vacancies and dislocations in lattices. Shock-induced impact bonding of metals is now commercial (Park, 1962).

In geophysics, shock-wave research in the laboratory has provided some of the first data ever gained on phase changes that may occur deep in the earth's mantle; and in chemistry shock waves have contributed uniquely to understanding kinetics of fast reaction in gases.

But applications and accomplishments thus far, though impressive, are modest and tentative, compared with what shock research may accomplish—if certain of its inherent difficulties can be overcome.

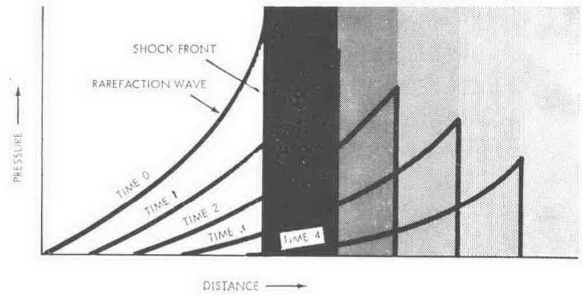

Fig. 3. Rarefaction phase of shock wave—where pressure tails off to ambient from its peak value in shock front—travels faster than shock front itself, progressively overtakes it. This causes entire shock wave to decay in amplitude.

SOME DIFFICULTIES

There are several serious obstacles to the rapid expansion of shock-wave research. One is the shortage of skilled personnel at all technical levels in the field. Another is the violence of strong shock waves—particularly in solids and liquids. Shocks are usually generated by explosives, and the resulting hazards and noise traditionally force operations to remote sites. Ingenuity and forethought may relax this condition; for example, gas guns for producing shock by impact have already been successfully used near office areas, and enclosed shooting chambers may, in the future, permit the detonation of high explosives in relatively populous areas.

Older techniques for measuring details of shock-wave structure have been limited to time resolutions of about 10^{-8} seconds. New electro-optical methods are being developed which promise resolutions approaching 10^{-9} seconds (Barker, 1967). Details of shock structure provided by such resolution are expected to provide important new insights into parameters of dissipation and relaxation in solid materials.

Last, shock-wave research on solids and liquids is relatively expensive. A minimum installation for making quantitative, dynamic measurements probably costs on the order of $100,000, aside from the cost of a remote location. Because experimental assemblies are complicated and require precision manufacture and assembly, the cost of each fully instrumented shot is at least about $1000, including data analysis. Moreover, the thought of an elegant and precise assembly being destroyed in each experiment is almost more than some scientists can bear, and this approach to experimentation calls for a psychological readjustment on the part of many experimenters.

Applications depend largely on the effects a shock wave has on the material through which it passes. However, the material reciprocally affects the structure of the shock wave itself, altering and complicating it. One of the chief goals of basic shock-wave research is to unravel the connections between the original structure of a shock, the properties of the material through which it travels, and the effects upon the shock of its brief journey through the material. The better we understand these relationships, the more likely become applications that we cannot now foresee.

CHARACTERISTICS OF SHOCK WAVES

We all know what a shock wave is, in a sense—it is the boom from a supersonic aircraft, the crack of a bullet, or the blast from an explosion. Yet a more precise definition of a shock wave is not so easy to formulate. We commonly use the term to refer to any almost-instantaneous increase in the value of stress or pressure in a material, so long as the velocity with which the stress transition travels through the material is greater than the velocity of sound in the substance. Also essential to our definition is the idea that the stress transition retains its characteristic abruptness as it travels through the medium. As shown in Figure 3, the abrupt transition itself is called the shock front, or shock; it is the compressive phase of the entire shock wave. Behind this, where pressure tails off rapidly from its peak value to its pre-shock ambient value, is the wave's rarefaction phase.

Immediately ahead of the shock front at any instant, the material through which the shock is propagating remains undisturbed, blissfully unaware of what's to come. But an infinitesimal distance behind the shock front the material is in the shocked state: it's compressed to a higher density, and its constituent particles are accelerated. This additional particle velocity behind the shock, added to the wave's propagation velocity, permits the rarefaction portion of the shock wave to travel faster than the shock front itself. Therefore, the rarefaction part of the wave gradually overtakes the shock front and, as suggested by Figure 3, the entire shock wave simultaneously lengthens and decreases in amplitude as it travels. In a sense, the shock front—by accelerating particles as it passes—sets in motion the cause of its own ultimate undoing.

The details of shock-wave structure depend upon how the wave was generated, how far it has propagated, geometry of generation and of the medium, and upon the material properties of the medium itself. It is this last which is most often of interest, and in consequence, the attempt is made to generate incident shocks so that their detailed structure can be related to properties of the medium. This requires that the experimental geometry be simple and calculable: therefore shock waves for dynamic measurement are most often generated in plane geometry where the direction of propagation and the lapse of time since propagation are the two independent coordinates. This can be done in several ways.

HOW TO MAKE PLANE SHOCK WAVES

This may be accomplished by shaping the detonation in an explosive to form a plane wave or by accelerating a flat-faced projectile in a gun and allowing it to impact on the plane face of the target.

In the first case the explosive may be placed in direct contact with the target, as in Figure 4B, or it may be used to drive a flyer plate which produces a plane shock in the target on impact, as in Figure 4A. The flyer plate produces higher pressures than the contact explosive because it accumulates momentum from the explosive during its entire flight across the gap and delivers it to the target in a very much smaller time. Flying plate pressures up to nearly 10,000 kilobars have been reported by Russian scientists (Kormer *et al.*, 1962); flier plates are commonly used at pressures as low as 300 kilobars. The price paid for flier plate data is high in dollars and in loss of quality, but when high pressures are required, they can be achieved in this way.

When explosive is in contact with the driver plate, as in Figure 4B, a point initiation is again converted into a plane wave by a lens. This plane detonation wave impinges directly on the driver plate, inducing in it a shock pressure which increases with its mechanical impedance. This factor, as we shall see, determines the peak pressure that can be induced in the driver plate and hence in the specimen.

Since the detonation wave in the explosive is itself a shock wave—driven by expansion of the chemically reacting gases behind it—one might reasonably ask, why not use this shock wave directly? Why interpose between this detonation shock and the specimen all the impedimenta shown in Figure 4—especially the explosive slab and the driver plate? In essence, the answer is that the driver plate smooths irregularities in the detonation front, improving resolution.

Moreover, introduction of the driver plate and explosive slab into the array gives us three independent parameters for controlling the shock pressure finally induced in the specimen: (1) the kind of explosive used; (2) the material of the driver plate; (3) the ratio of driver-plate thickness to explosive-slab thickness. Thus, for example, the range of pressures that can be produced in a single material with the kind of setup in Figure 4B is about four to one. Pressures attainable are in the 100–1500 kbar range, intermediate to those obtainable with the flying plate or gun-launched projectile discussed below.

The use of guns to drive projectiles against flat target plates, thus producing shocks by impact, has been increasing in recent years. The reasons for this are several: the initial investment in a