Shock Dynamics Laboratory
Physics Department
Washington State University
Pullman, Wa. 99163

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RESPONSE AND USE OF A QUARTZ GAUGE

Y. M. Gupta

ABSTRACT

The usage of x-cut quartz as a stress transducer in shock wave experiments is reviewed and analyzed. A discussion of the piezoelectric response, various modes of operation and anomalies encountered is presented. The discussion is limited to only compressive loading. It is shown that x-cut quartz can be used very effectively at early times of loading. The behavior at later times is subject to error due to "ramping." A number of suggestions are made regarding the use of quartz gauges in shock experiments.

I. Introduction

X-cut quartz, due to its piezoelectric current response, has been widely used as a high-time-resolution stress transducer in shock work for more than ten years. It can be used to observe wave profiles in a material at both the impact face and the rear surface. By taking suitable care one can study samples of any desired thickness. The main advantages are (i) the high time resolution and (ii) ease in experimental use. The two main limitations are (i) impedance mismatch for transmitted wave profiles, particularly studies involving time dependent phenomena, and (ii) the upper limit for well characterized stress response in quartz is about 40 kbars. Despite these limitations the quartz gauge has been very useful in shock studies.

Almost all of the work done on the quartz gauge has been at Sandia Laboratories and some of the people most responsible for this development are Graham, Nielson, Benedick, Jones, Ingram, etc.[1-6] This report is an attempt to synthesize some of the existing work on quartz gauges to help workers using this gauge. No attempt towards completeness is made and the reader is referred to the bibliography at the end for individual details. A brief account of the theory of piezoelectric current analysis of the quartz gauge is given first; this is followed by the various modes of operation, and, finally, some recipes for use under shock loading are suggested along with some of the anomalies encountered. There are a number of personal suggestions and tips in this report; thus anybody who is going to use this technique heavily is suggested to find the optimum conditions for himself. Also a liberal use of the material in the references has been made.

II. Piezoelectric Current Analysis

Polarization charges are set up in a slab of x-cut quartz when a stress difference is applied to the two faces. We consider a shock wave of amplitude σ incident on a quartz disc as shown in Fig. 1(a). The two surfaces of the quartz disc are shown as -x and +x electrodes. These electrodes are defined such that a compressive wave of amplitude less than 50 kbar when travelling from -x to +x electrode produces a positive current.[2] (Current obtained by short circuiting the two faces.) To analyze the piezoelectric response of quartz the following assumptions are made.[3]

(a) State of one dimensional strain in quartz

(b) Electric fields due to the piezoelectric effect are one dimensional

(c) Stress instantly and uniformly applied to the whole face

(d) Electric short circuit exists between the two faces of quartz

(e) Infinitesimal strain

(f) Propagating shock wave does not disperse in time

(g) Wave velocity is constant, i.e. quartz is linear elastic

(h) Zero conductivity

(i) Dielectric permittivity remains constant

(j) Piezoelectric polarization is proportional to normal component of stress

While the list of assumptions is formidable almost all of them can be met to a good degree and deviations from these will be briefly discussed in Section V. With the above assumptions we get[3] (the derivation has been left out and the reader is strongly urged to read the piezoelectric current analysis section in Ref. 3)

$$i = \frac{kAU_s(\sigma - \sigma_\ell)}{\ell} \qquad (1)$$

where i = current output

A = electrode area collecting charge

U_s = wave velocity in quartz

ℓ = thickness of gauge

σ = stress at impact face of quartz

σ_ℓ = stress at rear surface of quartz

k = piezoelectric current coefficient.

For $0 < t < \ell/U_s$, i.e., less than one transit time, Eq. (1) reduces to

$$i = \frac{kAU_s\sigma}{\ell} . \quad (2)$$

This is the fundamental relation in the use of quartz gauges and by doing a symmetric impact experiment (quartz on quartz), one can produce a stress pulse of known amplitude as shown in Fig. 1(a). The current jump associated with such a stress pulse can be measured; an idealized version is also shown in Fig. 1(a). This allows the calculation of k from Eq. (2), since all other quantities can be measured. By doing this for various stresses it is possible to obtain k for the whole stress range. Then an arbitrary stress jump produced in a shock experiment can be determined through Eq. (2) by measuring the current associated with such a jump.

It is important to recognize that in the above mentioned calibration procedure, one essentially calibrates a square wave input. However, in a typical shock experiment, a continuous current-time profile is converted into a stress time profile even though beyond the first jump the current corresponding to a denoted stress did not come about as a square wave input. This is more easily understood by referring to Fig. 1. In Fig. 1(a) we show the stress pulse and the current-time profile it produces. In Fig. 1(b) we have a typical current-time profile on the right side of the gauge. Such a current-time profile is converted to a stress-time profile shown in the same figure by using Eq. (2). This procedure is certainly justified for position 1 since it comes by a jump similar to Fig. 1(a). The same cannot be said for position 2 since it comes by a current drop from position 1. Similarly we can see that positions 3, 4 and 5 did not come by a jump from position 0. *The use of a set of discrete calibration prints to obtain a continuous stress-time response is one of the basic assumptions of the quartz gauge.* The justification for such a procedure is provided by comparison of profiles from other techniques and doing multiple structure calibration experiments. Anomalies are known to exist under certain conditions and these are taken up in Section V.

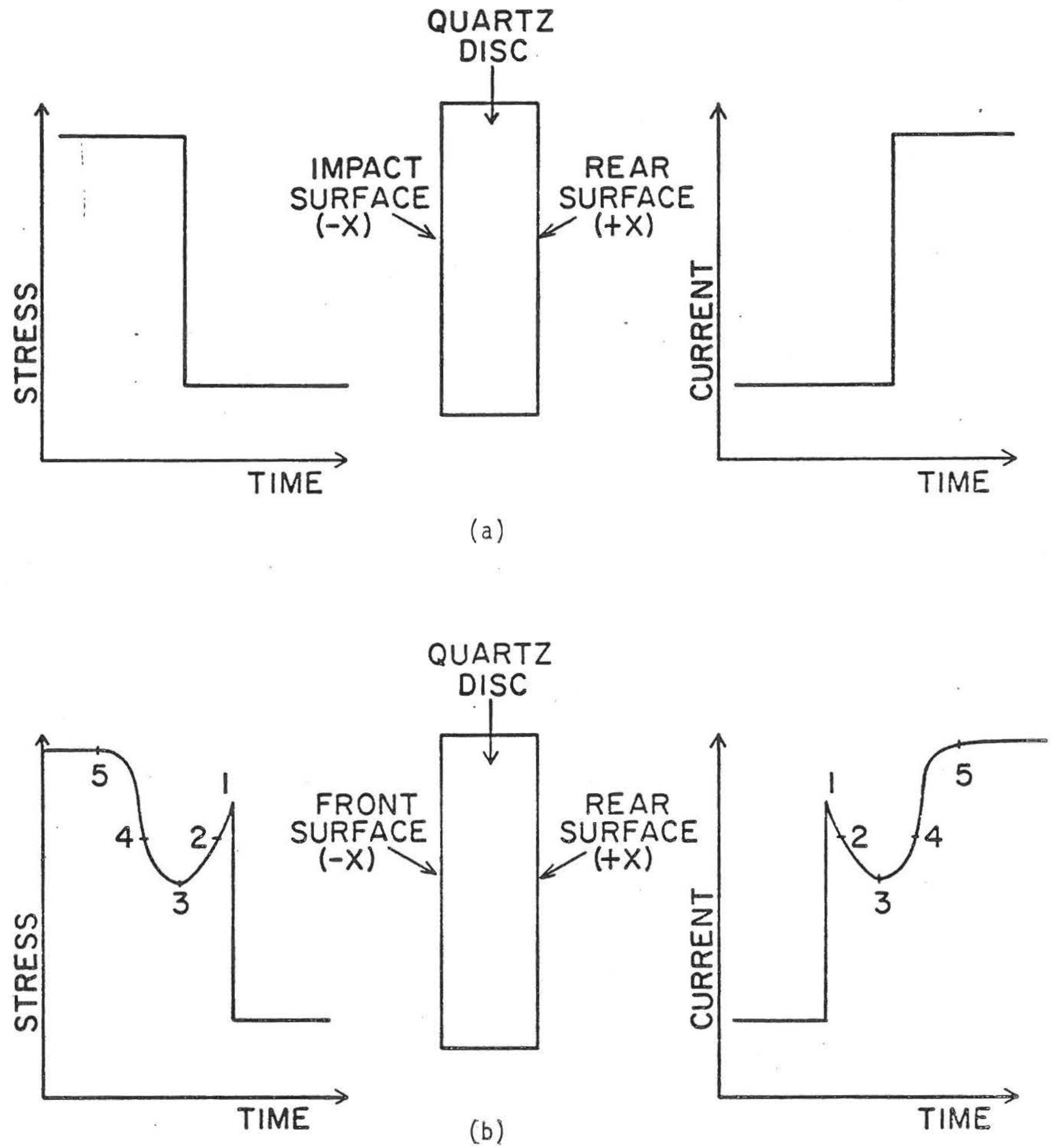

Fig. 1 Schematic view to illustrate the working of a quartz gauge.
(a) Calibration experiment result showing idealized square wave input and output.
(b) Arbitrary experiment result showing current-time profile and deduced stress time profile.

III. Modes of Operation

The quartz gauge can be used with an open circuit or a short circuit between the two faces of the gauge, to get the stress time profile in a shock experiment. Equations (1) and (2) are a consequence of the short circuit usage. The open circuit analysis is given in Appendix I where it is shown that the measurements give the average stress in quartz. This is not a very desirable situation for shock experiments involving time-dependence and we will only be concerned with short-circuit usage in the rest of the paper. The quartz gauge has been used in the following modes or configurations.

A. Fully Electrodes Discs

These were the earliest types of gauges and did not have any guard rings.[1,2] The basic design for use is shown in Fig. 2. The response of the gauge is strongly controlled by the diameter to thickness ratio ($\frac{d}{\ell}$). Graham et al. have reported a range of mean values for k (for stresses between 9 to 25 kbar) depending on the d/ℓ values. These are[3]

$$1.90 \times 10^{-8} \text{ coul-cm}^{-2}\text{-kbar}^{-1} \leq k_{mean} \leq 2.17 \times 10^{-8} \text{ coul-cm}^{-2}\text{-kbar}^{-1}$$

for $$2.0 \leq d/\ell \leq 25.0.$$

The current distortions are smaller for large d/ℓ values. But there is a serious problem in working with large discs when observations are made on relaxing wavefronts. This will be discussed in a subsequent section.

