gas gun is probably somewhat less than required for an explosive site, better shock amplitude control is achieved through control of projectile velocity with gas pressure and volume, the gun is better adapted to laboratory operation, and safety problems are perhaps somewhat less than

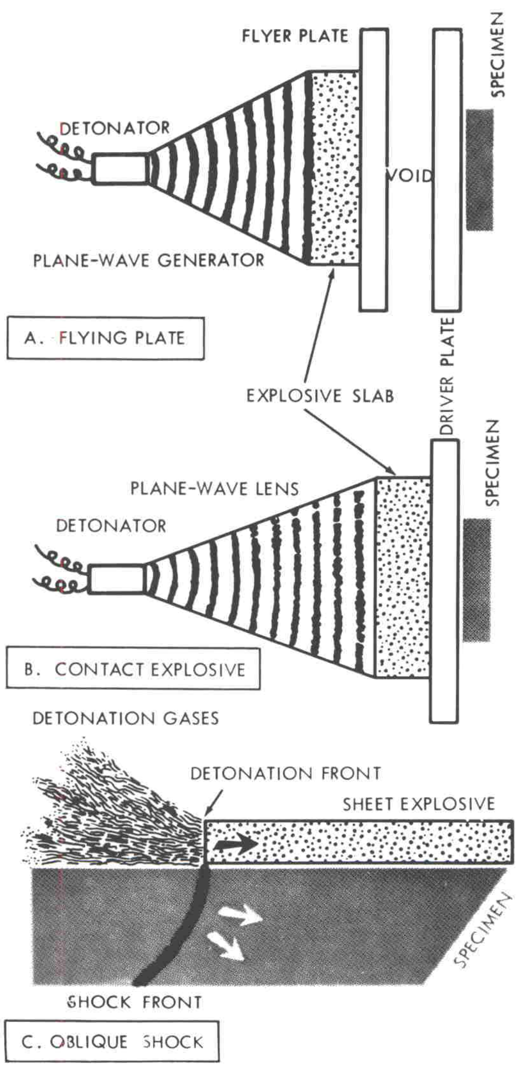

Fig. 4. Explosive methods to deliver shock to a specimen differ in cost, pressures they can attain, and ease of interpretation: (Top) Flying plate is most difficult, usually most costly, but attains highest pressures; contact explosive reaches intermediate pressures at comparable or slightly lower cost; Oblique shot is least expensive of methods shown, achieves only low pressures, requires large sample, and geometry complicates interpretation.

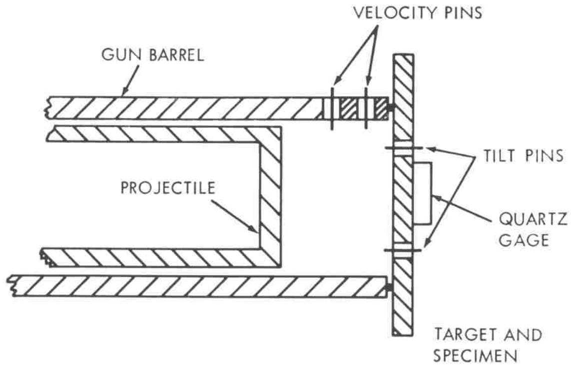

Fig. 5. Schematic arrangement for a shock experiment using a gas-driven projectile.

with explosive handling. Early gun models were limited to low projectile velocities and shock pressures of a few tens of kilobars. The art of gun design has improved and pressures of several hundred kilobars can be obtained with single stage gas guns, while pressures of several megabars have been produced by two-stage guns (Jones *et al.*, 1966).

A gun experiment is shown schematically in Figure 5. The shock detector at the right may be a quartz or manganin gage or one of the systems commonly used in explosive experiments (Linde and Schmidt, 1966).

PRODUCTION OF OBLIQUE SHOCK WAVES

A fourth shock-generating method, the method of oblique detonation shown in Figure 4C, differs from the others in geometry, yielding a curviplanar shock instead of a one-dimensional one. The chief advantages of this method are: first, it offers lower pressures than any other explosive method (18 kbars in aluminum, for instance), making it useful in attempts to correlate shock work with static high-pressure studies; second, it offers a continuous record of both pressure and density from a single experiment, making it valuable for equation-of-state measurements; third, it is the least costly way to make shocks, because large, precise plane-wave generators are not required to initiate detonation. Disadvantages arise from the more complex geometry of the shock wave, which makes data interpretation more difficult than in other methods.

