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STRESS-CHARGE RELEASE RELATIONSHIPS
FOR FERROELECTRIC CERAMICS

by

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RELEASED FOR ANNOUNCEMENT
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THE UNIVERSITY OF TEXAS

✓ STRUCTURAL MECHANICS RESEARCH LABORATORY

Austin, Texas

June 8, 1962

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PREFACE

This is the final report prepared for the Sandia Corporation under Contract AT(29-2)-621. Previous reports prepared under this contract are listed as follows:

Stress-Strain Characteristics of Materials at High Strain Rates, Part I, Displacement Measurements During High-Velocity Impacts, by Donald Paul Fitzgibbon, July 15, 1958

Stress-Strain Characteristics of Materials at High Strain Rates, Part II, Experimental Results, by E. A. Ripperger, August 29, 1958

Stress-Strain Characteristics of Materials at High Strain Rates, Part III, Strain Rate Effects and Plastic Wave Propagation, by James W. Turnbow, January 5, 1959

Stress-Strain Characteristics of Materials at High Strain Rates, Part IV, Experimental and Theoretical Analysis of Plastic Impacts on Short Cylinders, by Charles H. Karnes, June 21, 1960

Stress-Strain Characteristics of Materials at High Strain Rates, Part V, Dynamic Compressive Yield Stresses, by E. A. Ripperger, August 1960

Stress-Strain Characteristics of Materials at High Strain Rates, Part VI, The Propagation of Plastic Waves in Finite Cylinders of Strain-Rate-Dependent Material, by Byron D. Tapley, August 1960

Stress-Strain Characteristics of Materials at High Strain Rates, Part VII, Further Studies of Dynamic Compressive Yield Stresses, by William L. Guyton, June 1961

Propagation of Elastic Waves in Thin Plates, Part I, An Experimental Study of Low-Amplitude Waves, by Donald M. Donohoe and E. A. Ripperger, June 2, 1960

Propagation of Elastic Waves in Thin Plates, Part II, An Analytical Study of Elastic Waves Using Approximate Equations of Motion, by Billy C. Ellis, August 1960

Propagation of Elastic Waves in Thin Plates, Part III,
An Experimental Study of Strains Produced by High-
Velocity Impacts, by Philip L. Stanton, June 1961

A Strain-Gage Pulsing Device, SMRL RM-1-61, by
John Alford, January 6, 1961

Contact Times for Flat-Faced Projectiles and Specimens,
SMRL RM-2-61, by C. H. Karnes and W. G. Guyton,
January 12, 1961

A part of the material in this report was used by Mr. Douglas Hart in his Master's thesis entitled Charge Release of Ferroelectric Barium Titanate Under Impact.

On behalf of the authors, I wish to acknowledge the contributions of Mr. Charles Karnes and Mr. W. L. Guyton who made many of the measurements, of all the other staff members who assisted in the research, and particularly of the office staff, headed by Mrs. Marie Wilson, which so efficiently attended to all the details of preparing not only this report but all the others listed above.

Finally, on behalf of the entire staff of the laboratory and of the many students who have been trained in the methods of scientific research while being supported by this contract, I express our sincere appreciation first to the Sandia Corporation for the significant support this contract has provided for our graduate program, and then to Mr. A. F. Beck and Dr. S. E. Whitcomb without whose efforts and counsel this work could not have been carried on.

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June 8, 1962

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ABSTRACT

The relationship between charge released, electrical load, and stress has been studied for two ferroelectric materials, barium titanate (ceramic B) and lead zirconium titanate (52-48). Stresses which cover the range from zero to 10 Kilobars are applied dynamically, in the axial mode, by allowing stress waves generated by an impact to pass through a specimen of the material. The stress applied is measured by the split pressure-bar technique. By properly correlating stress and charge measurements which are recorded as functions of time, stress-charge curves for a given electrical load are constructed. These curves show that the two materials investigated have a dynamic stress-charge relationship which is essentially the same as the static stress-charge relationship. The saturation stress, or the stress at which all the available charge is released is between 4 and 5 Kilobars for both materials. Charge released is virtually independent of electrical load for pure ohmic loads between 8 and 1000 ohms. Electrical energy released increases almost directly with electrical load.

A PZT in the "Far Rhombohedral" range (92-8) was also studied briefly. Charge release from this material seems to be dependent, on both rate of stress application, and stress amplitude.

INTRODUCTION

Background

Early interest in the commoner types of ferroelectric materials was centered on their piezoelectric properties rather than on their behavior as ferroelectrics. This interest was stimulated by such applications as sonar, phonograph pickups, ultra sonic generators, and other electro-mechanical devices in which small strains and small fields are involved. In this area, the characteristics of many of these materials, including barium titanate, have been rather thoroughly explored. As a result, the small-signal piezoelectric and elastic constants have been well established.^{1, 2}

At the other end of the scale, it generally has been believed that a shock wave of sufficiently high intensity passing through a sample of polarized ferroelectric material, would completely destroy the residual polarization, thus releasing all of the theoretical bound surface charge. This makes some of the ferroelectrics look particularly attractive as one-shot, high energy transducers.³ Since such transducers are needed in several different fields of science, the effects of passing high-intensity shock waves through specimens have been studied extensively. Quite surprisingly, it has turned out that in many cases the charge released by the passage of the shock wave is less than the theoretically available charge. Raising the level of intensity of the shock wave produces no increase in charge release. Indeed, the charge release is more likely to decrease than to increase as the shock intensity increases.⁴ Evidence obtained, to date, seems to suggest that there is an optimum shock-wave

intensity, or stress condition, which depends upon material, mode of operation, and electrical loading. For a given material and a given mode of operation, the relationship between electrical output, electrical load, and peak stress is believed to be representable by a three-dimensional plot similar to the one shown in Fig. 1. The rate of loading is not considered in this presentation, since the reference here is to the passage of stress waves through the material; and, within this concept, rate is not believed to be a significant factor.

Objectives

The prime objective of the study which has led to this report has been to establish, as specifically as possible, the nature of surfaces, such as the one shown in Fig. 1, for two different materials, namely barium titanate (ceramic B) and lead zirconium titanate (PZT 52-48). The stress was to range from 0 to 25 Kilobars, and the electrical-load conditions were to vary from short circuit to open circuit. Cylindrical specimens loaded in the axial mode were to be used. As a preliminary effort, a brief investigation of the effect of specimen geometry on charge release was to be made.

