[1970] and later extended by *Cowperthwaite and Williams* [1971]. The technique provides a means of mapping the data into the stress-volume and stress-particle velocity plane.

The results of this work can be summarized as follows:

1. Complete stress-time and particle velocity–time histories have been measured in quartz rock subject to high-pressure dynamic loading and relief.

2. Loading into the mixed phase region occurs by two shock waves for stresses below about 400 kbar. Partial transformation to the high-density phase occurs in the final shock front. The degree of transformation depends on the peak driving stress.

3. An effort was made to determine a continuing transformation rate after initial shock loading. We determined that it had to be at least 3 orders of magnitude lower than the initial transformation rate in the shock front.

4. Dynamic unloading from pressure-volume points in the mixed phase region is shown to occur along, or close to, paths of frozen phase concentration down to about 80 kbar.

5. Below 80 kbar a reverse phase transition of the high-density material to a lower density is suggested by the data. The phase transition appears to be rate-dependent with a characteristic time of the order of ⅓ μs.

EXPERIMENTAL PROCEDURE

The novaculite used in these experiments was obtained from Norton Company of Littleton, New Hampshire. This material is a white, homogeneous, cryptocrystalline quartz rock with a grain size of about 0.01-mm diameter and nearly zero porosity. The longitudinal sound speed was measured as 5.9 mm/μs, and the density of our specimens was 2.63 g/cm^3.

Manganin stress gage system. Dynamic loading was provided by impact from explosively driven flyer plates on samples of the test material, as is indicated in Figure 1. Unloading occurred from the back surface of the flyer plate. Peak loading stress is controlled by flyer plate velocity. The flyer plate velocity was determined by the type and mass of the explosive and the flyer plate material and thickness. The flyer plate materials used in the present work were aluminum and magnesium. Flyer plate thicknesses were 0.63 and 1.0 cm.

Target samples of the various rock materials were 15 by 25 cm rectangular slabs 0.15–1.25 cm thick. Stress gages were mounted between slabs of material, two gages per plane in each of three planes. The back slab was sufficiently thick to ensure that relief occurred only from the flyer plate free surface. Gages lay along the large dimension and continued out the ends. The 25-cm dimension exceeded the diameter of the flyer plate by 5 cm. This precaution increased gage lifetime by reducing shearing strains in the vicinity of gage leads exiting from the rock sides.

Stress gages were photoetched from 50-μ manganin foil. The 1-Ω four-lead grid was approximately 1.5 cm square. Copper foil leads were soldered to the gage element to provide connection to the external circuit. The remainder of the volume in the gage plane was filled with C-7 epoxy. Final thickness of the gage plane was 50–75 μ.

Gage current excitation of about 5 A was provided by a constant current manganin gage supply [*Keough,* 1968]. Output was recorded via RG213 transmission cable on oscilloscopes in a differential mode. Frequency response rise time of the electronic system was approximately 0.01 μs. An additional high-frequency limitation occurred owing to pressure equilibration in the 50- to 75-μ-thick gage plane. A rise time can be estimated from the mechanical impedance properties of the gage plane epoxy [*Keough,* 1968] and the rock material. In the present work this was about 0.035 μs.

The gage material used in the present work was as-received Driver Harris foil. The loading calibration coefficient used was a cubic pressure-resistance expression provided by *Lyle et al.* [1969]. The calibration data are comparable with, but showed less scatter than, similar data obtained by *Keough* [1968].

On unloading, 20–30% residual change was observed on all stress data in this work, consistent with work reported by *Rosenberg and Ginsberg* [1972]. They have shown that prior work hardening of the gage material significantly reduces the observed residual resistance but an equivalent reduction in the loading coefficient also occurs. In the present work, as-received manganin was used, and a linear unloading calibration was assumed with the residual resistance level set to zero stress. The calibration used was:

Loading

$$\sigma = \alpha(\Delta R/R) + \beta(\Delta R/R)^2 + \gamma(\Delta R/R)^3 \tag{1a}$$

Unloading

$$\sigma = \sigma_{\max}(\Delta R/R - \Delta R/R_{\text{res}})/(\Delta R/R_{\max} - \Delta R/R_{\text{res}}) \tag{1b}$$

$$\alpha = 3.7 \times 10^2 \quad \beta = -1.32 \times 10^{+1} \quad \gamma = 4.42 \times 10^{+1}$$

where $\sigma_{\max}$ is the pressure obtained at $\Delta R/R_{\max}$ and $\Delta R/R_{\text{res}}$ is the residual resistance change after unloading. Stress records in softer rock material have been obtained in which no residual resistance is observed. We have found no explanation and must conclude that complete understanding of gage behavior on unloading from high stress levels is still not available.

One further point about calibration: although care was taken to select a flyer plate material that is of lower impedance than the rock on unloading, achievement of this cannot be verified before the fact. Unloading to zero stress in one reverberation is provided by this precaution. Final proof that the unloading to zero stress occurred was provided by the pressure–particle velocity curves obtained from the analyzed data after the fact. Results showed that the quartz on unloading has higher impedance.

Particle velocity gage system. In experiments using magnetic particle velocity gages as the recording transducer [*Dremin and Shvedov,* 1964; *Edwards et al.,* 1970], dynamic loading was provided by in-contact explosive systems. Stress unloading was allowed to proceed in two ways. First, a Taylor wave, originating in the explosive gases, provided a rather gentle unloading behind the shock front. The magnitude of this unloading depends on the stiffness of the test material; it is of the order of 5–10% over several microseconds in the novaculite. Useful conclusions were obtained concerning the high-pressure behavior of quartz using the Taylor unloading wave. Second, a more rapid relief was provided by reflecting the induced shock wave off the free surface of the sample.

