SHOCK EFFECTS ON FROZEN MATERIALS
EXPLODING WIRE EXPERIMENTS

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PREFACE

This work was performed by Mr. James L. Smith, Research Civil Engineer, under the general direction of Mr. A.F. Wuori (Chief, Applied Research Branch) and Mr. K.A. Linell (Chief, Experimental Engineering Division), U.S. Army Cold Regions Research and Engineering Laboratory. This report was published under DA Task 1T062112A13001, *Cold Regions Research, Applied Research and Engineering.*

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The report was technically reviewed by Dr. Y. Nakano and Dr. I. M. Fyfe.

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CONVERSION FACTORS

Multiply	*By*	*To obtain*
millimeters	0.03937	inches
cm/sec	0.03281	ft/sec
dynes/cm^2	1.45×10^{-5}	psi
kilobars	1.45×10^4	psi
g/cm^3	62.43	lb/ft^3

SHOCK EFFECTS ON FROZEN MATERIALS

Exploding Wire Experiments

by

James L. Smith

INTRODUCTION

The dynamic loading process gives rise to the dynamic equation of state, or Hugoniot, of a material. The Hugoniot not only gives basic information regarding the shock loading process but also relates to the fundamental properties of materials. Most of the empirical data used in determining Hugoniot curves have been obtained by making velocity measurements. The shock velocity and particle velocity are measured simultaneously and the conservation equations are used to compute the pressure-volume relationships.

Conservation of mass and momentum across the shock wave requires that

$$\rho_0 = \rho_1 (U_s - U_p) \qquad \text{(mass)} \tag{1}$$

$$P_0 + \rho_0 U_0^2 = P_1 + \rho_1 (U_s - U_p)^2 \qquad \text{(momentum)} \tag{2}$$

where:

U_s = the shock velocity

U_p = the particle velocity behind the shock wave

P_0 = initial pressure

ρ_0 = initial density.

The pressure behind the shock wave is

$$P_1 = \rho_0 U_s U_p + P_0. \tag{3}$$

In these tests the shock compression is at least on the order of several hundred atmospheres so that the ambient pressure or initial pressure of about one atmosphere can be neglected. Then,

$$P_1 = \rho_0 U_s U_p. \tag{4}$$

From the definition of strain,

$$\epsilon = \frac{V_0 - V}{V_0} = \frac{\rho - \rho_0}{\rho} = 1 - \frac{\rho_0}{\rho}$$

where V is the specific volume, and eq 1,

$$\epsilon = 1 - \frac{\rho_0}{\rho} = \frac{U_p}{U_s} \qquad (5)$$

so that the dynamic stress and strain can be determined from U_s and U_p, the variables usually directly or indirectly measured in shock wave experiments (Cook *et al.*, 1962; Dennen, 1965).

TEST PROCEDURE

The exploding wire technique utilizes electrical energy stored in a capacitor system and released rapidly to explode a thin wire which in turn creates a pressure pulse uniform along the length of the wire and propagating radially from the axis of the wire (Fyfe, 1968). A schematic of the capacitor discharge system is shown in Figure 1.

The test samples were obtained from the permafrost tunnel at Fairbanks (Fox), Alaska. The frozen silt samples were cored with a slightly modified USA CRREL ice auger. Tungsten carbide cutters were substituted for the conventional steel cutters and the core barrel was adapted to a hand-held rotary percussion electric drill. The samples were cut to the desired length (approximately 10 cm) and a hole was drilled along the length of the cylinder. The position of this hole was varied to obtain free-surface velocities at different stress levels. The closer the hole, or wire, to the surface the greater the stress.

Density determinations were made from carefully measured values of the weight to the nearest 0.5 g and the diameter and length to the nearest millimeter. Routine soil analysis was performed on samples representative of the material tested (Fig. 2).

The shock parameters (U_s and U_p) obtained from the exploding wire technique were determined from measured values of shock arrival time at the free surface and the free-surface motion. These tests were made with the exploding wire positioned at various radial distances from the surface of the specimens. The tests were performed under a controlled temperature of −10°C.