Fig. 1. Hypothetical Relationship Between Electrical Load, Electrical Output and Stress for a Ferroelectric Material

MEASUREMENT TECHNIQUES

Pressure Bar

The simultaneous measurement of stress and charge released as a stress wave passes through a sample of ferroelectric material is a difficult problem. To solve this problem, the pressure-bar technique has been employed.^{5,6} With this technique, the specimen is attached to the end of a long cylindrical bar of hardened steel with the axes of the bar and specimen collinear, as shown in Fig. 2. Strain gages mounted on the bar measure the stress waves which propagate along the bar after the projectile impacts the specimen. The strain-gage signals are recorded as a function of time by a Polaroid camera and an oscilloscope. Charge released is measured by recording, as a function of time, the voltage across a pure ohmic load or by recording the voltage built up across a capacitive load on the specimen. Since a finite time is required for the stress waves in a bar to propagate from the specimen end to the strain gages, the stress signal and the output signal from the specimen do not coincide in time. To correlate these two signals, the time required for the wave to propagate from the impact end to the gages must be known. In addition, it must be assumed that the wave does not change in form as it propagates. Under some conditions, this is a valid assumption. However, for stress waves with steep fronts, the type desired for these studies, it is not a good assumption. A stress wave with a steep front will undergo an appreciable change of form as it propagates along the bar. The short waves, which help to give the front

Fig. 2. Experimental Arrangement for Direct Impact Measurements

its steepness, fall behind the faster-moving, longer waves. As a consequence, the toe of the front is rounded off, and the slope decreases. This change makes it difficult to correlate anything but the peak stress with the current output, if the impact really produces a steep wave front. The impact will not produce a steep front if there is any appreciable inclination between the two impacting surfaces; and, since it is very difficult to avoid some inclination, the stress fronts are seldom steep. Because of the problem of correlation, and the desirability of having a plane wave pass through the specimen, this technique was used only in the preliminary study of the effect of specimen geometry.

Split Pressure Bar

After the study of specimen geometry was completed, the pressure-bar technique was modified so as to place a bar ahead of and another behind the specimen, as shown in Fig. 3. With this arrangement, the projectile impacts the end of the front bar, not the specimen. The stress wave generated propagates along the front bar, develops a plane front perpendicular to the axis of the bar as it goes, and then passes into and through the specimen, and on into the back bar. The pulse is measured and recorded as it passes a gaging station on the front bar. It is also measured and recorded as it passes the gages on the back bar. Since it is desirable, because of the high gain in the strain-measuring circuits, to keep both the front and back bars at ground potential, the polarized specimen is isolated from one of the bars by placing an unpolarized piece of the same material as the specimen between the bar and the specimen, as shown in Fig. 3. Thus, there are

Fig. 3. Instrumentation and Measurement Arrangements Used for the Split Pressure Bar Technique

three interfaces, or joints, which the stress pulse must cross as it propagates through the test section of the bar. The interfaces between the ceramic and the pressure bars represent acoustic discontinuities. As a consequence, the stress wave is partially reflected and partially transmitted as it arrives at these interfaces. This complicates the interpretation of the pressure-bar measurements and makes it necessary to resort to a special technique for analyzing the results and deducing the stress in the specimen. This technique is discussed in detail in a subsequent section.

Other Instrumentation

The instrumentation used for the measuring and recording of stress and charge as a function of time is shown in Fig. 3. With the exception of the air gun, this equipment is all standard, commercially available instrumentation which requires no description. The air gun used to provide the impacts has been described in previous reports.⁷ It may be noted, in Fig. 3, both voltage across the current viewing resistor, and the integral of this voltage are recorded. The somewhat exaggerated notch which may be seen near the impact end of the projectile is a part of the projectile velocity-recording system. Passage of this notch, and a second notch 2 in. behind it, by a proximity-velocity pickup near the end of the gun barrel provides signals which are recorded and used for determining the impact velocity.

Recording of the oscilloscope traces is all done with Polaroid cameras.

Charge-stress relations under static or quasi-static loading are

obtained by loading a polarized specimen between two nonpolarized specimens in a standard testing machine. A one-microfarad capacitor is used as the electrical load on the specimen, and an x-y plotter is used for recording. A Keithley electrometer is used to provide the high impedance needed between the capacitor and the plotter. A transducer in the load-weighing system of the testing machine supplies a signal proportional to the load on the specimen.

Instrumentation Difficulties

The split pressure-bar technique proved to be satisfactory for making the measurements required in this investigation. Some difficulties were encountered, however, other than those connected with the interpretation of the data. For the benefit of others who may wish to use this technique, a discussion of some of those difficulties follows:

(1) Lack of a suitable bar material for making measurements at stresses as high as 25 Kilobars. It was originally intended to include in this investigation stresses of that magnitude, but 15 Kilobars proved to be the practical limit. Heat-treated, alloy steel was used to reach the 15-Kilobar limit. A great deal of trouble was encountered in preparing the pressure bars due to the tendency of the bars to warp during quenching in the heat-treating process. A satisfactory pair of bars was finally prepared by suspending them in a vertical position while they were being heated in a tube furnace, and then lowering them directly into a quenching bath beneath the furnace. Even with this procedure, warping occurs;

but by repeating the process often enough, some acceptable bars are finally produced. No doubt heat-treated, straight rods of the type required, are commercially available, but no source could be located at the time the bars were needed. Excellent case-hardened shafting is available but this is not satisfactory for pressure bar use at 15 Kilobars.

For reaching stresses higher than 15 Kilobars, aluminum oxide, which is highly linear to about 21 Kilobars under static loading was investigated as a possible bar material. Under impact loading, it failed at less than 5 Kilobars.

When the experimental results indicated that nothing significant was likely to be learned at stresses between 15 and 25 Kilobars, the search for a suitable bar material for that range was abandoned.

(2) Lack of ruggedness in the strain gages and the lead wire attachments. At the higher impact velocities, failures of strain gages, or of the lead wires from the gages to the external circuits, were quite frequent. These failures, for the most part, seemed to occur after the passage of the stress wave of interest; and were probably caused by bending waves in the bar or by the rigid body motion that takes place after the impact. The latter can be limited to some extent, but limiting it usually results in the generation of severe bending waves in the bar. This difficulty can be minimized by reducing the size of the projectile which is fired against the end of the bar. A projectile 1-1/2-in. in diameter and 6 in. long was used for most of the measurements made. This particular diameter was used because that is the bore diameter of the air gun used to

fire the projectile. A projectile with the same diameter as the pressure bar would have produced as high a stress as was required, and would have had much less energy to dissipate. This reduction in energy would, no doubt, have reduced the number of strain-gage failures. A further advantage is also gained by having the bore of the gun and the pressure-bar diameter the same. The end of the front pressure bar can be inserted in the gun a short distance. This requires evacuation of the barrel, but makes alignment quicker and easier. It also improves the alignment, and thereby reduces the rise time of the pulse. The air gun has been modified to make a 1/2-in. bore available and arrangements for impacting in a vacuum have been provided, but these modifications were not completed in time to be used in the investigation.

Preparation of Specimens

As indicated previously, the polarized specimen is isolated from one of the bars by an unpolarized, unelectroded specimen of the same material and same diameter, but not necessarily the same length. It is not essential, but usually the nonpolarized piece is placed between the negative side of the polarized specimen and the back pressure bar. Aluminum foil, 0.001-in. thick is cemented to each electrode of the polarized specimen with a thin film of Eccobond 56 C conducting epoxy. Tensolite lead wires are then attached to this foil either by using the conducting epoxy, or by soldering, using an aluminum solder known as Eutectic Alutin. The conducting epoxy connections have been found to

have appreciable resistances in some instances. As a consequence, in the latter stages of the investigation, all connections were made by soldering. The soldered connections have negligible resistance and are more convenient to make. An assembled specimen is shown in Fig. 4.

