TABLE 1. Measured Values and Uncertainties for Polycrystalline Longitudinal and Shear Velocities in NaCl

Pressure, kbar	v_p, m/s	$\sigma(v_p)$, m/s	v_s, m/s	$\sigma(v_s)$, m/s	No. of Runs
25	5007	49	2679	48	9
30	5088	53	2696	53	9
35	5165	59	2710	64	9
40	5238	65	2722	74	9
45	5307	73	2732	85	9
50	5380	74	2750	86	9
55	5450	76	2768	88	9
60	5518	77	2785	90	9
65	5585	75	2804	86	9
70	5648	73	2820	82	9
75	5710	71	2835	79	9
80	5769	71	2849	79	9
90	5877	69	2867	76	8
100	5986	75	2894	84	7
110	6092	78	2923	90	7
120	6193	83	2950	98	7
130	6290	54	2976	51	2
150	6478	80	3033	91	2
170	6647	56	3076	52	2
190	6785	51	3083	44	2
210	6915	55	3088	58	2
230	7056	48	3123	38	2
250	7188	45	3154	21	2
270	7304	...	3169	...	1

The parameter n is any positive number and is assumed to be independent of pressure. The change in the specimen density and thickness can be determined from the data as follows:

$$X^{n-2} = 1 + \left(\frac{n-2}{n}\right) \frac{1}{4d_0^2\rho_0} \int_0^P Y\,dP \qquad (8a)$$

for $n \neq 2$, and

$$X = \exp\left[\frac{1}{8d_0^2\rho_0} \int_0^P Y\,dP\right] \qquad (8b)$$

for $n = 2$, where

$$Y = \frac{1 + \Delta}{\Delta f_p^2 - 4\Delta f_s^2/3}$$

If the forces acting upon a specimen are perfectly balanced, such as they are in a liquid pressure transmitting device, the parameter n in (6) is equal to 3.0. All strains are due to hydrostatic stresses. The assumption of hydrostatic compression led *Ahrens and Katz* [1962] to use an expression identical to (8*a*) with $n = 3$. If the deformation of the specimen is pistonlike, i.e., the side walls are rigid and only the thickness changes, then the value of n is 1.0. If the side walls either are rigid or move outward as the thickness decreases, $n \leq 1.0$.

The value of n to be used with the present device in future investigations of materials for which the equation of state is unknown is determined from the present NaCl data set. A plot of the log of the ratio of the specimen thickness at zero pressure to the thickness at pressure versus the log of the density ratio should yield a straight line whose slope is equivalent to the parameter n in (6). The results of this analysis for the NaCl runs are shown in Figure 2. Since all data start at 25 kbar, the initial thickness d_0 has been calculated with the assumption of $n = 1$. Use of other values of n would only require the y axis to be shifted left or right.

The straight line which best fits the specimen thickness data has a slope of 1.5, as is shown in Figure 2. The error bars represent the maximum run-to-run variation in the data. Thus a value of $n = 1.5$ may be used in (6) for the present device, with the large uncertainty indicated by the error bars.

The lines shown in Figure 2 for $n = 3.0$ and $n = 1.0$ represent the locations of the ratios if the compression in the pressure cell were hydrostatic or pistonlike. It should be noted that while the run-to-run variation in the compression of a specimen is large, in all cases the specimen diameter is decreasing during increasing pressure. This is in contrast to most solid pressure transmitting devices in which the diameter would be stationary or increasing.

DISCUSSION

In order to analyze the data it has been assumed that shear stresses in the sample and heating of the sample during pressurization can be neglected and that the effect of dislocations on the velocity is small. These assumptions will be considered first. Finally, the velocity data will be compared with previous experimental data and theoretical predictions, and their use for pressure calibration will be discussed.

Analysis of Assumptions

Neglect of shear stresses. The pressurization with the variable lateral support Bridgeman anvil device is not purely hydrostatic. Thus shear stresses must exist within the specimen, probably not greater than the shear strength of NaCl. If the shear stress is large, two problems arise. First, use of (3) may be invalid. Second, use of a resistance-based pressure calibration may be inappropriate for ultrasonics because the average specimen pressure, important in ultrasonics, is significantly different from the highest pressure in the specimen, which is measured in resistance-based calibrations.

