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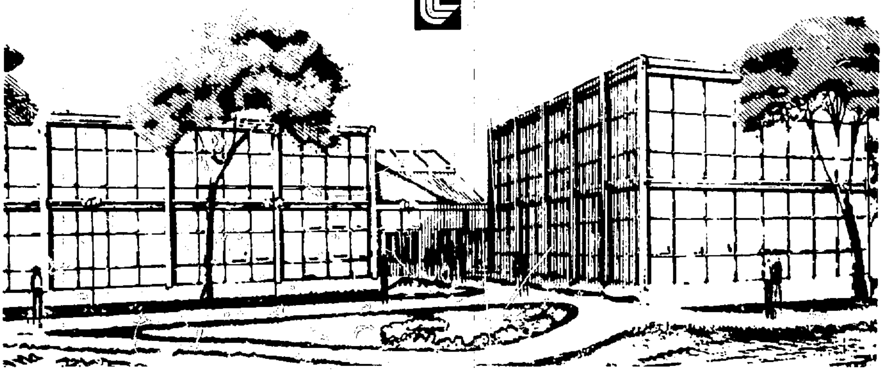

HUGONIOT ELASTIC LIMITS AND COMPRESSION PARAMETERS FOR BRITTLE MATERIALS*

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INTRODUCTION

The physical properties of brittle materials are of interest because of the rapidly expanding use of these materials in high-pressure and shock wave technology, e.g., geophysics and explosive compaction as well as military applications. These materials are characterized by unusually high sonic velocities, have large dynamic impedances and exhibit large dynamic yield strengths.

EXPERIMENTAL METHOD

When a shock wave traverses a material that exhibits a dynamic compressive yield point or Hugonoit elastic limit (HEL) it may break up into two successive waves depending upon the velocity of the compressional waves. In such a case the first wave (usually called the elastic wave) brings the material up to the plastic yield point and propagates at about longitudinal sound speed. The plastic yield occurs in the second or plastic wave front which compresses the mat rial to the final stress achieved in a given shock. The velocity of the second wave depends upon the strength of the initial shock.

If a phase transition occurs, a three wave structure may be present. In this case, the second wave, displaying roughly constant shock and particle velocities, brings the material up to the point where the phase transition is initiated. The actual transition occurs in the third wave which takes the material to the final stress state.

Determination of the dynamic yield strength in compression or Hugoniot elastic limit for a brittle material requires different techniques than those used for stress measurements on materials where the elastic wave can be easily overdriven. This is because a strong elastic wave (e.g., $\sim$ 4 or 5 GPa) can trigger ordinary shock arrival sensors and thus mask the arrival of the plastic wave.

There are several techniques that are used to resolve multiple wave shocks. These methods fall into two catagories; those that continuously measure the

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material free surface velocity as each wave passes through it and those that use a transducer to measure pressure directly. Detailed descriptions by those who introduced the techniques are available. Recently Graham and Asay (14) published a critical review of all of the techniques used for measuring wave profiles in shock loaded solids.

For multiple-wave structures the application of the conservation of mass and momentum and energy across the shock front leads to the basic Hugoniot equations which are:

$$\sigma_n = V_{n-1}^{-1}\left(U_{s_n} - U_{p(n-1)}\right)\left(U_{p_n} - U_{p_{n-1}}\right) + \sigma_{n-1} \tag{1}$$

$$V_n = V_{n-1}\left(U_{s_n} - U_{p_n}\right)\Big/\left(U_{s_n} - U_{p_{n-1}}\right) \tag{2}$$

$$E_n = 1/2\,(\sigma_n - \sigma_{n-1})\,(V_{n-1} - V_n) + E_{n-1} \tag{3}$$

The free-surface approximation, i.e., $U_{p_n} = U_{fs_n}/2$, was used for the elastic and phase transitional waves. This is a reasonable approximation since for brittle or relatively incompressible materials the rise in temperature and hence the change in internal energy is small.