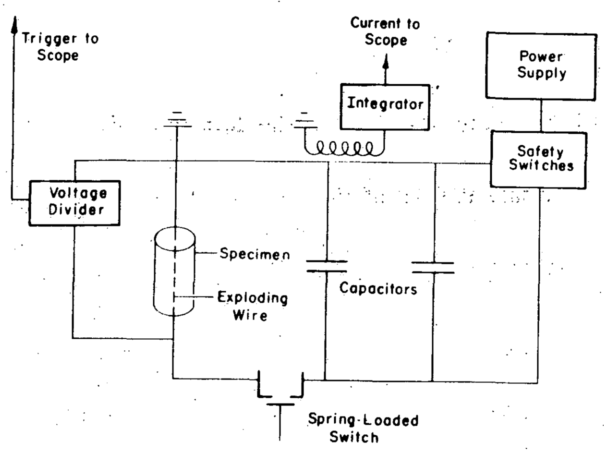
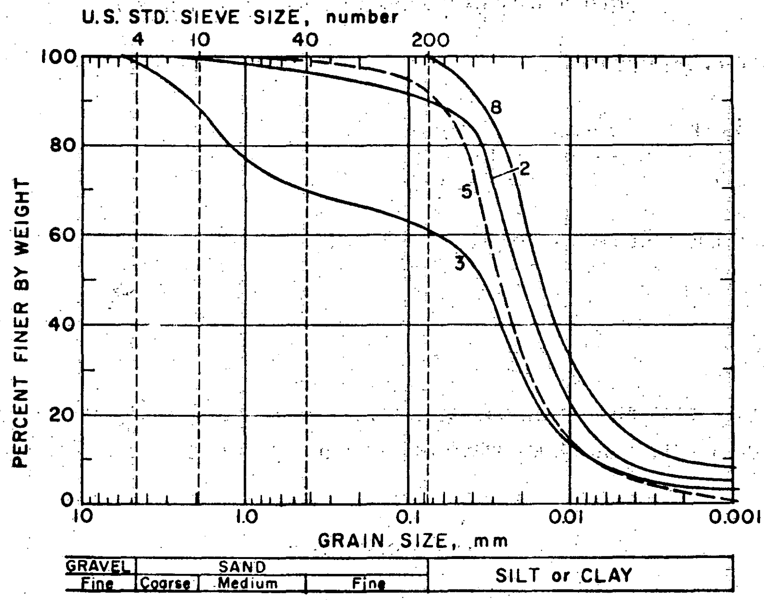


Figure 1. Schematic of capacitor discharge system.



Sample no.	Classification	WC	LL	PL	PI	ρ_0	S.G.
8	organic silt OH	129.7	58	50	8	1.29	2.71
2	organic silt OL	98.5	45	44	1	1.38	2.43
5	organic silt OL	66.1	35	NP	NP	1.45	2.63
3	organic sandy silt OL	45.6	39	42	NP	1.65	2.63

Figure 2. Typical gradation curves.

TEST RESULTS

The shock wave velocities were determined from a plot of the time required for the shock wave to travel the distance from the exploding wire to the free surface of the specimens (Fig. 3, 4).

These data were fitted to the equation

$$r = a_0 + a_1 t + a_2 t^2 \tag{6}$$

where the velocity of the shock wave at time t would be

$$U_s = \frac{dr}{dt} = a_1 + 2a_2 t. \tag{7}$$

Table I gives the results of the analytical fit of the data to eq 6.

Table I. Analytical fit of the data to $r = a_0 + a_1 t + a_2 t^2$.

ρ_0 (g/cm²)	a_0	a_1	a_2
1.26	2.16	2.95	-0.019
1.41	-1.83	4.03	-0.067
1.50	-3.47	4.22	-0.060
1.58	-5.19	5.28	-0.130

