$$S_L - S_1^T + C_V \ln(T^T/T_L) + \Gamma\rho C_V(V - V_L) = (V_2^T - V_1^T)dP/dT, \tag{73}$$

$$E_L - E_1^T - P_L(V_2^T - V_L) - f(V_2^T; V_L) + \Gamma\rho C_V T_L(V - V_L) + C_V(T^T - T_L) = (V_2^T - V_1^T)(-P^T + T^T dP/dT). \tag{74}$$

The above procedures for determining ΔV and the equation of state of the second phase are simple to describe, but it is not evident that they are easy to use. McQueen *et al.* (1967, 1970) and Carter (1973a) have made extensive second-phase calculations. McQueen *et al.* choose the reference point to be at ambient temperature and pressure in the metastable region of phase 2. The reference curve of compression is assumed to be the R–H curve through this ambient point, characterized by a linear $U_s - U_p$ relation:

$$U_s = C_0 + sU_p. \tag{75}$$

Density at the ambient point, C_0 and s are then adjusted by trial and error until the observed R–H curve in phase 2 is reproduced. They have shown that changes in initial density translate the recalculated R–H curve in the $U_s - U_p$ plane, changes in C_0 rotate it, and changes in s influence its curvature. The entire calculation is carried out numerically and its use is simple when computer programs have been established.

These procedures for estimating equation of state of the second phase produce uncertainties arising from estimates made for C_V and Γ. There are additional unassessed errors because of the difference between p_x, which is measured, and P, which is used in the theory, as indicated earlier in Sec. II. Other errors result from the difference between transition pressure measured in shock compression, p_x^{TL} or $\bar{p}^{TL}$, and equilibrium transition pressure $\bar{p}^T$, to be discussed in Sec. IV.

III. EXPERIMENTAL TECHNIQUE

A. Introduction

Theory of the mechanics, thermodynamics, and finite transformation rates associated with shock-induced polymorphic phase transformations can be used to predict basic features of the phenomena and as a framework for interpretation of experimental results. Nevertheless, the assumptions underlying present theory are expected to lead to oversimplified descriptions of real material behavior, and experimental observations must play a leading role in the development of improved understanding of shock-induced transformations. This section contains a summary of experimental techniques that have been used to probe the characteristics of transformations. No attempt will be made to provide a comprehensive picture of shock loading techniques. More comprehensive reviews of techniques (Graham and Asay, 1977; Fowles, 1973) or individual research papers may be consulted for experimental details, which are often important to the interpretation of measurements. Loading methods and measurement techniques will be briefly described after some general underlying considerations are presented.

The determination of characteristics of a transformation is impeded by very-high-pressure transient characteristics of the experiment. The chaos perceived by the naked eye and ear is avoided in shock loading experiments that are designed to be completed in the few nanoseconds or microseconds of time for which a sample is subjected to well-controlled uniaxial strain produced by plane loading over a large area. This limited time scale, the need for uniaxial configurations, and the destructive nature of the experiment prohibit or severely limit measurements that are commonplace at atmospheric pressure or in static high-pressure studies. Development of a measurement technique is often a lengthy and involved process; as a result, shock probes, although sophisticated, are not yet able to use many tools of modern solid-state physics. In spite of these difficulties, the ability to readily achieve very high pressures and the ease with which pairs of stress-volume states can be determined have stimulated numerous experimental investigations of shock-induced transformations.

Most of our knowledge about shock-induced transformations is derived from measurements of shock and particle velocities produced by well-controlled loading. These quantities are sensitive to stress-volume states of the sample material since they are direct manifestations of inertial reaction to the loading. Their interpretation is complicated by plastic deformation and by temperature increases which accompany shock compression.

Electrical measurements have been successfully used to indicate the onset of transitions under static high pressure. Similar measurements under shock compression have been of limited value owing to complications of the environment. For example, interpretation of electrical resistance measurement under shock loading is complicated by difficulties of achieving *in situ* measurements and by plastic deformation. Since resistivity is sensitive to defects, the massive and varied defects produced by shock loading are hard to untangle from other effects. Magnetization change, on the other hand, is less sensitive to defects, but measurements have been limited to a few ferromagnetic alloys. Although there is promise for improvement in electrical probes of shock-induced transformations, their contributions to date have been minimal and most experimental results have been obtained from detection and analysis of stress profiles resulting from well-controlled loading.

B. Loading methods

Shock-wave loading systems are designed to apply loads over large plane areas of samples so that the sample is maintained in a state of uniaxial strain for sufficient time for measurements to be completed. As high-pressure loading waves interact with lateral boundaries, lateral release waves propagate inward and reduce pressures as they arrive at interior locations. This means that samples must have large diameter-to-thickness ratios, with diameters which typically range from 25 to 300 mm. Observations are then limited to central regions of the sample. Total durations of experiments are typically 1 μs; hence loads must be applied simultaneously over a sample surface within times

