different interpretations of the shock data which show a substantial loss of shear strength when sapphire is shocked above the HEL. These are:

1. a common high pressure compression curve, independent of the HEL values,
2. shock-velocity values substantially less than local bulk sound speed,
3. and measurements of the volume offset obtained when the high pressure data are extrapolated to zero pressure.

These same criteria are generally applicable to other materials in investigating shear strength effects.

(g) *Comparison with static data*

To this point the conclusions concerning the shear stress offset are based entirely upon the shock data. There are two static pressure measurements which can be used for an independent determination of the high pressure isotropic compression curve. Both of these are shown in Fig. 6.

The compression measurements of Hart and Drickamer[39] were accomplished with X-ray techniques in a high pressure anvil apparatus. Although the measurements show a large experimental error they can be used as a nominal guide to compressions at high pressure.

The most accurate measurements are the ultrasonic wave velocity measurements of Gieske and Barsch[36] to 10 kbar. Although these data must be extrapolated to significantly higher compressions, the determination of higher-order elastic constants in the elastic range show that the bulk modulus and its pressure derivative should give an accurate description of the compression to values used in the present experiments. The comparison of ultrasonic extrapolation and X-ray data show an appreciable difference but the difference is probably within the experimental error of the X-ray measurement.

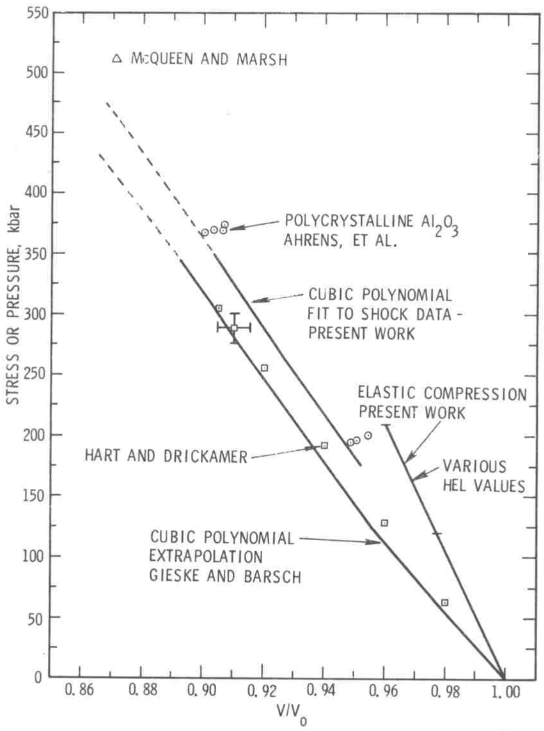

Fig. 6. Compression data for Al_2O_3 derived from various sources. The data obtained in the present investigation is shown by the various polynomial statistical fits. The data of Hart and Drickamer were obtained from lattice parameter determinations. Estimates of their experimental error are shown on one experimental point. The ultrasonic data of Gieske and Barsch measured to 10 kbar are extrapolated with a cubic polynomial to compare to the shock data. The point of McQueen and Marsh for single crystal Al_2O_3 is reported in Ref. [2]. The shock data on a high density Al_2O_3 is shown for comparison with the single crystal data. The cubic polynomial fails to give an accurate representation above a stress of 350 kbar and is shown by a dotted line for comparative purposes only. A logarithmic equation such as a Murnaghan equation gives an excellent correspondence between the data of the present work and that of McQueen and Marsh.

The temperature rise due to shock compression of sapphire is not appreciable because of the relatively small compressions involved. Accordingly, the thermal pressure correction computed from conservation of energy is not significant; amounting to about a 6 kbar correction at 400 kbar and about a 1 kbar correction at 150 kbar. These thermal pressure corrections are less than the experimental scatter and small compared to the offset between the static and shock data; hence, the correction has not been applied to the shock data.

The stress offset observed between the extrapolated ultrasonic data and the best fit to the shock data range from 38 to 43 kbar depending upon the pressure range where the comparisons are accomplished. Likewise the volume offsets are observed to range from 1·1 to 1·3 per cent. Similar offsets to the data of Hart *et al.* are 0·75 to 1·0 per cent and 25 to 38 kbar. These values for stress and volume offsets are in excellent agreement with the values derived from the shock data alone, yet grossly different from values predicted from the elastic–plastic theory and the measured HEL values. Thus, the direct comparison of the static and shock data also demonstrates that when sapphire is shocked to pressures greater than the HEL that a substantial loss of shear strength is observed.

A striking feature of both sapphire and quartz is that both materials show about a 1 per cent volume offset to the isotropic compression curve after a substantial loss of shear strength is experienced. Thus there may be some similarities to the condition of these materials after the loss of shear strength.

Because of the unusual character of the loss of shear strength it is not implausible that the thermodynamic treatment of the yield is inadequate. Unlike yield under elastic–plastic conditions which is analogous to a second order phase transition, the loss of shear strength is analogous to a first-order phase transition. For example, the shear strain elastic energy for sapphire at 200 kbar is 12 cal/g. The loss of shear strength on the time scale of the shock experiments will cause this energy to appear as thermal pressure with an average value of about 6 kbar. Although this pressure is about a factor of five too small to account for the observed difference between static and shock results, the possibility of severe local inhomogeneities due to failure along specific crystallographic planes might cause sufficient complications to cause concern as to the proper treatment of these thermal effects. In any event it appears that more detailed study of possible thermodynamic effects is warranted.

(h) *Hugoniot elastic limit values*

The unusually large HEL values observed for sapphire and the equally unusual loss of shear strength in the high pressure region suggest fundamentally different shear-failure mechanisms than observed for metals. It is, therefore, instructive to compare the maximum shear stress supported by sapphire to predictions of the theoretical shear strength, i.e., the inherent shear strength of the perfect crystal. Present capability for calculating the theoretical shear strength are not sufficiently realistic to give accurate estimates[40, 41]. However, most calculations give a lower bound to the shear strength of about 0·03 G, where G is the appropriate shear modulus. Experimental measurements of values for theoretical shear strength are limited to Brenner's measurements[42] on metallic whiskers which gave values of 0·027 G for Cu, 0·036 G for Au and 0·052 for Fe.

The largest HEL value observed in sapphire was 210 kbar which corresponds to a maximum shear stress of 83 kbar based on the atmospheric pressure elastic constants. This maximum shear stress value is 0·056 C_{44}; large enough to approach estimates of the theoretical shear strengths. The case for quartz is even more noteworthy since the highest HEL observed is 0·11 C_{44}. Thus, both sapphire and quartz exhibit shear strengths under shock compression which could reasonably be theoretical shear strengths and both sapphire and quartz lose shear strength and collapse toward an isotropic compression curve when shocked above the HEL.

On the basis of the limited data it is premature to suggest a general model for the loss of shear strength; however, it is worthwhile to examine the existing shock-compression literature for evidence of large HEL values and shear stress offsets. These data are collected in Table 4. There are reasonably complete