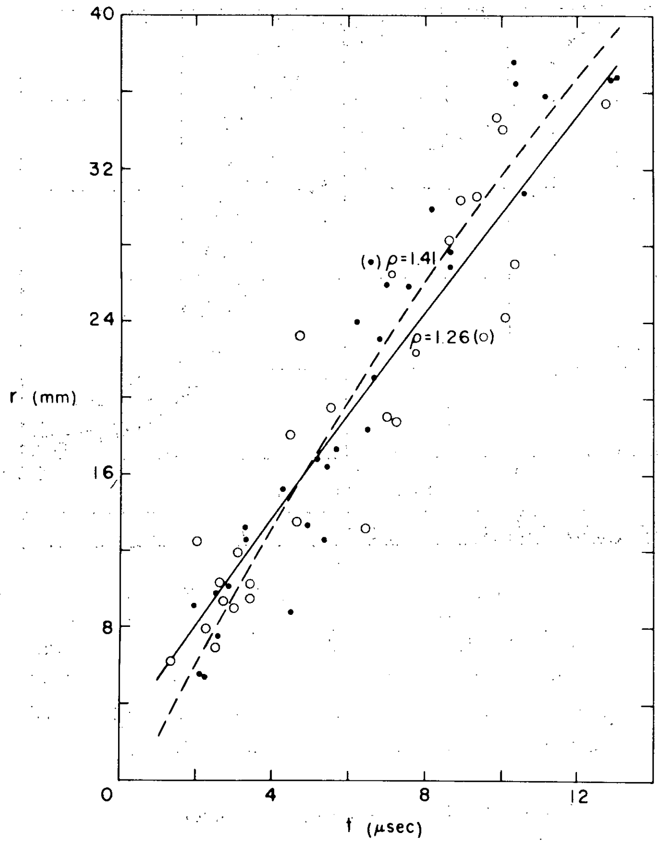


Figure 3. Radius versus shock transit time.

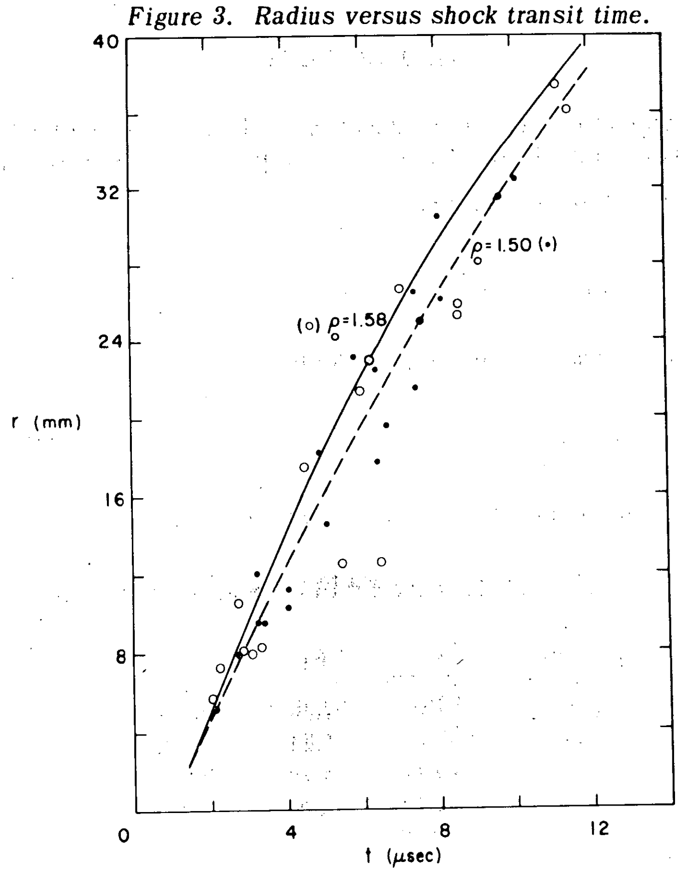


Figure 4. Radius versus shock transit time.

The shock wave velocity for each test specimen was computed using eq 7 and the results are tabulated in the Appendix.

The experimental value of U_p cannot be directly obtained; however, the free-surface velocity (U_{fs}) can be measured and a value of 2 is used for U_{fs}/U_p. The value of 2 for this ratio is not necessarily exact, but has been found to be very close so long as the free-surface velocity is understood to be the immediate response of the specimen surface to the arrival of the shock.

The particle velocities as determined from the free-surface velocities for each specimen are recorded in the Appendix.

Extensive single Hugoniot measurements on a large number of substances indicate that, for almost all materials, shock velocity and particle velocity are linearly related as

$$U_s = C + S\,U_p \tag{8}$$

where C and S are constants characteristic of the material (McQueen and Marsh, 1960). A specific linear relation holds only for a single phase. When a material undergoes a phase change the slope changes at the pressure where the phase change occurs. For materials not represented by a single straight line on the ($U_s - U_p$) curve, there are indications that a series of straight lines would be applicable (Dennen, 1965).

Plots of the Hugoniot in the shock velocity-particle velocity plane (Fig. 5) show a definite change in slope occurring at a particle velocity around 0.03 to 0.04 mm/μsec. Table II gives the shock velocity-particle velocity relationship prior to the phase change.

Table II. Analytical fit of the data to $U_s = C + S\,U_p$.

ρ_0 (g/cm³)	C (mm/μsec)	S
1.26	2.42	10.45
1.41	1.91	49.63
1.50	2.36	51.68
1.58	1.78	73.57

Assuming this linearity holds after the phase change, Table III gives the shock velocity-particle velocity relationship after the phase change.

