

The Hugoniot Equation of State of Sodium Chloride in the Sodium Chloride Structure*

J. N. Fritz, S. P. Marsh, W. J. Carter, R. G. McQueen
University of California, Los Alamos Scientific Laboratory

ABSTRACT

The Hugoniot equation of state of NaCl has been obtained by measuring the shock velocity through NaCl on copper and 2024 aluminum base plates. Shock velocities through the base plates and standard impedance-matching were used to obtain the Hugoniot curves for both single crystal (in various orientations) and pressed powder samples. The smooth behavior of the resulting shock locus up to 230 kb indicates that NaCl exists in the sodium chloride structure up to this pressure. In the shock-particle velocity plane the best linear fit to the data reported here is u_s (km/sec) = $(3.528 \pm .012) + (1.343 \pm .009)u_p$. A quadratic fit, which gives a large weight to the measured bulk sound speed in NaCl, is $u_s = 3.403 + 1.5422 u_p - 0.07345 u_p^2$. Isotherms at 293° K, using different forms for the Grüneisen parameter and a simple Debye model for the specific heat, are calculated from the Hugoniots and are presented here. They should prove useful when NaCl is used as an internal standard in high pressure X-ray devices.

*Work done under the auspices of the U. S. Atomic Energy Commission.

Paper to be presented at Symposium on the Accurate Characterization of the High Pressure Environment, October 14-18, 1968, U. S. Dept. of Commerce, National Bureau of Standards, Gaithersburg, Maryland.

Introduction

Since Jamieson¹ first used NaCl as an internal pressure standard in his high pressure X-ray apparatus, it has been a serious candidate for a pressure standard in high pressure X-ray work. Decker² has advocated the use of NaCl as a standard. His proposal was based on a Born-Mayer equation of state. Parameters were fixed by the initial density and sound speed of NaCl at zero pressure and he achieved a prediction of the curvature of the P-V isotherm, which can be converted in terms of variables familiar to workers in the dynamic-pressure field to a prediction of the slope of the shock velocity vs. particle velocity Hugoniot. His results were supported by the then existing shock wave data. An increase of 1.3 percent in the value of the sound speed he used in his work would bring his isotherm into agreement with the result of the present report.

Objections have been raised^{3,4,5} to using NaCl as a standard because of the possibility of the transition to the CsCl structure at a pressure as low as 20 kb. Such a low pressure transition would unacceptably complicate the use of NaCl as a continuous pressure standard. Others^{6,7,8,9} have found no evidence for a transition as low in pressure as this. From the work of Jamieson^{9,10} on the solution salts, $\text{Na}_x\text{K}_{1-x}\text{Cl}$, one can conclude that the B1 to B2 transition must be considerably above 130 kb in the pure end number,

NaCl. Finally, Bassett et al.¹¹ have found and reversed the B1 to B2 transition in NaCl at approximately 300 kb at room temperature. It would seem that whatever the remaining phenomena is at 20 kb, it does not involve the B1 to B2 transition, and that NaCl will remain in the B1 structure to high and useful pressures.

Perez-Albuerne and Drickamer⁸ have compared NaCl by X-ray techniques with Ag and Mo. If the compression curves of Ag and Mo are known, this would determine a NaCl isotherm. Using older shock wave data¹², results were obtained which, because of the individual scatter in a data point, were used only to verify the calculation of an isotherm from a particular form of a Born-Mayer treatment. Their calculated isotherm is in agreement with the isotherm we report as well as that of Bridgman⁶.

Direct shock-particle velocity data on NaCl could not be obtained because of the impracticality of fabricating the assemblies required for our shock-wave techniques. Hence we have employed the shock-wave impedance match technique using 2024 aluminum base plates as the standard. In this way, NaCl becomes a secondary standard, dependent on the Hugoniot and extended equation of state of 2024 aluminum. If the 2024 aluminum Hugoniot is accepted as known, a shock-locus for NaCl is obtained that is felt to be accurate to 1% in pressure. Subsequent modifications, if any, of the primary standard may be easily translated to a new Hugoniot locus for NaCl. As always, the largest uncertainty in an isothermal curve derived from shock-wave data is related to the choice of the

Grüneisen gamma used to reduce the Hugoniot to an isotherm. Several functions of volume have been used for $\gamma(V)$ and the resultant isotherms reported.

Experimental Methods and Results

The impedance matching technique used for obtaining the shock locus for NaCl has already been adequately described¹². Single crystals in the (100), (110) and (111) orientations as well as some pressed powder samples were shock-loaded on base plates of 2024 aluminum, copper, and 921-T aluminum. The data taken on 921-T aluminum base plates has been discarded for reasons described elsewhere¹³. In this report only those data whose final shocked state is believed to remain in the B1 structure are reported. The majority of the data were taken on 2024 aluminum with a few points taken on copper base plates as a consistency check. The data necessary for impedance calculations for the primary standards are:

$$\begin{aligned} \text{2024 aluminum: } \rho_0 &= 2.785 \text{ g/cm}^3, u_s = 5.328 + 1.338 u_p \text{ km/sec} \\ (\partial E / \partial P)_V &= 0.19 \text{ cm}^3/\text{gm} \end{aligned}$$

$$\begin{aligned} \text{Copper: } \rho_0 &= 8.93 \text{ g/cm}^3, u_s = 3.940 + 1.489 u_p \text{ km/sec} \\ (\partial E / \partial P)_V &= 0.057 \text{ cm}^3/\text{gm} \end{aligned}$$

A constant $(\partial E / \partial P)_V$ was used to generate the release isentropes necessary for the impedance match calculations. The data are reported in Table I and illustrated in Fig. 1. In addition to the tabulated data, data points showing the onset of the B1 to B2 (presumably) phase transition are included in the figure for both

(100) and (111) orientations.

