BAS

Sensor Notes

Note 1

June 1973

Instrumentation Evaluation for Surface Bursts in Underground Cavities

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ABSTRACT

A study was conducted to determine the capabilities for instrumenting a Cavity Nuclear Test (CANT) type experiment. It was determined that existing instrumentation is not capable of measuring the high stresses produced by the experiment. Some of the proposed ground motion measurements are not feasible but the required data can be acquired by other means. It was recommended that development continued on gages capable of making high-stress measurements as a CANT-type experiment will be meaningless without this data. Other parameters can be measured with existing instrumentation.

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SECTION I

INTRODUCTION

1. BACKGROUND

The Cavity Nuclear Test (CANT) is a proposed series of energy coupling tests planned to parameterize the manner in which energy given off by a nuclear device is coupled into the ground. A free-surface nuclear blast gives off a set amount of energy, in the form of radiation and debris, during a short interval of time. This energy enters the surrounding environment causing a blast wave in the air and a shock wave in the nearby earth. These waves induce mechanical motion in structures, it is this motion which is of prime importance in assessing the vulnerability of the U.S. Defense System to nuclear attack.

The waveform of the airblast is known (ref. 1) and its effects upon structures can be simulated through the use of the high-explosive simulation technique (HEST) or blast on structures simulator (BOSS). However, formation of the ground shock is not clearly understood; the model by which the energy from the device is coupled in the earth needs to be defined along with the manner in which the shock wave is relieved at the surface and its rate of attenuation in the ground. This is important in the field of cratering and in determining the credibility of any model describing the ground motion produced by a nuclear blast.

Thus, the need to develop an experimentally verified model for energy coupling is paramount. The experiment (or experiments) must measure the energy output of the device and the pressure/time history of the shock wave induced into the ground. The pressure/time history should be measured as close as possible to the detonation and should extend out farther to measure the attenuation and the ground motion in the lower stress regions. This essentially is the plan for the CANT series of shots.

2. PURPOSE

The purpose of the study documented in this report was to describe and evaluate instrumentation requirements for CANT. These requirements include the measurement of high stresses (> 500 kbar), low stresses, ground motion, cavity growth, fireball growth, and temperature. Electromagnetic pulse (EMP) measurements are described briefly because the EMP measurements are normally performed by other agencies and are usually classified. Existing gages are described along with undeveloped and proposed gages.

3. SCOPE

A literature survey, personal experience of the author, and consultation with others working in the field were used in this study. As the instrumentation described and evaluated is necessary for the conduct of the CANT series of tests; this study is, in essence, an evaluation of the CANT proposal.

SECTION II

HIGH-STRESS INSTRUMENTATION

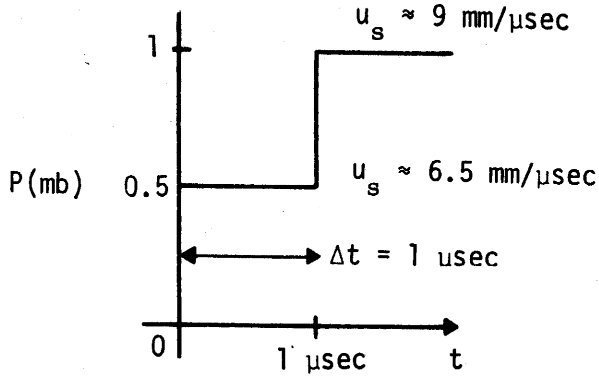
1. BACKGROUND

A primary purpose of a CANT-type experiment is to determine the manner in which energy from a nuclear device is coupled into the ground to form a shock wave. This shock wave should be parameterized as it is transmitted through the earth. To accomplish these goals either the stress/time history or a related parameter (i.e. particle velocity) must be measured as close to the event as possible. This requirement is critical for both the loading and the unloading portion of the pulse.

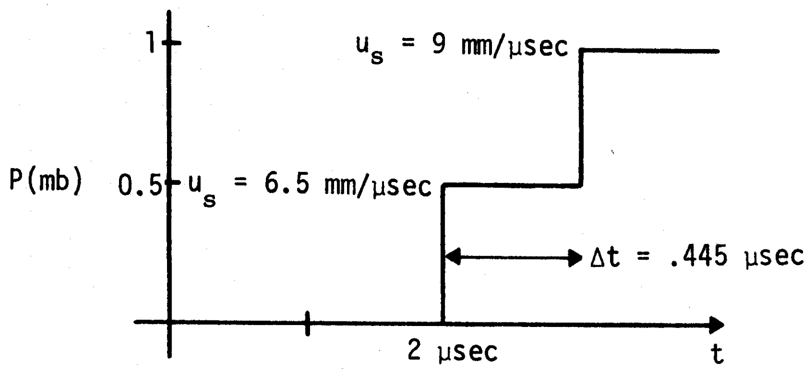
A nuclear detonation in a granite cavity could load the walls in a steplike manner as shown in figure 1(a). The initial pulse stress level is 0.5 mbar, a second pulse raises the stress level to 1.0 mbar. The corresponding shock velocities for these stress levels are approximately 6.5 and 9.0 mm/μsec. Figure 1(b) and 1(c) shows the from the shock front would have (presuming no attenuation) after different periods of time. Notice that after 3.6 μsec the loading steps are not distinguishable; the distance traveled by the front during this time is approximately one-third meter. Thus, even from this extreme example, the necessity of measuring the stress pulse in a region as close as possible to the volume of massive energy disposition is evident.

As these measurements are on the order of 1.0 Mbar or greater, high-stress instrumentation (capable of measuring from 500 kbars to 2 Mbars) is needed. This instrumentation will be subjected to an electromagnetic and radioactive environment as well as to the stresses produced by the detonation. The duration of the stress pulse is longer than the lifetime of most gages (several hundred msec); however, the gages should provide sufficient information about stress pulse decay before they are destroyed.

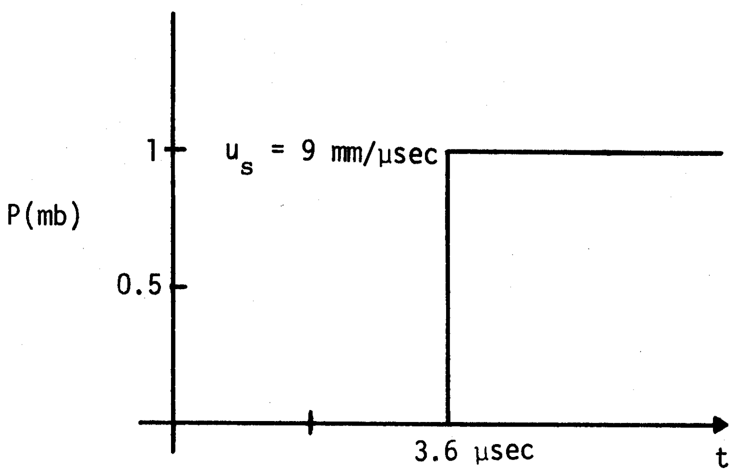
As the ability to measure high-stress/time histories does not exist at this time, the area of high-stress instrumentation includes mostly gages which are undergoing development. However, the ability to measure peak stress is a proven technique. One gage in this area is the impedance mismatch high-stress transducer (IMHST). Other gages which are being developed for possible use as



(a)



(b)



(c)

Figure 1. Shock Front Formation in Granite After Hypothetical Step Loading

time-history gages for the shock wave are the mutual inductance particle velocimeter (MIPV), the thermoelectric thermopile transducer (T^3), the microwave waveguide, and the manganin gage*.

2. EVALUATION

a. Impedance Mismatch High-Stress Transducer

The IMHST, probably the simplest of the gages, measures shock velocity in a known material as induced from the environment. The basic components of the gage are two or more piezoelectric crystal pins embedded in a matrix with a known monotonic-pressure-versus-shock velocity Hugoniot. A typical gage is shown in figure 2. Acrylic was chosen for the matrix material since it effectively impedance matches its environment and has a resonable Hugoniot. These points are demonstrated in figures 3 and 4.

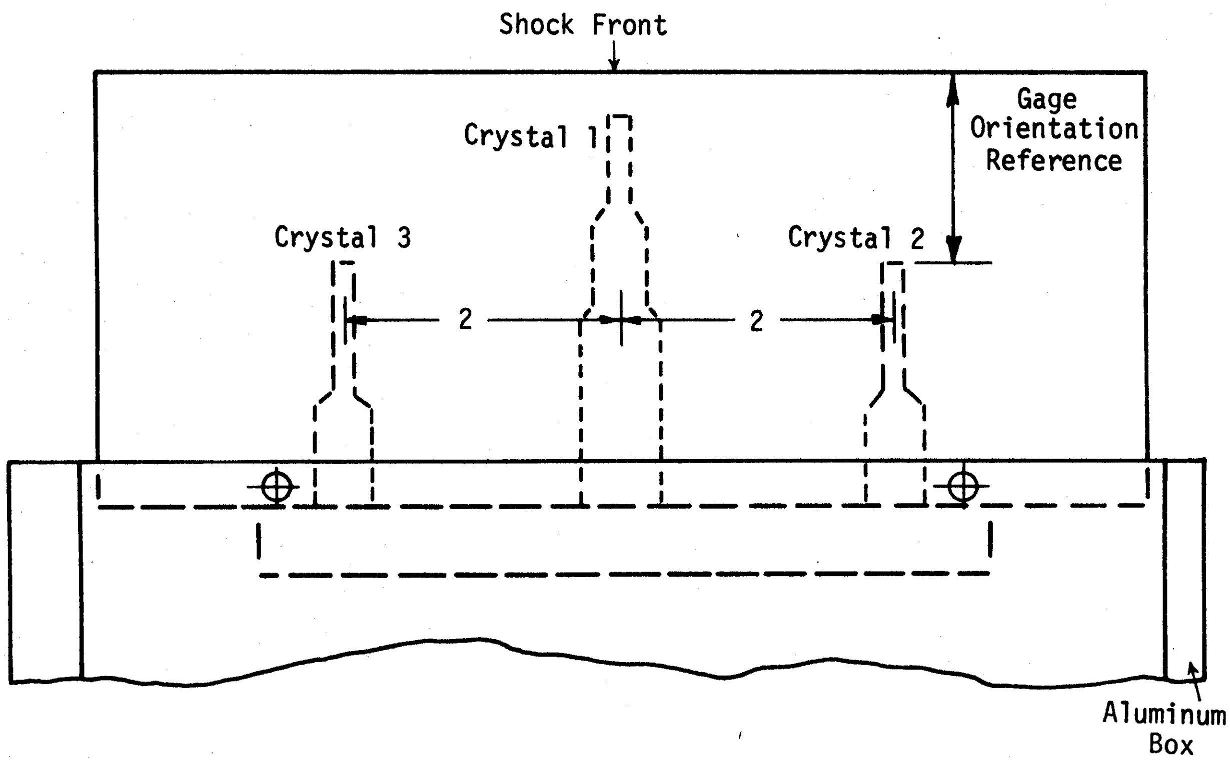


Figure 2. IMHST Gage Crystal Configuration (ref. 2)

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* This is not a complete list of the gages being developed. For example, LASL is developing a magnetic gage which measures the velocity of a buried plate in a magnetic field. ITTRI has used a material piezoresistive gage but this has previously been dropped from consideration

