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POR-3005
(WT-3005)

FERRIS WHEEL SERIES
FLAT TOP I EVENT

PROJECT OFFICERS REPORT—PROJECT 1.4

CLOSE-IN SHOCK STUDIES

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Sandia Corporation
Albuquerque, New Mexico

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DEPARTMENT OF DEFENSE
WASHINGTON, D.C. 20301

ABSTRACT

Three measures of shock pressure and wave shape were made in the 1-to-10 kilobar pressure region resulting from the detonation of a 20-ton TNT charge on a limestone surface. Results influenced by the presence of a large electrical disturbance after zero time, indicates stress levels of 7.0 ± 1, 5.75 ± 1.5 and 4.0 ± 1 kilobars at ranges of 3.04, 3.96 and 5.18 meters respectively.

Hugoniot equation-of-state measurements on the limestone material permitted preshot calculation of the pressure levels as a function of distance from the charge and indicated the likely formation of a two-wave shock structure.

PREFACE

Field operations were conducted by personnel of the Nuclear Test Department of Sandia Laboratory. Field operation was directed by Mr. John S. Talbutt.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Flat Top I event was a surface detonation of a 20-ton TNT charge. The detonation took place on limestone in the Banded Mountain region of the Nevada Test Site. The essentially spherical charge, made up of 1126 cast TNT blocks, was detonated at the center of the half-buried assembly. The lower half of the charge, with an approximate radius of 1.4 meters, was separated from the limestone excavation by several inches of an epoxy material whose Hugoniot equation of state was similar to that of limestone.

1.2 OBJECTIVES

The objective of Project 1.4, Close-In Shock Studies, was the gathering of experimental data on shock pressure and wave shape at several distances from a detonation on limestone to aid in the definition of the pressure-distance relation for such a detonation.

This report is also being used to report the determination of the Hugoniot equation of state for the limestone near the charge.

CHAPTER 2

EXPERIMENTAL METHODS

2.1 HUGONIOT MEASUREMENTS

A knowledge of the Hugoniot equation of state (Reference 1) for the limestone medium is required for any calculation or prediction of pressure as a function of distance from the detonation. This activity was conducted well in advance of the test period. Material samples from the shot area were subjected to explosive tests in March and April, 1964.

The Hugoniot relation for strong shock waves results from a consideration of conservation of mass and momentum in the material system and is often stated as

$$P = \rho_o uV \tag{2.1}$$

and

$$\rho_o V = \rho(V-u) \tag{2.2}$$

where P is the shock pressure in a material whose particle velocity is u and shock velocity is V. Density ahead of and behind the shock front is ρ_o and ρ, respectively. Laboratory measurement of particle velocity and shock velocity over a range of shock pressures allows determination of shock pressure as a function of compressed density using Equations 2.1 and 2.2.

Details of the measurement technique are readily available elsewhere (References 1 and 2); only the general method is described here.

The impedance mismatch (Reference 1) technique has been utilized for these measurements. In this measurement, a material whose Hugoniot and reflection Hugoniot is well known is used to drive the unknown material. An explosive shock is passed through this driver material and then into the unknown sample. Since the Hugoniot of the driver material is known, a measure of the velocity of the explosively generated shock in the driver determines the pressure in the driver material; and as its reflection Hugoniot (unloading path) is known for the shock state achieved, a measure of the shock velocity reached in the unknown coupled with its preshock density is all that is required to define the Hugoniot at one point. In the experiments involved, brass and aluminum were used as the driver materials. Explosive shock loading was accomplished with shock waves generated from 8-inch diameter explosive plane-wave generators. Shock pressures above the level available from in-contact explosive tests were obtained from flying plate or momentum transfer experiments (Reference 3). These higher pressures, well above the level that could be obtained from the Flat Top I detonation, were necessary to accurately determine the shape of the Hugoniot relation in the limestone.

In each experiment, it is possible to obtain up to six independent electronic measures of shock velocity in the unknown. These independent measures are usually averaged to minimize effects of inhomogeneity in the test sample. The over-all inaccuracy in determination of shock velocity in a given experiment is less than 5%.

Measurements of the Hugoniot elastic limit of the limestone and the Hugoniot data in the region having a two-wave shock structure were made with X-cut quartz transducers measuring the transmitted stress from an explosively shocked sample. Detail of the technique is available in Reference 4.

2.2 EXPERIMENT DESIGN

Four quartz pressure transducers were used to determine shock pressures in the limestone as a function of distance from the center of the 20-ton explosive charge. These same transducers also measured a portion of the shape of the shock wave.

A prediction of stress level was made to determine desired transducer locations. The maximum stress at which the quartz transducer could be expected to operate is below 40 kilobars (a successful short duration measurement at this level was obtained on the Shoal nuclear detonation in granite), and a lower limit of interest was in the one-kilobar region. An estimate of the magnitude of the expected stress level can be made from the measured Hugoniot of the limestone, the reflection isentrope of the explosive, and empirical data available on the attenuation of strong shocks with distance from the point of detonation. The Hugoniot of Banded Mountain limestone was used along with the reflection isentrope (References 5 and 6) of TNT with densities of 1.5 and 1.64 gm/cm^3. An attenuation rate as observed on the Shoal and Hardhat (Reference 7) detonation was used.

Figure 2.1 shows the measured Hugoniot and the isentrope. The intersection of the Hugoniot and the isentrope indicate pressures in the 190-to-220 kilobar range at the explosive-limestone interface. In Figure 2.2, Estimated Peak Shock Pressure versus Range, values of 190 and

220 kilobars were used at the charge radius of 1.42 meters. A power-law decay consistent with Shoal and Hardhat observations indicates pressures of 35, 20, 10, and 4.5 kilobars at ranges of 2.59, 3.04, 3.96, and 5.18 meters.

