Equations of state for graphite, aluminum, titanium, and iron at pressures > 13 Mbar

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New experimental results are reported on strong shock waves at pressures in the terapascal range, where contradictory data had been obtained earlier. These new results do not support the conclusion of Avrorin *et al.* that shell effects have a significant influence on the equations of state.

In a 1976 experiment we studied the equation of state of aluminum at pressures above 100 Mbar. We used photodetectors to detect the time at which a shock wave reached the free surfaces of two aluminum obstacles 14 cm and 16 cm thick. We detected no deviations from the theoretical equation of state, since the measured difference between propagation times, 245 ± 7 ns, which corresponds to a wave velocity of 81.6 ± 2.3 km/s and a pressure of 138 Mbar at the front (the indicated errors correspond to a confidence level of 0.68), agreed well with the results of thermodynamic calculations carried out from the equation of state of aluminum on the basis of the Thomas-Fermi statistical model.

Some unexpected results on the shock compressibility of substances were reported by Avrorin *et al.*[3] and led us in 1981 to experimentally test the comparative propagation dynamics of shock waves for two pairs of substances. In these experiments we used photodetectors to measure the time intervals between a reference pulse essentially

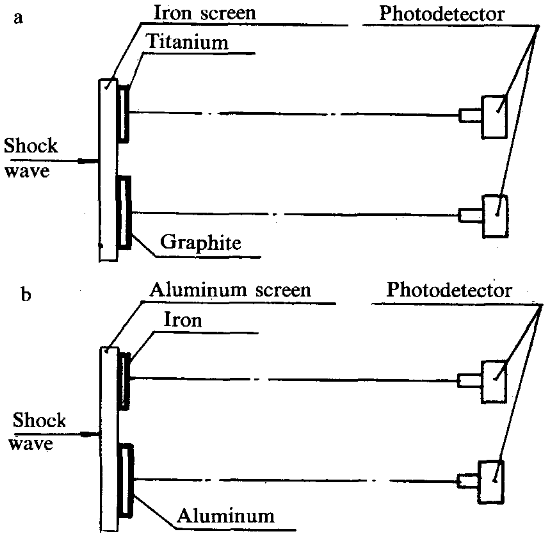

FIG. 1.

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TABLE I.

Screen	P_{scr}, Mbar	Sample	Density g/cm^3	h cm	P_0 (0) Mbar	P_0 (h) Mbar	t_p ns	Δt_p ns	Δt_e ns
Iron	46	Titanium	4,51	3	33.4	25	967	91	100±28
		Graphite	1,82	4	19.6	13	1058		
Aluminum	35	Aluminum	2.71	4.5	35	21	1218	363	390±29
		Iron	7,85	2,5	55.6	33.5	855		

coinciding with the time at which the shock wave begins to move across the screen (Fig. 1) and the time at which the shock waves emerge at the surface of the obstacles of the substances under study.

The time intervals detected for screen-titanium and screen-graphite pairs (Fig. 1a) with an iron screen were 2120 ± 20 and 2220 ± 20 ns, respectively. In the second pair (Fig. 1b), the screen was made of aluminum, and relative measurements were carried out for iron and aluminum. The time intervals detected here were 1620 ± 20 and 2010 ± 20 ns, respectively.

The last column in Table I shows the measured differences Δt_e in the shock-wave propagation times through the samples of titanium and graphite and of iron and aluminum. The value of Δt_e depends on the amplitude of the shock wave in the screen and on the equations of state of the screen and of the samples, so it can be used to test the equations of state of these samples.

TABLE II.

Substance	Density, g/cm^3	a	b	Pressure Range Mbar
Iron	7.85	5.82	1.23	30 – 60
Titanium	4.51	4.8	1.21	20 – 40
Graphite	1.82	7.13	1.21	13 – 30
Aluminum	2.71	6.06	1.2	20 – 40
		5.35	1.22	40 – 150

Gasdynamic calculations on the propagation of shock waves through the plates were carried out with the equations of state of the substances found from the Thomas-Fermi statistical model of the atom. As in Ref. 8, in constructing the cold component of the interpolation equation of state we used experimental data at low pressures[4,9] (the cold pressure and the cold energy are zero at the standard density of the substance), and at high compressions we used the results of numerical calculations[10,11] from the Thomas-Fermi model with quantum and exchange corrections. Table II shows coefficients found from the expression $D = a + bU$, used to approximate the dependence of the wave velocity D on the mass velocity U over the pressure range of interest (according to Ref. 8) for aluminum, iron, titanium, and graphite. The curve of $D(U)$ for iron is approximately equal to the interpolation adiabat in Ref. 4 and agrees with the experimental point from Ref. 1. The shock adiabat of aluminum is in agreement with the experimental data of Ref. 7, but it differs from the interpolation curve of Ref. 4 by $\sim$4.4%, in the direction of an increase in the wave velocity at a given mass velocity.

The amplitude of the shock wave that enters the screen is found from the total time required for the propagation of the pressure pulse through the screen and one of the samples being compared. Calculations show (Table I) that a plane shock wave excited in an iron screen with a pressure $P_{\text{scr}} = 46$ Mbar at the front propagates, after the decay of the discontinuity, through a titanium plate $h = 3$ cm thick for $t_p = 967$ ns. The pressure at the wavefront decreases from $P_0(0) = 33.4$ Mbar to $P_0(h) = 25$ Mbar. Data on all the samples studied are collected in Table I.

Comparison of the theoretical and experimental values shows that Δt_p and Δt_e agree within the experimental errors. The agreement improves if we let the shock wave propagate at a velocity 2.2% lower through the aluminum sample.

In contrast with Ref. 3, where the measured time intervals differed from the theoretical values by 15–20%, our experimental results agree well with the description of gasdynamic processes in calculations which use the equations of state of substances according to the Thomas-Fermi statistical model without consideration of the shell structure of the atom.

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