using piezoelectric (tourmaline) gauges in the weak-shock experiments, we measured an incident water shock pressure of 60 bar and calculated pressures ranging from 80 to 100 bar with small particle flow (~5 m/sec) in the explosives. The measurements at this point were made close to the elastic limit. The explosives usually were recovered from these experiments unchanged, although several were cracked by the shock. Measurements in several plastics indicate the velocities of these weak shocks essentially are those of longitudinal sound waves.[17–19] These are 10%–30% greater than the bulk sound velocities calculated from elastic constants. Since data on sound velocities in explosives are scarce,[20] the

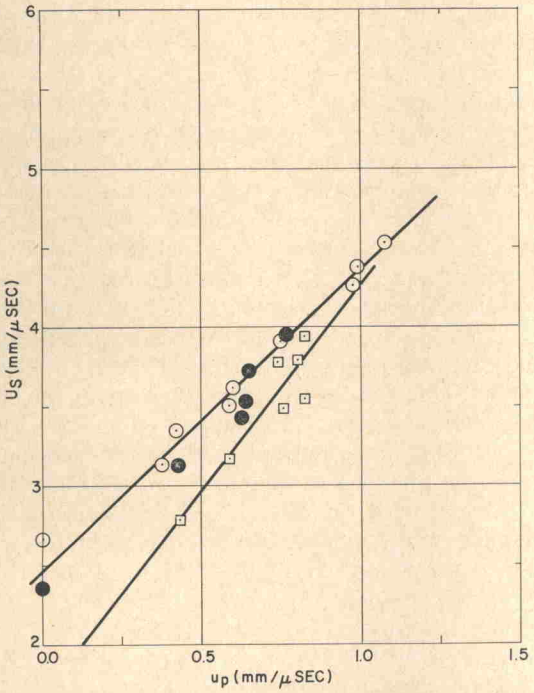

FIG. 8. Shock-wave velocity, U_s, vs particle velocity, u_p, of DATB (○), TNB (●), and TNA/Zytel (□).

longitudinal wave velocities, obtained from the weak-shock measurements, are listed in Table III.

The weak-shock values are shown at $u_p=0$ in the U_s-vs-u_p diagrams for comparison with the higher-amplitude shock-wave measurements. However, they were not included in the linear treatment of the U_s-vs-u_p data.[21] Consequently, few shock-wave data were obtained for $u_p<0.3$ mm/μsec, and the linearity of the lower region of the shock-velocity–particle-velocity curve is not fully established. Also, the possibility may

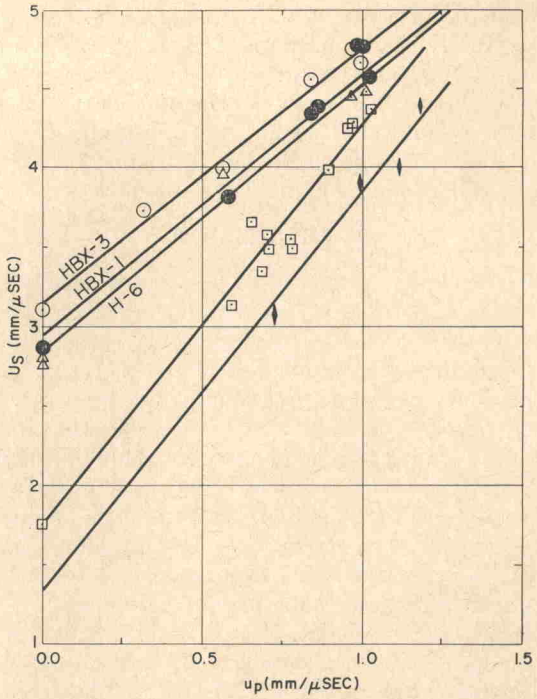

FIG. 9. Shock-wave velocity, U_s, vs particle velocity, u_p, of several aluminized explosives and propellants. ○ HBX-3, ● HBX-1, △ H-6, □ EJC, ◆ FFP.

TABLE III. Equation-of-state constants.

Explosive	Longitudinal sound velocity [(cm/sec)×10⁵]	A[a] [(cm/sec)×10⁵]	B[a]
TNT	2.572	2.390±0.032	2.050±0.034
Composition B-3	2.736	2.710±0.046	1.860±0.065
TATB	2.050	2.340±0.065	2.316±0.076
DATB	2.660	2.449±0.043	1.892±0.058
TNB	2.356	2.318±0.072	2.025±0.123
TNA	...	1.700±0.243	2.531±0.337
EJC	1.760	1.724±0.147	2.550±0.183
FFP	...	1.327±0.148	2.430±0.146
HBX-1	2.860	2.936±0.078	1.651±0.095
HBX-3	3.095	3.134±0.017	1.605±0.024
H-6	2.759	2.832±0.068	1.695±0.083
PBX 9404-03	2.919	...	...
LX-04-1	2.539	...	...
LX-04-0	2.688	...	...

[a] A and B are the intercept and slope, respectively, of the shock-velocity–particle-velocity curve.

[17] For Plexiglas, e.g., we measured a wave velocity of 2760 m/sec. The reported longitudinal sound velocity is 2770 m/sec.[18] The incident and transmitted shock-wave velocities in the water were 1492 and 1490 m/sec. The precise sound velocity is 1481.63 m/sec [19] in distilled water at 20°C.

[18] M. Auberger and J. S. Rinehart, J. Appl. Phys. **32,** 219 (1961).

[19] W. D. Wilson, J. Acoust. Soc. Am. **31,** 1067 (1959).