Table III. Analytical fit of the data to $U_s = C + S\,U_p$.

ρ_0 (g/cm³)	C (mm/μsec)	S
1.26	2.82	0.30
1.41	3.64	0.68
1.50	3.73	1.42
1.58	4.40	1.66

When the shock velocity and particle velocity are linearly related the equation of state can be written explicitly in terms of the constants C and S as

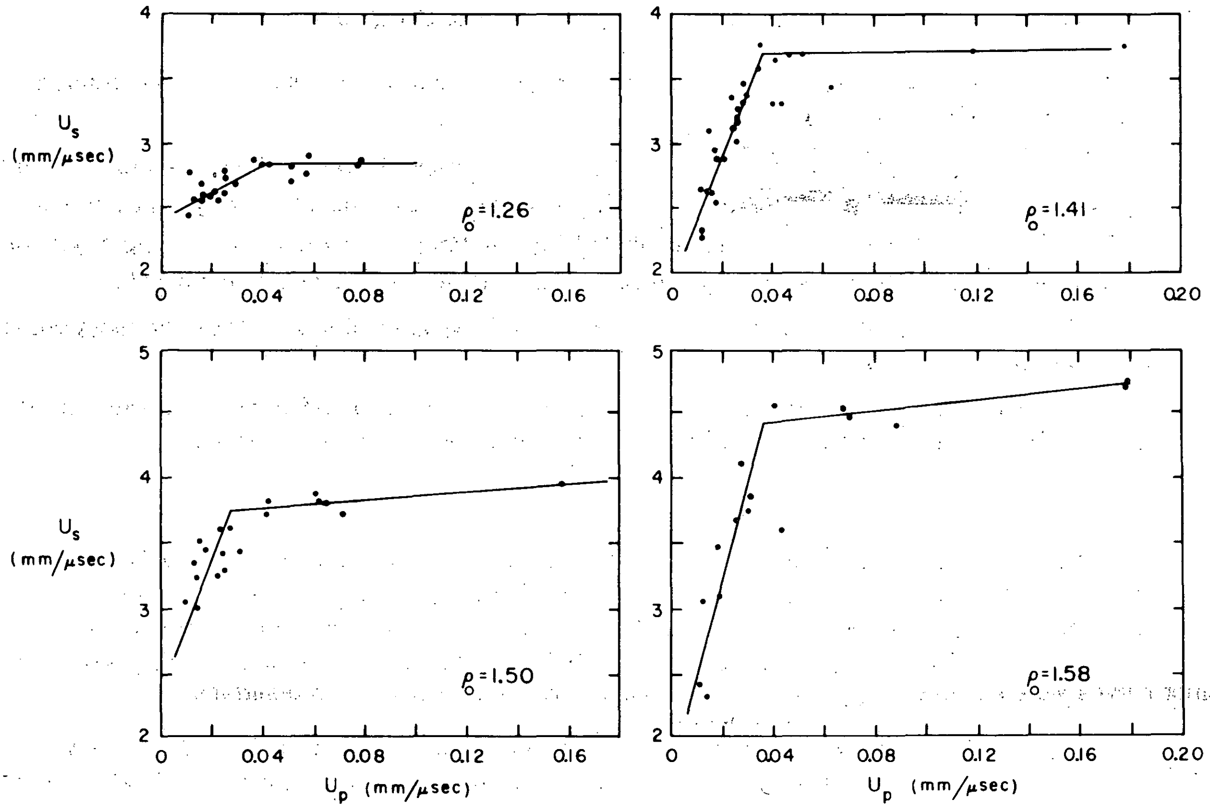


Figure 5. Hugoniot in the shock velocity-particle velocity plane.

