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THE PIEZOELECTRIC RESPONSE OF QUARTZ BEYOND ITS HUGONIOT ELASTIC LIMIT

by

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ABSTRACT

X-cut quartz shocked in the X-direction gives an electrical output for shock pressures up to 300 kilobars. When the quartz is shocked in the positive X-direction, the charge output increases slowly with pressure beyond about 50 kilobars; higher pressures primarily distort the output waveform. When the quartz is shocked in the negative X-direction beyond about 55 kilobars, the charge output reverses and becomes positive.

A proposed model for this behavior is based on the elastic-plastic double-shock wave which has been found in quartz. It is proposed that only the elastic zone responds piezoelectrically, and that the plastic zone behaves as a relief of the elastic distortion and electrical polarization. Beyond the elastic limit, unilateral conduction exists in the quartz according to the direction of the electric field relative to the shock fronts. When the shock is moving in the positive X-direction, the plastic zone conducts, and the amplitude of the output is determined by the amplitude of the elastic wave. When the shock is moving in the negative X-direction, the elastic zone conducts, and the reversed output is due to the relieving plastic zone.

THE PIEZOELECTRIC RESPONSE OF QUARTZ BEYOND ITS HUGONIOT ELASTIC LIMIT

Introduction

The study of the piezoelectric response of materials shocked by high explosives involves the effect of the Hugoniot elastic yield and pressure-induced phase transitions on the piezoelectric properties of the material. It also involves the effect of the combination of high pressures and high electric fields on the conductivity, dielectric constant, and dielectric strength of the materials. This paper is a report of the effect of the Hugoniot elastic yield on the behavior of alpha quartz. A detailed study of the behavior of quartz is of considerable interest because of its ability to produce electrical pulse power outputs well into the megawatt region and its ability to measure high shock pressures by means of its piezoelectric response.

Experimental Procedure

The experimental setup for the study is shown in Fig. 1. The setup consists of a high-explosive plane-wave generator, a metal driver plate (which is also the ground electrode for the quartz), the quartz sample, an output electrode (usually aluminum), and the electrical load. The quartz is an X-cut disk, shocked along the X-axis, with a large diameter-to-thickness ratio to primarily insure a one-dimensional strain.

The applied pressure is varied by using various combinations of explosive compositions and driver plates. A variation of resistive and capacitive loads is used, and the electrical output is displayed on a high-speed cathode-ray oscilloscope.

Experimental Results

For pressures of about 25 kilobars (Fig. 2), which are well below the elastic limit, and with the quartz oriented so that the output is positive relative to the driver electrode, a reasonably square current pulse is obtained into a fairly low resistive load. The charge output is a reasonable extrapolation of that expected from the small-signal piezoelectric constants, and the duration of the pulse is the elastic wave-velocity transit time. The small step at the beginning of the waveform is due to the elastic-wave produced by the brass driver plate.

For a pressure of 50 kilobars (Fig. 3), which is approaching the elastic limit, the charge output is still a reasonable extrapolation from the small-signal constants, but the waveform has begun to distort with a spike near the end.

At a pressure of 65 kilobars (Fig. 4), which is just above the elastic limit, the charge is somewhat higher than that expected and the distortion is more of a ramping top. The initial low-amplitude pulse is again due to the elastic wave produced by the steel driver.

At 150 kilobars (Fig. 5), the charge is somewhat lower than at 65 kilobars into the 1000-ohm load but is about the same into a load of only a few ohms. The waveform is now badly distorted, with a low-amplitude initial value and a high-amplitude spike near the end.

At 300 kilobars (Fig. 6), the charge is only slightly higher than at 150 kilobars, but the waveform is more severely distorted. Measurements for pressures higher than 300 kilobars have not yet been made.

When the orientation of the quartz is reversed so that the output should be negative relative to the driver electrode, the charge begins to decrease as a function of pressure in the range of 8 to 10 kilobars, and it reverses for pressure beyond the elastic limit. This behavior is shown by a comparison of the two orientations at a pressure of 65 kilobars with a capacitive load (Fig. 7). A steel driver is used, and the low-amplitude elastic wave from the driver (approximately 7 kilobars in the quartz) produces equivalent positive and negative outputs for the two orientations. When the 65-kilobar wave enters the positive unit, the positive charge output during elastic transit time is nearly a linear ramp, but after transit time it falls off much more rapidly than the RC-time constant of the circuit. When the 65-kilobar wave enters the negative unit, the charge output is positive, with a rise time several times longer than the elastic transit-time; it then decays according to the RC-time constant of the load circuit. The rise of the negative unit and the fall of the positive unit are very similar in duration and waveshape. The positive output of the negative units into resistive loads greater than a few ohms is quite variable from test to test and produces only a fraction of the voltage obtained from a positive unit at the same pressure and load.

Model of Behavior

Our proposed model for the behavior is based on the double-shock wave structure reported by J. Wackerle.[1] The model is shown in Fig. 8. The double-wave structure produces three zones in the quartz: a plastic zone behind the high-pressure plastic wavefront, increasing in thickness from zero at the plastic wave velocity; an elastic zone between the elastic and plastic wavefronts, increasing in thickness from zero at the difference between the elastic and plastic wave velocities; and an unshocked zone ahead of the elastic front, decreasing in thickness from the thickness of the sample at the elastic-wave velocity. The strain-induced polarization is zero in the unshocked zone, a saturated value P_o in the elastic zone, and zero in the plastic zone which is proposed to be a complete relief of shear constraints and thus of shear-produced polarization.

The conditions for the positive and negative units are shown in Fig. 9. The equation for the sum of the voltages in each zone and the load, without internal conduction, is given by

$$V_L + D_3 v_p t + (D_2 - P_o)(v_e - v_p) t + D_1 (d_o - v_e t) = 0, \tag{1}$$

[1] J. Wackerle, Bull. Am. Phys. Soc. Ser. II, **5**, 510 (1960).

where

V_L = voltage across the load Z_L times the dielectric constant of the quartz,

D_3 = electric displacement or surface charge density of zone 3,

D_2 = electric displacement of zone 2,

D_1 = electric displacement of zone 1,

v_p = plastic-wave velocity,

v_e = elastic-wave velocity,

P_o = piezoelectric induced polarization of the elastic zone 2,

t = time, and

d_o = thickness of the quartz disk.

