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BLAST AND SHOCK MEASUREMENT
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REVIEW

R.H. Rowland

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INTRODUCTION

This state-of-the-art review was prepared at the request of the Shock Physics Directorate, DASA, to provide the following:

1. A definition of the present level of blast and shock measurement instrumentation development

2. A survey of the instrumentation systems now available and being used

3. A medium for the exchange of information among agencies and individuals engaged in developmental work

4. A document with insight into the field for the interested engineer or scientist who has had little previous contact with blast phenomenology or blast and shock measurement.

With the above in mind, the material in this review is organized to give the reader first an overview of the phenomena associated with an explosive detonation, and then an introduction to methods and equipment used to measure the various blast and shock effects.

The introductory paragraphs provide a background to nuclear blast research efforts and instrumentation requirements and give a brief outline of the DASA blast and shock test instrumentation development (TID) program. Section 1 contains a summary of blast phenomena and includes descriptions of shock formation, air blast, ground motion, underwater phenomena, and target response to shock loading. Section 2 is an introduction to measurement systems and describes the principles of the various sensing elements, gages, and transmission and recording systems used in blast and shock research. These brief summary sections are not definitive sourcebook presentations, but are intended to place both the measurement objectives and measurement methods in a meaningful order. The remaining sections discuss the existing types of measuring systems grouped by physical phenomena measured. In describing the systems a pragmatic approach has been used and although the response characteristics of individual components are noted, the limitations of the entire system (when known) rather than those components are emphasized. Where possible, details are given for the problems noted, and solutions advanced to solve these problems, in the field use of the described systems.*

BACKGROUND—BLAST AND SHOCK RESEARCH

A great deal of theoretical and experimental work has been undertaken to determine the nature and the effects of explosively-produced shock waves. In order to predict the damage from a nuclear weapon, it is necessary to gain a thorough understanding of the various possible interactions of shock waves and targets, as well as knowledge of the magnitude of the modification of these interactions due to changes in burst conditions or alterations of the target. For some cases, simple exposure to a blast is adequate, such as in proof tests of existing equipments where the effects may be determined visually after the detonation. But in order to establish design criteria and to verify laboratory and theoretical studies, a more fundamental approach is needed.

The primary purpose of a given effects test is to gain information on phenomenology—not to develop instrumentation. Thus the researcher tends to use a particular assembly of gages that seemed to have worked on the preceding test. One adverse effect of this procedure is that little critical study has been performed to determine which portion of a particular observed response could be an actual parameter of the shock wave and which portion was artificially dictated by the design of the gage or recording system used.† Normally, in any weapons test series a few prototype instruments are tested, the main criterion for acceptance being performance that

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* The identification of commercial products by name is for convenience only. No criticism or endorsement of these products is intended, and none should be implied. None of the statements regarding the performance of a particular instrument were experimentally verified by DASIAC.

† This is not to say that unforeseen or incomprehensible perturbations in data are not often ascribed to vagaries in gage or recorder response.

exceeded the current instrumentation for that test. These prototypes, usually with modifications, are then often considered as standard instrumentation for a future series. An important recent development has been the specification (usually by the contracting agency or laboratory) of certain fragility, radiation, acceleration, and temperature limitations on proposed instruments to be used to gather data. The value of these specifications has long been recognized, but simulation of the conditions encountered in nuclear environments is a formidable problem.

Some of the earliest instruments employed in nuclear weapons test work were primarily used to determine the percentage of available energy that went into the blast wave. As the importance of blast as a damage mechanism was emphasized, field studies centered on testing the reliability of empirically determined scaling laws and overpressure versus height-of-burst curves. Investigation of response of structures and equipments to blast loading in the 10- to 25-psi region, with the objective of strengthening existing structures to what was at that time considered to be high overpressures, was conducted concurrently. With the shift of interest to underground defensive structures, and the later transfer of all nuclear testing underground, most work on blast loading and free-stream parameters in the high shock region above 100 psi was halted, and the major emphasis was on the study of energy coupling into the ground and the resultant ground motions.

In general, the field of blast phenomenology is fairly well understood for a surface burst with the exception of high pressures, dynamic pressures in water- or dust-laden air, or blast wave interaction with a non-ideal terrain. Since few measurements are available from high-altitude or space bursts, the existing predictive theories cannot be verified. Underground phenomena in the domain of non-linear elastic and hydrodynamic responses are yet to be adequately documented.

Today the measurement requirements encompass a wide research area designed to augment the existing knowledge of blast phenomena and target interaction. In addition to the continuation of studies on the loading and response of various military structures and equipments at relatively modest overpressure levels, there is a renewed interest in the free-stream high-overpressure region—the basic blast and shock phenomena, structural loading, and structural response—to enable design criteria to be formulated for the construction of hardened structures which cannot be buried underground. There is now a requirement to determine the loading and response of targets exposed to detonations at extremely high altitudes in order to establish the vulnerability of rocket-launched vehicles entering the atmosphere. The increased use of the oceans as protective cover for mobile missile launching sites requires more knowledge of the coupling of airblast energy into water. Finally, there is interest in both the underground and underwater phenomena close to the center of the detonation.

DASA TEST INSTRUMENT DEVELOPMENT PROGRAM REQUIREMENTS

Current DASA interests in developmental programs fall into two distinct areas of research. First, under the safeguard provisions by which the United States Congress ratified the Limited Nuclear Test Ban Treaty, the scientific community, through DASA and the AEC, maintains a six-months readiness capability to resume atmospheric testing. For instrumentation this directive entails defining the system to be used for a particular test, updating existing instrumentation systems incorporating new techniques and developments, initiating new developments for particular problem areas, and long-range instrument development planning for the post-test period. The second broad area concerns the Nuclear Weapons Effects Research (NWER) and the Nuclear Weapons Effects Test (NWET) programs for simulation testing using (for blast studies) high explosives or detonable gases, shock tubes, and blast load generators. Systems designed for the readiness program often are tested in the simulation environments.

SECTION 1

BLAST PHENOMENA

SECTION I
BLAST PHENOMENA

FORMATION OF A SHOCK

The almost instantaneous release of thermal energy during an explosion produces a sudden local pressure increase. This local pressure unbalance is relieved by an intense pressure wave (or shock wave) traveling radially from the detonation center. Although the shock front actually has a small but finite thickness which may be calculated, for computational convenience the shock front may be considered a discontinuity of the pressure, density, temperature and particle velocity parameters which define the wave.

A fully developed shock-wave system forms with about the same general configuration, irrespective of the assumed initial positive pulse; the propagation of the shock depends almost entirely upon conditions met in the surrounding media. The wave moves through an isotropic medium with a constantly diminishing velocity which is in excess of the sonic velocity in the medium. If the shock is expanding into a continuously larger volume, its strength decreases rapidly with increasing shock radius.

The molecules or particles which make up the wave in the medium must always move at velocities less than that of the shock front. Both the particle and wave velocities are functions of the pressure, but the relationship between pressure, shock velocity, and particle velocity is independent of the magnitude of the explosion. The distance from the detonation at which a particular pressure or velocity is observed and the relation that governs the time interval between the initial pressure increase and the return of pressure to ambient are functions of the magnitude of the explosion (and the properties of the media of propagation).

AIRBLAST

The compressional shock wave propagating in air is called a blast wave because of the strong wind associated with the wave. A typical blast wave, as observed at a location away from the center of the explosion, has the configuration shown in Figure 1. At least three parameters must be measured to describe the blast wave completely:

1. Initial shock intensity, usually identified by a measure of maximum or peak overpressure, but also by any parameter mathematically related to the intensity, such as the Mach number or particle velocity
2. Time duration, usually the duration of the positive phase
3. The impulse, or force-time product*.

Usually a single instrument records the intensity, duration, and wave decay while the impulse is integrated from these parameters.

It is usually important to differentiate between measurements specifying the blast wave per se and those indicating how the wave parameters are modified when the wave interacts with a boundary or target.