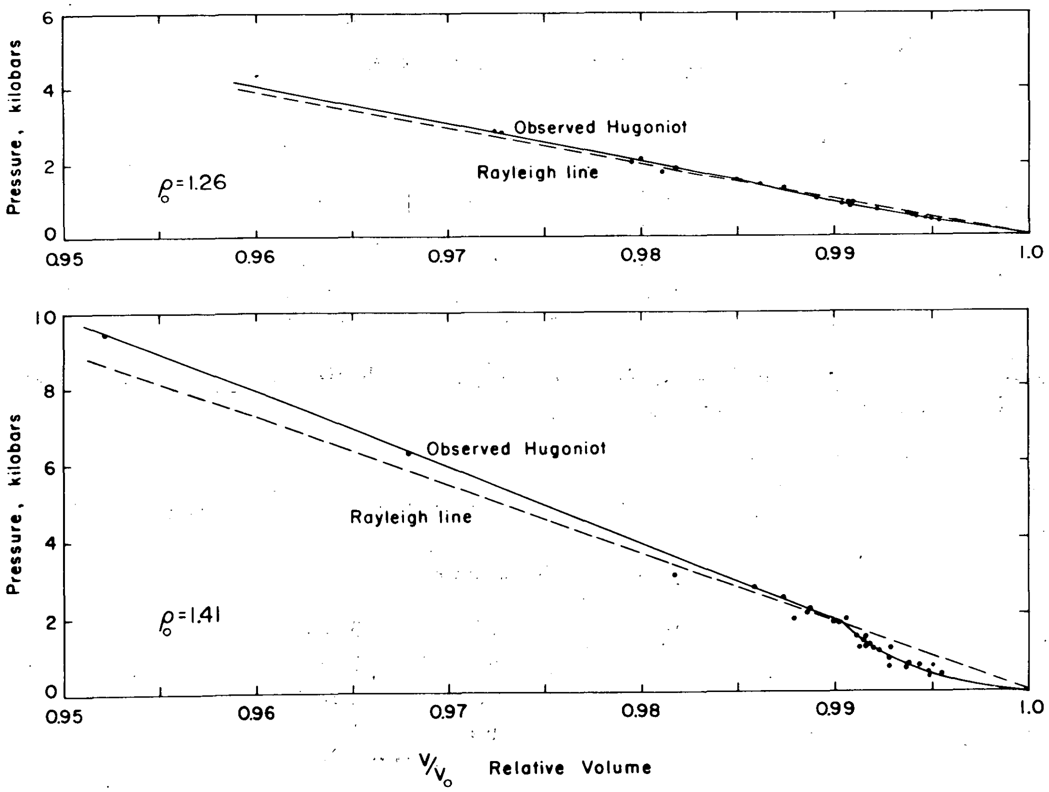


Figure 6. Hugoniot in the pressure-relative volume plane.

