to realism concerning difficulties in interpreting measurements and the necessity for more detailed measurements if scientifically useful data are to be obtained. In this review, we hope to bring the present state of knowledge of shock-induced phase transition into perspective in hopes that major problems will come into focus for further work.

The results of experimental observations of shock-induced transformation are shown in Tables AI and VII of this review. Some discussion of these results is contained in Secs. IV and VI. Section II provides an introduction to the necessary mechanics, thermodynamics, and kinetics of shock-wave propagation; Sec. III describes various experimental methods used to study transformation; and Sec. VII contains concluding remarks and some suggestions for future efforts.

If the reader is totally unfamiliar with shock-wave phenomena and experimentation, he may find it helpful to consult some general references (Duvall, 1968; Duvall and Fowles, 1963; Al'tshuler, 1965; Zeldovich and Raizer, 1966 and 1967; Glass, 1974; Courant and Friedrichs, 1948).

II. MECHANICS OF SHOCK-WAVE PROPAGATION

A. Stress and strain conventions

We shall be dealing almost exclusively with plane waves in one space dimension. Cartesian coordinates are used with x axis in the direction of propagation. All equations will refer to mechanically isotropic materials. Shock waves in anisotropic elastic and plastic media have been treated (Pope and Johnson, 1975), but effects of anisotropic properties on phase transition phenomena have received little consideration though they appear to exist, even at relatively high pressure (Fritz *et al.*, 1971). Materials of interest are solids or viscous fluids, so shear stresses commonly exist. Diagonal stress components will be exclusively compressive, so it is convenient to follow the practice of fluid dynamics and use the pressure tensor p_{ij}, which is the negative of the stress tensor σ_{ij} commonly used in solid body mechanics[2]:

$$p_{ij} = -\sigma_{ij} . \tag{1}$$

With the coordinate convention described above, x, y, z are principal coordinates; off-diagonal components of p_{ij} vanish, and diagonal components can be described by a single subscript: $p_x \equiv p_{xx}, p_y \equiv p_{yy}, p_z \equiv p_{zz}$. Because of the symmetry of one-dimensional plane waves, $p_y = p_z$. No motions parallel to wave fronts will be considered, so the only nonvanishing component of strain is $\eta_x \equiv \eta_{xx}$; this is called a "state of uniaxial strain."

The only pressure component normally measured in experiments with plane shock waves is p_x, which can be looked upon as composed of mean pressure,

$$\bar{p} = (p_x + p_y + p_z)/3$$
$$= (p_x + 2p_y)/3 , \tag{2}$$

and a shearing stress τ. This useful resolution is a simple identity:

$$p_x = (p_x + 2p_y)/3 + 2(p_x - p_y)/3$$
$$= \bar{p} + 4\tau/3 , \tag{3}$$

where

$$\tau = (p_x - p_y)/2 . \tag{4}$$

Often called "maximum resolved shear stress," τ is shear stress on planes with normals at 45° to the x axis. When dealing with hydrodynamic states, or when shock-wave results are to be compared with static measurements, $\bar{p}$ will be identified with hydrostatic pressure P.

B. Equations of propagation

The differential equations of motion and mass conservation in one-dimensional plane geometry are

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial p_x}{\partial x} = 0 , \tag{5}$$

$$\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} = 0 , \tag{6}$$

where ρ is mass density and u is particle velocity. Another quantity commonly used is specific volume,

$$V \equiv 1/\rho . \tag{7}$$

The equation of energy conservation, when combined with Eqs. (5) and (6), reduces to the first law of thermodynamics:

$$\frac{dE}{dt} = -p_x \frac{dV}{dt} + \frac{dQ}{dt} , \tag{8}$$

where E is internal energy per unit mass, dQ is heat added per unit mass, and $d/dt = \partial/\partial t + u\partial/\partial x$ is the convective derivative. Equations (5), (6), and (8) are often called "the flow equations."

The flow equations do not of themselves define a physical problem. The description of the material in which propagation is to occur and initial and boundary conditions serve to complete the problem definition. The material description is stated as a set of *constitutive relations*. In the simplest case this set is the equation of state alone. More generally it includes equations describing various irreversible and rate-dependent processes important to the problem at hand. For example, constitutive relations for a ductile solid would include an equation of state, specification of the yield stress, specification of the plastic flow rule following yield, and a recipe for calculating shear stresses. The equation of state might consist of a relation among P, V, E, but is not necessarily limited to such a relation.

The simplest problem of shock-wave propagation is that in which a uniform pressure P_1 is suddenly applied to the surface of half-space and thereafter held constant. Figure 2 portrays the resulting flow field for a simple

[2] Writers on shock-wave problems sometimes use the term "stress" to denote the term p_{ij} and the term "pressure" to denote mean pressure $\bar{p}$ and hydrostatic pressure P alone. Since some of the figures in this paper are derived from other work, coordinates are sometimes labeled "stress" to indicate that the quantity being plotted is p_x, not $\bar{p}$ or P. Whether "pressure" or "stress" is used, the quantity is positive in compression.