Both linear and quadratic terms in u_p were used to fit these data. In the absence of other information, there would be no point in going to an order higher than linear to fit the data; however, consideration must be given to the measured sound speeds in NaCl. In fact, the c_0 coefficient in our quadratic fit was forced to agree with the sound speed obtained from Haussuhl's¹⁴ measurement of the elastic constants of single crystal NaCl. The least squares analysis of the data gives r. m. s. deviation of $\Delta u_s = \pm 0.056$ km/sec or less over the range of the data. Within the range of the data, the quadratic and linear fits agree to within this Δu_s except for the lowest four data points. The low shock pressures for these four points (< 40 kb) were produced by relatively complicated driver arrangements that depend on impedance mismatches. It is not impossible that overtaking waves could influence these measurements. The shock velocities at these pressures are notably below some of the single crystal longitudinal velocities. Premature closure of flash gaps could give rise to the sort of discrepancy we see here, but since a low-pressure cannon shot has indicated that the Hugoniot elastic limit of NaCl is only about 2/3 of a kilobar, there is not sufficient motion imparted to a shim to close any flash gaps used here. Gap closure corrections are more critical in this pressure regime and conceivably could cause errors in shock wave velocity, but not of the size to explain these low pressure shots. In any event, forcing the Hugoniot through

the sound speed prevents these points from appreciably influencing the fit to the data. The large bulk of the data at higher pressure with its linearity fixes the next two terms of the series. Some evidence that these lower points influence the slope in the right direction is afforded by Bartels and Schuele's¹⁵ measurement of $(\partial B_S / \partial P)_T = 5.27$.

From the thermodynamic identities

$$s_0 = [1 + (\partial B_S / \partial P)_S] / 4$$

and

$$(\partial B_S / \partial P)_S = (\partial B_S / \partial P)_T + \gamma (T/B_S) (\partial B_S / \partial T)_P$$

and Haussuhl's¹⁴ value for $(\partial B_S / \partial T)_P$ of $-0.000117 \text{ Mb}/^\circ\text{K}$, we obtain $s_0 = 1.513$. This is in satisfactory agreement with our fitted slope of 1.542. Although a linear fit represents the shock-wave data adequately, emphasis should be placed on the ultrasonic measurements in the low pressure region. The quadratic fit

$$u_s = 3.403 + 1.5422 u_p - 0.07345 u_p^2 \quad (\text{km/sec}) \quad (1)$$

represents the ultrasonic data in the low pressure region and the shock-wave data in the high pressure region. The number of significant figures quoted in the above equation gives the exact form of the Hugoniot used in a subsequent reduction to an isotherm. The r. m. s. spread in u_s about the fitted values is $\pm 0.05 \text{ km/sec}$. Our data for NaCl in the B1 phase are in agreement with the data of Larson, et. al.³ to within the quoted error. Unpublished data of Hauver and Melani¹⁶ are in

agreement with ours in the vicinity of $u_p = 1$ km/sec and are 0.07 km/sec higher than ours near $u_p = 2$ km/sec. However, their data were based on the old 2024 aluminum standard. Revision of the necessary impedance match calculations will bring the results into better agreement.

Reduction of the Hugoniot to a 293 °K Isotherm

Details of this calculation have been discussed earlier.¹³ The auxiliary information needed for this reduction is given in Table II. Original references should be consulted for the accuracy of these numbers. The table gives the exact input used in our calculations. The particular numerical code used integrates the equation

$$dT_H = -T_H \frac{\gamma dV}{V} + \frac{(V_0 - V)dP_H + P_H dV}{2 C_V} \quad (2)$$

for the temperature along the Hugoniot. A Debye expression,

$$E_T = 3nkT D_3(\theta(V)/T) \quad (3)$$

$$D_3(x) = \frac{3}{x^2} \int_0^x \frac{z^3 dz}{e^z - 1} \quad (4)$$

$$\gamma = -d \ln \theta / d \ln V \quad (5)$$

is used for the thermal part of the energy.

With a γ that depends only on volume, the appropriate fractional thermal energy and corresponding thermal pressure may be subtracted from the Hugoniot to yield the desired isotherm. The choice of Debye

theta at zero pressure and 293 °K was dictated by the value of C_V at these conditions, since this is the important quantity in the integration of (2). Since the numerical value for $E(P = 0, T = 273 \text{ }^\circ\text{K}) - E(0, 0)$ predicted by this model ($+ 1.76 \times 10^9$ ergs/g) agrees with the value obtained by fitting $C_P(T)$ ($\Delta E = 1.77 \times 10^9$, JANAF Tables)²¹ we have some evidence that we have an overall fit for $C_V(T)$ at the lower T region as well.

Probably the largest uncertainty in transforming a Hugoniot to an isotherm comes from ignorance about the way the Gruneisen gamma behaves at high pressures and temperatures. In the few cases where its high pressure behavior has been measured, the assumption that $(\partial E / \partial P)_V$ is constant has been adequate to represent the data within the experimental precision, but other forms for $\gamma(V)$ are not excluded. We have used this assumption to calculate our "base room temperature isotherm". The results, finely spaced for more convenient usage, are given in Table III.

It is of interest to see what effect varying the parameters that went into the calculation will have on the calculated isotherm. The equation

$$\gamma(V) = \frac{t-2}{3} - \frac{1}{2} \frac{d \ln \{ d [P_K(V) V^{2t/3}] / dV \}}{d \ln V} \quad (6)$$

is a generalization of the Slater, Dugdale - MacDonald and Free Volume relations between $\gamma(V)$ and $P_K(V)$ which has been used by Grover et. al.²² in their comparison of static and dynamic high-pressure data on the alkali metals. Values of t of 0, 1 and 2 correspond to the above theories, but the value of t can be chosen to give the proper thermodynamic value of γ at the Hugoniot centering point. Further, if the expression for $\gamma(V)$ obtained from differences between the Hugoniot curve and the zero Kelvin curve is equated with the above expression for γ , the Hugoniot centering point is taken to be at zero pressure and temperature, and a linear $u_s - u_p$ Hugoniot is used, an integro-differential equation for $P_K(V)$ is obtained. When solved this gives not only $P_K(V)$, but also a $\gamma(\eta)$, where $\eta = 1 - \rho_0 V$, that parametrically depends only on t and the slope, s , of the $u_s - u_p$ Hugoniot. At zero compression, this reduces to the relation

$$\gamma_0 = 2s - (t + 2)/3 \quad (7)$$

between γ_0 , t , and s . A linear $u_s - u_p$ Hugoniot for NaCl that passes through most of the shock wave data and the measured sound speed has $s = 1.429$. With the correct γ_0 , (7) yields $t = 1.761$. The $\gamma(\eta)$ obtained in this fashion will not significantly differ from one where the precise experimental Hugoniot is used as input and where the difference between the temperature of the Hugoniot centering point and zero temperature is taken into account. The resulting $\gamma(\eta)$,

as well as others, are shown in Fig. 2. This $\gamma(\eta)$ may be accurately represented by a polynomial in η for $0 < \eta < 0.5$.

