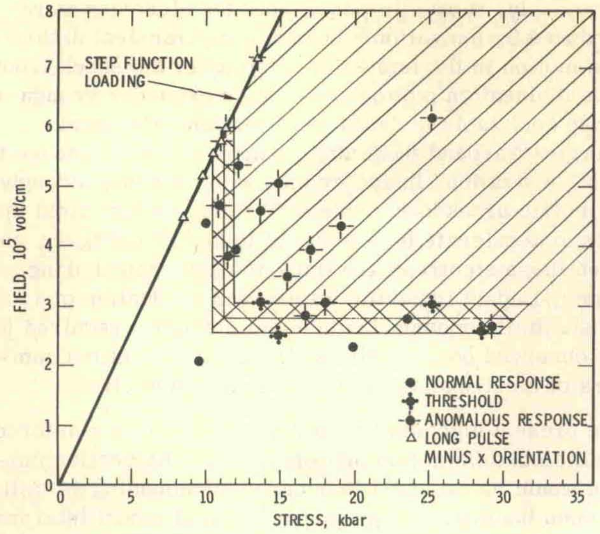

FIG. 7. Data on anomalous or normal response in Fig. 4 are transformed to the stress-vs-field plane. This representation shows that anomalous response is observed when *both* an electric field of $(2.8\pm0.3)\times10^5$ V/cm and a stress of (11.2 ± 0.7) kbar are achieved. The electric field threshold is found to be independent of stress amplitude for stresses greater than 11.2 kbar.

$$E_2=\frac{-P}{\epsilon}\left(1-\frac{T_0}{t_s}\right),\quad T_0<t<t_0 \tag{10}$$

where $t_s=l_s/U$.

These solutions for the fields have significantly different characteristics than those previously obtained for step-function loading; specifically, the solutions for step-function loading, when the displacement of the input electrode is neglected, are

$$E_2=\frac{-P}{\epsilon}\left(1-\frac{t}{t_0}\right),\quad t<t_0 \tag{11}$$

and

$$E_1=\frac{+P}{\epsilon}\left(\frac{t}{t_0}\right),\quad t<t_0. \tag{12}$$

The normalized solutions for Eqs. (9)–(12) are depicted in Fig. 6.

Until stress unloading occurs at $t=T_0$, the short pulse and step-function loading pulses produce identical responses. After the unloading wave enters the sample, i.e., when $t>T_0$, the magnitudes of the fields are constant in time. Furthermore, the magnitudes of the fields for a given polarization are directly proportional to the relative pulse durations. Thus, by introducing various pulse durations at a given stress, the amplitudes of the fields are fixed at different values.

It is important to note that the polarity of E_3 relative to the unloading front is the same as that encountered when shock-induced conductivity is observed to occur in $-x$ orientation disks under step-function loading. The shock-induced conductivity in $-x$ orientation disks was found to be a result of a free-electron source immediately behind the loading shock front.[9]

Although the solution for piezoelectric current in an external short circuit with finite conductivity in the unloaded region is not yet available, a solution for a completely shorted unloaded region, as given in the Appendix, predicts a current-time waveform similar to that observed when conditions well above the threshold are attained. Since a waveform of this sort can only be obtained by a model assuming conductivity in region 3, the anomalous response is clearly due to conduction in that region. Hence, the results will be analyzed on the premise that conductivity occurs in region 3.

The electrical field values in region 3 for each experiment are determined from Eq. (10) with results as displayed in Fig. 7. The same symbolism as in Fig. 4 is used for each experiment; each point shown indicates either normal response or an anomalous conductivity "tail". Study of the data in the field-stress plane indicates that the threshold for conductivity is achieved when an unloading stress of (11.2 ± 0.7) kbar *and* an electric field of $(2.8\pm0.3)\times10^5$ V/cm are simultaneously achieved. As stated earlier, the spread in threshold values is thought to be a result of various concentrations of acmite inclusions. Furthermore, the threshold amplitude of the electric field is observed to be independent of stress from 11.2 to 29 kbar, and the threshold stress of 11.2 kbar is found to be the same as that observed for the $-x$ orientation. We will consider the implications of these results in Sec. V.

V. DISCUSSION

Section IV demonstrated that the "anomalous" current-vs-time response observed in the short-duration shock-loading experiment is a result of shock-induced conductivity in the region of the disk that has been shock loaded and subsequently unloaded. This shock-induced conductivity is found to occur when both a threshold unloading-stress amplitude and a threshold electric field amplitude are exceeded. The threshold stress is found to have the same value as that observed for step-function loading of $-x$ orientation disks. In addition, the polarity of electric field in the unloaded region is the same as that encountered in the $-x$ orientation disks.

The polarity dependence of the conductivity in step-function loading permits the source of free electrons to be located immediately behind the loading shock front. Although the present observations do not uniquely require a source of electrons immediately behind the unloading shock front, they are consistent with the loading shock-front observations. The stress thresholds are the same for shock-induced conductivity in both loading and unloading; hence, the most consistent explanation for shock-induced conductivity in x-cut quartz is a source of electrons associated with both loading and unloading shock fronts.

