subject to closer control, and more convenient for a conventional laboratory operation. Projectile velocity is varied continuously by varying gas pressure or powder charge and projectile mass.

All guns are custom made (Thunborg *et al.*, 1964; Taylor and Rice, 1963; Halpin *et al.*, 1963; Barker and Hollenbach, 1964; Linde and Schmidt, 1966; Fowles *et al.*, 1970), but bore diameters of 63.5 and 102 mm are common. Bore diameter determines maximum sample size; hence larger bores are used when thicker samples and longer observation times are essential. Barrel lengths range from 3 to 24 m.

Projectile velocities range from 30 m/s to 1.5 km/s with compressed gas guns, up to 2.3 km/s with guns driven by chemical propellants, and up to 8 km/s with two-stage light gas guns (Jones *et al.*, 1966). A recently developed drop weight impactor has produced precisely controlled impacts from 0.9 to 3.5 m/s with tilt at impact of 10 μrad (Flinn *et al.*, 1975).

In an impact experiment the input pulse duration is controlled by thickness of the impactor. If the impactor surface opposite the impact face is backed with air or a low impedance material, the shock wave from the impact surface reflects, reduces pressure, and propagates back through the impactor into the sample. Such unloading wave experiments are becoming increasingly important for probing sample response in high-pressure states.

4. Pulsed radiation [Fig. 15(d)]

Pulsed radiation has not been widely used to investigate shock-induced phase transformations, but the intense radiation pulses from lasers and electron beams have been used effectively in other material property studies. Deposition times may be short enough that absorption of radiation occurs under conditions of essentially constant volume, producing large stresses and high temperatures (see, for example, Gauster *et al.*, 1973).

5. Special loading configurations

The impedance match (McQueen *et al.*, 1970) and quartz gauge impactor (Ingram and Graham, 1970) configurations are special variations in loading methods which are widely used. The impedance match method is based upon determination of shock velocity, particle velocity, and compression characteristics of standard materials. Some standard materials are 2024 aluminum alloy, 921-T aluminum alloy, copper, iron, and a uranium–molybdenum alloy (McQueen *et al.*, 1970). Loading is applied to the standard material, and measurement of shock velocities in the standard and the sample is sufficient to establish pressure and particle velocity in the sample. Use of the standard material eliminates the need to measure particle velocity, which is the more difficult measurement.

Use of a quartz gauge mounted on a projectile as an impactor makes it possible to directly determine stress and particle velocity histories at the impact interface, provided impact stress in the gauge does not exceed 4.0 GPa. A facing of sapphire on the quartz permits measurements to 8.0 GPa, and a facing of tungsten carbide permits measurements to 15 GPa. The technique is especially useful for study of materials that propagate complex wave profiles, for experiments at elevated temperatures, or for materials with time-dependent responses. The quartz impactor may be combined with more conventional rear surface measurement of propagated wave profiles to provide detailed knowledge of both input and propagated stress profiles.

C. Measurement techniques

In a typical shock experiment the sample is loaded in uniaxial strain to the desired input pressure and response of the sample is determined with detectors whose response characteristics have been determined beforehand. Most measurements are directed toward determination of pairs of shock-wave velocity and particle velocity values at critical locations on wave profiles. Detailed descriptions of the various detectors are unnecessary here; but technique is still a crucial element in establishing our knowledge of properties under shock loading conditions, and major features of the detectors are noted. A summary of detectors which have been used for phase transition studies is given in Table I.

Shock velocity is determined by detecting times of arrival of the wave at two or more stations at known locations. This is conceptually simple, but large errors are easily introduced if, for example, care is not taken to control or determine tilt of the wave in the plane of the detectors and to determine response times of detectors. In many experiments, arrival times must be determined within a few nanoseconds to achieve suitable accuracy in the derived shock velocity. As indicated in Table I, methods for discrete determination of arrival time include charged pins and argon flash gaps that luminesce when shocked to high pressure.

These same discrete arrival time detectors can be used to determine particle velocity in experiments in which the wave is reflected from a free surface and arrival time of the free surface is measured as it moves outward and contacts detectors at discrete locations. Since total free surface displacement is usually much smaller than sample thickness, free surface measurements are more difficult than shock velocity measurements. Free surface velocities are obtained by differentiation of the displacement versus time data, and particle velocity may be taken as one-half the free surface velocity; corrections to this approximation are made as required (Walsh and Christian, 1955). More accurate determination of particle velocity is obtained if detectors are used to determine impact velocity in a symmetric impact configuration.