Those familiar with the operation of a parallel-plate capacitor will realize the presence of edge effects perturbing the one dimensional electric fields. The edge effects from lateral rarefaction waves make the situation worse. This mode will not be discussed in any further detail here and the reader is referred to the earlier work on quartz gauges for this information.[1-3]

B. Quartz Gauge with a Guard Ring (Shunted Mode)

The quartz gauge with a guard ring is shown in Fig. 3. The difference in this and the fully electroded disc is the presence of a guard ring on rear surface of the gauge. This allows only the central portion within the guard ring to be the region of interest; thus avoiding the edge effects encountered in the fully electroded disc. The guard ring quartz gauge has two modes of operation, viz., shunted and shorted. These are now described.

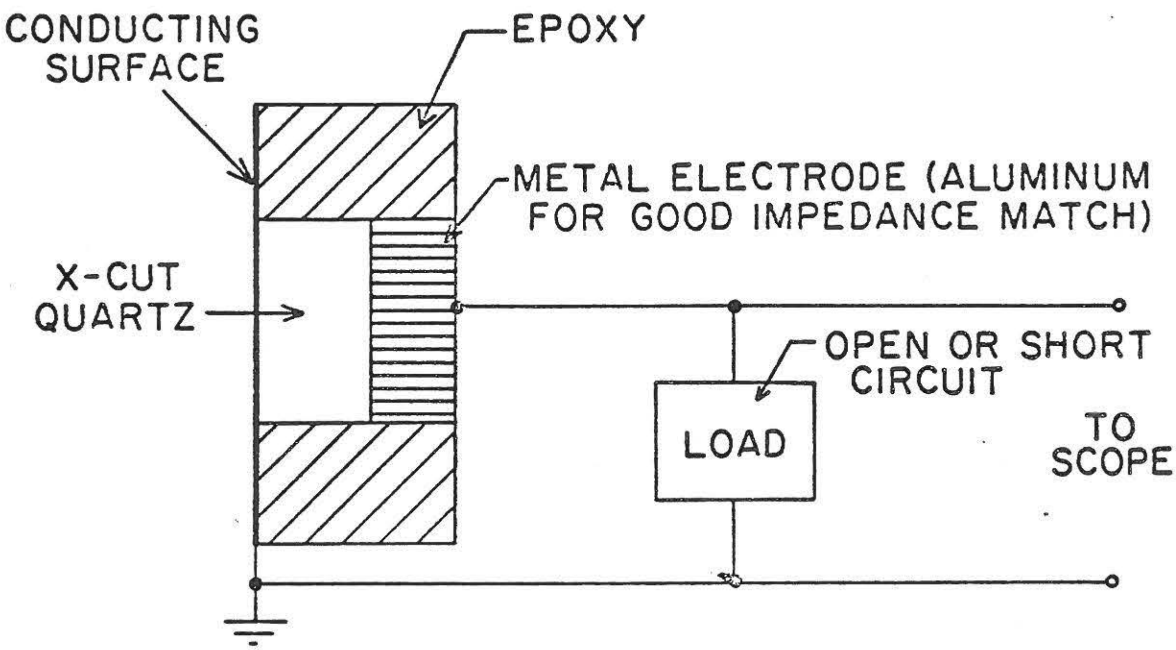

Fig. 2 Fully electroded x-cut quartz disc. (Ref. 2)

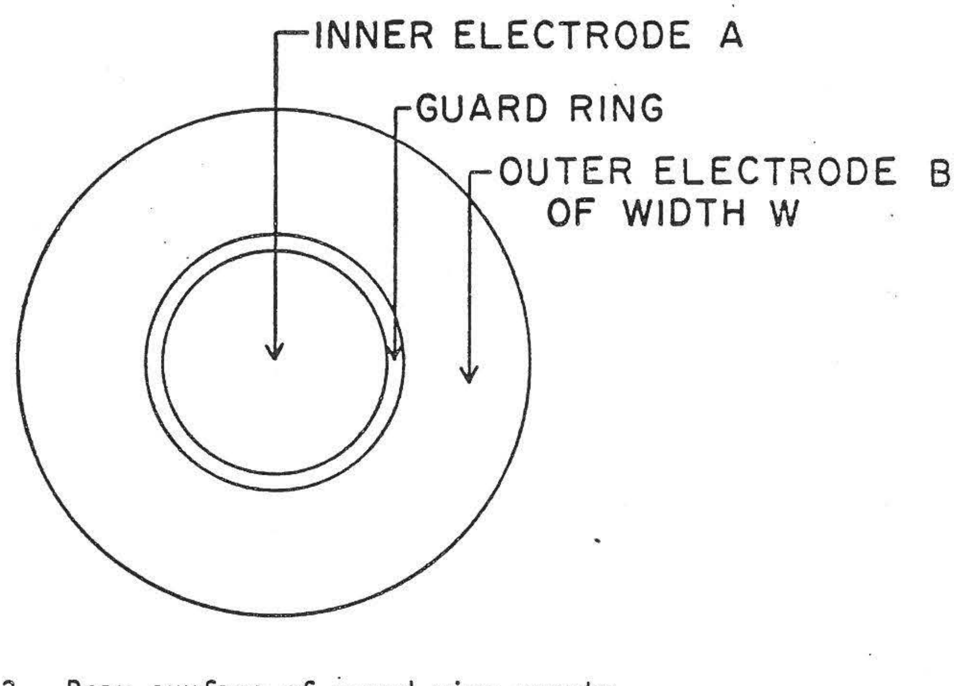

Fig. 3 Rear surface of guard ring quartz gauge showing the various regions.

The shunted quartz gauge with a guard ring is the most thoroughly investigated and calibrated mode of operation.[3,6,7-10] The basic gauge design is shown in Fig. 4(a). Attention is drawn to the lack of gold plating on the side of the gauge and the presence of a ballast or shunt resistor R_B. The short circuit condition is not completely satisfied, instead it is the voltage drop across a small resistance which is monitored on the oscilloscope. While Graham suggests a small value for $R_A (\leq 10\Omega)$, it might be more useful to use $R_A \approx 50\Omega$, to avoid the problem of cable reflections due to a small capacitance at the scope. Also 50Ω is still negligible compared to resistance across the quartz, thus the gauge can still be considered as a constant current supply.

In order to approximate zero fields across the guard ring gap to insure no distortion of one dimensional field lines, a ballast or shunt resistor R_B is used such that

$$R_B = \left(\frac{A_A}{A_B} \right) R_{eff} \qquad (3)$$

where A_A = area of electrode A
A_B = area of electrode B
and $\frac{1}{R_{eff}} = \frac{1}{R_A} + \frac{1}{R_T}$

(Refer to Figs. 3 and 4(a). R_T = termination resistance at scope.)

To clarify this point the following explanation is given. The assumption of uniform and equal surface charge density over the two electrodes A and B in Fig. 3 is reasonable. Thus the current from each electrode on short circuiting is proportional to the areas A_A and A_B respectively. The voltage drops between the two electrodes and ground are $i_A \cdot R_{eff}$ and $i_B \cdot R_B$ (see Fig. 4(a)). For zero field across the gap we immediately get Eq. (3). It should be pointed out that the above relation is at best an approach to minimize the fields across the gap since the fields or charges across the outer electrode area are not uniform due to edge effects of both types (electrical field fringing and lateral release at the outer perimeter of electrode B). Graham et al. have empirically determined that for $w \geq 1.5\ell$ (where w is defined in Fig. 3 and ℓ is the thickness of gauge) the distortion from the outer electrode does not affect the current response during the first wave transit time.

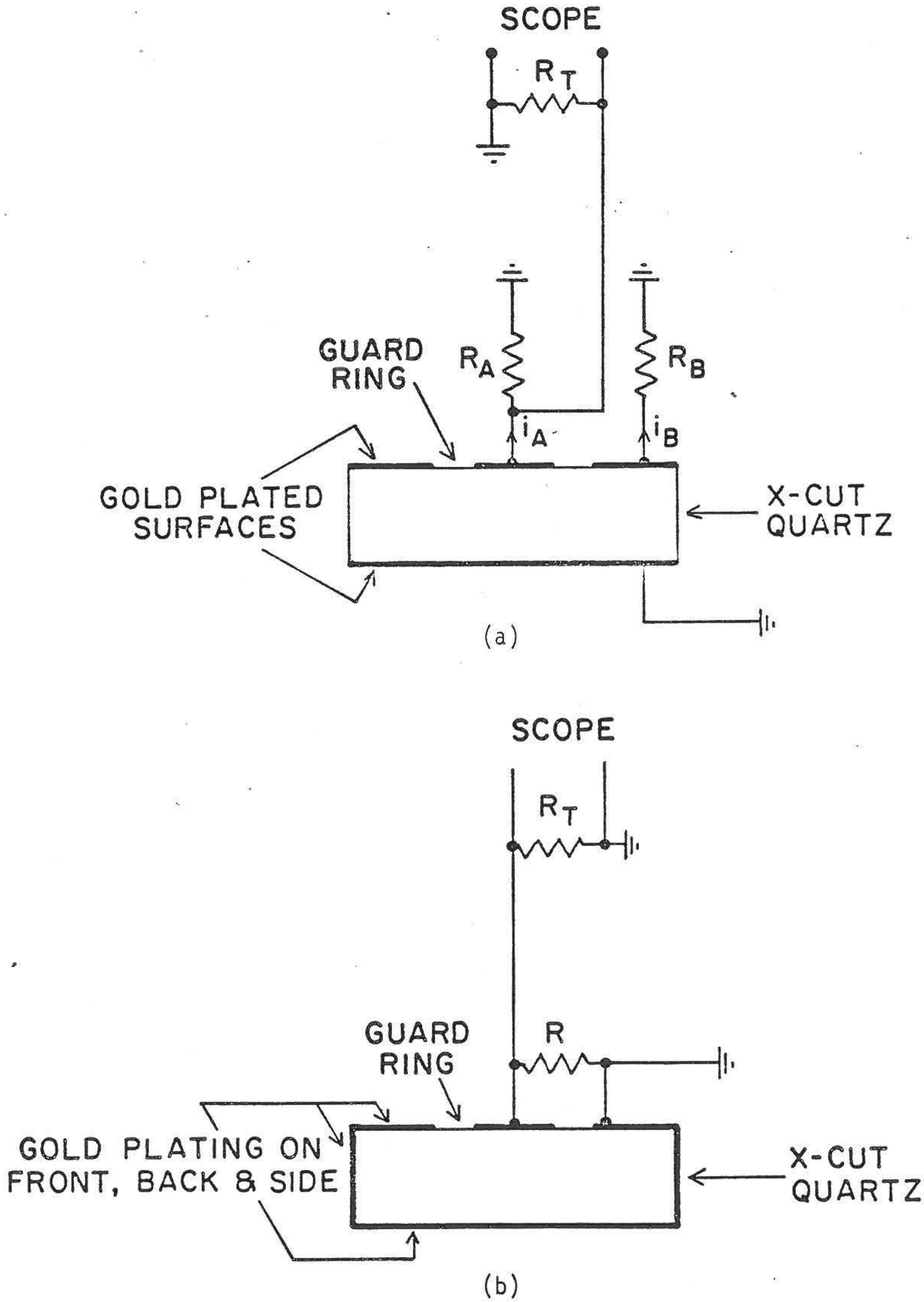

Fig. 4 Guard ring quartz gauge configurations. Scope termination resistor is R_T.
(a) Shunted gauge
(b) Shorted gauge

