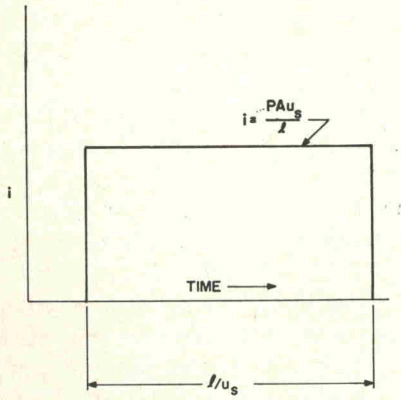

FIG. 2. Expected one-dimensional current waveform.

drop in current when the wave front exits from the specimen.

DISCUSSION OF THE EXPERIMENTAL REQUIREMENTS

We have assumed in the analysis that the wave propagation velocity is constant for all stress amplitudes within the elastic range. Some experimental verification is needed for this assumption. A stress wave front propagating from the impact surface will propagate under one-dimensional strain conditions. For the x-cut crystals[10] used here, the propagation is along the x axis with the propagation velocity given by

$$u_s = [c_{11}/\rho_0]^{\frac{1}{2}}, \qquad (4)$$

where c_{11}= the one dimensional strain elastic constant for quartz in the x direction, ρ_0 and u_s as previously defined.

Bechmann[11] has published an internally consistent set of elastic constants which are the results of many observations. The values were reported to have a high degree of reproducibility. He gives $c_{11} = 86.74 \times 10^9$ newton/m^2. Using the density 2.65×10^3 kg/m^3 the one-dimensional strain velocity is 5.72×10^3 m/sec.

In an anisotropic solid such as quartz, it is not generally true that the particle motion is normal to the wave front and hence truly longitudinal motion alone.[12] There are certain directions of propagation called specific directions along which the particle motion is truly longitudinal. The x axis is a specific direction for quartz and the trigonal system in general[13] so no uncertainties arise in these experiments due to nonspecific particle motion.

Bridgman[14] showed that the mean linear compressibility[15] of x-cut quartz was linear up to a hydrostatic stress of 8 kilobars. The piezoelectric constant d_{11} of quartz has also been confirmed to be the low signal value up to 3.5 kilobar.[16] Our experiments are designed to begin at stress as low as 5 kilobars and then extend to higher stress levels. If linear behavior is noted in the relation between impact stress and electric charge and this extrapolates to zero within the precision of the data, a confirmation is obtained of the linearity of the combination of the piezoelectric response and the elastic constant c_{11}. For stress regions in which nonlinear behavior is observed, the stress may not be computed from the known particle velocity.

The time taken for the stress wave to propagate through the specimen is indicated on the charge release records. This time may be used to determine the wave propagation velocity. The amount of closure time complicates a precise measure of wave velocity at low impact velocities, but at an impact velocity of 2000 ft/sec our data show the wave velocity to be equal to the low signal value to within 1%.

In these experiments, each experimental point is obtained with a different specimen since the specimen is destroyed by the impact. Experimental scatter is introduced by the variation in properties from one specimen to another. For the case of quartz, a search[17] of the literature shows remarkable consistency in the c_{11} elastic constant as reported by many different investigators using different techniques. From these reported values, it is estimated that the c_{11} constant of our quartz specimens did not vary more than 0.5% from one specimen to another. The experimental results we have obtained indicate that no inconsistency is present that could be attributed to this cause.

Instantaneous Closure

The requirement for instantaneous closure of the entire contact surfaces is the most difficult to meet experimentally but is so important that an unambiguous experiment cannot be achieved without meeting the requirement. The flat cylinder relationships given here have been known for many years, probably originating from St. Venant in 1867.[18] There has been a noted lack of success in applying them at points close to the impact surface, however, due to difficulties in achieving instantaneous closure. The general approach that many experimenters have used to overcome this difficulty is to use rounded impact surfaces and apply other impact relationships.[19,20] The simplicity of the form of the imposed stress pulse for a flat surface impact which produces a plane stress wave normal to the axis of the speci-

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[10] For definition of crystal cuts, elastic and piezoelectric notation see Proc. Inst. Radio Engrs. **37**, 1378 (1949).

[11] R. Bechmann, Phys. Rev. **110**, 1060 (1958).

[12] For a discussion of this see, R. F. S. Hearmon, *Applied Anisotropic Elasticity* (Oxford University Press, New York, 1961), p. 79.

[13] F. E. Borgnis, Phys. Rev. **98**, 1000 (1955).

[14] P. W. Bridgman, Am. J. Sci. **X**, 483 (1925), also given in R. B. Sosman, *Properties of Silicia, Part II* (Book Department, The Chemical Catalog Company, Inc., New York, 1927), p. 430.

[15] For definition of linear compressibility see, J. F. Nye, *Physical Properties of Crystals* (Clarendon Press, Oxford, England, 1957), p. 145.

[16] J. L. Karcher, Sci. Papers Bur. Standards **18**, 257 (1922).

[17] For one such search see, R. F. S. Hearmon, Brit. J. Appl. Phys. **3**, 120 (1952).

[18] B. De Saint-Venant, Journal de Mathematiques (Journal de Liouville) 2e Series, **XII**, 237 (1867).