The magnitude or intensity of the pressure wave (usually expressed in pounds per square inch [psi] above ambient) measured side-on to the advancing wave, is called the incident pressure.† The time interval between the initial pressure rise and the return to ambient (the positive duration) is usually taken as proportional to the cube root of the explosive yield and varies from a few milliseconds for high explosives to seconds for large nuclear detonations. In a homogeneous medium, the maximum pressure decreases and the positive duration increases with increasing distance from the detonation. The positive phase of the wave is followed by a negative phase (a pressure below the pre-shot atmospheric) which has a duration longer than the positive and is associated with a reversal of the particle flow. The negative phase has its origin in the inertia of the particle movement associated with the movement of the compressional wave because the initial particle displacement is to a distance which is greater than the distance corresponding to a state of equilibrium with the atmospheric pressure.

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* The impulse measurement can refer to the force from either the incident overpressure or the dynamic pressure.

† There are a number of synonyms for this phenomenon—static pressure and side-on pressure being the most common. See Appendix A for blast and shock terminology.

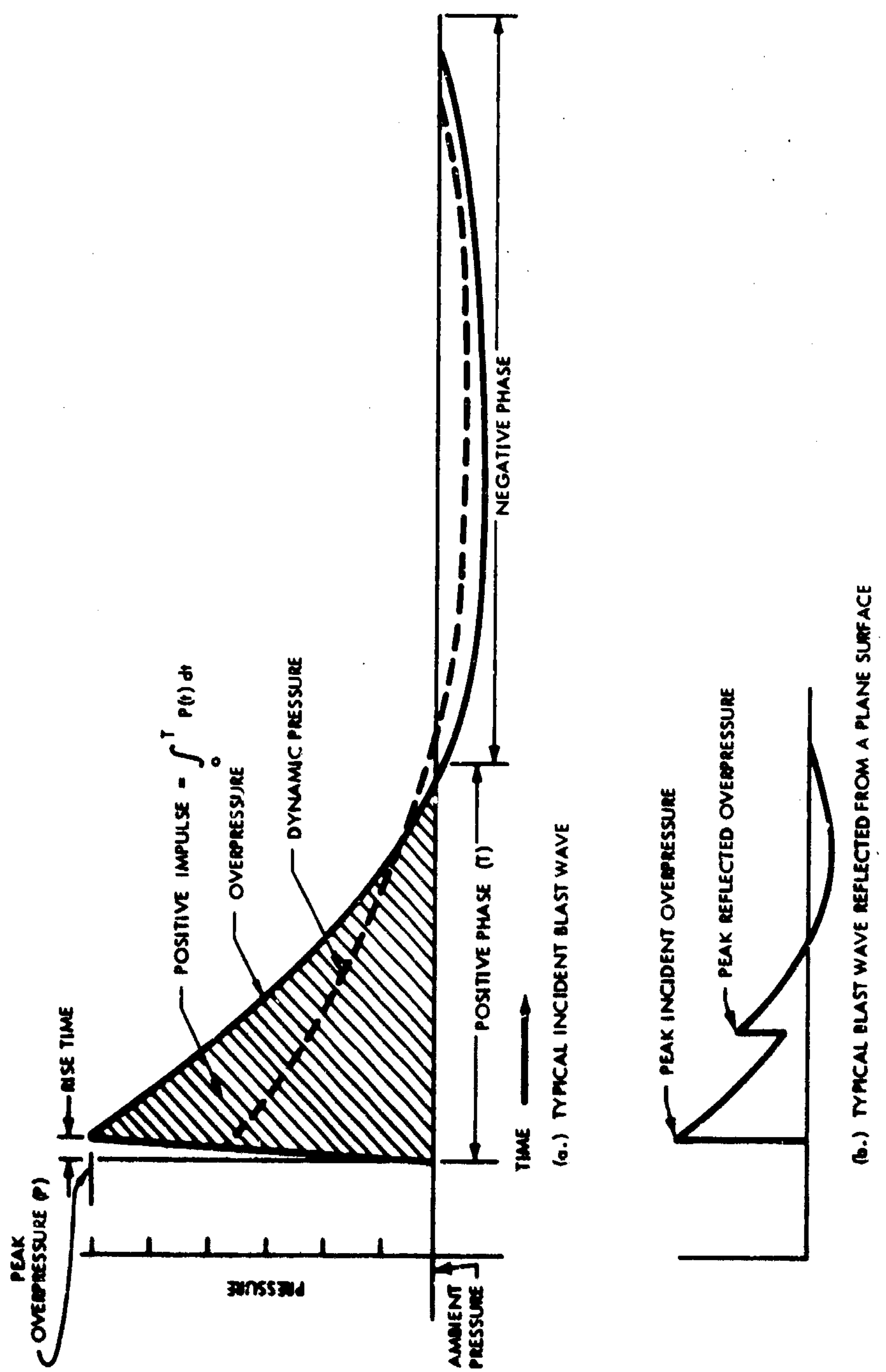

Figure 1. Blast wave configurations.

Since the blast wave produces particle motions, static measurement of the incident pressure is complicated by dynamic effects. The side-on measurement must be made in such a manner that the particle flow over the sensing element is, as nearly as possible, identical with that which would occur in the plane of the sensing element if the gage were not present. A sensor at an angle to the wave will experience a force component resulting from a deflection of the motion of the particles in addition to the side-on component. When the measurement is made at an angle to the blast wave (facing toward the direction of propagation), a reflected pressure develops on the sensor, or target, surface.* The maximum reflected pressure, recorded when the sensor is normal to the blast wave, is greater than the incident pressure by factors of from about 2 for weak shocks to almost 8 for incident pressures of 10,000 psi. Since the reflected pressure is superimposed on the incident pressure, the duration of its influence is a function of the time required for the particles in the blast wave to clear the target.

In contrast to the static forces of incident and reflected pressure, a dynamic pressure results from the transient velocity and density of the particles in the blast wave. Since targets impede the flow of these particles, a force results which has a duration dependent upon the weapon yield and maximum pressure level. The dynamic duration increases both with increasing weapon yield for any particular pressure level and with distance from detonation for a given yield. The maximum dynamic pressure decreases with distance from detonation. The measurement of dynamic pressure is complicated by the fact that large quantities of dust (or possibly water for an overwater detonation) are often raised from the earth's surface and carried along in suspension with the wave. This dust loading alters the flow of air and constitutes in itself a significant source of target damage in that it (1) increases the density, thus increasing dynamic pressure; (2) directly impinges on the target, eroding the surface and increasing the loading by dust momentum transfer; and (3) results in momentum exchange between the decelerating dust and the more rapidly decelerating air, causing an increase in the pressure in the gas phase of the mixture in the area ahead of the target.

---

* Actually, both reflected and transmitted waves are created. The partition of energy between the waves is dependent on the relative density and rigidity of the media on both sides of their boundary.

The force on a target resulting from the air particles coming to rest on the reflecting surface and transferring their momentum to static pressure is termed head-on or stagnation pressure.* This pressure is sustained as long as there is flow, and its magnitude, being a function of the flow velocity and density, will be greater than the incident pressure since it is the sum of the incident and dynamic pressures.

When the spherical shock wave from a detonation in the air strikes an infinite boundary, like the earth's surface, the reflected wave which is formed travels through the air already traversed by the incident shock. This reflected wave will propagate at a velocity greater than the initial blast wave since it travels through a medium shocked to a higher pressure and greater temperature by the passage of the initial blast wave. The expanding circular area of regular reflection ends when the angle of shock wave incidence reaches a critical value and the intersection of the incident and reflected wave fronts form the upper perimeter of an expanding and rising cylindrical shock front known as the irregular region or Mach stem (Figure 2). Measurements of blast wave parameters made in the Mach stem region are often termed "free stream" measurements while the "free air" parameters usually refer to measurements made above the rising Mach stem, i.e., in the region of regular reflection. The junction of the incident and reflected waves and the Mach stem is termed the triple point, although actually it is a ring. The locus of the triple point trajectory defines a slipstream, or density discontinuity, involving no pressure change but separating singly-shocked from doubly-shocked air.

The intense prompt thermal radiation from a nuclear burst can generate a hot surface layer through which the shock wave must propagate. This hot layer, by changing the local ambient conditions, leads to a distortion of the blast wave, forming a precursor shock and a pseudo Mach wave.† Since the thermal output decreases rapidly and is attenuated by the atmosphere, the effect decreases with distance from burst, and the true Mach front soon catches the precursor, reforming into an ideal wave.