This condition gives the saturation of the charge at the elastic limit but does not give the distortion of the waveform or the reversal of the output of the negative units. To meet these conditions, we propose a unilateral conduction mechanism according to the direction of the electric field relative to the shock fronts. For the positive units the conduction is from the plastic front across the plastic zone and for the negative units the conduction is from the elastic front. Such conduction amounts to a build-up of charge at the front and thus a discontinuity in the electric displacement, D, across the front.

The equations for these conditions for the positive units are

$$D_2 = D_1,$$
$$D_3 = 0, \text{ and} \qquad (2)$$
$$V_L + D_1(d_o - v_p t) = P_o\,(v_e - v_p)\,t.$$

For high conductivity in the plastic zone, the voltage across the plastic zone is zero. The internally generated voltage is thus proportional to the saturated polarization and the time-varying thickness of the elastic zone. The zero-voltage plastic zone decreases the internal impedance of the unit at the plastic wave velocity, causing the distortion of the current waveforms for resistive loads and the fall-off of the voltage after elastic transit-time for capacitive loads.

The equations for the proposed conduction conditions for the negative units are

$$D_2 = P_o \cdot D_3 = D_1 + P_o, \text{ and} \qquad (3)$$
$$V_L + D_1\,d_o - (v_e - v_p)\,t = -P_o\,v_p t.$$

For high conductivity, the voltage across the elastic zone is zero. However, the relief of the charge-neutralized polarization by the plastic front produces a negative voltage across the plastic zone proportional to P_o and to the time-varying thickness of the plastic zone.

A comparison of the calculated outputs based on this model with the experimental outputs for positive units with low resistive loads is given in Fig. 10. The upper curves are for a pressure of 65 kilobars and the lower curves for 150 kilobars. The agreement is very good.[2]

The agreement for negative units with capacitive loads is fairly good, but with resistive loads the agreement is more qualitative than quantitative. The discrepancy seems to be primarily due to the inability of the plastic zone to consistently support much voltage, a factor which is not considered in the model. A more complete model is also necessary to explain the results very near and somewhat below the elastic limit.

The proposed conduction mechanism is being investigated in terms of the aluminum-sodium impurity complex in quartz. The source of negative carriers at the shock fronts and the luminescence reported by W. P. Brooks[3] are believed to be due to ionization of this impurity complex. Initial comparisons of the luminescence and conduction for swept quartz which has had sodium removed by an electric field along the Z-axis at elevated temperatures and for quartz grown from a potassium solution instead of a sodium solution indicate a decrease in the luminescence and conductivity.

REFERENCES

Work done after presentation of the present paper is reported in the following:

1. R. A. Graham, "Piezoelectric Behavior of Impacted Quartz," J. Appl. Phys. **32**, 55 (1961). Reprinted as SCR-280.

2. F. W. Neilson, W. B. Benedick, W. P. Brooks, R. A. Graham, and G. W. Anderson, "Electrical and Optical Effects of Shock Waves in Crystalline Quartz," Colloque International 1961 sur les "Ondes de Détonation," Paris, 1961. Preprinted as SCR-416.

3. R. A. Graham, "A Technique for Studying Piezoelectricity Under Transient High Stress Conditions," Rev. Sci. Instr. **32**, 1308-1313 (1961). Reprinted as SCR-448.

4. R. A. Graham, "Dielectric Anomaly in Quartz for High Transient Stress and Field," Scheduled for May 1962 issue of the J. Appl. Phys.

5. R. A. Graham, "Alpha Quartz Piezoelectric Constant for High Transient Stress," Bull. Am. Phys. Soc. Series II, **7**, No. 2 (1962).

6. W. B. Benedick, O. E. Jones, and F. W. Neilson, "Dynamic Yield Behavior of Explosively Loaded Metals Determined With Quartz Transducers," Bull. Am. Phys. Soc. Series II, **7**, No. 2 (1962).

[2]M. D. Clark, Comparison of Theoretical and Experiment Data for Quartz, Explosive-To-Electric Transducers, SCTM 61-61(51), March 24, 1961.

[3]W. P. Brooks, F. W. Neilson, Bull, Am. Phys. Soc. Ser. II, **5**, 510 (1960).

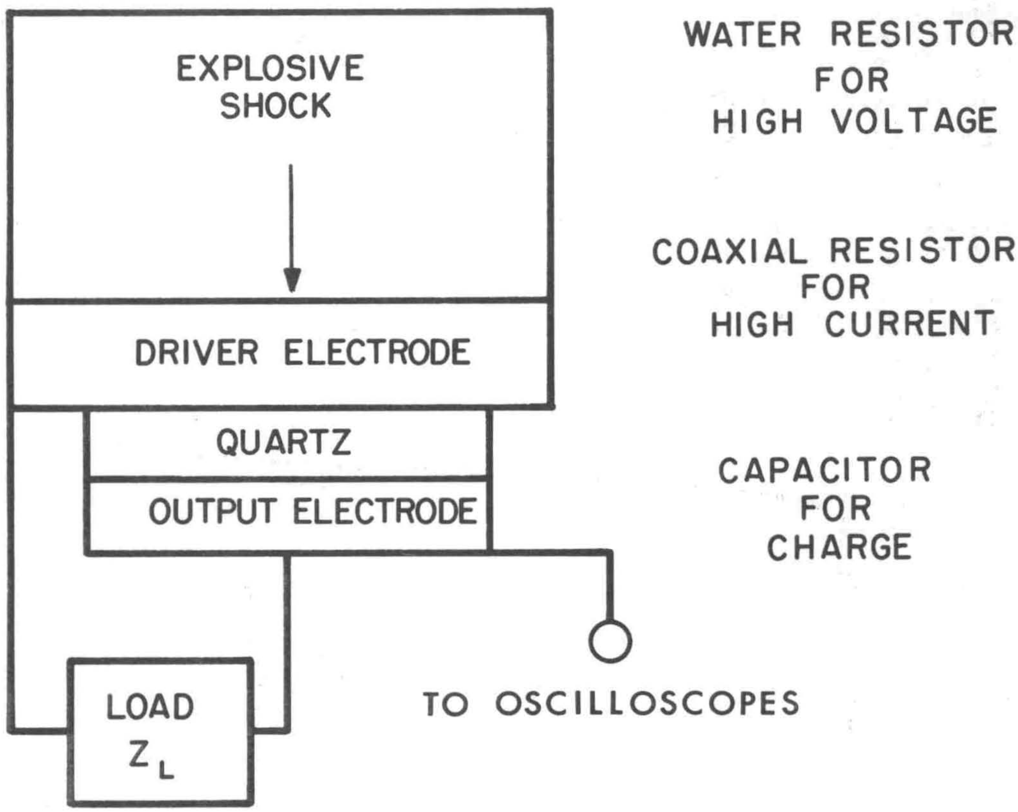

EXPLOSIVE
SHOCK
DRIVER ELECTRODE
QUARTZ
OUTPUT ELECTRODE
LOAD
Z L
TO OSCILLOSCOPES
WATER RESISTOR
FOR
HIGH VOLTAGE
COAXIAL RESISTOR
FOR
HIGH CURRENT
CAPACITOR
FOR
CHARGE

