TABLE I. Summary of plane-wave data for $BaTiO_3$ (5% $CaTiO_3$).

SHOT NO.	EXPLOSIVE	DRIVER Material	DRIVER Thickness (cm)	DRIVER Press. (kbar)	NOMINAL SPECIMEN THICKNESS (mm)	FIRST WAVE[a] U_1 (mm/μsec)	FIRST WAVE[a] u_1 (mm/μsec)	FIRST WAVE[a] σ_1 (kbar)	FIRST WAVE[a] ρ_0/ρ	SECOND WAVE U_2 (mm/μsec)	SECOND WAVE u_2 (mm/μsec) Imp. Match	SECOND WAVE u_2 (mm/μsec) $\frac{1}{2}u_{fs_2}$	SECOND WAVE σ_2 (kbar)	SECOND WAVE ρ_0/ρ
7400	P-40[b]	2024 Al	1.25	125[c]	6	6.15	0.108	37	0.982	4.74 4.89[d]	0.56	0.48	144 149	0.898 0.901
7446	P-60[e] + 1" Baratol	2024 Al	1.25	133[c]	3 12.5	-- 6.15	-- 0.107	-- 37	-- 0.982	-- 4.76 5.18[d]	-- 0.6 --	0.56 } -- } --	154 167	0.8875 0.896
7447	P-60 + 1" Comp B	2024 Al	1.25	245	3 6	-- 6.32	-- (0.11)[f]	-- (40)	-- (0.982)	-- 5.82	0.98 --	0.96 } 0.82 }	310	0.8363
8445	P-60	Annealed Armco Fe	2.2 (6° taper)	7.9 131[c]	6	5.25[g] 6.12	0.0175 (0.10)	5.1 (33)	0.9967 (0.9828)	-- --	-- --	-- --	-- --	-- --
8748	P-60 + 1" Baratol	4340 steel RC 30	4.6 (10° taper)	18	5	5.90	0.0492	16	0.9917	--	--	--	--	--
8882	P-60	Brass + Lucite	1.25 1.2 (2° taper)	32	6 (max) 10° wedge	6.15	0.098	34	0.9840	--	--	--	--	--
8883	P-60	4340 steel RC 50	3.2 (10° taper)	23	5.4	6.08	0.065	22	0.9891	--	--	--	--	--
8884	P-60	4340 steel + Lucite	4.6 (10° taper) 0.6	2.5[c]	6	5.24	0.016	4.7	0.9969	--	--	--	--	--

a. These data through Shot No. 7447 are approximate and not plotted in figures. This is because u_{fs} is not constant behind the first wave and its initial value was determined more precisely in wedge shots.
b. A 4-inch explosive plane wave generator.
c. Not measured, but assumed on basis of other shots.
d. Determined from reverberation arrival, as in Fig. ~~16~~ 8. Only these points and Shot 7447 ($U_2 \sim U_1$) are included in the figures.
e. A 6-inch explosive plane wave generator.
f. Most uncertain values indicated by parentheses.
g. Apparent velocity of peak amplitude; near foot of wave, apparent velocity ~5.0 mm/μsec.

in terms of wt%, were SiO_2 (0.32), Al_2O_3 (0.30), SrO^+ (0.23), Na_2O^+ (0.18), and P_2O_5 (0.12). Purity of the calcium titanate additive is unknown. The mean densities of the bars were in the range 5.52 to 5.56 g/cm^3, with about 1% variation within any given bar (density highest near surface). The longitudinal sound speed (c_L) was found to be 5.4±0.1 mm/μsec at room temperature. The variation of c_L with temperature over a range including the Curie temperature (115°C) is shown in Fig. 1; the significance of these data will be discussed below. Figure 2 shows the results of static stress–strain measurements made at Sandia Corp.[4] These were nominally one-dimensional compressive stress experiments with $\frac{1}{3}\times\frac{1}{3}\times3$-in. specimens; the strain was determined with a strain gauge cemented to the side of the specimen. The curves were terminated by shattering of the specimens.

The 95/5 PZT specimens were supplied in the form of circular disks, 2 in. in diameter by $\frac{1}{3}$- or $\frac{7}{8}$-in. thick, fabricated by hot pressing.[5] Their average densities ranged from 7.61 to 7.89 g/cm^3, varying perhaps 1% in any given specimen (theoretical density is 8.16 g/cm^3). Values of c_L ranged from 3.9 to 4.3 mm/μsec, generally increasing with density. A static stress–strain curve is included in Fig. 2.

[4] A. E. Binder (private communication).
[5] Supplied by Minneapolis–Honeywell, Minneapolis.

EXPERIMENTS

The experiments were performed in two configurations, both of which have been described previously.[6] In one, a plane shock wave is produced in a specimen by means of an explosive plane-wave generator. In the other, an oblique shock wave is produced in a large specimen block by a detonation wave propagating in a thin sheet of explosive in contact with one face of the block. Shock velocities and particle velocities were deduced from shock arrivals and free-surface motion recorded with a smear camera. The polished ceramic reflected enough light from the argon bomb so that a metallic coating was unnecessary. The inclined mirror and optical lever techniques that were used have been described previously.[6,7] Examples of smear camera records from both types of shots are shown in Figs. 3 and 4.

