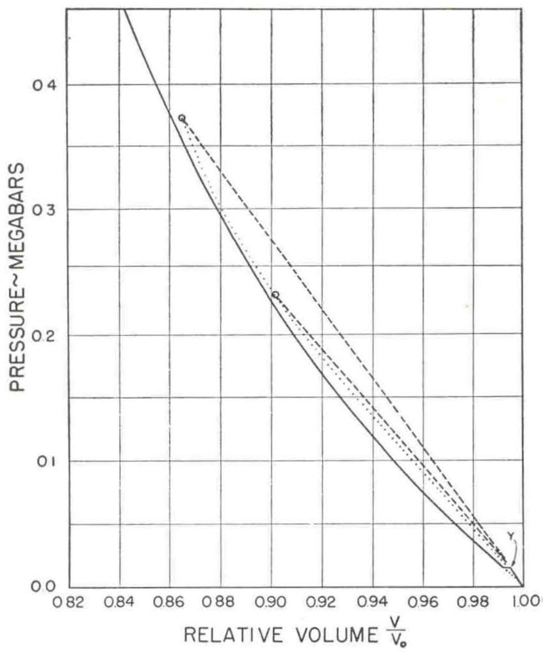

FIG. 2. Solid line represents a hypothetical isentropic equation of state of steel subjected to uniaxial compression, showing effect of shearing stress below the dynamic yield point Y. Shock wave velocity is given by the expression $D=(-\Delta p/\Delta V)^{\frac{1}{2}}V$, where V is the specific volume of the material ahead of the shock; Δp is the incremental shock pressure; and ΔV, the change in specific volume due to the shock.

Below the dynamic yield point, compressional waves are propagated with the sound velocity, proportional to the square root of the slope of the solid line.

Above dynamic yield point, compressional waves are propagated with velocities proportional to the square root of the slope of the dashed lines. By joining the end points of the dashed lines, one obtains the representation of the "Rankine-Hugoniot" equation of state shown by the dotted curve. This lies above the isentropic because of the entropy change under shock conditions. Upper dashed line represents a shock traveling with the velocity of sound at low pressures, i.e., a shock not preceded by an elastic wave.

is exceedingly abrupt and that the amplitude of this abrupt rise is constant provided the material behind the wave is uniformly compressed. Constancy of pressure behind the shock front may be achieved approximately by using a sufficiently large block of high explosive. If, however, the wave is not plane, its space configuration varies as it proceeds, and if the compression behind the front is not uniform, the magnitude of the virtually discontinuous pressure change is not constant. Furthermore, even if the wave is perfect in terms of the above criteria the plane of the waves may not be parallel to the plane of the plate. A variety of special precautions has been introduced to minimize effects of these possible sources of error. Continual improvement in the preparation of the H.E. and the "lens" have virtually eliminated departures from planeness and tilt in the wave itself. A small residual tilt of the front does not affect (to errors of the first order) the inferred velocities if the pins are properly arranged in small circles. In some experiments, as many as nine circles of eight pins each are used to supply simultaneous information.

In addition to the above difficulties it has been found that small irregularities or scratches in the surface of the plate result in jets which may cause erratic pin discharge. Indeed owing to the polycrystalline structure of the metal itself, some irregularities in the moving free surface are invariably present, the magnitude of these irregularities being of the order of the size of the individual metallic crystal grains. Because of this unavoidable roughness, it is not practical to make free surface velocity measurements over extremely short ranges of motion. Experiment has shown, however, that these irregularities are not too serious if the total range covered by the pins exceeds 5 mm.

A further limitation on the method results from the fact that in certain materials (e.g., steel) an elastic wave of compression moves with a higher velocity than the shock wave up to a certain pressure which depends on the dynamic yield point (see Fig. 2). In such cases, the necessary information can be achieved by the use of piezoelectric crystals (see Figs. 3 and 4).

One further technical experimental point deserves brief mention. As has been mentioned, some decay of pressure is encountered with increasing thickness of the plate. It is thus essential that the shock wave velocity and the mass velocity be obtained for an equivalent particle, namely a particle close to the free surface of the plate. But the probes for measuring propagation velocity are perforce distributed through the thickness of the plate, and, since the amplitude of the shock is varying, so also does the propagation velocity vary. The simplest way of finding shock velocity at the free surface is to make the portion of the plate where the shock velocity is measured somewhat thicker than the portion where the free surface velocity is measured, so that an average value for the former will be compatible with the observed value of the latter.

From the measured free surface velocity, the mass velocity of the compressed material may be inferred. It is, of course, necessary to complete the measurement of free surface velocity before reverberations can occur in the target plate. Otherwise, one obtains a measure not of mass velocity but of momentum transfer from explosive to plate. Furthermore because of the decay of pressure behind the shock front, one might expect the *observed* free surface velocity to diminish as the motion proceeds, but such an effect has not been detected. With these considerations in mind each set of 8 contactors is usually spaced over an interval of about 5 mm from the

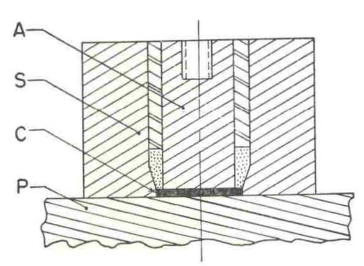

FIG. 3. Assembly for holding piezoelectric crystal in place. *A* Metal electrode and inertial support for crystal. *S* Guard ring. *C* Crystal. *P* Specimen through which shock-wave proceeds.

back surface of the plate, though for very thin plates an even closer spacing may be necessary in spite of the uncertainties caused by roughness of the moving free surface as previously mentioned, and the shorter reverberation time.