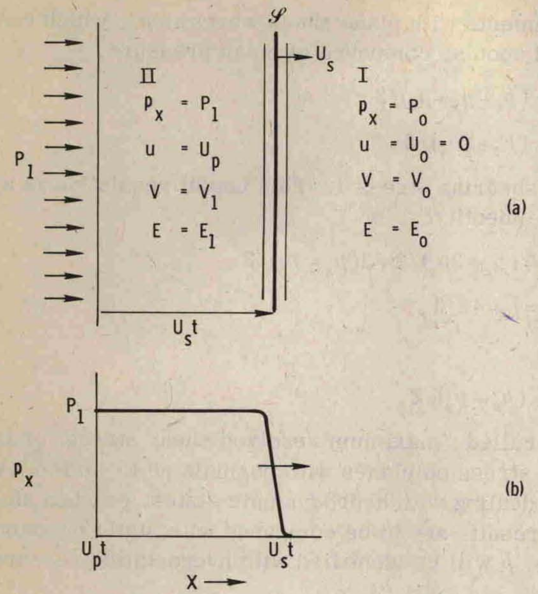

FIG. 2. A uniform pressure is applied to the plane surface, $x=0$, at $t=0$. (a) After time t the shock front divides the space into two uniform regions: I, undisturbed, and II compressed and accelerated. (b) $p_x(x)$ at time t. $\mathcal{S}$ is the shock front. The relation between P and V is shown in Fig. 3.

fluid with the isentropic compression curve shown in Fig. 3. In Fig. 2(a) is shown a section of a half-space to the surface of which a constant pressure P_1 has been applied since zero time. The shock front $\mathcal{S}$ is a region of rapid but not discontinuous change of state variables. It divides the half-space into two regions: I, in which the effects of applied pressure P_1 have not yet been experienced, and II, which is a constant state between surface and shock front. The corresponding pressure profile is shown in Fig. 2(b). Constitutive relations in this case consist of a single equation, $P=P(V,E)$.

If the shock front of Fig. 2 is unchanging in form as it propagates, the flow equations can be reduced to a set of jump conditions connecting compressed and undisturbed states (Band and Duvall, 1961):

$$P_1 - P_0 = (U_s - U_0)(U_p - U_0)/V_0\,, \tag{9}$$

$$1 - V_1/V_0 = (U_p - U_0)/(U_s - U_0)\,, \tag{10}$$

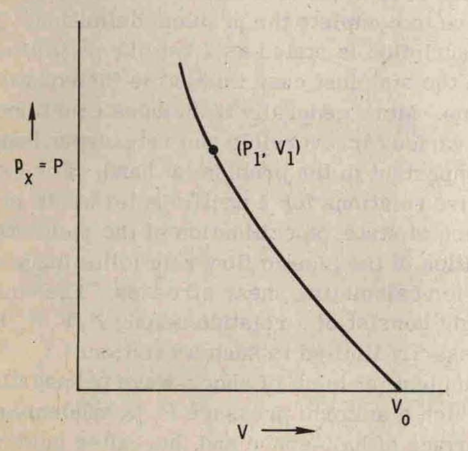

FIG. 3. Isentropic compression curve for a normal liquid.

$$E_1 - E_0 = (P_1 + P_0)(V_0 - V_1)/2\,. \tag{11}$$

Here U_s is propagation velocity of the shock front; U_0 and U_p are particle velocities ahead of and behind the shock, respectively. Equations (9)–(11) apply even if connected states are not uniform, provided the shock front is a discontinuity in P, V, U_p, and E (Courant and Friedrichs, 1948). As a practical matter, the jump conditions are assumed to apply if field variables are changing much more rapidly in the shock front than before or behind it. Some caution must be exercised in defining shock propagation velocity if the shock front is not steady (Barker, 1975). If resolved shear stresses are significant, hydrostatic pressures P_1 and P_0 are replaced by p_{x1} and p_{x0}. The thermodynamics of compression are then complicated by irreversible processes like plastic flow and fracture (Duvall, 1973).

Equation (11) is called the "Rankine–Hugoniot Equation." When combined with an equation of state of the form $E_1 = E(P_1, V_1)$, and P_1 is varied, it produces a set of curves in the (P, V) plane, one for each set of initial points (P_0, V_0). The curve through (P_0, V_0) is said to be "centered" at P_0, V_0 and is known variously as the "Rankine–Hugoniot $P-V$ curve," "Hugoniot $P-V$ curve," "Hugoniot" or "R–H curve" centered at P_0, V_0. It will be called R–H curve in this review. The shock process is adiabatic but not isentropic (Courant and Friedrichs, 1948). The R–H curve lies above the isentrope centered at the same point. It is usually called the "shock adiabat" or "dynamic adiabat" in Russian literature.

Equations (9) and (10) can be combined to give expressions for U_s and U_p in terms of P_1, V_1, P_0, V_0, and U_0:

$$U_s - U_0 = V_0[(P_1 - P_0)/(V_0 - V_1)]^{1/2}\,, \tag{12}$$

$$U_p - U_0 = [(P_1 - P_0)(V_0 - V_1)]^{1/2}\,. \tag{13}$$

The R–H curve centered at P_0, V_0 thus maps into a curve in the $U_s - U_p$ plane. This is also called an R–H curve and provides a convenient representation of shock-wave data when U_s and U_p are measured quantities, which is frequently the case. In the absence of phase transformations, the U_s vs U_p curve can usually be fitted to a straight line:

$$U_s - U_0 = C_0 + s(U_p - U_0)\,, \tag{14}$$

where C_0 is equal to, or very nearly equal to, the bulk sound velocity at $P = P_0$, s is the slope of the $U_s - U_P$ relation, and

$$C_0 = \sqrt{K_0 V_0}\,, \tag{15}$$

where K_0 is bulk modulus at P_0.

Elimination of $U_s - U_0, U_p - U_0$ from Eqs. (12)–(14) yields a form of $P-V$ relation frequently used to describe R–H curves:

$$P - P_0 = \frac{C_0^2(V_0 - V)}{[V_0 - s(V_0 - V)]^2}\,. \tag{16}$$

Temperature in a shock wave can be calculated by integrating the differential equations of the R–H curve (Duvall, 1973) or by comparison with temperature on the isentrope at the same volume (Goranson *et al.*, 1955; Duvall and Zwolinskii, 1955). Temperature on the isentrope through the initial state is given by the expression: