value stress over a range of stress which can be quite large.[6]

In summary, an impact experiment suitable for well-defined physical property measurements has the following general features:

1 Precise alignment of the impacting surfaces of facing and specimen disks
2 Provisions for impact in vacuum
3 Precise measurement of velocity at impact
4 Capability of obtaining a preselected impact velocity

The Impact Relationships

If the impact of two flat surfaces is achieved under the conditions described above, the particle velocity imparted to the specimen as a result of the impact can be precisely determined. The relations that specify the impact conditions follow from the consideration that for all times when the impacting and impacted surfaces are in contact, the stress and particle velocity must have the same values across the interface. Thus, it follows that:

$$U_0 - u_a = u_b \tag{3}$$

and

$$\sigma_a = \sigma_b \tag{4}$$

where U_0 is the impact velocity, u is the particle velocity, and σ is the stress in the impact direction imparted to the facing. The subscript a refers to the facing and b refers to the specimen. Combining these relations with equation (1) results in the relation:

$$u_b = \frac{Z_a}{Z_a + Z_b} U_0 \tag{5}$$

where Z represents the shock-wave impedance ($\rho_0 U$) for the stress and particle velocity of the experiment.[7] Thus, if the properties of the facing and specimen are known, the particle velocity can be computed from the measured impact velocity. In general, however, these properties are unknown or not known with sufficient precision so that it is difficult to perform precise experiments with dissimilar materials impacting upon each other.

However, if the facing and specimen are the same material, equation (5) is greatly simplified since

$$u_a = u_b = u = (1/2)U_0. \tag{6}$$

For this condition the particle velocity imparted to the target is precisely known regardless of the material used or whether its properties are known. The impact of identical materials, termed the symmetric impact, is clearly the best defined condition for use in impact experiments and is utilized in the major portion of the work to be presented.

Physical Property Measurements

Impact techniques are best illustrated by describing specific methods employed for various measurements. Some of these measurements are reported here for the first time while others are reported in more detail elsewhere and are shown here only to illustrate particular features of technique.

Piezoelectric Properties of X-cut Quartz [19, 23]

The most extensive measurements accomplished to date have been made to determine the piezoelectric properties of X-cut quartz (references [19–23]) under shock-wave compression. As illustrated in Fig. 3, both facing and specimen are disks of X-cut quartz. For a given experiment the velocity of the impacting disk is measured along with the short-circuited current which results from the shock wave traversing the specimen disk. Previously it was demonstrated [23] that this current, i, produced by the piezoelectric effect is:

$$i = f_{11} \frac{\sigma A U}{l}, \qquad 0 < t < l/U \tag{7}$$

where f_{11} is the piezoelectric coefficient relating the component of stress to the resulting charge on the x-face; A is the area of the disk; σ is the x-component of stress; l is the thickness of the disk, and t is the time. In the low signal limit, $f_{11} = e_{11}/c_{11}$, where e_{11} is the piezoelectric stress constant and c_{11} is the elastic stiffness constant. It is apparent from equations (6), (7), and (1) that measurements of U and U_0 along with the resulting current and predetermined dimensions of the disk are sufficient to determine the piezoelectric coefficient.

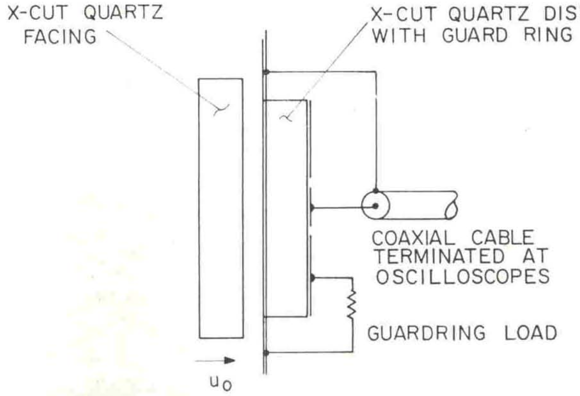

Fig. 3 Experimental arrangement for the measurement of the piezoelectric coefficient. The guard ring geometry is employed to obtain one-dimensional conditions.