The original calibration of Graham et al. was for gauges where the guard ring area was 2% to 4% of the inner electrode area.[3] (See Fig. 3) This restriction was mostly due to gauges available at that time. This condition has been relaxed since then and the new calibration given below is for any reasonable size guard rings. Freeman's calculation shows that field-fringing due to variations in guard ring gap width does not cause significant deviations from the one-dimensional model.[7] Thus Eq. (2) for current response for this mode is given as[8]

$$i = \frac{kAU_s \cdot \sigma}{\ell}$$

where k = $[2.004 \pm 0.0056 + (9.65 \pm 0.29)10^{-3}\sigma] \times 10^{-8}$ coul cm^{-2} kbar^{-1}

A = area of inner electrode plus half the guard ring gap area

U_s = 5.72×10^{5} cm sec^{-1}

ℓ = thickness in cms

i = current in amps

σ = stress in kbars

One of the main advantages of the shunted gauge is that Eq. (2) is dimensionally scaled with respect to A and ℓ in this mode. The calibration of Graham et al. is good to about 2%. Without a doubt this mode of operation is the best to use since the gauge meets the assumption made in deriving the theory of piezoelectric response. However, there are some fabrication problems in actually using this mode with insulators and there are taken up in Section IV. It has been pointed out by Graham that U_s is just a dummy variable, i.e., any value of U can be used to compute k from the calibration experiments provided the same value is used in all subsequent inverse calculations.[8] This calibration is good to 40 kbars and takes care of non-linear behavior.

C. Shorted Quartz Gauge

This mode of operation is widely used but calibration work on this gauge is sparse. The first work was that of Jones[4] and Jones and Halpin.[5] They observed that the two types of quartz gauges (shunted and shorted) gave currents within 2% of each other when subjected to identical stresses. The basic gauge design is shown in Fig. 4(b).

The main difference is the gold plating on the side which allows for the ground electrode to be on the same side as the inner electrode. This is the main advantage and shortcoming of this gauge. It makes it very easy to use the gauge but theoretical analysis is not too well understood.[11,12] There are various expressions for calibration constants given for this mode. The calibration given here is that determined from the work of Hayes and Gupta.[13]

$$k = (1.8623 + 12.54 \times 10^{-3}\sigma) \times 10^{-8} \text{ coul cm}^{-2} \text{ kbar}^{-1} \qquad (4)$$

All other quantities are as defined earlier. It should be noticed that $dk/d\ell$ for the shorted mode is nearly 30% larger than that for the shunted mode. It has also been determined that the shorted gauge is not dimensionally scaled with respect to A and ℓ.[12] Thus the above value of k is good only for the particular shorted gauge type employed in the calibration work of Hayes and Gupta,[13] i.e., a gauge 1/2 inch in diameter and 1/8 inch thick with an inner electrode diameter of 3.5 to 3.8 mm and a guard ring gap area which is 5 to 8 percent of the inner electrode area.

This mode of operation has been recently criticized by Graham because it does not meet the assumption made in the piezoelectric response theory.[14] The major shortcomings are (i) deviations in response from the shunted gauge, which makes the response to arbitrary wave shapes hard to judge quantitatively, especially at later time. (ii) Each shorted gauge configuration has to be calibrated due to lack of universal scaling. (iii) This reflects deviation from one dimensional behavior. It should be emphasized that the main shortcoming of the shorted gauge is not due to the absence of the shunting resistor. The work done by Hayes and Gupta suggests that the presence of fields across the gap can be ignored if the effective charge collecting area is taken to include half the guard ring gap area.[13] Also the nonexistence of fields across the gap even in the shunted gauge is only approximately satisfied. It is the presence of the gold plating on the side as shown in Fig. 4(b) which appears to be the serious problem. Graham suggests that it is the conductivity originating from regions of concentrated fields at the side of the gauge which causes breakdown in one dimensional field conditions.[14] This appears to be plausible as seen from Graham's data shown in Fig. 5.[15] The percentage deviation of the shorted gauge from the shunted gauge is plotted as a function of the ratio w/ℓ where w and ℓ have been defined in Fig. 3. For large w/ℓ

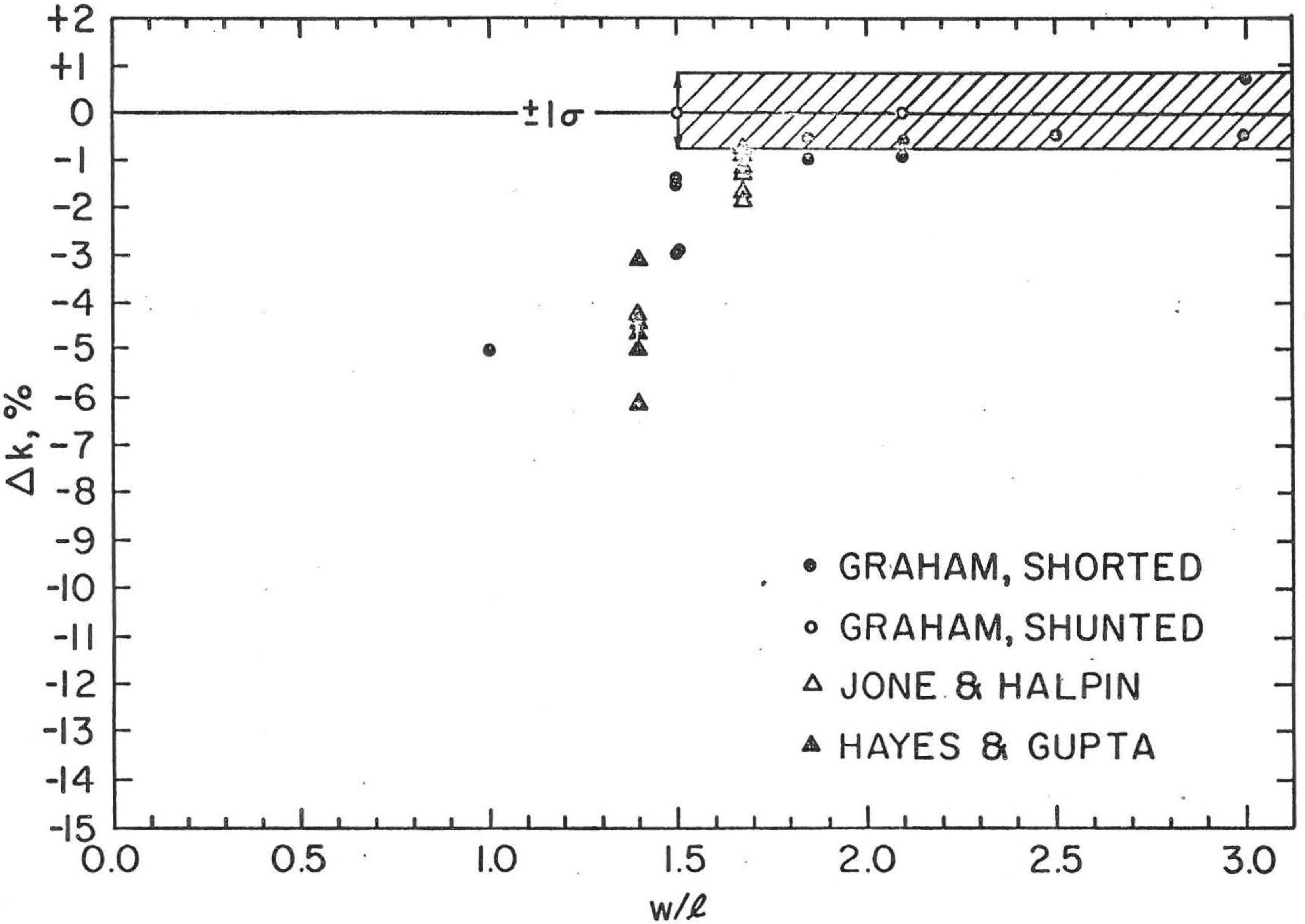

Fig. 5 Percentage deviations of shorted gauge k-values from shunted gauge plotted as a function of w/ℓ. (Ref. 15)

the two gauges have similar behavior. In fact for $w/\ell \geq 3.0$ the two gauges give the same response. This is probably due to the fact that conductivity effects at the peripheral edge of the gauge are very far to influence the behavior within the central electrode.

Three features of the shorted gauge can be summarized; (i) the initial current jump can be related to stress by Eq. (2) if that particular configuration has been calibrated, (ii) the shorted gauge with $w/\ell \geq 3.0$ can be used in lieu of the shunted gauge at all times, (iii) the fields across the gap do not appear to be a serious problem.

IV. Recipes for the Use of a Quartz Gauge

As mentioned in Section I, the quartz gauge can be used to monitor the stress-time profiles in specimens of various thickness. In this section we will briefly describe how the gauge can be used to yield the required stress profiles. First some of the important precautions needed in quartz gauge experimentation are described. The reader is urged to see references 6, 11, and 12 for use of quartz gauges.

A. Precautions in Use of Quartz Gauge Experiments

1. The dimensions of the gauge should be so as to allow recording under uniaxial strain conditions for times of interest. If we are only interested in the compressive wave then time of recording is given by $t_r < U_s/\ell$ and $w \geq 1.5\ell$. If using shorted gauges, then $w/\ell \geq 3.0$ is needed to use shunted gauge calibration. If a specimen is bonded to a gauge, then the lateral dimensions of crystals should be such as to maintain uniaxial strain conditions in this assembly. For studying unloading waves and reverberations, the lateral dimensions would have to be adjusted accordingly to maintain uniaxial strain condition.