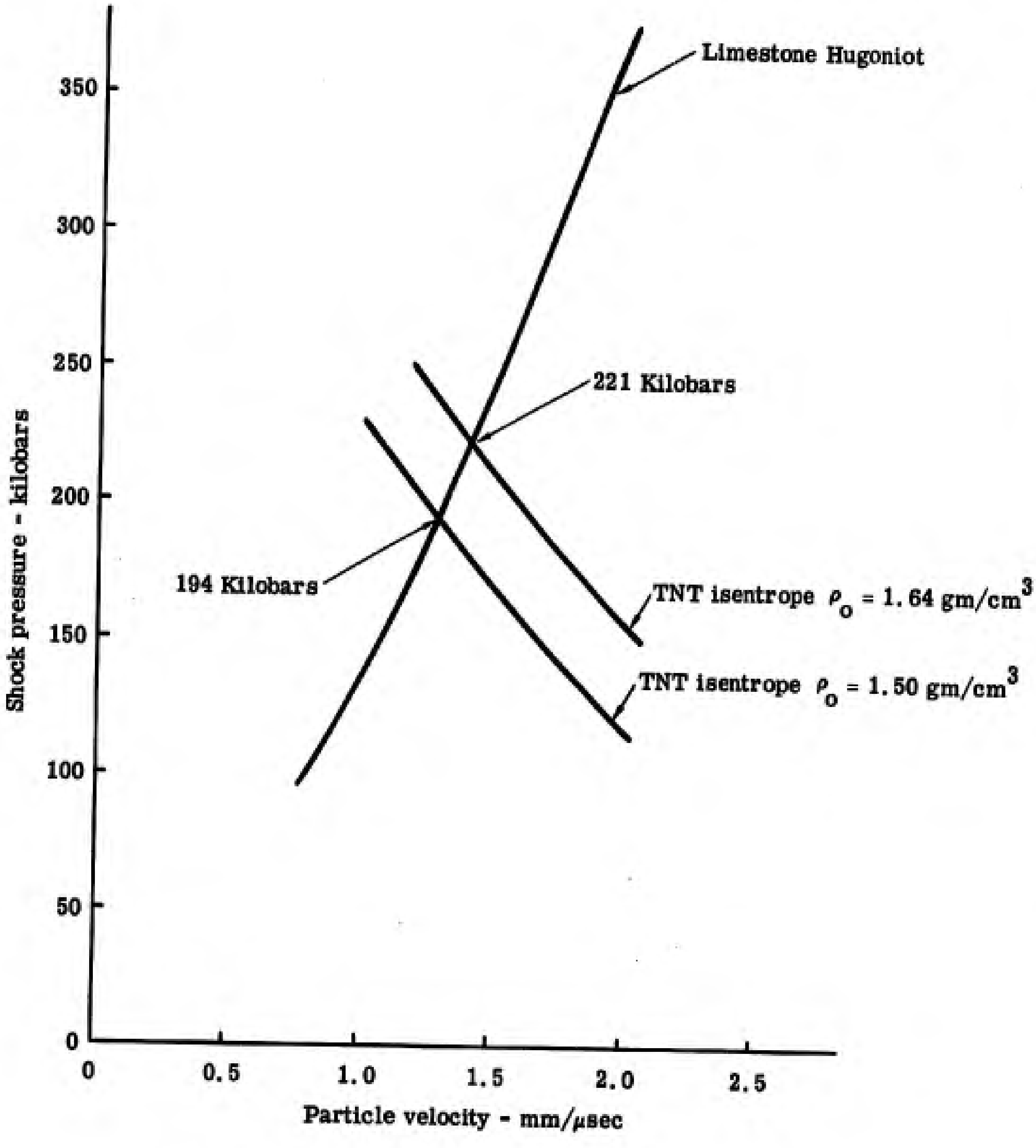


Figure 2.1 Limestone Hugoniot and TNT isentrope.