ELASTIC-PLASTIC BEHAVIDR

If a material is shocked to a state lying along the deformational Hugoniot and is able to support a shear stress of magnitude τ_{max} the Hugoniot will be offset above the isothermal hydrostat by a stress

$$\Delta\sigma_{HEL} = \frac{4}{3}\,\tau_{max}. \tag{4}$$

If a shock-induced phase transition occurs this shear stress may cause a difference between the measured shock transition stress and the corresponding transition pressure determined hydrostatically. If the shear stress does not aid in the transition and temperature effects are neligible then the transition stress that should be compared with the hydrostat is $\bar{P}_{Tr.}$ not $\sigma_x^{\,Tr.}$

$$\bar{P}_{Tr} = \sigma_x^{\,T} - \frac{2}{3}\left(\frac{1 - 2\nu}{1 - \nu}\right)\sigma_x^{\,HEL} = \sigma_x^{\,T} - \frac{4}{3}\,\frac{Cs^2}{C_L^{\,2}}\,\sigma_x^{\,HEL}. \tag{5}$$

When the elastic wave data was analyzed through use of Eqs. (1) and (2), the particle velocity was obtained from the free surface velocity approximation $U_p = U_{fs}/2$. This implies that the entropy increase related to the elastic shock state is small and the material properties in the initial and final states are substantially the same.

It has been found that many materials exhibit a linear relationship between shock and particle velocity, i.e.,

$$U_s = C_o + S\,U_p \quad \text{where } S = dU_s/dU_p. \tag{6}$$

The compression at zero pressure is $\lambda = (V_o - V_1)/V_o = U_p/U_s$. (7)

Substitution into (6) yields

$$U_p = C_o \lambda/(1 - S\lambda), \text{ and } U_s = C_o/(1 - S\lambda). \quad (8),(9)$$

From which we obtain the equivalent of a stress-volume shock locus, namely

$$\sigma_1 = {}_oC_o{}^2 \lambda/(1 - S\lambda)^2. \quad (10)$$

At zero pressure $\gamma = 2S - 1$. (11)

In order to estimate the temperature at regimes above the HEL and any phase transitions that may exist we have used a simple Gruneisen equation-of-state model.

We assume a specific heat $C_v = 3R$ and a Grüneisen γ derived from the slopes of the continuously joined sections corresponding to the segments in the U_s, U_p plots. The 's are assumed linear in volume. The temperatures are then computed as if the Hugoniot represented equilibrium states.

HUGONIOT ELASTIC LIMITS

In this paper a brittle material has been arbitrarily defined as being one that has a Hugoniot elastic limit of about 2.0 GPa or more. Table 1 lists the existing HEL measurements that fall into that category (excluding geological materials). Data prior to 1968 has been surveyed by Jones and Graham (19). Their compilation also lists many HEL measurements with amplitudes less than 2.0 GPa.

The HEL data for most materials display considerable scatter. A unique value may only be obtained when strain rate effects or time dependent yield phenomena are negligible. These effects can be monitored by varying the amplitude of the driving pressure and be varying sample thickness. Many times, however, results from using these techniques are inconclusive, i.e., no definite trend is noted. One would expect, for example, that materials of extreme purity and ordered atomic array like single crystals would exhibit a unique value but that is not the case. For a given driving pressure and thickness, the HEL values for extremely pure crystalline Si, Ge and Al_2O_3 (Table 1) vary about 10% with no apparent relation to strain-rate or time-dependent phenomena.

HIGH STRESS REGIME

References for published high-pressure deformational Hugoniots for the brittle substances listed in Table 1 include: AISI4340, maraging and AMS5656 steels (6,9), W(9), Si and Ge (11,14), SiO_2 (17,18,19,20,33), TiO_2 (22), MgO (23,24), $CaCo_3$ (25,34), Al_2O_3 (26,27,28,35), B_4C (9,27), BeO (27), SiC (9,32), TiB_2 (32), Be_4B (32).