FIGURE 1

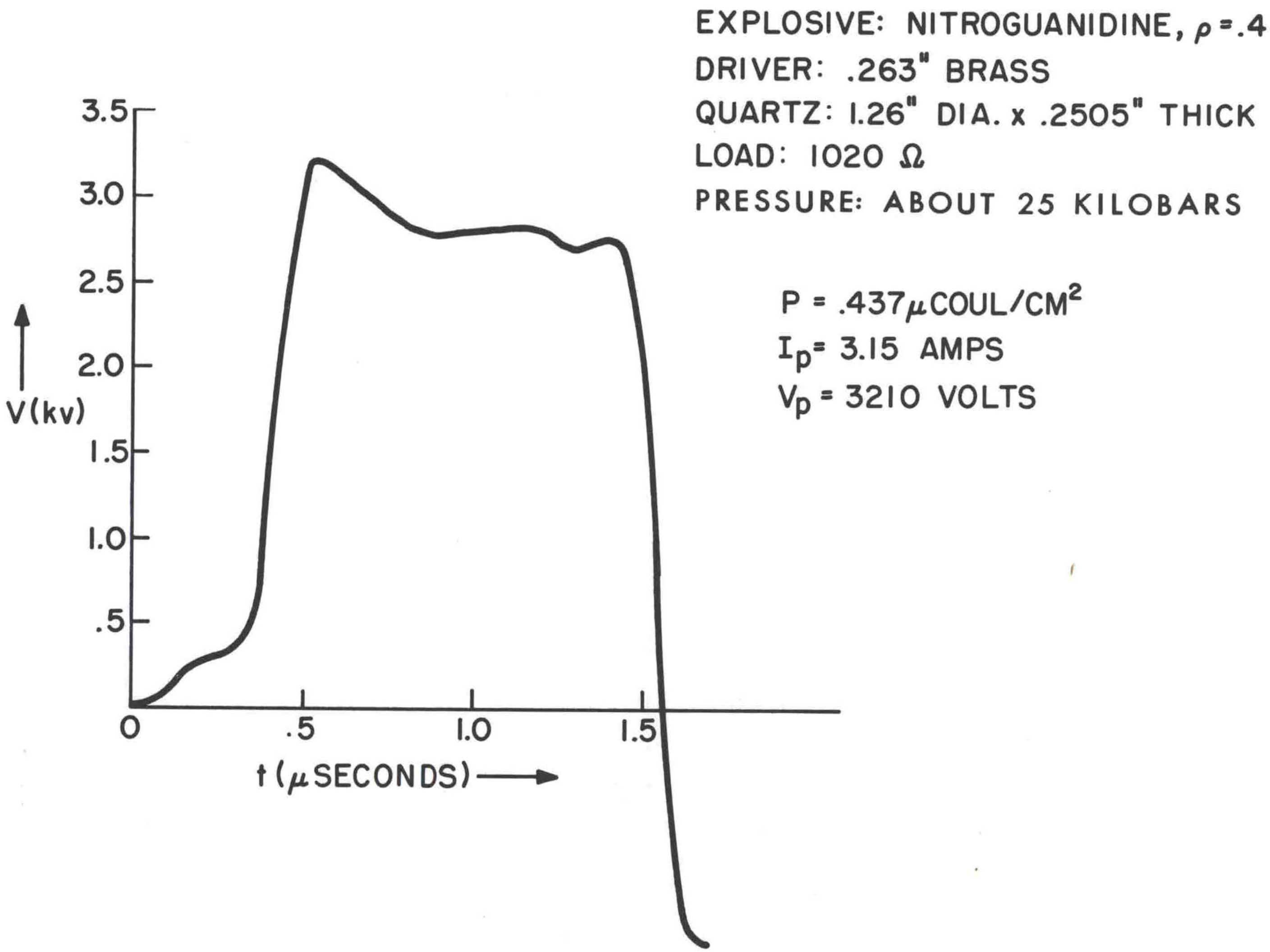

EXPLOSIVE: NITROGUANIDINE, ρ = .4
DRIVER: .263" BRASS
QUARTZ: 1.26" DIA. x .2505" THICK
LOAD: 1020 Ω
PRESSURE: ABOUT 25 KILOBARS
P = .437μCOUL/CM²
Ip = 3.15 AMPS
Vp = 3210 VOLTS
3.5
3.0
2.5
2.0
1.5
1.0
.5
V(kv)
0
.5
1.0
1.5
t (μSECONDS)