For the low-load shots, a 10-ohm resistor is connected directly across the specimen ($R = 0$ in Fig. 3). For the higher electrical loads, precision resistors of 100, 1000, 10K, and 100K are connected in series with the 10-ohm resistor which is then used as a current-viewing resistor.

Test Procedure

A specimen such as the one shown in Fig. 4 is cemented with Eastman 910 first to the front bar, and then to the back bar. Short lengths of Tensolite wire are then soldered to the foil tabs. The assembly at this stage is shown in Fig. 5. After the slotted upper half of the tube which supports the pressure bar is replaced, the strain-gage lead wires and the Tensolite wires from the specimen are brought through the slot. When the sleeve and protective cover have been put in place, the ends of the Tensolite are soldered to the load resistance (Fig. 3). To reduce the danger of flash-over at the higher electrical loads, the load resistors are placed in a lucite holder as shown in Fig. 6. This arrangement also helps to keep lead-wire length to a minimum, and thus to minimize inductive and capacitive loading. The voltage developed across the 10-ohm current viewing resistor is applied across the integrator and the input of the

Fig. 4. Specimen Assembled for Testing

Fig. 5. Arrangement of Pressure Bars, Specimen, and Projectile

Fig. 6. Pressure Bar and Specimen under the Protective Cover, Load Resistor in Place, and Trigger in Position for a Shot

current recording oscilloscope. The strain-gage lead wires are connected into bridges whose differential outputs are, in turn, connected into the dual-trace, stress-recording oscilloscope.

When all connections have been made, the impact end of the front bar is aligned with the projectile face for plane impact, so that the rise time of the wave front reaching the specimen will be as short as possible. Alignment adjustments are provided for by lateral and vertical motion of the microslides at the front and back of the pressure-bar support tube, as shown in Fig. 7, and discussed in previous reports.⁷ The pressure bars, it might be noted, are supported on polyethylene or teflon bushings inside the support tube, and hence are free to slide in the longitudinal direction. The support tube is also held in teflon bushings so it, too, is free to slide longitudinally. After alignment, the projectile is rammed, and the trigger wire is set to make contact with the projectile the instant it impacts the pressure bar.

Scopes are calibrated just prior to each shot to minimize errors due to amplifier drift. Integration of the voltage across the 10-ohm, current-viewing resistor is accomplished by an integrator consisting of a 10K precision resistor and a capacitance of 0.05 μ fd connected in series. By elementary circuit analysis, the relationship between the total charge, Q , released by the specimen, and the measured voltage e_o across the integrating capacitor is shown to be

$$Q = 0.6 \times 10^{-4} e_o$$

A typical set of records is shown in Fig. 8 for a 1/2-in.-diameter, 1/8-in.-long barium titanate specimen, and an impact velocity of 27 fps.

Fig. 7. Pressure Bar Support and Alignment Adjustments

Fig. 8. Typical Records Obtained from a 1/2-in. -diameter, 1/8-in. -long Barium Titanate Specimen

ANALYSIS OF SPLIT PRESSURE-BAR MEASUREMENTS

Consider the transmission of a short rectangular pulse through the specimen assembly. Assume that the steel-ceramic interfaces are ideal, i. e., 100 per cent contact exists between the two surfaces at each interface. Neglect the effects of dispersion. Assume also that all acoustic impedances and all propagation velocities can be computed from the elastic constants of the materials involved. Fig. 9 shows graphically the significant transmitted and reflected pulses and their magnitudes relative to the incident pulse as seen by the gages at positions 0 and 3.* These magnitudes are calculated by taking the product of the appropriate coefficients of transmission and reflection. These coefficients are given by the following expressions in which the subscripts i, r, and t refer to incident, reflected, and transmitted waves respectively.⁸

$$\sigma_r = \left[\frac{1 - r_z \cdot r_a}{1 + r_z \cdot r_a} \right] \sigma_i, \quad \text{and} \quad \text{--- (1)}$$

$$\sigma_t = \left[\frac{2}{1 + r_z \cdot r_a} \right] \sigma_i, \quad \text{--- (2)}$$

r_z = the ratio of the characteristic impedances of the material carrying σ_i to that of the material transmitting σ_t

r_a = the ratio of the cross-sectional areas, in the same order.

Characteristic impedance = ρC where ρ is the material density and C is the "bar" velocity.

---

*The propagation velocities in steel and most ceramics are not the same. Consequently, the lines in Fig. 9(b) should have a different slope in the steel than they do in the barium titanate. They are drawn with the same slope here for convenience.

Fig. 9. Analysis of a Rectangular Pulse Propagating through a Specimen with Ideal Interfaces

The ratio $\frac{\sigma_r}{\sigma_i}$, i. e., the number in brackets in Eq. (1), is the reflection coefficient R . The ratio $\frac{\sigma_t}{\sigma_i}$, is the transmission coefficient, T . These coefficients are specified for a certain interface when the material characteristics, the areas, and the direction of the incident wave are known. The magnitude of a wave after any number of reflections and transmissions is the product of the corresponding coefficients and the original incident stress. For example, the pulse shown at 15 μ sec in Fig. 9(c), and labeled (c), is the product $T_1 R_2 T_1'$ where the prime indicates the direction opposite to the direction of propagation of σ_i , and the subscripts denote the interface. If there is a third interface, as in the actual experimental arrangement between like materials, the reflection coefficient is zero, and the transmission coefficient is unity, provided there is no change in area at the interface. For the barium titanate used in the example in Fig. 8,

$$T_1 = 0.78$$

$$R_1 = R_2 = 0.22$$

$$T_2 = T_1' = 1.22$$

Consequently, the product $T_1 R_2 T_1'$ is +0.21. Thus, the amplitude of the pulse (c) is 0.21. If the incident stress pulse has any other shape than the one considered here, it can be analyzed by breaking it up into a series of short rectangular pulses. For example, if the incident pulse is a long rectangular pulse (ideally this is the type which would be produced in the experimental procedure) the stress seen at the two gage stations would be as shown by the broken lines in Fig. 9; and at the midpoint of the

specimen, the stress is as shown in Fig. 9(d). From this diagram, it is seen that a single pulse reflecting back and forth in the specimen between the two end faces quickly decays to a negligible amplitude.

When a succession of pulses of the same amplitude and duration propagates through the specimen, the reflected portion within the specimen soon builds up to a constant amplitude and adds to the incoming pulse to produce an amplitude which is essentially the same as that of the incident wave in the steel bar, and the transmitted wave in the back bar. Note that the amplitude of the dip in Fig. 9(c) is exactly the same as the initial amplitude of the stress in Fig. 9(d). This is because the initial amplitude in the sample depends only on the transmitted stress, and this has to be equal to the algebraic sum of the reflected and incident stresses in the front bar.

The transmission through the specimen of a pulse with a sloping front is illustrated in Fig. 10. The sharp rectangular notch with a duration of twice the transit time through the specimen has now been replaced by a gentle dip which has a duration which depends on both the transit time and the rise time of the pulse. The pulses which appear below the base line in Fig. 10(a) represent the reflections which take place at the first steel-barium titanate interface. The pulses above the line and at the right represent reflections returning from the second interface. These latter pulses have been transmitted through the first interface twice, once from steel to barium titanate, and once from barium titanate to steel.