$$\gamma = 1.6044 - 0.9955\eta + 1.4961\eta^2 - 1.9284\eta^3 \quad (8)$$

This representation, along with the more precise Hugoniot fit, was then used in the numerical code that calculates the isotherm. The resultant curve, labelled (1), is shown in Fig. 3. An ionic solid may not be the best place to use such a theory for $\gamma(\eta)$, but it does offer an alternate $\gamma(\eta)$ behavior to compare with the base isotherm.

Another $\gamma(\eta)$ behavior is offered by Decker². A term linear in the change in lattice parameter was added to γ_0 to give the best fit to high temperature (i. e., a slight increase in volume) thermal expansion data. This should give the right initial slope of $\gamma(\eta)$ but as Decker says, it is uncertain whether this volume dependence remains accurate to the large volume changes obtained in the shock wave data. This $\gamma(\eta)$ is given by

$$\gamma = 1.6044 + 2.55 \left((1-\eta)^{1/3} - 1 \right) \quad (9)$$

Decker actually used the value $\gamma_0 = 1.59$. A polynomial fit to (9) was used to calculate isotherm (2) in Fig. 3.

Isotherms (3) and (4) show the effect of varying γ_0 by plus and minus 10%. For these isotherms $(\partial E / \partial P)_V$ was kept constant.

Isotherms (5) and (6) show the effect of scaling C_V by plus and minus 10%. This was done by changing the value of $3nk$ in the calculations.

Isotherms (7) and (8) were obtained by adding and subtracting, respectively, 0.05 km/sec to c_0 in the input Hugoniot.

Comparison with other Isothermal Data and Discussion.

The "base isotherm" is shown in Fig. 4 along with Decker's, that calculated by Perez-Albuerne and Drickamer, and Bridgman's data. The agreement between our isotherm and that of Perez-Albuerne and Drickamer's is well within the experimental error of both methods. The latter isotherm is slightly lower (1-2 kb) than ours in the pressure range from 40 to 100 kb. Bridgman's isotherm is still lower by again this pressure difference in this region. The lower portion of our isotherm is chiefly determined by using Haussühl's sound speed. The initial slope of the $u_s - u_p$ Hugoniot could be changed from 1.542 to 1.512 to agree with Bartels and Schuele, but this would decrease the computed isotherm by only 1/4 kb at 40 kb. At 60 kb, the shock-wave measurements are slightly above the fit used. Above this, where the shock wave measurements should be relatively free of elastic-plastic flow effects because of the low Hugoniot elastic limit of NaCl, the fit and the data are consistent. Decker's isotherm falls below ours, with the spread in pressure being about 5 kb at 100 kb, 12 kb at 200 kb, and remaining approximately the same thereafter. As he noted; Decker's isotherm is most sensitive to the value of the bulk modulus used. A choice of bulk modulus equivalent to the sound speed we have used would bring the two isotherms into essential agreement. It is perhaps worthwhile to emphasize at this point that at and above 80 kb, and to a lesser extent at 60 kb, our isotherm does not particularly depend on

on the precise value of the bulk modulus used, because the shock-wave data then determines the Hugoniot used to calculate the isotherms.

Jeffrey, et. al.²³ have given the pressures of various phase transitions by determining a/a_0 of NaCl used as an internal standard. Using their values of a/a_0 and Decker's pressure scale they obtain 24.8 ± 0.8 kb for the Bi I-II transition, 53.3 ± 1.2 kb for the Ba I-II transition, and 73.8 ± 1.3 kb for the Bi III-V transition. Using our isotherm and their a/a_0 values these numbers become $25.8 \pm .8$, 56.3 ± 1.2 and 78.2 ± 1.3 . Bridgman's volume scale as reported by Jeffrey, et al., has 25.4, 58.8 and 88 kb for these transitions, McWhan²⁴ also measured the Bi III-V transition with NaCl as an internal standard. He took his values on the increasing pressure cycle, whereas Jeffrey, et. al, averaged increasing and decreasing pressure readings. McWhan's $V/V_0 = 0.816 \pm .006$ corresponds to 81.7 ± 4.5 kb on our isotherm. The Birch-Murnaghan equation and the input parameters as used by McWhan for his pressure value is consistent with our isotherm up to a pressure of 100 kb. Beyond that, the Birch-Murnaghan value for the pressure increases more rapidly than our isotherm by 6 kb at 150 kb and 13 kb at 200 kb.

The highest measured pressure on our Hugoniot for the B1 phase is 264 kb. The offset down to the isotherm is about 16 kb at this volume. Our isotherm above 250 kb is then a consequence of an extrapolation of the Hugoniot data. The downward curvature of the quadratic $u_s - u_p$ fit is a relic of trying to fit the ultrasonic data and

shock data smoothly together in the lower pressure region and probably should not be there. Both the data alone and calculations of a $u_s - u_p$ curve from a Born-Mayer form for the interaction potential indicate a linear behavior in this region. Accordingly we have listed in Table IV the isotherm above 200 kb that obtains from the best linear fit to our data. In this calculation we have again used constant $(\partial E / \partial P)_V$. From 200 to 230 kb this is essentially identical to the isotherm resulting from the quadratic fit. Above 230 kb it becomes stiffer.