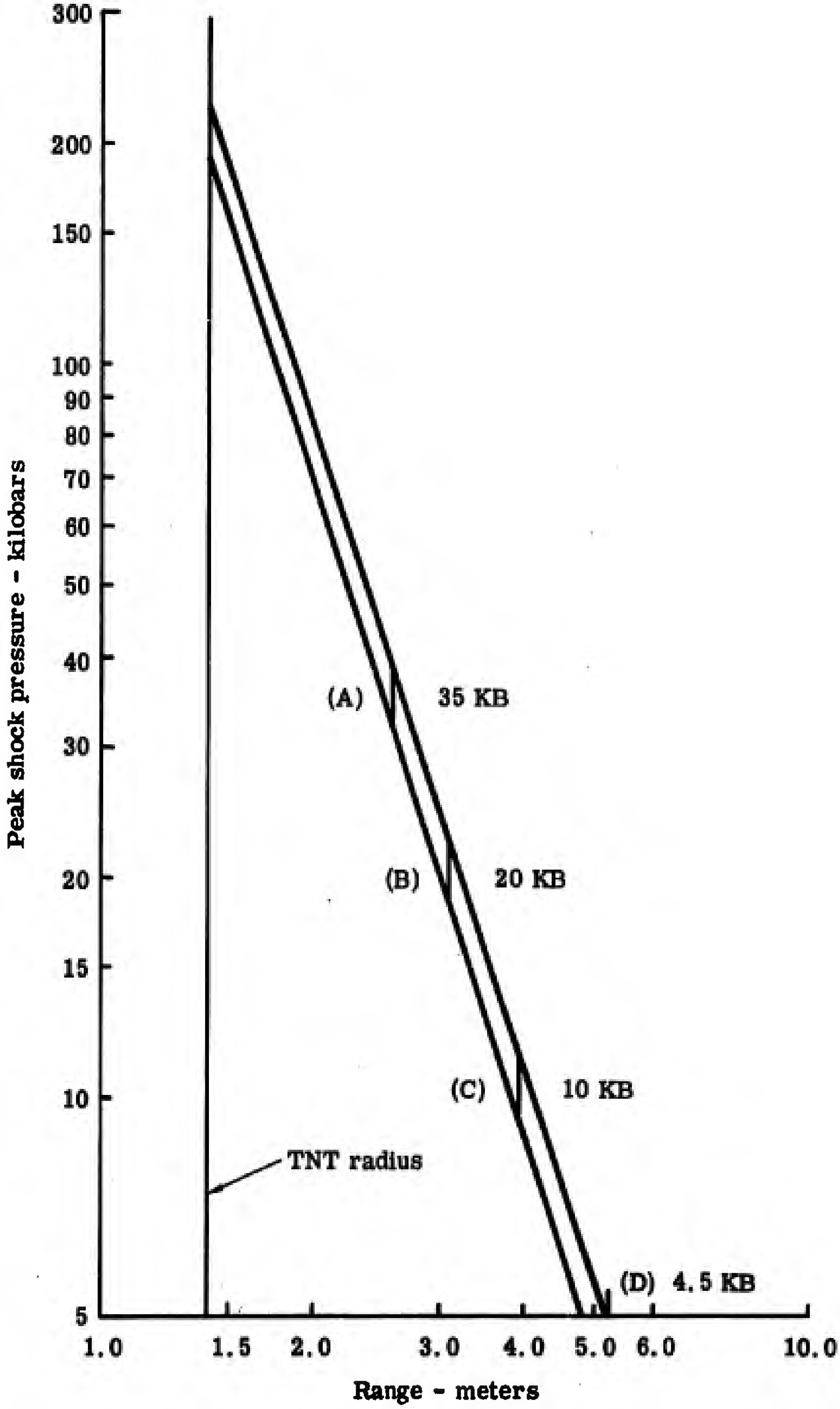


Figure 2.2 Estimated pressure radius relation for experiment planning.

CHAPTER 3
INSTRUMENTATION

3.1 INSTRUMENTS

The pressure measurements were made with X-cut quartz discs (0.5 inch diameter by 0.050 inch thick) mechanically coupled to the surrounding limestone by a magnetite grout. Figure 3.1 shows the two types of quartz disc transducers used. Unidirectional stress along the X axis of a single quartz disc produces a piezoelectric charge given by

$$q = d_{11}(A)\sigma \qquad (3.1)$$

where

q = charge on quartz disc

d_{11} = piezoelectric constant for X axis charge with stress applied along the X axis (2.25×10^{-8} coulombs/cm^{2}kilobar) (Reference 8)

A = area of quartz disc surface

σ = stress in kilobars

X axis polarization from stress on the Y and Z axis is of opposite polarity to the X axis polarization from stress on the X axis, hence a reduction in X axis charge results from Y and Z axis stress. This X axis charge degradation should be small in the transducers because of the thickness and area ratios of the three axes. It is thought that the error in charge value due to stress on the Y and Z axis is less than the system calibration error and consequently the output from the quartz represents stress on the X axis.

Charges produced by stress on the quartz discs were integrated by accumulation on a capacitor as shown in Figure 3.2. The total accumulation capacitance is the parallel combination of the quartz disc capacitance, the cable capacitance, and the capacity of C_A. The input impedance of the emitter follower shown in Figure 3.2 is 1.47×10^7 ohms, making the RC time constant of the integrating circuit about one second and permitting the observation of stress profiles tens of milliseconds in duration. Non-linear operation of the emitter follower limits the voltage from a net negative charge to approximately -0.25 volt. This type operation is not detrimental to usual stress measurements because the quartz delivers a net positive charge. However, should a negative charge be stored on the accumulation capacitor from some other source, the voltage out of the emitter follower could indicate a stress lower than the actual stress because a part of the positive charge from the quartz would be required to destroy the negative charge stored on the accumulation capacitor. This effect would appear on a stress record as a shift in the zero reference to -0.25 volt.

3.2 INSTALLATION

Quartz transducers of the type shown in Figure 3.1 (a) were installed at radial distances of 2.59, 3.04, and 3.96 meters from the center of the charge. A transducer as shown in Figure 3.1 (b) was installed at a radial distance of 5.18 meters. All four transducers were attached to a single one-eighth-inch steel cable and suspended in a twelve-inch-diameter hole drilled from the charge center and 60 degrees below a horizontal plane through the charge center. The transducer string was grouted in place with a mixture designed by Waterways Experiment Station to match material density and approach observed sonic velocity.

The hole containing the transducers extended from the charge to a horizontal drift approximately 30 feet below the charge. This geometry permitted the signal cables to be brought out behind the transducers. Integrating circuits were located in this horizontal drift. One hundred feet of teflon dielectric coaxial cable connected each transducer and its integrator. Approximately 2000 feet of type RG8 coaxial cable conveyed the transducer signal from the integrator to the recording system.

3.3 RECORDING

As shown in Figure 3.3, an oscilloscope photographic record and a magnetic tape recording were made of each quartz transducer signal.

All oscilloscope sweep circuits were armed approximately 200 microseconds after zero time by a delayed zero fiducial to prevent trigger from an electromagnetic disturbance expected at time of detonation. The oscilloscope camera shutters were opened one second before and closed one second after zero time by remote signals.

The magnetic tape record was made on an Ampex Model CP 100 tape recorder. Each transducer signal was recorded by both the direct and FM techniques, giving a bandwidth from dc to 250 kilocycles. A zero fiducial was recorded on one tape channel to permit a measure of the time required for the shock wave to travel from the charge to each transducer. The tape transport was remotely started two minutes prior to zero time to permit tape speed stabilization.

3.4 CALIBRATION

The piezoelectric constant of quartz is well defined for a unidirectional stress of less than 25 kilobars along the X axis.