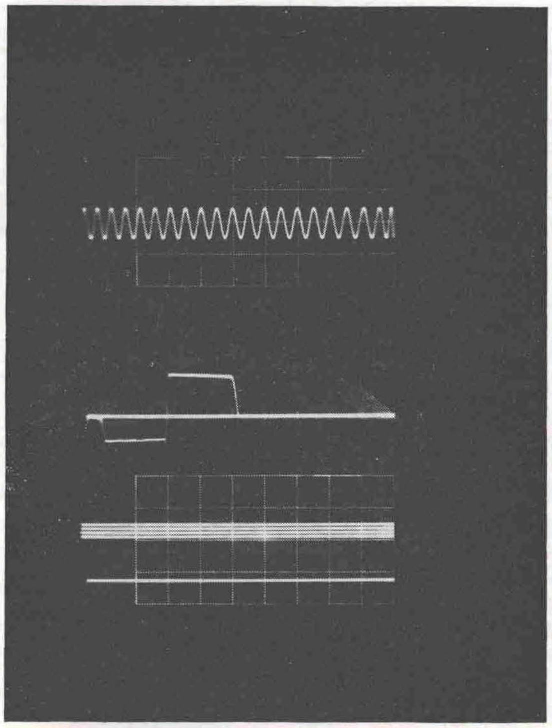

Fig. 4 Typical current-time record from impact loaded quartz. A timing wave of 10 Mc is shown at the top and the amplitude calibration is below the signal. Time increases from right to left. The positive signal corresponds to the transit of the wave through the crystal. The negative signal is that due to the reflected wave from the rear of the specimen.

A typical current-time oscilloscope trace is shown in Fig. 4.

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[6] The author has performed experiments from 2.5 to 450 kbar with the gun described in reference [11].

[7] In general, the impedance of the solid will depend upon the stress; thus a graphical solution would be employed for the particle velocity rather than the analytical method implied by equation (5). See reference [2], p. 179.

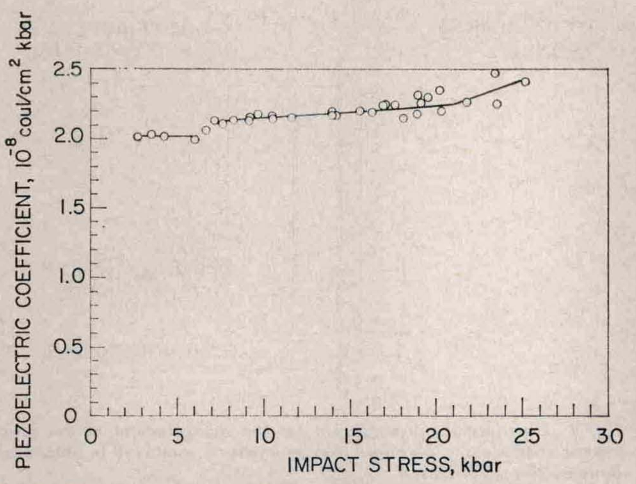

Fig. 5 The piezoelectric coefficient of *X*-cut quartz under shock-wave compression. These data should not be confused with the previously reported current coefficient which is employed when quartz is used as a gage [23].

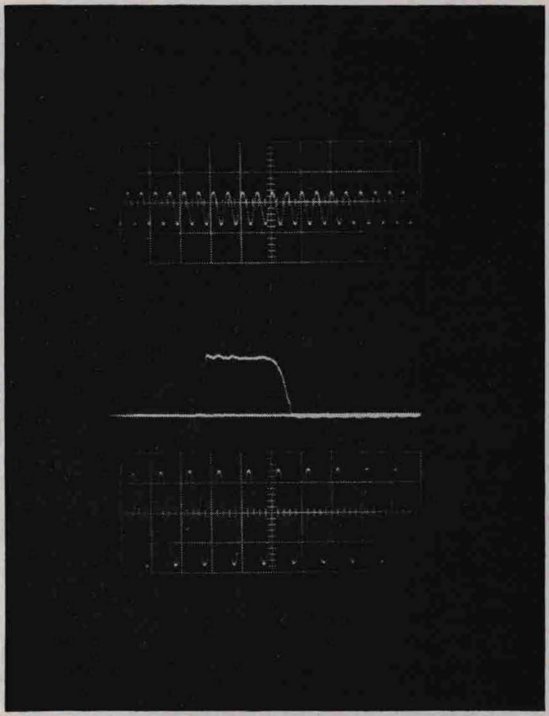

Fig. 6 Typical current time record due to the permittivity change induced by shock wave of 32 kbar. A timing wave of 20 Mc is shown at the top and the amplitude calibration is below the signal. The signal amplitude is about 8.5 × 10^{-4} amp with a 32-mm dia disk 3.2 mm thick. An electrostatic potential of 730 volts was applied to the specimen.