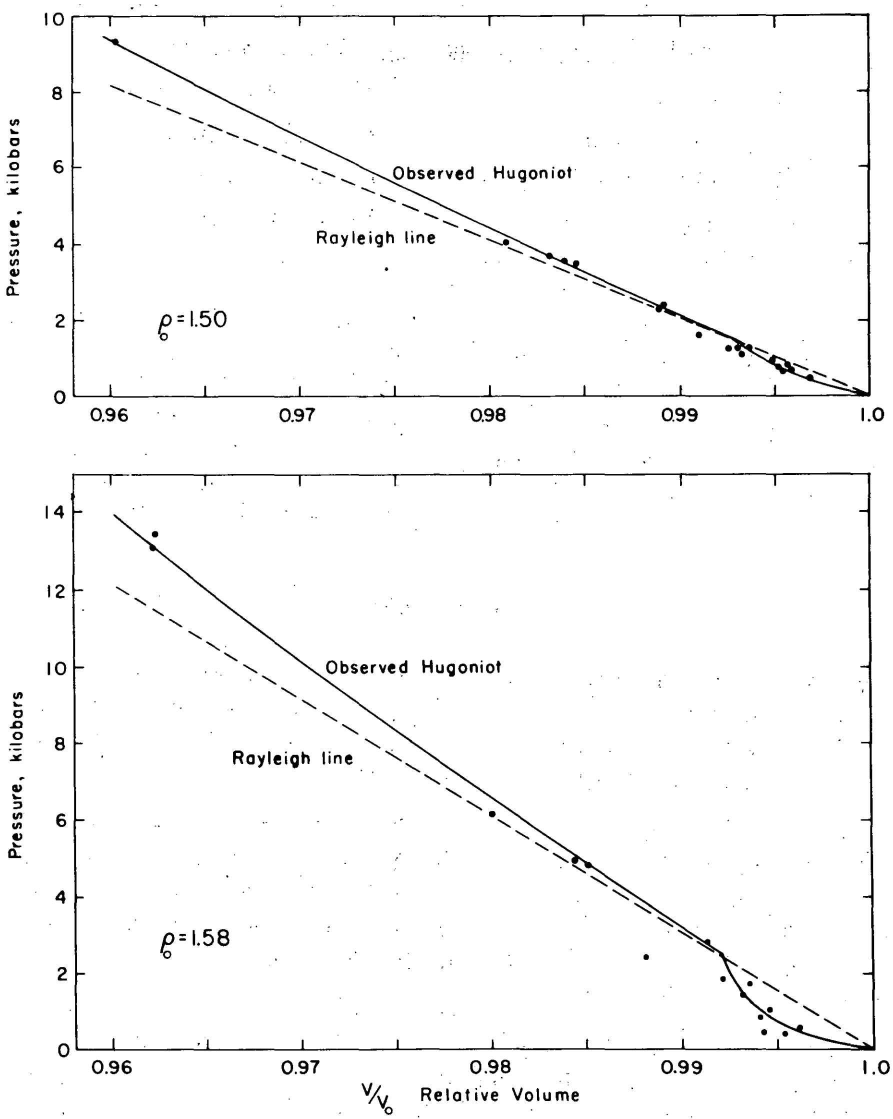


Figure 7. Hugoniot in the pressure-relative volume plane.

$$P = C^2 (V_0 - V_1) / [V_0 - S (V_0 - V_1)]^2. \quad (9)$$

The Hugoniot in the pressure-relative volume plane is shown in Figures 6 and 7. The data points are plotted and the observed Hugoniot was computed using eq 9 with the values for the constants C and S from Tables II and III.

Tests were conducted to determine the complex Young's modulus, complex shear modulus, damping characteristics and velocity of wave propagation under dynamic load for selected frozen soil samples representative of the material tested (Stevens, 1966). The samples were subjected to sinusoidal steady-state vibrations, first in the longitudinal direction and then in the torsional direction. The fundamental resonant frequency and up to four harmonics were determined under a range of drive forces or stress levels. Table IV gives the material constants derived from the test data.

Table IV. Material constants under dynamic load.

ρ = density
E^* = complex Young's modulus
C_p = phase velocity (longitudinal)
C_1 = compressional velocity
G^* = complex shear modulus
C_s = shear velocity
ν = Poisson's ratio
C_0 = bulk sound velocity

ρ g/cm³	E^* dynes/cm²	C_p cm/sec	C_1 cm/sec	G^* dynes/cm²	C_s cm/sec	ν	C_0 cm/sec
1.24	0.97×10^{11}	2.80×10^{5}	3.72×10^{5}	3.53×10^{10}	1.69×10^{5}	0.37	2.95×10^{5}
1.43	1.21	2.90	3.86	4.26	1.75	0.37	3.19
1.55	1.35	2.95	3.92	4.94	1.78	0.37	3.34

DISCUSSION

Hugoniot curves were generated from simultaneous measurements of shock and free-surface velocities obtained from samples of frozen Fairbanks (Fox) silt using the exploding wire technique. The Hugoniots in the U_s-U_p plane are shown in Figure 5 and the linear relationship $U_s = C + S\,U_p$ was determined for the two segments at each density.

Values for the pressure and relative volume obtained from the measured values of shock velocity, particle velocity and density for each sample are recorded in the Appendix. The Hugoniots in the P-V plane (Fig. 6, 7) show these data points with the fitted curve computed using eq 9. Since these samples were neither homogeneous nor isotropic there was considerable scatter in the data. However, it was considered that enough data were obtained at each test density to ascertain reliable results for the velocity measurements.

The abrupt change in slope of the U_s-U_p curve (Fig. 5) is indicative of a phase change. With the measurement technique for the free-surface velocity used, it is not possible to state whether or not a two-wave shock structure exists. The important thing to note is that transformations are indicated by the kink in the U_s-U_p Hugoniot.

Figure 8 shows two P-V Hugoniots and the resulting U_s-U_p Hugoniot (McQueen *et al.*, 1967). Hugoniot data for both *A* and *B* would be recorded as shown in *C* in this type of experiment. In *A* it has been assumed that the material does not begin to transform at the equilibrium condition and that it is possible to overdrive the transition pressure; however, with time, the material transforms and the pressure decays. In *B* it has been assumed that transformation begins but does not go to completion. This means that, although the pressure lies slightly above the Rayleigh line through the mixed phase region, the slope does not increase as rapidly as it would if the material had stayed in the initial phase.

The Hugoniot curves generated from the exploding wire technique (Fig. 5, 6, 7) exhibit the characteristics of *B* and *C* in Figure 8 indicating a phase change but incomplete transformation.

Since this phase change apparently occurs around 2 kb, the approximate value at which ice at a temperature of -10°C exhibits a transformation to water, the inference is that the transformation of the ice volume to water is begun but the test limitations do not allow completion of the phase change.