Charge sensitivity for a one kilobar stress and a single quartz disc can be obtained from Equation 3.1. Since this sensitivity is for a single quartz disc, the value of charge obtained is doubled for the two disc transducers. Charge sensitivity for a one-kilobar stress and a knowledge of system gain, optimum signal voltage at the input of the recording system, and expected stress permits calculation of the required lumped accumulation capacity from

$$C_A = \frac{qG_s}{E} - (C_t + C_c) \qquad (3.2)$$

where

q = charge on quartz disc

C_A = lumped accumulation capacity (farads)

E = optimum voltage at recording system input

G_s = system gain from integrator input to input of recording system

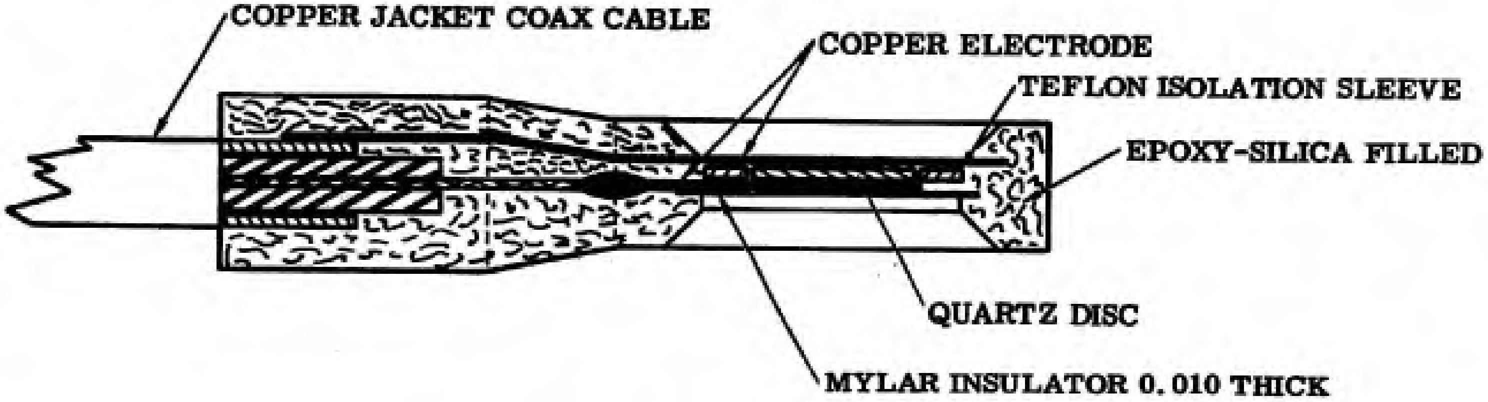
C_t = capacity of transducers (farads)

C_c = capacity of cable between transducer and integrator (farads)

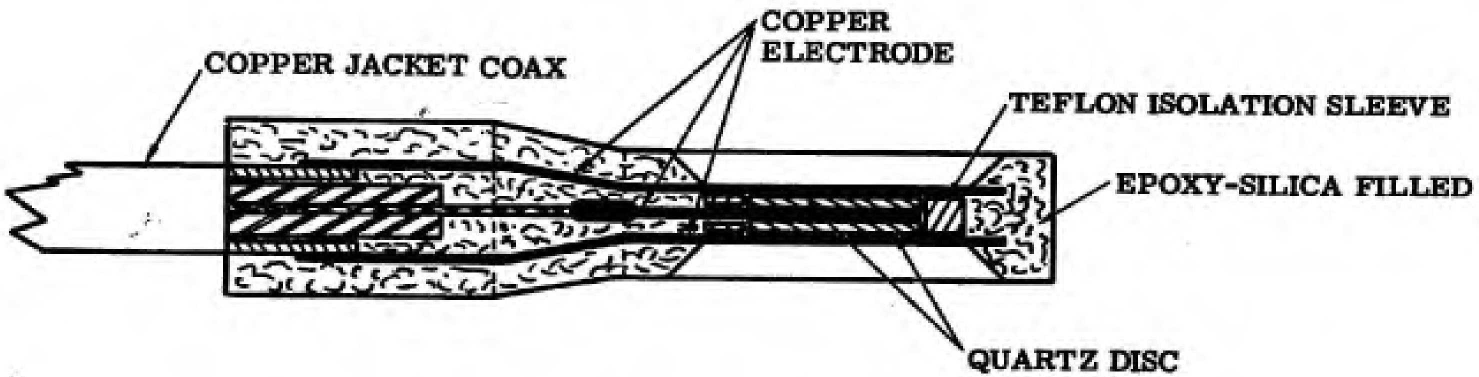
Since it may be difficult to obtain a capacitor of the exact value calculated for C_A, a practical value of capacity close to the calculated value is installed in the integrator and the voltage sensitivity (e) at the recording system input per kilobar of applied stress is obtained from

$$e = \frac{qG_s}{C_A + C_c + C_t} \qquad (3.3)$$

The vertical sensitivity of each oscilloscope was calibrated before the event and a voltage amplitude calibration was applied to each magnetic tape channel prior to zero time. This tape calibration provided a check on recording system gain and made it possible to reproduce the data through a playback system of unknown gain.



Single Disc Quartz Transducer



Double Disc Quartz Transducer

Figure 3.1 Quartz transducers.