A clear indication of a phase transition is exhibited by the higher pressure data points plotted in Fig. 1. Although (111) and (100) oriented crystals have indistinguishable Hugoniot at lower pressures, they clearly separate in the region where the phase transition occurs. Since a uniaxial compression of 50% in the (111) direction produces the B2 structure from the B1 structure, one can expect that a shock wave in this direction will see a lower energy barrier in the way of this transition. Indeed, the (111) data are lower. If a shock wave is not complicated by relaxation effects and deviatoric stresses, a phase transition with a sufficient ΔV and an appropriate slope in the P-T plane appears as a horizontal plateau in the $u_s - u_p$ plane. This is because the flash gaps measure the shock velocity of the first wave in a two-wave structure, which remains constant as we increase the driving pressure, and the particle velocity, measured indirectly by measuring the shock velocity of the standard, is increasing with the

driving pressure. Time dependent effects clearly influence the NaCl data in this region, but the onset of a phase transition is beyond question. At these pressures, even though a considerable time may be required for a phase transition to go to completion, any part of the ΔV of the reaction manifests itself immediately as a shock velocity less than would be expected from a smooth continuation of the initial phase. A plateau has been drawn somewhat arbitrarily through the (111) data. Although the data scatter upwards from this line, the clustering toward the bottom is sufficiently sharp to give some credence to the plateau as drawn.

The behavior of the (100) data is different; it tends to drift slowly upward in a manner which one might expect from a reaction whose relaxation time is comparable to the time it takes a shock wave to traverse the sample. The (111) plateau intersects both the linear and quadratic fits to the B1 phase at $u_s = 5.94$ and $u_p = 1.80$ km/sec. The pressure on the Hugoniot is 231 kb, the density is 3.105 g/cm^3 and the temperature is between 1120 and 1130 $^\circ\text{K}$. This number should provide an upper bound to the actual transition pressure.

Basset, et. al.¹¹, have observed the B1-B2 transition at a $V/V_0 = 0.643 \pm .002$. Using our isotherm from the extrapolated linear Hugoniot, we find the pressure of this transition as 307 ± 5 kb. The extrapolation of the quadratic fit would have yielded 295 ± 5 kb. This should set the upper limit of pressure for the use of NaCl in the B1 phase as an internal pressure standard at room temperature.

Acknowledgements.

The authors would like to thank G. E. Hauver and A. Melani for the opportunity to look at their unpublished data and D. L. Decker for sending us his tabulated pressure-volume isotherms.

References

1. J. C. Jamieson, *Science* 139, 1291 (1963).
2. D. L. Decker, *J. Appl. Phys.* 36, 157 (1965).
3. D. B. Larson, R. N. Keeler, A. Kusubov, and B. L. Hord, *J. Phys. Chem. Solids* 27, 476 (1966).
4. V. V. Evdokimova and L. F. Vereshchagin, *J. Exp. Theor. Phys.* 43, 1208 (1962); 16, 855 (1963).
5. C. W. F. T. Pistorius, *J. Phys. Chem. Solids* 25, 1477 (1964).
6. P. W. Bridgman, *Proc. Am. Acad. Arts Sci.* 76, 1 (1945).
7. Q. Johnson, *Science* 153, 419 (1966).
8. E. A. Perez-Albuerne and H. G. Drickamer, *J. Chem. Phys.* 43, 1381 (1965).
9. J. C. Jamieson, Physics of Solids at High Pressures, pp. 444-459, C. T. Tomizuka and R. M. Emrick, eds. (Academic Press, New York, 1965).
10. J. C. Jamieson, private communication.
11. W. A. Bassett, T. Takahashi, H. Mao, and J. S. Weaver, *J. Appl. Phys.* 39, 319 (1968).

12. M. H. Rice, R. G. McQueen, and J. M. Walsh, *Solid State Phys.* 6, 1 (1958).
13. W. J. Carter, S. P. Marsh, J. N. Fritz, and R. G. McQueen, "The Equation of State of Selected Materials for High Pressure References," NBS Symposium on the Accurate Characterization of the High Pressure Environment, Washington, 1968.
14. S. Haussühl, *Zett. f. Physik* 159, 223 (1960).
15. R. A. Bartels and Schuele, D. E., *J. Phys. Chem. Solids* 26, 537 (1965).
16. G. E. Hauver and A. Melani, private communication.
17. W. H. Johnson, Jr. and A. O. Nier, Handbook of Physics, E. V. Condon and H. Odishaw, eds., pp. 9-65, 2nd ed., (McGraw-Hill, New York, 1967).
18. National Bureau of Standards Circular 539, 2, 41 (1965).
19. T. Rubin, H. L. Johnston, and H. W. Altman, *J. Chem. Phys.* 65, 65 (1961).
20. T. H. K. Barron, A. J. Leadbetter, and J. A. Morrison, *Proc. Roy. Soc. A* 279, 62 (1964).
21. JANAF Thermochemical Tables, The Dow Chemical Company, Midland, Michigan.

22. R. Grover, R. N. Keeler, F. J. Rogers, and G. C. Kennedy,
"On the Compressibility of the Alkali Metals," J. Phys. Chem.
Solids (to be published).
23. R. N. Jeffery, J. D. Barnett, H. B. VanFleet, and H. T. Hall,
J. Appl. Phys. 37, 3172 (1966).
24. D. B. McWhan, J. Appl. Phys. 38, 347 (1967).