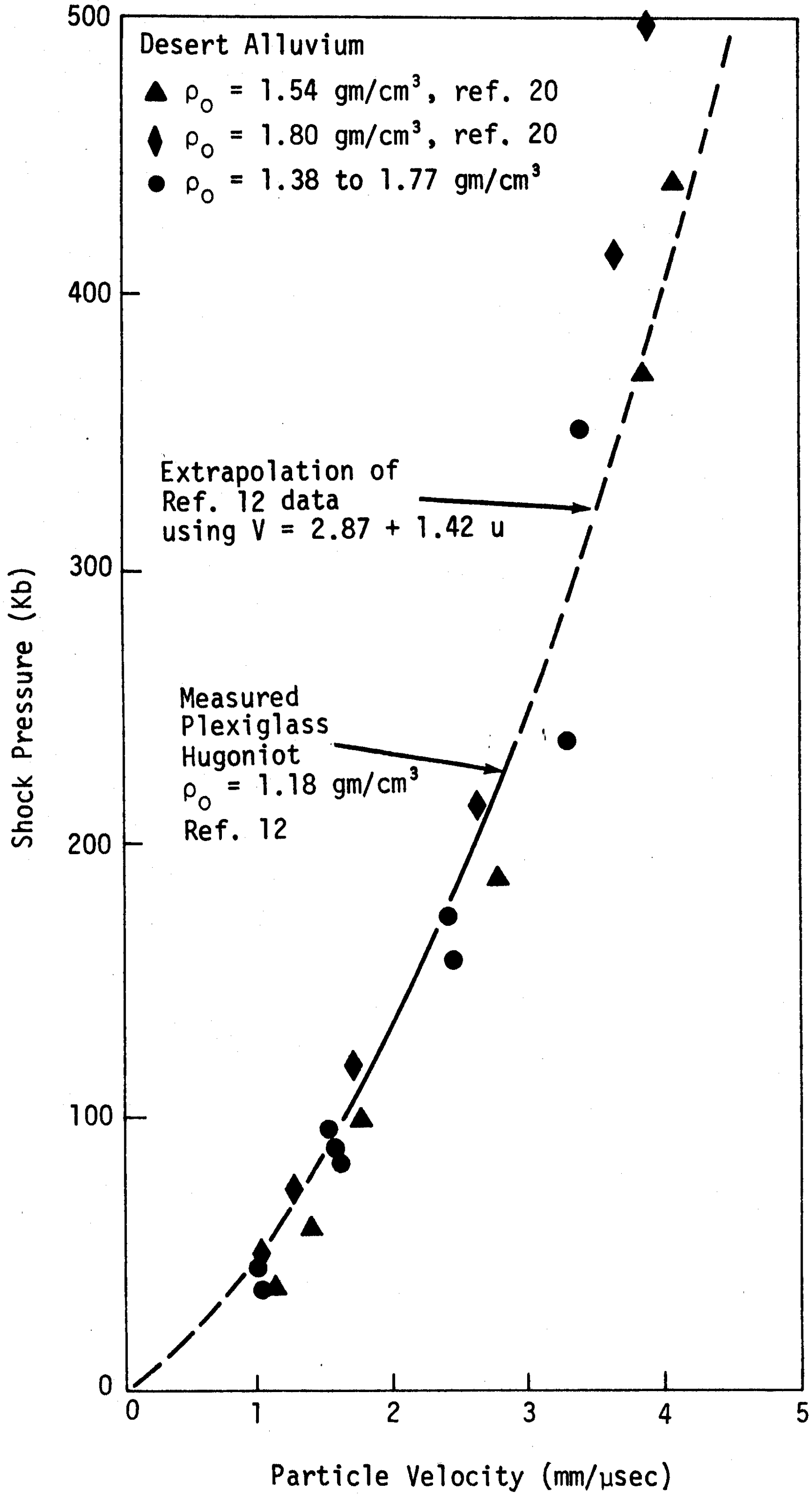

Figure 3. Comparison of Hugoniots Desert Alluvium and Plexiglass

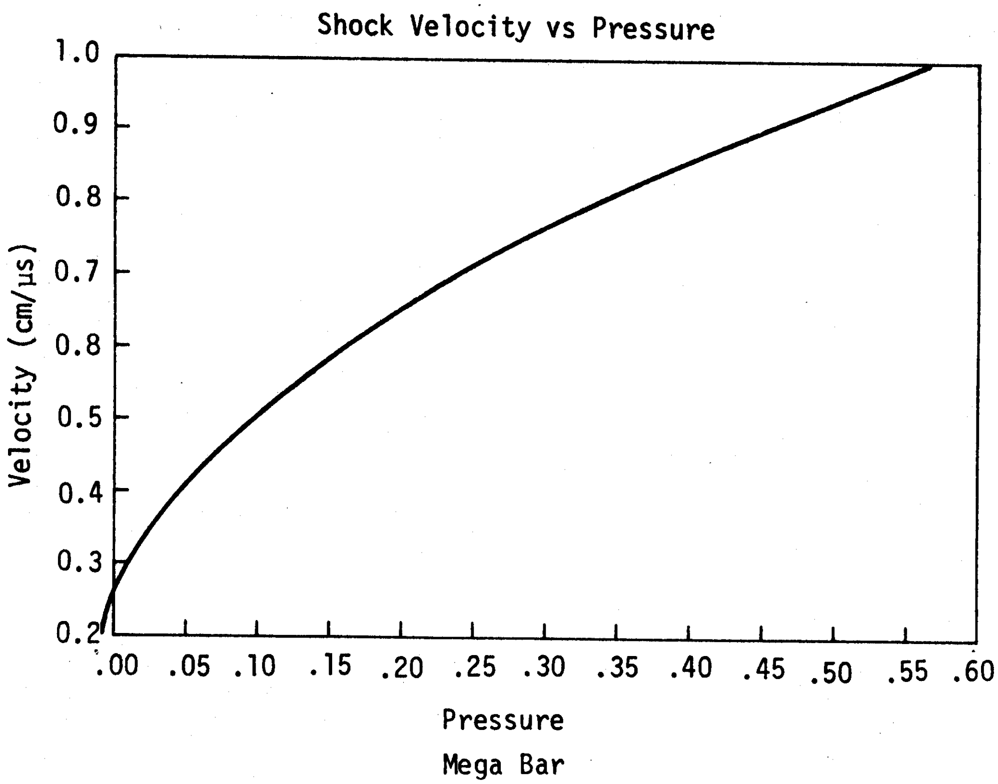

Figure 4. Shock Velocity versus Pressure in Acrylic

The real value of the gage is that the matrix and the environment do not have to be impedance matched by the user. This may be summarized by explaining the manner in which a shock wave interacts at the boundary of two materials. First, consider the case of a known material propagating a shock wave into the unknown material of lower modulus as shown in figure 5a. Conservation of mass and momentum demand that at the interface, the states of the known and unknown materials be identical (ref. 3). Thus, the state of the unknown material must lie along the locus of possible end states of the known material. In this case, the reflected wave is a rarefaction and must lie on the reflection of the known material through the line passing through points $(\sigma_1 \mu_1)$ and $(0, \mu_1)$. The intersection of the curve and the line $(\rho_o c)_B$ thus determines the state of stress in the unknown material.

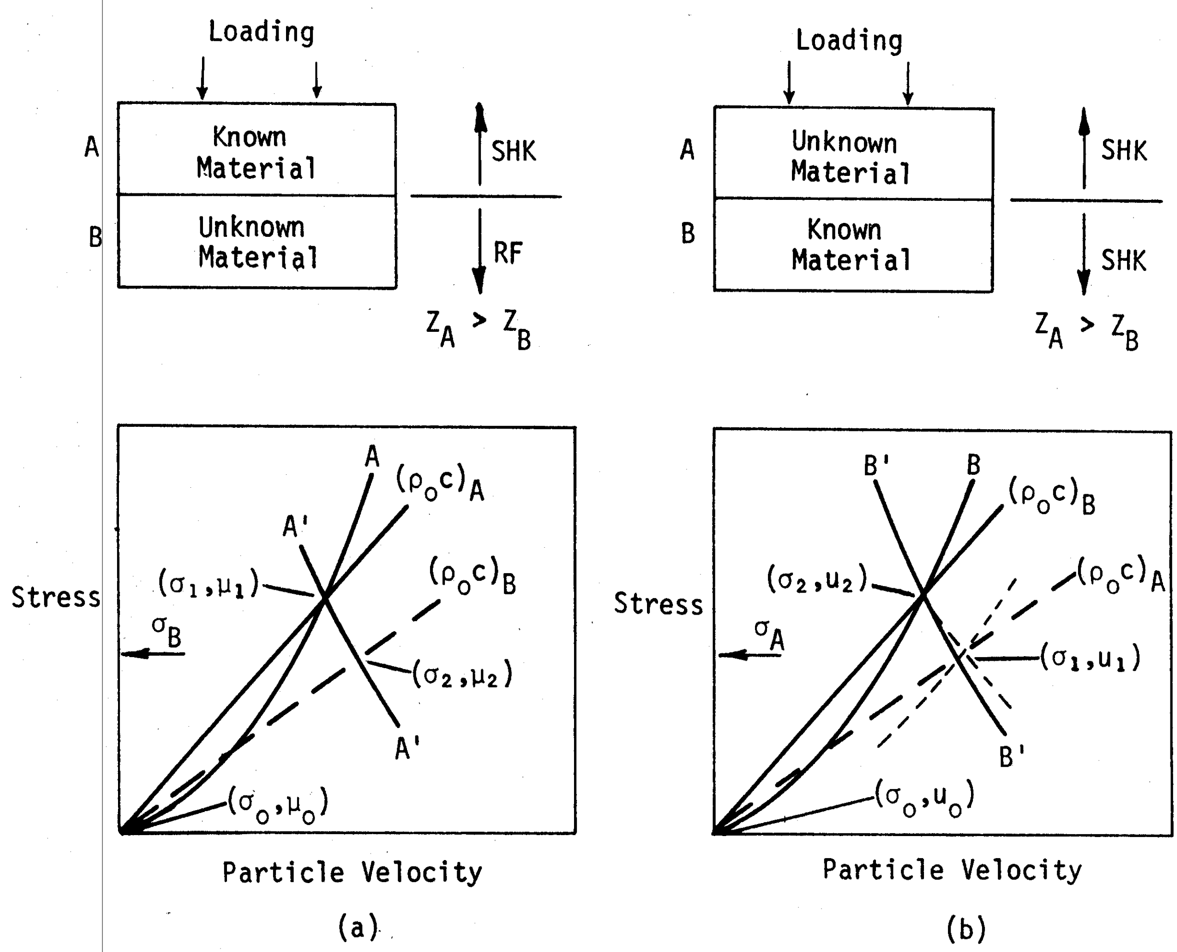

Figure 5. Principles of Impedance Matching

Now consider the case in figure 5b, which represents conditions encountered in the field. The error limits may be minimized by noting that the release adiabat of the known material must be somewhere between B' and the normal distance to $(\rho_o c)_A$. Thus, if the Hugoniots are not radically different, the state of stress in the unknown material might be determined with reasonable accuracy. These are the general operating principles of the IMHST gage. The concept is simple, the gage has been fielded on high explosive tests and appears to function quite well. The only thing debatable about the transducer is the electronics utilized to condition and multiplex the pin signals onto a single line. While there is a significant cost savings, the system is probably vulnerable to the radiation field. Any electrical circuit with high-impedance components could have survivability problems when placed in the vicinity of a nuclear event. Despite the fact that the electronics were hardened as much as reasonably possible, the gage should be prooftested in a nuclear test.

b. Mutual Inductance Particle Velocity Gage

The MIPV gage was originally developed by Engineering Physics Company (ref. 4) and is presently being modified by AFWL for use in the high-stress region. Stanford Research Institute is carrying on a similar effort in developing the gage for low-stress applications.

The gage (figure 6) consists of at two parallel rectangular loops embedded in a matrix. Here, I is the constant current flowing through the primary loop; E_o is the voltage output from the secondary loop. As a shock wave passes over the gage with velocity c, the loop ends flow at the particle velocity u. This movement causes a change in the mutual inductance, M, of the system which provides the consequent signal.

This signal can be shown to be

$$E_o = -\frac{d(IM)}{dt} \qquad \text{(ref. 3)}$$

where t is the time.

Since the current is set at a constant value, the above equation reduces to

$$E_o = -I\frac{dM}{dt} = -I\frac{dM}{dx}\frac{dx}{dt}$$

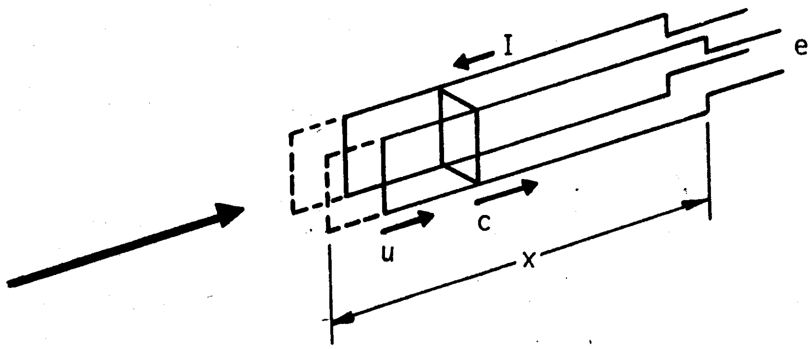

Figure 6. Model of Mutual Inductance Particle Velocity Gage Undergoing Deformation Due to Shock Wave

The presumption that the ends of the loops move with the particle velocity yields the conclusion that

$$u = -\frac{dx}{dt}$$

or

$$E_o = -uI\frac{dM}{dx}$$

When the gage is much longer than it is wide, dM/dx remains constant to within 1 percent even until the gage is shortened by 50 percent. Thus, the output of the gage is proportional to the particle velocity in the flow field.