2. Examine gauge carefully for plating and other defects. Plating resistance and acmite count supplied by the supplier should be low. Do not use a gauge which has an unplated spot in the circular cylindrical region of the inner electrode. A small unplated region ($\approx 10^{-4}$ inches in diameter) in the B electrode region can be tolerated. There should be no protruding gold spots on the impact or the -ve electrode side of the quartz gauge. On the positive side there should be no spots in inner electrode region. Try not to scratch the gauge excessively. Never use a gauge which has been dropped.

3. The guard ring should be so cut as to satisfy all the dimension requirements relating w and ℓ. In fact an inner electrode diameter of 3.5mm to 4.0 mm is a good optimum. Any smaller diameter than this makes gauge harder to use and also increases gap area to inner electrode ratios. This is given as $A_G/A_i = 2\pi r\delta r/\pi\gamma^2 = 2\delta r/r$ for small δr. A larger diameter, while easier to work with, not only makes for expensive gauges but can severely degrade the quality of profiles due to tilt for relaxing profiles similar to those shown in Fig. 1(b). This is due to the fact that the quartz gauge integrates the response over an area and for finite tilt, this would mean that stress is increasing in one part and decreasing in the other. See work by Asay for a detailed discussion of tilt on response of quartz gauges.[16]

4. The guard ring should be cleaned with well defined edges (not jagged) and free of any conducting material.

5. Minimum amount of solder and heat should be used to connect leads to the gauge. Resistor should be as close to the plating as possible. The copper wire used should have large enough dimensions to reduce inductance effects and yet be easily soldered. The last two conditions are useful to avoid current loops which degrade rise times.

6. If the quartz gauge is impacted or bonded with another material then the gauge should be very clean on the impact side. When the gauge is bonded to a specimen the epoxy bond should have a thickness of the order of 1-2μm.

7. If the quartz is going to see a stress in excess of 40 kbar, use another technique.

8. Coaxial cables to bring out the signal from the gauge to oscilloscopes should be carefully selected to avoid degradation in rise times and signals.

B. Quartz Gauge Use for Transmitted Wave Profiles

Here the wave profiles are observed by the quartz gauges bonded to the back of the specimen of desired thickness. A point of concern here is the difference in shock impedances of the specimen and quartz. If a time dependent phenomenon is being studied then a large difference in the shock impedances make the experimental results useless without access to a flow code.

The shorted gauge shown in Fig. 4(b) is very easy to use with both metallic and insulating specimens. The gauge (with guard ring already cut) should be bonded to the back of the specimen with a minimum of epoxy. With a little care the epoxy bonds can be made less than 1-2μm.[11,12] This can be then potted in the target ring and wires connected observing the precautions mentioned earlier.

In using the shunted quartz gauge, the -x electrode (as defined in Section II) has to be grounded. With metal specimens this poses no problem, as the ground lead can be connected to the specimen itself. The situation is not so simple with insulating specimens. In principle one can get around by plating the back of the specimen with aluminum or chrome-gold. This can then be used to connect the ground lead. There are some distinct experimental problems involved in maintaining ground contact and it might be better to use a shorted gauge with $w/\ell \geq 3.0$. If the experimental conditions force one to use a shunted gauge, then the following technique is suggested. Plate the side of the crystal to which the gauge is to be bonded with silver or chrome-gold. After carefully bonding the gauge, deposit a large amount of aluminum or chrome-gold on the same side, taking care to mask the gauge. (Chrome-gold is advisable if the specimen is to be handled a lot after plating; silver is a good conductor but forms sulphides in air; aluminum is not as good a conductor as silver or chrome-gold.) This assembly can then be potted in the target ring and wires connected.

C. Quartz Gauge Use for Impact Face Wave Profiles

Here the quartz gauge is directly impacted on to a specimen and the wave profile at the impact face of the specimen is obtained. The continuity of stress and particle velocity across the interface allow the obtaining of σ-u states in the material directly. Recently Hayes has used this technique very effectively to study solid-solid phase transformations.[12] He has obtained transformation rates directly from the data obtained at the impact surface.

The use of a shorted gauge is straightforward.[11,12] The use of a shunted gauge with metals is again easy, but with insulating specimens the projectile and target assembly have to be plated with aluminum or chrome-gold to obtain ground contact with -x electrode of gauge. Again if possible, a shorted gauge with $w/\ell \geq 3.0$ can be used. The gauge can be mounted in the target and specimens in the projectile or vice-versa. But the projectile gauge is a necessity for measuring front surface stress time profiles in specimens at temperatures other than room temperature.

D. Combined Front Surface and Rear Surface Measurement

If a quartz gauge is impacted with a specimen which has a gauge bonded to the back surface, then such an experiment yields three pieces of information: (i) front surface profile, (ii) rear surface profile, (iii) shock velocity in specimen. Care has to be taken in obtaining stress-time profile from the gauge mounted in the projectile. The high frequency signals can be severely degraded by large pieces of unshielded conductors. The shock velocity measurements also require care especially with matching cable lengths for accurate measurements.

V. Anomalies Encountered in Quartz Gauge Use

The piezoelectric response equation was derived with the various assumptions given in Section II. In this section we analyze these assumptions and the situations where these are not met and thus the consequence. In Table I (taken from Ref. 10) the most commonly violated assumptions are shown.

Table I

Potential Deviations from Linear Relation

$$i(t) = \frac{kA}{t_0} \sigma(t) = 100\%$$

Effects	Typical Percentage Deviations (at 25 kbar)
Conductivity	100
Arbitrary Gauge Configuration	100
Nonlinear Piezoelectric Constant	10
Finite Strain	10
Dielectric Constant Change	1
Electromechanical Coupling	1
Variable Shock Velocity	1

Two other assumptions are also violated, these involved the short-circuit condition and instantaneous application of stress over the -x electrode face. The first one has been discussed in Section IV(B). The second violation involving "zero tilt" is serious for relaxing wave fronts only. This can be minimized by keeping the recording area to a minimum. The variable shock velocity deviation in Table I is eliminated by using the same value in both the calibration and its inverse experiment. The deviations involving dielectric constant-change and electromechanical coupling change are too small for just the compressive wave and will be neglected. For unloading and shock reverberation experiments, these can be very large and a discussion of this problem has been given by Lysne.[17]

The non-linear piezoelectric constant is corrected by incorporating the $dk/d\sigma$ as shown in the text. The finite strain correction can be corrected by the technique of Graham et al.[3] and Asay has shown that the instantaneous current jump i_o and current at time t are related by[16]

$$i(t) = i_o \left[1 + \frac{2\varepsilon_x U}{\ell} \cdot t\right] \quad (5)$$

where ε_x is the longitudinal strain of quartz assumed linear elastic, (the correction for non-linear behavior is a second order correction and can be ignored) then Eq. (5) becomes

$$i(t) = i_o (1 + \alpha P_x \cdot t) \quad (6)$$

where $\alpha = 2U/C^{\ell}_{11}$ $(U \equiv U_s)$

U and the longitudinal velocity C_ℓ are the same for linear elastic material. C^{ℓ}_{ij} are the elastic constant.

The conductivity anomaly causes the largest deviation and is not often obvious. It can occur and cause deviations as in a shorted gauge unless $w/\ell \geq 3.0$. It can also occur for loading in the -x orientation, i.e., if the wave is travelling from +x to -x electrode. It can also occur under short duration pulses in shock-loading.[9] Graham and Ingram[9] have discussed this in detail and have shown that it is due to shock induced conductivity in a region that has been first loaded and then unloaded. *It should be emphasized that until unloading occurs, the gauge response is normal in all respects.* Normally this happens beyond the transit time through the gauge, which is the time of interest anyway. There are two exceptions to this rule; (i) in time dependent phenomena, frequently the shock is unstable and the first wave decays till the second wave catches up, e.g., stress relaxation and phase transition studies. (ii) The unloading history of a specimen is to be studied, in which case the thickness of a specimen and/or flyer plate is ℓ_f and $T_o < t_o$ where T_o and t_o are transit times through flyer plate and gauge respectively. It has been shown that the time of transit through stressed region $t_s \approx t_o$. Also $2\ell_f/U = T_o$. For various T_o/t_s ratios the response as a function of stress is shown in Fig. 6. The shaded region represents anomalous response. For $T_o/t_s > 1.0$ there is no problem since we no longer have a short pulse. (See above condition in italics.)