Table I. NaCl Hugoniot Data in the B1 Phase

u_s	u_s std.	u_p	P	ρ
km/sec	km/sec	km/sec	kb	g/cm ³
<u>(100 orientation)</u>				
4.03	5.67	0.33	29	2.358
4.10	5.75	0.40	35	2.397
4.12	5.79	0.44	39	2.423
4.31	5.94	0.58	54	2.502
4.36	5.96	0.60	57	2.510
4.59	6.17	0.79	78	2.613
4.59	6.19	0.81	80	2.625
4.95	6.45	1.03	111	2.735
4.89	6.45	1.04	110	2.748
4.99	4.96*	1.07	116	2.755
4.99	6.50	1.09	117	2.766
4.99	6.54	1.12	121	2.789
5.01	6.55	1.13	122	2.793
5.51	6.92	1.44	172	2.932
5.43	6.91	1.44	170	2.949
5.47	6.92	1.45	171	2.942
(110) 5.47	6.92	1.45	171	2.941
5.59	5.41*	1.53	184	2.977
5.67	7.07	1.57	193	2.992
5.84	5.58*	1.70	215	3.052
5.94	7.36	1.82	234	3.121
5.96	7.37	1.84	237	3.129
6.12	7.47	1.92	254	3.151
6.12	7.47	1.92	254	3.152
6.15	7.51	1.95	259	3.166

Table I. - Page 2

u_s	u_s std.	u_p	P	ρ
km/sec	km/sec	km/sec	kb	g/cm ³
6.15	7.51	1.95	259	3.167
6.13	7.52	1.96	260	3.185
6.20	7.54	1.97	264	3.170
<u>(111 orientation)</u>				
4.08	5.75	0.40	35	2.399
4.32	5.96	0.60	56	2.515
4.31	6.00	0.63	59	2.538
4.59	6.19	0.81	80	2.626
4.59	6.20	0.82	81	2.632
4.96	6.44	1.03	110	2.729
4.98	4.96*	1.07	115	2.757
5.01	6.50	1.08	117	2.760
4.99	6.50	1.08	117	2.765
4.99	6.53	1.11	119	2.780
5.03	6.55	1.13	123	2.787
5.02	6.56	1.13	123	2.795
5.45	6.92	1.45	171	2.947
5.47	6.92	1.45	171	2.944
5.57	5.41*	1.53	184	2.981

* Copper base plates. The rest are 2024 aluminum.

Table II. Thermodynamic Parameters for NaCl

Quantity	Value	Reference
M	58.443 g/mole	17
N	6.02252×10^{23}	
a_0	5.6393 Å at 22 °C	19
$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P$	$1.195 \times 10^{-4} / ^\circ\text{K}$ at 20 °C	19
B_s	0.2505 Mb at 22 °C	14
C_p	12.05 cal/mole - °K at 20 °C	20, 21

Derived Values at 293 °K

$$\rho = 2.1645 \text{ g/cm}^3$$

$$B_s = 0.2507 \text{ Mb}$$

$$C_p = 0.8627 \times 10^6 \text{ ergs/gm-}^\circ\text{K}$$

$$c_0 = 3.403 \times 10^5 \text{ cm/sec}$$

$$\gamma = \beta c_0^2 / C_p = 1.6044$$

$$\gamma\beta T = 0.0562$$

$$C_V = 0.8168 \times 10^6 \text{ ergs/gm-}^\circ\text{K}$$

$$B_T = 0.2374 \text{ Mb}$$

$$K_T = 4.213 \text{ Mb}^{-1}$$

$$\left(\frac{\partial P}{\partial T} \right)_V = 0.0284 \text{ Kb/}^\circ\text{K}$$

$$\left(\frac{\partial E}{\partial P} \right)_V = 0.2880 \text{ cm}^3$$

$$3nk = 0.8535 \times 10^7 \text{ ergs/gm-}^\circ\text{K}$$

$$C_V / 3nk = 0.9570$$

$$\theta_D / T = 0.9420$$

$$\theta_D = 276 \text{ }^\circ\text{K}$$

Table III. The $(\partial E/\partial P)_V$ Constant, 293 °K NaCl Isotherm and
its Antecedent Hugoniot

P Kb	Hugoniot		Isotherm		
	ρ_H g/cm ³	T_H °K	ρ g/cm ³	V/V ₀	a/a ₀
0	2.1645	293	2.1645	1.0000	1.0000
5	2.206	302	2.208	.9803	.9934
10	2.245	311	2.248	.9629	.9875
15	2.281	319	2.286	.9469	.9820
20	2.314	328	2.321	.9326	.9770
25	2.347	336	2.355	.9191	.9723
30	2.377	345	2.386	.9072	.9680
35	2.406	355	2.417	.8955	.9639
40	2.434	365	2.446	.8849	.9601
45	2.461	375	2.473	.8753	.9566
50	2.486	386	2.500	.8658	.9531
55	2.511	398	2.526	.8569	.9498
60	2.535	410	2.552	.8482	.9466
65	2.558	423	2.576	.8403	.9436
70	2.581	436	2.600	.8325	.9407
75	2.602	450	2.623	.8252	.9380
80	2.624	464	2.645	.8183	.9354
85	2.644	479	2.667	.8116	.9328
90	2.664	494	2.689	.8049	.9302
95	2.684	510	2.710	.7987	.9278
100	2.703	527	2.731	.7926	.9254
105	2.722	544	2.751	.7868	.9232
110	2.740	562	2.771	.7811	.9210
115	2.758	580	2.790	.7758	.9189

Table III. - Page 2

P	ρ_H	T_H	ρ	V/V_0	a/a_0
Kb	g/cm^3	$^{\circ}K$	g/cm^3		
120	2.776	599	2.809	.7706	.9168
125	2.793	618	2.828	.7654	.9147
130	2.810	637	2.847	.7603	.9127
135	2.827	657	2.865	.7555	.9108
140	2.843	678	2.883	.7508	.9089
145	2.859	699	2.901	.7461	.9070
150	2.875	721	2.918	.7418	.9052
155	2.891	743	2.935	.7375	.9035
160	2.906	765	2.952	.7332	.9017
165	2.921	788	2.969	.7290	.9000
170	2.936	811	2.986	.7249	.8983
175	2.951	835	3.002	.7210	.8967
180	2.865	859	3.019	.7170	.8950
185	2.980	884	3.035	.7132	.8934
190	2.994	909	3.051	.7094	.8919
195	3.008	934	3.067	.7057	.8903
200	3.022	960	3.082	.7023	.8889
205	3.035	986	3.098	.6987	.8873
210	3.049	1013	3.113	.6953	.8859
215	3.062	1040	3.129	.6918	.8844
220	3.075	1067	3.144	.6885	.8830
225	3.089	1094	3.159	.6852	.8816
230	3.102	1123	3.174	.6819	.8802
235	3.114	1151	3.189	.6787	.8788
240	3.127	1180	3.204	.6756	.8774
245	3.140	1209	3.218	.6726	.8762
250	3.152	1238	3.233	.6695	.8748

