The first apparatus to produce and measure transverse displacement histories was developed by Abou-Sayed et al. [76A1, 76A2]. Direct measurements of transverse velocity histories were later reported by Gupta [76G5] and by Koller and Fowles [79K2]. Abou-Sayed et al. impacted an inclined-face projectile on a similarly inclined sample, with both impact velocity and angle of inclination varied to produce a range of combined longitudinal and transverse motions. A similar approach has been used by Gupta [78G6] to induce pressure and shear waves in an epoxy sample.

Combined motions are also encountered in crystals subjected to normal impact when the direction of wave propagation is not a "specific" direction [65B4]. Johnson [71J1] and Luzin [75L1] have given a linearized analysis of this problem and Kim et al. [77K2] and Chhabildas et al. [79C1] have recently made such measurements on Y-cut quartz. It has been shown in this latter work that the strong transverse waves generated in the quartz can be introduced into other materials to study their response to shear. A recent symposium on transverse waves is summarized in Bull. Am. Phys. Soc. 24 (1979) 715.

3.2. Hydrodynamic approximation to the behavior of solids

When the strength of a shock greatly exceeds the maximum shear stress that a material can sustain, the differences among the principal stress components (the shear stresses) in the compressed material are small relative to their average value, which is the pressure, p. The neglect of this relatively small shear stress reduces consideration of the response of a solid to that of an inviscid fluid and is called the *hydrodynamic approximation*. The validity of this approximation involves the two rather separate issues of (1) whether the thermodynamic properties of the material are adequately approximated by relations derived from an energy density function depending on specific volume and temperature or entropy density (see section 3.2.4), and (2) whether the influence of the shear stress, rate effects, etc., that are being neglected have a negligible effect on the mechanical behavior of the material in a given circumstance. Certain phenomena, such as attenuation of stress pulses, are profoundly affected by shear stresses having negligible thermodynamic consequences.

Investigations of the behavior of solids in the hydrodynamic regime form the oldest and most fully-developed branch of the subject of shock compression of solids. Various aspects of this work have been reviewed by Rice et al. [58R1], Al'tshuler [65A2], Zel'dovich and Raizer [66Z1], Zharkov and Kalinin [71Z2], McQueen et al. [70M1], Royce [71R1], Duvall [73D5], and in several of the other works mentioned in section 1.1.

The hydrodynamic model is used to interpret data obtained in most shock-compression experiments conducted at applied stresses that are an order of magnitude or so greater than the static yield strength of the material. For a typical metal this threshold may be 10 to 20 GPa. In this section, material behavior at pressures ranging from this rather ill-defined lower limit to the upper limit of the experimental measurements, presently about 6000 GPa, is considered.

Stresses in the lower part of the hydrodynamic regime, say from 10 to 50 GPa, were first produced by detonation of explosives in contact with the material under investigation. This limit was raised to about 250 GPa when investigators began to impact samples with thin plates accelerated to high velocity (~ 5 km/s) using explosives. A further increase to over 500 GPa occurred when convergent geometries were employed [62S2, 68A4]. Soviet investigators have reported measurements in the range 300–1000 GPa; they have not described the methods by which these pressures were produced but it appears that convergent detonation waves were used. With the development of gun technology, stresses covering the range from about 0.1 to over 600 GPa became accessible to well-controlled plane-wave experiments [68I1, 74M2, 75M1, 79M1]. The highest pressure experiments conducted in the United States [77R1] have used underground nuclear explosions and the same is undoubtedly true in the Soviet Union [68A3]. Preliminary investigations have been conducted of the feasibility of applying large pulsed lasers [78V1, 79T3] and electron beam accelerators intended for fusion energy research to the production of strong shocks. The use of small projectiles accelerated to very high velocity by electrically vaporized metal foils is also being considered [78S5].

3.2.1. Hugoniot data

High-pressure Hugoniot data have been obtained for some hundreds of materials. This work has been done over a span of thirty years and in laboratories scattered throughout the world. Most of the lower-pressure data, say from 10–200 GPa, have been obtained by J.M. Walsh, M.H. Rice, R.G. McQueen, J.N. Fritz, J.W. Taylor, S.P. Marsh, W.J. Carter, and others at the Los Alamos Scientific Laboratory [69G2, 70M1]. Most data for shocks stronger than this have been reported by L.V. Al'tshuler, A.A. Bakanova, S.B. Kormer, R.F. Trunin, and others in the Soviet Union [65A2, 77A1]. The experimental methods of the Los Alamos group have been described in considerable detail [70M1] but the Soviet workers have not provided a similarly detailed description of their techniques.

The "Compendium of Shock Wave Data", compiled by van Thiel et al. [77V1] is a reasonable place to start in any search for high-pressure Hugoniot data. The data contained in these volumes have not been critically reviewed, however, and this necessary step must be taken by the user. Some references to recently published data are given in table 3.3. This list is not comprehensive, but gives a selection of summary data, recent works where other references can be found, data on materials of special interest, etc.

Any discussion of experimental measurement must include some consideration of errors. Formulae for the relative error in inferring pressure and density of the shock-compressed material from measurements of U and u are easily derived [58A1, 68A3]. When measurements involve the use of equations of state for other materials, rational analysis of errors is possible, but becomes complicated and remains somewhat subjective. Each case requires careful, individual consideration if a convincing estimate is to be made. Most investigators estimate the precision of their recent particle and/or shock velocity measurements to be about 1 per cent. This corresponds to an error of about 0.5 per cent in compression and 2 per cent in pressure. In addition to these errors of measurement, Hugoniot data are subject to a variety of errors of interpretation, as discussed in section 3.2.4.

For most purposes it is convenient to smooth, summarize, and interpolate Hugoniot data by fitting a smooth function, the *Hugoniot curve*, through them. When the coordinate is chosen so that $U > 0$ and $u^+ = 0$, this curve can usually be the straight line: $U = a + bu$ of eq. (2.16). This linear relation does not describe liquids or porous metals satisfactorily, and the addition of a small quadratic term improves the representation of some other data. When materials undergo shock-induced transformations from one crystalline phase to another, the Hugoniot curve exhibits a discontinuity or change of slope, but data in the separate intervals above and below the transition are often accurately represented by linear relations. Numerous investigators have remarked on the widespread validity of the linear representation of the (U, u) Hugoniot, and the matter of its generality and significance has been discussed [67R4, 71S3]. No fundamental explanation has been given for the linearity, however, and both experimental data and theoretical considerations