curve for copper. This material is easily studied because it has a low elastic limit, does not exhibit any transitions between crystalline phases, and is not subject to significant structural or compositional variation. The various reported investigations are summarized in table 3.4 and fig. 3.1. Related literature on shock compression of porous copper, elastic-plastic behavior of both mono- and polycrystalline samples, acoustic behavior, spall fracture, metallurgical effects, theoretical interpretation, and other matters is extensive.

The general agreement among the data plotted in fig. 3.1 is quite striking. In practice, most investigations cover only a small fraction of the range shown and, as indicated in the table, coefficients of straight-line fits through data on these short intervals can differ considerably even though the points themselves look well placed on the large graph. This suggests that caution be exercised in extrapolating data, even if it be granted that a linear relation is adequate.

A variety of experimental methods have been used in the reported investigations. The low-pressure range has been covered by contact detonation. At somewhat higher pressures, explosively-driven flying plates have been used. The range to 450 GPa has also been covered using gun-driven

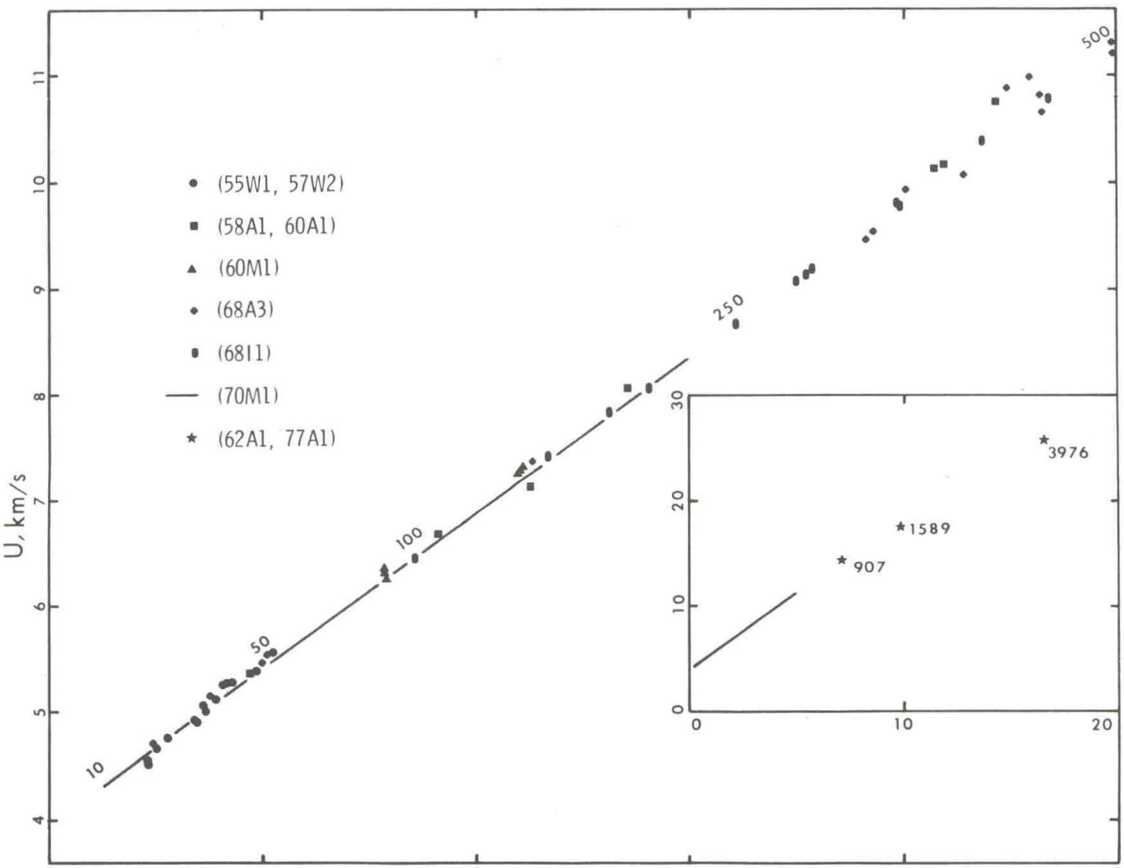

Fig. 3.1. High-pressure (U, u) Hugoniot data for copper obtained by several investigators. The numerals along the curve indicate pressures in GPa. The line on the small inset figure represents the entire range of the larger figure, while the three points represent the results of Soviet ultrahigh pressure experiments (see table 3.4).

impactors. The high-pressure experiments of Argous and Aveillé have employed flying plates driven by a spherical implosion. Al'tshuler et al., have failed to report any details of the loading method used to obtain their 907 GPa point, except that an iron impactor driven at 14.68 km/s was used. These data, if augmented by various elastic-plastic data discussed elsewhere in this review, cover the entire range of compression to 2.854 times normal, i.e., to a density of 25490 kg/m^3.

The most recent Hugoniot curves from the United States [68I1, 70M1], the Soviet Union [77A1], and France [68A4] agree to 1 per cent at 50 GPa; the United States and Soviet Hugoniot curves agree to 0.1 per cent. It should be noted, however, that two of the Hugoniot curves given in table 3.2 are in serious disagreement with the others. These latter curves also disagree with extrapolations of static and ultrasonic data. (Ultrasonic measurements of Barsch and Chang [67B2] suggest the Hugoniot curve $U = 3916 + 1.62u$.) A systematic error seems to have occurred in the collection or processing of these data and they serve to exemplify the need for careful evaluation and cross-checking of any data before they are used.

3.2.2. Shock compression of porous solids

The principal Hugoniot curve of a substance is a single locus on its equation-of-state surface. To locate the entire surface, other state points must be determined. This has been done by shock compression of porous samples and by multiple-shock compression.

As indicated in fig. 3.2a, shock compression of loosely-compacted powder or other distended material to a given pressure gives rise to larger thermal effects than compression of the same material from its normal solid form to the same pressure. By varying the initial distention, it is possible to produce a family of widely separated Hugoniot curves, as illustrated in fig. 3.2b. The temperatures achieved can easily exceed several thousand kelvins and the associated thermal pressures are sometimes so great that the density of the shock-compressed material is less than the normal density of the cold solid.

Zel'dovich [57Z1] was the first to call attention to the behavior of porous materials under shock compression, and to point out that the knowledge of a family of Hugoniot curves corresponding to various initial distentions would suffice for decomposition of the pressure at a given specific volume into its cold and thermal components. This method was adopted by Al'tshuler [58A1] and, in a more comprehensive investigation, by Krupnikov et al. [62K2, see also 65A2]. Some work has been done since this time [70M1, 71N1, 76B1] but the technique has not been widely used.

All states achieved by shock compression of distended solids lie at higher internal energy than states on the principal Hugoniot curve, i.e., they have higher pressure for a given specific volume. When interest lies with temperature effects such as anharmonicity or excitation of the electron gas in metals, study of the behavior of distended solids is indicated. When interest lies with measuring such effects of compression as the volume dependence of Grüneisen's parameter, these experiments have the disadvantage that they not only fail to provide access to states of the highest possible density, but also produce thermal effects that serve to complicate interpretation of the volume dependencies.

Experimental investigation of distended materials presents special difficulties and requires unusual care in design of the test assemblies. Precision is very important in this work because interest usually lies not only with the position of the Hugoniot curves, but with differences in position of adjacent curves. Early concern that a steady shock would be slow to evolve in coarse-grained material has been alleviated [62K1, 70B4] but thermal equilibration may still not have been achieved and many practical experimental problems remain.