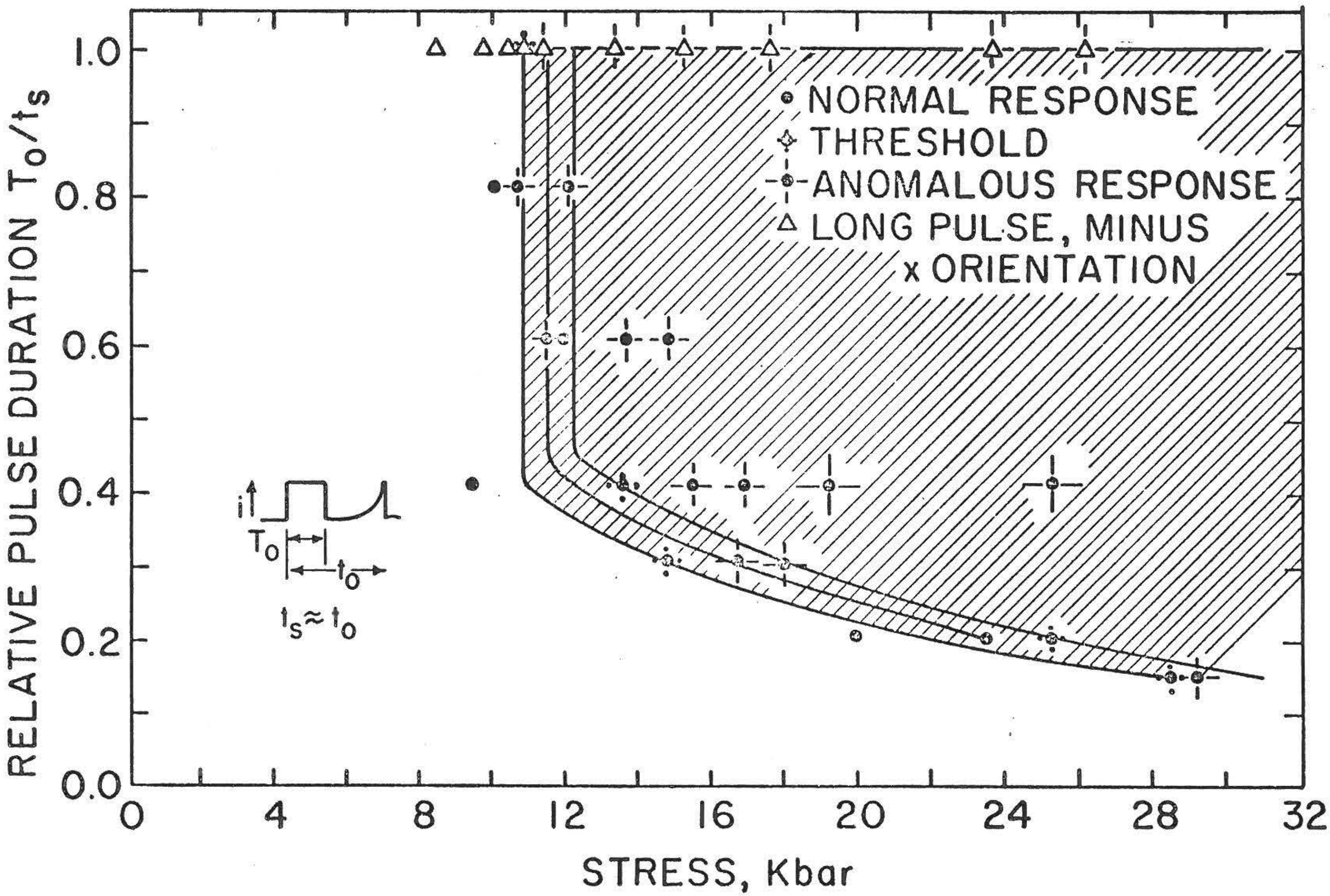

Fig. 6 Response of different pulse durations as a function of stress. Shaded region represents anomalous response. Experiments on -x orientation long duration are shown along the line $T_o/t_s = 1.0$. (Ref. 9)

To know whether an anomalous response is going to occur or not, measure thickness (time coordinates) of pulse which is unloading and find ratio to t_0 and use the Fig. 6 with a knowledge of the peak pulse stress.

While the finite strain causes the current to increase after the initial jump, not all of the increase can be attributed to it. In Fig. 7 we show a quartz record from the work of Hayes.[11] The broken line gives the profile obtained without any correction. The solid line is the ideal behavior expected. The finite strain cannot account for all the increase. This "ramping" appears to be inversely correlated to d/ℓ values where d is the diameter of the quartz gauge and ℓ the thickness. This reasoning is purely empirical and based on observation of quartz records. There is no theoretical way to correct for it at the present moment. Hayes has suggested correcting this ramping by assuming a linear ramp and writing an expression for $i(t)$ similar to Eq. (5).[11]

$$i(t) = i_0 (1 + \beta \cdot t) \tag{7}$$

The term β is to be adjusted numerically so as to give $i(t) = i_0$ at all times of interest. Hayes has shown that near the first jump this reduces current by about 0.2%.[11] Such a procedure, though good for initial times can be in error at late times, if the material property of the sample itself causes a stress increase. It is felt that "ramping" is probably the most serious limitation in studies where accurate stresses are needed at later times. An example is the second wave amplitude in a two wave structure.

VI. Concluding Remarks

In this report some of the important features of the quartz gauge have been briefly described. The attempt here was to make the various advantages, shortcomings and uses known to anybody starting out work in quartz gauges. Once such information is available, the user can then decide the best conditions for his experiment and find out the detail involved. The very details of the actual fabrication for different uses have been left out and the author can be consulted for these or the references 6, 11, 12 and 16 can be looked up. Also the discussion in this paper has generally been limited to observations for less than one transit time through gauge. For larger times and unloading waves the reader is referred elsewhere.[17] The one final word of caution is to avoid deviations from the stringent conditions required and using an arbitrary gauge design in the hope of easier experimentation for this would make the final interpretation of experiments impossible.

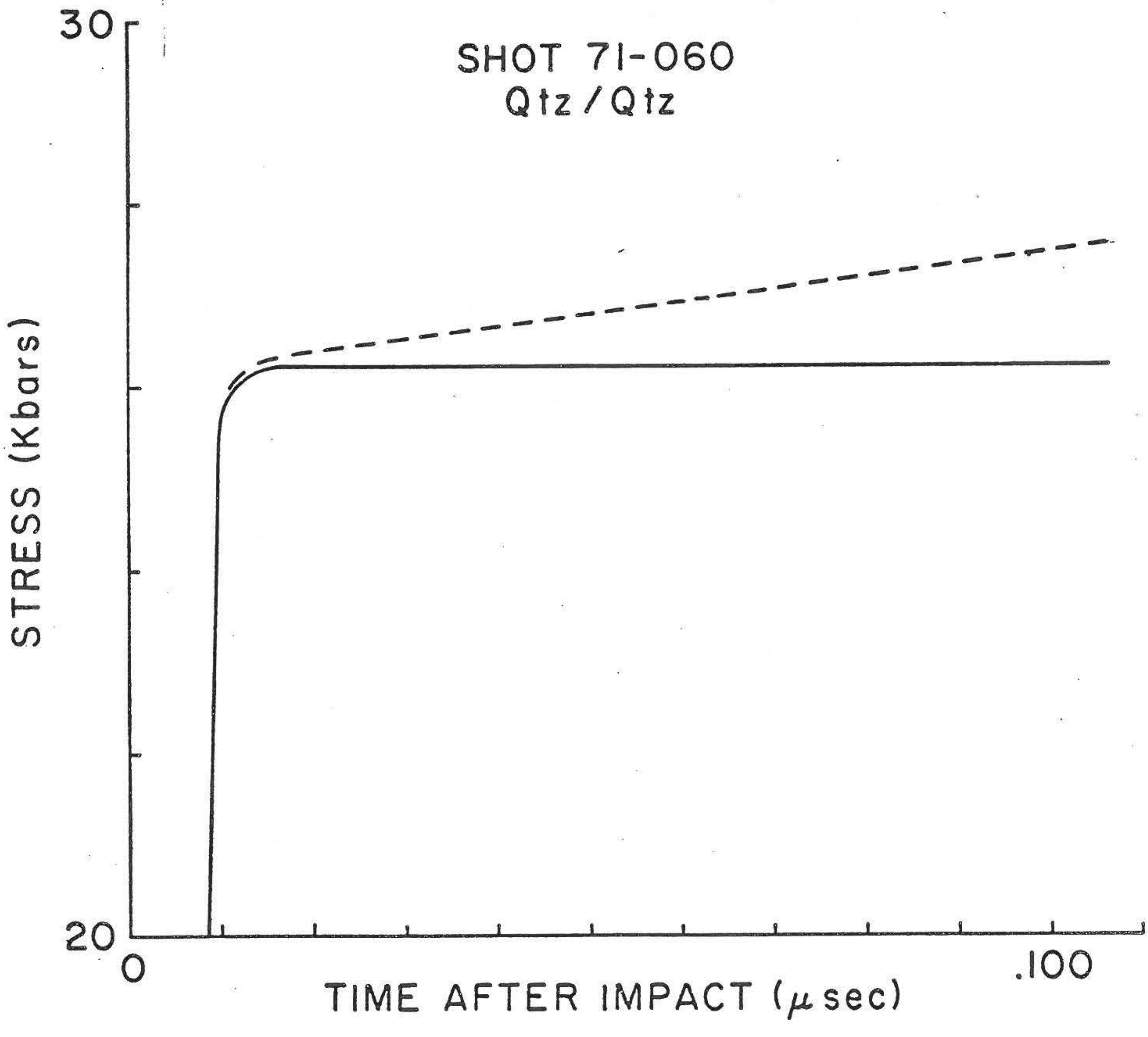

Fig. 7 Quartz calibration shot demonstrating ramping. Broken line gives observed behavior; solid line is idealized response with no ramping. (Ref. 11)

ACKNOWLEDGMENTS

Helpful discussions with Mr. R. A. Graham and Professor G. E. Duvall are gratefully acknowledged. The author is thankful to Professor Duvall for his thoughtful criticism of the text presented here.

APPENDIX I

Open Circuit Analysis of a Quartz Gauge

The short circuit assumption given in Section II will be replaced by the open circuit existence. Other terms remain the same. The displacement field within the quartz is given by

$$D(x,t) = \varepsilon(x,t) \cdot E(x,t) + P(x,t) \tag{1}$$

or

$$\int_0^\ell D \cdot dx = \int_0^\ell \varepsilon E \cdot dx + \int_0^\ell P \cdot dx \tag{2}$$

where E = electric field

P = polarization field

and ε = dielectric permittivity.

Making use of the zero conductivity assumption we have $\nabla \cdot \vec{D} = \partial D/\partial x = 0$. This gives

$$D = \frac{1}{\ell} [\int_0^\ell \varepsilon E \cdot dx + \int_0^\ell P \cdot dx] . \tag{3}$$

The open circuit condition gives $\int_0^\ell E \cdot dx = -V$ and assuming constant permittivity we get

$$D = \frac{1}{\ell} [-\varepsilon V + \int_0^\ell P \cdot dx] \tag{4}$$

Also open circuit implies no current flow, i.e., $i = 0$ or

$$i = \frac{dq}{dt} = \frac{d}{dt} \int \nabla \cdot \vec{D}\, dv = A \cdot \frac{dD}{dt} = 0. \tag{5}$$

This gives

$$\frac{d}{dt} (\varepsilon V) = \frac{d}{dt} \{\int_0^\ell P(x) \cdot dx\} \tag{6}$$

By the last assumption in Section II, $p(x) = f\sigma(x)$. Also since wave velocity is constant and there is no dispersion, we have $\sigma(x,t) = \sigma(x - U_s \cdot t)$.

Thus $\varepsilon \frac{dV}{dt} = -fU_s \int_0^{\ell} \frac{\partial\sigma}{\partial x} \cdot dx = -fU_s \, [\sigma(\ell) - \sigma(0)]$ (7)

also permittivity $\varepsilon = \frac{\ell c}{A}$ where c is capacitance, so V can be obtained from Eq. (7).

$$V = \frac{fAU_s}{c} \left[\frac{1}{\ell} \int_0^t [\, \sigma(0) - \sigma(\ell)] \cdot dt \, \right]. \tag{8}$$

The term in the brackets gives the average stress in the quartz disc.