[19] For a review of work on the impact of long cylinders, see R. M. Davies, "Stress Waves in Solids," *Surveys in Mechanics*, edited by G. K. Batchelor and R. M. Davies (Cambridge University Press, New York, 1956), p. 68.

[20] W. Goldsmith, *Impact* (Edward Arnold, Ltd., London, 1960), p. 267.

men makes it a much more desirable system with which to study piezoelectric behavior. Because of this, the experiments are designed to satisfy the requirement of instantaneous closure.

Instantaneous from the real point of view depends upon the time scale of the experiment. The duration of the event to be observed in these experiments is the time taken for the stress wave to propagate the length of the specimen. For a given impact velocity and angular misalignment of the two impacting surfaces, the diameter of the specimen will determine the duration of closure time. To minimize closure time relative to transit time, one should make the diameter-to-length ratio d/l as small as possible. A specimen size of $\frac{1}{2}$ in. diam by $\frac{1}{4}$ in. long ($d/l=2$) was chosen for use in connecting data from the 5-kilobar region into the higher stress region. The transit time for this length specimen is about one microsecond.

Before the experiments were conducted, it was felt that if the closure time could be kept to less than 10% of transit time, the instantaneous closure assumption would be satisfied. Using the extreme precautions for alignment given later, this duration of closure time can be achieved. As a verification that this criterion is valid, the experimental data show no effect on results for closure times varying from 1 to 25% of the transit time.

Stress Profile Assumption

Having met the instantaneous closure requirement, we have confidence of achieving a well defined input into the specimen impact face. We must now consider if the stress profile for all points within the specimen may be considered one-dimensional and time-independent for times after the wave arrival. This requirement is opposed from a practical viewpoint by the instantaneous closure requirement. The $\frac{1}{2}$ in. diam by $\frac{1}{4}$ in. long specimen chosen is obviously a bounded solid and the effects of the boundedness[21] of the specimen on the stress profile at all points must be considered.

Although the use of an ill-defined bounded solid offers extreme complications for most solids, in the case of a stress-transducing solid as used here the effect of the boundedness may be determined by varying the geometry of the specimen and noting the effect on the charge release characteristics. As the wave front moves along the boundary between the quartz and the surrounding potting material, conditions of transient stability require that shear and unloading waves be generated. These waves travel inward at velocities dependent upon the particular elastic constants involved. In the case of quartz, a piezoelectric response would be expected from these unloading effects. Since the unloading effects from the lateral boundary occur at fixed velocities relative to the longitudinal velocity, the diameter-to-length ratio of a specimen is a valid parameter to use for observing the effects of the boundaries. The effects must be reserved for experimental determination.

The actual determination of the one dimensional strain piezoelectric constant must be made on a very thin specimen (large d/l) but this can be done at high impact velocity where instantaneous closure is easier to achieve if linearity has been confirmed up to that velocity. Although they are more difficult to execute, experiments can also be conducted with the charge being observed from only the center portion of a large diameter specimen. Because of the geometry of the experimental arrangement, one would not expect to see one-dimensional stress behavior.

THE EXPERIMENTAL ARRANGEMENT

To attain instantaneous closure as required by the analytical development, special experimental precautions are required. The importance of the necessity for precise alignment cannot be overemphasized. To accelerate the projectile to the desired impact velocity, an extensively modified U. S. Army 40-mm antiaircraft gun was used. To achieve the required precision of alignment, it is necessary to arrange the impact so that it occurs while the projectile is still being guided by the bore of the gun. The gun was accurately machined to a smooth bore and provisions were made to attach the specimen directly to the end of the barrel. Various impact velocities are achieved by using different amounts of T28EI propellant fired with a T104E6 electric primer. The gun as modified has the capability of achieving carefully aligned impacts for a velocity range of from 200 to 3100 ft/sec.

The o.d. of the flat-faced steel projectiles are ground 0.001 in. smaller than the bore of the barrel. The flat impact face of the projectile is ground so that it is less than 0.0002 rad out of perpendicular to the sides of the projectile. An x-cut quartz cylinder of larger diameter than the

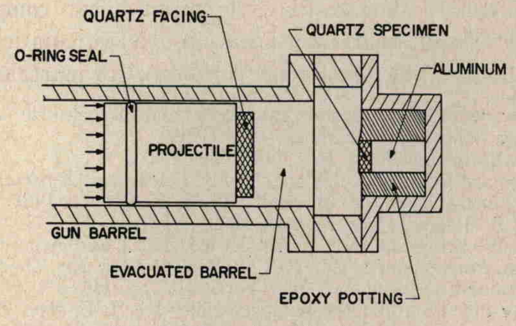

FIG. 3. Schematic of the impact.

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[21] In stress wave propagation there are two extremes of boundedness that are well defined; the solid infinite in lateral extent and the wire. In the former case there are no effects on the wave profile from lateral stress-free boundaries. In the latter case the solid is subjected to no lateral confining stresses. "Boundedness" as here used is meant to imply the relative position of the specimen between the two extremes in so far as its effects on the wave are concerned. The solid infinite in lateral extent has no boundedness, and the wire approaches infinite boundedness.