Gage sensitivity can be improved by increasing the number of primary and secondary loops. However, this leads to a trade-off with the rise time of the system since the inductance is increased. As a compromise the gage being tested by AFWL has four primary and three secondary turns.

The original analysis was made for a planar shock front propagating parallel to the axis of the gage. However, this case is difficult to obtain on an actual experiment where a gage is close to an effective point source. As a result, calculations of these effects of divergence and off-axis flow were made. Figure 7 shows that the probable worst case of 20° off-axis tilt and a 2-meter distance from a point source gives accuracy within 5 percent.

Theoretical gage performance has been verified by recent low-pressure, gas-gun shots conducted at the AFWL Impact Facility (K-Tech). However, when

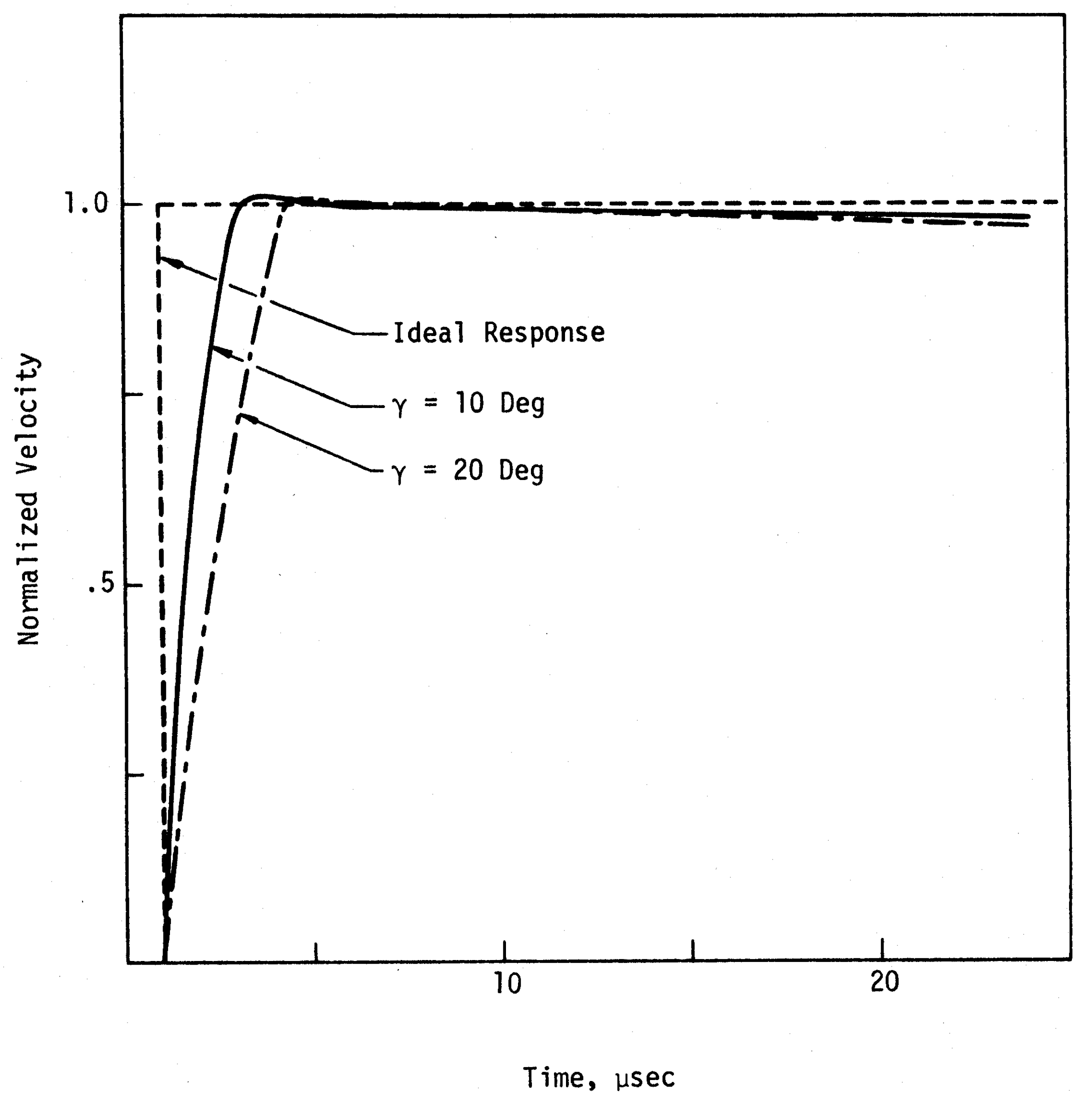

Figure 7. Response of Velocity Gage to Off-Axis Shocks (u = 1.70 mm/μsec, c = 4.15 mm/μsec, Source = 2 Meters)

subjected to stresses of approximately 150 kbar in the MIXED COMPANY and MIDDLE GUST events, the gage encountered the same materials problem that appears to plague all time-history, high-stress gages (refs. 5 and 6).

The materials problem may be understood by noting that all electrical gages are dependent upon the insulating properties of the matrix surrounding them. If the signal observed is to have a meaningful interpretation, the output must be dependent only on stress and motion of the gage elements in the media. To accomplish this, the matrix material embedding the gage must not conduct at the pressure of interest and must not produce significant signal due to piezoelectric behavior during the passage of a shock wave. Unfortunately, all insulating materials exhibit a Mach transition (insulator-conductor) at some pressure.

Virtually all insulators also exhibit some piezoelectric effect when subjected to a shock wave. This effect is due either to the asymmetry of the molecules causing a dipole movement which preferentially aligns with the shock propagation direction or to the recombination and movement of electrets formed in the matrix when it is solidified.

These problems are particularly acute in the case of the MIPV if the matrix becomes a conductor. Since the induced current in the secondary obeys Lenz's law, it thus opposes the current flow in the primary. However, if the matrix becomes a conductor (power factor = 1), the output is in phase with the input. This causes a signal of opposite sign than the one expected. This is precisely what happened on the MIDDLE GUST IV and V and the MIXED COMPANY events.

This gage is still in the developmental stage and should not be fielded until the problems, primarily those with the maxtrix, are solved. However, it has the advantages of low impedance and high durability. These, along with a favorable prognosis for successfully overcoming the materials problem, make the gage one of the prime candidates for coupling experiments.

c. Thermoelectric Thermopile Transducer

When a thermocouple is shock loaded, its voltage output is 3 to 5 times greater than would be expected from the heating caused by the adiabatic compression of the junction. This phenomenon was first observed by the French (refs. 7 and 8) and later confirmed by the Russians (ref. 9) and the Americans (ref. 10) in that they all noted that the initial peak output was proportional to the maximum stress at the junction.

The effect has been tested up to a pressure of 1.6 Mbar by the French (ref. 8) and by AFWL at the Lawrence Livermore Laboratory to 300 kbar (ref. 11). The results of these tests are shown in figure 8. While the magnitude of the signals from individual thermocouples is small, the effect is additive (ref. 12). Thus, it is possible to design a thermopile gage which contains 30 to 40 junctions at each end with an approximate impedance of 50 Ω.

The thermopile used on the MIDDLE GUST I and III events is shown in figure 9. The encapsulating material (C-7 epoxy) is vulnerable to the matrix problem described previously. The problem of the piezoelectric moment generated in the matrix is particularly acute for the T^3 gage. Despite the fact that the gage is low impedance, large signals generated in the matrix apparently affect the signals generated by each junction. This is the principal reason that the gage does not act in an analog manner. This would explain the observed result of a reproducible peak with an absence of a consistent off-loading signal. It has also been empirically shown (ref. 11) that this is the probable cause for the inconsistent behavior of the gage when it unloads.

The theoretical model for the gage is based on a solid-state interpretation of the thermopower in which the density of d-states are varied in a manner quantitatively related to the change in thermopower. This in no way indicates that the gage itself behaves solely as a peak pressure gage; it is felt that if an appropriate matrix can be found, it would behave in an analog manner. The particular advantages of the gage are its low impedance, self-generating characteristics, and demonstraged durability under shock loading. However, until the matrix problem is resolved and it is demonstrated that the gage will properly function, it should be considered developmental and should not be fielded.

d. Microwave Waveguide

The microwave waveguide (figure 10) tracks the movement of the metal plate reflector with additional information gained because of the reflection of some of the microwave energy of the shock front. This, along with the presumption that metal plate reflector moves with the particle velocity in the soil, is the operative mechanism of the gage. Thus, this device may simultaneously measure the shock and particle velocity (ref. 13).

The system operates on the principle that a standing wave pattern is set up through the interaction of the energy reflected from the plate and the energy transmitted by the device. The motion of the metal plate relative to the