The record not only shows the current amplitude but also the time taken for the shock wave to traverse the known thickness of the specimen disk. From this measured transit time and the measured impact velocity, the particle velocity and shock velocity are precisely specified on each experiment. This method of measuring the shock velocity has the desirable feature of an intimate connection between the measurements of the shock-wave amplitude and the resulting piezoelectric polarization. Since both shock velocity and current are measured from the same record, any peculiarities in response such as a transient rate effect have a direct observable effect on both quantities.

Equation (7) was derived assuming infinitesimal strain and no permittivity change. As shown in the typical record, the current actually increases slightly in time which can be shown to be the result of the strain, electromechanical coupling, and a slight increase in permittivity. The solutions for the effect of these variables on the current [23] show that the current at one-half transit time is, for the conditions of our experiments, equal to that expected from equation (7). Hence, this current is a measure of the piezoelectric coefficient, f_{11}. Values obtained for f_{11} are shown in Fig. 5. Note that a typical increment of stress is about 2 kbar and that in the vicinity of 6 and 18 kbar, 1 kbar increments are achieved. The lowest stress point is within the previously reported [24] region of constant piezoelectric response.

In the low signal limit when a small correction is made for the area of the insulating ring, the data show a value for e_{11}/c_{11} of 2.01 × 10^{-8} coul/cm^2 kbar which is in excellent agreement with the value of 2.02 × 10^{-8} coul/cm^2 kbar by Koga, et al. [27] and 1.97 coul/cm^2 kbar by Bechmann [28].

The relations given in equations (1) and (2) describe the propagation of single shock waves. Frequently, a slope discontinuity or cusp exists in the stress-volume relation as a result of exceeding the Hugoniot elastic limit[8] or inducing a phase transition. For stresses in excess of the amplitude of the cusp it is possible for two waves to propagate at distinctly different shock velocities and in order to properly interpret the data, it is essential to determine if multiple wave fronts exist. The Hugoniot elastic limit of X-cut quartz has been found to be about 50 kbar [25, 26].

As the stress approached the Hugoniot elastic limit and beyond, it was not possible to obtain a satisfactory analytical expression for quantitative data reduction. Hence, even though this experiment was performed to about 150 kbar, no results are reported in the vicinity of the Hugoniot elastic limit.

For these measurements the reproducibility of the impact conditions was found to be particularly useful. It was possible to look extensively at the effects of deviations from one-dimensional conditions resulting from the geometry of the specimen. These effects produce distortions to the current-time waveforms which are similar to the effects of permittivity change. Thus, they are a potential source of error unless carefully investigated.

Recently, impact techniques have been used to determine the piezoelectric coefficient, f_{11}, under shock-wave compression at liquid nitrogen temperatures [29]. Also, the current produced from impacted ferroelectrics has recently been measured and analyzed [30].

Permittivity of Sapphire Under Shock-Wave Compression

An experimental arrangement similar to that used for quartz has been used to measure the permittivity change induced in sapphire by shock-wave compression. Here the shock wave is induced in the specimen by the symmetrical impact of sapphire disks [31]. If an electrostatic potential is applied to the specimen disk, a current flows in an external short-circuit due to the capacitance change induced by the shock wave. This capacitance change results from two effects: the strain and the stress induced permittivity change. For conditions of infinite resistivity, one-dimensional strain, and electric field, small strains and small permittivity changes, it can be shown that the short-circuited current is given by:

$$i = \frac{VAU\epsilon_0}{l^2}\left[\frac{\Delta\epsilon}{\epsilon_0} + \frac{u}{U}\right], \qquad 0 < t < l/u \qquad (8)$$

where V is the electrostatic potential on the disk, $\Delta\epsilon$ is the change in permittivity, and ϵ_0 is the unstressed permittivity. It is evident from equation (8) that if values of U and u are obtained along with the resulting current, the permittivity change can be computed. The experiment consists of the symmetrical impact of sapphire disks and a measurement of the resulting current-time pulse. A typical record is shown in Fig. 6. Note that as was the case with the quartz experiments, the current-time trace indicates the time for the shock wave to traverse the disk and thus provides

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[8] The Hugoniot elastic limit is the stress amplitude corresponding to the cusp in the stress-volume relation resulting from the transition between elastic and plastic compression under the one-dimensional strain conditions of shock-wave loading.