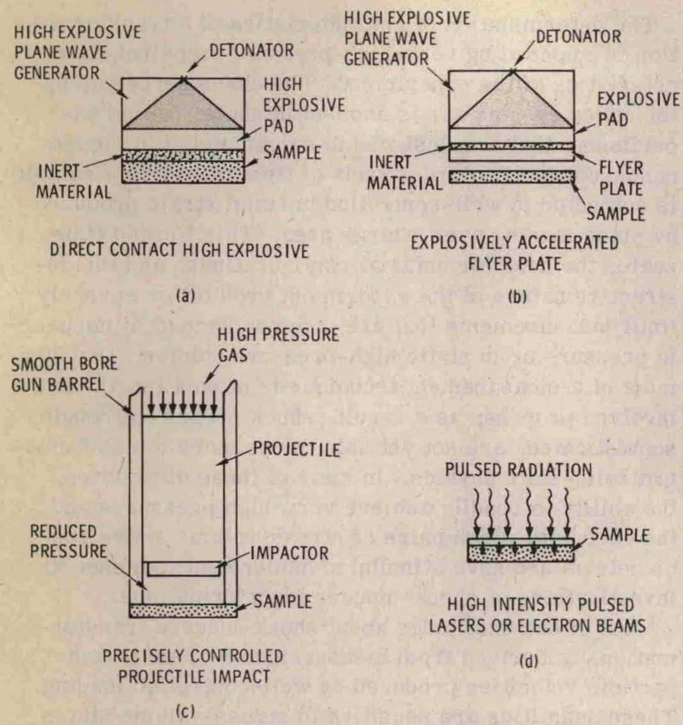

FIG. 15. The methods most commonly used to apply shock loading to samples are shown. In all cases the loading methods introduce waves into samples over diameters from 25 to 300 mm with simultaneity of about 10 ns.

of about 10 ns. It is also desirable that the loading system maintain a constant pressure input whose amplitude can be easily changed from experiment to experiment and whose duration can be easily controlled.

Loading methods in widespread use are shown in Fig. 15; each will be briefly described in turn. Less attention will be directed toward explosive loading since it has been described in recent reviews (Fowles, 1973; McQueen *et al.*, 1970). Actual input pressure values and profiles in a sample depend explicitly on sample properties; values quoted are representative only.

1. Contact explosives [Fig. 15(a)]

The first quantitative scientific shock loading experiments were made possible by fabrication of high explosive lenses that produce plane shock waves over diameters up to about 300 mm (see the comprehensive treatment of data obtained with these systems in Rice *et al.*, 1958). These plane-wave generators, with various explosive pads, produce pressures in aluminum samples in the range 10 to 40 GPa under relatively routine conditions. Pressure imparted to a sample depends upon the particular explosive material and mechanical impedance of the sample. Typical pressures in aluminum are 17 GPa with Baratol, 24 GPa with TNT, 35 GPa with Composition B, and 40 GPa with Octol (Deal, 1962; Los Alamos, 1969). Special nitroguanidine lenses have been developed to produce pressures of 4 GPa in aluminum (Benedick, 1965). The contact explosive loading method has been widely and successfully used but several disadvantages have led to development of other techniques.

Direct contact explosives have limited capacity to produce pressures less than 10 GPa and more than about 40 GPa in materials with impedances like aluminum. Accordingly, projectile impact techniques were developed for lower input stresses, and explosively accelerated flying plates were developed for higher-pressure experiments. Other disadvantages of direct contact explosives relate to the difficulty of varying input pressure in small increments and lack of control on pressure release. Furthermore, the ability to fabricate explosive lenses is limited to a few laboratories, and the large amount of explosive material detonated in an experiment requires special experimental ranges.

2. Explosively accelerated flyer plates [Fig. 15(b)]

To achieve higher pressures, plane-wave generators are used with explosive pads to accelerate flyer plates to high velocities as shown in Fig. 15(b). Separation of the explosive from the flyer plate by a thin plastic insert or a thin air space reduces peak pressure in the flyer plate and damage to and heating of the plate are minimized. In order to maintain planarity and integrity of the plate, the free run distance to impact is typically a few centimeters, i.e., a small fraction of its diameter. Typical impact velocities range from 1 to 7 km/s and produce pressures in aluminum from 10 to 100 GPa. For materials of higher impedance, such as iron, pressures of several hundred GPa are achieved. Systems of this type are described by McQueen *et al.* (1970). The flyer plate velocity can be measured near the plane of impact, providing an additional measured experimental parameter.

3. Projectile impact [Fig. 15(c)]

During the past ten years, impact loading with precisely controlled projectiles accelerated in smooth-bore guns has become a widely used method of shock-wave loading. Originally developed for research at low pressures, guns have now been developed to achieve the same maximum pressures produced by explosive loading (Isbell *et al.*, 1968).

A precisely dimensioned projectile is faced with the desired impacting material, smoothly accelerated in vacuum through a distance of many projectile lengths, and allowed to strike its target in a plane impact with precise alignment of impacting surfaces. For given impactor and target materials the stress produced at impact increases monotonically with impact velocity. If impactor and target are of the same material, the impact is called "symmetric." Then particle velocity imparted to the sample is exactly one-half the projectile velocity. Since projectile velocity may easily be measured with an accuracy of 0.1%, the symmetric impact experiment provides the most precisely known input conditions of any shock-wave loading experiment.

The principal problem in impact experiments is maintenance of alignment of the impacting surfaces. Limits on allowed misalignment, called "tilt," vary with impact velocity, but tilt values of 500 μrad are normally acceptable for projectile velocity of about 1 km/s.

Compressed gases or propellants are used to accelerate projectiles to the desired velocity. Compressed gas has been more widely used because it is cleaner,