Previously unpublished sound velocity, deviatoric stress and Hugoniot data for a number of polycrystalline ceramics are given in Table 2. Except for ZnS and ZnSe experimentally determined hydrostats could not be located so the shear strength characterstics were not determined.

Iron carbide, Fe_3C does not exhibit a large enough HEL to qualify as a brittle material by our standards. However, there is current interest in this substance as a possible component of the earths core so it has been included.

The Hugoniot for Fe_3C exhibits a discontinuity at U_p = 2.5 km/s (138 GPa) that is probably related to a phase transition. Earths core calculations should take that into account.

The U_s, U_p plot for HfC also exhibits a discontinuity at U_p = 1.0 km/s. However, the Hugoniot for U_p > 1.6 km/s was obtained with HfC that was less dense (10.9 vs 12.3 Mg/m^3). Because of this it is not clear that this discontinuity is related to a phase transition.

The HEL's for WC and BeB_6 were found to be 7.0 and 14.0 GPa respectively. No unusual features were observed. The WC data agrees well with that by R. G. McQueen et al. (16).

It has been noted (20-28) for crystalline SiO_2, MgO, crystalline Al_2O_3, BeO, W and perhaps B_4C that the high pressure Hugoniots and the isotropic compression curves are essentially coincident. These materials exhibit fairly large HEL's (2.5 - 21 GPa) but apparently have zero shear strength for shock loading greater than the HEL. They have been characterized as elastic-isotropic solids rather than elastic-plastic solids. Grady et al (28) have suggested that the loss of strength for quartz is caused by localized melting in shear deformation bands. Their recovered specimens exhibited planar deformation lamella that attested to a non-uniform yield process.

Shock-induced phase transitions were observed at about 17.5 GPa for ZnS and at 14.5 GPa for ZnSe. Comparisons with uncorrected data by Bridgman show that both materials exhibited shear strength above the HEL. The calculated deviatoric stress correction for ZnS is 2.5 GPa so, neglecting a small temperature rise, the comparable hydrostatic pressure is 15.0 GPa. This agrees exactly with the hydrostatic values reported by Le Nienäre et al. (31) and by Piermarini and Block (32). Other reported values for the ZnS transition pressure are 24.0 GPa by Samara and Drickamer (33) (later revised to 18.5 GPa) and 11.8 GPa by Ruoff and Chan (34).

NOTATION

B	Bulk Modulus	U_p	Particle Velocity
C_B	Bulk Sound Speed	V	Specific Volume
C_L	Longitudinal Sound Speed	γ	Grüneisen Coefficient
C_S	Shear Sound Speed	ν	Poissons Ratio
E	Internal Energy	ρ	Density
P	Hydrostatic Pressure	σ	Stress
T	Temperature	τ	Shear Stress
U_s	Shock Velocity		

TEXT REFERENCES

1. D. Bancroft, E. L. Peterson and S. Minshall, J. Appl. Phys. 27, 291 (1956).

2. G. E. Duvall and G. R. Fowles, in High Pressure Physics and Chemistry, R. S. Bradley Ed., (Academic Press London and New York, 1963) Vol. 2.

3. G. Eden and P. W. Wright, Proceedings of the Fourth International Symposium on Detonation, (Government Printing Office, Washington, D.C., p. 573, 1966).