FIGURE 2

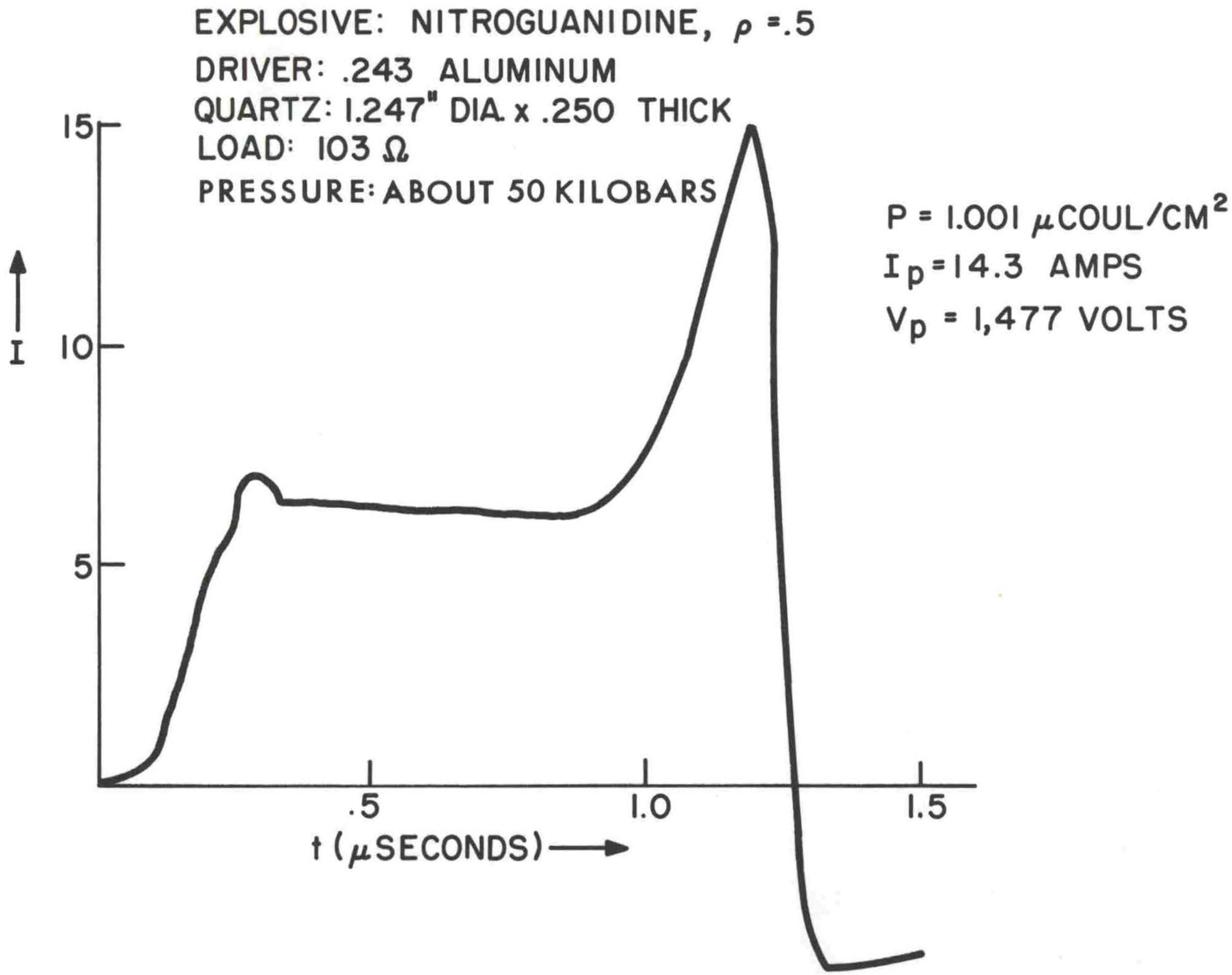

EXPLOSIVE: NITROGUANIDINE, ρ =.5
DRIVER: .243 ALUMINUM
QUARTZ: 1.247" DIA. x .250 THICK
LOAD: 103 Ω
PRESSURE: ABOUT 50 KILOBARS
P = 1.001 μCOUL/CM²
Ip = 14.3 AMPS
Vp = 1,477 VOLTS
15
10
5
I
.5
1.0
1.5
t (μSECONDS)