An example of U_s vs U_p data obtained with flash gaps in the impedance match configuration is shown in Fig. 16. A phase transformation in NaCl should be characterized by a horizontal line, under ideal conditions, since flash gaps detect only the arrival time of the first wave (cf. Sec. II.D). Transition pressure and volume are computed from the $U_s - U_p$ point where there is a substantial break in the behavior. Such a break is fairly clearly indicated for [111] data; the situation for [100] data is uncertain.

If a single shock wave of constant amplitude is to be

TABLE I. Experimental techniques used for detection of shock-induced phase transformations.[a]

Displacement versus time—discrete measurements	
1. Electrically charged pins	Minshall, 1955b
2. Flash gaps	McQueen *et al.*, 1970
3. Optical time of arrival	Coleburn, 1964
Displacement versus time—continuous measurements	
4. Inclined optical mirror	Doran, 1963a
5. Optical image	Davis and Craig, 1961
6. Inclined prism	Eden and Wright, 1965
7. Displacement capacitor	Hughes *et al.*, 1961
Time-resolved velocity or stress	
8. Quartz gauge	Graham *et al.*, 1965; Graham, 1975
9. VISAR (optical interferometer)	Barker and Hollenbach, 1972
10. Electromagnetic velocity gauge	Dremin *et al.*, 1965
11. Manganin gauge	Keough and Wong, 1970
12. Sapphire gauge	Graham and Ingram, 1968
13. Velocity capacitor	Rice, 1961; Ivanov and Novikov, 1963
Electronic property measurement	
14. Electrical resistance	Keeler and Mitchell, 1969
15. Magnetization change	Graham, 1968; Royce, 1968
Postshock sample examination	
16. Metallurgical	Fowler *et al.*, 1961; Johnson *et al.*, 1962
17. X-ray diffraction	Coleburn and Forbes, 1968
18. Petrographic analysis	Chao, 1967
19. Other conventional probes	...
Others	
20. Flash radiograph	Breed and Venable, 1968
21. Flash x-ray diffraction	Johnson *et al.*, 1972

[a] For a more complete description of these and other measurement techniques, see Graham and Asay (1977) and Fowles (1973).

measured, discrete displacement-versus-time measurements are sufficient to determine shock and particle velocity values with good accuracy. If, however, material response is not ideal and there is structure in the wave profile, discrete displacement time detectors may not provide a good measure of changes in structure.

When free surface displacement is continuously recorded, the presence of multiple shock fronts is detected, and data interpretation is more precise than when flash gaps are used. Closely spaced pin measurements of surface displacement provide an approximation to the required data; three optical methods, the inclined mirror, the inclined prism, and the optical image, provide better approximations (Table I). One edge of the inclined mirror is in contact with the sample free surface, and shock arrival and free surface displacement are detected by monitoring reflected light with a high-speed streak camera. The optical image technique monitors position of a wire and its image in a polished free surface. Continuous optical and pin techniques are more productive than the flash gap technique since they provide data on the second, higher-pressure shock wave, which can be used to determine thermodynamic properties of the high-pressure phase.

Even continuous measurements of displacement cannot follow fine detail, since measured data are differentiated to obtain free surface velocities. Direct time-resolved measurement of stress or particle velocity can be accomplished with quartz gauges or optical interferometers or other devices with more limited time resolution (Table I).

The quartz gauge is an x-cut quartz disk affixed to the surface at which stress is to be measured. When a shock wave crosses the interface between sample and gauge, a piezoelectric current is produced that is nearly proportional to the normal stress component at the interface. Its time resolution is limited by circuit response and wave tilt at the interface. Its useful recording time is propagation time of a dilatation wave through the disk. The greatest pressure it can reliably report is about 4.0 GPa. Under favorable planar impact conditions it has a time resolution of a few nanoseconds. Other piezoelectric gauges have been studied. One which is useful to about 1.0 GPa is lithium niobate (Graham and Jacobson, 1973; Graham and Asay, 1977).

The VISAR, an acronym for Velocity Interferometer System for Any Reflector, has a time resolution of about 3 ns. It is a modification of the Michelson interferometer in which fringe shift is made proportional to velocity instead of displacement. It can be used to monitor velocity of a free surface or of an interface between sample and a transparent buffer. Its maximum pressure measurement capability is limited only by the integrity of solid surfaces and it can be used on diffusely reflecting surfaces (Barker and Hollenbach, 1974).

The remainder of the techniques in Table I will not be discussed in detail. The difficulty of interpreting resistance measurements under shock compression was