Previous work [*Piermarini et al.*, 1973; *Block and Piermarini*, 1975] has shown that large pressure gradients can exist across a specimen of NaCl. The largest gradients occur in ungasketed specimens. More pressure uniformity occurs with gasketed specimens. *Block and Piermarini* [1975] report pressure varia-

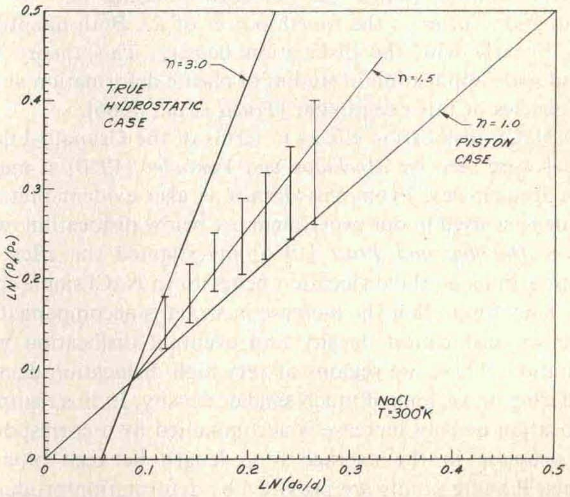

Fig. 2. Specimen thickness ratio versus the density ratio as determined for the nine data sets used in this paper. The figure has been normalized for the piston (n = 1.0) case. The straight lines representing the expected ratio for the piston and the purely hydrostatic (n = 3.0) cases are shown for comparison.

tions of 11 kbar at an average pressure of 100 kbar in a gasketed NaCl specimen in a diamond anvil device. More uniformity than that is expected in the present device because the gasket support is increased as the force upon the anvil is increased. In addition, the larger specimen thickness in our device should minimize surface effects on the average stress distribution.

While no direct measurements of the pressure variations are available, there are observations that indicate a small pressure gradient. Resistometric transitions are spread out on resistance versus load plots by pressure gradients. Full-sized bismuth specimens were observed in the present device to have resistometric phase changes spread out over a few kilobars [*Homan*, 1975]. A thin strip of bismuth embedded in NaCl showed almost no spread in pressure for the resistance changes. In addition, the ratio between the Bi resistance peaks due to the I-II transition and the II-III transition was 3.31, compared to 3.35 previously measured in a hydrostatic medium (discussed by *Gilmore* [1968]). Another indication is the observation of ultrasonic interference patterns at distinct frequencies. If the acoustic velocity were significantly different in different regions of the specimen, because of pressure gradients the minima in the echoes would be smeared out over a range of frequencies.

Neglect of heating effects. The analysis assumes isothermal compression. To insure the validity of this assumption, the temperature effects on the velocities due to pressurization at different rates were looked for in two runs. None were found. To insure maximum heat dissipation, all other runs were done at the slowest possible pressurization rate (approximately 3 kbar/min), and runs were made at intervals of 3 hours or more. Since the changes of the elastic constants with temperature at zero pressure are 0.02%/°K for c_{44} and 0.03%/°K for c_s [*Demarest*, 1972*a*], the effect of heating upon the measurements is deemed negligible.

Effects of dislocations on the sound velocity. The theory of the effect of dislocations on the mechanical properties of crystalline solids at megacycle frequencies is based on the dislocation strain model of *Granato and Lücke* [1956]. This model predicts that at frequencies below the dislocation resonance the decrease in the velocity of sound due to dislocations is proportional to the square of the average effective loop length between pinning points L_e; the corresponding part of the attenuation varies as the fourth power of L_e. Both quantities vary linearly with the dislocation density. This theory has found wide application in studies of plastic deformation at the frequencies of this experiment [*Truell et al.*, 1966].