4. W. C. Davis and B. G. Craig, Rev. Sci. Instrum. 32, 579 (1961).

5. L. M. Barker and R. E. Hollenbach, Rev. Sci. Instrum. 35, 742 (1964).

6. M. H. Rice, Rev. Sci. Instrum. 32, 449 (1961).

7. A. G. Ivanov, S. A. Novikov, and V. A. Sinitsyn, Soviet Physics Solid State 5, 196 (1963).

8. B. T. Bernstein and D. D. Keough, J. Appl. Phys. 35, 1471 (1964).

9. P. J. A. Fuller and J. H. Price, Brit. J. Appl. Phys. 15, 751 (1964).

10. A. V. Ananin, A..N. Dremin, and G. E. Kanel, Combust. Explos. Shock Waves 9, 381 (1973).

11. O. E. Jones, F. W. Neilson, and W. B. Benedick, J. Appl. Phys. 33. 3224 (1962).

12. R. A. Graham, F. W. Neilson and W. B. Benedick, J. Appl. Phys. 36, 1775 (1965).

13. V. M. Zeitsev, P. F. Pokhil, and K. K. Shvedov, Acad. Sci. USSR Proc. Phys. Chem. 132, 529 (1960).

14. R. A. Graham and J. R. Asay, High Press.-High Temp. 10, 355 (1978).

15. R. N. Keeler and E. B. Royce, Physics of High Energy Density, P. Caldirola and H. Knoepfel Eds., (Academic, New York, pp. 51-150, 1971).

16. R. G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz, and W. J. Carter, High Velocity Impact Phenomona, Ray Kinslow, Ed., (Academic, New York, 1970) pp. 294 ff.

17. J. M. Walsh and R. H. Christian, Phys. Rev. 97, 1544 (1955).

18. L. V. Altshuler, Usp. Fiz. Nauk. 85, 197 (1965) Engl. Transl. Soviet Physics USPESKI, 8, 52 (1965) .

19. O. E. Jones and R. H. Graham in Proceedings of Accurate Characterization of The High Pressure Environment, E. C. Lloyd, Ed. (U.S. Government Printing Office, Washington, D.C., 1971).

20. J. Wackerle, J. Appl. Phys. 33, 922 (1962).

21. T. J. Ahrens and R. K. Linde in Behavior of Dense Media Under High Dynamic Pressures, (Gordon and Breach, New York, 1968), p. 325.

22. L. V. Altshaler, R. F. Trunin, and G. U. Simikov, Trans. Izv. Earth Physics Series, No. 10, 1-6 (1965).

23. R. G. McQueen and S. P. Marsh in Elastic Constants, Handbook of Physical Constants, S. P. Clark, Jr., Ed., (Geol., Soc. of America, New York, 1966).

24. E. A. Perez-Albuerne and H. G. Drickamer, J. Chem. Phys. 43, 1381 (1965).

25. W. H. Gust and E. B. Royce, J. Appl. Phys. 42, 276 (1971).

26. D. P. Dandekar, J. Appl. Phys. 47, 4703 (1976).

27. S. N. Vaidya and G. C. Kennedy, J. Phys. Chem. Solids 33, 1377 (1972).

28. D. E. Grady, W. J. Murri, and P. S. DiCarli, J. Geophys. Res. 80, 4857 (1975).

29. D. Stoffler, J. Geophys. Res. 76, 5474 (1971).

30. P. W. Bridgman, Proc. Am. Acad. 76, 55 (1948).

31. B. Le Neindre, K. Suito, and N. Kawai, High Temp.-High Press. 8, 1 (1976).

32. G. J. Piermarini and S. Block, Rev. Sci. Instr. 46, 973 (1975).

33. G. A. Samara and H. G. Drickamer, J. Phys. Chem. Solids 23, 457 (1962).

34. A. L. Ruoff and K. S. Chan, in Proceedings of the 6th AIRAPT Intern. High Pressure Conference, (Plenum Press, New York 1978).

TABLE 1 Hugoniot Elastic Limits for Brittle Materials

Material	σ_{HEL}[a] (GPa)	Condition	Sample Thickness[b] (mm)	Technique[c]	Reference
		Metals			
4340 steel	1.9-1.4†*	annealed	6-50	G-9	1
4340 steel	2.3-2.1	annealed	3- 6	G-7	2
4340 steel	1.7	R_c15	25	E-7	3
4340 steel	1.7-1.9	R_c15	12	G-6	4
4340 steel	1.6	R_c30	23	E-9	5
4340 steel	1.6-2.0	R_c32	12	G-6	4
4340 steel	2.5	R_c35	25	E-7	3
4340 steel	2.0-1.8	R_c40	20-51	E-9	5
4340 steel	2.2	R_c50	23	E-9	5
4340 steel	1.4-3.1	R_c54	12	G-6	4
4340 steel	1.0-2.8	R_c61	6	E-4	6
Maraging steel	2.6-5.3	Vascomax 350	6	E-4	6
AMS 5656C steel	1.0-3.3	As Received	6	E-4	6
HF-1 steel	2.4-2.1	R_c40	3.2-6.4	G-9	7
W	3.8	99.9% pure 293K	9.5	G-9	8
W	2.3	1223K	9.5	G-9	8
Be	2.5	Arc melted	0.5-1.0	G-7	9