There is no convenient relationship between the stress at the gages

(a) Stress at gages on front bar

(b) Stress at midpoint of specimen

Fig. 10. Propagation of a Pulse with a Sloping Front through a Specimen with Ideal Interfaces

in the front bar after the reflections return, and the stress in the specimen. To determine the stress in the specimen, the initial part of the stress record from the gages at station 0 must be used. This is the incident stress, σ_i . Assuming that the front of the stress pulse does not change appreciably as it propagates from station 0 to the specimen, it is seen that the stress at the midpoint of the specimen can be determined from the incident stress by applying a multiplication factor which changes at intervals which correspond to the transit time through the specimen. If time zero is taken as the time at which the pulse first arrives at the midpoint of the specimen, and τ is the transit time, the stress at the midpoint at a given time is shown in the following table

Interval	σ_s/σ_i
0 - τ	T_1
$\tau - 2\tau$	$T_1(1 + R_2)$
$2\tau - 3\tau$	$T_1(1 + R_2 + R_2^2)$
$3\tau - 4\tau$	$T_1(1 + R_2 + R_2^2 + R_2^3)$
$4\tau - 5\tau$	$T_1(1 + R_2 + R_2^2 + R_2^3 + R_2^4)$

For steel bars and a barium titanate (ceramic B) sample, these multipliers have the following values.

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Fig. 11. Propagation of a Rectangular Pulse through a Specimen with Nonideal Interfaces

from Eqs. (1) and (2). This procedure greatly increases the number of pulse products required to adequately describe the variation of stress with time at a selected plane. The complexity of the propagation pattern is illustrated in Fig. 11. A long rectangular pulse has been assumed, and the results in Fig. 11(a) and (c) show approximately what would be observed at the gage stations on the front and back bars. Figure 11(b) shows a few of the reflections that a short rectangular pulse will undergo. This diagram, like the one in Fig. 9(b), has been simplified by taking the velocity of propagation in the ceramic and in the steel to be the same. Many of the triple reflections shown, and all of the higher order reflections, may possibly be neglected, as shown in Fig. 9, either because of their low magnitudes or the lateness of their arrivals at the gages. It is necessary, however, to consider a great number of these reflections to be sure that they are negligible in the aggregate as well as individually. This means that perhaps as many as 1,000 reflections may need to be accounted for. To keep track of that many reflections and to determine the magnitudes, one obviously needs a high-speed computer. Since there is no way to determine either the area ratio, if it is not unity, or the lengths of the transition zones, it is not possible to compute in any direct way, knowing the incident stress, the stress in the specimen at a given time. Should it be necessary to consider nonideal interfaces, the area ratios and transition lengths would have to be determined by trial and error. To do this, a set of values would be assumed. Then using the first part of the stress signal appearing at the gages in the front

pressure bar, the appearance of the rest of the signal would be computed. This computed signal would be compared to the observed signal. If the two agree reasonably well, the correct values have been assumed. If the two do not agree, a new set of values is assumed and the calculations are repeated. This procedure is repeated until computed and observed pulse forms agree. Fortunately, however, it appears that 100 per cent contact, or the equivalent of 100 per cent contact, can be obtained at the interfaces and, as a consequence, this trial and error procedure is unnecessary.

Initially, it was believed that, if the surfaces of the pressure bars and the ceramic test pieces were all smooth, plane, and perpendicular to the common axis, a light compression of the specimen by the bars would be sufficient to insure 100 per cent contact at the interfaces. This light compression was achieved by rubber bands attached to O-rings on the bars. However, stress records obtained using this assembly technique showed an appreciably steeper front in the back bar than in the front bar. This was at first believed to be caused by the tendency of a shock wave to form in barium titanate due to the upward concavity of its static stress-strain curve. However, when the specimen was omitted and the bars were held together with the same compression, the same difference in rise times in the two bars was noted. Then it was found that if the bars were cemented together with a thin layer of Duco or Eastman 910, the rise times were identical, and the stresses in the two bars were essentially the same. Dally and Beadle also concluded that they obtained 100 per cent contact between the end faces of two cylinders of aluminum if a thin layer of cement was used at the interface.⁹

As an aid, and perhaps as a further refinement in the interpretation

of measurements, some development work has been done on a computer program for tracing the propagation of a short rectangular pulse through changes in cross section and acoustic impedances such as those illustrated in Figs. 9 and 11. This program is discussed in Appendix I.

EXPERIMENTAL RESULTS

Barium Titanate

Composition and static stress-strain characteristics. The barium titanate used for this investigation is called Ceramic B by its manufacturer, the Clevite Corporation. This ceramic is composed of 95 per cent BaTiO_3 , and 5 per cent CaTiO_3 . Typically, it has a mass density, ρ of 5.5 grams per cubic centimeter, and a propagation velocity C , of 4.6 mm/ μsec .¹⁰

The Ceramic B specimens supplied by the Clevite Corporation for this investigation were cylindrical in shape with silver electrodes covering the end surfaces. The four specimen sizes included in the study were 1/2-in. dia. x 1/8-in. length, 1/4-in. dia. x 1/8-in. length, 1/4-in. dia. x 1/4-in. length, and 1/4-in. dia. x 1/2-in. length. These sizes provide length-to-diameter ratios of one-fourth, one-half, one, and two respectively.

Typical static stress-strain curves for this material are shown in Fig. 12. One of the curves for Ceramic B was obtained by Dally,¹¹ and the other two were obtained by personnel of Division 1313-2 of the Sandia Corporation. A fourth curve has also been included, which was obtained in the course of this study using a material composed of 94 per cent BaTiO_3 , 4 per cent PbTiO_3 and 2 per cent CaTiO_3 . Note that the stress-strain curve for this ceramic falls between the three curves for Ceramic B, thus indicating that differences between stress-

Fig. 12. Static Stress-Strain Curves for Barium Titanate.

strain curves for specimens of the same material may be greater than the differences between the stress-strain curves for specimens of different materials. The upward concave curvature of the stress-strain curves indicates that shock waves should develop in this material even at low stresses, if dynamic stress-strain characteristics are similar to the static characteristics.

Effect of specimen geometry. Actually, only one geometry was used. Specimens were all cylindrical in shape, but the length, L , to diameter, D , ratio was varied. As indicated previously, tests for the effect of L/D were conducted in the axial mode by the direct-impact method. For these tests, the polarized specimen is glued to the end of the pressure bar and an unpolarized barium titanate piece, of the same diameter as the polarized specimen, is glued to the front face of the projectile to insulate the electrode on the impact face of the specimen from ground. An impact velocity of 100 fps and an electrical load of 8.33-ohm was used throughout this series. Results of the tests are shown in Fig. 13. These results show as much scatter in the charge release for duplicate shots as they do for shots at different L/D ratios. Thus it must be concluded that specimen geometry, insofar as it is represented by L/D ratio, is not a significant factor. Consequently, specimen dimensions, although generally specified, are not considered important for results in subsequent sections of this report.