In NaCl, dislocation effects in terms of the Granato-Lücke model were seen by *Merkulov and Yakovlev* [1960] at megacycle frequencies. From this data it is also evident that the frequencies used in our experiment are below dislocation resonance. *Davidge and Pratt* [1964] investigated the effect of plastic strains on the dislocation behavior in NaCl single crystals. They found that the increase in strain is accompanied by increased dislocation density and eventual dislocation wall formation. These are regions of very high dislocation density bordering on regions of much smaller density. In this regime a dislocation density increase is accompanied by a corresponding decrease in the average loop length between pinning points. Pinning points are provided by deformation-produced defects [*Frankel and Meisel*, 1967] and by other dislocations. This effect has been seen in attenuation measurements during deformation accompanying a sharp yield point in magnesium single crystals which had been solution-treated with a small amount of nitrogen [*Chiao and Gordon*, 1963] and for repeated fatigue-type deformation in pure aluminum crystals and polycrystalline aluminum alloys [*Chick et al.*, 1963; J. Frankel, unpublished data, 1970]. In these experiments a decrease in attenuation develops after a certain amount of deformation, so that the increase in dislocation density must be accompanied by a decrease in L_e. The velocity change should also show evidence of this behavior with sufficient deformation because of its second-order dependence on L_e. *Merkulov and Yakovlev* [1960] found that the velocity decreased linearly up to values of 0.43% and 0.16% for the maximum 2.5% strain of their experiment for two similar NaCl single crystals with different thermal histories. Their data suggest that this level of strain is associated with a relatively small increase in dislocation density (and hence no drastic drop in L_e); this finding is supported by the direct dislocation density measurements of *Davidge and Pratt* [1964].

Our samples, which were deformed during powdering and compaction by an unknown amount, were subjected to an additional plastic strain of about 6% at the 270-kbar pressurization. Thus our samples should be considered severely cold-worked into the region of wall formation and decreasing L_e. If we extrapolate the larger of the velocity changes in the Merkulov and Yakovlev experiment to our 6% plastic deformation, we obtain a 1% drop in the velocity at 270 kbar and certainly not more than 2% if we include the cold work performed during fabrication. Thus the maximum estimated error due to dislocations is well within the total experimental error. A systematic change in the velocity with succeeding runs in one specimen as the cold work increased was looked for, and none was found. An in situ irradiation technique to pin the dislocations completely and evaluate the dislocation effect directly is not possible with the present equipment.

Velocity Results

The isotropic acoustic velocities of NaCl are contained in Table 1. The uncertainties given do not include the uncertainty due to the pressure calibration or that in the Decker equation of state. In Figure 3 the data are seen to agree within the uncertainty of the measurement with available velocities up to 80.5 kbar [*Voronov et al.*, 1971; *Voronov and Grigorèv*, 1971].

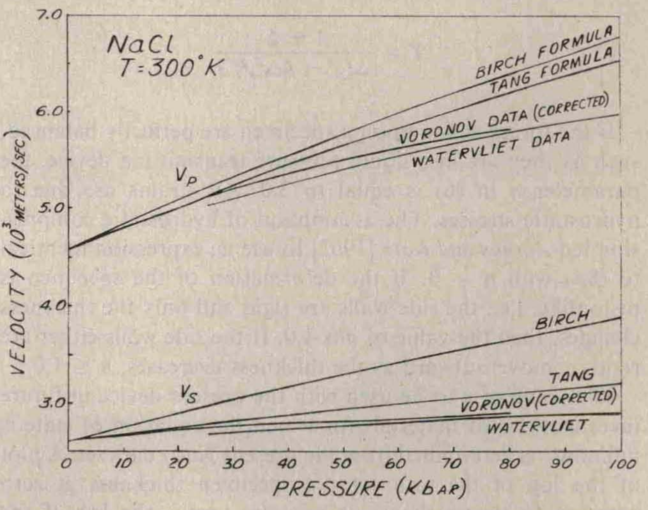

Fig. 3. Acoustic velocities (longitudinal and shear) at static pressures to 100 kbar for polycrystalline NaCl at room temperature. The measurements made by the present authors and the measurements of *Voronov et al.* [1971] and *Voronov and Grigorèv* [1971] are shown together with the estimates of *Birch* [1938] and *Tang* [1966].