* The stagnation pressure is equal to the sum of the incident overpressure and the dynamic pressure at low pressure levels where the compressibility of air is negligible.

† Present theory indicates this precursor formation would not be expected over heat-reflecting surfaces such as concrete or water, but would be enhanced over a dusty surface or a heat-absorbing one.

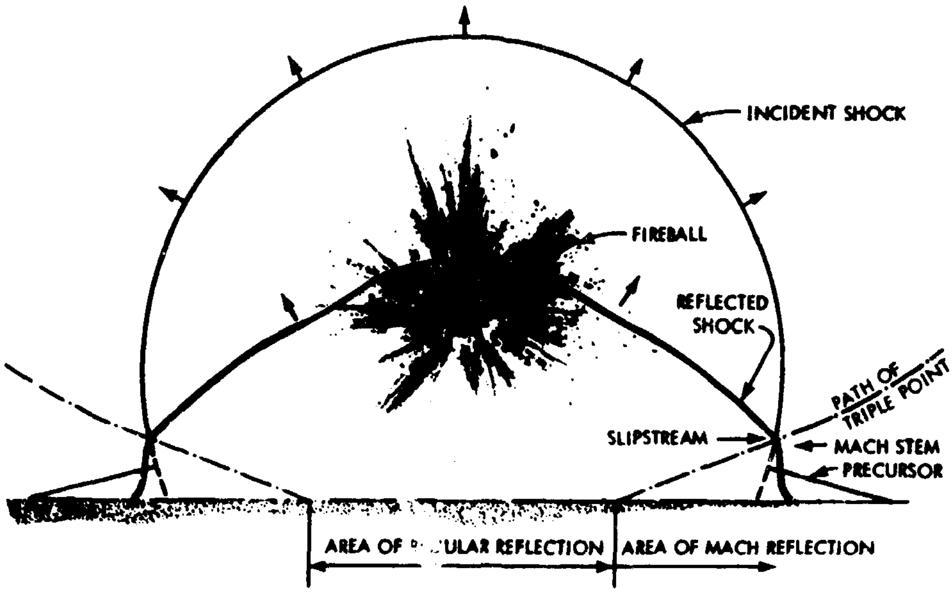

Figure 2. Blast wave terminology for low air burst.

The phenomena thus far described refer to a near-surface burst. In a surface burst, often referred to as a contact burst, the region of regular reflection does not exist and a Mach stem does not form. A fraction of the downward-directed energy of the blast is coupled directly into the earth and is dissipated by mechanisms described in a later section. The incident blast wave retains its normal characteristics, but it appears to contain almost twice its normal energy.

As the height of an explosion is increased, those relations between overpressure, distance, and time (which depend on the ambient conditions of the atmosphere) vary with the change in ambient pressure. With increasing altitude the absolute value of overpressure from a given yield at a given distance, measured at the altitude of the burst, decreases, and there will be a concomitant increase in both the shock arrival time and the positive duration. For moderate changes in altitude, these values may be obtained by relatively simple scaling laws.

At high altitudes, say above 100,000 feet, the initial thermal energy, which is the source of the blast wave, is distributed through the tenuous atmosphere over a large volume of space. The time necessary to form a shock wave is greater and the maximum shock pressures are lower. At extremely high altitudes, i.e., 250,000 feet, the radiation which produces the thermal heating is distributed over kilometers of space, and the actual debris from a nuclear explosion will be a primary source of the shock phenomena.

At the other extreme of underground or underwater explosions, the air shock which may be produced is a complex function of the energy coupling into the medium and of reflection and rarefaction phenomena (and bubble formation for underwater bursts). The air blast from such explosions is generally characterized by multiple peak pressures and a non-ideal waveform. The wave form is so non-ideal, in fact, that some investigators prefer to use the term "pressure increase" rather than "shock wave," since the term "shock wave" implies an almost instantaneous pressure rise.

GROUND MOTION PHENOMENA

Energy from a surface or near-surface detonation may be coupled into the ground to induce a motion by two distinct processes. The first process is an air-induced (also called blast-induced and slap) shock caused by a blast wave moving over the ground surface generating time-dependent stress waves into the ground. The second mechanism is by ground-transmitted shock which is a direct conversion of the hydrodynamic energy of the detonation into mechanical energy in the immediate vicinity of the explosion resulting in a wave motion that is essentially seismic in character. The almost instantaneous loading of a small surface element constitutes the initial disturbance, and the elastic waves which are propagated outward from the loaded segment are quantitatively similar to those emanating from a shallow-focus earthquake.

The height (or depth) of burst is critical in determining the initial partition of energy between the blast-induced and the direct-induced mechanisms; i.e., for an air burst both the air- and direct-induced energies have their source in airborne shock waves, but the seismic energy received by the ground from a subsurface burst is imparted directly. In the region of normal interest, i.e., areas subjected to stresses from a low-air or contact-surface burst, the observed motions are a complex result of the two distributions of stress generated by the air- and direct-induced components.

In general, when the earth is subjected to a shock stress, dilatational, distortional, Rayleigh, and Love waves are generated into the medium.

> The dilatational wave (P wave, longitudinal or compression wave) effects ground motion by imposing compressive or tensile stresses. The velocity of the wave corresponds to the soil, or rock, seismic velocity.
>
> The distortional wave (S wave, transverse or shear wave) induces ground motion by imposing horizontal shear. These shear stresses are of lesser intensity than the compressional stresses and the shear wave velocity is less than that of the dilatational wave.
>
> Rayleigh waves are surface waves which induce vertical particle motion in a radial plane extending outward from the source. Absolute particle motion for Rayleigh waves is retrograde elliptical with the vertical displacement being about half the horizontal displacement at the surface. Rayleigh waves attenuate rapidly with depth. Since their arrival time usually coincides, or is masked by, the arrival of the air shock, it is difficult to evaluate their effect.
>
> The Love wave is characterized by particle motion in a horizontal plane. Its presence depends upon the existence of impacted shear energy and reflective containment through the presence of a low seismic velocity layer overlaying a higher velocity layer.

In a layered medium, the phenomenology of shock propagation becomes extremely complex due to effects of boundaries, discontinuities, and density gradients.

The partition of the observed ground effects into direct- and air-induced components may be convenient for a broad description of the events which follow an air burst, but these definitions are not entirely unambiguous. The seismic energy is not coupled into the ground instantaneously and the blast-induced component does not appear until the Mach stem is formed. Thus, since blast energy is actually coupled to the ground continuously, these somewhat arbitrary definitions cannot provide a means of determining the time at which the transfer of seismic energy is complete, or the time at which the ground begins to receive blast-induced energy.

Usually the effects of air-induced and ground-induced ground motion are discussed separately. Each, however, has definite "zones" of interest. For the ground-induced motions, the following three areas based on the resulting deformation of the soil or rock mass are generally recognized:

The hydrodynamic zone—characterized by an inelastic transfer of energy in which the tensile and shear stresses are far in excess of that which the medium can transmit

The plastic or visco-elastic zone—which is a region of permanent non-linear deformation

The elastic zone—in which earth motion is (as the name implies) elastic in nature, exhibiting either a transient movement with no permanent displacement, or a linear response to the stress.

The following three zones are usually recognized for air-induced ground motion also, but these are defined by the relationship between the velocity of the blast wave and velocity of the ground wave rather than by the effects produced in the medium:

The superseismic region—close to the point of detonation, in which the airblast velocity will be greater than the velocity of the dilatational waves in soil

The transeismic region—in which the airblast velocity has decreased below that of the dilatational wave but still remains above the distortional wave velocity

The subseismic region—in which the velocity of the airblast has dropped below the distortional wave velocity. *

The overpressure at which the ground shock "outruns" the airblast, i.e., in the subseismic and transeismic regions, depends on both the yield of the device and the seismic velocity of the medium. Table 1 (taken from Reference 1) presents the approximate overpressure at which outrunning occurs from a large-yield surface burst.

* Some investigators prefer to use two divisions, superseismic and subseismic, referring the airblast propagation velocity to the dilatational wave only.

Table 1. Overpressures at which the velocity of wave propagation in the ground exceeds the airblast velocity.

