EQUATION OF STATE OF ICE AND FROZEN SOILS, E. S. Gaffney, Pacifica Technology, Del Mar, California 92014

Data exist in the "grey literature" on the shock response of ice and several frozen soils. The purpose of this paper is to provide access to those data for a larger audience and to propose some generalizations that may be helpful in extrapolating to martian or other outer solar system conditions; however, the main emphasis will be on the data rather than their interpretation. Anderson reported data from explosive plate impacts on ice, frozen sand, and frozen sandy silt with peak pressures from 3.5 to 30 GPa, 6 to 49 GPa, and 7.5 to 54 GPa, respectively[1]. He also reported release adiabats for ice, dry sand and saturated sand. He measured impact velocity, shock velocity and, in some cases, free surface velocity. Particle velocities were determined by impedence match. Stresses and volumes were calculated from the Hugoniot jump conditions. Nakano and Froula reported data from gas gun experiments on frozen sand[2]. Their data is summarized in Table 2. They measured impact velocity and stress and determined particle velocity by impedence match. Shock velocities and volumes were calculated from jump conditions. Froula's experiments were continued by Gaffney who reported data from gas gun experiments on polycrystalline ice and frozen sand [3]. Some of his data is presented in Tables 1 and 2. (Data obtained with steel flyer plates are not reliable due to a poorly determined equation of state for the steel; hence, those data have been omitted from this summary.) Equation of state parameters were determined in the same manner as by Froula[2]. Larson et al. conducted both plate impact and spherical explosive tests in ice, frozen sand and frozen sandy silt[4]. Only the impact data are presented here. They measured particle velocity histories at several horizons in the samples and used a Lagrangian analysis to determine stress and volume. Data for ice (Table 1) is taken directly from a tabulation in their report except that shock velocities at σ=0.695, 0.31 and 0.285 were calculated by me from σ and u assuming a two step shock. Data for the soils was taken off of figures of stress vs. specific volume with shock and particle velocities calculated assuming a single shock; hence u and D for these data will be somewhat in error. Louie reported data from gas gun and explosively driven plate impact tests on frozen clayey silt at initial temperatures between 263 K and 271 K (exact temperatures were not reported)[5]. This data is summarized in Table 4. In both types of tests the impact velocity and shock velocity were measured. Particle velocity was determined by impedence match and other values calculated from jump conditions. All of the studies described above, except Larson et al.; included materials at saturations between 100% and dry, but the data have been omitted for reasons of space. Two other sets of experiments were conducted using exploding wire sources in frozen sandy silt [6], silty clay[6] and silt[7]. These data are not reported here because they require the assumption that the free surface velocity is twice the particle velocity, an assumption found to be incorrect by Anderson[1].

Some generalizations can be made based on these data. First, at stresses above about 3 GPa, both ice and frozen soils melt. The Hugoniot of ice in that range can be calculated from that of water with the initial density of ice rather than water. The Hugoniot of frozen Ottawa sand can be calculated from the mass weighted sum of the water and quartz Hugoniots at the same pressure. Since this approach assumes mechanical but not thermal equilibrium, it should break down on extrapolation to very high stresses or for shocks of large duration, both situations of interest to the planetary community. At

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lower pressure all investigators who noted a two-wave structure[1-4] attributed it to melting of ice. However, Gaffney has since pointed out that an elastic-plastic transition for ice at about .15 to .2 GPa followed by melting at about .25 to .3 GPa fits some of the data better[8]. At stresses below .5 GPa the Hugoniot of frozen soil is not the simple sum of ice and quartz observed above 3 GPa. However, it can be fit by assuming a "plastic" Hugoniot for ice below .5 GPa which is parallel to the observed curve in σ-V space between .2 and .4 GPa and passes through V_0 at σ=0, and summing as above 3 GPa.

References: [1] G.D. Anderson, USACRREL-RR-257 (June 1968).[2] Y. Nakano & N.H. Froula, Permafrost:No. Am. Contr. 2nd Int. Conf., 359(1973).[3]E.S. Gaffney, SSS-R-73-1557(Apr. 1973).[4] D.B. Larson et al., Permafrost:No. Am. Contr. 2nd Int. Conf., 318(1973).[5] N.A. Louie, SH2155-08(Feb. 1968).[6] I.M. Fyfe, MSNW Rept. No. 68-53-1(Mar. 1968).[7] J.L. Smith, USACRREL-RR-287(June 1970).[8] E.S. Gaffney, Bull. Am. Phys. Soc. 20, 1514(1975);Trans. Am. Geophys. U. 57, 1008(1976).