Target construction followed the procedure discussed previously for stress gages. The U-shaped gages were photoetched from 50-μ copper foil. Ribbon width was 1.5 mm. The center-to-center active element gage length was 11.6 mm. Gages were mounted between slabs of rock and on the free surface along the greater length of the target. Pulsed Helmholtz coils provided a uniform quasi-static magnetic field for the duration of the experimental measurement ($\sim$5 μs). General description of the method used was given by *Murri* [1972]. The target assembly was located between the Helmholtz coils so that the volume traversed by the active element gage during the shock was in the center of the uniform flux region. Gage output was recorded differentially by cathode ray oscilloscopes. Voltage-time profiles $\mathcal{E}(t)$ were reduced to particle velocity–time $u(t)$ through the relation

$$u(t) = \mathcal{E}(t)/lB \quad (2)$$

where l is the center-to-center active gage length and B is the magnetic field.

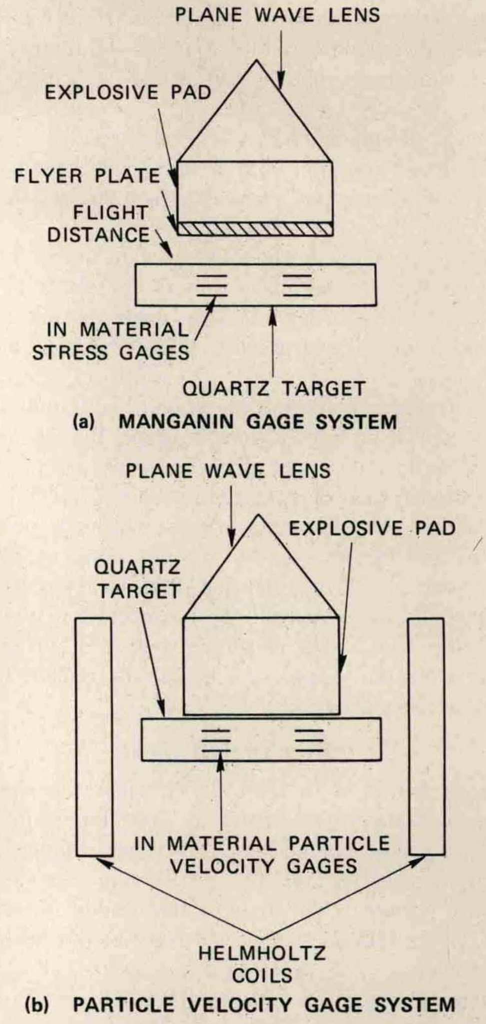

Fig. 1. Experimental systems.

Analysis and Interpretation

Stress gage experiments. A set of manganin gage stress-time profiles obtained in one flyer plate experiment in Arkansas novaculite is shown in Figure 2 along with the experimental configuration. The profile dispersion at increasing distance from the impact surface can be seen from consecutive gage records. Two gages in each plane show the reproducibility of gage response. Four experiments of this type were performed.

In the loading portion a two-wave structure was observed in all but the 440-kbar peak stress experiment. The first wave is associated with yielding at the Hugoniot elastic limit in polycrystalline quartz and propagates with a velocity of about 6.1 mm/μs. In experiments where a two-wave structure was observed on loading, a tendency for the stress amplitude of the first wave to decay with propagation distance was noted. The amount of attenuation was about 4–5 kbar over the 6-mm propagation distance from the first to third gage plane. This stress-relaxing effect has been discussed by *Ahrens and Duvall* [1966]. The attenuation observed was of the order of the scatter in the data, and the Hugoniot elastic limit values stated in Table 1 are an average of this behavior.

The second wave, loading the material to peak stress, provides the final Hugoniot state in Table 1. In the 440-kbar peak stress experiment the elastic precursor was overdriven and thus not observed. The elastic and final state Hugoniot data obtained in the present work are shown in Figure 3. They are in agreement with previous shock wave data on quartz [*Ahrens and Rosenberg*, 1968; *Wackerle*, 1962].

The propagation characteristics of the unloading wave in polycrystalline quartz are also seen in the stress-time profiles in Figure 2. The average relief wave velocity is considerably faster than the loading wave velocity and indicates strongly dissipative wave propagation. Pronounced dispersion is shown by spreading of the relief wave in consecutive profiles.

The sharp break in the relief wave seen in Figure 2 was observed in all stress gage experiments. It occurred at approximately 80 kbar, regardless of peak stress. It is not a phenomenon associated with the manganin gage material. Similar records obtained in other rock material fail to show this behavior. We believe that the break in the relief wave is associated with a reverse transition of high-density quartz to a lower-density material during unloading. The behavior of the stress wave propagation in the lower region of the relief profile does not appear to be forming a rarefaction shock. There appears rather to be a break in slope in individual records and a faster dispersion of the wave in this region. This would be the wave structure expected if transition to a lower-density phase were occurring with a finite relaxation time. A rough calculation assuming a simple stress-relaxing solid results in a relaxation time constant of the order of ⅓ μs. The poorer quality of profiles in this region prohibited a more detailed study.

According to the method of analysis developed originally by *Fowles and Williams* [1970] and extended by *Cowperthwaite and Williams* [1971], multiple-stress gages providing stress-time histories at neighboring Lagrangian coordinates are sufficient to determine the stress-volume path of a material element within the region of the gages. Velocities C_σ and C_u of constant stress or particle velocity levels are estimated from the data and in conjunction with the equation of mass and momentum are used to determine the stress-volume paths. This analysis provided relief adiabats in the mixed phase region. In the present work a dependence of C_σ on the Lagrangian coordinate h could not be determined. In the event that C_σ is a function of σ only and propagation