REFERENCES

1. O. E. Jones, F. W. Nielson and W. B. Benedick, J. Appl. Phys. 33, 3224 (1962).
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7. J. R. Freeman, "Field Fringing Around the Insulating Gap in Guard Ring Quartz Gauges," Sandia Laboratories Report, SC-RR-69-55 (1969).
8. R. A. Graham, private communication (latest calibration), (1972).
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10. R. A. Graham, "Conductivity in Shock-Loaded X-cut Quartz," Sandia Laboratories Report, SC-RR-72-2877 (1971).
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12. Y. M. Gupta, Ph.D. Thesis, Washington State University (1973).
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14. R. A. Graham, private communication and APS Meeting at Denver (1972).
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17. P. C. Lysne, J. Appl. Phys. 43, 425 (1972).

FIGURE CAPTIONS

Fig. 1 Schematic view to illustrate the working of a quartz gauge.
(a) Calibration experiment result showing idealized square wave input and output.
(b) Arbitrary experiment result showing current-time profile and deduced stress time profile.

Fig. 2 Fully electroded x-cut quartz disc. (Ref. 2)

Fig. 3 Rear surface of guard ring quartz gauge showing the various regions.

Fig. 4 Guard ring quartz gauge configurations. Scope termination resistor is R_T.
(a) Shunted gauge
(b) Shorted gauge.

Fig. 5 Percentage deviations of shorted gauge k-values from shunted gauge plotted as a function of w/ℓ. (Ref. 15)

Fig. 6 Response of different pulse durations as a function of stress. Shaded region represents anomalous response. Experiments on -x orientation long duration are shown along the line $T_o/t_s = 1.0$. (Ref. 9)

Fig. 7 Quartz calibration shot demonstrating ramping. Broken line gives observed behavior; solid line is idealized response with no ramping. (Ref. 11)

MEMORANDUM

TO: Shock Dynamics Laboratory Group

FROM: Y. M. Gupta

DATE: November 20, 1973

SUBJECT: Latest quartz calibration data

The latest quartz calibration is given as a supplement to other quartz gauge work. If you reference it, please check with me first. Any questions, contact me.

YMG/ms

On the basis of eight symmetrical quartz on quartz shots the following calibration data has been obtained to be used with the piezoelectric response equation for quartz gauges.

$$i = \frac{k\sigma UA}{\ell}$$

where i = current output, amps

σ = stress, kbars

ℓ = thickness of gauge, cm

U = wave velocity, use 5.72 mm/μsec

A = effective charge collecting area obtained by using average of inner and outer guard ring diameter, cm^2.

$k = (1.8835 + 10.558 \times 10^{-3}\sigma)10^{-8}$ $coul/cm^2/kbar$

It is emphasized that this data is for 1/2" x 1/8" shorted quartz gauges and the k-values are applicable at the initial stress jump only. Anybody using this should make allowance for ramping and proper units. The accuracy of the linear fit is about ±1.5%. The experiments conducted were in the range 19 to 32 kbars. The calibration is slightly different from Hayes and Gupta's[1] work as reported in an earlier internal report.[2]

REFERENCES

1. D. B. Hayes and Y. M. Gupta, Calibration of Shorted Quartz Gauges (to be published)
2. Y. M. Gupta, Response and Use of Quartz Gauges, S.D.L. Internal Report 73-03.

MEMORANDUM

TO: Shock Dynamics Laboratory Group

FROM: Y. M. Gupta

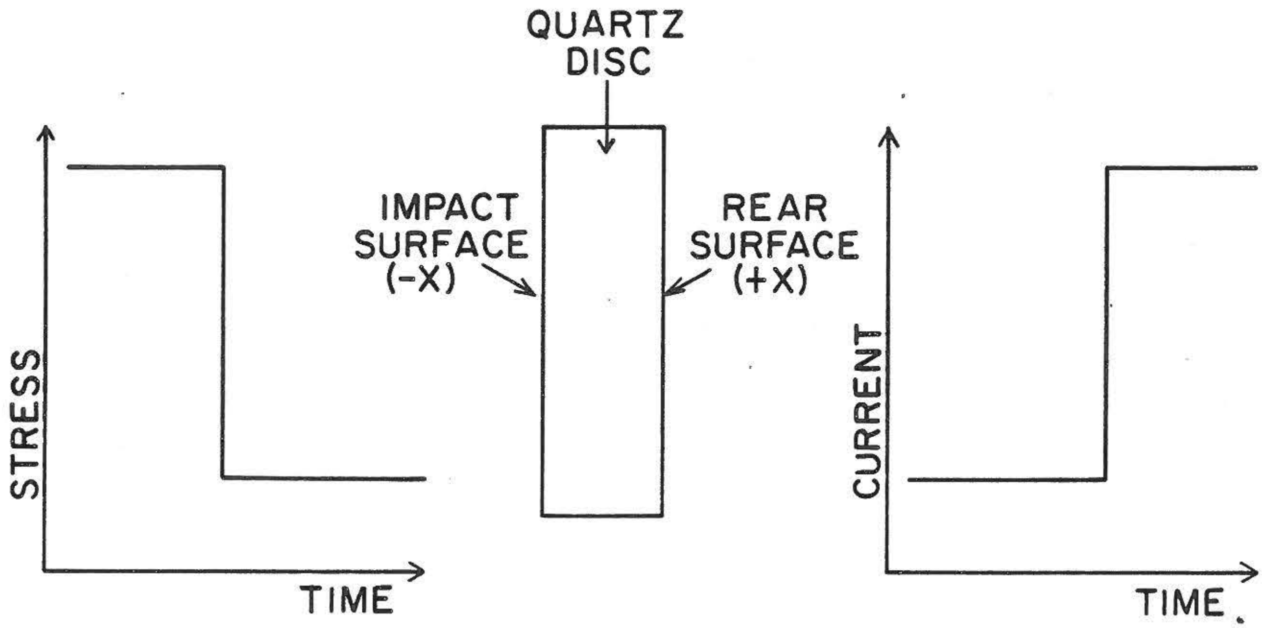
DATE: May 4, 1973

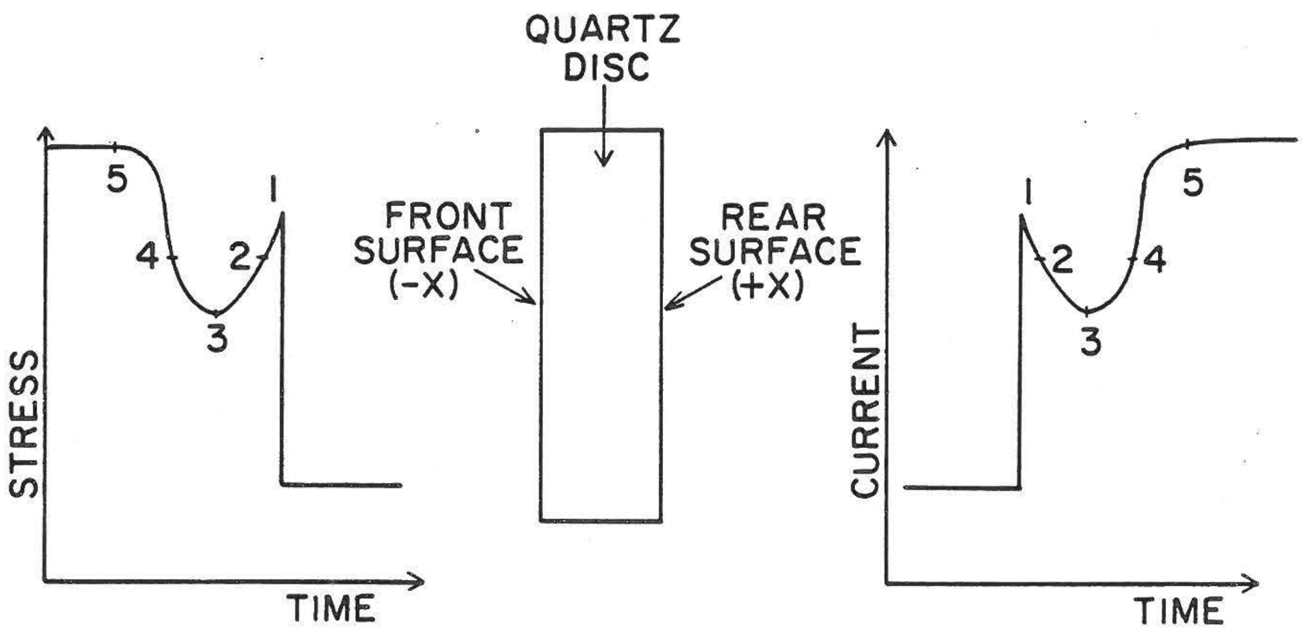
Attached is an internal report for your information only.

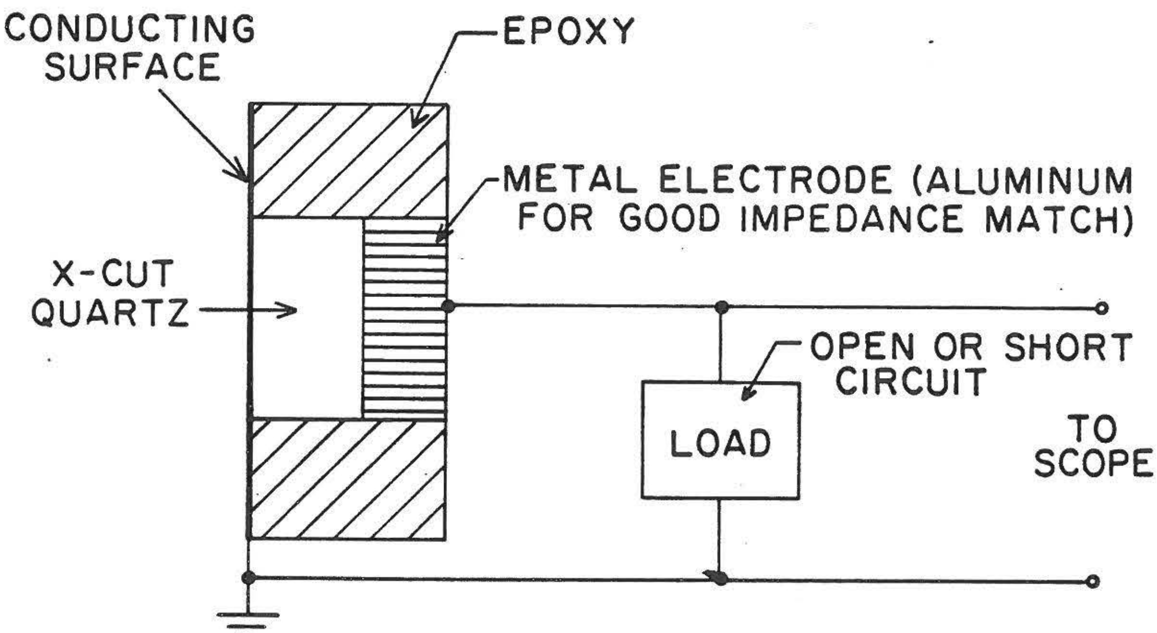
Please do not quote any material from this report without checking with me since a number of unpublished results belonging to various people are presented here.