Charge release and stress. Charge-release results for shots at impact velocities up to 135 fps with an 8.33-ohm electrical load are shown in Fig. 14. "Steady-state," front-bar stress (in Kilobars) produced in these tests by a given impact velocity is approximately

Fig. 13. Charge Release and the L/D Ratio of Cylindrical Specimens of Barium Titanate.

Fig. 14. Charge Release and Impact Velocity for Barium Titanate.

one-tenth of the velocity (in fps). Since this stress is also very close, as shown previously, to the maximum stress occurring in the specimen during a particular shot, the saturation stress appears to be between 5 and 6 Kilobars. The maximum charge released is about 10 microcoulombs/cm². Charge-release results obtained by Jaffe¹² for static loading, and also some obtained in this laboratory in the course of the present study, are shown in Fig. 14, using the conversion factor of 0.1, mentioned above to express the stress in terms of an impact velocity. The dashed line represents an extrapolation of the solid line which is drawn as an estimated "best fit" for the impact results. Note how well this extrapolation fits the results obtained by static loading. It is clear, however, from these results, that although the static and dynamic measurements appear to give the same results at the lower stresses or impact velocities, the specimens loaded statically are saturating at lower stresses and giving up less total charge than the specimens loaded dynamically.

Results of some of the dynamic, stress-charge measurements are shown in Fig. 15. These curves, which show the cumulative charge released as a function of stress in the specimen, were obtained by correlating transient, measured charge release with transient specimen stress computed from the pressure-bar measurements. In preparing these curves, it is assumed that a specimen begins releasing charge the instant a stress wave arrives at its front face. Consequently, time correlation is obtained by taking $t = 0$ as the time in both the charge and the stress records as the time at which the two quantities begin to develop.

Fig. 15. Barium Titanate Charge-Stress Data Obtained by the Split Pressure-Bar Technique.

By reading from the stress curve, prepared from the front pressure-bar measurement according to the procedure outlined in the discussion of data analysis, at selected times, and by reading from the charge curve the charges at those same times, number pairs are obtained which may be used to plot the q -vs- σ curves. Obviously, an error in the time correlation of the two curves will distort the apparent q -vs- σ relationship. This is particularly true in those regions in which either stress or charge release are changing rapidly. Errors in time correlation are difficult to avoid due to the nature of both curves near the origin. Consequently, it is believed that errors as large as $0.5 \mu\text{sec}$ may be present in some of the time correlations. Viewed from this point, the general similarity of all the curves shown in Fig. 15 is quite remarkable. The one curve which seems to fall somewhat outside the general pattern can be brought into much better agreement by shifting the time origin of the charge curve by $1/2 \mu\text{sec}$ in the later direction. The effect is illustrated by the two curves drawn for the 127-fps impact. Results of three static stress charge measurements are also shown in Fig. 15. These results indicate that, with one important exception, the relationship between charge released and stress is essentially the same whether the load increases from zero to peak in $10 \mu\text{sec}$ or in 2 minutes. The important exception is that under the rapid loading, the specimens consistently release about 10 per cent more total charge than they do under slow loading. It should also be noted that under dynamic loading, as compared to static loading, a significantly higher stress level was reached before failure occurred.

A discussion of several possible explanations for the greater charge release under dynamic loading follows:

(1) Significant leakage during the static measurements.

The input impedance of the electrometer used between the charge-accumulating capacitor and of the recorder is 10^{14} ohms. If the shunt resistance of the test specimen and capacitor is estimated to be 10^9 ohms, a very conservative estimate, the time constant of the circuit is over 15 minutes. It may also be noted that the maximum voltage across the specimen during loading does not exceed 12 volts, and for a specimen 1/8-in. thick, this gives a gradient of 0.096 volts/mil. Thus, it does not appear that leakage can be a significant factor unless under the stressed condition the resistance across the specimen is significantly reduced.

(2) Mechanical failure of the specimen. The static tests represented by the three curves shown in Fig. 15 were terminated by mechanical failure of the specimens at stresses slightly less than 5 Kilobars. The results of Fig. 12 indicate that ceramic B should not fail until the stress in uniaxial compression reaches at least 6 Kilobars. Failure at less than 5 Kilobars may indicate a nonuniform stress condition which produces failure before complete depolarizing can occur.

(3) Additional energy imparted to the material by dynamic loading. Since the essential feature of charge release from barium titanate is the depolarization which occurs when the titanium ions are sufficiently energized to enable them to escape from their potential troughs, it would appear that any

method of loading which imparts additional energy to the material will also produce more complete depolarization, and, hence, more charge release. Thus, the passage of a stress wave which carries both potential and kinetic energy might be expected to produce a more complete depolarization than the application of a static stress of the same magnitude as the dynamic stress.

The stress at which the transition from the hexagonal to the cubic phase in barium titanate should take place has been given as 16 Kilobars by Brody.¹³ The validity of this value is doubtful since it represents the intersection of a phase line given by Merz¹⁴ for single crystals under hydrostatic pressure in the range 0 to 2.5 Kilobars, and the pressure-temperature curve for the region immediately behind a shock front.

The discrepancy between the predicted 16 Kilobars and the 4 - 5 Kilobars, shown in Fig. 15, is an indication of either (a) how far astray one may be led by unjustifiable extrapolations of inapplicable data, or (b) the stress required to give complete depolarization when a shock wave is formed is considerably higher than the stress required under dynamic loading conditions which do not produce a shock front. The first interpretation seems to be the more plausible one.

Charge release and electrical load. This phase of the investigation was carried to loads of 5000 ohms, but usable results were obtained only up to 1000 ohms. Voltages developed across the specimens were

1 to 2 volts per ohm of load. Consequently, when the load exceeded 1000 ohms, considerable trouble with electrical breakdown, leakage and flashover developed. To minimize these troubles, the specimen and the load should be potted if the load resistance exceeds 1000 ohms. Due to a lack of suitable potting facilities, and because of space limitations in the test setup, no potting of specimens was attempted, and efforts to obtain data at load resistances greater than 1000 ohms were abandoned. The charge released into load resistances of 8.33, 100, and 1000 ohms are shown in Fig. 16.

The projectile velocity for all of the measurements shown was 50 fps. Since this impact velocity is just at the borderline between complete and partial depolarization, it is possible that the small reduction in charge release which increasing the electrical load appears to bring is really just an indication that a saturation stress was not produced. It seems more likely, however, that the reduction is simply a consequence of the normal variation in total charge output. For a sufficiently large number of tests at each load, the averages would probably show an insignificant variation. In that connection, it might be noted that the difference between the highest and lowest values of total charge release in the static test results shown in Fig. 15 was about 10 per cent. This is slightly greater than the difference between the two extreme values shown in Fig. 16. The obvious conclusion is that charge release is not dependent on load within the range of loads covered.