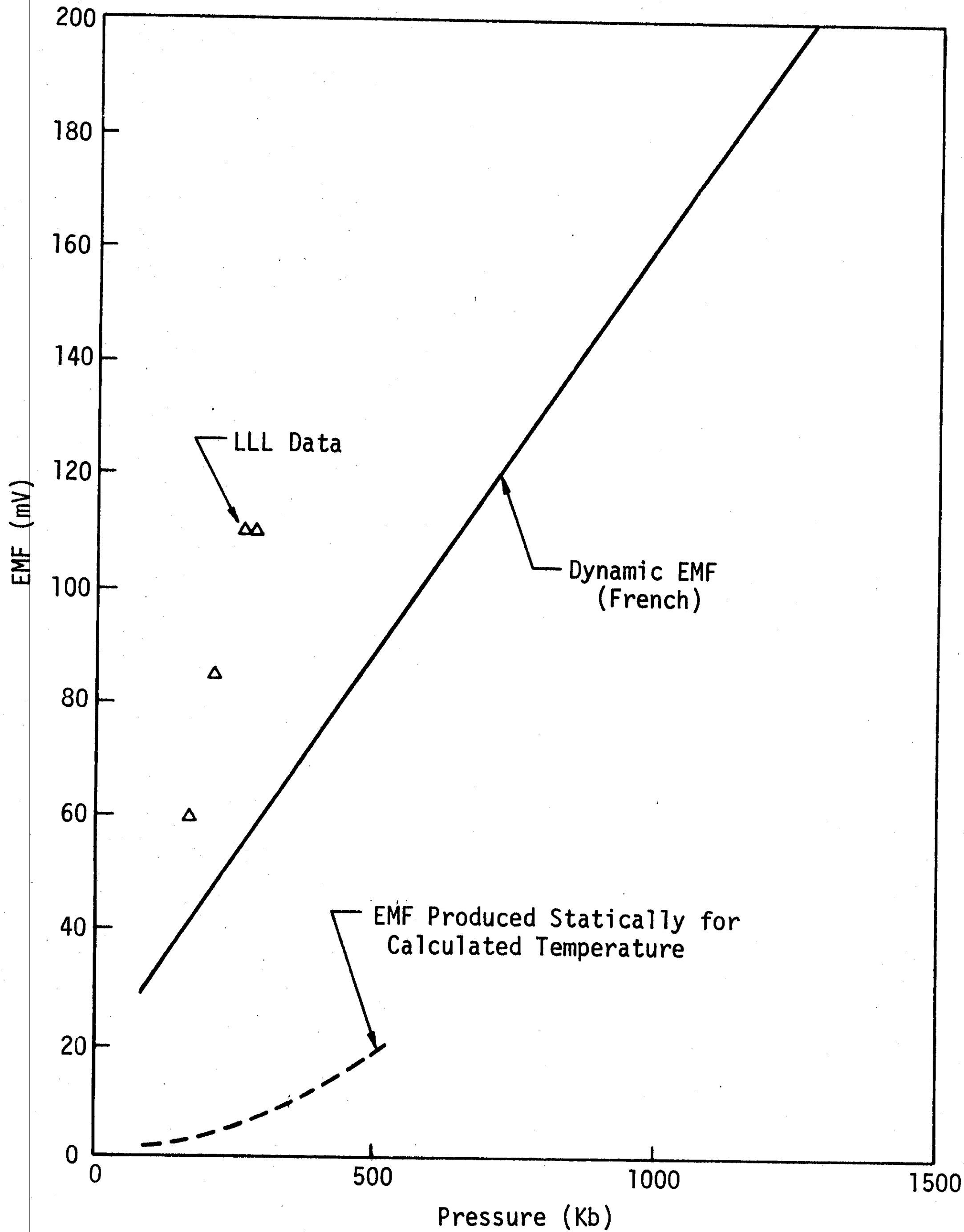

Figure 8. Pressure Response of Thermocouple

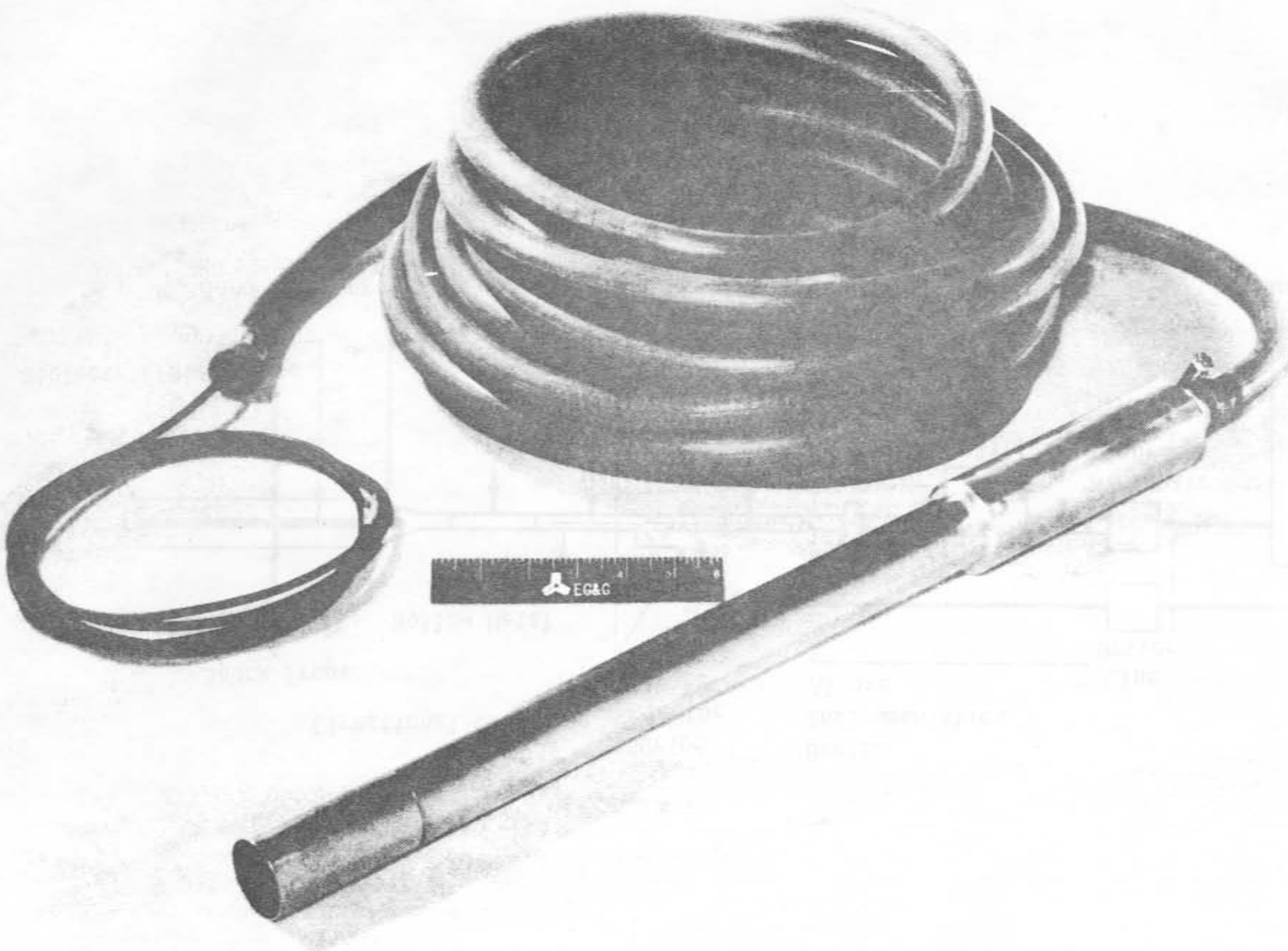

Figure 9. Gage Final Configuration

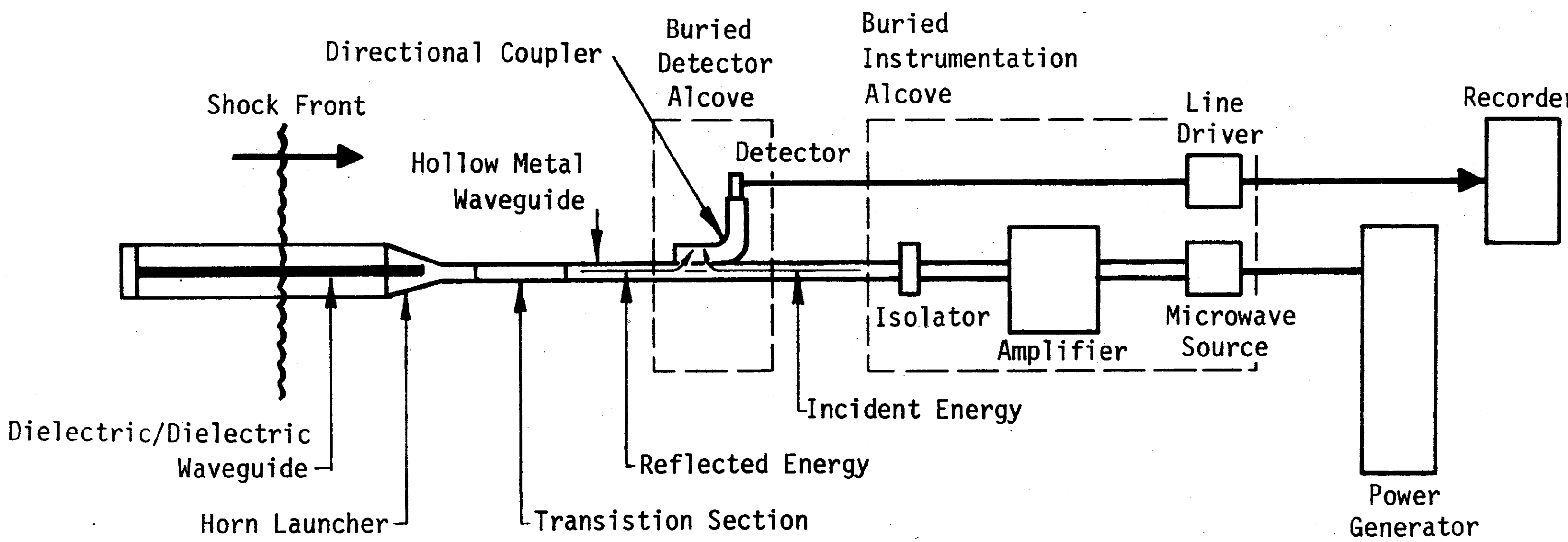

Figure 10. Microwave System (After Lieberman)

receiver thus causes a shift in the standing wave pattern. This shift exhibits itself with the detection of minima by the detector when the metal reflector has apparently moved through a distance of a half wavelength. This is more easily understood by describing the conceptually simpler Michelson interferometer* (figure 11).

The conceptually simpler Michelson operates on the same principle as the microwave waveguide and, if the source is colimated, a standing wave pattern is produced along the line CD. As the mirror is moved through a distance equal to a half wavelength of the source, the amplitude at the detector observes a transition through an intensity extrema (a fringe). This occurs since the optical distance (twice the distance from C to A) has varied by a full wavelength since any variation in the optical path length between C and A causes a shift in the standing wave or a variation in the intensity observed at the detector.

This variation in optical path length can be accomplished in a number of ways other than the simple movement of the reflector. An example of this is a modified Michelson interferometer (figure 11b) that can be used to measure the the change in index of refraction of a gas. In this case, the pressure (and consequently the density, ρ) of the gas in the cell is varied. The optical length of the path CA changes causing a subsequent change in the intensity at the detector because a change in gas density varies the index of refraction. This variation may be described in the first approximation by Gladstone-Dale model (ref. 14) with

$$\frac{dn}{n-1} = \frac{d\rho}{\rho}$$

The change in optical path length is thus

$$2(\Delta n)\ AE = 2\ \frac{(n-1)\ \Delta\rho}{\rho}$$

or

$$\frac{\lambda}{2} = (n-1)\ \frac{d\rho}{\rho}$$

when the detector has gone through a fringe.

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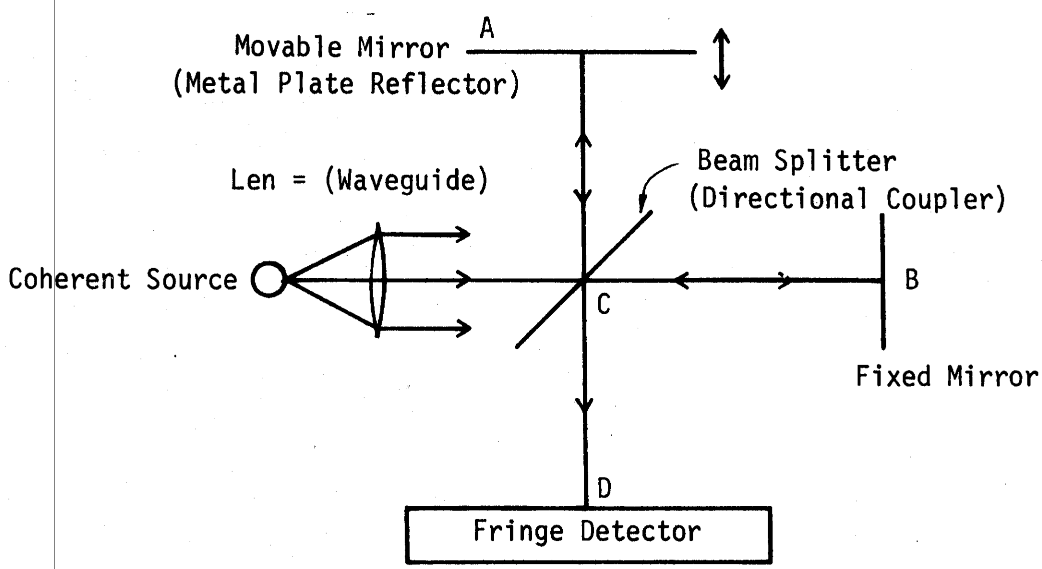
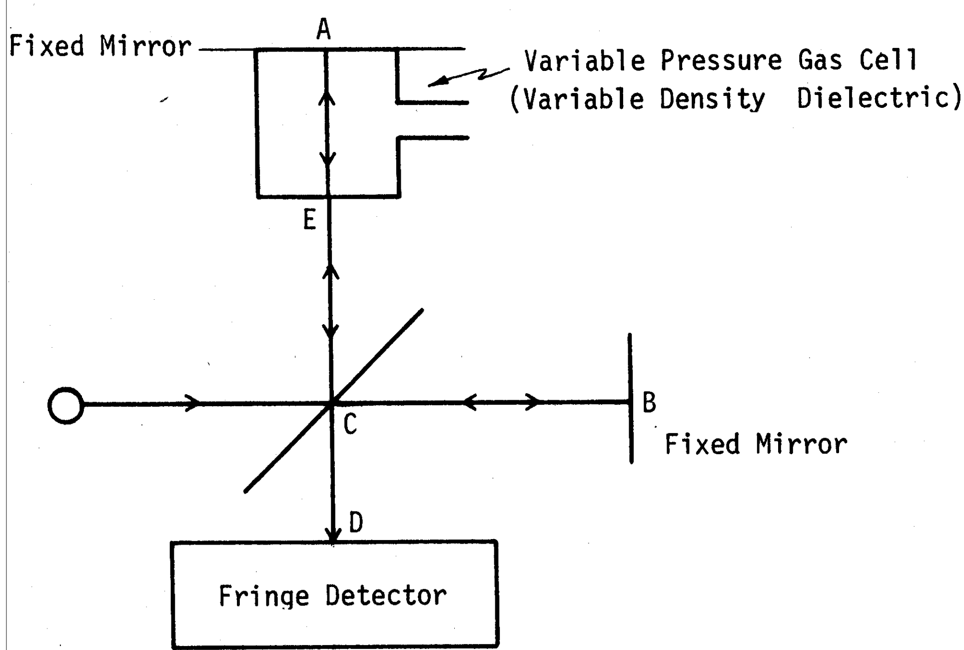
* Here, for simplicity, the isolator was left out. However, its optical analogy of a polarizor and quarter wave plate could be included.



(a) Unmodified



(b) Modified

Figure 11. Michelson Interferometer

If this analogy is applied to the case of the microwave waveguide, both effects occur. Namely, after the shock wave passes over its end, the plate is moving at a velocity related to the particle velocity, and the dielectric material in front of the plate is being compressed causing a consequent change in its effective index of refraction and a related change in its permittivity and dielectric constant.* Both of these effects change the apparent position of the reflecting plate. Thus, the received signal is an indication of both of these effects.