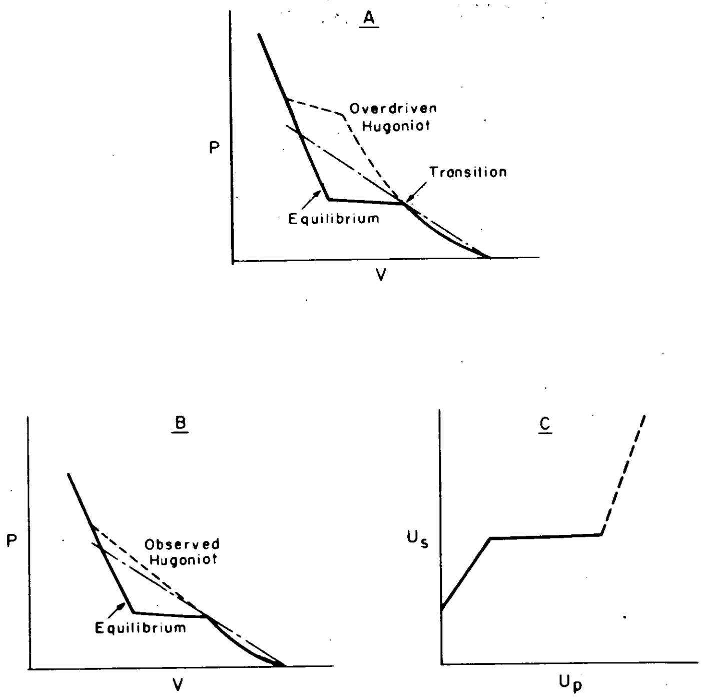


Figure 8. Two P.V. Hugoniots and the resulting U_s-U_p Hugoniot. (After McQueen et al., 1967.)

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APPENDIX A: HUGONIOT DATA

ρ_0 = 1.26 g/cm³

t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0	t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0
3.00	9.02	0.04185	2.836	1.50	0.98524	1.35	6.17	0.05806	2.899	2.12	0.97997
4.65	23.19	0.01064	2.773	0.37	0.99616	9.32	30.68	0.01588	2.596	0.52	0.99388
4.46	18.08	0.02495	2.780	0.87	0.99103	10.32	27.09	0.02347	2.558	0.76	0.99082
12.73	35.44	0.01143	2.466	0.36	0.99536	2.61	10.31	0.03920	2.851	1.41	0.98625
2.03	12.48	0.03615	2.873	1.31	0.98742	5.50	19.51	0.02514	2.741	0.87	0.99083
2.26	7.90	0.07788	2.864	2.81	0.97281	8.90	30.38	0.02510	2.612	0.83	0.99039
6.99	19.05	0.02920	2.684	0.99	0.98912	4.64	13.60	0.05685	2.774	1.99	0.97951
8.60	28.31	0.02055	2.623	0.68	0.99217	2.53	6.93	0.07874	2.854	2.83	0.97241
10.01	34.13	0.01500	2.570	0.48	0.99416	6.44	13.21	0.05105	2.705	1.74	0.98113
3.41	10.26	0.05144	2.820	1.83	0.98176	7.18	18.83	0.01615	2.677	0.54	0.99397
2.70	9.36	0.04265	2.847	1.53	0.98502	10.08	24.27	0.01270	2.567	0.41	0.99505
3.41	9.47	0.04222	2.820	1.50	0.98503	9.85	34.77	0.01370	2.576	0.44	0.99468
						3.10	11.95	0.03915	2.832	1.40	0.98618

