume data are derived from shock-wave experiments relating the measured velocities of the shock wave, U_s, and of the material behind the shock front, u_p, to the pressure P and specific volume V of the compressed material. The relationships are given by the Rankine–Hugoniot equations,

$$V/V_0=(U_s-u_p)/U_s \tag{1}$$

and

$$P=(1/V_0)U_s u_p. \tag{2}$$

The shock-wave velocity in the explosive, or propellant, specimen is obtained from the measured transit

TABLE I. Specimen materials.

Formula or composition	Experimental density (g/cm^3)
2,4,6-Trinitrotoluene (TNT) cast	1.614
1,3,5-Trinitrobenzene (TNB)	1.640
1-Amino-2,4,6-trinitrobenzene (TNA)[a]	1.600
1,3-Diamino-2,4,6-trinitrobenzene (DATB)[b]	1.780
1,3,5-Triamino-2,4,6-trinitrobenzene (TATB)	1.847
60/40 RDX/TNT (Composition B-3)[c] cast	1.680
85/15 HMX/Viton (LX-04-0)[d]	1.879
85/15 HMX/Viton (LX-04-1)	1.863
94/3/3 HMX/nitrocellulose/ chloroethyl-phosphate (PBX 9404-03)	1.829
RDX/TNT/Al/Wax	
40/38/17/5 (HBX-1) cast	1.750
31/29/35/5 (HBX-3) cast	1.850
44.76/29.53/20.95/4.76 (H-6) cast	1.760
Propellant[e] (FFP)	1.760
Propellant[f] (EJC)	1.900

[a] Zytel (nylon) 5%.
[b] Zytel (nylon) 1%.
[c] Mixture of 60% cyclotrimethylene trinitramine (RDX) and 40% TNT.
[d] Cyclotetramethylene tetranitramine (HMX) 85% and Viton 15%, a fluoro elastomer from DuPont.
[e] Plastic composition of ammonium perchlorate and aluminum.
[f] Plastic composition of HMX, nitroglycerine, nitrocellulose, ammonium perchlorate, and aluminum.

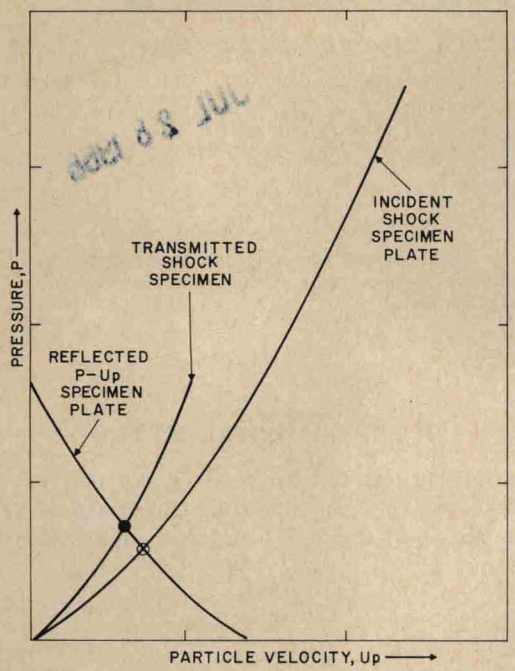

FIG. 1. Graphical solution for particle velocity and pressure in the shocked specimen. ● Specimen, ○ specimen plate.

time of the shock through the specimen. The particle velocity is obtained graphically[7] using the known Hugoniot for the material on which the specimens were mounted. The latter is referred to hereafter as the "specimen plate." The rarefaction locus is drawn in the P, u_p plane for the specimen-plate material and the shock locus is drawn with slope $(P/u_p)=(1/V_0)U_s$ for the specimen. The point of intersection of the two curves gives the pressure and particle velocity in the specimen. The rarefaction locus is approximated by reflecting the shock Hugoniot for the specimen plate (P-vs-u_p curve, Fig. 1) about the plane which includes the experimental P-vs-u_p point for the specimen-plate material.

III. EXPERIMENTAL ASSEMBLIES

For measurements from 10 to 90 kbar we used the arrangement in Fig. 2. The components consisted of an explosive plane-wave system,[8] a specimen plate, and several test specimens. The specimens[9] were formed into short cylinders, ranging from 5 to 13 mm in diameter and 1 to 5 mm in height. (The specimen height was measured to ±0.003 mm.) The height-to-diameter ratio was generally about 0.1 to 0.3, never greater than 0.5.

Typically, with the arrangement of Fig. 2, the shock wave produced by the detonating explosive system arrives at the free surface of a 2.5-cm-thick specimen plate. The arrival is plane parallel to within ±0.01 μsec across an 8- to 10-cm diameter. The specimens are placed within this plane region.[10]

We varied the pressure transmitted to the specimens in the following ways:

(1) By changing the composition or thickness of the explosive plane-wave system; e.g., one system uses a 15.8-cm diameter, plane-wave lens to ignite a liquid explosive, nitromethane, of detonation pressure = 102 kbar.

(2) By changing the composition or thickness of the specimen plate, e.g., brass or Plexiglas.

(3) By using a shock attenuator composed of alternating layers of high- and low-density materials between the explosive system and test specimens.

Table II gives several typical shock-producing systems.

The shock-wave arrivals at the free surfaces of the specimen plate and the specimens were recorded by a smear camera using a reflected-light technique.[11–13] In this method light is reflected continuously from the free surfaces into the camera. The shock-wave arrival at any point along the surface produces a sudden change in light reflected from that point. The light was provided by two exploding-wire light sources, each composed of a 0.025-mm-diam tungsten wire threaded into a 10-cm-long glass capillary tube. Typically, the energy used to explode the series-connected wires was obtained from the discharge of a 4 μF capacitor charged to 8 kV. To increase the reflectivity, aluminized Mylar film was placed on the surface of the specimen. The

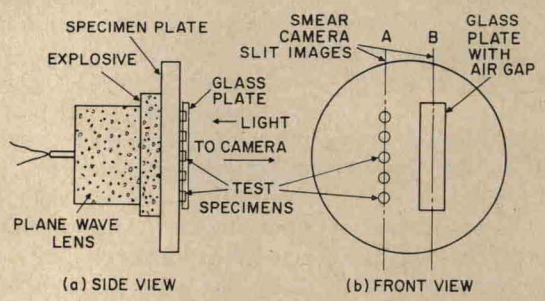

FIG. 2. Arrangement for delivery of plane shock wave and for measuring shock-wave velocities in the specimens and the free-surface velocity of the specimen plate.

[7] J. M. Walsh, M. H. Rice, R. G. McQueen, and F. L. Yarger, Phys. Rev. **108,** 196 (1957).

[8] J. H. Cook, Research (London) **1,** 474 (1948).

[9] In several experiments, specimen wedges were used. The wedges were of two sizes; 25° with 14-mm apex height, and 30° with 26-mm apex height. See S. J. Jacobs, T. P. Liddiard, Jr., and B. E. Drimmer, Symp. Combust. 9th Cornell Univ., Ithaca, N.Y., 1962, 517 (1963).

[10] A layer of silicone grease about 0.003 mm thick filled the gap between the specimen and the highly polished specimen plate. The specimen was held in place by a small amount of Eastman 910 adhesive placed around the periphery of the specimen.

[11] W. A. Allen and C. L. McCrary, Rev. Sci. Instr. **24,** 165 (1953).

[12] N. L. Coleburn, Naval Ordnance Laboratory Technical Report, NavWeps Report 6026 (1960).

[13] T. P. Liddiard, Jr., and B. E. Drimmer, J. Soc. Motion Picture Television Engrs. **70,** 106 (1961).