Table 1. Hugoniot data for ice at 263 K

Stress (GPa)	u (km/s)	D (km/s)	V_0 (m^3/Mg)	V (m^3/Mg)	Ref	Comments
30.1	4.19	7.81	1.091	0.5055	[1]	polyxl
27.4	3.94	7.55	1.091	0.5207	[1]	monoxl, orientation ?
26.6	3.88	7.48	1.091	0.5251	[1]	polyxl,rel.to(u,σ)=(4.67,15.2);(7.1,0)
20.7	3.36	6.72	1.091	0.5445	[1]	polyxl
20.6	3.35	6.69	1.091	0.5447	[1]	polyxl,rel.to(u,σ)=(4.19,12.2),(6.04,0)
18.0	3.19	6.12	1.091	0.5212	[1]	monoxl,volume seems low(ESG)
10.6	2.30	5.00	1.091	0.5889	[1]	polyxl
10.1	2.22	4.98	1.091	0.6047	[1]	polyxl,rel.to(u,σ)=(2.8,5.28),(3.7,0)
3.75	1.25	3.21	1.091	0.666	[1]	monoxl
3.55	1.30	2.95	1.091	0.6081	[1]	mionoxl,questionable data(GDA)
0.854	0.455	2.05	1.091	0.848	[3]	polyxl
0.695	0.412	1.45	1.091	0.792	[4]	polyxl,2nd wave(σ_0=.2)V_0 seems low(ESG)
0.525	0.272	2.10	1.091	0.950	[3]	polyxl,rel.to(u,σ)=(.392,.11)
0.457	0.186	2.68	1.091	1.014	[3]	polyxl
0.310	0.117	2.14	1.091	1.044	[4]	monoxl,D||<10$\bar{1}$0>,2nd wave(σ_0=.164)
0.305	0.120	2.76	1.091	1.041	[4]	monoxl,D||<11$\bar{2}$0>,2nd wave(σ_0=.19)
0.290	0.132	2.91	1.091	1.032	[4]	monoxl,D||<0001>,2nd wave(σ_0=.157)
0.285	0.125	1.75	1.091	1.035	[4]	monoxl,D||<0001>,2nd wave(σ_0=.158)
0.258	0.090	2.99	1.091	1.058	[4]	monoxl,D||<11$\bar{2}$0>,2nd wave(σ_0=.18)
0.200	0.060	3.96	1.091	1.074	[4]	polyxl
0.190	0.056	3.90	1.091	1.074	[4]	monoxl,D||<11$\bar{2}$0>
0.180	0.051	4.05	1.091	1.075	[4]	monoxl,D||<11$\bar{2}$0>
0.164	0.045	4.10	1.091	1.078	[4]	monoxl,D||<10$\bar{1}$0>
0.158	0.049	3.76	1.091	1.075	[4]	monoxl,D||<0001>
0.157	0.047	3.95	1.091	1.076	[4]	monoxl,D||<0001>

Table 4. Hugoniot data for frozen Suffield silty clay at 263 K to 271 K[6].

4.8	1.092	2.42	0.5525	0.3031	100% saturated, dry density not given
2.1	0.470	2.46	0.5525	0.4466	100% saturated, dry density not given
1.4	0.370	2.03	0.5525	0.4518	100% saturated, dry density not given
1.1	0.302	1.96	0.5525	0.4674	100% saturated, dry density not given
0.92	0.242	2.11	0.5525	0.4889	100% saturated, dry density not given
0.72	0.181	2.18	0.5525	0.5064	100% saturated, dry density not given
0.7	0.14	2.6	0.5525	0.5222	100% saturated, dry density not given
0.3	0.09	1.7	0.5525	0.5227	100% saturated, dry density not given
0.12	0.043	1.60	0.5525	0.5375	100% saturated, dry density not given

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Table 2. Hugoniot data for frozen Ottawa sand at 263 K.