The more extreme case is that in which compression of the dielectric becomes so intense that the dielectric becomes a conductor. In this case all, or nearly all, the energy is reflected at the shock front masking the effect of the metal reflector plate. In this case, the only quantity that can be measured is the shock velocity.

The materials problem affects this gage more acutely than it does the others because the gage is sensitive both to transitions and variations in the properties of the dielectric under pressure.

These reasons, along with the apparent vulnerability of the equipment to EMP effects do not completely exclude the gage from consideration, but they do make it one of the less promising gages.

e. Manganin Gage

The manganin gage is a piezoresistive gage that changes its resistivity by approximately 0.25 percent per kilobar (ref. 15). Manganin is particularly suited for piezoresistive measurements of pressure in a shock front because of its virtual temperature insensitivity ($\approx 5 \times 10^{-5}$ $\Omega/\Omega/°C$). Manganin gages are presently being used in the stress range of 0 to 200 kbar and have become extremely useful tools in these pressure ranges especially for measuring the planar impact phenomenon experienced by samples in gas guns. However, a strain sensitivity (gage factor ≈ 2) problem which is common to all piezoresistive gages appears when the gage is used in the field. Thus, if the gage is placed in a divergent or off-axis flow field, significant errors in pressure measurements

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* If n_{eff} is the effective index of refraction, μ the permittivity, ε the dielec-constant, and c_0 the speed of light in vaccum, then $n_{eff} = \sqrt{\mu\varepsilon}/c_0$.

occur due to changes in gage length. This problem, although difficult, should be solvable. The strain field may be minimized by choosing an appropriate geometry for the gage relative to the flow field it will be subjected to.*

Measurement of pressure/time history at high-stress levels poses two other difficulties; gage lifetime and materials problem. The lifetime of the manganin gage is limited by the different shock impedance characteristics of the piezoresistive element and by the electrical leads to which it is attached. The materials problem, as for other gages, becomes particularly acute when the gage is subjected to a high-stress loading condition. The conductivity of the matrix short circuits the piezoresistive element making it useless, and significant polarization interferes with the output signal. The Stanford Research Institute is presently undertaking a program to look at different materials for use in the manganin gage; hopefully they will have some success in this field.

Even though the gage is presently being used in the pressure region of 0 to 200 kbar, its status as a high-pressure transducer should still be considered developmental. The primary problems to overcome are those associated with the matrix and the lifetime of the gage.

3. ANALYSIS

For the results of a CANT-type experiment to be meaningful the shock wave time history must be measured close to the detonation. Pressures in this area will be on the order of 1 Mbar which exceeds the capabilities of existing information. The T^3, the MIPV, the microwave waveguide, and the maganin gages are under development for use in this measurement range.

An ideal sensor has an output dependent on only one quantity. Of the sensors considered, the T^3, MIPV, and manganin gages are dependent on only one parameter. The microwave waveguide is dependent on several parameters and must be extensively shielded against EMP or else placed some distance from the detonation. These factors eliminate the microwave waveguide from further consideration.

The materials problem is a serious matter in the consideration of the other three gages. The likelihood of solving this problem is probably 10 to 20 percent for the T^3 and MIPV gages. Many different materials can be used with the manganin gage so the likelihood of solving the materials problem for this gage is much higher.

* For an example, see H. D. Glenn, "Diagnostics Techniques Improvement Program--High Explosive Development Phase," DNA 2978T, September 1972.

SECTION III

LOW-STRESS INSTRUMENTATION

1. BACKGROUND

Low-stress instrumentation is needed to validate code calculations and to empirically follow shock wave attenuation in the media surrounding the detonation. For this study low-stress measurements were defined as those from 1 to 500 kbars. The study considered five gages for use in this area: manganin, ytterbium, carbon, and quartz and a column-type gage. The manganin, ytterbium, and carbon gages are piezoresitive, the quartz page is piezoelectric, and the column-type gage is a strain-type transducer. Pressure gages for making measurements below 1 kbar are so numerous that they were not covered in this study.

2. EVALUATION

a. Manganin Gage

The manganin gage was discussed in the previous section because of its applicability to high-stress measurements. In that section is was pointed out that the manganin gage operates successfully in the stress region below 200 kbars. The difficulties with the strain sensitivity and the related gage placement problems were also described. These, along with the gage lifetime limitation, are the negative points associated with the gage. However, since the gage has been used it is well parametized, and its development for use as a high-stress gage could possibly make it useful for both high- and low-stress measurements.

Figure 12 gives a calibration of gages embedded in two different encapsulating media.

b. Ytterbium Gage

Ytterbium is a rare earth element with a comparatively high piezoresis-- tive coefficient (figure 13). This property has made it attractive for possible use as a shock pressure gage. Its apparent high sensitivity to pressure is probably because, like the rest of the rare earth metals (4 f) and some transition metals (3 d) it behaves in a manner more akin to semiconductors than metals (ref. 16). This is caused by $s \rightarrow f$ ($s \rightarrow d$) scattering in which the conduction electrons are scattered into available states in the + (S_1) band. These available states or holes are probably greatly affected by the symmetry and interatomic distance. Thus, one may infer a high piezoresistive coefficient from this effect along with the normal change in cross-sectional areas under stress.

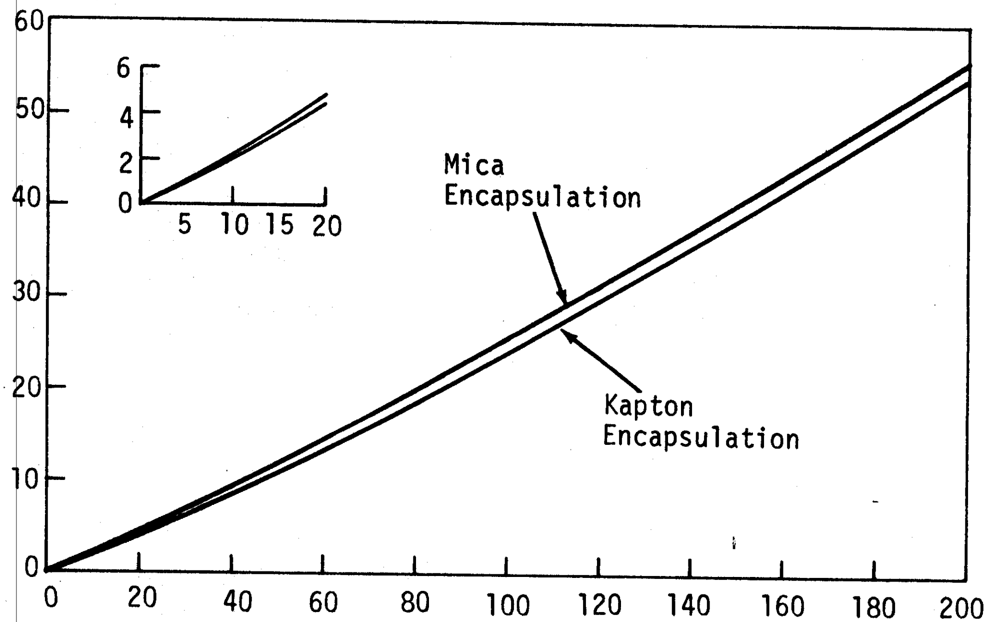

Figure 12. Manganin Pressure Gage
(refs. 15, 19, and 20)

Ytterbium, like manganin, has a relatively low temperature coefficient (~0.0008Ω/Ω/°C) (ref. 17). Another point in favor of the ytterbium gage is that it is less strain sensitive than the manganin gage (ref. 18). Thus the ytterbium gage is one of the better candidates for a time history gage. However, it has two limiting factors; the maximum usable range is 39.4 kbars, at which point ytterbium undergoes a polymorphic phase change (fcc → bcc) and the resistance decreases abruptly to a point lower than its normal room temperature resistance (ref. 19). The second negative point about ytterbium is its extreme hysteritic behavior on unloading. This is shown graphically in figure 13 for one loading path. This latter point, while not completely negating consideration of the gage, should be examined further before the ytterbium gage is used as a time history stress gage.

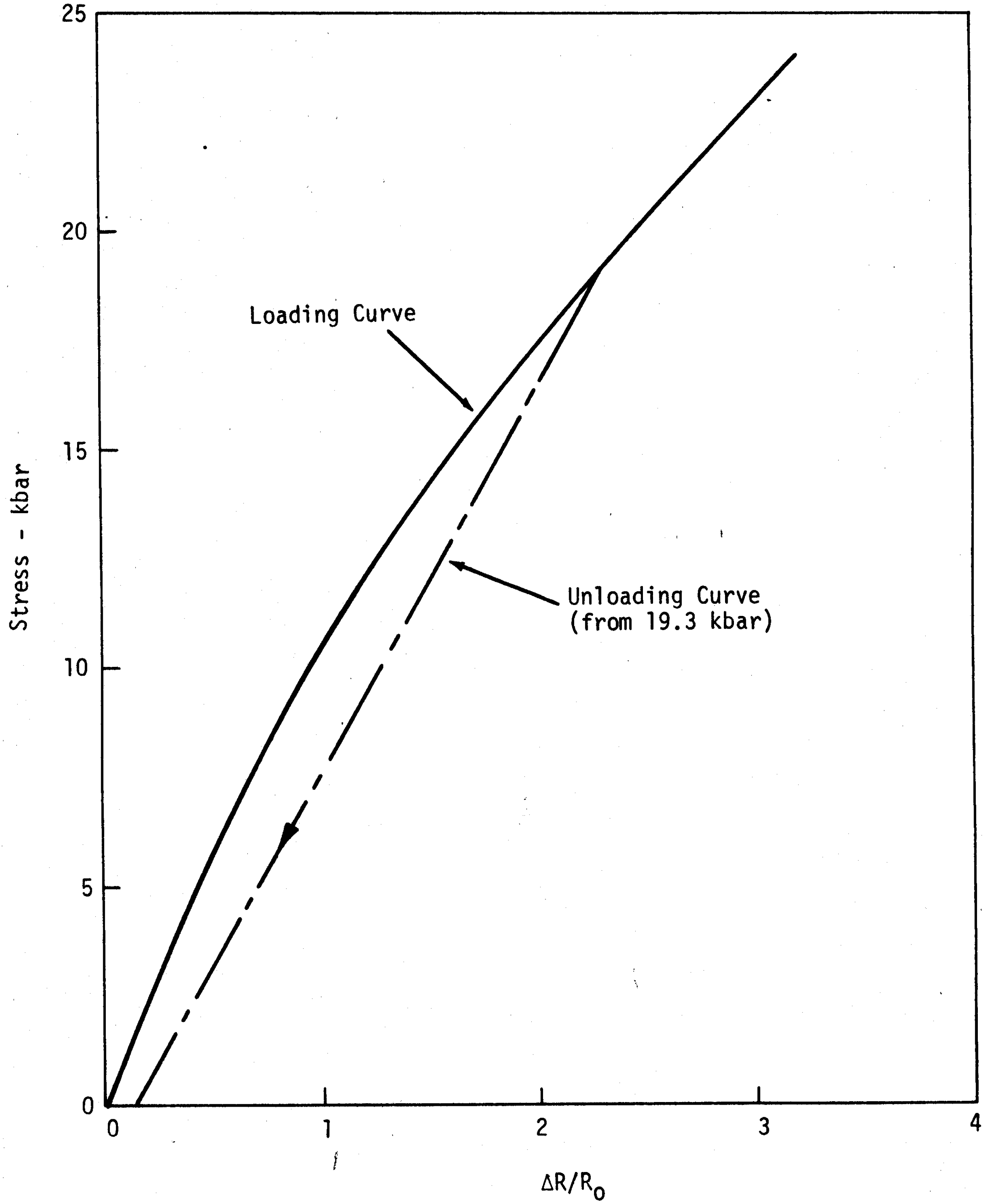

Figure 13. Ytterbium Calibration Data with One Unloading Path (After Smith et al.)

c. Carbon Gage

The use of carbon in piezoresistive shock pressure gages is a comparatively recent development. Its probable greatest advantage is its sensitivity (see figure 14). Here it should be noted that carbon does not behave as a normal piezoresistive element in that its resistance decreases with increasing pressure. This is probably due to two effects. First, the increase of the effective current cross section due to increased contact areas between the particles of carbon, and second, its behavior as a semiconductor in which the band gap decrease outweighs the increased probability for scattering of the charge carriers. Of these effects probably the first is most significant and it is here that carbon will be efficient only until a volume change occurs causing resistivity to increase instead of decrease. This effect will probably occur at about 150 kbars (ref. 21). This sets an upper limit on the gage as the sensitivity decreases to a point that it is no better than manganin at approximately 80 kbars. Thus, a practical usable limit for the gage may be approximately 100 kbars.