Material	σ_{HEL} (GPa)	Shock Propagation Direction	Sample Thickness (mm)	Technique	Reference
		Single Crystals			
Be	4.0	c-axis	-	G-7	10
Si	9.2±1.0	[100]	6.4	E-4	11
Si	5.0±0.5	[110]	6.4	E-4	11
Si	5.4±0.3	[111]	6.4	E-4	11
Si	4.0	[111]		E-10	12
Ge	5.3-4.6*	[100]	6-12	E-3	12
Ge	4.7*	[100]	6	G-7	13
Ge	5.8±0.8	[100]	6.4	E-4	14
Ge	4.7±1.0	[110]	6.4	E-4	14
Ge	4.4±0.5	[111]	8	G-7	15
Ge	4.1-3.5*	[111]	6-12	E-3	12
Ge	4.8±1.4	[111]	6.4	E-4	14
CdS	> 3.2	c-axis	-	E-9	16
CdS	> 2.8	a-axis	-	E-9	16
(SiC_2)	9.8-4.8*	x-cut	5-25	E-5	17
(SiO_2)	6.6-5.5*	x-cut	6	E-2	18
(SiO_2)	11.0-8.2*	y-cut	10	E-5	17
(SiO_2)	8.6-6.5*	y-cut	3-6	E-2	18
(SiO_2)	14.5-12.0*	z-cut	10	E-5	17
(SiO_2)	14.8-10.0*	z-cut	3-6	E-2	18
(SiO_2)	14.5- 6.0	z-cut	-	E-3	19
(SiO_2)	6.0	$[12\bar{1}0]$	-	E-3	20
(SiO_2)	8.5	$[10\bar{1}0]$	-	E-3	20
(SiO_2)	14.8	[0001]	-	E-3	20
(Al_2O_3)	12.0-20.0	z-cut	10-13	E-5	21
(Al_2O_3)	13.5-18.0	x-cut	10-13	E-5	21
TiO_2	7.0	[100]	6	E-8	22
TiO_2	10.0	[001]	6	E-8	22
MgO	3.7	[100]	-	E-2	23,24
MgO	8.9±10	[100]	-	E-2	23,24
($CaCO_3$)	2.2	$[12\bar{1}0]$	6	E-2	25
($CaCO_3$)	2.4	$[10\bar{1}0]$	6	E-2	25
($CaCO_3$)	1.9	[0001]	6	E-2	25
(C_aCO_3	1.9	$[10\bar{1}1]$	-	E-2	25