Stress (GPa)	u (km/s)	D (km/s)	$^3V_0$ (m^3/Mg)	^3V (m^3/Mg)	Ref	Comments
48.7	3.52	7.04	0.5102	0.2550	[1]	100% sat
44.0	3.31	6.77	0.5102	0.2603	[1]	100% sat
43.4	3.22	6.88	0.5102	0.2714	[1]	100% sat,rel.to(u,σ)=(4.37,13.3),(7.6,0)
42.9	3.24	6.74	0.5102	0.2649	[1]	100% sat
42.8	3.24	6.73	0.5102	0.2646	[1]	100% sat,rel.to(u,σ)=(3.8,25.6)
40.4	3.81	6.39	0.6061	0.2449	[1]	dry
33.9	2.85	5.96	0.5102	0.2632	[1]	100% sat
33.5	2.85	6.01	0.5102	0.2683	[1]	100% sat,rel.to(u,σ)=(3.45,21.4)
33.4	2.85	5.97	0.5102	0.2666	[1]	100% sat,rel.to(u,σ)=(3.92,10.9),(6.36,0)
30.3	2.67	5.77	0.5102	0.2736	[1]	100% sat
30.0	2.71	5.63	0.5102	0.2646	[1]	100% sat
27.4	3.13	5.31	0.6061	0.2486	[1]	dry
20.1	2.01	5.10	0.5102	0.3091	[1]	100% sat
18.7	1.83	5.20	0.5102	0.3306	[1]	100% sat,rel.to(u,σ)=(2.41,11.2)
18.6	1.83	5.19	0.5102	0.3303	[1]	100% sat,rel.to(u,σ)=(2.78,52.2),(3.49,0)
15.0	2.25	4.05	0.6061	0.2697	[1]	dry
14.6	2.17	4.07	0.6061	0.2823	[1]	dry
8.0	1.05	3.86	0.5102	0.3714	[1]	100% sat
8.0	1.01	4.00	0.5102	0.3813	[1]	100% sat
7.6	1.03	3.77	0.5102	0.3708	[1]	100% sat
1.70	0.343	2.31	0.5051	0.4301	[2]	100% sat,3.73 km/s precursor
1.00	0.266	1.93	0.5128	0.4422	[4]	100% sat,~100 MPa precursor
1.16	0.270	2.20	0.5128	0.4500	[4]	100% sat,~150 MPa precursor
1.22	0.303	2.06	0.5128	0.4375	[4]	100% sat,~150 MPa precursor
0.88	0.219	1.96	0.5051	0.4485	[2]	100% sat,4.85 km/s precursor
0.55	0.138	1.99	0.5051	0.4695	[3]	100% sat
0.53	0.137	2.09	0.5051	0.4717	[2]	100% sat,3.88 km/s precursor
0.47	0.100	2.39	0.5051	0.4840	[3]	100% sat,85 MPa precursor
0.41	0.103	2.04	0.5128	0.487	[4]	100% sat,~100 MPa precursor
0.17	0.037	3.53	0.5051	0.5000	[2]	100% sat,4.41 km/s precursor
2.5	0.379	2.53	0.5051	0.4466	[3]	100% sat,2.94 km/s precursor, 2.1 GPa

Table 3. Hugoniot data for frozen West Lebanon silt at 263 K

54.2	3.34	7.54	0.4662	0.2596	[1]	100% sat
46.7	3.11	7.01	0.4662	0.2593	[1]	100% sat
45.1	3.65	6.57	0.5376	0.2393	[1]	dry
33.2	2.59	5.96	0.4662	0.2636	[1]	100% sat
30.8	2.94	5.62	0.5376	0.2552	[1]	dry
21.8	1.94	5.25	0.4662	0.2939	[1]	100% sat
16.7	2.16	4.17	0.5376	0.2589	[1]	dry
16.4	2.08	4.19	0.5376	0.2695	[1]	dry
8.3	1.00	3.90	0.4662	0.3466	[1]	100% sat
1.17	0.261	2.12	0.471	0.413	[4]	100% sat
0.97	0.227	2.01	0.471	0.418	[4]	100% sat
0.95	0.233	1.92	0.471	0.414	[4]	100% sat precursor~0.15 GPa
0.81	0.195	1.96	0.471	0.424	[4]	100% sat
0.41	0.088	2.19	0.471	0.452	[4]	100% sat

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