glass, soda-lime glass, and fused silica, respectively. Graphical plots of these data (Figures 3, 4, and 5) correlate a range of refractive index within a specimen with the peak shock pressure to which the specimen was subjected.

For shock compression below 80 kb for fused silica and 40 kb for tektite and soda-lime glasses, the densification appears reversible, since the changes in refractive index 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 in the pressure range 80 to 230 kb, there is an equivalent decrease in index to the subinitial value $n = 1.5211$. Similar behavior is exhibited by fused silica shocked to pressures between 140 and 460 kb; however, for fused silica there is a refractive index plateau for material shocked to pressures between 140 and 300 kb, an index decrease of 0.025 for material shocked to pressures between 300 and 310 kb, and a low-density glass for material shocked to pressures up to 460 kb.

DISCUSSION

Figures 6 and 7 show the Hugoniot and release adiabat data for fused silica [*Rosenberg et al.*, 1968]. The Hugoniot data reflect the low-pressure, mixed-phase, and high-pressure regimes that *McQueen et al.* [1963] recognized as representing, respectively, fused silica, a mixture of fused silica and a high-density phase, and the high-density phase, presumably stishovite [*DeCarli and Milton*, 1965]. *Wackerle* [1962] recognized the Hugoniot elastic limit (HEL) of fused silica as 98 kb; the discontinuity that he observed at 262 kb represents complete transformation to some form of the high-density phase. Postshock densities were calculated from the measured refractive indices of fused silica using a modified Gladstone-Dale law:

$$(n - 1)/\rho = (n_0 - 1)/\rho_0 \qquad (1)$$

where n, n_o, ρ, and ρ_o are the initial and final refractive indices and densities, respectively. *Anderson and Schreiber* [1965] have found that refractive index–density relationships of silica polymorphs are quite close ($\pm 1.5\%$) to the Gladstone-Dale law at low density. Specific volumes calculated from the postshock densities range from 0.406 to 0.453 ± 0.004 cm^3/g; this range is comparable to that of the release-adiabat specific volumes illustrated in Figure 7 (these data are tabulated in Table 4). These

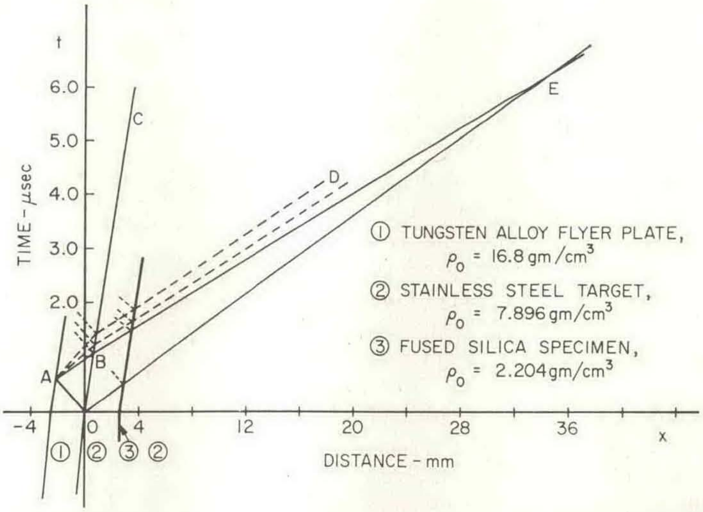

Fig. 2. x-t diagram of the impact of a 2.5-mm tungsten alloy flyer plate (1) against a stainless steel 304 target (2) containing a fused silica sample disk (3) OE is the trajectory of shock wave in the target, OA is the trajectory of shock wave in flyer plate, A is the pole of centered rarefaction wave, ABE and AD are rarefaction waves, and OBC is the trajectory of advance of flyer plate–target interface. Attenuation of the shock pulse in the sample starts at 1 μsec after the initial shock and 0.7 μsec after the sample has reached peak pressure.