Formation	Overpressure (psi)	Formation	Overpressure (psi)
Alluvium	< 40	Shale	650–2,500
Gravel, dry	10–100	Metamorphic	> 1,000
Gravel, wet	40–500	Limestone	> 1,500
Sandy clay	100–500	Granite	> 3,000
Sandstone	500–2,000		

In the field of underground study, it is often a misnomer to use the terms "shock waves" or "ground shock" because the use of these implies a sharp rise in pressure. Most workers prefer either "stress wave" or "ground motion."

UNDERWATER PHENOMENA

A detonation under water produces a shock front by compressing successive shells of water around the burst point. The shock wave produced has an extremely high pressure and a high initial particle velocity which is rapidly attenuated to acoustic values, its velocity being that of the speed of sound in water, or about 5,000 ft/sec. The peak pressure decays less rapidly with distance than does a pressure wave in air; thus peak values in water are much greater than at the same distance from an equivalent explosion in air. The overpressure durations are quite short, on the order of milliseconds, compared to airblast durations. Due to the comparative incompressibility of water, the initial pressure pulse has a very small negative phase; however, the initial shock wave is reflected from the air-water surface as a refraction wave which interacts with the direct pressure wave and may result in pressures slightly below the preshot ambient. This interaction of the direct and refraction waves becomes an important factor in target response studies by causing a sharp decrease in the water shock pressure (the surface cutoff).

In general, the surface phenomena can be divided into two major categories: first, those produced by the initial shock wave, and second, those produced by the mass motion of the water which accompanies bubble pulsation and its emergence to the surface. The actual observed surface effects depend on the size and nature of the explosion and the depth at which it is detonated.

The gas bubble formed by the explosion products expands to a maximum size, dependent upon the yield of the explosion and the depth of burst. After reaching the maximum, this bubble contracts to a minimum size or state of high compression before expanding again. During the short interval of high compression, a second compressional wave is propagated through the water. This "first pulse wave" exhibits a definite rise time rather than the almost instantaneous discontinuity of the initial shock wave; it also shows a slower rate of decay. The gas bubble continues to oscillate and produce bubble pulses during its upward migration toward the surface. The absolute motion of the bubble is affected both by its buoyancy and by the proximity of the water-air surface, the sea bed, or other boundary surfaces. Since the damage to a target is due to both the shock wave and the subsequent bubble pulses, these effects must be evaluated separately. One measurement usually made is that of the bubble period of oscillation—the time intervals between successive minima in the bubble radius. The length of the first bubble period is related to the energy left after passage of the shock wave. In general, the longer the period, the greater the energy.

The pressure field in water is usually complicated by reflections from various boundaries within the system; the reflected wave from a rigid surface is a wave of compression and that reflected from a free surface, like the air-water interface, is a wave of tension. The parameters of a pressure wave at a distance from the blast where the wave is of acoustic intensity may be affected by such other factors as refraction by velocity gradients and attenuation by viscosity effects.

TARGET RESPONSE TO SHOCK LOADING

An analysis of a particular structure or equipment subjected to the forces of blast or shock resolves to a problem of response to rapidly applied dynamic forces. The complete configuration of a deforming complex structure usually defies accurate mathematical description, for the dynamic behavior of most targets is exceedingly complex. There are mixtures of elastic and inelastic vibrational modes; different parts do not respond in phase with each other, and differences in strength, mass, ductility, and general design greatly affect response.

The forces which result from the action of shock pressure are termed "loading." Airblast loading is a function of both the characteristics of the incident blast wave—the overpressure, dynamic pressure, rise time, decay, and duration—and the shape, orientation, and rigidity of the target.

The response or distortion of a structure due to a particular loading may be described as having two components—diffraction-induced and drag-induced.

Diffraction loading results from the differential forces of an airblast wave as it strikes an obstacle and is deflected around it. Different surfaces of the structure are subjected to different peak pressures and pressure-time histories; the time required for a wave to engulf the target and pressures on the first-struck face cause net lateral loads in the direction of wave motion. The damage caused during the diffraction stage will be determined by the magnitude of the loading and its duration, which is, of course, related to the peak overpressure.

The loading caused by the transient aerodynamic winds behind the blast front is termed "drag loading." A target will be subjected to this loading during the entire positive phase duration of the wave.

A target will undergo both the drag and diffraction phases of loading; however, some structural types will be more sensitive to a particular loading. For instance, a box-like structure with few openings will be diffraction sensitive, while a structure with a large percentage of openings, such as a truss bridge, will be primarily a drag-sensitive target.

In order to evaluate the response and structural integrity of underground targets subjected to the effects of a surface nuclear detonation, one must first determine the surface loading, next evaluate the underground stress field and resultant motions caused by these surface loadings, and finally assess the ability of a particular structure to withstand these motions. Thus, in addition to the parameters of acceleration, velocity, displacement, and deformation measured on a target subjected to an airblast, an underground target must be instrumented to determine its response to various specialized soil-structure interactions.

Two aspects of the propagation of stress waves through soil or rock are important to understanding buried-structure response: the attenuation of the pressure pulse, and the development of a finite rise time due to the non-linearity of the earth stress-strain curve. As the pressure pulse traverses the underground structure, the loading on that structure is uneven and unsymmetrical. In order for the structure to deform to those unequal loads, it is necessary for the soil adjacent to the structure to also undergo deformations. It is in this broad area of study, which is not concerned directly with structural response but rather with the extent to which deformation of structures is influenced by the surrounding medium, where surface and underground response measurements differ. The three major areas of concern are (1) reflection of pressures at the interface between the soil and the structure, (2) arching, which is a function of the shear strength of the medium and the flexibility of the structure, and (3) depth of earth cover required to reduce the sensitivity of buried structures to unsymmetrical load distributions.

The loading on an underwater target from an underwater explosion depends not only on the magnitude of the explosion and its distance but also on the geometric relationship between the burst point, the target, and the surface. These three distances control the time interval between the direct and reflected shock waves which, in turn, determines the shock impulse on the target before the surface cut-off effect is produced.

BASIC REFERENCES

Possibly the finest single unclassified source of information about phenomenology and target reaction is The Effects of Nuclear Weapons, Samuel Glasstone, Ed., 2nd Edition, 1962, prepared by the Department of Defense and published by the Atomic Energy Commission.

Other general references treat a particular aspect of the subject, usually with a rather high degree of scientific sophistication, and are recommended for a broad background in shock studies.

For Air Blast:

Explosive Shocks In Air, by Gilbert Ford Kinney, MacMillan Company, New York, New York, 1962.

Primarily an exposition of the characteristics of a non-nuclear air-blast and the general mechanism of airblast damage.

Underwater

Underwater Explosions, by Robert H. Cole, Princeton University, 1948 (also published by Dover Publications, Inc., 1965).

The standard sourcebook for underwater shocks.

Underground

Nuclear Geoplosics: A Sourcebook of Underground Phenomena and Effects of Nuclear Explosions, in 5 volumes by the staff of Stanford Research Institute, Fred M. Sauer, Ed., DASA 1285, 1964.

Covers the entire underground subject field from the theories of ground motion to the effects on structures and equipment.

A Review of Nuclear Explosion Phenomena Pertinent to Protective Construction, by H. L. Brode, RAND Report RM-425-PR, 1964.

Augments The Effects of Nuclear Weapons by including information about the very high overpressure region.

Air Force Design Manual: Principles and Practices for Design of Hardened Structures, by N. M. Newmark and J. D. Haltiwanger, AFSWC-TDR-62-138, 1962.

Readers with access to classified documents should include:

Introduction to Underwater Explosion Research (U), by A. H. Keil, U.S. Navy UERD Report 19-56 (C), 1956.

(U) Both a theoretical and empirical study of the applied mechanics of damage processes to naval structures exposed to underwater blasts.

Nuclear Weapons Blast Phenomena (U), by J. F. Moulton, Jr., 3 volumes, DASA 1200 (S), 1960.

(U) The definitive work using weapons test data.