Notable advantages of a carbon gage would be its relative radiation insensitivity because of carbon's low atomic number, and its low temperature sensitivity (-0.009Ω/Ω/°C). For these reasons, there has been much interest in carbon gages because of their application to radiation deposition measurements in different materials. Carbon gages have functioned during the Diamond Skulls and Dido Queen nuclear tests. In these tests carbon gages were placed in a known material and used to measure the shock induced by radiation at a given distance from the source. In this manner, the sample and the gage could be aligned to ensure planar impact of the short duration pressure pulse generated in the gage. Preliminary results of gas gun tests up to 2.0 kbars indicated that the Dynasen Kapton encapsulated carbon gage followed the theoretical pulse shape even better than manganin (ref. 22). This comparison appeared to indicate that the gage functioned more satisfactorily in kapton than mica. Here again the well controlled gas gun tests insured a uniaxial strain loading of short duration.

To the best of the author's knowledge, carbon gages have not been evaluated as a ground shock gage.* If used to measure ground shock, it is expected that extreme care will have to be taken in placing and orienting the gage because its strain sensitivity or gage factor are approximately the same degree as for manganin gages.

* A carbon gage was fielded on the MIXED COMPANY 500 ton HE test, but there was an electrical failure somewhere in its system prior to the test.

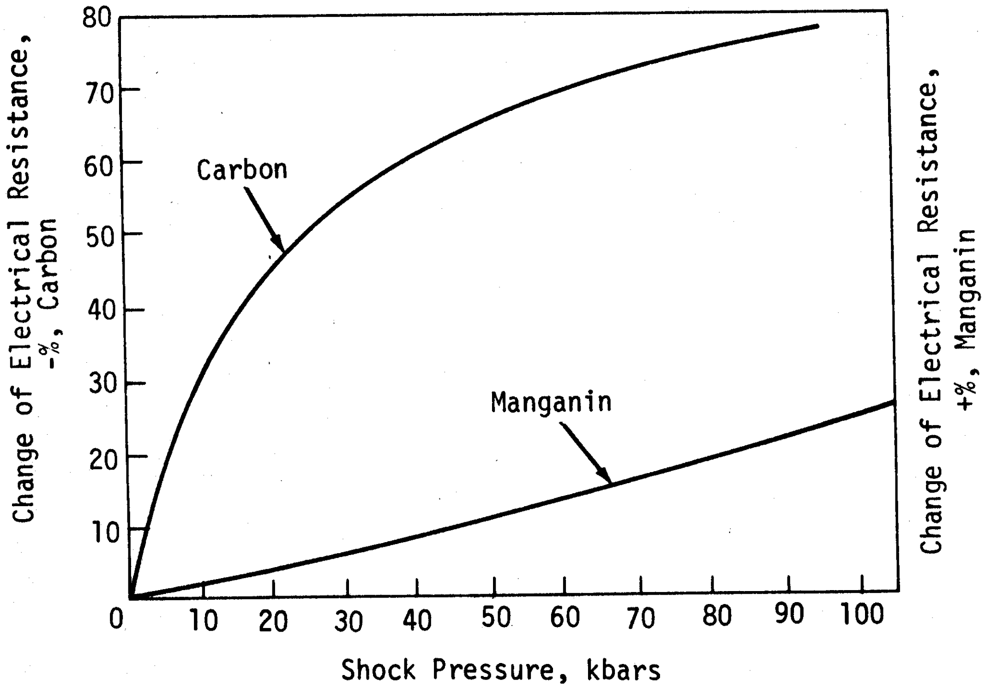

Figure 14. Carbon and Manganin Calibration Curves

The carbon gage appears to function well when the geometry of the stress pulse seen by the gage can be controlled in a suitable manner. However, its use in situ has yet to be thoroughly examined. An in situ investigation will probably show that the placement and lifetime problems are similar to those of manganin and ytterbium gages. Even with these difficulties, the high sensitivity and demonstrated response accuracy make the gage a prime candidate for use up to 100 kbars.

d. Quartz Gage

The quartz piezoelectric gage has been extensively evaluated and used over the past 10 to 15 years. This extensive experience with the gage probably makes it the best parameterized time history gage for shock applications.*

The output current (I) of the gage may be shown to be (ref. 23)

$$I = PAu_s/H_s$$

* For example, see references 23 through 28.

where P is the polarization due to the application of a stress, A is electroded area normal to the shock front, u_s is the shock velocity and H is the gage thickness. By virtue of the fact that the shock velocity is nearly constant (5.728mm/μsec) up to 24 kbars (ref. 24), the relationship above will reduce to

$$I = (kA/t_0)\ \sigma(t),\ o < t < t_0$$

Here σ(t) is the stress wave input, to the shock transit time and k is the piezoelectric coefficient given by

$$k = (2.011\ k\ 10\text{-}8 + 1.07 \times 10^{-10}\sigma)\ \text{coulomb}^{-2}\ \text{kbar}^{-1}$$

for stresses up to 25 kbars. At higher stresses, the second term in the above equation becomes larger. This along with the fact that the shock velocity can no longer be considered constant causes nonlinearities in the gage. The gage requires no calibration, is direct reading and self-generating and produces a large current that is easily measured and has a rise time that is not limited within the gage itself. These advantages have made the gage a widely used shock wave detector in the fields of flier plates and radiation measurements, where the planarity of the input is well controlled and the pulse duration is short.

To use the gage for ground shock measurements one should note the require ment of planarity and the measurement time limitations of the gage. The useful time is limited to one shock transit time through the gage and is thus limited by the physical dimensions of the gage. To ensure 1-D electric fields and uniaxial strain, the gage must be larger in diameter, D, than in thickness, H. Practical experience (ref. 27) with the gage has set the limitation that the ratio of D/H ≥ 4. Additionally, there is a physical limitation on the side of single x-cut quartz crystal. The maximum available diameters are approximately 3 in. or roughly 80 mm. Thus, the thickest gage available is about 20 mm, this corresponds to a maximum reading time of 3 to 4 μsec. The normal limit placed on the planarity is 10 percent (ref. 23) or roughly ±300 ns across the surface of this gage.

Despite the fact that the gage can be used to 70 kbars (nonlinear above 25 kbars) the planarity and **reading time limitations make it unsuitable for use as a ground shock profile detector.**

f. Column Gage

The column gage or the similar sized spool gage both depend on the strain measurement on a column of known material. Its upper limit is the yield strength of the material; in the case of steel, this is roughly 40,000 psi or roughly 3 kbars.

The design of the gage involves protecting the sides of the column in such a manner that the strain sensing element (at least for a finite time) does not experience external pressure. Figure 15 shows an example of a typical spool gage.

Recording time is limited by the time it takes to significantly compress the soft material protecting the strain gage. However, in the range of 1 to 3 kbars significant stress amplification in the column cannot be tolerated. Thus, the column must be much larger than its rim. This yields the conclusion that the gage would have to be fairly large. For the measurement to be meaningful, the entire column has to be in relative equilibrium and since this is controlled by the shock transit times through the material, the rise time of the gage will probably be in the realm of microseconds. It is thus unsuitable for use in this range and should be used for the pressure range that it was designed for, namely, zero to thousands of psi.*

3. ANALYSIS

There are two gages suitable for use from 1 to 200 kbars. These are made of manganin and carbon. Manganin, in addition to the fact that it has been effectively utilized in this range, has the advantage that it's application may extend into the high-stress region. Carbon should be effective up to approximately 100 kbars.

Both quartz and the column gage are unsuitable for this ground shock stress range. Ytterbium, while the most sensitive of the piezeoresistive gages, has the disadvantage because its behavior upon unloading cannot be accurately interpreted. Thus, it is again recommended that carbon be utilized in its place.

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* See, for example, P. A. Abbott, K. B. Simmons, C. M. Rieff, and S. Mitchell "Recent Soil Stress Gage Research," Proceedings, International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, edited by G. E. Triandalilifis, The University of New Mexico Press, page 221, 1968.

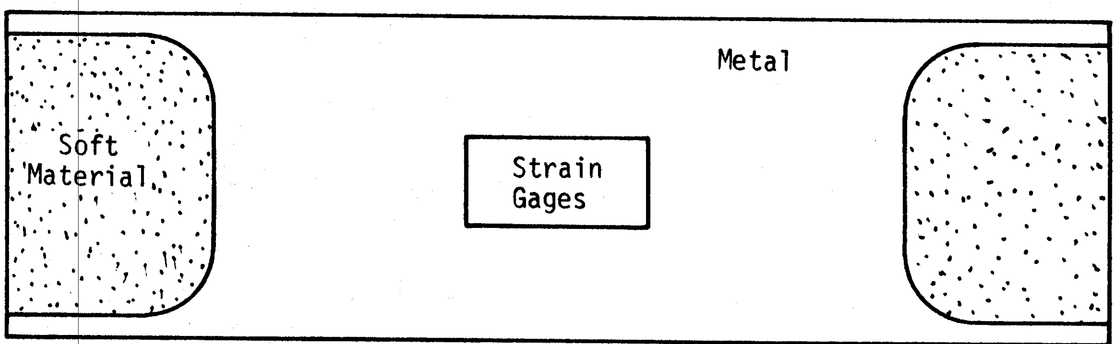

Figure 15. Spool Gage

SECTION IV

GROUND MOTION INSTRUMENTATION

1. BACKGROUND

The ground motion instrumentation plan described in the proposal requires that the instrumentation be placed in an area subjected to pressures up to 100 kbars. Because of the lack of instrumentation suitable for use in these pressure ranges, this study evaluated the proposed instrumentation plan before considering specific transducers.

2. EVALUATION OF PROPOSED INSTRUMENTATION PLAN

The proposed instrumentation plan required the placement of ground motion instrumentation close to detonation. In this area, the gages would have to withstand pressures up to 100 kbars long enough to take meaningful measurements.

The measurement time must be longer than the rise time of the instrumentation. As an actual relationship between these times is controversial, the author has arbitrarily decided to use a 10:1 ratio for this study. High-frequency limits were also considered with the assumption that a velocity gage should have a high-frequency cutoff at 10 kHz and that an accelerometer should have a high-frequency cutoff at 50 kHz. If one uses the common rule that the upper 3db point for a second-order system multiplied by the 10 to 90 percent rise time is approximately 0.35, then the measurement times should be 0.035 msec for a velocity gage and 0.007 msec for an accelerometer.

The next point considered was the cannister design required to survive long enough to make the measurement before collapsing. This led to some assumptions about gage movement inside the collapsing cannister with respect to movement in the ground surrounding it. To minimize this uncertainty one has to minimize the cannister size to ensure that the shock transit time will be small in comparison to the collapse time and yet there must be enough clearance inside the cannister so there is a volume to collapse into. In consideration of these parameters, some arbitrary assumptions were made. The first of these assumptions was that the gage itself has a minimum separation of roughly 1 inch (2.5 cm) from the inside of the canister. If the inside of the canister spalls when the shock wave passes over it, the fragments will move with a velocity equal to the free surface velocity or, at these pressure, on the order of mm/μsec. This means that the maximum survival time would be 25 μsec or less, much smaller than that required for a meaningful measurement. This is the lower limit on gage survival. The upper limit can be found by presuming the canister behaves as a rigid body. If one assumes this, the first thing that should be noted is that the strength of the material used to manufacture the canister has little, if no effect on preventing collapse. This should be obvious since the yield strength of a comparatively strong material such as steel is about 40,000 psi and the gage will be subjected to 100 Kbars or 1,500,000 psi. Thus, the only significant force reacting to collapsing forces is due to the inertial mass of the canister walls. The reacting force, in this case, is simply the product of mass times acceleration. Since the total force is the area multiplied by the pressure one can easily see that the accleration will be equal to pressure, P, divided by area density ρ_A. Thus, the required area density can be found from the relationship

$$\rho_A = \frac{P}{2\,S}\,t^2$$

where t is the time required for measurement and S is the collapse distance. Thus, using the previous assumption concerning the time and distance, the requirement area densities are approximately 10^3 gm/cm^2 for an accelerometer and 25 x 10^3 gm/cm^2 for a velocity gage. Since we do not have access to a nova, a practical material to us would be lead. In this case, the above area densities correspond to roughly 90 cm of lead for an accelerometer and 2.2 m of lead for a velocity gage. A gage package of these sizes and densities would not move in the same manner as the surrounding media.