Total energy released and electrical load. Since the total charge released is independent of electrical load, it might be expected that

Fig. 16. Charge Release and Electrical Load For Barium Titanate.

unless the time required for the charge to be released is materially increased as the load increases, the total energy output from the specimen will increase. The time for charge to be released remained essentially constant in these measurements since it appears to depend on the time required to reach the saturation stress. As a consequence, the energy released increases with load. The relationship is illustrated in Fig. 17. These results were obtained by squaring and integrating the voltage across the current viewing resistor, and then multiplying by the load resistance and dividing by the area of the specimen. The results obtained from the 1/4-in. -dia. x 1/4-in. -long specimen lie on a straight line, but the 1/2-in. -dia. x 1/8-in. -long specimen released more than 3 times as much energy per square centimeter as the 1/4-in. -dia. specimen. Although this seems strange at first glance, it has a very logical explanation. Assuming that the charge for both specimens is released in about the same period, it is clear that for the same load resistance, the average current for the 1/2-in. -diameter specimen will be 4 times as large as the current for the 1/4-in. -diameter specimen. Thus, the total energy released by the larger specimen will be 16 times as large as the total energy released by the smaller specimen, and the energy per unit area will be 4 times as much.

The energy released during a static test of a 1/4-in. -diameter specimen is also shown for comparison with the dynamic results. The electrical load for the static tests was a one-microfarad capacitor, as pointed out previously. It is shown here as being arbitrarily

Fig. 17. Electrical Energy Output and Load Resistance for Barium Titanate.

equivalent to an 8.33-ohm load simply because the maximum voltage developed across the capacitor was approximately the same as the maximum voltage which would have been developed across an 8.33-ohm load.

The increase in energy output with load seems to be in accord with the well-known rule that a generator delivers maximum power when working into an impedance equal to its own internal impedance.

Summary. For direct impact of a cylindrical barium titanate projectile on a cylindrical barium titanate specimen at 100 fps with an electrical load of 8.33 ohms, total charge release is independent of the L/D ratio. The charge release per unit of area is the same from a large thin disk as it is from a long slender rod-like specimen.

The relationship between charge release and stress at the loading rates established in these measurements is essentially the same as if the load had been applied statically except for one important difference. Dynamic loading, if the maximum stress produced is at least 4 Kilobars, produces a total charge release that is appreciably larger than the charge released by static loading.

Electrical load, in the range from 10 to 1000 ohms, has no appreciable effect on total charge released. Electrical energy released increases with the electrical loading in the range investigated.

A pertinent question which should now be asked is how does this fit into the concept represented by Fig. 1. The answer is: if the electrical output to be considered is charge, the cross sections through

the surface, parallel to the σ , q plane will all be identical for electrical loads between 8.33 and 1000 ohms, and the profile will have the general shape shown by the curves in Fig. 15. Although no data were obtained for loads between 0 and 8.33-ohms, it seems quite reasonable to expect that the charge released into a short circuit will be the same as that released into 8.33-ohms if all other parameters are the same. If the electrical output considered is total energy, then profiles which represent cross sections through the surface parallel to the E , Z plane will all be identical for stresses greater than the saturation stress, or about 4 Kilobars. The output will increase almost, but not quite, linearly with the load resistance. No doubt an optimum load resistance exists, but it probably will not be determined by ordinary theoretical considerations. Such factors as the maximum electrical gradient the specimen can withstand will probably determine the optimum value.

Lead-Zirconate-Titanate (PZT)

Composition and characteristics. The material to which most of the attention in this part of the investigation was devoted is a solid solution of 52 per cent lead titanate and 48 per cent lead zirconate, with 1 per cent by weight of Nb_2O_5 . The percentages of titanate and zirconate in the solution refer to the molar ratio. This material has a typical density of 7.6 gr/cm^3 , with a velocity of elastic wave propagation of $4.4 \text{ mm}/\mu\text{sec}$.

In addition to the 52-48 PZT, 92-8 PZT with 1 per cent Nb_2O_5 added has also been studied to a limited extent. The 92-8 PZT has essentially the same density and propagation velocity as the 52-48 PZT. Static stress-strain curves for 52-48 PZT and for 95-5 PZT are shown in Fig. 18. The latter is shown rather than a curve for the 92-8 PZT because a curve for the 92-8 PZT was not available. The two materials are both in the same part of the phase diagram, have the same structure, and, hence, probably have essentially the same stress-strain relationship.

Charge release and stress. The relationship between charge release and stress for 52-48 PZT loaded dynamically in the axial mode is shown in Fig. 19. These curves were prepared from the original Polaroid records following the same procedure previously discussed in the analysis of the barium titanate data. A typical set of the original records of the type from which the results in Fig. 19 were prepared are shown in Fig. 20.

The factors by which the stress indicated in the front bar is multiplied to obtain the stress in the specimen are as follows:

time interval	stress
$0 - \tau_1$	$T_1 \sigma_i = 0.91 \sigma_i$
$\tau_1 - \tau_2$	$T_1(1 + R_2) \sigma_i = 0.99 \sigma_i$
$\tau_2 - \tau_3$	$T_1(1 + R_2 + R_2^2) \sigma_i = 0.998 \sigma_i$

Fig. 18. Static Stress Strain Curves for PZT.

Fig. 19. PZT (52-48) Charge-Stress Data Obtained by the Split Pressure-Bar Technique.

6 amp/div

5 $\mu\text{sec}/\text{div}$

(a) Current

2.08 Kb/div

Front Bar
Back Bar5 $\mu\text{sec}/\text{div}$

(b) Stress

11.8 $\mu\text{coulombs}/\text{cm}^2/\text{div}$ 5 $\mu\text{sec}/\text{div}$

(c) Charge Release

Fig. 20. Typical PZT Records (52-48)

The first interval represents the time required for a wave to travel from the midpoint of the specimen to the interface at the back bar and back to the midpoint of the specimen. The second time interval ($\tau_1 \tau_2$) is the time required for a pulse to travel from the midpoint to the front face of the specimen and back again to the midpoint. The third time interval is the same as the first. Thus, it is seen that the stress recorded at the front-bar gage station differs appreciably from the stress seen at the midpoint of the specimen only during the first time interval. For an assembly consisting of a 1/8-in. -thick specimen and a 1/2-in. -thick insulating piece, this time interval will be 6.5 seconds. The problem here, as it was with the barium titanate, is to determine precisely the point where time zero should be taken on the stress and the charge records. Small errors in establishing this point may change the appearance of the charge release-stress curve considerably. In view of the difficulty in establishing zero time accurately, the agreement between the different curves in Fig. 19 is considered quite good.

The agreement is all the more remarkable in view of the range in impact velocities (0 to 100 fps) and the fact that three different sizes of specimens are represented in the data.

These curves indicate that the saturation stress for 52-48 PZT is between 4 and 5 Kilobars, or about the same as for barium titanate. Also, it appears that there is no significant difference between the dynamic and the static results. If there is an optimum stress for

charge release, the results shown in Fig. 19 do not indicate what it is. They do indicate that if it exists, it is rather broad since the curves, in general, seem to be asymptotic to some straight horizontal line. The effects which produced the optimum stress indicated by previous results⁴ apparently are not significant at these low stresses.