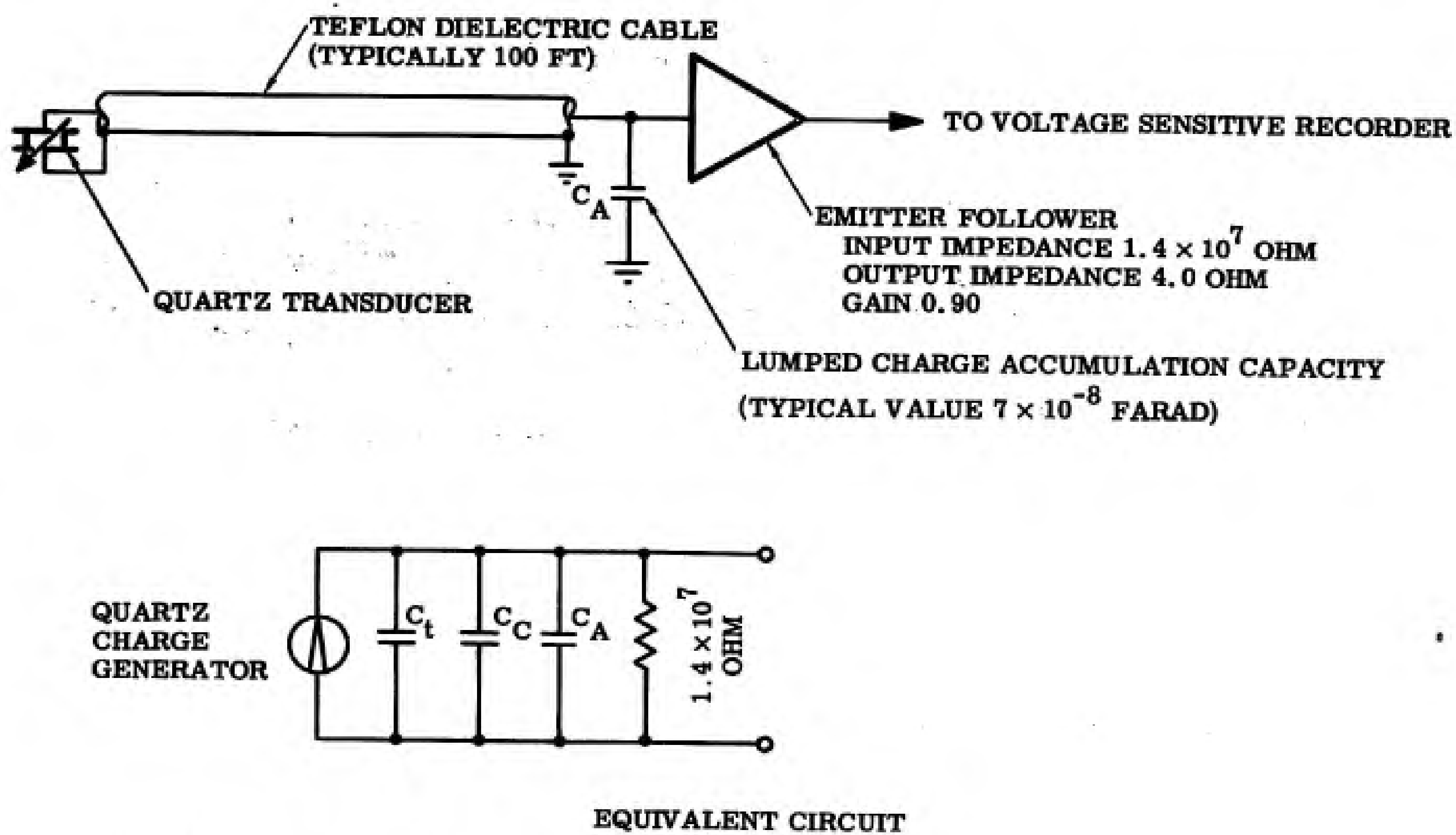


Figure 3.2 Quartz charge integrating circuit.