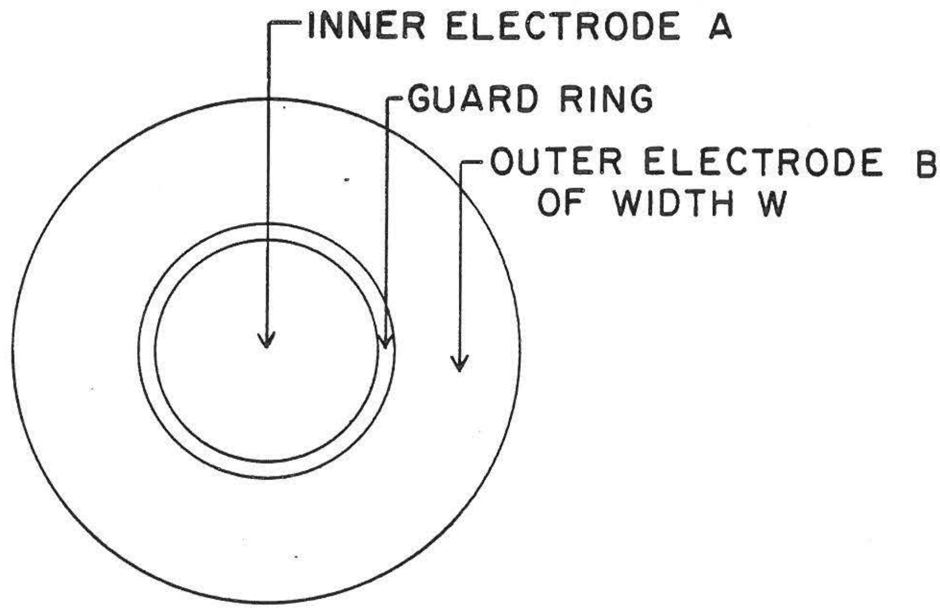
YMG/ms

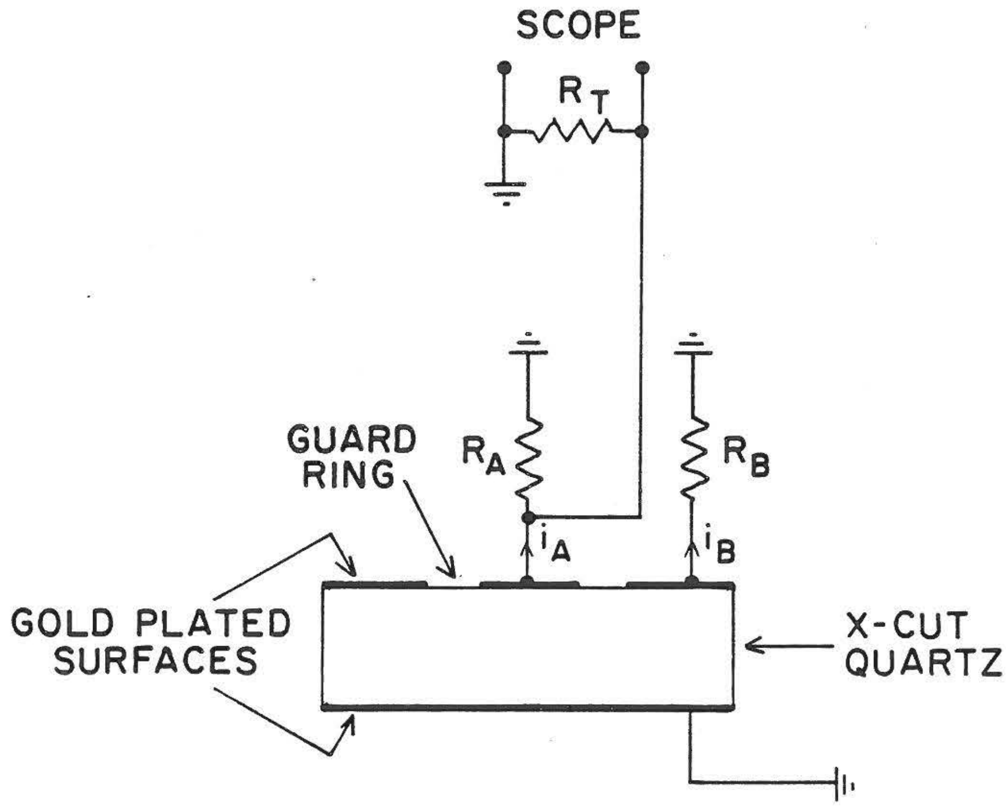
attachment

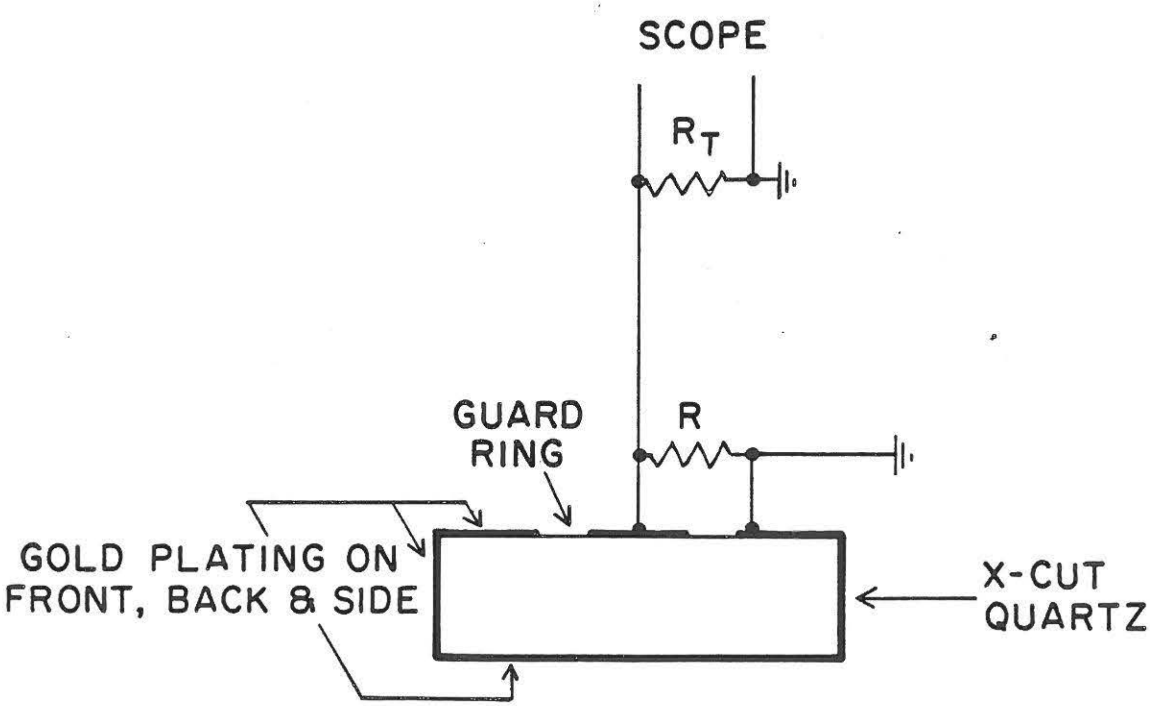

QUARTZ DISC
IMPACT SURFACE (-X)
REAR SURFACE (+X)
STRESS
TIME
CURRENT
TIME

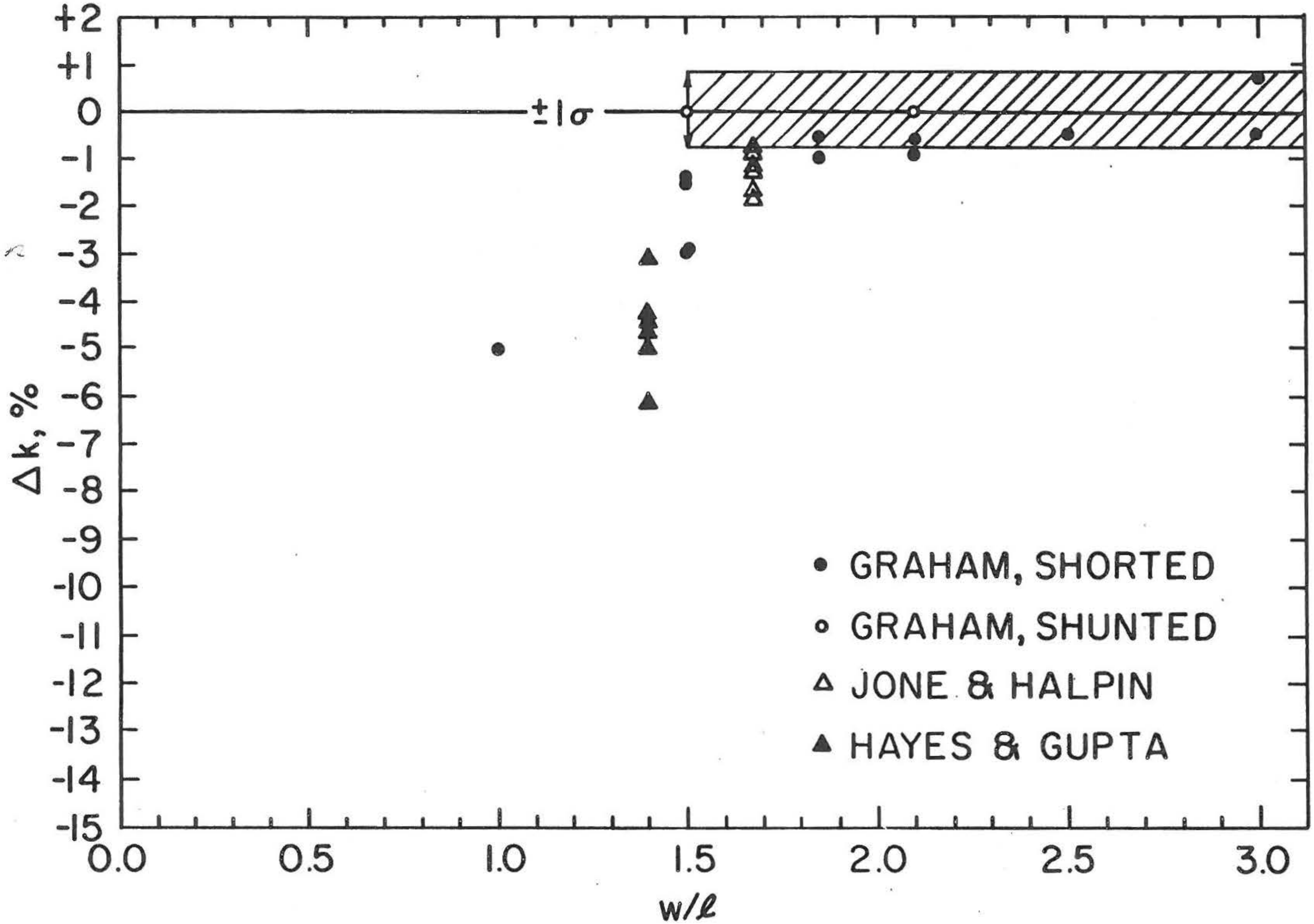

QUARTZ DISC
FRONT SURFACE (-X)
REAR SURFACE (+X)
STRESS
TIME
CURRENT
TIME
1
2
3
4
5

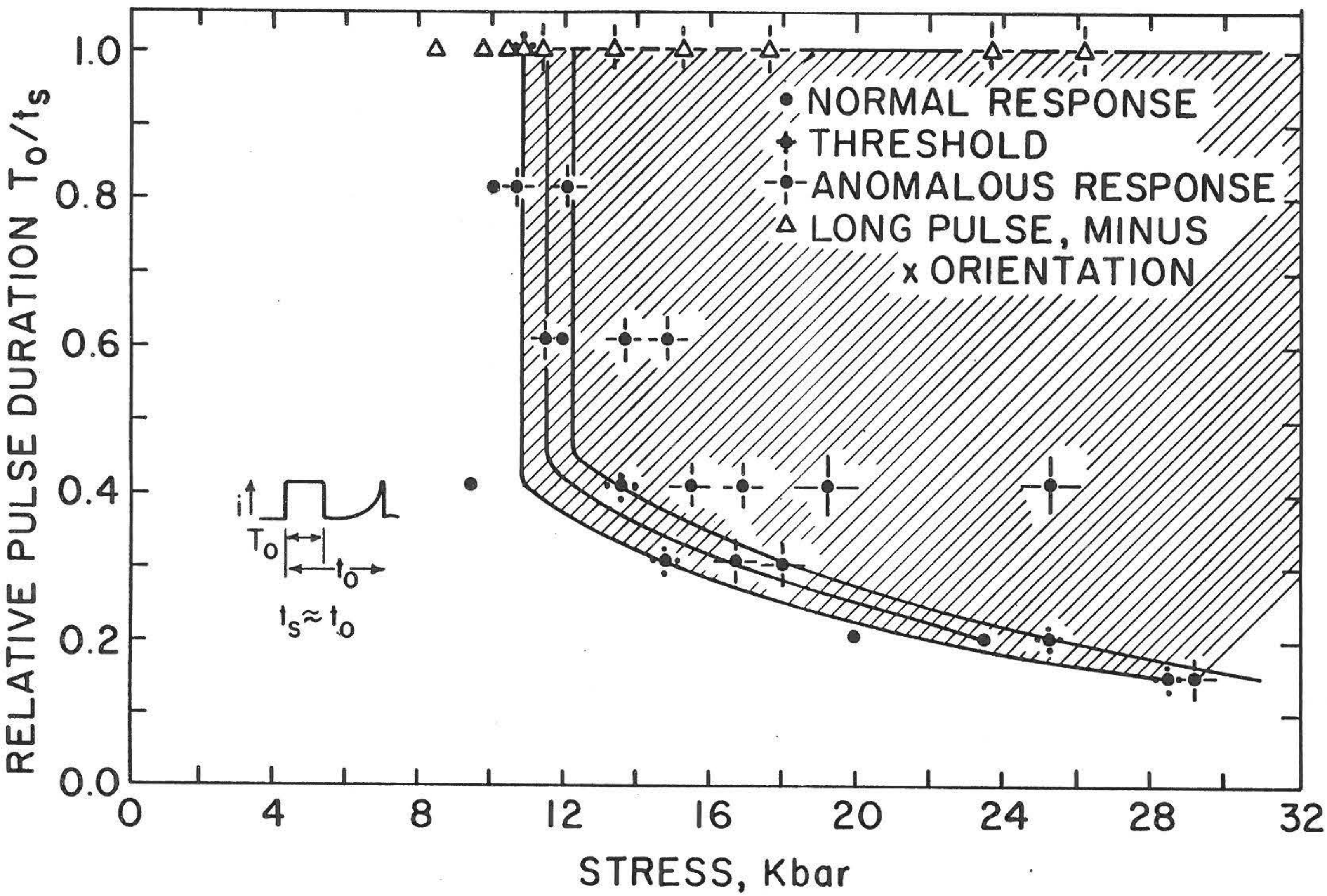

CONDUCTING SURFACE
EPOXY
METAL ELECTRODE (ALUMINUM FOR GOOD IMPEDANCE MATCH)
X-CUT QUARTZ
OPEN OR SHORT CIRCUIT
LOAD
TO SCOPE


INNER ELECTRODE A
GUARD RING
OUTER ELECTRODE B
OF WIDTH W

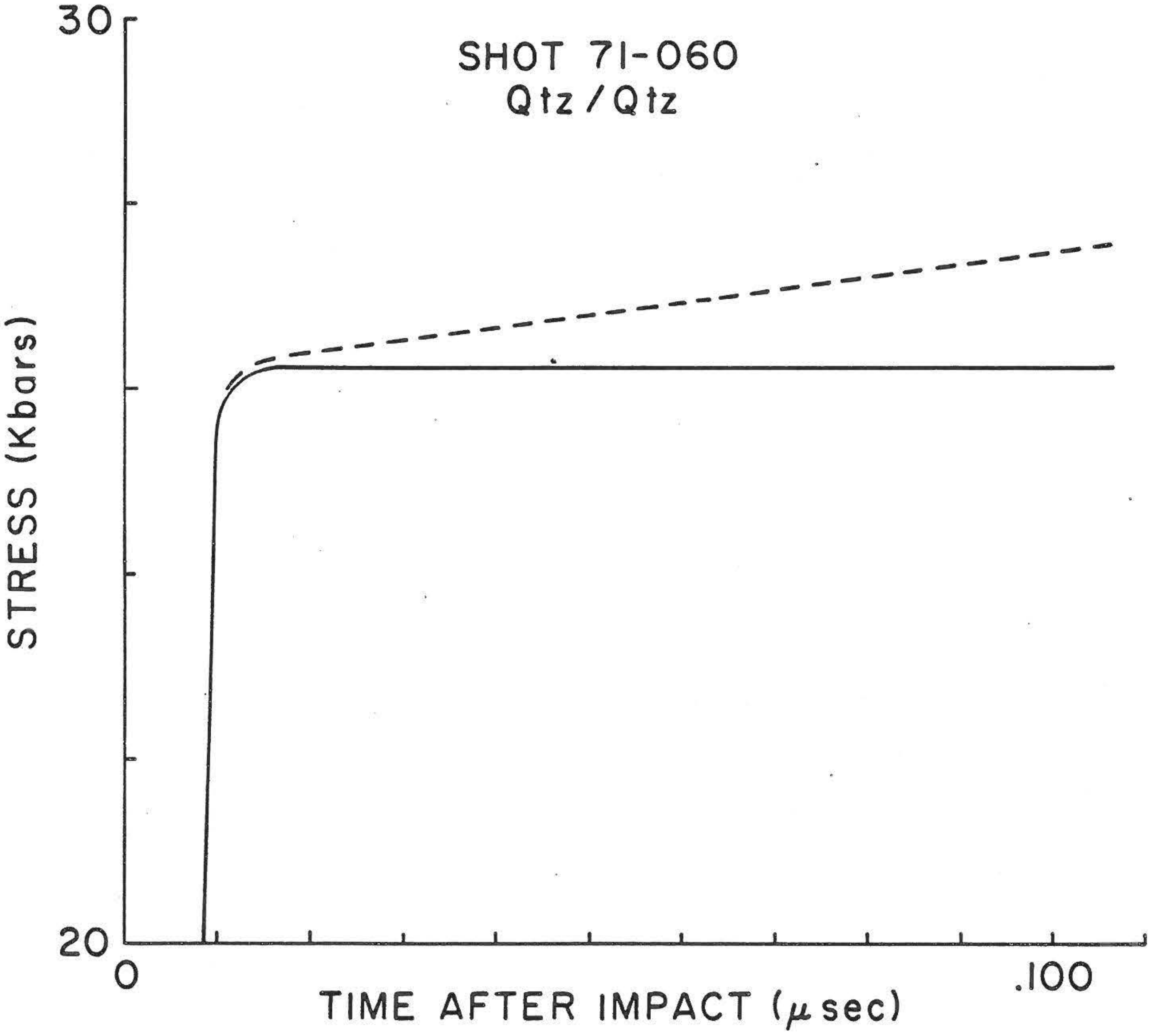

SCOPE
R_T
GUARD RING
R_A
R_B
i_A
i_B
GOLD PLATED SURFACES
X-CUT QUARTZ


SCOPE
R_T
GUARD RING
R
GOLD PLATING ON FRONT, BACK & SIDE
X-CUT QUARTZ


+2
+1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
Δk, %
±1σ
GRAHAM, SHORTED
GRAHAM, SHUNTED
JONE & HALPIN
HAYES & GUPTA
0.0
0.5
1.0
1.5
2.0
2.5
3.0
w/ℓ



RELATIVE PULSE DURATION T_o/t_s
1.0
0.8
0.6
0.4
0.2
0.0
0
4
8
12
16
20
24
28
32
STRESS, Kbar
NORMAL RESPONSE
THRESHOLD
ANOMALOUS RESPONSE
LONG PULSE, MINUS
x ORIENTATION
i
T_o
t_o
$t_s \approx t_o$


SHOT 71-060
Qtz / Qtz
30
20
STRESS (Kbars)
0
.100
TIME AFTER IMPACT (μ sec)