VOL. 76, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 1971

# Shock Metamorphism of Silicate Glasses[1]

REX V. GIBBONS AND THOMAS J. AHRENS

*Division of Geological and Planetary Sciences*
*California Institute of Technology, Seismological Laboratory*
*Pasadena, California 91109*

The changes in refractive index caused by shock compression have been determined for tektite, soda-lime, and silica glasses shocked to pressures up to 460 kb. For shock compression below 80 kb for fused silica and 40 kb for tektite and soda-lime glasses, compression is reversible as the refractive indices are within 0.0025 of the starting values. Index increases of 0.01, 0.04, and 0.06 are observed for soda-lime, tektite, and silica glasses shocked to pressures of 80, 130, and 140 kb respectively. For soda-lime glass subjected to shock pressures between 80 and 230 kb there is a decrease in the postshock refractive index to $n = 1.5211$ at 230 kb. For fused silica shocked to pressures of 140 to 460 kb, refractive index drops from 1.52 to 1.47. The reasons for these decreases in index are not obvious. New values for postshock temperatures for fused silica based on release adiabat data, e.g. ~1000°C for a shock state at 250 kb, suggest that the decreases in refractive index are caused by a combination of decompression along release adiabats and reconstructive transformation from a shock-induced stishovitelike phase to a low-density glass. Postshock densities calculated from the refractive index data agree closely with those calculated from the release adiabat data.

Shock recovery experiments to peak pressures of 460 kb have been carried out on three series of silicate glasses, namely, tektite, soda-lime, and silica. Our goal in carrying out these experiments has been to determine the changes in refractive index produced by shock densification in order to use these data to deduce the pressure and temperature histories of naturally shocked lunar and terrestrial glasses. The fused silica has been of special significance because of its simple composition and because other investigators have studied its shock densification and equation of state (e.g. *Arndt et al.* [1971] and *Wackerle* [1962]). Permanent increases in density of silica glass were first observed by *Bridgman and Simon* [1953] in static isothermal compression studies; they observed a threshold of densification of approximately 100 kb. Subsequent static high-pressure studies of fused silica by *Roy and Cohen* [1961], *Kennedy et al.* [1962], *Craig* [1969], and others have yielded similar results but with thresholds of densification of less than 60 kb. Recently, *Bless* [1970] observed comparable irreversible densification of fused silica in isentropic magnetic pinch experiments to more than 100 kb.

$SiO_4$ tetrahedra, which comprise fused silica, are the major network-forming polyhedra in all silicate glasses; the other glasses differ from fused silica by the presence of such network-modifying cations as $Mg^{++}$, $Fe^{++}$, $Ca^{++}$, $Na^{+}$, and $K^{+}$, which occupy possible 6-, 8-, and 12-fold sites in the irregular network. As those large cations are added to the silica glass, the threshold pressure of irreversible densification progressively decreases. We therefore suspected that shock compression of fused silica might generally provide a pattern for the behavior of the tektite and soda-lime glasses.

## Sample Preparation and Experimental Procedures

The glasses studied were tektite (indochinite IC298 from American Meteorite Laboratory), soda-lime (cover glass 19130 from Kimble (Exax)), and fused silica (General Electric schlieren grade type 151). Chemical compositions of the first two glasses were quoted in *Ahrens et al.* [1970]. Initial zero-pressure densities were 2.44 ± 0.02 g/cm³, 2.43 ± 0.02

[1] Contribution 1957, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena 91109. Lunar Science Institute Contribution 41.

g/cm³ (R. L. Fleischer, private communication to TJA, 1970), and 2.204 ± 0.003 g/cm³ (present study) respectively.

The samples were machined into thin wafers from which disks 4.75 mm in diameter were cored; the disks were ground and polished to a final thickness of 0.15 mm. The finished specimens were loaded into aluminum '2024' or stainless steel '304' cylindrical containers of 19-mm diameter and 7-mm thickness. The sample containers were in turn mounted into massive aluminum '2024' or stainless steel '304' cylindrical target blocks some 10 cm in diameter and 8 cm thick.