FIGURE 3

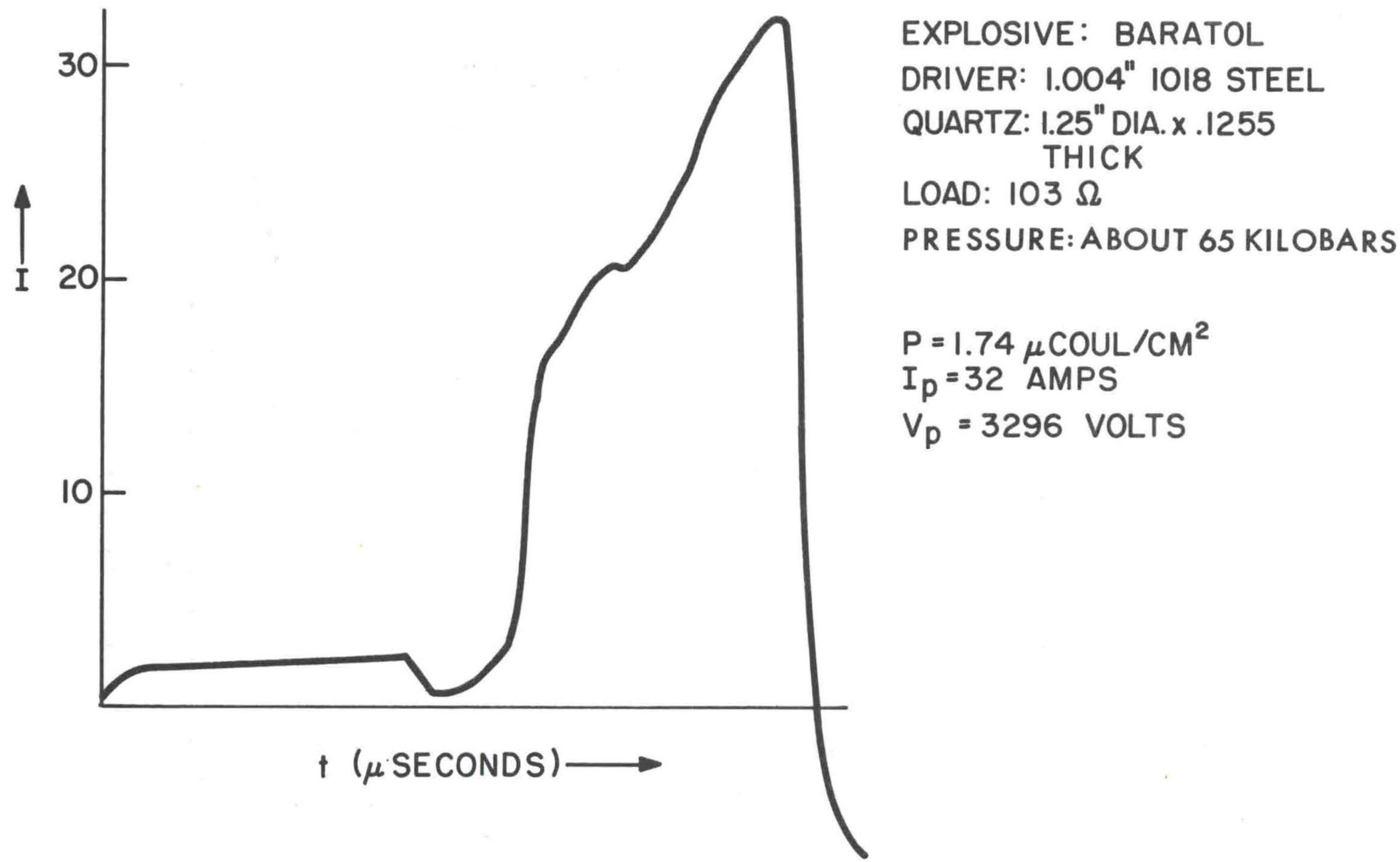

30
20
10
I
t (μ SECONDS)
EXPLOSIVE: BARATOL
DRIVER: 1.004" 1018 STEEL
QUARTZ: 1.25" DIA. x .1255
THICK
LOAD: 103 Ω
PRESSURE: ABOUT 65 KILOBARS
P = 1.74 μCOUL/CM²
Ip = 32 AMPS
Vp = 3296 VOLTS

FIGURE 4

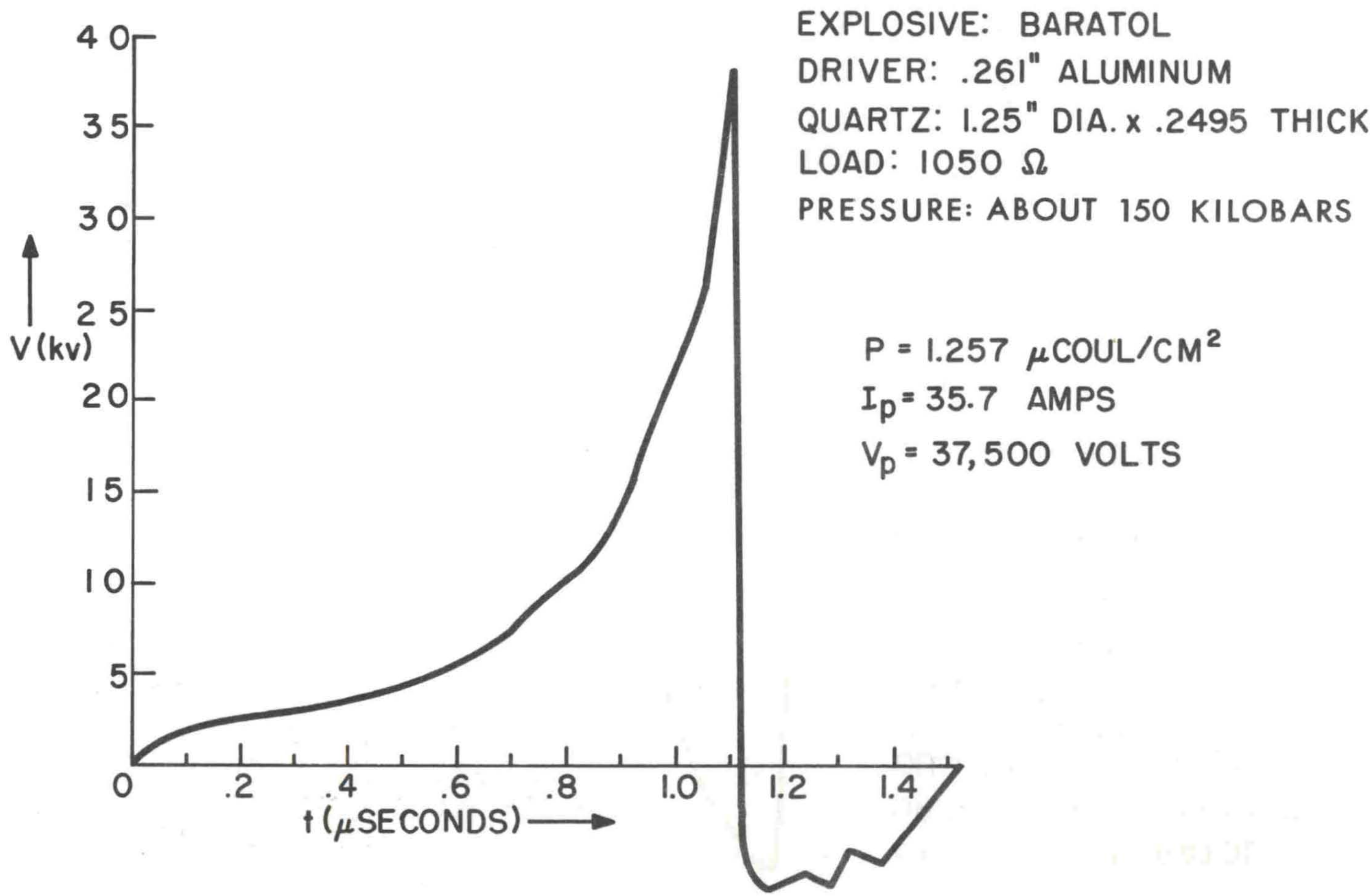

EXPLOSIVE: BARATOL
DRIVER: .261" ALUMINUM
QUARTZ: 1.25" DIA. x .2495 THICK
LOAD: 1050 Ω
PRESSURE: ABOUT 150 KILOBARS
P = 1.257 μCOUL/CM²
Ip = 35.7 AMPS
Vp = 37,500 VOLTS
V (kv)
40
35
30
25
20
15
10
5
0
.2
.4
.6
.8
1.0
1.2
1.4
t (μSECONDS)