SECTION 2

AN INTRODUCTION TO MEASUREMENT SYSTEMS AND METHODS

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AN INTRODUCTION TO MEASUREMENT SYSTEMS AND METHODS

The particular methods of obtaining shock wave measurements and the systems used to obtain these measurements will vary greatly depending on the source of the shock and the objectives of the experiment. However the final results may differ, all systems have a great deal in common and the useful methods of measurement are based on few physical phenomena.

Two basic systems are in general use: optical systems (described on page 93 *et seq*), and gage systems.

All shock measuring gage systems are composed of four major elements: first, a sensing device which converts shock-induced motion into a mechanical or electrical signal that is proportional to the parameter of experienced motion; second, a gage or instrument containing one or more sensing devices in a particular housing*; third, a transmission system which can transfer or modify the response of the sensing element; and finally, a recording mechanism to make a permanent record of the phenomena measured by the sensing device.

There are three types of gage measuring systems: (1) purely mechanical, such as a diaphragm (the sensing element) with an attached scribe (the transmission system) scratching a plate (the recorder) within a housing (the gage); (2) purely electrical, where

* The word transducer is often used synonymously for both the sensing device or element and the gage. This usage can be confusing when a gage contains more than one sensing element. In this report, sensing devices may be interchanged with transducers but the term transducer will not be used as a synonym for gage. The reader is cautioned, however, that in reports of field experiments this distinction does not often exist.

the sensing element directly converts the energy of the forcing function into an electrical pulse which is transmitted and recorded; and (3) electromechanical, where there is either an electronic amplification of a mechanical response or a mechanical linkage between the forcing function and an electronic sensing device. Most present gage systems are electromechanical.

The sensing elements within a gage may be broadly classified as either mechanical, self generating, resistance, or reactance. The mechanical sensor requires little explanation; it is usually configured as a deflecting plate or deformable bellows for pressure measurements and as a mass-spring system for low-frequency displacement measurements. In a self-generating sensor, the electrical charge is generated as a direct result of the applied force.* In a resistance or reactance circuit sensor, the applied force is converted into a corresponding change in the electrical characteristics of either a solid material, for magnetostrictive and piezoresistive elements, or in the electrical constants of inductance, capacitance, or resistance. In the brief review that follows, piezoelectric sensors are the only ones considered under the heading "Self Generating." In fact, of course, those inductive-type sensors that operate under the principle of electrodynamics, electromagnetics, eddy current, and magnetostriction are by encyclopedic definition truly self-generating sensors, but they require outside excitation.

SENSING ELEMENTS

Reactance Sensors

Variable reactance sensing elements convert displacement into corresponding change in the electrical constants of inductance, or capacitance. These elements may be arranged electrically as voltage dividers or bridge circuits. These circuits must be energized by a source of outside power, either ac or dc depending on the type of sensor.

Variable-Inductance Sensors

Sensing elements which function in accordance with variations in the principles of magnetism are used extensively for blast and shock

* Often a self-generating piezoelectric <u>sensor</u> is used as, and called, a <u>gage</u>. This gage, of course, would be a purely electrical gage. However, the self-generating element may also form the sensing portion of an electro-mechanical gage.

measurement. The change in inductance of an indicator as the result of relative displacement of its elements may be readily measured. The inductance change may be achieved by a change in magnetic core position, by a variable air gap (i.e., the movement of an armature position with respect to a coil), or as a result of a change in mutual inductance between two coils by varying their distance, relative location, cross-sectional area, or the magnetic permeability of an iron core coupling the coils. Underlying the principle of operation is the fact that large variations in the reluctance of the magnetic circuit result from relatively small displacements of the armature.

Two general types of variable-inductance sensors are now employed: the differential transformer and the variable reluctance and permeance type. Differential transformers sense the displacement of a magnetic armature by translating the physical change into an a-c voltage which is a linear function of the displacement over a particular range. The differential transformer is composed of primary and secondary coils wound on a ferromagnetic or air coil. A movable armature is used to control the electrical coupling between them. Variable reluctance sensors consist of a coaxial coil and a high-permeability probe assembly. Movement of the probe causes a variation in coil inductance causing a shift in carrier frequency of an associated oscillator circuit.

The linear variable differential transformer (LVDT) is normally used in gages designed to respond by a linear motion to the parameter they measure (for example, strain gages). The LVDT most common in blast and shock studies measures the position of a movable ferrous armature in relation to three coils—an exciting coil between two signal coils. When the middle coil is excited with carrier voltage, the difference between the voltages induced in the outer coils, obtained by connecting them in series opposition, is a (nearly) linear function of the position of the armature around which the coils are wound.

The variable reluctance sensor is used in gages responding to non-linear or rotational motions, such as airblast gages, velocity gages, and accelerometers. A form commonly encountered in blast studies is shown in Figure 3. The movable armature, A, is activated by the carrier voltage. Movement of this armature asymmetrically changes the reluctance in the magnetic path of the inductances L_1 and L_2, which are connected as two arms of a bridge or balanced modulator circuit.

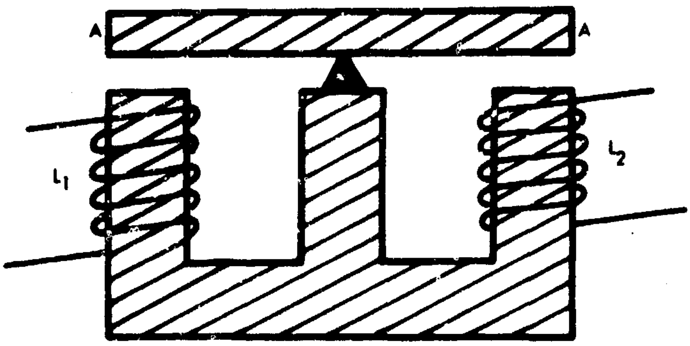

Figure 3. Schematic diagram of a variable reluctance sensor.

Due to the inherent strength of their mechanical parts, inductance sensors used in blast studies are usually considered less vulnerable than other types of sensors to either blast-produced failure or to environmental conditions encountered in field use. Their low impedance output enables them to produce relatively large currents which often require no amplification. However, the sensor is operative only when the carrier voltage is ac, and the resolution of most inductance sensors is not adequate to measure very small displacements.

The main radiation weaknesses of the variable-inductance sensors involve the use of silicon transistors, fluorine-evolving insulation, and organic damping-oils. Most of these weaknesses can be corrected. If attempts are made to modify the component parts of the sensor to enable it to operate in a nuclear environment, the radiation damage threshold should approach 10^{18} n/cm^2 and 10^{11} ergs/g gamma (Reference 2). It should be remarked that the radiation damage levels cited in this section refer to the sensor only. In most cases the actual gage is more vulnerable. These values should be considered as an upper limit for radiation hardening under current technology.

Variable-Capacitance Sensors

In this class of sensors, the output is proportional to the change in capacitance between two plates. The electrical capacitance is varied by a change in the spacing between plates, a change in the area of the plates, a change in the dielectric constant of the dielectric, or a combination of these.

Two types are in use: one consists of a stretched metal diaphragm moving between two electrodes; the other type, usually used in high-pressure gages, consists of a double diaphragm which forms a capacitive circuit transformer coupled by a coaxial cable to the recorder. The signal from the sensor can either modulate an a-c carrier or the sensor may be biased with a d-c voltage through a high resistance.

Capacitance sensors are highly sensitive to small displacements but the electronics and required auxiliary equipment are relatively complex because a high-frequency carrier oscillator system must be used to remote-record the vibration frequencies encountered in the blast measurement. There are advantages, however, in the simplicity of installation, sensitivity, wide displacement range, and wide frequency range.

Existing sensors exhibit a radiation threshold between 10^{13} and 10^{16} n/cm^2 and 10^5 to 10^9 ergs/g for gamma. It is believed (Reference 2) that the organic materials used in the conventional sensor can be replaced easily with a ceramic- and mineral-filled epoxy which will substantially increase both the radiation tolerance and the operating temperature.

Eddy-Current Sensors

When a nonferrous plate of low resistivity is moved in a direction perpendicular to the flux lines of a magnet, a current is generated in the plate which is proportional to the displacement of the plate. These eddy currents set up a magnetic field in a direction opposing the magnetic field that creates them.

