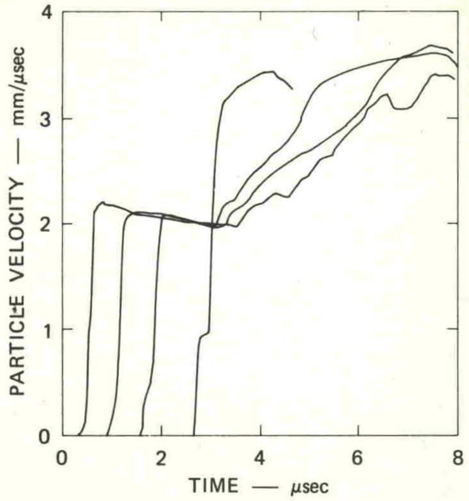

Fig. 5. Collective plot of four particle velocity profiles including one on the free surface in Arkansas novaculite shocked to a peak stress of 300 kbar.

$$C_\sigma = \left(1 + \frac{b}{a}\right) U \tag{7}$$

By using (5), the stress-volume path in the unloading region is determined.

$$\frac{d\sigma}{dV} = -\rho_0^2\left(\frac{a+b}{a-b}\right) U^2 \tag{8}$$

Note that the values of C_σ and C_u can be quite unusual. For instance, $C_\sigma = 2U$ and $C_u = \infty$ correspond to stress unloading at constant volume.

Two experiments were performed with different thickness of explosive. The experimental parameters obtained from the data are given in Table 2. The errors in a and b are average values determined from ambiguity in the profiles. Errors in the shock velocity are small in comparison with errors in a and b. The quantity C is the acceleration wave velocity at which the foot of the relief wave from the free surface of the novaculite propagates (Figure 5). Values for U and C refer to Lagrangian or material coordinates.

To determine whether the quartz-stishovite phase transition is occurring behind the shock front, the stress-volume unloading path from the Hugoniot point in the mixed phase region is compared with the slope of the frozen concentration path. The slope of the frozen concentration curve is determined from the acceleration velocity C, a frozen sound speed being assumed, and is consistent with estimates from thermodynamic data.

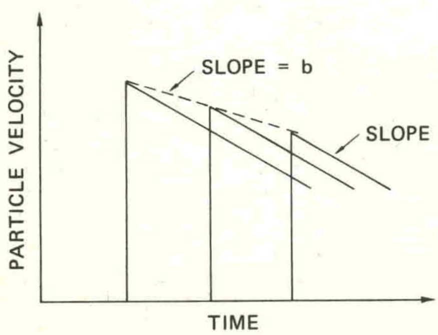

Fig. 6. Triangular wave profiles representing initial unloading behavior due to Taylor wave.

TABLE 2. Relief Wave Data

Shot	σ_H, kbar	U_u, mm/μs	U, mm/μs	C, mm/μs	a, mm/μs²	b, mm/μs²
8909-2	301	2.10	5.45	16.5	-0.090 ± 0.014	-0.09 ± 0.014
1883-6	241	1.63	5.65	12.4	-0.106 ± 0.02	-0.12 ± 0.04

The results for both experiments are shown in Figure 7. The error in a and b results in an uncertainty in the stress-volume path. Initial unloading is within the shaded cones shown in the figure. The dashed lines are slopes of frozen quartz-stishovite concentration curves. The data suggest a slight tendency toward the stishovite phase; however, within experimental error we conclude that unloading is along paths of constant concentration at the considerably lower unloading rates of these experiments. This result is the same as that obtained at a much higher unloading rate in the plate impact experiments.