Charge-stress relationships for 92-8 PZT, sometimes referred to as Far Rhombohedral or FRH because of its structure, and its position in the phase diagram, are shown in Fig. 21. The abrupt changes in these curves at which charge increases with no increase in stress appear to indicate the existence of a critical stress. This is not the case, however. The stress applied to these specimens increases from zero to the maximum value in about 6 μ sec. The maximum stress is then maintained for at least 30 μ sec if the specimen does not fail. The maximum stress reached depends upon the impact velocity. As indicated previously, the stress in Kilobars is roughly one-tenth of the velocity in feet per second. With this in mind, it is seen that the abrupt changes which occur in the charge-stress diagrams take place at the maximum stress produced by the impact. This means that there is a time delay in the release of the charge, and, as a consequence, the specimen continues to release charge for some time after a stress is applied. This delay in the charge release is reduced as the stress is increased. As a consequence, the appearance of the charge-stress curve changes as the impact velocity is increased

Fig. 21. PZT 92-8 Charge-Stress Data Obtained by the Split Pressure-Bar Technique.

until at the highest impact velocities, virtually all the charge available has been released by the time the maximum stress is reached. From the typical records which are shown in Fig. 22, it may be seen that the charge is not released continuously, but in spurts or pulses. As the impact velocity increases, the first pulse increases and the subsequent pulses decrease until they virtually disappear at impact velocities in excess of 50 fps.

The reason for this behavior is not apparent, and the static stress-strain curve gives no clue as to its explanation. Obviously, however, it is connected with the composition of the material since neither the barium titanate nor the 52-48 PZT exhibited this type of charge release when stressed in the same manner.

The rate of change of stress appears to be influencing the charge release, since otherwise all the curves in Fig. 21 would be identical up to the maximum stress produced by the lowest impact velocity. This indicates that the simple concepts which have been developed for the ferroelectrics such as barium titanate and PZT, with compositions in the middle of the phase diagram, cannot be applied to materials which are near the boundaries of the phase diagram. More research on the physical behavior of these materials is required before a satisfactory theory concerning the charge-release mechanism can be formulated.

Charge release and electrical load. The effect of electrical load on the charge released by 52-48 PZT is shown in Fig. 23. It appears that there may be a very slight reduction in charge released as the load increases. There is, however, a strong

3 amp/div

10 $\mu\text{sec}/\text{div}$

(a) Current

1.19 Kb/div

Front Bar

Back Bar

10 $\mu\text{sec}/\text{div}$

(b) Stress

5.9 $\mu\text{coulombs}/\text{cm}^2/\text{div}$ 10 $\mu\text{sec}/\text{div}$

(c) Charge Release

Fig. 22. Typical Records for PZT FRH-3.

Fig. 23. Charge Release and Electrical Load for PZT (52-48)

possibility that the charge shown for the highest load is a little low because of leakage or flash-over during the measurement. The peak electrical gradient in the specimen during the test was about 60 volts/mil and the only protection provided against external leakage and flash-over was a coating of Dow Corning DC-4 insulating paste.

Total energy and electrical load. The total energy released by an impact velocity of 50 fps is shown in Fig. 24 as a function of the load resistance. This energy was obtained, as explained in the discussion of barium titanate results, by squaring the current output and integrating, and then multiplying by the load resistance. The energy obtained from a Far Rhombohedral specimen with an impact velocity of 58 fps, and an 8.33-ohm load is shown. Also, the energy obtained during static loading is shown. The latter was obtained with a capacitor as the load, but it is shown as though the load were 8.33-ohms since the maximum voltage across the capacitor was about the same as the maximum voltage measured across the 8.33-ohm load during dynamic loading of a specimen.

The remarks made concerning the effect of load resistance on energy release for the barium titanate also apply to PZT.

Summary. For 52-48 PZT, the saturation stress is about the same as for barium titanate, that is, between 4 and 5 Kilobars. The charge-stress relationship for dynamic loading is about the same as it is for static loading when load is applied as in these tests. No optimum stress, once saturation has been reached,

Fig. 24. Electrical Energy Output and Load Resistance for PZT.

is indicated by these results.

Electrical load may have a slight effect on charge release, but it is not significant.

Electrical energy released increases almost linearly with load resistance.

For the 92-8 PZT, charge release seems to depend upon rate of change of stress as well as stress magnitude. A considerable amount of charge may be released without any corresponding increase in stress, particularly at low-impact velocities. At impact velocities in excess of 50 fps, this material behaves very much like the 52-48 PZT.

CONCLUSIONS

(1) Under dynamic loading conditions in which stress waves, but not necessarily shock waves, are passed through the material, both barium titanate (ceramic B) and PZT(52-48) give up a charge corresponding to their remanent polarization at a stress somewhere between 4 and 5 Kilobars.

(2) The charge released by cylindrical specimens of barium titanate is independent of the length-to-diameter ratio of the specimen.

(3) The dynamic stress-charge curves for both materials are essentially the same as the static stress-charge curve. However, barium titanate appears to release about 10 per cent more charge under dynamic loading than it does under static loading.

(4) If there is an optimum set of conditions for obtaining maximum charge release other than the saturation stress indicated above, it lies outside the range of conditions investigated.

(5) The charge released by both barium titanate and PZT (52-48) is independent of electrical load, or virtually so.

(6) The electrical energy released into an ohmic load increases almost linearly with the resistance up to at least 1000 ohms. The energy released by static loading falls virtually on the same curve obtained for dynamic loading if the energy is expressed in terms of an equivalent resistor.

(7) Charge release from Far Rhombohedral PZT (92-8) appears to depend on rate of stress application as well as magnitude

of stress. As the rate of stress application is increased, the charge-stress curve approaches, in appearance at least, the charge-stress curve for (52-48 PZT).

Further study of this material is required before a satisfactory theory concerning its dynamic behavior can be formulated.

APPENDIX A

REFLECTION AND TRANSMISSION OF A PULSE AT A TYPICAL SPECIMEN ASSEMBLY

Fig. A-1. Model of a Typical Specimen Assembly

If the interfaces between the specimen and the two pressure bars are not ideal, *i. e.*, there is less than 100 per cent contact at the surfaces, the assembly may be represented by the arrangement shown in Fig. A-1. Here, for the sake of simplicity, the per cent of contact at each interface has been assumed to be the same, and the length of the transition sections have all been assumed to be the same, although, as it will be shown later, it is often more convenient to take different lengths for these transition sections. Two problems are involved here. The first is, given a strain measurement at station 0 or station 7, how can the nature of the contacts between the specimen and the bars be determined; and second, with the first question answered, how can the stress at a given point in the specimen be determined as a function of time?

The first question can only be answered by a trial-and-error procedure in which conditions at the interface are assumed, and then

the resulting stress at either 0 or 7 is calculated. The assumptions are varied until finally experimental and computed results match up. The number of parameters which may be varied and the number of computations which may be involved make the use of a simple, systematic approach to the computation imperative. The basic elements of such an approach are presented below.