Most of the low-pressure data for BT were generated in the oblique geometry; the advantage of this technique is that a range of pressures is covered in each shot. In particular, it is the most sensitive technique to study small variations of shock velocity with variations of shock amplitude. Of particular interest in the present work is a comparison of data from shots

[6] D. G. Doran, *High Pressure Measurement*, A. A. Giardini and E. C. Lloyd, Eds. (Butterworths Scientific Publications, Inc., Washington, 1963), p. 68.
[7] G. R. Fowles, J. Appl. Phys. **32**, 1475 (1961).

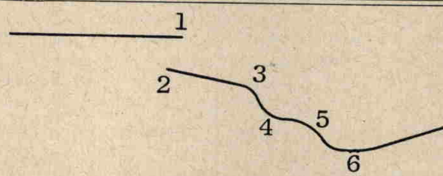
TABLE II. Summary of oblique geometry data for $BaTiO_3$ (5% $CaTiO_3$). (Most questionable values indicated by parentheses.)

(a) General shot data

Shot No.	Specimen designation[a]	Wedge angle (A)	Explosive Type	Explosive Thickness (in.)	Explosive Det. vel. (mm/μsec)	Initial temperature (°C)	Initial density (g/cm³)
7396	A	40°33′	Comp B	0.188	7.86	20	5.54±0.02
7477	C	25°29′	Comp B	1.00	7.97	20	5.54±0.02
7540	D	62°17′	EL-506-D	0.017	7.31	17	5.54±0.02
7592	Test-C[b]	64°30′	EL-506-D	0.017	7.31[b]	20	5.54±0.02
7612	E	62°38′	EL-506-D	0.017	7.37	21	5.54±0.02
8113	J	70°47′	EL-506-D	0.015	6.81[c]	130	5.53±0.02

[a] Wedge dimensions 5x5x20 cm max., except No. 7592 (see note b).
[b] Test wedge—from specimen block *C*. Maximum length = 10 cm. Detonation velocity assumed same as for Shot No. 7540.
[c] Explosive also at 130°C.

(b) Shot No. 7477



First wave[a] (points 1–2) U_1 (mm/μsec)	u_1 (mm/μsec)	σ_1 (kbar)	ρ_0/ρ	Ramp[b] (points 2–3) U^* [b] (mm/μsec)	u^* (mm/μsec)	σ^* (kbar)	$\rho_0/\rho_{av}{}^*$	Second wave[c] (points 3–6) U_2 (mm/μsec)	u_2 (mm/μsec)	σ_2 (kbar)	ρ_0/ρ
6.35	(0.096)	(33.7)	(0.9849)	(5.5)	(0.129)	(44)	(0.9790)	(4.63)	(0.515)	(142)	(0.895)
6.27	0.0887	30.8	0.9859	5.3	0.129	43	0.9782	4.57	0.355	99	0.929
	0.0882	30.6	0.9859	5.3	0.127	44	0.9782	4.54	0.368	102	0.926
	0.0898	31.1	0.9857	5.3	0.137	45	0.9782	4.40	0.300	83	0.937
	0.0854	29.6	0.9864	5.3	0.135	45	0.9782	4.33	0.327	90	0.932
	0.0876	30.4	0.9860	5.3	0.126	41	0.9782	4.28	(0.283)	(78)	(0.938)
	0.0854	29.6	0.9864	5.3	0.121	41	0.9782	4.20	0.280	76	0.938
	0.0870	30.2	0.9861	5.3	0.128	42	0.9782				
	0.0876	30.4	0.9860	5.3	0.118	39	0.9782				

[a] The first wave, ramp, and second-wave data do not correspond to the same positions on the wedge face.
[b] The asterisks indicate effective quantities based on $U^* = \frac{1}{2}(U_{a2}+U_{a3})$, where U_{ai} is the apparent velocity of feature *i* of the trace, etc.
[c] Jump 3–4 is due to the "reverberation" of the first wave (see text). Three discrete jumps were assumed in calculating the increase in free-surface velocity between points 3 and 6. U_2 was computed from the average of U_{a5} and U_{a6}.

at 20°C with data from one shot at 130°C, above the Curie temperature of ~115°C. The experimental setup and smear camera record for the latter shot are shown in Fig. 4.

One oblique geometry shot was fired with a thick pad (1 in.) of explosive to obtain data on the two-shock profile.

All the data on 95/5 PZT were obtained in the plane-wave configuration.

RESULTS

Barium Titanate

Hugoniot data for BT are presented in Tables I and II and in Figs. 5–7. A two-wave structure is observed below 300 kbar, the highest point measured in this study. The first-wave amplitude is ~30 kbar and the velocity is ~6.27 mm/μsec.[8] These values are from the oblique wave experiments and are considered more accurate than those from plane-wave shots. This is particularly true of the first-wave amplitude because the stress and particle velocity continue to increase behind the essentially discontinuous wavefront, and hence it is difficult to measure the *initial* free-surface velocity accurately with the inclined mirror technique. The highest first-wave amplitude measured was 35 kbar, and there is a suggestion of shear stress relaxation[9] as the first wave propagates, i.e., the first-wave amplitude decreases somewhat with propagation distance in the presence of a following second wave.

The calculation of states behind the second wave is less straightforward than for the first wave because the second wave arrives at the free surface only after it has interacted with the reflection(s) of the first wave from the free surface. For two plane-wave shots (Nos. 7400 and 7446), the free-surface velocity clearly in-

[8] Corresponding values for "pure" $BaTiO_3$ are 25 kbar and 5.90 mm/μsec. (See Ref. 2.)

[9] See Ref. 1, p. 248.