FIGURE 5

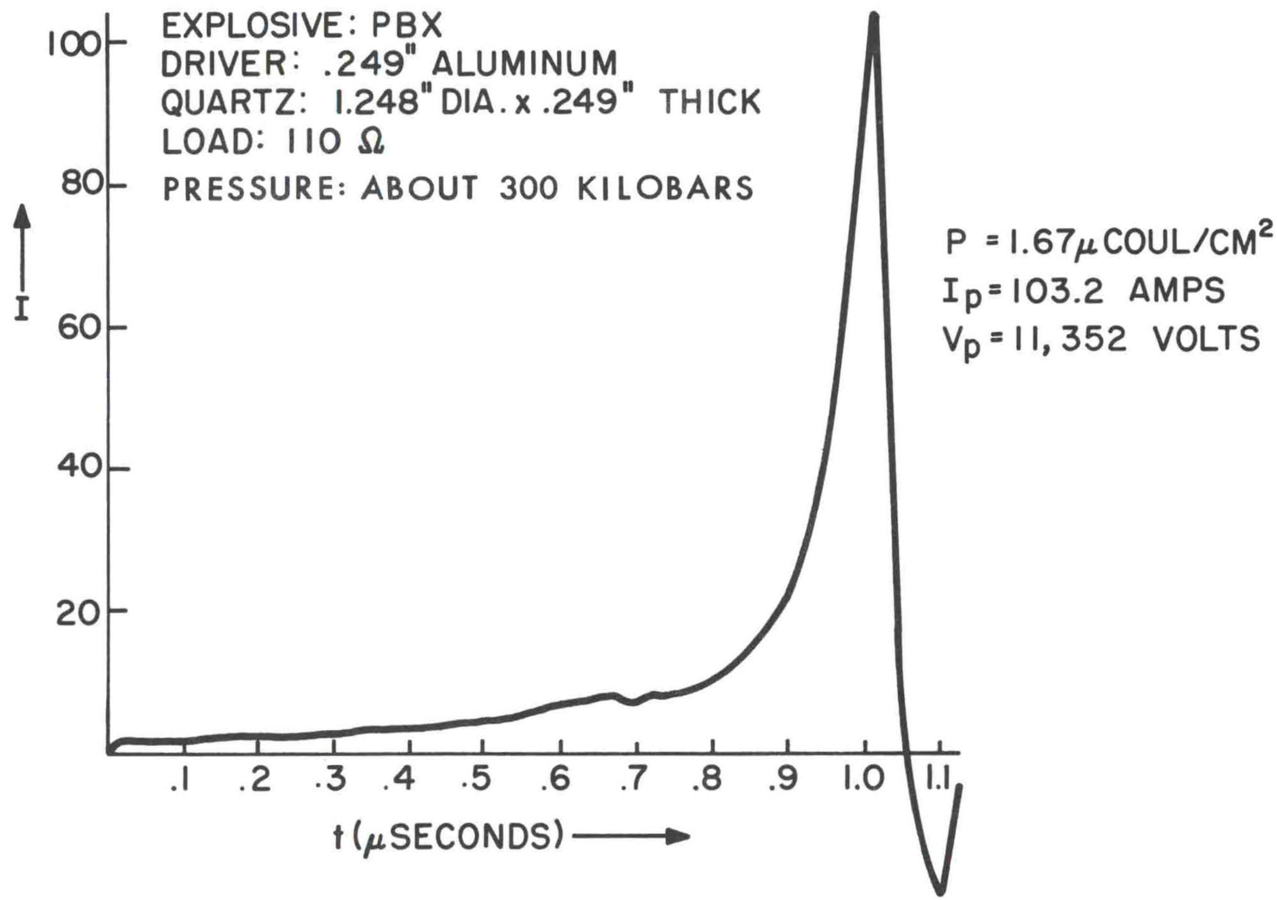

EXPLOSIVE: PBX
DRIVER: .249" ALUMINUM
QUARTZ: 1.248" DIA. x .249" THICK
LOAD: 110 Ω
PRESSURE: ABOUT 300 KILOBARS
P = 1.67μ COUL/CM²
Ip = 103.2 AMPS
Vp = 11,352 VOLTS
I
100
80
60
40
20
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
t (μSECONDS)