This explanation points out the impracticality of building a canister that will operate for the required lengths of time in a peak stress region of 100 kbars. This, along with the fact that the canister will have a vulnerable cable attached to it, negates the possibility of use in this stress range. Thus, it is recommended that velocity gages and accelerometers not be used close to the detonation; they should instead be used in areas where the pressures encountered are such that the strength of the canister material plays a significant role in reacting to the collapsing pressure. Realistic pressures are in the realm of a few kbars. Similar measurement plans have previously supplied a few milliseconds of usable data.

At present the only usable ground motion measurements that can be obtained in the 100 kbar region are those described in the first part of the high-stress section. Here a developmental Lagrangian gage was described, namely the mutual inductance particle velocimeter.

It is thus recommended that instrumentation similar to that used on Tiny Tot (ref. 29) be used in the stress range of 0.5 to 2 kilobars. This instrumentation includes crescent-type velocity gages and piezoelectric accelerometers.

In the low stress regions where canister failure is not a significant factor, it is recommended that the Sandia DX velocity gage be used. This recommendation is based on a recent evaluation of different velocity gages carried out at CERF (ref. 30). In this evaluation it was shown that the DX gage performed as well or better then other gages with the possible exception of the Endevco integrating accelerometer on which further evaluation has to be performed. Thus, because of the extensive experience with the DX gage and the fact that data reduction schemes and transfer functions* have already been developed for it, the recommendation for its use seems reasonable.

3. DESCRIPTIONS OF POTENTIAL INSTRUMENTATION

a. Mesa Diode Accelerometer

A new type of accelerometer, that should exhibit some advantages over previously used devices, is presently being developed by CERF in conjunction with AFWL and RADC. The device uses a transduction element somewhat different from those presently used. This element is a mesa diode to which stress is applied by the action of a seismic mass.

The primary advantage of the system lies within its sensitivity as shown in figures 16 and 17. These figures indicate the blocking voltage (V_0) used at the recording device and the biasing voltage (V) applied to the p-n junction. The design in this case was made for application to low g levels and consisted of a silicon needle on which a point (a 1-mil radius of curvature) was etched and into which a junction was diffused (figure 18). However, the application for which the device is to be used calls for higher g's and a more reproducible

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* See for example, P. Sonnenberg and G. Schulz, "Response of an Orthogonal System of Pendulum Type Velocity Gages," in AFWL Symposium on Advancement in Instrumentation for Civil Engineering Applications, May 1973.

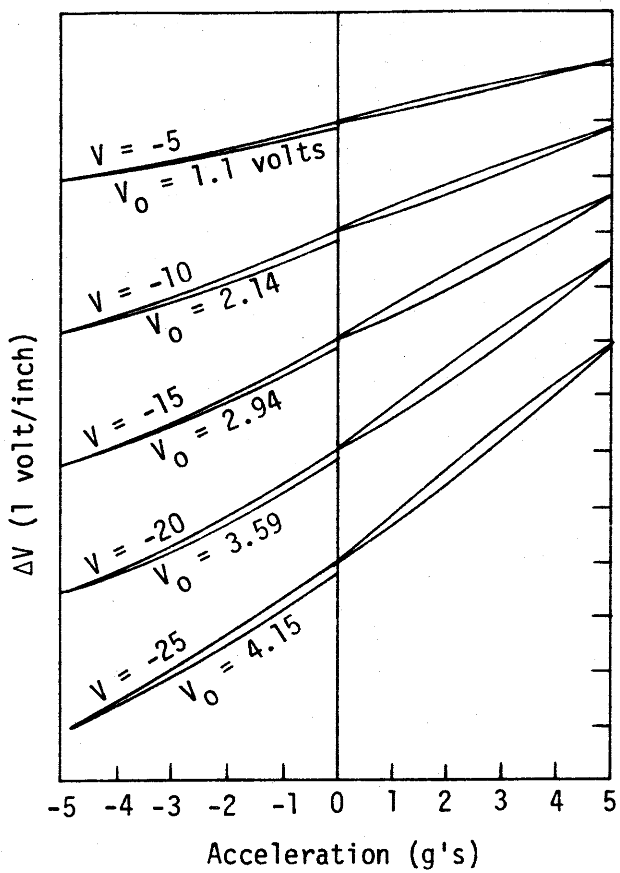


Figure 16. Recorder Plot of ΔV as a Function of Acceleration for the Reverse Biased Mode (after Wortman)

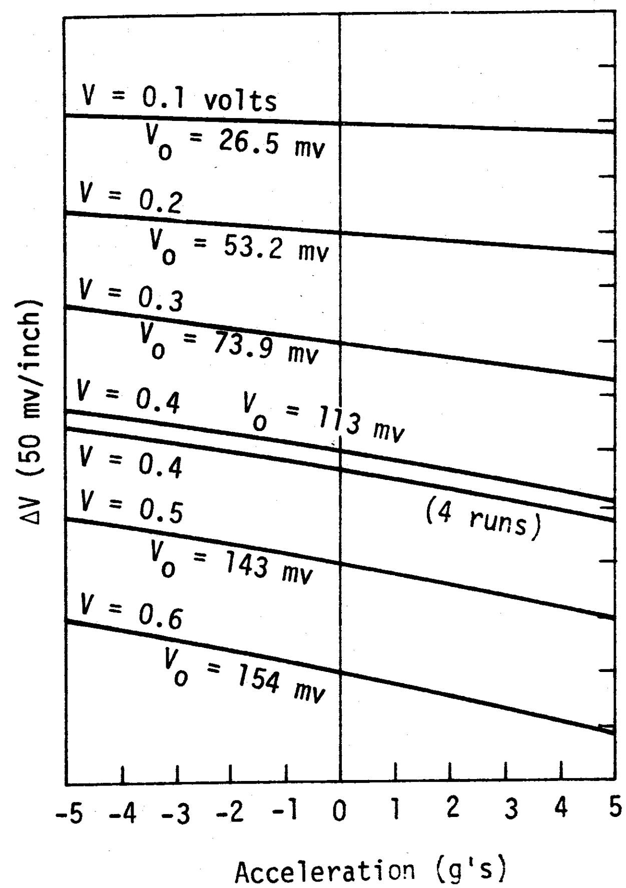


Figure 17. Recorded Plot of ΔV as a Function of Acceleration for the Forward Biased Mode (after Wortman)

and less costly method of construction. For these reasons a mesa configuration was chosen (figure 19). An experimental evaluation of these devices (ref. 31) indicates good agreement with the results previously obtained by Wortmann (refs. 32 and 33).

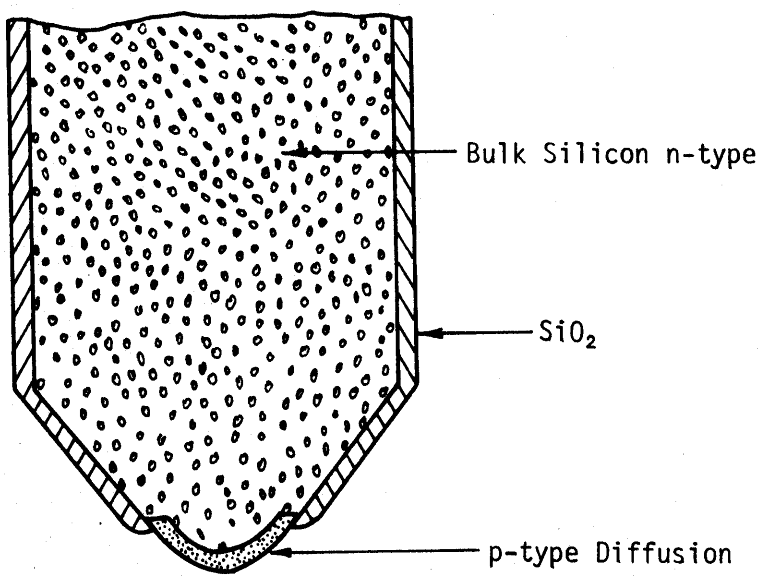


Figure 18. A Sketch of the Silicon Needle Diode Sensor (after Wortman)

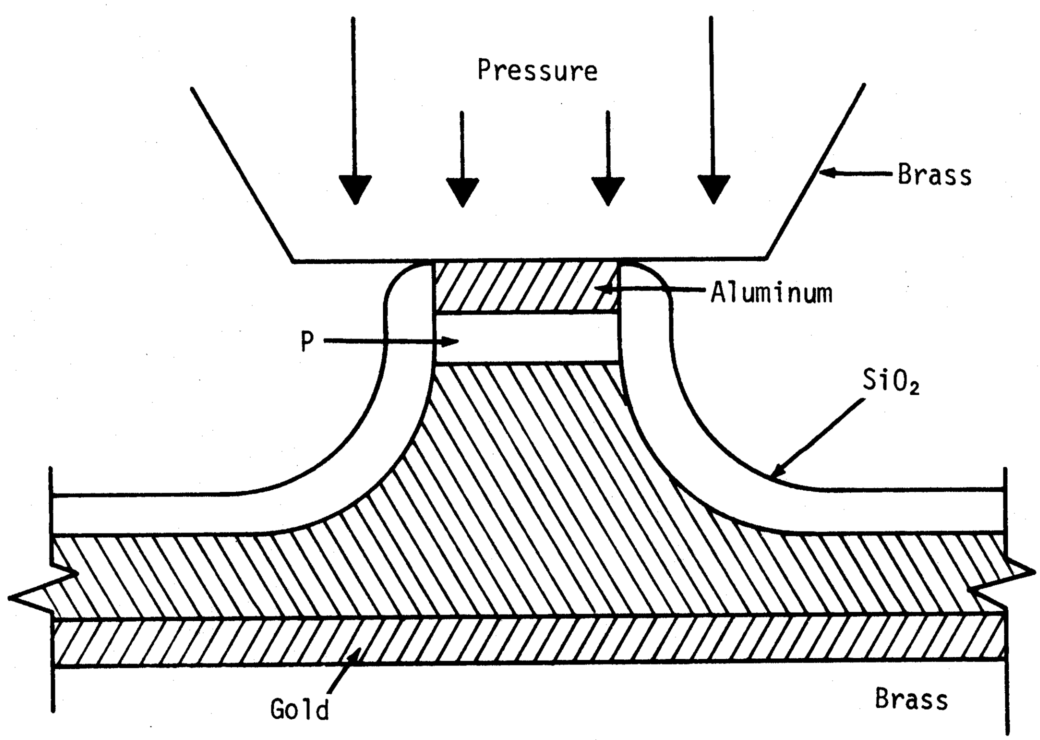


Figure 19. Mesa Configuration

The theory describing the mechanism of device operation has been given elsewhere. In essence, it states that under uniaxial stress the carrier concentration is varied and that the greatest effect exists when the stress exceeds 9.8×10^8 dynes/cm^2 when theoretically loaded in the [100] direction for silicon. Experimentally, this effect is observed at 9.3×10^8 dynes/cm^2. For this reason all accelerometers were designed to operate in the range of 10^9 to 10^{10} dynes/cm^2.

The observed frequency response along with the projected low cost and essentially zero cross-axis sensitivity has led to the decision to build prototype devices that have the configuration shown in figure 20. It is hope that these devices will more adequately fulfill the requirements of ground motion studies than those presently being used.

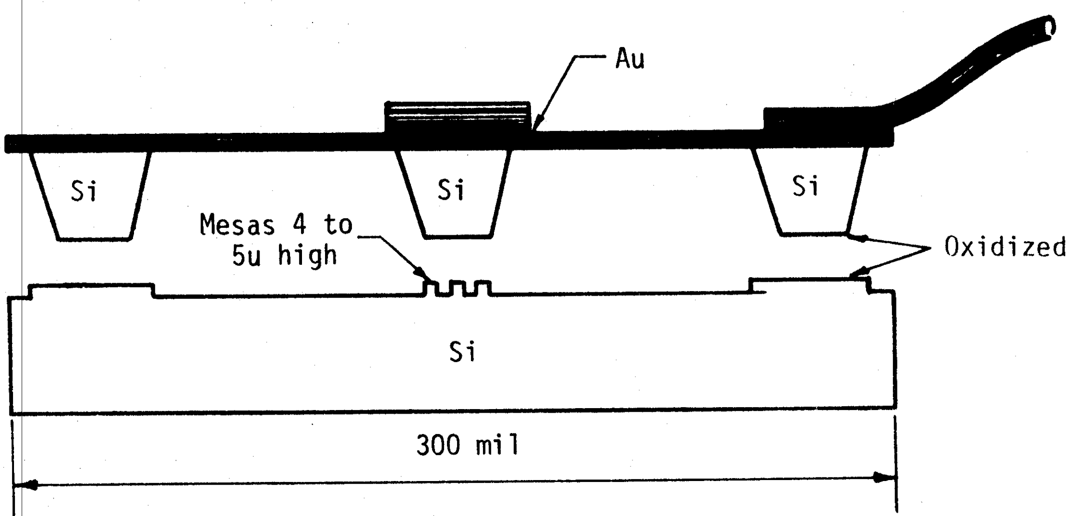


Figure 20. Proposed Accelerometer

b. Fall Related Absolute Memorizing Integer Seismic Transient Axial Transducer (FRAMISTAT)

The FRAMISTAT has been proposed by Pickett and Baum (ref. 34) to measure transient displacement in the earth or in loaded structures.

