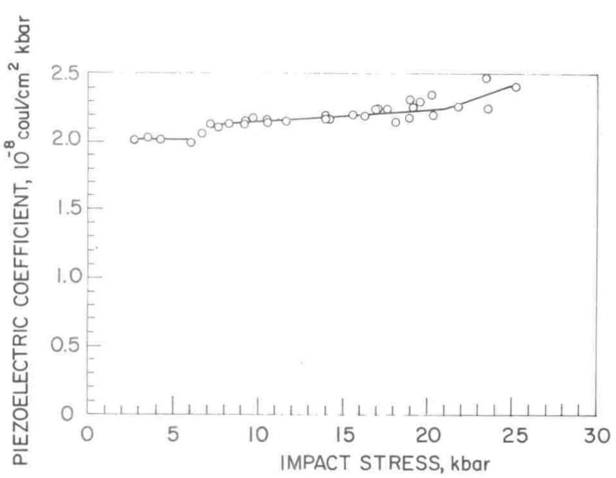

Fig. 5 Piezoelectric coefficient of X-cut quartz under shock-wave compression. These data should not be confused with the previously reported current coefficient which is employed when quartz is used as a gage (23)

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 x 10^{-8} coul/cm^2 kbar which is in excellent agreement with the value of 2.02 x 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

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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.

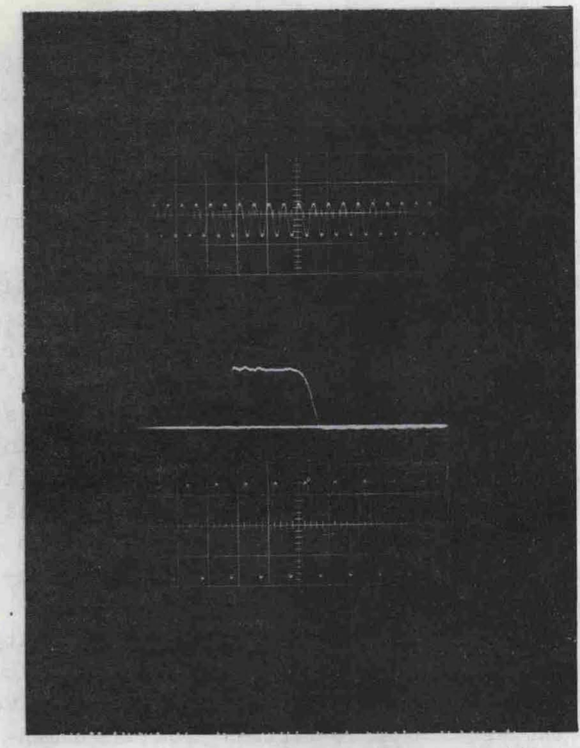

Fig. 6 Typical current-time record due to the permittivity change induced by shock wave of 32 kbar. A timing wave of 20 Mc is shown at the top, and the amplitude calibration is below the signal. Signal amplitude is about 8.5 x 10^{-4} amp with a 32-mm-dia disk, 3.2 mm thick. An electrostatic potential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

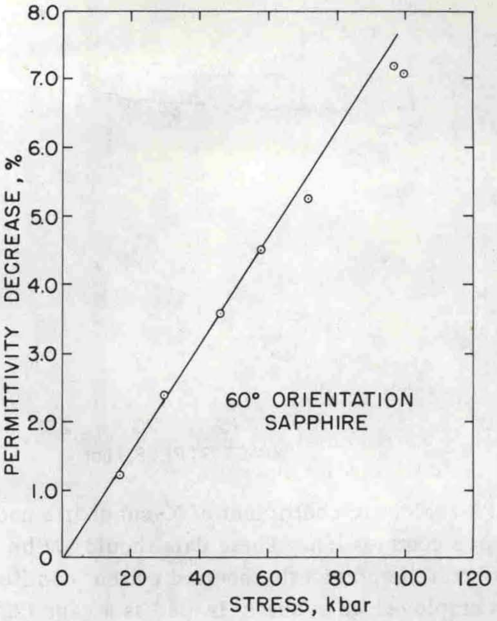

Fig. 7 Permittivity change of sapphire under shock-wave compression as computed from equation 8

and small permittivity changes, it can be shown that the short-circuited current is given by

$$i = \frac{VAU\epsilon_o}{\ell^2}\left[\frac{\Delta_\epsilon}{\epsilon_o} + \frac{u}{U}\right] \qquad o < t < \ell/u \qquad (8)$$

where V is the electrostatic potential on the disk, Δ_ϵ is the change in permittivity, and ϵ_o 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 the data necessary to compute the shock velocity. The particle velocity is determined from the measured impact velocity according to equation (6).

To measure the Hugoniot elastic limit, which determines the limit of the elastic wave region, subsidiary experiments were performed with explosive loading (32). The observed values depend upon the total pressure imparted to the sample and the crystalline orientation, and vary from 120 kbar to 200 kbar.

Experiments to measure the permittivity change have been performed on 60 deg orientation sapphire[9] from 20 to 150 kbar, with results as shown in Fig.7. Up to 60 kbar, the permittivity is observed to decrease linearly with stress at a rate of 0.078 percent per kilobar. The two higher stress points at 70 and 100 kbar are below the linear extrapolation based on the lower stress data. The current-time waveforms for the higher stresses indicate that conduction is occurring within the sapphire, lowering the current below that predicted from equation (8). Thus the permittivity change is apparently linear to 100 kbar. At higher stresses, we are presently unable to adequately interpret the data in an ex-

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[9] In an anisotropic crystal, pure longitudinal wave motion is possible only in certain directions, called "specific" directions. Although the 60 deg orientation is not theoretically a specific direction for the trigonal system, we have found that under shock-wave compression, longitudinal motion is exhibited to a very close approximation. This is not entirely unexpected considering the small variation in elastic constants in the various crystallographic directions.