Material	σ_{HEL}(GPa)	Initial Density Mg/m^3	Sample Thickness (mm)	Technique	Reference
		Polycrystalline Ceramics			
Al_2O_3	11.2±1.2	3.97	6	E-2	26
Al_2O_3	13.4±0.8	3.92	6	E-2	27
Al_2O_3	8.3±0.5	3.81	6	E-2	26
Al_2O_3	7.8±0.5	3.72	6	E-2	27
Al_2O_3	6.1±0.5	3.42	6	E-2	27
Al_2O_3	7.0 - 13.6	3.97	-	E-6	28
B_4C	15.4±1.0	2.50	6*	E-2	27
BeO	8.2±1.0	3.01	6	E-2	27
$BaTiO_3$	2.5	5.54	13	E-5	29
$BaTiO_3$	∿3.0$^+$	-	3-13	E-3	30
Lead Zirconate Titanate (PZT 95/5)	∿4.0$^+$	-	4-13	E-2,3	30
Lead Zirconate Titanate (PZT 52/48)	1.9	- -	13	E-5	29
Maganese-Zinc Ferrite	2.3 $^\Delta$	-	14	E-9	31
Yttrium Iron Garnet	>6.0	-	8	E-9	31
TiO_2	3.3-7.5	-	-	E-2	22
BeB_6	13.9±3.9	2.32	6.4	E-4	This Work
Fe_3C	0.74	6.98	6.4	E-4	This Work
SiC	8.0±3	3.1	6.4	E-4	32
W C	7.0	14.9	6.4	E-4	This Work
HfC	11.9	12.5	6.4	E-4	This Work
ZnS	3.4	4.07	6.4	E-4	This Work
ZnSe	3.0	5.27	6.4	E-4	This Work
		Intermetallic Compounds			
TiB_2	8.6±3.0	4.51	3.2, 6.4	E-4	32
Be_4B	7.4±1.0	1.97	6.4	E-4	32
Be_4B + 8% BeO	7.7±1.0	1.99	6.4	E-4	32
AlB_{12}	8.7	2.54	6.4	E-4	32
$TiBe_{12}$	5.3	2.28	6.4	E-4	32
Be_2B	6.5	1.99	6.4	E-4	32
$ZrBe_{13}$	7.1±12	2.73	6.4	E-4	32

a. Symbols: +Sample thickness effect observed; *Stress relaxation observed; ^Poorly defined elastic wave front.

b. When a range of sample thicknesses is given + is noted; the larger HEL value corresponds to the thinner sample and vice-versa.

c. Letters describe method of loading: E explosive loading and G gun impact. Numbers denote measurement techniques and references cited in the text.

1. Pins [1]
2. Inclined Mirrors [2]
3. Optical Lever [2]
4. Inclined Prisms [3]
5. Knife Edge [4]
6. Slanted Resistance Wire [5]
7. Capacitor [6,7]
8. Manganin Wire [8,9,10]
9. Quartz Gage [11,12]
10. Electromagnetic Probe [13]

References for Table 1

1. B. M. Butcher and D. E. Munson, in Dislocation Dynamics, (McGraw-Hill New York 1968).
2. R. A. Graham, D. H. Anderson, and J. R. Holland, J. Appl. Phys. 38, 223 (1967).
3. F. S. Minshall in Response of Metals to High Velocity Deformation, (Interscience Publishers, New York 1961).
4. B. M. Butcher and J. R. Canon, AIAA Journal 2, 2174 (1964).
5. O. E. Jones, F. W. Neilson, and W. B. Benedick, J. Appl. Phys. 33, 3224 (1962).
6. W. H. Gust, D. J. Steinberg, and D. A. Young, High Temp. - High Press. (in press, 1979).
7. W. Mock, Jr., W. H. Holt, and C. R. Crow, Naval Surface Weapons Center Rept. No. NSWC/D.L-TR-3519 (1976).
8. R. W. Rhode, J. Appl. Phys. 40, 2988 (1969).
9. R. G. McQueen, S. R. Marsh, J. W. Taylor, J. N. Fritz, and W. G. Carter in High Velocity Impact Phenomena, Ray Kinslow, Ed., (Academic Press, New York 1970).
10. J. W. Taylor in Dislocation Dynamics, (McGraw-Hill, New York, 1968).
11. W. H. Gust and E. B. Royce, J. Appl. Phys. 42, 1897 (1971).
12. M. N. Pavlovskii, Soviet Phys. Solid State 9, 2514 (1968).
13. R. A. Graham and G. E. Ingram in Proc. IUTAM Colloq. on the Behavior of Dense Media Under High Dynamic Pressures (Gordon and Breach, New York, 1968).
14. W. H. Gust and E. B. Royce, J. Appl. Phys. 43,, 4437 (1972).
15. R. A. Graham, O. E. Jones and J. R. Holland, Phys. Chem. Solids 27, 1519 (1966).
16. R. G. McQueen in Metallurgy at High Pressures and High Temperatures (Gordon and Breach, New York, 1964).
17. J. Wackerle, J. Appl. Phys. 33, 922 (1962).
18. R. J. Fowles, J. Geophys. Research 72, 5729 (1967).
19. C. Peyre, J. Pujol and J. Thouvenin, in Proc. Fourth Symposium on Detonation, ACR-126 (U.S. Government Printing Office, 1965).
20. G. R. Fowles, J. Appl. Phys. 32, 1475 (1961).
21. W. P. Brooks and R. A. Graham, Bull. Am. Phys. Soc. 11, 414 (1966).
22. R. K. Linde and P. S. DeCarli, J. Chem. Phys. 50, 319 (1969).