Shock waves were induced in the samples by impacting the target with 2.5-mm- and 5-mm-thick metal flyer plates of brass (Cu 65%, Zn 33%, Pb 2%) or tungsten alloy (W 90%, Ni 7%, Cu 3%) imbedded in the front surface of Lexan (plastic) projectiles. The projectiles were launched using the 1-meter-long, 2-cm-diameter Caltech propellant gun to velocities in the range of 0.4 to 1.5 km/sec. Projectile velocities were measured using a 'free-flight' method described by *Hörz and Ahrens* [1969].

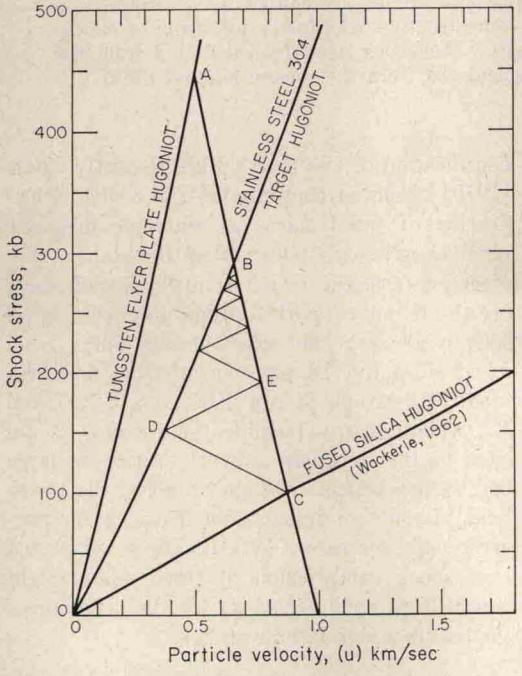


Fig. 1. Graphical representation of the 'impedance matching' method of determining shock pressures using as an example an impact of a tungsten flyer plate into a stainless steel target containing a specimen of fused silica at a free-flight velocity of 1 km/sec. *B* is the peak pressure attained in the target; *C* is the initial pressure in the fused silica. *CD, DE* represent shock reverberations in the fused silica that progressively increase its shock pressure until the peak pressure *B* of the target is reached. The time required to reach peak pressure is approximately 0.3 μsec.

The measured velocity, the Hugoniot of the target material, the Hugoniot of the flyer plate, and the Hugoniot of the sample were used in a graphical 'impedance matching' method of determining the shock pressure transmitted into the target and the sample (Figure 1 and *Duvall and Fowles* [1963]). From consideration of Figures 1 and 2, it is clear that for an impact at 1 km/sec of a tungsten alloy flyer plate into a stainless steel '304' target, shock-wave reverberations across the sample raised its pressure to the peak pressure of the target before a rarefaction wave originating from the black surface of the flyer plate caught up to and attenuated the peak shock stress. The period of maximum shock pressure in the samples, before rarefaction attenuation, was approximately 1 or 2 μsec; these values correspond to the two-way shock transit times through 2.5-mm and 5-mm flyer plates, respectively.

The accuracy of measurement of the projectile velocity is better than 1%. However, errors due to inaccuracy of the Hugoniot curves and application of the graphical impedance match solution increase the errors in the shock pressures to ±3%.

After shock loading, the sample containers were machined open to expose the shocked specimens. The character of the specimens varied from coarsely fractured to finely powdered. For refractive index measurements, some care was taken to remove sample material from the centers of the specimen disks, in case effects of the disk edges on the shock pulse might have resulted in a radial change in pressure. Refractive indices were measured by standard immersion techniques at Caltech and by interference microscopy at the laboratory of E. C. T. Chao, United States Geological Survey, Washington, D.C.

## EXPERIMENTAL RESULTS

The data on shock pressure and refractive index are given in Tables 1, 2, and 3 for tektite