Table IV. The NaCl Isotherm above 200 kb using the Linear $u_s - u_p$ Fit

P Kb	Hugoniot		Isotherm		
	ρ_H g/cm ³	T_H °K	ρ g/cm ³	V/V_0	a/a_0
200	3.023	950	3.081	.7025	.8890
205	3.036	977	3.096	.6991	.8875
210	3.050	1004	3.111	.6958	.8861
215	3.063	1031	3.126	.6924	.8847
220	3.075	1059	3.140	.6893	.8834
225	3.088	1087	3.154	.6863	.8821
230	3.100	1116	3.168	.6832	.8808
235	3.113	1145	3.182	.6802	.8795
240	3.125	1174	3.196	.6773	.8782
245	3.137	1204	3.210	.6743	.8769
250	3.148	1234	3.223	.6716	.8757
255	3.160	1264	3.236	.6689	.8745
260	3.171	1295	3.249	.6662	.8734
265	3.183	1326	3.262	.6635	.8722
270	3.194	1357	3.275	.6609	.8711
275	3.205	1389	3.288	.6583	.8699
280	3.216	1421	3.300	.6559	.8689
285	3.227	1454	3.313	.6533	.8677
290	3.238	1487	3.325	.6510	.8667
295	3.248	1520	3.337	.6486	.8656
300	3.259	1553	3.349	.6463	.8646
305	3.269	1587	3.361	.6440	.8636
310	3.279	1621	3.373	.6417	.8625
315	3.289	1656	3.384	.6396	.8616
320	3.299	1690	3.396	.6374	.8606

Figure Captions

Fig. 1. The Shock Velocity-Particle Velocity Hugoniot of NaCl. The elastic wave velocities were obtained from data in reference (14). The larger symbols indicate multiple data points.

Fig. 2. The Various Functions Used for the Grüneisen Parameter.

Fig. 3. Pressure Variations in the Base Isotherm Due to Various Changes in the Input Data. In this figure we show the fractional change in pressure from the base isotherm,

$$\delta P/P = P(\text{new parameters})/P(\text{base}) - 1,$$

at a given density. The actual abscissa is the pressure of the base isotherm at this density.

Fig. 4. NaCl Isotherms. The solid line shows the isotherm calculated from the quadratic fit to the Hugoniot in the $u_s - u_p$ plane. The isotherm from the linear fit is parallel to Decker's isotherm and roughly maintains a constant pressure offset from Decker's isotherm from 200 to 320 kb.