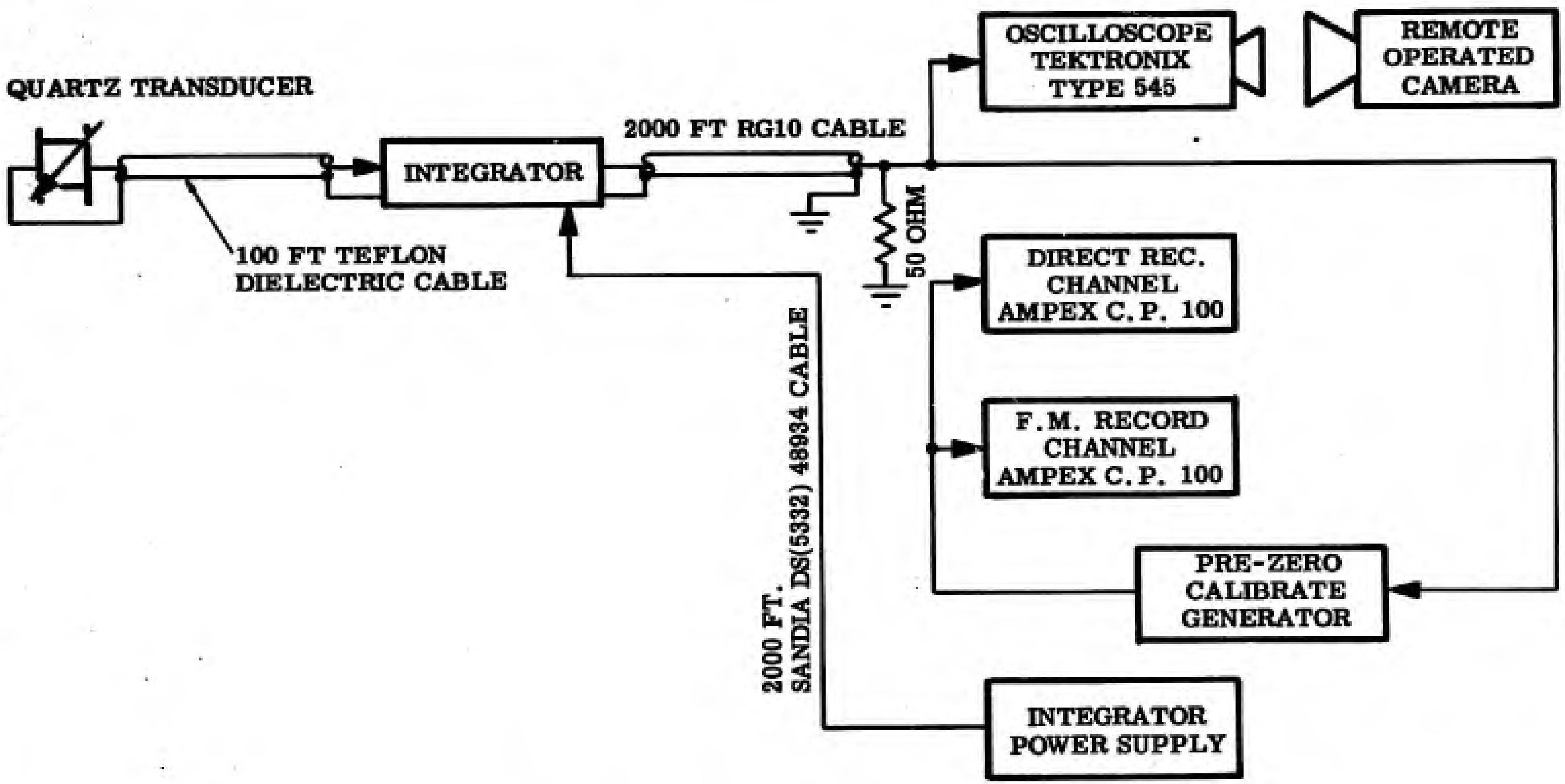


Figure 3.3 Quartz transducer channel.

CHAPTER 4

RESULTS

4.1 DATA ACQUIRED

A difficulty in triggering prevented any data from being recorded on oscilloscopes. The presence of an EM-like disturbance at plus 235 microseconds triggered the oscilloscopes at that time, and data were either obscured in the disturbance or occurred following the oscilloscope sweep time. As previously reported, all data channels were recorded in parallel on magnetic tape having a frequency response of up to 250 kilocycles. This frequency response is consistent with the estimated maximum time of 5 microseconds required for equilibrium within the quartz measurement assembly, and no data were lost as a result of the oscilloscipe trigger problem.

No output was obtained from the transducer located at 2.59 meters range. This particular gage was not operating properly after installation, and the loss of information is assumed to be due to some damage during installation or to improper fabrication.

Good data records were obtained on both the direct and FM tape channels for the transducers located at 3.04, 3.96, and 5.18 meters. The outputs of these transducers are shown in Figure 4.1, a plot of stress in kilobars above the indicated base line as a function of time.

4.2 HUGONIOT MEASUREMENTS

The results of the Hugoniot measurements made on samples of Banded Mountain limestone are given in Table 4.1. The samples tested were obtained from core drilling directly below the shot location. The chemical composition of the material was reported (Reference 9) as 97.4% $CaCo_3$ and 0.99% $MgCo_3$. The remainder of 1.61% was not identified.

An elastic precursor of 5.5 kilobars was observed in one- and two-centimeter samples driven at a pressure of 110 kilobars in Experiments 275 and 279. The velocity of this elastic wave was measured as $0.578^{+.020}_{-.014}$ centimeter per microsecond.

A plot of the data in Table 4.1 is shown in the form of shock velocity as a function of particle velocity in Figure 4.2. Values of the constants C and S appearing in the relation

$$V = C + Su$$

are as follows:

$P > 250$ kilobars	$C = 0.425$ cm/μsec, $S = 1.32$
$P < 250$ kilobars	$C = 0.296$ cm/μsec, $S = 2.19$

TABLE 4.1 BANDED MOUNTAIN LIMESTONE HUGONIOT DATA

Experiment Number	Number of Measurements	Shock Velocity cm/μsec	Particle Velocity cm/μsec	Density gm/cm^3	Pressure Kilobars	V/V_o
277	3	0.801	0.280	2.66	596.9	0.651
286	4	0.723	0.231	2.66	443.3	0.680
271	2	0.648	0.162	2.66	278.9	0.750
268	3	0.581	0.135	2.66	208.6	0.768
279	1	0.474	0.084	2.66	105.9	0.823
275	6	$0.578^{+.020}_{-.014}$	0.00358	2.66	5.5	---