ρ_0 = 1.41 g/cm³

t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0	t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0
5.40	16.40	0.04014	3.306	1.87	0.98786	2.84	10.11	0.04128	3.649	2.12	0.98869
2.57	7.48	0.04685	3.686	2.43	0.98729	1.92	9.07	0.03556	3.773	1.89	0.99058
4.47	8.94	0.06283	3.431	3.04	0.98169	5.64	17.37	0.02656	3.274	1.23	0.99189
2.51	9.75	0.05207	3.694	2.71	0.98590	12.84	36.73	0.01181	2.309	0.38	0.99489
8.63	26.88	0.02084	2.874	0.84	0.99275	6.43	18.32	0.02623	3.168	1.17	0.99172
6.94	25.98	0.01524	3.100	0.67	0.99508	10.38	36.50	0.01189	2.639	0.44	0.99550
3.30	12.57	0.03520	3.588	1.78	0.99019	8.09	29.90	0.01664	2.946	0.69	0.99435
4.90	13.34	0.02988	3.373	1.42	0.99114	6.66	21.13	0.02511	3.138	1.11	0.99200
6.19	23.98	0.02634	3.200	1.19	0.99177	12.97	36.79	0.01181	2.292	0.38	0.99485
6.78	23.06	0.02446	3.121	1.08	0.99216	5.14	16.75	0.02855	3.341	1.34	0.99146
4.24	15.21	0.02890	3.462	1.41	0.99165	2.26	5.31	0.11938	3.727	6.27	0.96797
7.51	25.86	0.02642	3.024	1.13	0.99126	2.11	5.46	0.17907	3.747	9.46	0.95221
11.12	35.75	0.01824	2.540	0.65	0.99282	5.39	12.62	0.04420	3.308	2.06	0.98664
10.56	30.77	0.01646	2.615	0.61	0.99371	3.28	13.34	0.03572	3.590	1.81	0.99005
5.01	15.81	0.02393	3.359	1.13	0.99288	10.37	37.72	0.01380	2.640	0.51	0.99477
						8.67	27.71	0.01769	2.868	0.74	0.99383

ρ_0 = 1.50 g/cm³

t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0	t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0
2.74	7.92	0.05974	3.891	3.49	0.98465	3.27	12.05	0.06120	3.828	3.51	0.98401
4.04	10.26	0.07148	3.735	4.00	0.98086	6.37	22.43	0.01757	3.456	0.91	0.99492
3.41	9.52	0.06416	3.811	3.67	0.98316	7.63	24.99	0.02461	3.304	1.22	0.99255
4.09	11.28	0.04100	3.729	2.29	0.98901	5.04	14.49	0.02285	3.615	1.24	0.99368
5.85	23.16	0.01512	3.518	0.80	0.99570	6.65	19.60	0.02375	3.422	1.22	0.99306
7.42	21.56	0.01326	3.330	0.66	0.99602	9.65	31.47	0.00952	3.062	0.44	0.99689
8.10	26.18	0.02190	3.248	1.07	0.99326	3.17	9.55	0.04160	3.840	2.40	0.98917
6.46	17.83	0.03078	3.445	1.59	0.99107	7.40	26.56	0.01355	3.332	0.68	0.99593
4.92	18.31	0.02710	3.630	1.48	0.99254	10.10	32.44	0.01380	3.008	0.62	0.99541
8.06	30.53	0.01555	3.253	0.76	0.99522	2.16	5.18	0.15743	3.961	9.35	0.96026

ρ_0 = 1.58 g/cm³

t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0	t (μsec)	r (mm)	U_p (mm/μsec)	U_s (mm/μsec)	P (kb)	V/V_0
8.54	25.23	0.01818	3.076	0.88	0.99409	2.25	7.14	0.17780	4.700	13.80	0.96217
6.24	22.88	0.02489	3.670	1.44	0.99322	8.58	25.85	0.01195	3.066	0.58	0.99610
2.04	5.74	0.17912	4.754	13.45	0.96232	5.48	12.42	0.03063	3.866	1.87	0.99208
3.12	7.90	0.06980	4.475	4.94	0.98440	3.36	8.20	0.08824	4.413	6.15	0.98000
11.52	36.02	0.01334	2.308	0.49	0.99422	2.74	10.52	0.03963	4.573	2.86	0.99133
4.53	17.39	0.02667	4.111	1.73	0.99351	6.49	12.52	0.04282	3.606	2.44	0.98813
7.02	26.62	0.01917	3.469	1.05	0.99447	2.84	7.98	0.06774	4.546	4.87	0.98510
5.49	21.21	0.02997	3.747	1.77	0.99200	11.16	37.36	0.01116	2.401	0.42	0.99535

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13. ABSTRACT

Hugoniot curves were generated from simultaneous measurements of shock and free-surface velocities, obtained from samples of frozen Fairbanks (Fox) silt, using the exploding wire technique. The abrupt change in slope of the U_s-U_p Hugoniot is indicative of a phase change. The shape of the P-V Hugoniot suggests that the transformation begins immediately but does not go to completion. This means that, although the pressure lies slightly above the Rayleigh line through the mixed phase region, the slope does not increase as rapidly as it would if the material had stayed in the initial phase.

14. KEYWORDS

Exploding wires
Frozen soils
Shock waves