FIGURE 6

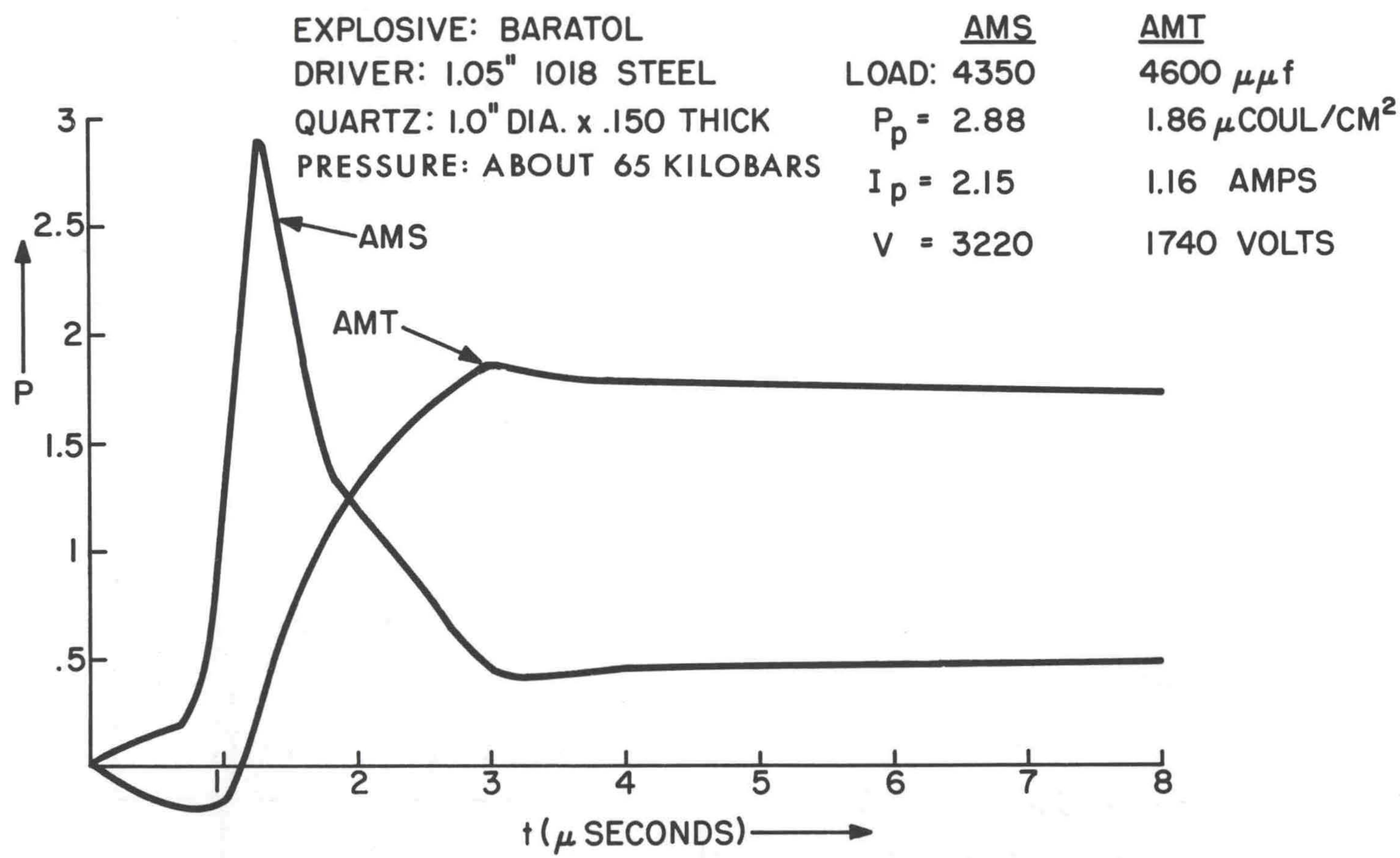
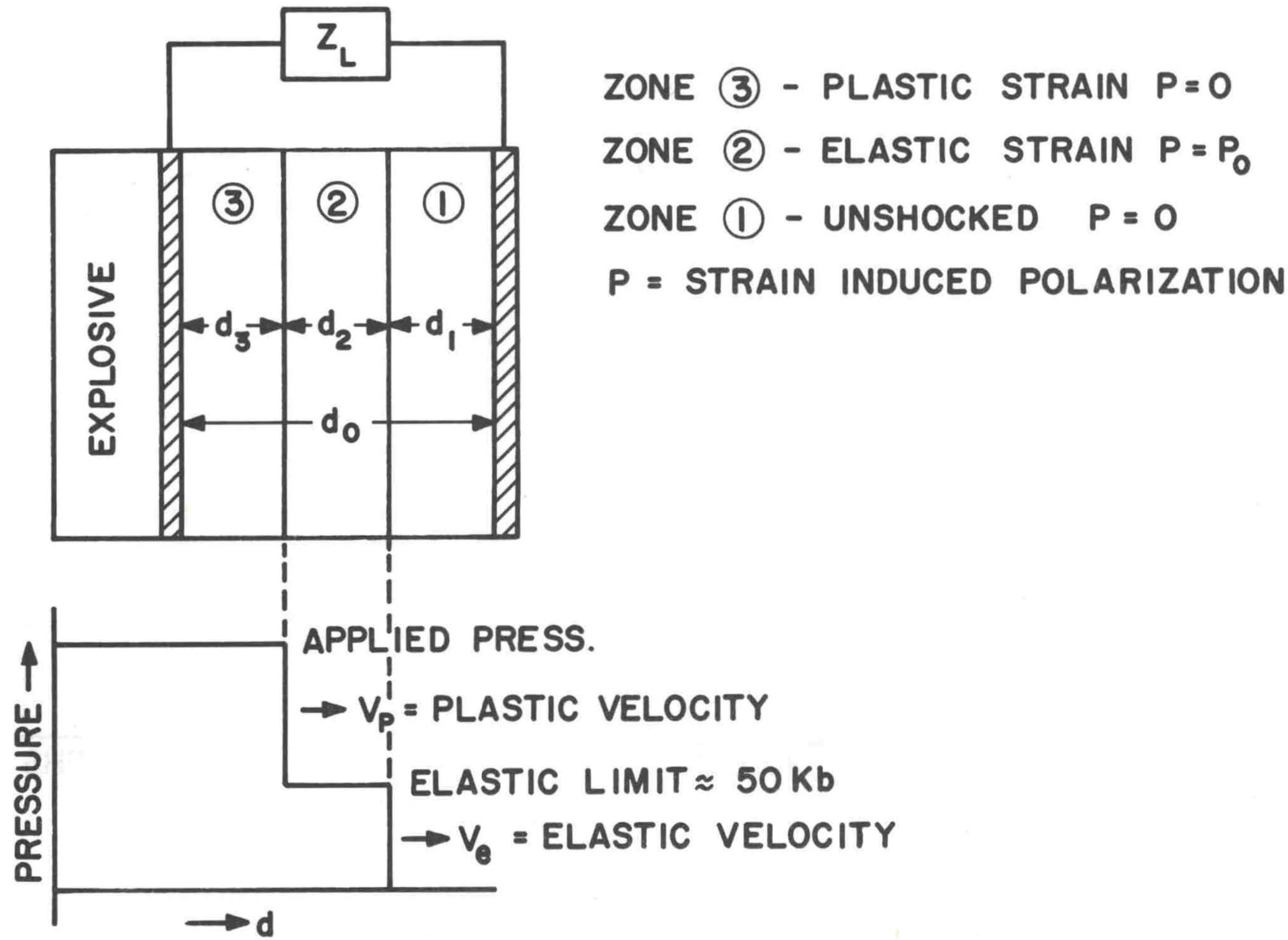
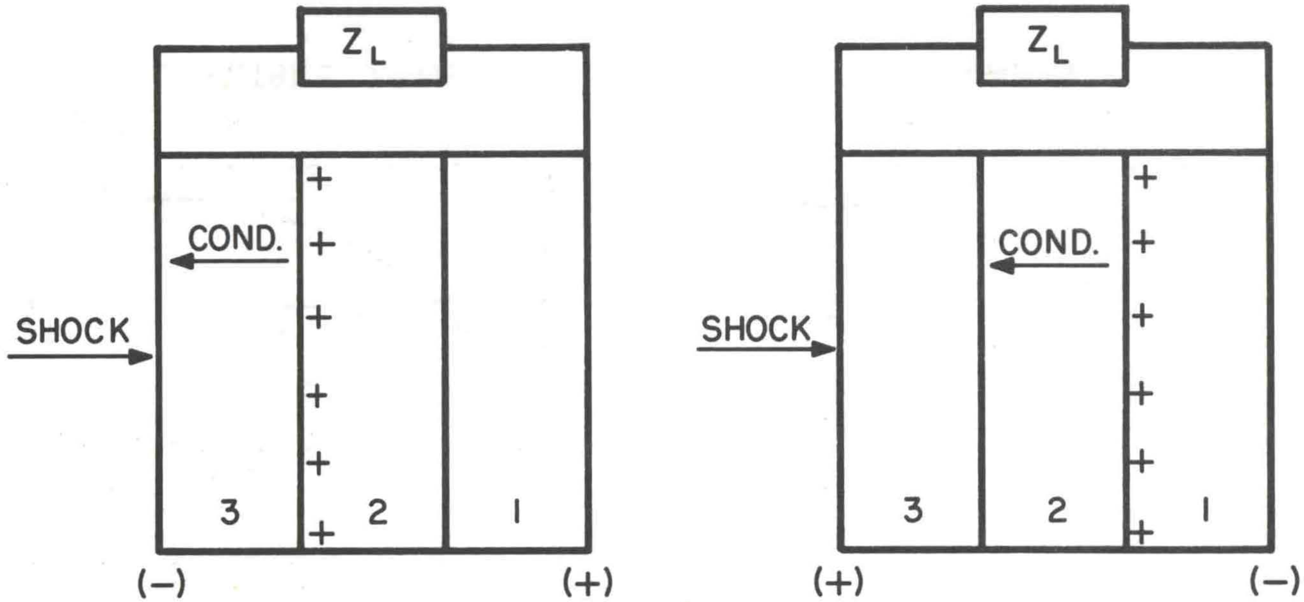