TABLE 1. Refractive Index Measurements of Shock-Loaded Tektite Glass

Shot Number	Shock Pressure, kb	Refractive Index (n)
...	0	1.5051 ± 0.0002[a] 1.5055 ± 0.0005
119	43 ± 2	1.5060 ± 0.0005
120	56 ± 3	1.5087 ± 0.0005
122	53 ± 2	1.5065 ± 0.0005
123	32 ± 2	1.5055 ± 0.0005
124	28 ± 2	1.5055 ± 0.0005
142	133 ± 10	1.5419 ± 0.0002[a] 1.5404 ± 0.0005
143	38 ± 2	1.5065 ± 0.0005
144	42 ± 3	1.5075 ± 0.0005
152	112 ± 2	1.5247 ± 0.0002[a] 1.5265 ± 0.0005
145	83 ± 4	1.5137 ± 0.0007

[a] Measurements by interference microscopy; all others by standard immersion methods.

results indicate that there is some relationship between postshock density and range of stability of the different phases along the Hugoniot. At peak pressure, the recovered fused silica is not irreversibly compressed to a maximum density; the final state appears to be very dependent on the release-adiabat path from the peak pressure. It is interesting that adiabatic release from the highest shock pressure, 460 kb, results in a glass of lower postshock density, 2.27 g/cm^3, than release from 290 kb, 2.44 g/cm^3. This may arise by reconstructive transformation of a stishovitelike material to a high-density glass and subsequent annealing resulting from the high postshock temperature.

Besides annealing effects, the release-adiabat specific volumes that correspond to the ambient pressure, postshock temperature states will be slightly higher (by the thermal expansion) than those inferred from the room temperature index data. This difference is negligible (~ 0.2%) on the accuracy level of the present study.

We have observed reversible compression of the silica glass to 80 ± 3 kb; this result is compatible with the dynamic HEL value observed by *Wackerle* [1962]. A somewhat lower pressure threshold for permanent densification of less than 60 kb has been obtaind by *Bless* [1970] in magnetic pinch experiments under rapid isentropic conditions. *Arndt et al.* [1971] have studied samples recovered from single shock experiments and obtained an apparent elastic limit of 55 ± 5 kb; they also observed a decrease in refractive index for fused silica shocked to pressures of 140 to 200 kb (Figure 5). In our experiments, sample shock pressures were attained through multiple shock reflection rather than single shock (the 460 kb shock of *Arndt et al.* [1971] was also produced by multiple shock reflection). Differences between postshock temperatures calculated for the two techniques are illustrated in Table 5, compared with those calculated by *Wackerle* [1962] for single shock experiments on the basis of different assumptions about release adiabats.

As stated above, the tektite and soda-lime glasses are modifications of fused silica caused by the addition of large network-modifying cations; the elastic limits and permanent compressibilities of the glasses should be lower than those of fused silica because of the effects of such cations on the stability of the glass structural network of silica (plus alumina for the tektite and soda-lime) polyhedra. Our results do show the elastic limit (here taken to mean no irreversible compaction) to be 40 ± 5 kb for each of these glasses. *Dremin and Adadurov* [1964] observed a dynamic elastic limit (HEL) ranging from 36 to 73 kb, depending on sample thickness, for a soda-lime glass of only slightly different composition from ours; the data are obviously compatible.

The permanent densification observed for those glasses above their elastic limits may represent compaction like that observed under

TABLE 2. Refractive Index Measurements o Shock-Loaded Soda-Lime Glass

		Refractive Index (n)	
Shot Number	Shock Pressure, kb	Interference[a] Method	Immerson Method
...	0	1.5239	1.5242 ± 0.0005
IV	57	1.5275	1.5285 ± 0.0005
150	62 ± 2	1.5249	1.5275 ± 0.0009
151	79 ± 2	1.5367	1.5312 ± 0.0010
148	113 ± 2	1.5220	1.5230 ± 0.0010
147	118 ± 2	1.5229	1.5249 ± 0.0010
164	134 ± 3	1.5239	1.5233 ± 0.0009
167	230	1.5211	1.5211 ± 0.0011
179	93 ± 2	1.5261	1.5272 ± 0.0010
180	89 ± 2	1.5262	1.5266 ± 0.0010

[a] Error, ±0.0002.