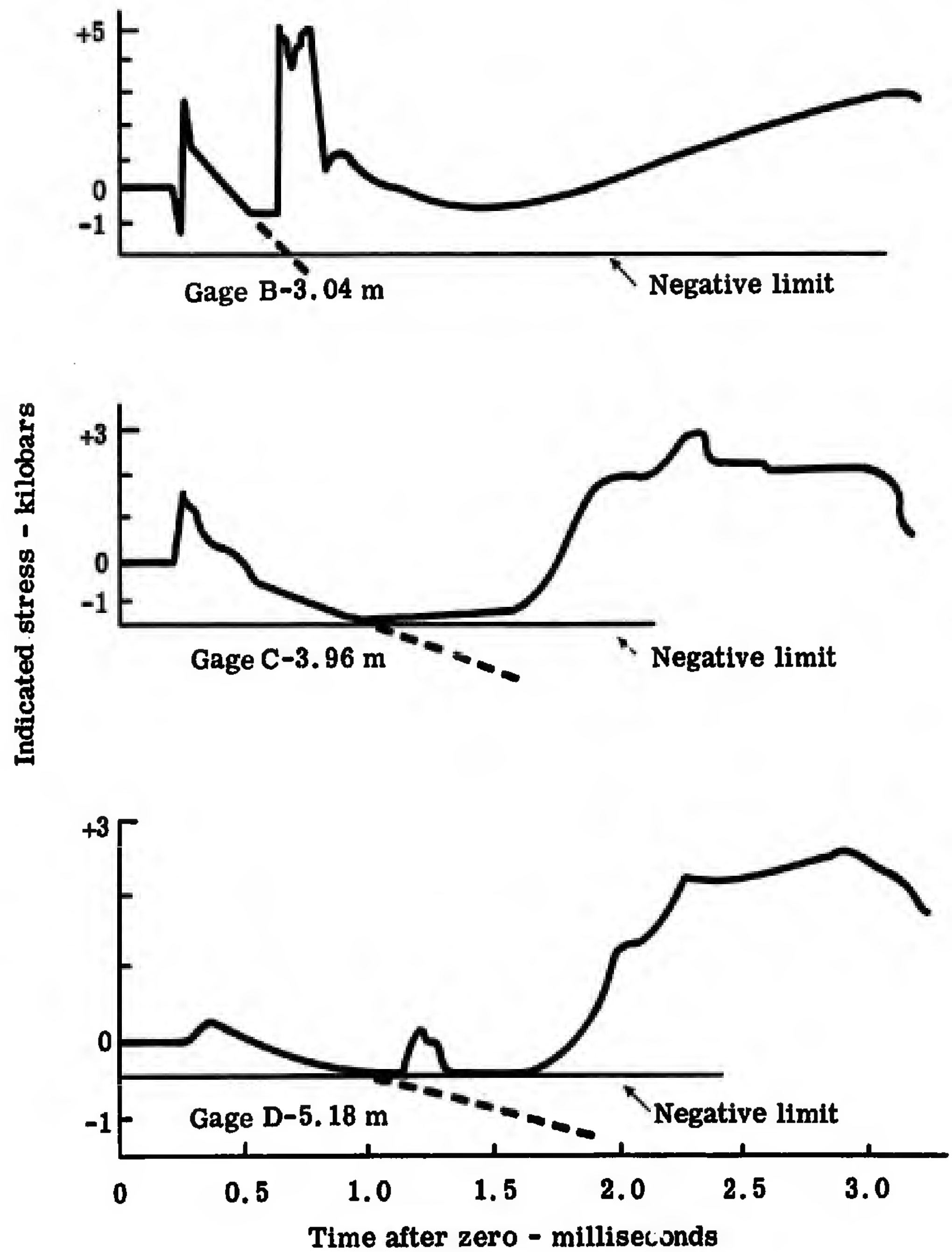


Figure 4.1 Transducer outputs as a function of time after detonation.

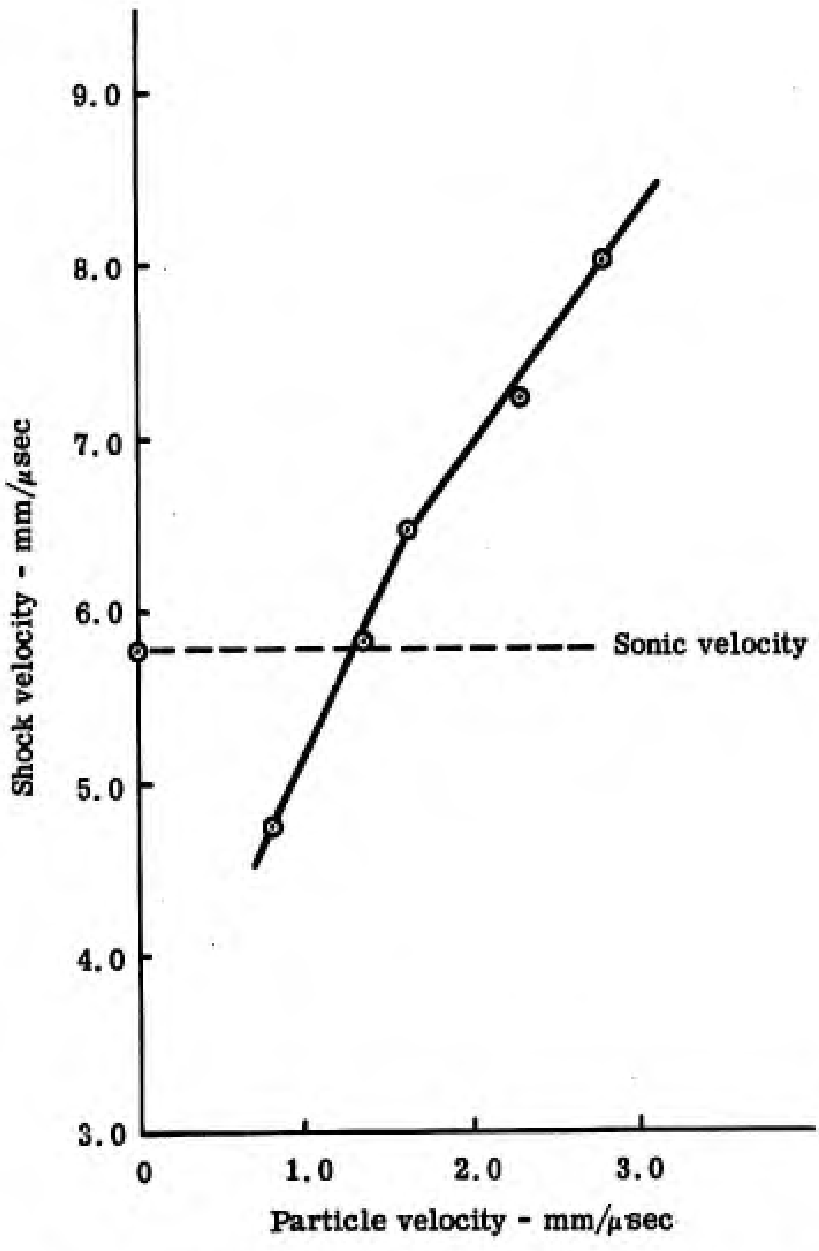


Figure 4.2 Shock velocity versus particle velocity, Banded Mountain limestone.