We now know what shock waves are, and how to generate them. Next, let's trace the energy delivered from explosive to specimen further along its path to dissolution.

THE SHOCK EQUATIONS

Back in Figure 4B, for example, when the plane shock wave in the driver plate reaches the interface between driver plate and specimen, part of the wave is transmitted into the specimen, and part is reflected back into the driver plate. In order to determine the amplitude (and ultimately the energy) of the transmitted wave, we must use the equations which describe the effects of shock transition on both the mechanical and the thermodynamic states of the medium.

These equations express the fact that mass, momentum, and energy are conserved in the shock transition:

$$u_1 = (p_1 - p_0)/\rho_0 U \qquad (1)$$

$$U^2 = V_0^2(p_1 - p_0)/(V_0 - V_1) \qquad (2)$$

$$u_1 = [1 - (\rho_0/\rho_1)]U \qquad (3)$$

$$E_1 - E_0 = \tfrac{1}{2}(V_0 - V_1)(p_1 + p_0) \qquad (4)$$

In these equations, which apply precisely to a shock which connects two uniform states—indicated by the subscript (0) for an initial unshocked state, and (1) for a subsequent shocked state—p is the component of compressive stress parallel to the direction of shock propagation. Density is denoted by ρ, and its reciprocal—the specific volume—by V. The velocity of propagation of the shock relative to the unstressed material just ahead of it is U. As mentioned earlier, the shock compresses material to a higher density, and simultaneously increases its particle velocity by u_1. The work done on a unit of mass by the force driving the shock thus shows up as an increase in the internal energy per unit mass of the shock, E, along with an increase in kinetic energy. Equation (4) represents this energy conserved with kinetic energy eliminated by means of Equations (1) and (3).

Equation (4), known as the Rankine–Hugoniot relation, plays a key role in shock theory. Its particular importance depends on the fact that it contains no velocity terms—only thermodynamic quantities.

When the Rankine–Hugoniot relation is combined with the equation of state of any material, a unique relation between p and V is obtained. This relation is called the Rankine–Hugoniot (R–H) curve of the material (see Fig. 6). This curve expresses the locus of all states (p_1, V_1, E_1, and so on) that can be reached from an initial state (p_0, V_0, E_0) by shock compression. In an analogous way, the ordinary adiabat or adiabatic curve may be defined as the locus of all states that can be reached from the initial state by adiabatic compression.

At the point B, which represents initial unshocked conditions in the material (p_0, V_0, E_0), the R–H curve and the adiabat through point B have the same slope and curvature, but only at that point; at all higher pressures the R–H curve lies above the corresponding adiabat, because unlike adiabatic compression, shock compression dissipates energy, and is, therefore, irreversible.

As shown in Figure 6, the increase in internal energy in a shock whose pressure amplitude is p_1 is represented by area ABCD. Loss of energy in a shock can be illustrated by comparing this area thermodynamically with that associated with a weaker shock, area ABC′D′, for example. It can also be shown by simple calculation that just as

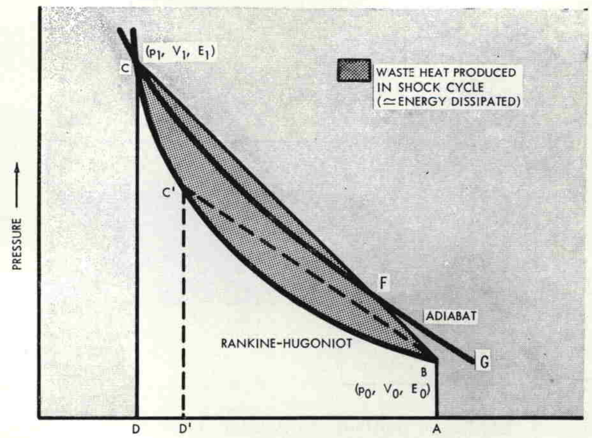

Fig. 6. The Rankine–Hugoniot curve defines states that can be induced in substance by shock compression in terms of pressure (p), specific volume (V), and internal energy (E). Shock compression from initial state B to shocked state C follows the straight line BC. Expansion follows the adiabat CFG. The energy dissipated in shock is approximately equal to the gray area.