Discussion

In the present work, stress wave profiles have been measured that exhibit the nature of dynamic wave propagation in the high-pressure mixed phase region of quartz and stishovite. In particular, certain features of the shock-induced transition from α quartz to stishovite have been observed. The dynamic loading is characterized by a two-wave structure. The first wave is associated with mechanical yielding of the material. Application of the Hugoniot conservation relation to both loading waves places the material well into the mixed phase region. The partial phase transition apparently occurred within the final shock front. There is no indication in the observed loading profiles that the yielding process and the phase transition occur at different stress levels. Within the frequency response of the transducer system, no width was observed in the final load-

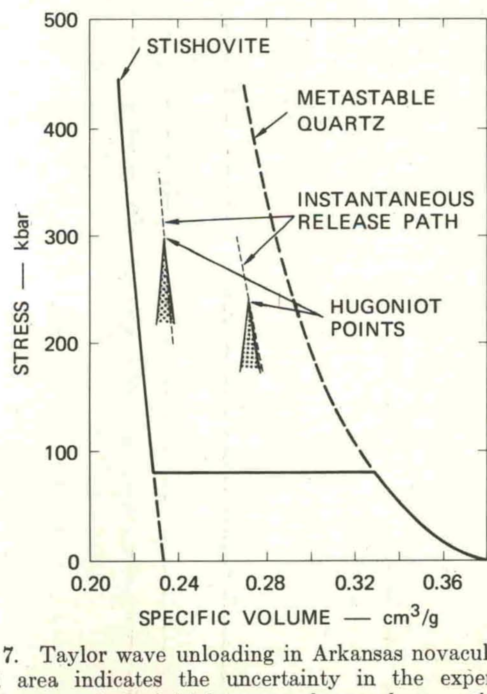

Fig. 7. Taylor wave unloading in Arkansas novaculite. The shaded area indicates the uncertainty in the experimental determination of the initial stress-volume release path behind the shock front.

ing wave that would indicate a relaxation time with the initial phase transition. It can be stated that the relaxation time is substantially less than 0.035 μs, which is the limit of resolution of the present system.

For stress levels less than about 430 kbar the transition ceases (or substantially reduces in rate) before complete stishovite density is reached. The proportion of material transformed depends on the peak stress attained behind the shock front. Experiments performed in this work indicate that the initial transformation rate (in the shock front) and the continuing transformation rate (behind the shock front) differ by at least 3 orders of magnitude.

Analyses of the present experimental results have shown that the pressure-volume behavior of the material during dynamic relief from states in the mixed phase region is along, or close to, paths of frozen concentration. This is a consequence of the extremely reduced transformation rate after initial shock loading.

The character of the measured profiles below about 80 kbar on unloading indicates that a transformation of the higher-density phase to a lower-density material is proceeding. This conclusion is consistent with recovery work of several authors. *Wackerle* [1962] observed amorphous quartz in one recovered specimen of shock-loaded quartz. Similar observations were made by *De Carli and Milton* [1965] on quartz sandstone, and analogous results have been obtained on quartz powder in a copper matrix by *Kleeman and Ahrens* [1973].

In the interpretation of the present results it has been tacitly assumed that strength effects could be ignored after yield occurred in the quartz material. Consistency of the present results with that assumption suggests that it is reasonable. Further justification is provided by the close agreement of stishovite initial density as determined from shock wave data and by measurement on stishovite samples.

Acknowledgments. The authors wish to express appreciation to the staff of Poulter Laboratory, especially M. Cowperthwaite, D. R. Curran, P. S. De Carli, and C. F. Petersen for many discussions with us and to B. Y. Lew and Fred Richey for patiently reading and analyzing the gage records, for computer programing, and for endless calculations. We wish to acknowledge the assistance of A. C. Wheeler, L. B. Hall, and D. Walter in preparing the experimental assemblies and the electronic and explosive instrumentation. We also wish to thank D. B. Larson of Lawrence Livermore Laboratory for his contributions in several discussions. This work was supported by the U.S. Atomic Energy Commission.

REFERENCES

Ahrens, T. J., and G. E. Duvall, Stress relaxation behind elastic shock waves in rocks, *J. Geophys. Res., 71,* 4349–4360, 1966.

Ahrens, T. J., and J. T. Rosenberg, Shock metamorphism: Experiments on quartz and plagioclase, in *Shock Metamorphism of Natural Materials,* edited by B. M. French and N. M. Short, pp. 59–81, Mono Book, Baltimore, Md., 1968.