In order to obtain extensive data on the equation of state of the material under study, it is necessary to produce in the specimen compressional shock waves of arbitrary amplitude. There are three ways in which this has been accomplished:

(1) By increasing the thickness of the specimen, the pressure decays naturally, because the amplitude of the pressure discontinuity remains constant only if the pressure in the compressed material is everywhere uniform. With blocks of high explosive of finite dimensions, this condition is not satisfied, and a continuous degradation of shock pressure is always encountered.

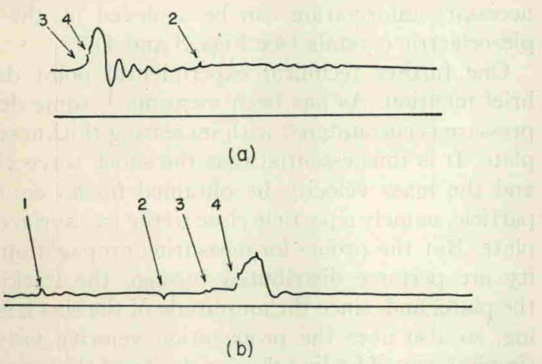

FIG. 4. Oscillograph records of shock-wave profile after moving through (a) 0.25 in. (b) 1.25 in. of SAE 4340 steel. (1) is cross talk from (a); (2) is the synchronizing time pip for the two records; (3) is the elastic-wave front; and (4) is the main shock front. Total sweep length is 10 μsec. Elastic pressure is 0.0157 mb; peak shock pressure in (b) is 0.225 mb; elastic velocity is 0.585 cm/μsec; and shock velocity is 0.510 cm/μsec. (Oscillations in shock front are reverberations in crystal probes.)

(2) The detonation pressure may be varied by using different compositions of high explosive.

(3) The amplitude of the transmitted shock may be adjusted by placing an intermediate metal between the block H.E. and the specimen "plate," as would be possible with acoustic waves.

OBSERVED DATA

The data obtained by the measurements made in 1945 are summarized in the first two columns of Table II. The more recent measurements made on Duralumin are listed in the first two columns of Table III.

In the foregoing two tables, the recorded data represent averages taken from a large number of individual determinations. In Table II the standard deviation for both wave velocities is of the order of 2%. Unfortunately, in the case of steel, the presence of the elastic wave renders the computation of shock pressure and compression somewhat uncertain; the magnitude of the correction appears, however, to be less than 1%. In Table III the standard deviations as computed from the residuals do not exceed 0.5% in any case. In compiling both tables the original oscillographic data were analyzed by the method of least squares. Table II is based on the assumption that the measured free surface velocity is twice the mass velocity. In Table III a correction to this approximation has been made. All units are as specified in Table I.

TABLE II. Early data on aluminum, cadmium, and steel.

Material	Shock velocity	Free surface velocity	$\eta-1$ (computed)	Pressure (computed)	Pressure (crystal)
Aluminum	0.738	0.295	0.250	0.294	——
Cadmium	0.396	0.145	0.224	0.248	0.231
Steel		0.115	0.122	0.223	(calibration)
Shock wave	0.510 (Average)	0.166	0.195	0.332	0.324
Elastic wave	0.588	0.00667	0.006	0.015	0.0157

NUMERICAL COMPUTATIONS AND RESULTS

In order to reduce the shock pressures in Table II to adiabatic pressures, the data of Table IV are required. The data of the first four columns were computed from material to be found in the usual sources, notably Birch's Handbook,[3] the Metals Handbook,[4] and the Handbook of Chemistry and Physics.[5]

The values of β_s in the fifth column are those deduced by correcting the data of Table II to isentropic conditions and then fitting Eq. (17) to the observed point.

In the case of steel, only the point obtained at the lower shock pressure was used in computing the value of β_s. At the higher pressure, the computed value of μ appears to be much too large, and would imply an even smaller value of β_s. Further work will be required to verify the discrepancy between Bridgman's work and ours, but the available data seem worth recording because of the interest which may attach to the peak pressure as recorded by the tourmaline crystal and the relatively good agreement between this pressure and that computed by Eq. (2).

Values of β_s may also be computed by an analysis of Bridgman's more recent work,[2] and for aluminum and iron these appear in the last column of Table IV.

TABLE III. Recent data on 24 ST Duralumin.

Shock velocity	Free surface velocity	Mass velocity (computed)	$\eta-1$ (computed)	Shock pressure (computed)	Isentropic pressure (computed)
0.6460	0.1629	0.0814	0.1442	0.1462	0.1435
0.6850	0.2254	0.1126	0.1967	0.2144	0.2079
0.7005	0.2395	0.1196	0.2059	0.2329	0.2250
0.7426	0.3014	0.1503	0.2538	0.3103	0.2952
0.7520	0.3179	0.1584	0.2668	0.3312	0.3139

[3] Francis Birch, *Handbook of Physical Constants* (Geological Society of America, 1942).

[4] *Americal Society of Metals*, "Metals handbook," 1948.

[5] Charles D. Hodgman, *Handbook of Chemistry and Physics* (Chemical Rubber Publishing Company, Cleveland, 1952).