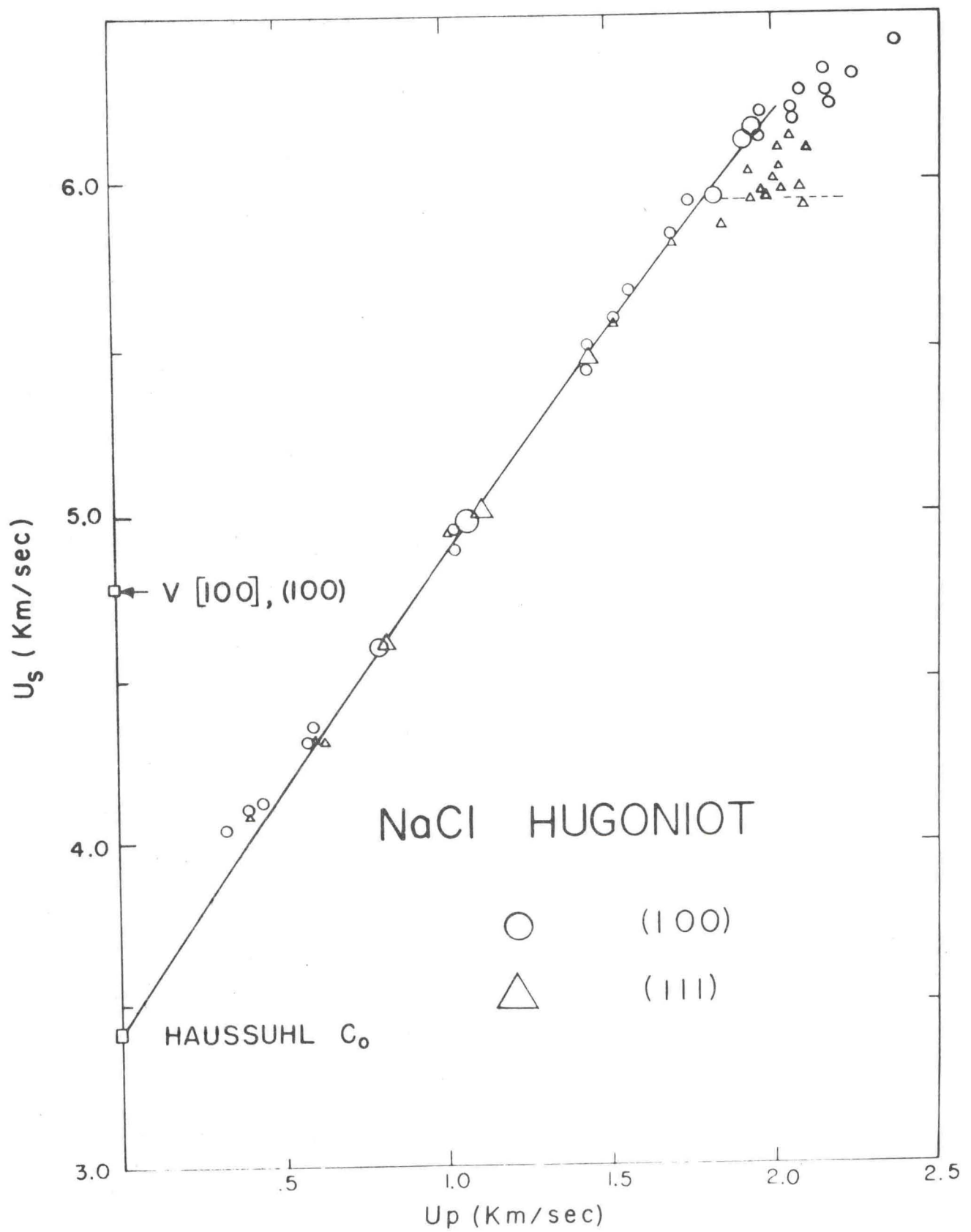


Figure 1

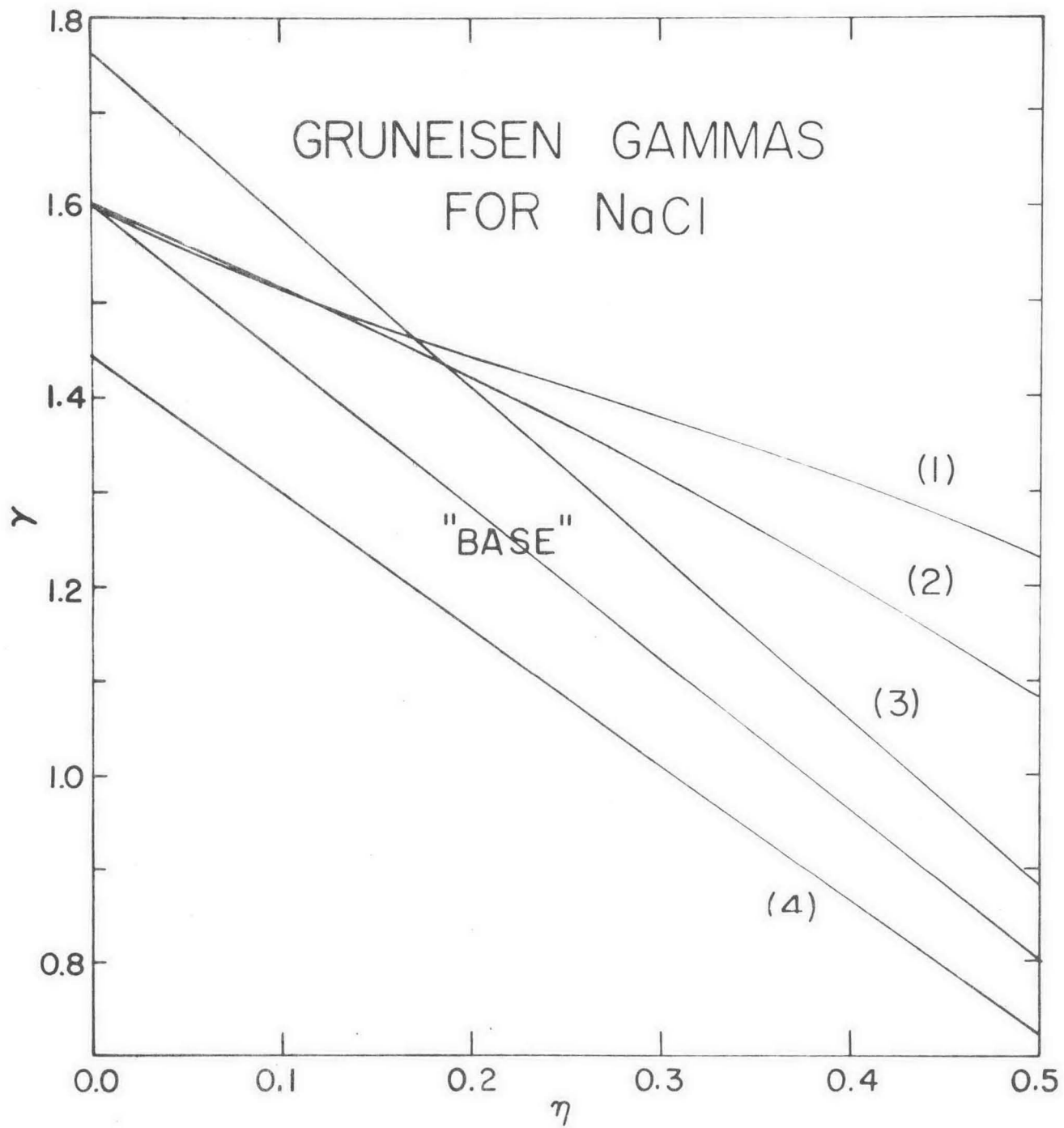


Figure 2