The use of a high-frequency oscillator circuit allows extremely high-frequency response from the sensor. For a particular sensitivity range, the limiting frequency response will be the resonant frequency of the nonferrous plate.

Variable-Resistance Sensors

Force is measured by an element which changes its electrical resistance as a function of pressure. A common form of resistance sensor employs a contact sliding along a continuous resistor, or potentiometer. The overpressure physically moves the sliding contact. The input power can be obtained from a low-voltage supply and the relatively large potentiometer output signal can drive a galvanometer without amplification. The sensor is usable at dc, and will measure a permanent displacement. Because resolution is limited by the diameter and spacing of the resistance wire, there is a finite resolution, or incremental output. This type of sensor is used mainly in displacement-measuring instruments or strain gages, although the principle can be applied to a very-low-frequency accelerometer.

Unfortunately, the elements used in the construction of a potentiometer which provide the extreme accuracy, good linearity, and temperature resistance characteristics, are usually the same materials that are affected most by high-energy particles and gamma rays (Reference 2). Materials of known resistance to radiation are now being incorporated into the manufacture of these sensors. The approach has been to eliminate as many organic materials as possible, to use ceramic-coated wire, metal-film depositions on ceramic base, glass insulation and potting, and lubricants known to be resistant to breakdown under a flux of ionizing radiation. Present threshold levels for radiation damage in sensors utilizing the high-radiation-tolerant materials approach 10^{18} n/cm^2 for fast neutrons and 10^{11} ergs/g gamma irradiation.

Strain-gage sensors convert a physical displacement into an electrical signal by using the principle that as a strain-sensitive element (such as a resistive wire) is stretched, its diameter decreases and its electrical resistance changes in proportion to the strain. The strain is in turn proportional to the displacement of one end of the wire. Three general classes of strain gages have been developed—the unbonded, the bonded, and the solid state. New techniques of manufacture and design have eliminated some of the disadvantages of strain gages, such as their fragility, limited frequency response, and temperature sensitivity, and the principle is finding almost universal acceptance in recent measuring systems.

Wire and foil strain gages can be used in a radiation environment only when the basic materials used in their construction are carefully selected and protected. The Radiation Effects Information Center lists four types of radiation damage which must be considered: (1) weakening of the bond between the bridge legs and the base, (2) breakdown of insulation between the bridge leg terminals and the metal supports of the base, (3) changes in resistance of the sensing wire itself, and (4) a change in sensitivity or gage factor due to aging and flexing. One major problem encountered with strain-gage sensors operating in a nuclear environment is an insulation resistance breakdown in the leadwire, causing degradation of performance.

Unfortunately, the wires and foils which have a desirable strain-sensitivity also exhibit a change in resistance with temperature variations. Partial temperature compensation can be obtained by the proper arrangement of the legs in the Wheatstone circuit.

The unbonded strain-gage sensor consists of a grid of fine, strain-sensitive wire strung under slight tension between a stationary frame and a movable armature. The force to be measured can be made to move the armature with respect to the frame, increasing tension in one-half of the grid and decreasing the tension on the rest. The change in resistance is measured on a Wheatstone bridge circuit whose output voltage is amplified to drive a recording instrument with a self-balancing bridge. Since the initial forcing function requirement of unbonded strain elements is low, small-size and low-range sensors are readily available. Substantial overload protection and damping are easily incorporated into the sensor or gage. The sensor can be fabricated of entirely inorganic and high-temperature-resistive materials permitting operation in radiation and extreme temperature environments. Unbonded, temperature-compensated strain gages have been made to operate at temperatures as high as 1,600° F and in radiation fluxes of 10^{15} to 10^{18} n/cm^2 and 10^{10} ergs/g gamma (Reference 2).

The bonded strain gage is also a strain-sensitive wire or foil, but is entirely attached by an adhesive to the member whose strain is to be measured. The bonded sensors will operate in tension, compression, and bending modes. They can be used only in the location where they are originally applied and, if not mounted in a gage, cannot be removed successfully for subsequent use. Electrical insulation is provided by the adhesive or insulated backing material. A gage may be constructed by bonding the strain gage to a diaphragm or rod; however, the force required to produce a displacement which can be measured is greater than that required by an unbonded sensor because of the additional stiffness of this member.

Since the gage measurement is obtained by transferring the strain from the metal member through the bonding adhesive and backing material, the accuracy of the measurement is limited by the response characteristics of these materials.*

The commonly used adhesives and backings are usually of epoxy, which has low radiation tolerance and thus restricts the use of bonded gages in radiation environments. These adhesives disintegrate at temperatures above 250° F. Further, there have been problems of gage separation from a rapidly stressed structural member. The temperature sensitivity can be compensated for, in part, by using dummy arms on the bridge circuit, and high-temperature ceramic bonding adhesives have greatly decreased both temperature and radiation sensitivity. Recent developments in weldable strain elements hold promise of solving all three problems.

The phenomenon of piezoresistance in semiconductors is also used in the design of strain-gage sensors. To some extent all materials exhibit the piezoresistive effect, but in silicon semiconductors the effect is very large.

The silicon crystals are grown with a controlled dopant content to obtain the required properties of resistance, thermal coefficient of resistance, gage factor (i.e., the fractional change in resistance of the sensor with applied strain), thermal coefficient of gage factor, and stability. These properties can be controlled and optimized for a specific application by changing the dopant level; however, the properties cannot be controlled independently and must be selected as a group. In general, the silicon strain-gage sensors provide a higher gage factor than do the metal wire and foil sensors. Values as high as 200 may be obtained for semiconductor sensors, compared to gage factors of 2 to 4 for conventional strain-gage elements.

A rather recent development has been the introduction of a thin-film semiconductor strain-gage sensing element. These are manufactured by vacuum deposition of a thin film of a piezoresistive material, such as silicon or calcium, on an electrical insulating substrate. The sensing element may have any configuration and can

* A reviewer of this document—who shall remain anonymous—wanted this paragraph to conclude "... and the technician's ability to produce a decent job. Human error has accounted for more loss of data than the gages themselves." However, since the main topic of this section is description of types of sensors rather than gages _per se_, this comment was not included.

be deposited on diaphragms, beams, or columns. The four deposited arms of a bridge circuit are electrically connected and the leadwire attachment is made directly to the film.

The resistance of the gage is controlled by the thickness of the deposited film; thus resistance can be held to a constant value even if the physical size of the gage is reduced. The high resistance of the bridge permits higher excitation voltages at the same power input, proportionally increases the output level, and provides a higher signal-to-noise level.

The semiconductor strain sensor exhibits a very non-linear, strain-dependent response. There is a possible problem of mismatch between the thermal coefficient of expansion of the semiconductor and other materials.

Nuclear radiation damage can be permanent, because of changes to the structure-sensitive and surface properties, which are of major importance in semiconductors, or it can be temporary, such as a decrease in insulation resistance due to a prompt gamma pulse. It is estimated that flux levels of 10^{12} n/cm^2 and 10^7 ergs/g gamma could be tolerated, whereas levels above 10^{13} n/cm^2 and 10^8 ergs/g gamma would render these elements inoperative; however, the level of dopant in the silicon can control to some extent the radiation sensitivity. It is possible that higher levels could be reached.

Piezoresistive wire is used as the sensing element in some very-high-pressure gages. Gold-chromium and manganin wire are ordinarily used because they have unusually low-temperature coefficients of resistance, but other materials, such as lead, indium, and cadmium, have been considered and tested. Manganin, which is an iron-nickel alloy, is preferred and is used in most gages. A helix or coil of wire or a metal foil is embedded in an insulating material (usually an epoxy) and oriented to present a thin surface to the direction of shock propagation. Since the wire is very thin and because the pressure and particle velocity are continuous across the interface between the manganin and the insulator, the waves of reflection from the two interfaces will very nearly cancel each other. Within a few hundredths of a microsecond, the pressure in the wire will have come to equilibrium with the incident pressure. The pressure record is readable for a longer period of time than the record from a quartz gage which shows the shock-wave reflections.

A manganin gage, when exposed to a short pulse of 25- to 30-Mev electron radiation (Reference 3) to determine the magnitude of radiation-induced spurious output, exhibited a sizable response to the emission of secondary electrons. Grounding the gage reduced this radiation-induced signal by two orders of magnitude.