Ahrens, T. J., D. L. Anderson, and A. E. Ringwood, Equations of state and crystal structures of high-pressure phases of shocked silicates and oxides, *Rev. Geophys. Space Phys., 7,* 667–707, 1969.

Ahrens, T. J., T. Takahashi, and G. F. Davies, A proposed equation of state of stishovite, *J. Geophys. Res., 75,* 310–316, 1970.

Anderson, D. L., and H. Kanamori, Shock-wave equations of state of rocks and minerals, *J. Geophys. Res., 73,* 6477–6502, 1968.

Anderson, O. L., The use of ultrasonic measurements under modest pressure to estimate compression at high pressure, *J. Phys. Chem. Solids, 27,* 547–565, 1966.

Butkovich, T. R., The influence of water in rocks on effects of underground nuclear explosions, *J. Geophys. Res., 76,* 1993–2011, 1971.

Chao, E. C. T., J. J. Fahey, J. Littler, and D. J. Milton, Stishovite, *Amer. Mineral., 46,* 807, 1962.

Cowperthwaite, M., and R. F. Williams, Determination of constitutive relationships with multiple gages in nondivergent flow, *J. Appl. Phys., 42,* 456–462, 1971.

Davies, G. F., Equation of state and phase equilibria of stishovite and a coesitelike phase from shock wave and other data, *J. Geophys. Res., 77,* 4920–4933, 1972.

De Carli, P. S., and D. J. Milton, Stishovite: Synthesis by shock wave, *Science, 147,* 144–145, 1965.

Dremin, A. N., and K. K. Shvedov, The determination of Chapman-Jouguet pressure and of the duration of reaction in the detonation wave of high explosives, *Zh. Prikl. Mekh. Tekh. Fiz., 2,* 154–159, 1964.

Edwards, D. J., J. O. Erkman, and S. J. Jacobs, The electromagnetic velocity gage and applications to the measurement of particle velocity in PMMA, NOLTR 70-79, 1970.

Fowles, R., Dynamic compression of quartz, *J. Geophys. Res., 72,* 5729–5742, 1967.

Fowles, R., and R. F. Williams, Plane stress wave propagation in solids, *J. Appl. Phys., 41,* 360–363, 1970.

Keough, D. D., Procedure for fabrication and operation of manganin shock pressure gage, *Tech. Rep. AFWL-TR-68-57,* Stanford Res. Inst., Menlo Park, Calif., 1968.

Kleeman, J. D., and T. J. Ahrens, The shock-induced transition of quartz to stishovite, *J. Geophys. Res., 78,* 5954, 1973.

Lyle, J. W., R. L. Shriver, and A. R. McMillan, Dynamic piezoresistive coefficient of manganin to 392 kbar, *J. Appl. Phys., 46,* 4663–4664, 1969.

McQueen, R. G., J. N. Fritz, and S. P. Marsh, On the equation of stishovite, *J. Geophys. Res., 68,* 2319–2322, 1963.

McWhan, D. B., Linear compression of α-quartz to 150 kbar, *J. Appl. Phys., 38,* 347–352, 1967.

Murri, W. J., Equation of state of rocks, final report, contract AT(04-3)-115, proj. 8909, Stanford Res. Inst., Menlo Park, Calif., 1972.

Rosenberg, J. T., and M. J. Ginsberg, Effect of cold work in piezoresistance of manganin foil, *Bull. Amer. Phys. Soc., 17,* 1078, 1972.

Stishov, S. M., and S. V. Popova, A new dense modification of silica, *Geokhimiya,* no. 16, 923–926, 1961.

Trunin, R. F., G. V. Simakov, and M. A. Podurets, Compression of porous quartz by strong shock waves, *Izv. Acad. Sci. USSR Phys. Solid Earth,* no. 2, 33–39, 1971.

Wackerle, J., Shock-wave compression of quartz, *J. Appl. Phys., 33,* 922–937, 1962.

Wang, C., Constitution of the lower mantle as evidenced from shock wave data for some rocks, *J. Geophys. Res., 73,* 6459–6476, 198.

(Received June 21, 1973;
revised October 11, 1973.)