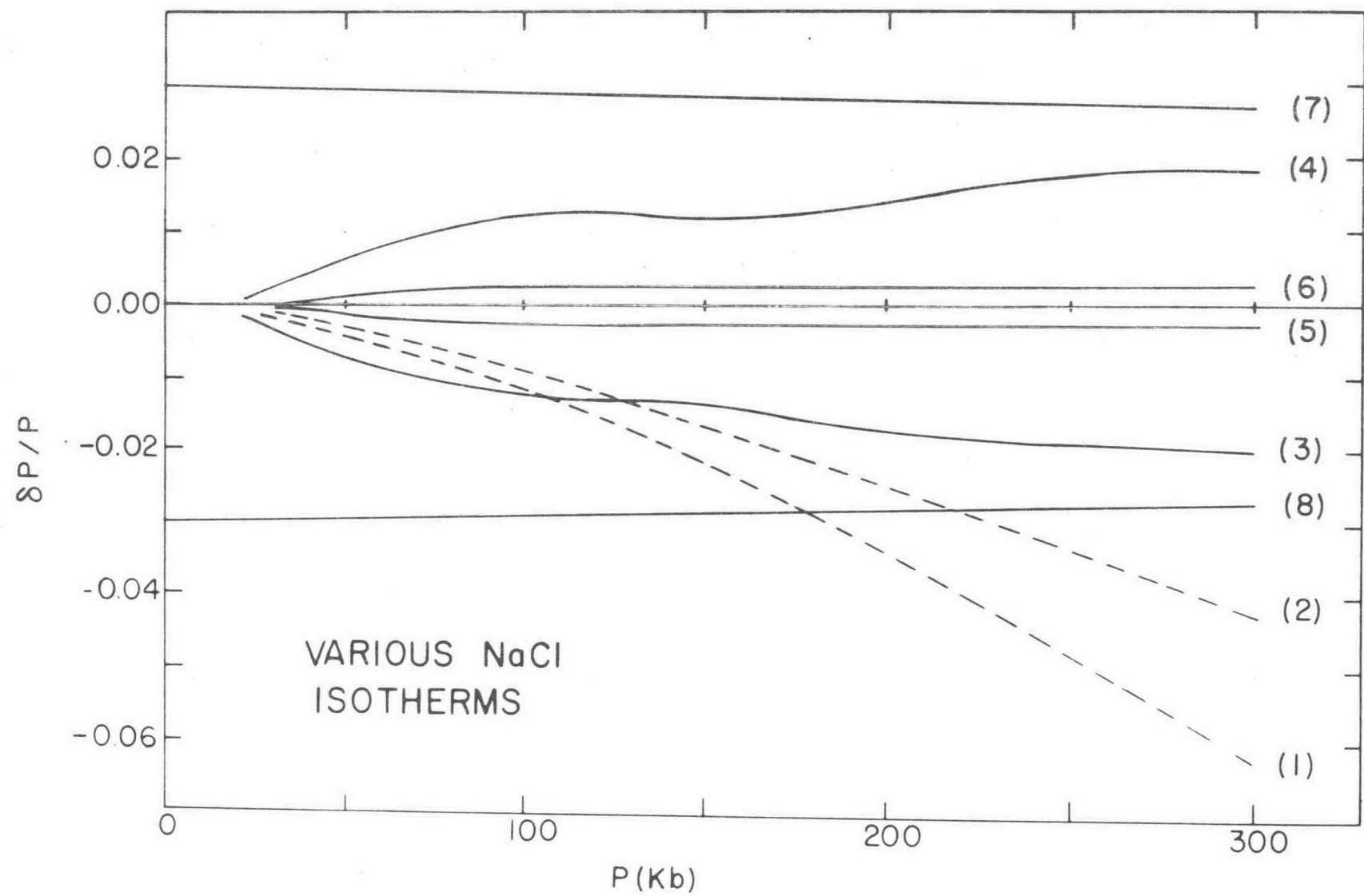


Figure 3

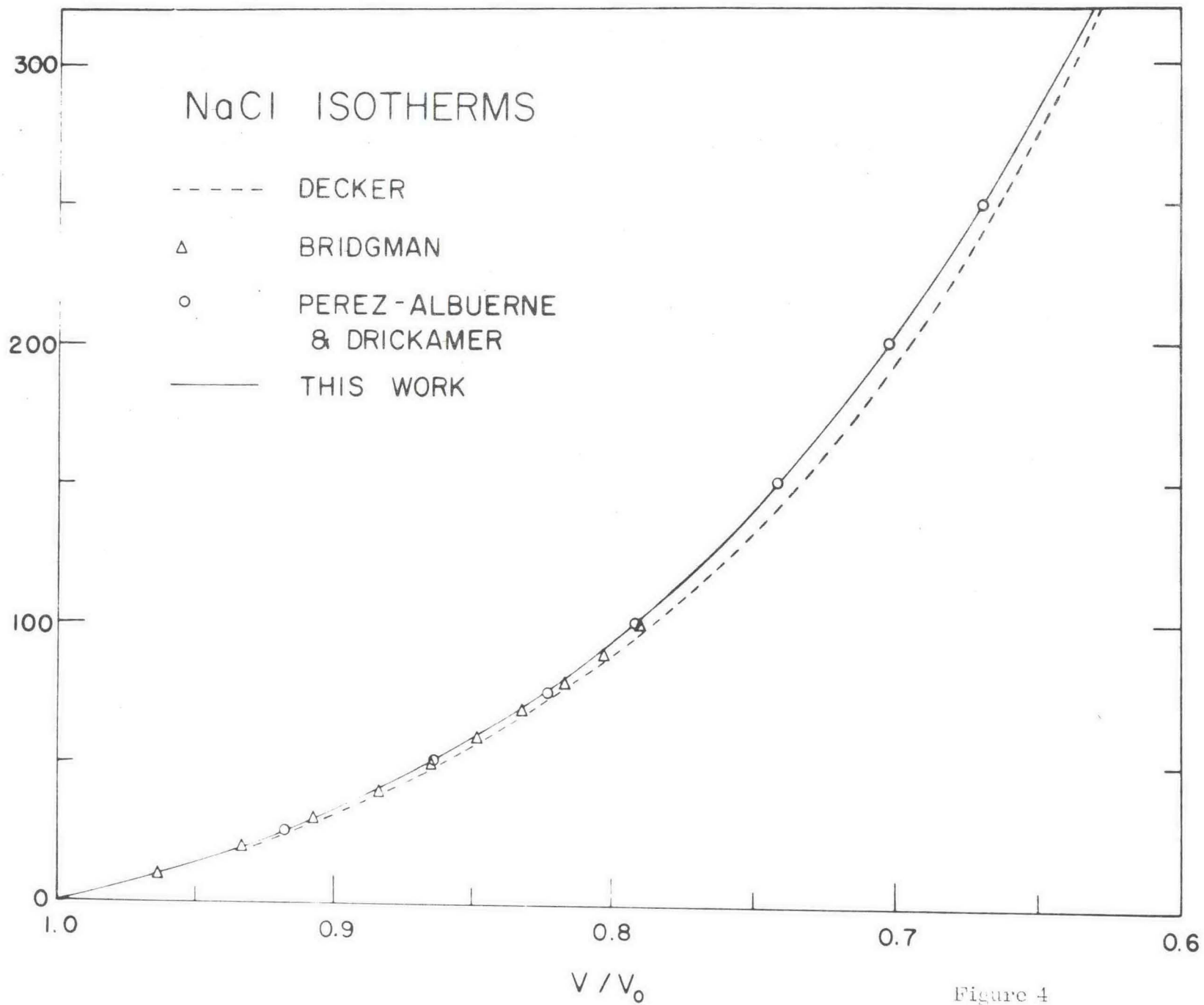


Figure 4