[20] For comparison with sound velocity of TNT obtained from ultrasonic measurements, see L. Aronica, Naval Ordnance Laboratory Report 6087 (1961); J. B. Ramsay and A. Popolato, "Analysis of Shockwave and Initiation Data for Solid Explosives," Symposium on Detonation, 4th, U.S. Naval Ordnance Laboratory, Silver Spring, Maryland, October 1965; R. J. Wasley and J. F. O'Brien, "Low Pressure Hugoniots of Solid Explosives," Symposium on Detonation, 4th, U.S. Naval Ordnance Laboratory, Silver Spring, Maryland, October 1965.

[21] Where only several data were obtained, e.g., H-6, the weak shock velocity was included.

exist of the presence of elastic precursor waves in the explosives at low amplitudes. Therefore, any extrapolation of the data to particle velocities much below 0.3 mm/μsec perhaps is not justified. Table III, though, lists the sound velocities and the constants A and B with their probable errors as determined from the weighted data by the method of least squares.

V. DISCUSSION

The sources of experimental error are: shock-wave curvature (± 0.01 μsec), uncertainty in record analysis (0.1% to 0.5% of U_s, depending on record quality), specimen density variation (± 0.002 g/cm^3), and effects of chemical reaction on the velocity measurements. The latter errors were minimized by the following means (1) The velocity measurements were made in cylinders with heights of only 1–5 mm; and (2) the experiments reported here were limited to transmitted pressures below 90 kbar. At a given input pressure the maximum height of each specimen depended upon the shock sensitivity of the particular explosive sample.

In practice the maximum specimen height was set by the length of run over which the shock wave has a reasonably constant initial velocity as measured in wedge-test experiments.[22] The wedge test differentiates between explosives by the ease with which chemical reaction is initiated and grows from shock impact. The growth of chemical reaction produces an increase in the shock-wave velocity for increasing explosive thickness. The onset of chemical reaction is dependent upon the amplitude and duration of the shock. For pressures below 90 kbar in 25° wedges (apex angle 90°), 14-mm apex height, the velocity of the shock in most of the materials showed no significant increase within the first 5 mm of travel. In several insensitive explosives no velocity increase was measured in much greater shock transit distances, e.g., at 60–70 kbar, TATB (>14 mm) and cast TNT (8 mm). Both of the latter explosives display initial constant velocities for distances longer than 5 mm with shocks of 100 kbar or more. The above precautions eliminated all experiments in which gross buildup of reaction would be present. The possibility of weak reaction behind the transmitted shock must still be considered.

In the wedge-test experiments the shock wave cannot be a true square step. Therefore, one would expect that rarefactions would cause such shocks to decay with distance of travel. In two experiments with TATB the decay was observed. The failure to decay in other experiments could be due to energy being fed into the shock front by chemical reaction. However, in the region of initial constant velocity it is very unlikely that reaction effects could exactly balance rarefaction effects to achieve steady velocities for relatively long periods. It is more likely that the shock velocity is not a sensitive function of pressure.

Majowicz and Jacobs[22] have indicated that the transition from pure shock to detonation in cast solids may involve an induction period before chemical reactions begin, as inferred from the region of constant shock velocity. (The existence of induction periods in liquid explosives and explosive single crystals is generally accepted.) However, Cachia and Whitbread,[23] also Campbell, Davis, Ramsay, and Travis,[24] conclude that even for small shock amplitudes the transmitted shock in polycrystalline explosives is accelerating, and initiates a small amount of chemical reaction in certain regions with essentially no delay.

It is possible, of course, that isolated sites of chemical reaction have resulted from the sudden impact even at the lowest pressures of our experiments. If so, during the shock transit times (<1 μsec) such reactive sites might be expected to contribute only to a small degree, perhaps 1%–2% or less, to the energy of the shock. Since the shock-velocity–particle-velocity relations are linear for many nonreactive solids, a linear behavior for the explosives given here is a significant indication that our measurements are essentially free of reaction effects. If appreciable chemical reaction occurred during any compression experiment, its energy contribution would cause the shock to accelerate.[25] This, typically, would be indicated by an abrupt increase in the slope of the U_s-vs-u_p curve and perhaps by luminous traces on the smear-camera records. Both the acceleration of U_s and the presence of luminosity were obtained for the plastic-bonded explosive LX-04-0. As seen in Fig. 5, the data at about $u_p=0.5$ mm/μsec are in line with that of cast Composition B-3. At about $u_p=0.8$ mm/μsec and above, though, the LX-04-0 specimens were obviously reacting, whereas for Composition B-3 there apparently is little reaction at this shock level. PBX 9404-03 reacted too readily to give any unreacted data even at the lower pressures. Incidentally, cast rather than pressed TNT was used in our experiments since the latter also reacts too fast to give reliable unreacted Hugoniot data much above 20 kbar.

The usual experimental error in measuring dynamic compressibilities, where no reaction is possible, is about 5%. We, therefore, consider that the deviations caused by reaction in our explosive specimens are not enough to affect appreciably the unreacted compression results in this spread of error, except where noted. The probable mean-square errors of ± 59 m/sec in U_s and ± 33 m/sec in u_p for Composition B-3 are typical of the data. These results lead to a probable relative error of $\pm 6.7\%$

[22] J. M. Majowicz and S. J. Jacobs, Naval Ordnance Laboratory Report 5710 (1958).

[23] G. P. Cachia and E. G. Whitbread, Proc. Roy. Soc. (London) **A246,** 268 (1958).

[24] A. W. Campbell, W. C. Davis, J. B. Ramsay, and J. R. Travis, Phys. Fluids **4,** 498 (1961).

[25] S. J. Jacobs, T. P. Liddiard, Jr., and B. E. Drimmer, Symp. Combust. 9th Cornell Univ., Ithaca, N.Y., 1962, 517 (1963).