the internal energy increases or decreases as the shock is stronger or weaker, so the entropy of the final shocked state also increases with the shock strength. Although such calculations are valuable in computing the entropy of the shocked state, they are insufficient for calculating the total energy dissipation resulting from passage of the shock wave. However, referring again to Figure 6, the gray area (BCC′B)—bounded below by the Rankine–Hugoniot curve and above by the straight line connecting the initial, unshocked point B with the final shocked state C—is a fair approximation to the energy dissipated in the shock cycle, sometimes called the waste heat of the cycle. It is difficult to determine an exact expression for energy dissipated because thermal stresses are left behind in the material, even after the shock pressure has been relieved. Therefore, a precise calculation of the true energy dissipation in a decaying shock must account for hard-to-evaluate effects of thermally induced after-flow in the material. In practice we settle for the waste heat approximation.

We are now prepared to intelligently conclude our discussion of how a shock wave gets across an interface between two media—as from driver plate to specimen in Figure 4. Such transmission phenomena determine the magnitude of shock we finally get in the specimen, for a given combination of explosive and driver plate characteristics. They are also basic to determining the equation-of-state for unknown materials, using shock data.

## PROPAGATION AND TRANSMISSION OF SHOCKS

Every unique Rankine–Hugoniot curve derived from relations between pressure and specific volume—as in Figure 6—transforms to an equally unique relationship between pressure and the velocity of particles in the material. Figure 7 shows such curves for both the shock incident in the driver plate (OA), and the shock transmitted into the specimen (OB).

However, there is an all-important third wave in shock interactions that we also must consider. This is the wave *reflected* back into the driver plate from its interface with the specimen. This can be either a compression or a rarefaction. The

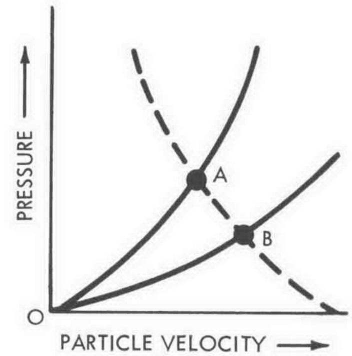


Fig. 7. Matching of interface conditions.

difference is critical because if it is compressive the shock transmitted to the specimen will be even stronger than that originally incident in the driver. But if, instead, the reflection is a rarefaction, the transmitted shock will be weaker than the incident.

The nature of the reflected wave, therefore, is part of the answer to an important practical question—what experimental conditions are necessary for achieving in a specimen a shock of specified pressure?

In Figure 7, the reflected wave is represented by cross-curve (AB), approximately the mirror image of the R–H curve (OA). Such a cross-curve plays the same role for reflected waves as do R–H curves for direct waves: it defines conditions that exist in a material as a result of a wave's passage.

For a given experimental arrangement, if conditions of pressure and particle velocity in the wave reflected back into the driver lie above point A on cross-curve (AB), the reflection is compressive. If, on the other hand, the reflection lies below point A, it is a rarefaction. Point B represents conditions common to both driver plate and specimen (at their interface only), and it is evident that the reflection illustrated is a rarefaction, and that the transmitted wave is weaker than the incident one.

This would be the case for a set up that combined a relatively harder driver—steel, for

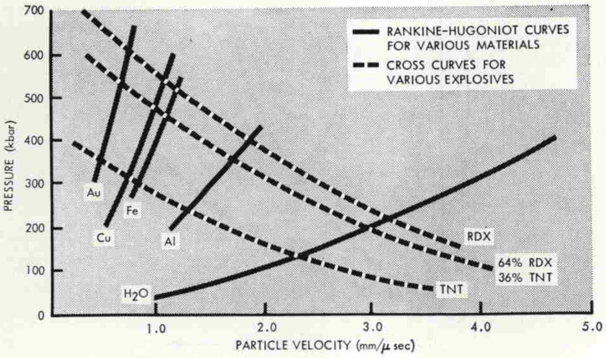


Fig. 8. Representative pressures that can be generated in various materials by different explosives are shown by points where curves cross. For example, a detonation wave in an explosive made up of 64% RDX·36% TNT, incident on aluminum, yields 360 kbar pressure.

instance—with a relatively softer specimen such as lucite. Reversing the relative hardness of driver and specimen would, of course, reverse the relative strength of transmitted and incident shocks.

These transmission concepts underlie the curves of Figure 8. This figure shows plane shock-wave pressures that can be reached in various materials with various explosives. The pressure that is attainable for a given combination of material and explosive lies at the intersection of the curve for the material with the curve for the explosive. For example, a plane detonation wave in an explosive made up of 64% RDX and 36% TNT, incident normally on aluminum, induces a shock pressure of about 360 kbars in the aluminum; in water, the same explosive would induce a pressure of only about 190 kbars.

All well and good; now let's get some idea of the data that come out of a shock experiment, and of how to get these data.

## VELOCITY MEASUREMENTS

We return to the experimental setup of Figure 4B. As the shock passes from driver plate to specimen, either the shock's velocity, or the free-surface velocity in the specimen, or both, are to be measured. How?

One method uses the familiar principle of the optical lever. As the incident shock wave produces small rotational displacements in an inclined polished surface on the specimen, reflections of light—incident on the same surface from point sources—are displaced a greater amount via appropriate reflection geometry. Reflections are recorded on film by a streak camera as a series of light streaks, against a base whose abscissa is time and whose ordinate is distance. Figure 2 shows such a record. Wave arrivals at points on both specimen and reference standard are indicated by abrupt displacements of successive traces.

The speed of the shock along the free inclined surface of the specimen is obtained from such a record by measuring the slope of the line that connects the same wave break in adjacent light traces.

An interesting feature of this record (Fig. 2) is that the first deflection of light traces in PZT is produced by an elastic wave that precedes the main shock wave. Since this elastic precursor travels with constant velocity, regardless of its amplitude, the first break in the light traces forms a straight line. But in the shock wave that follows it, the velocity is continually changing; and a trace-by-trace measurement must be made to determine the local slopes and velocity values in the decaying shock.

Another light-reflection technique for recording motion of shocked surfaces is based on the apparent change of reflectivity of polished or mirrored surfaces when they are struck by a shock wave. Figure 9 shows a streak camera record obtained from such a setup.

This technique allows the specimen's free-surface motion to be monitored continuously; hence, it is particularly useful where the wave in the sample consists of more than one shock front, as is the case in Figure 9. But the method is sensitive to both tilt and nonplanarity of the shock, so that good plane-wave generators are essential to its successful use.

Non-optical methods also can be used for measuring shock and free-surface velocities in specimens that are electrical conductors. One such is called the pin method, in which motion of a shock-accelerated surface closes a gap and strikes a pin. This short-circuits an RC network, which discharges through an oscilloscope. If the pin position is accurately known and the RC