Consider a single narrow rectangular stress pulse propagating from left to right in the assembly, and suppose that once this pulse has passed station 7, it never is seen again. The amplitude of this pulse when it first appears at station 0 will be σ_1 , the incident stress. Let station 0 be the observer's station. It is clear that pulses which are ultimately seen at 0 result from reflections at any of the 6 interfaces in the assembly, and that no pulse can appear at 0 which has undergone an even number of reflections within the assembly, i.e., pulses which appear at 0 must have undergone an odd number of reflections. These reflections also must alternate between those due to pulses approaching a discontinuity in the same direction as the initially incident pulse, and those approaching in the opposite direction. For example, a typical product might be

$$T_1 R_2 R'_1 R'_2 T'_1$$

where the primed coefficients indicate that the pulse approached the discontinuity in the opposite direction to that of the initially incident pulse. T indicates transmission and R denotes reflection. The subscripts refer to the discontinuities as shown in Figure A-1. If only the subscripts of the reflection coefficients are retained from the product,

an odd numbered combination of integers results which possesses the property that the first and third members are larger than the second member.

Further examples would show that number sets may be generated with the criterion that

$$I_1 > I_2 < I_3 > \dots < I_r$$

where I_r is an integer and $r = 1, 3, 5, 7, \dots$ such that all possible pulses resulting from r reflections are taken into account.

The enormity of such a compilation is illustrated in Table I which shows that if all pulses which experience up to 15 reflections are taken into account, there will be 501,175 combinations.

TABLE I

r	size
1	6
3	55
5	671
7	2,353
9	8,272
11	29,056
13	102,091
15	358,671
Total =	501,175

From these combinations, the time variation of the stress at point 0

can be constructed. The amplitude of each returning pulse is computed by taking the product of all the transmission and reflection coefficients which operate on the pulse. The arrival times of the pulses at station 0 are computed and all pulses which arrive at the same time are added in order to get the magnitude of the composite pulse. Although the magnitudes of some of the pulses are very small, there may be many pulses arriving at the same time so that the magnitude of the composite pulse could be quite significant. It is, therefore, important to note that an individual pulse cannot be disregarded simply because its magnitude alone is small. Computing the products of the reflection and transmission coefficients, and keeping track of all the pulses and their times of arrival at 0 obviously calls for the use of a high-speed digital computer. Writing of a program for doing this problem on The University of Texas Control Data Corporation 1604 Computer was undertaken, but the program was not completed for various reasons. The more significant reasons are as follows:

- (1) Since this is essentially a problem in logic rather than computation, it was believed at the beginning that programming should be done in machine language (CODAP). It now seems apparent that FORTRAN would be better since CODAP requires such a tremendous number of instructions, the chance for errors is almost prohibitive and a large portion of the machine storage is used up for these instructions, thus leaving insufficient storage space for the various pulses which must be retained until they are called for.

(2) The second problem would be common to any program.

This is the difficulty which is encountered in taking account of pulses which do not arrive in exact coincidence at the observer's station. This happens because the travel times between the discontinuities are not equal. This difficulty can be avoided by specifying the lengths of the various parts of the assembly in integer multiples of some unit of time, such as the pulse duration. This, of course, takes some of the generality out of the solution but it is still sufficiently general to fit most problems.

If, as was indicated in the discussion of data analysis, the problem of incomplete contact at the interfaces can be solved by cementing at those interfaces, the number of discontinuities is reduced to two and the problem is greatly simplified. However, the same systematic approach to the simpler problem can be used. With only two discontinuities to consider, it is readily seen that two single reflection pulses are possible, one from each interface. Since all the reflected pulses which appear at the gage station must have undergone an odd number of reflections, it is readily seen that only one pulse can appear at station 0 for each combination greater than 1. The amplitude of each reflected pulse appearing at the gage station after the first can be written in the general form

$$T_1 R_2 R_1' - - - - R_2 T_i$$

with the number of products of $R_2 R_1'$ being equal to $\frac{n-1}{2}$ where n is the total number of reflections. Each of these reflected pulses will arrive at the gage station separated by a time τ which is the

time required for a pulse to travel twice the length of the specimen. The first reflected pulse arrives at time τ^1 after the arrival of the incident pulse, where τ^1 is the time required for a pulse to travel from the gage station to the first interface and back to the gage station again.

Since the program for computation in CODAP is extremely long, and is not quite complete, it is not included here. A program written in FORTRAN for a similar problem has been published by Mr. Ray P. Reed in SC-4462 (RR), Stress Pulse Trains from Multiple Reflection at a Zone of Many Discontinuities - A Notation for Machine Solution, Sandia Corporation, August, 1961.

BIBLIOGRAPHY

1. Shirane, G., F. Jona, and R. Pepinsky, "Some Aspects of Ferroelectricity," Proceedings, IRE, December 1955, Vol. 43, p 1738 - 1793.
2. Berlincourt, Don A., Piezoelectric Properties of Barium Titanate Ceramics over a Wide Temperature Range, Sandia Corporation SC 3674 (TR), 1955.
3. Neilson, F. W., Ferromagnetic and Ferroelectric One-Shot Explosive-Electric Transducers, Sandia Corporation Technical Memorandum 230B-56-51, November 1956.
4. Unpublished data, Division 1313-2 Sandia Corporation.
5. Jones, Ieuan R., A Review of the Pressure-Bar Technique for Measuring Transient Pressures, Aerospace Corporation, TDR-594 (1208-01) TR-3, 1961, ASTIA AD 264-548.
6. Guyton, W. L., Stress-Strain Characteristics of Materials at High Strain Rates, Part VII, Further Studies of Dynamic Compressive Yield Stresses, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, 1961.
7. Karnes, C. H., Stress-Strain Characteristics of Materials at High Strain Rates, Part IV, Experimental and Theoretical Analysis of Plastic Impacts on Short Cylinders, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, 1960.
8. Ripperger, E. A. and H. N. Abramson, "Reflection and Transmission of Elastic Pulses in a Bar at a Discontinuity in Cross Section," Proceedings, Third Midwestern Conference on Solid Mechanics, pp 135 - 145, 1957.
9. Dally, J. W. and C. W. Beadle, Studies of Strain-Wave Propagation and Associated Charge Release in Ferroelectric Materials, Final Report to Sandia Corporation on P. O. 13-1516, July 1961, p II - 1.
10. Graham, R. A., A Survey of the Literature on the Elastic Constants of Barium Titanate Ceramics, Sandia Corporation Technical Memorandum 206-59-(51), June 1959.

BIBLIOGRAPHY

(Cont'd)

11. Dally, J. W., Studies of Strain-Wave Propagation and Associated Current Output in Barium Titanate, Sandia Corporation, Technical Memorandum 294-59-(51), November 1959.
12. Jaffe, H., "Piezoelectric Ceramics," American Ceramic Society Journal, 51, Pt. 2, November 1958, p 494.
13. Brody, P. S., Strong Shock Waves in "Polled" Barium Titanate Ceramics, Diamond Ordnance Fuze Laboratories, Report No. TR 869, October 1960.
14. Merz, W. J., "The Effect of Hydrostatic Pressure on the Curie Point of Barium Titanate Single Crystals," Physics Review, V. 78, April 1, 1950, pp 52 - 54.