Before discussing the gage it is fruitful to discuss the philosophy of instrumentation in the low-stress region. This neighborhood will be defined such that geology, in addition to position, plays a significant role in the determination of the motion experienced by a point. As an example, the motion of rock, next to a crack may be much greater than that of a point in a continuous medium. For this reason, one of two things must be done to obtain meaningful data that can be compared to predictions. The first of these is to obtain enough data points in a volume in order that a mean or average motion can be inferred. The second is to make a gage such that it measures the motion of a relatively large volume, thus negating the effects of small perturbations in the soil. The latter is the object of the FRAMISTAT.

The basic principle involved is the use of a free-falling body as a position reference during time of the measurement. The transduction method is the use of bar (restricted to one dimensional) with a series of light-passing holes in a Gray code pattern. A number of photodiodes, equal to the number of bits in the Gray code, indicate the position of the free-falling mass during the time of the measurement (figure 21). This data is stored at a known time in a digital memory, which may be an integral part of the device (figure 22).

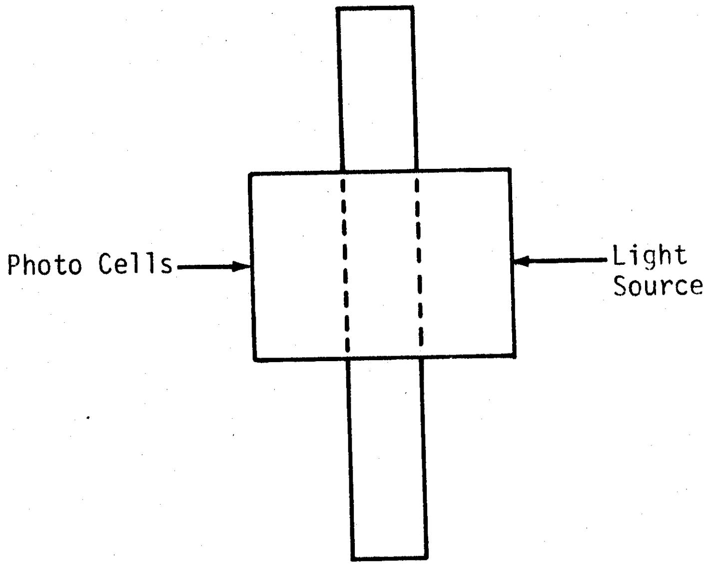
The measurement time of the device is determined by the length of the bar and the expected motion. For example, if the expected motion is $\pm$ 1 foot and the desired time is 250 msec, the bar must be 3-foot long.

There is no lower frequency response limt; the upper frequency limit is determined by the digitizing rate.

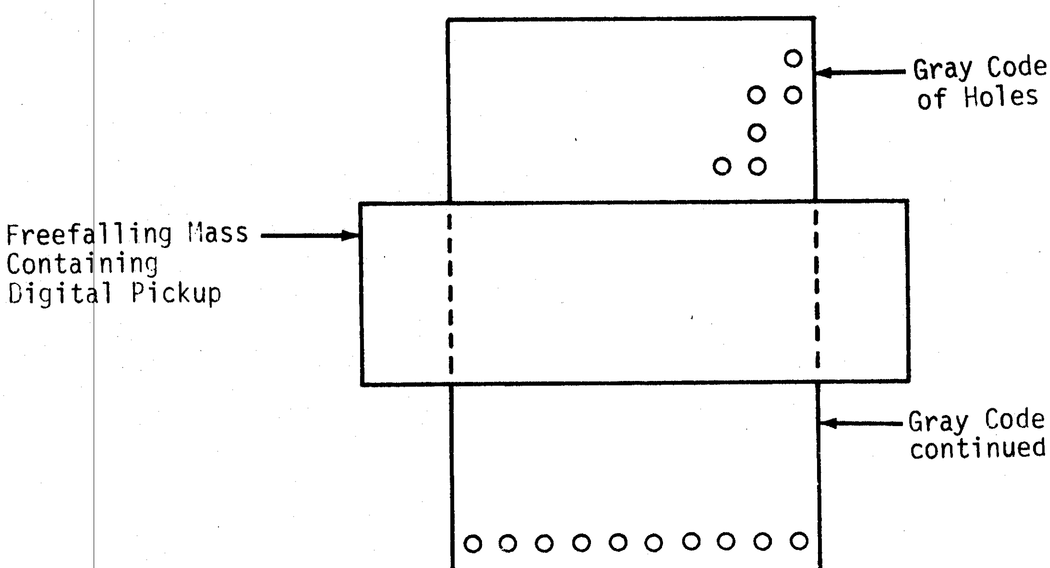
If desired, the device can be completely self contained (no cable). The triggering mechanism in this case will be the shock itself.

The only transfer function required for data reduction is the subtraction of $1/2\ gt^2$. This along with the fact that the output data is digital should be a significant advantage.

The particularly difficulty associated with the device, that has yet to be evaluated, is its sensitivity to cross axis loading. This could be a problem for ground motion measurements but can easily be limited in structure evaluations.



(a) Side View



(b) Front View

Figure 21. FRAMISTAT

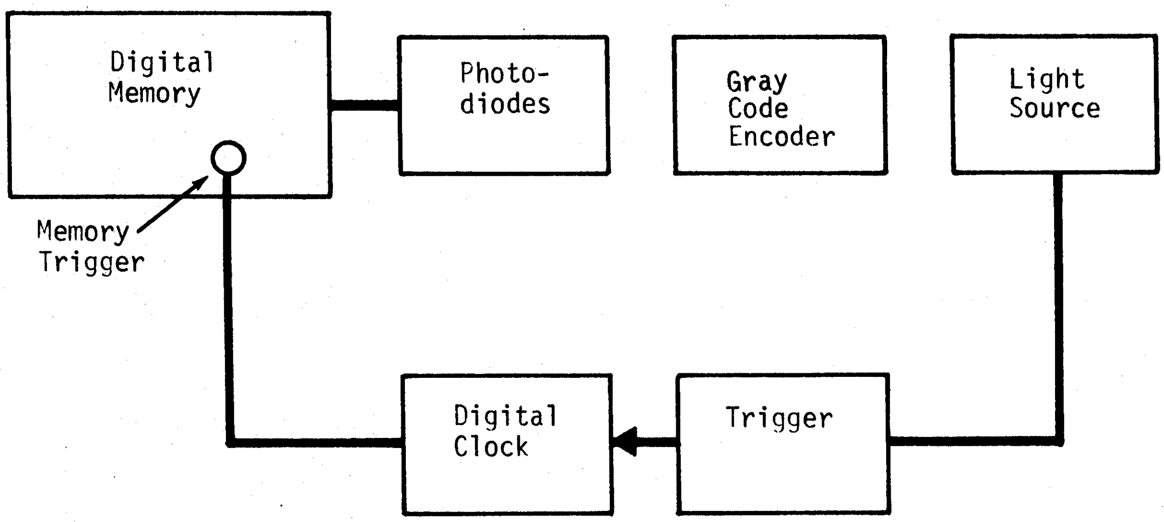


Figure 22. Flow Diagram for the FRAMISTAT

SECTION V

INSTRUMENTATION OF OTHER PARAMETERS

1. CRATER AND FIREBALL GROWTH

The experiments proposed for measurement of crater and fireball growth should be completely adequate.

2. RADIATION DIAGNOSTICS AND TEMPERATURE

The CANT proposal requires that measurements be made of the effective energy time history in the ground and of the device output magnitude and time history. To accomplish this a number of measurements must be undertaken, these include calorimetry, filter-fluorescers scatters, patch (burn-through), and pin-hole measurements. These experiments are not dealt with at length because the parameters are reasonably well understood and because descriptions of many of them are classified.

It should suffice to say that, while measurements of these phenomena are complicated, they have been performed successfully in the past and should not pose any problems for the CANT experiment.

3. ELECTROMAGNETIC PULSE (EMP)

The CANT proposal requires the empirical investigation of close-in EMP phenomena. Since the experiments will have a well defined environment, it is particularly suitable for this purpose.

To take full advantage of the relatively homogenous, well defined environment, no disturbances may exist close to the EMP transducers. As these disturbances are generated primarily from other transducers and their associated cabling, an entire quadrant of the cavity should be set aside for the EMP transducers.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

At this time the CANT experiment is not feasible because all of the instrumentation required for a coupling experiment does not exist in a developed state. Instrumentation is needed to transduce the pressure time history of a high-stress shock wave. The developmental efforts of some gages hopefully capable of performing these measurements has been described and should be continued as they are needed for the CANT experiment to accomplish its primary goal.

Thus, there exists a need to develop a high-stress measurement capability. Without this capability other ground motion studies are invalid since any extrapolation of the effects of an underground test to those caused by free surface blast is most probably incorrect. In other words, without CANT one cannot accomplish a meaningful assessment of the vulnerability.

This development will have to take the form of continued work on the recommended gages along with the initiation and feasibility study of new transduction concepts. This effort will not only take the form of laboratory and HE tests but also space will have to be made available for add on experiments on underground tests.

The remaining instrumentation required presently exists and should not act as a major impediment to the performance of CANT.

2. RECOMMENDATIONS

To make recommendations about the possible further development of high-stress instrumentations, it is expeditious to consider the prime quality of an ideal sensor; that is, that its output should be dependent on only one quantity. In the case of the MIPV, this quantity is the particle velocity in the stress wave; in the T^3 and the manganin gages, this quantity is pressure. It is agreed that all of these gages have difficulties associated with their matrix but this problem is being approached. The microwave waveguide principal output, on the other hand, is dependent on two quantities: the position of the reflector plate, and the state of stress in the core dielectric along with the volume of that compressed dielectric. Thus, there exists a fundamental difficulty in the basic approach to this latter transducer.

The vulnerability of the measurement system to EMP has been theoretically calculated for the MIPV, T^3 and manganin gages. The current level produced in these gages, while high, is very limited in duration. This condition yields a case where the calculated energy deposition in the wires is well within survivability limits, even considering their proximity to the event. The microwave system (generator, amplifier, detector, etc.) on the other hand, must either be placed some distance from the event or it must be extensively shielded.

The probability of solving the materials problem for the MIPV and T^3 gages is probably from 10 to 20 percent. The configuration of the manganin gage yields itself to the choice of many additional materials so its probability of successfully meeting this problem is much higher. However, the prospects of obtaining a reasonable gage lifetime under shock conditions is extremely limited.

Even though the prospects for any one of these three gages is extremely limited, taken collectively they represent a reasonable prospect of success. This, along with the critical necessity for a method capable of measuring the energy transfer into the ground, necessitates a continuation of this development effort along with the initiation and development of other possible systems. Thus, it is recommended that the development efforts on the MIPV, T^3, and manganin gages be continued and the the IMHST peak stress gage be fielded in order to determine its reliability and suitability for use on experiments such as the proposed CANT series.

ABBREVIATIONS AND SYMBOLS

A	electroded area caused by shock front
E_o	voltage output
EMP	electromagnet pulse
I	current
IMHST	impedance mismatch high-stress transducer
MIPV	mutual inductance particle veloci
M^p	mutual inductance
P	polarization caused by stress
P	pressure (unless specifically stated to mean polarization)
R	resistance
T^3	thermoelectric thermopile transducer
X	length of MIPV coil
Z	shock impedance
c	speed of sound
c_o	speed of light in vacuum
k	piezoelectric coefficient
n	refractive index
n_{eff}	effective index of refraction
t	time
t_o	single shock transit time along axis of quartz gage
u	particle velocity
u_s	shock wave velocity
r	shock angle
Δt	change in time
μ	permittivity
ρ	density
σ	stress

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