CHAPTER 5

COMMENTS ON THE DATA

5.1 LIMESTONE HUGONIOT

The Hugoniot measurements made on limestone samples obtained from a location approximately fifteen feet below the charge center indicate the formation of a two (or more) wave shock structure at pressures below 195 kilobars. This value is obtained by use of a plot of shock velocity as a function of particle velocity in the limestome (Figure 4.2). The Hugoniot of the limestone is represented by the line connecting the experimentally observed states in the material. It is seen that for particle velocity less than 0.130 cm/μsec, a shock velocity less than the sonic value of 0.578 cm/μsec will be observed. This slower main shock wave will always follow the first elastic or sonic wave. At any pressure above the state having particle velocity of 0.130 cm/μsec (pressure > 195 kilobars), no elastic wave will be expected.

In Experiments 275 and 279, a shock pressure of 110 kilobars was produced in the limestone and a forerunning elastic wave with magnitude of about five kilobars was observed. The possible variation of magnitude of this elastic wave with driving pressure was not investigated. Similarly, no study was made of the attenuation of this wave with sample thickness.

Since the pressure at the explosive-limestone interface was estimated (Figure 2.1) to be 190 to 220 kb even without consideration of the effect of the epoxy layer, a two or more wave shock likely existed over the entire close-in measurement region. The epoxy layer could only decrease the initial pressure since its shock impedance was reported to be lower than that of the limestone (Reference 10).

5.2 SHOCK PRESSURE AND SHAPE

The outputs of the transducers as shown in Figure 4.2 are not thought to be completely representative of either the peak pressure or wave shape at the transducer locations.

The basis for distrust of the transducer outputs as shown is the presence of a rather large electrical disturbance on all recorded channels and the lack of sufficient negative recording capability of the measurement system as discussed in Chapter 3. The significant electrical disturbance observed was not anticipated for a chemical explosive detonation, and adequate measures were not taken to minimize its effect.

The electrical disturbance occurred at the time that the explosive detonation front reached the edge of the explosive, not at the time of initiation of the charge. The earliest disburbance observed (Figure 4.1, Gage B) occurred at zero plus 240 microseconds. This value of time is consistent with the accepted explosive detonation rate of 6640 meters/second for cast TNT with density of 1.56 gm/cm^3.

The disturbance produced both positive and negative charges on the measurement system accumulation capacitors as shown by the records reproduced in Figure 4.1. The long-term effect in all cases was a negative charge. Each of the three transducer recording channels could accurately record a negative signal level of 0.25 volt. Negative values in excess of this amount will cause no change in the recorded level.

However, charge accumulation on the capacitor would continue and, as the discharge time constant is intentionally long, will effectively remain until balanced or exceeded by a positive output from the quartz transducers.

Any slowly increasing stress on the quartz element would decrease the rate of negative charge accumulation if it were still continuing but would not necessarily be sufficient to cause the recording of the stress until the accumulated negative charge is balanced or exceeded; and should the recording indicate a negative voltage in excess of 0.25v, an unknown amount of negative charge would have to be overcome.

The shock arrival times indicated by the recorded data are inconsistent within themselves and with the known sonic velocity of the material. Since this material, Banded Mountain limestone, can reasonably be expected to exhibit a two-wave shock structure, an estimate of arrival time based on sonic velocity is proper. For the ranges of 3.04, 3.96, and 5.18 meters, values of arrival times should be approximately 0.5, 0.7, and 0.9 millisecond, respectively.* An examination of the data shown in Figure 4.1 shows each system accumulating negative charge or near the negative recording limit at these times.

A small positive stress is indicated at 1.1 milliseconds in the record of Gage D. This can be taken as indicative of a slowly rising first wave.

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* These times are based on limestone sonic velocity of 0.578 cm/μsec and the observed 240 microsecond time for the detonation front at the explosive surface.

It is possible to make an estimate of the magnitude of the stress addition required to correct the observed values of stress for the limiting fault of the electronics. The indicated rate of negative charge accumulation before negative cut off is low, and an inspection of the output shown in Figure 4.1 would indicate the correction required would not be in excess of one or two kilobars for Gages B and D and one to three kilobars for Gage C. The magnitude of the addition was determined in the following manner. The rate of negative charge accumulation prior to the apparent shock arrival was assumed to continue through the measurement interval as indicated by the dashed lines in Figure 4.1. A value of the required stress addition was then obtained at the time of peak indicated stress. We feel that so long a period of negative accumulation is unlikely and consider the added values to be representative of an upper limit of the actual stress value. We conclude that the peak pressure values represented by the observations are 7.0 ± 1 kilobars, 5.75 ± 1.5 kilobars, and 4.0 ± 1 kilobars for the gages located at 3.04, 3.96 and 5.18 meters, respectively.

The output of transducer B (3.04 meters) appears to represent only the early portion of the shock front to a time of 0.7 millisecond after detonation. The recorded output after this time is typical of a damaged transducer and is consistent with many laboratory observations of transducer output following damage due to the incident stress.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Although not conclusive, our measurements indicate a two-wave shock structure likely existed in the limestone test media from a point very near the explosive-limestone interface to that location where the shock front was attenuated to a value below the Hugoniot elastic limit of the material. Measurements made by this project indicate this point was about five meters away from the center of the detonation.

An unexpectedly strong electromagnetic disturbance developed at the time the detonation front reached the edge of the explosive. Both positive and negative signals were observed from this disturbance which adversely affected recording of stress.

The peak stress at the three operable transducers located at 3.04, 3.96, and 5.18 meters was 7.0 ± 1, 5.75 ± 1.5, and 4.0 ± 1 kilobars, respectively.

The shape of the shock front was a slowly rising function, likely not reaching its full value until a time of about one millisecond after its first arrival.

6.2 RECOMMENDATIONS

In future chemical explosive tests, we must take precautions to eliminate bias of recorded data from electrical disturbance resulting from the detonation.

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