It should be recalled that shock-induced conductivity is not observed in step-function loading of $+x$ orientation disks, because the field polarity impedes electron motion away from the shock front. A critical test of the location of the source of electrons is accomplished if electric field polarity is changed relative to the unloading shock front. To accomplish this an experiment was

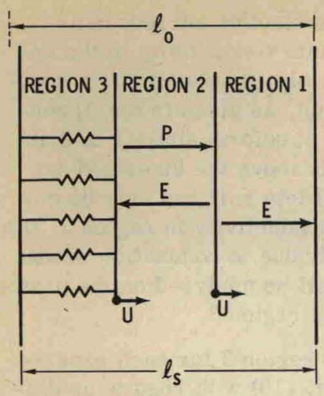

FIG. 8. Various electrical and mechanical regions along the thickness of the disk are shown when the short-duration pulse is entirely contained within the disk and the unloaded region 3 is highly conductive. This configuration would be expected to exist for stress and electric fields much greater than the observed threshold values.

conducted in which an incrementally stepped unloading wave shape was applied to a quartz gauge disk. The configuration was the same as that employed in the main part of the investigation except that the flier used to impact the quartz sample was a 1.5-mm-thick sapphire disk. Since the sapphire has a much higher mechanical impedance than quartz, the unloading occurs incrementally, unloading approximately one-half of the reflected stress amplitude in time increments equal to the round-trip transit time through the thickness of the flier. With an impact stress of 30.8 kbar, the stress was reduced to 15.9 kbar at the first unloading.

Extension of the analysis leading to Eq. (9) for incrementally stepped reductions of polarization showed that the polarity of the electric field after the first unloading was oriented so as to impede the acceleration of electrons from the unloading shock front. The current-time response from the disk showed no evidence for conductivity under these conditions. Later in time, after several unloading steps, the analysis shows that the electric field polarity reverses. When the reversal occurred and the electric field was greater than the threshold value, the observed current-time response from the disk was observed to have the same "anomalous" response as was observed for the complete unloading experiments.

The results of this incrementally stepped unloading experiment confirm that the unloading shock front is a source of electrons in a similar manner as observed for loading shock fronts. Furthermore, roughly the same threshold conditions are applicable to incremental unloading as for a shock front which causes complete unloading.

The principal requirements for a physical model to explain the shock-induced conductivity of x-cut quartz are (i) a mechanism for a threshold electric field for conductivity which is more than an order of magnitude lower than the electric field required for dielectric breakdown at atmospheric pressure, and (ii) a mechanism providing a source of electrons at the shock front under conditions in which the elastic strain energy and thermal energy are orders of magnitude too low for ionization of impurities. The experimental observation that the source of electrons is located immediately behind the shock front further restricts the model; the source is apparently transient and closely coupled to the shock fronts.

Previously, it was proposed[5] that the electrons were produced by ionization accompanying transient dislocation motion in the immediate vicinity of the shock front. This dislocation motion need not be extensive enough to cause detectable inelastic deformation. The local energies[23] around these dislocations are large enough to cause ionization. In accordance with presently accepted dielectric breakdown models,[24-26] the electric field then acts to accelerate the electrons to higher energies, and when these electrons are impacted upon neighboring atoms, impact ionization causes the production of a substantially enhanced number of electrons required for the observed conductivities. Hence, only limited numbers of electrons are required at the shock front.

The present unloading response observations reinforce the dislocation motion proposal, since dislocation motion would be expected to occur upon unloading as well as upon loading. The proposed physical model interprets the 11.2-kbar threshold stress as the threshold stress to cause limited dislocation motion in the shock fronts; the threshold field value of 2.8×10^5 V/cm is interpreted to be that field required to achieve impact ionization in x-cut quartz. This threshold electric field is a factor of about 30 lower than that required for dielectric breakdown at atmospheric pressure. The present observations indicate that the dielectric breakdown of x-cut quartz at atmospheric pressure is initiated by field ionization of impurities, whereas breakdown under shock compression is initiated by stress-induced ionization through dislocation motion above a critical stress value. The present model has the feature that the electric field threshold is independent of stress amplitude, in agreement with an important feature of the experimental observations.

In comparison to the present observations, it should be observed that analysis of the current-time waveforms previously reported for the $-x$ orientation experiments showed recovery of low values of conductivity when the electric field was reduced in amplitude.[9] Analysis of this recovery process showed that the recovery occurred when the electric field fell below $(1.9\pm0.5)\times10^5$ V/cm. This field amplitude was observed to be independent of stress amplitude, and the value is close to that observed in the present investigation. The experimental conditions of the present investigation are much better controlled and, unlike the analysis of the $-x$ orientation data, the present analysis does not depend critically upon details of the current-time wave shape. Hence, the electric field amplitudes of the present investigation are more accurately known than those obtained in the $-x$ orientation analysis. In any event, both the threshold electric field required to induce conductivity and the threshold electric field required to recover low conductivity values are observed to be independent of the amplitude of the stress.

The extent to which the present observation can be applied to stress pulses of arbitrary wave shape remains to be determined. The stepped unloading experiment reported in the present work and the widespread observation of anomalous response by various investigators who have subjected quartz disks to various wave shapes, demonstrate that the existence of the conductivity is not