23. T. J. Ahrens, J. Appl. Phys. 37, 2530 (1966).
24. T. J. Ahrens and R. K. Linde, Behavior of Dense Media Under High, Dynamic Pressure (Gordon and Breach, New York, 1968).
25. T. J. Ahrens and V. G. Gregson, Jr., J. Geophys. Res. 69, 4839 (1964).
26. T. J. Ahrens, W. H. Gust and E. B. Royce, J. Appl. Phys. 39, 4610 (1968).
27. W. H. Gust and E. B. Royce, J. Appl. Phys. 42, 276 (1971).
28. D. E. Munson, Sandia Laboratory Rept. No. SC-RR-69-803 (1970).
29. C. E. Reynolds and G. E. Seay, J. Appl. Phys. 33, 2234 (1962).
30. D. G. Doran, J. Appl. Phys. 39, 40 (1968).
31. O. E. Jones and R. A. Graham in Proc. of Accurate Characterization of the High-Pressure Environment, E. C. Lloyd, ed., (U.S. Government Printing Office, Washington, D.C., 1971).
32. W. H. Gust, A. C. Holt, and E. B. Royce, J. Appl. Phys. 44, 550 (1973).
33. A. N. Dremin and G. A. Adudurov, Soviet Phys. Doklady 128, 261 (1959).
34. L. V. Altshuler, R. F. Trunin and G. V. Simikov, Izv. Akad. Nauk., SSSR. Fizika Zemli No. 10 (1965).
35. R. G. McQueen and S. P. Marsh, Ch. 7, Handbook of Physical Constants, S. P. Clark Ed., (Geological Society of America, New York, 1966).

TABLE 2 Coefficients for $U_{s_n} = C_n + S_n U_p$

MATERIAL	INITIAL DENSITY (Mg/m^3)	SONIC VELOCITIES C_L (km/s)	C_S (km/s)	C_B (km/s)	HEL (GPa)	STRESS OFFSET (GPa)	2nd WAVE REGIME C_2	S_2	Limits (km/s) $<U_{p_2}<$	3rd WAVE REGIME C_3	S_3	Limits (km/s) $<U_{p_3}<$
Fe_3C	7.05	5.19	2.96	3.91	0.7	0.32	4.60	1.87	0.75-2.5	8.05	1.77	3.10-4.2
HfC	12.3	6.29	3.90	4.58	11.9	6.1	5.11	1.53	0.70-0.90			
	10.9	5.65	3.52	3.94						5.48	1.13	1.6 -3.9
WC (6% Co)	14.9	6.87	4.13	4.94	7.0	3.4	5.63	1.16	0.40-2.0			
Be_4B	2.33	13.6	8.83	8.99	14.0	7.8	8.40	1.80	0.64-1.6			
B_7O	2.52	13.4	8.47	9.16			12.1	1.83	3.7 -5.0	(Extrapolates to C_B)		
ZnS	4.075	5.45	2.92	4.25	3.4	2.5	4.8	1.14	0.35-0.80	3.93	1.86	1.1 -1.4
ZnSe	5.266	4.44	2.33	3.54	3.0	1.2	4.0	1.15	0.4 -0.65	3.66	1.83	1.1 - 1.4