The manganin sensor responds to pressures from 30 to almost 200 kb, and there is a requirement for measurements in the 1- to 20-kb range. Recent work by SRI (Reference 4) with a vacuum-deposited film of piezoresistive calcium shows promise at pressure levels from 5 to 25 kb.

Other materials which exhibit the changing properties of electrical conductivity due to pressure, such as sulphur, and even water, have been used in the construction of gages. This area of technological advancement is one of the most rapidly expanding today.

Piezoelectric Sensors

Some materials produce an electrical charge on each crystal surface when subjected to a mechanical strain along certain axes, a phenomenon known as piezoelectricity. This fact has long been utilized in the construction of pressure transducers. Tourmaline crystal gages were in use prior to World War II and were among the first electrical gages to supplant mechanical gages in blast studies.

Piezoelectric substances occur naturally, e.g., quartz and tourmaline. They are manufactured as synthetic crystals, such as lithium sulfate or Rochelle salt, and as ferroceramics like barium titanate and lead zirconate. Although the ferroceramics do not have piezoelectric properties in their manufactured state, they can, by special polarizing techniques, be made to behave piezoelectrically. The electrical charge, which is proportional to the applied pressure, is distributed over the gage and cable capacitance and leaks off with a time constant determined by the resistance and capacitance of the associated measuring circuit.*

Piezoelectric crystals are generally mechanically rugged, exhibit a linear and reproducible response, and have a high natural frequency. These advantages, however, are offset by a rather low signal output which usually requires an amplifier, by the need to pay considerable

* In order for the sensor output to represent accurately the forcing function, the time constant must be small with respect to the duration of the signal being measured.

attention to electrical insulation, by the fact that most piezoelectric materials exhibit no steady-state response to pressure and must be calibrated dynamically, and by the fact that piezoelectric materials are, for the most part, also pyroelectric and thus temperature sensitive.

Pyroelectric effects, or the appearance of charge on the crystal faces due to a change in the temperature of the crystal, are observed with materials such as barium titanate and tourmaline which have a unique polar axis. The magnitude of the pyroelectric effect depends upon whether or not the thermal expansion of the crystal is prevented. If a mechanically-constrained crystal (i. e., a crystal subjected to hydrostatic loading) is heated, the primary pyroelectric effect is noted. An unclamped crystal, which is sensitive to hydrostatic pressure, will also exhibit secondary pyroelectric properties superposed on the primary effect due to the volumetric change which must occur due to uniform heating.* A crystal which is not hydrostatically sensitive is not likely to exhibit pyroelectric effects except insofar as thermal gradients may induce non-uniform stresses producing strains along certain axes—termed tertiary pyroelectricity. The charges produced by the temperature fluctuations which may be expected under normal working conditions may be comparable with the pressure-induced signal and such crystals are only useful for very short duration measurements. The use of these pyroelectric crystals involves a continual adjustment of recording equipment to correct for drift, right up until the instant of making the dynamic measurement.

A crystal can be oriented with respect to three orthogonal axes designated X , Y , and Z . The Z axis is one of optical symmetry.† Light passing through the crystal along this axis suffers no change in polarization. Plane-polarized light transmitted through the crystal along the Z axis is not affected by rotation of the crystal about this axis either in intensity or plane of polarizations. This effect is used to determine the axis of the crystal.

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* The primary effect arises from a change in the electron distribution in the crystal, whereas the secondary effect is mainly the result of the relative displacements of positive and negative ions.

† The X axis is the electric axis and the Y is called the mechanical, or third, axis.

When quartz is strained in the direction of a polar axis only, charge separation occurs. Equal and opposite charges are induced in conductors placed on surfaces cut perpendicular to a polar axis and the charge is a linear function of the strain. X-cut crystals (major surfaces parallel to the Z and Y axes) are generally used in quartz pressure gages in preference to Y-cut crystals. There are several reasons for this. Charge appears on the surfaces in the same plane in which the pressure is applied (termed the d_{11}-strain coefficient for X-cut crystals). This makes electrode connection somewhat easier. The crystal is employed in a thickness vibration mode which gives a high natural frequency. Further, the crystal acts under simple compressive and tensile stresses. The use of other piezoelectric strain constants, i.e., recording the charge produced on the surfaces normal to the plane in which pressure is applied, would necessitate applying the pressure as a shearing or bending force and connecting electrodes to crystal faces other than those on which the load was acting. These alternative modes are sometimes used in order to obtain higher gage sensitivities, but at the expense of frequency response.

Quartz is chemically stable, free from hysteresis (the residual charge in a crystal that remains after a pressure cycle), mechanically strong, available as high quality material, easily worked to close tolerances, and not primarily pyroelectric. The quartz crystals have disadvantages, however. They have a low piezoelectric constant, a high impedance output, and are not sensitive to hydrostatic pressure. They only give reliable measurements when stressed below the dynamic elastic limit of quartz; stress wave reflections from other faces of the crystal result in short readable records. The first three disadvantages can be offset by using multiple crystal piles, a high resistance amplifier, and by ensuring that pressure is applied only to certain faces of the crystal.

Tourmaline exhibits a hydrostatic response, but material which is free from internal flaws is difficult to obtain. Natural tourmaline sources are nearly, if not completely, exhausted, and large crystals (2 inches or greater) are practically non-existent outside of museums. Smaller crystals (less than 1 inch) of good quality are still available in a stock maintained by the Naval Ordnance Laboratory. Investigation of practical methods for growing tourmaline crystals has indicated that this is possible, although none are being produced at the present time.

Because of their high dielectric constant, sensitivity, and ease of fabrication (and hence lower cost), polarized ferroceramics usually can be used to measure smaller stresses extending over a longer period of time than can piezoelectric crystals such as quartz. However, most ceramics suffer from hysteresis effects. The main advantage of barium titanate is its high piezoelectric strain constant, whereas that for tourmaline is comparable to quartz (X-cut quartz has a piezoelectric constant d_{11} equal to -2.04×10^{-12} coulomb/N, Z-cut tourmaline d_{33} equal to -1.84×10^{-12} coulomb/N, and $BaTiO_3$ equal to -5.6×10^{-11} coulomb/N). A major disadvantage of the ceramics is that the piezoelectric (i.e., polarization) characteristics are lost if the Curie temperature of the material is exceeded. This seriously restricts these sensors at the high temperatures which are encountered in nuclear blast measurements. Other disadvantages include relaxation effects at shock pressures greater than about 100 psi which cause erroneous results in measurement of shock-wave decay, marked temperature sensitivity in addition to the Curie effect, and change in calibration after being shocked.

Other piezoelectric materials, such as lithium sulfate, Rochelle salt, etc., are very brittle and sensitive to humidity. Some will lose water of crystallization and break up. Others attract water and tend eventually to dissolve.

Piezoelectric sensors are subject to degeneration of crystal characteristics when exposed to intense nuclear radiation; this degradation is especially apparent in high-frequency characteristics. It has been reported (Reference 2) that quartz crystals are not appreciably exposure-rate sensitive and that crystals with high natural frequencies are affected by prolonged irradiation approaching 10^{20} n/cm^2 of fast neutrons. Changes occur in density and lattice parameters. The self-generating characteristics of the ferroceramics are degraded about 10 percent when the material is irradiated to a flux level of 10^{16} n/cm^2.

Table 2 lists a summary of the characteristics of sensing elements. It must be remembered that some of the parameters are affected by the gage housing or the associated electronics, or both.

Those readers who wish a more thorough description of sensing devices are referred to the following:

Table 2. A summary of sensor characteristics.