EXPLOSIVE: BARATOL
DRIVER: 1.05" 1018 STEEL
QUARTZ: 1.0" DIA. x .150 THICK
PRESSURE: ABOUT 65 KILOBARS
AMS
AMT
LOAD: 4350
4600 μμf
P_p = 2.88
1.86 μCOUL/CM²
I_p = 2.15
1.16 AMPS
V = 3220
1740 VOLTS
AMS
AMT
P
3
2.5
2
1.5
1
.5
1
2
3
4
5
6
7
8
t (μ SECONDS)

FIGURE 7



THREE ZONE MODEL OF SHOCKED QUARTZ

FIGURE 8



$$V_L + D_3 v_p t + (D_2 - P_0)(v_e - v_p)t + D_1 (d_0 - v_e t) = 0$$

FOR (+) OUTPUT $D_2 = D_1$ $D_3 = 0$

$$V_L + D_1 (d_0 - v_p t) = P_0 (v_e - v_p)t$$

FOR (−) OUTPUT $D_2 = P_0$, $D_3 = D_1 + P_0$

$$V_L + D_1 \left[d_0 - (v_e - v_p)t\right] = -P_0 v_p t$$

FIGURE 9

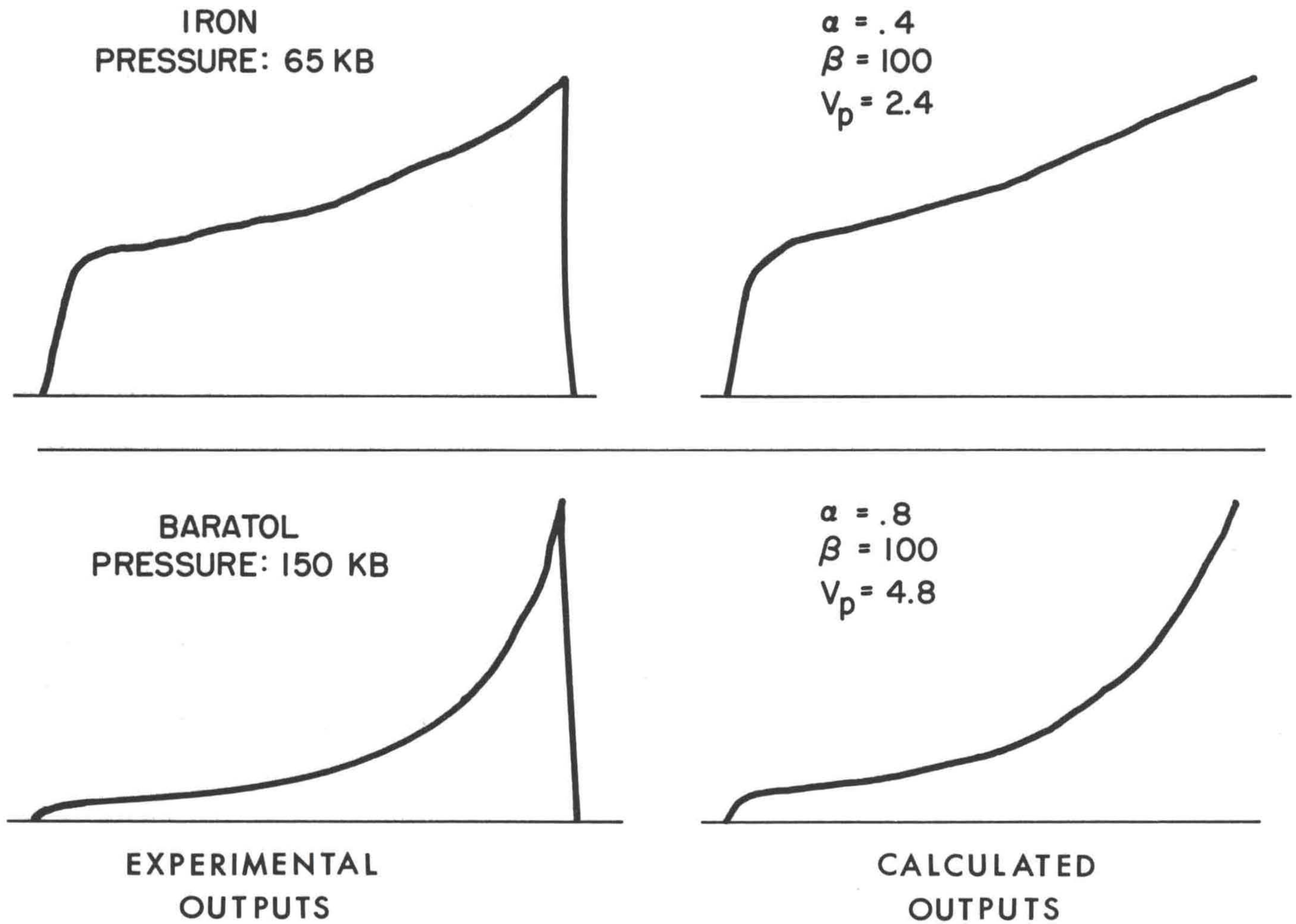

IRON
PRESSURE: 65 KB
α = .4
β = 100
V_p = 2.4
BARATOL
PRESSURE: 150 KB
α = .8
β = 100
V_p = 4.8
EXPERIMENTAL OUTPUTS
CALCULATED OUTPUTS

FIGURE 10

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