Type of Sensor	Linearity	Hysteresis	Repeatability	Field-use Adaptability	Resolution	Excitation	Frequency Response	Shock and Vibration Sensitivity	Thermal Sensitivity	Acceleration Sensitivity	Radiation Hardness, Relative Rank	Advantages	Disadvantages
Variable-inductance	Fair	Moderate	Fair	Good	Continuous	ac only	100 Hz to 5000 Hz	Moderate	Low	Moderate	2	FM output possible. Resistance to EMP.	Circuit balancing required. Magnetic fields affect response. Limited frequency response. A-c carrier only.
Variable-capacitance	Good	Low	Good	Good	Continuous	ac and dc	10 Hz to 60 kHz	Moderate	Low	Moderate	3	High frequency response. Small displacements may be measured.	Critical cable tuning. Limited cable length. A-c carrier only.
Variable-resistance Potentiometer	Good	Very low	Good	Good	Finite	ac and dc	N.A.	Low	Moderate	High	2	High output. Amplification and impedance matching usually not required. Low cost. Static calibration.	Finite resolution. Relatively short life. Noise and error increases with use and wear.
Bonded strain-gage	Excellent	Low	Excellent	Good	Continuous	ac and dc	dc to 50 kHz	Low	Low	Low	4	High frequency response. Shunt calibration possible.	Low output sensitivity. Useful only at high pressures or with high strains.
Un-bonded strain-gage	Good	Low	Good	Poor	Continuous	ac and dc	10 Hz to 70 kHz	Low	Moderate to High	High	4	Low pressure measurements possible. Shunt calibration possible. High frequency response.	Adhesive used is a critical factor in sensitivity. Low-output sensitivity. Sensitive to thermal shock.
Piezoresistive Solid-state	Poor to Good	Low	Good	Fair	Continuous	ac and dc	10 Hz to 70 kHz	Low	Low	Low	5	High output sensitivity.	Limited temperature range. High strains only.
Manganin	Poor	Moderate	Fair	Good	Continuous	ac and dc	N.A.	Low	Low	Low	1	Very high pressure measurements.	
Piezoelectric	Good	Very Low to Moderate	Fair	Fair to Good	Continuous	N.A.	50 Hz to 500 kHz	Low	Low to Moderate	Low	2	Long cable length possible. Low cost. Can be fabricated in a variety of shapes. Excellent high frequency response.	No steady-state response. Age effects sensitivity. High output impedance cathode follower or charge amplifier necessary. Humidity-sensitive. Temperature-sensitive.

Shock and Vibration Handbook, Vol. 1, Basic Theory and Measurements, by C.M. Harris and C.E. Crede, McGraw-Hill Book Co., Inc., New York, 1961.

A definitive text on measurement systems.

Telemetry Transducer Handbook, Vol. I, Flight Control Laboratory, Wright-Patterson Air Force Base, WADD TR 61-67, 1961 (available from the Defense Documentation Center as AD 267 367).

A rather full treatment of transducer fundamentals.

GAGES

The sensing elements described above may be employed singly or combined in gages used to measure a variety of physical phenomena. The following paragraphs do not describe a particular gage but rather list general requirements for any gage. More specific requirements for each measurement will be given in the sections describing existing measuring systems.

Fundamental Considerations

LINEARITY OF RESPONSE. It is highly desirable, but not strictly essential, that the gage response be directly proportional to the forcing function within some specified operating range. A non-linear gage response increases the complexity of data reduction and usually results in a variable gage accuracy, which is also a non-linear function.

TIME- AND ABSOLUTE-LOADING SENSITIVITY. The amplitude of the signal generated should depend only on the magnitude of the forcing function and be independent of its rate of application, within the expected range of measurement. Further, the gage sensitivity should not depend significantly on its past history of loading.

RESPONSE FREQUENCY. The gage must have a response time adequate to the parameter being measured. The natural resonant frequency of the sensing element bears a relation to the function of the gage in which it is used. A sensing element with a low natural frequency usually requires a sizable displacement to generate a signal. Since the element must sense this displacement without loading the system being measured, the low-frequency sensors are usually used in gages designed to measure displacement, strain, stress, and velocity. Sensing elements with a high natural frequency are better suited to measure minute displacements, and usually are used to measure rapidly changing pressure, acceleration, and velocity.

It is the frequency response of the gage that is the important factor, however, and the interaction of the sensing element and the gage must be considered. The same high-frequency response sensing element can, when coupled with a stiff spring and/or to a light mass, produce a gage with a high natural frequency, or, if coupled to a heavy mass and/or compliant spring, function as an instrument with a low natural frequency.

FREEDOM FROM FALSE SIGNALS. The gage should respond solely to the forcing function. Three common sources of false records are:

1. Distortion of the gage body by the pressure field, inducing a spurious output by straining the sensing elements

2. Stress waves, induced in the gage body at a point other than at the sensing element, traveling through the gage body and stressing the sensitive elements

3. Thermal effects in either the sensing element or in the gage body inducing strains and generating a spurious signal.

RUGGEDNESS. The gage must withstand the application of the force being measured without distorting the signal transmitted. This does not necessarily mean that the gage must be designed to survive in the environment being measured, or be recoverable for further use, but the gage must transmit a valid representation of the forcing function before it is damaged or destroyed.

SENSOR SIZE. That portion of the gage which senses the forcing function must be small enough so that no significant stress gradient exists across its surface. If the gage uses a diaphragm to transmit the forcing function, its thickness must be adjusted to the measurement requirement. The thicker diaphragm may be able to withstand the greater loading but it results in a reduced frequency response.

Other Considerations

In addition to the fundamental design requirements for all gages, particular environments or specific measurements impose further constraints on gage design. For instance, a gage designed to measure incident pressure is usually configured to insure that the sensing element is parallel to the particle flow of the wave.

For target response studies, a prime consideration is that the gage should add negligible mass to the target, but its presence should not alter the response.

It is in underground measurements that the design of the gage assumes a paramount importance. To measure soil stress and accelerations accurately, the gage must be small, must be density-matched to the displaced soil, must be insensitive to lateral stress, must exhibit a minimum friction between the gage and the soil, and finally must not resonate in the frequencies being measured.

THE TRANSMISSION SYSTEM

Classically, a measurement involves a calibrated reproducible measuring device or sensor, a means of information transferal, and a recorder of adequate dynamic range, fidelity, and frequency response.

The terms "transmission system" and "telemetry" are considered synonyms. They may be defined as any system by which analogs of a measurement performed at some location are reproduced at another location in a form suitable for display, recording, or insertion into data reduction equipment. In this report, "transmission system" is used to cover all of the methods of signal transfer, and "telemetry" is restricted to data transfer by radio waves. This is in line with recent usage which differentiates between "telemetry" and "wire transmission." This section will not deal with the intricate methods of linkage and transfer in mechanical gages.* We will restrict this brief discussion to the transmission of signals from electrical and electromechanical gages.

Transmission Fundamentals

The output signal from a gage can be transmitted at signal frequency if the sensing element is self generating, or if it is used to modulate a direct-current carrier. Most systems, however, utilize

* Where applicable, these mechanical problems are discussed in the sections on mechanical airblast gages and long-span displacement gages.

the signal from the sensor to modulate an a-c carrier, for this generally results in a lower noise level than the direct transmission.

An important requirement for any modulated carrier system is that the maximum signal frequency be much lower than the frequency of the carrier wave; otherwise the carrier cannot be properly modulated.

There are two fundamental methods of carrier modulation: amplitude modulation (AM) and frequency (or phase) modulation (FM). The FM system is usually preferred because it provides superior signal-to-noise ratio. A discussion of the relative merits of the two systems is beyond the scope of this report.

It is possible to multiplex a number of independent data signals on a single carrier channel and transmit them simultaneously and unambiguously. Two methods of multiplexing in common use are frequency division and time division.

Frequency-division multiplexing may employ a multiple-modulation technique; each signal modulates a separate subcarrier of different frequency, and all the subcarrier frequencies modulate a main carrier wave. In some instances, such as a short wire transmission link, the subcarrier frequencies may be fed directly to the line. The received and detected carrier (i. e., all the subcarriers), or the output of the wire link, is fed to a set of tuned subcarrier discriminators (receivers) which separate the individual subcarriers. The latter are then demodulated in the usual manner.

In time-division multiplexing, the signals are sampled in a definite sequence by a switching device called a multiplexer or commutator. This system is most appropriate when the signal magnitude does not vary rapidly with time, and thus finds little use in the measurement of transient blast waves.

Either AM or FM can be used to modulate either the subcarrier or the carrier. FM is most frequently used in shock studies. A system in which both subcarrier and carrier are frequency-modulated is designated an FM/FM system.

For any carrier frequency, 18 subcarriers, with center (unmodulated) frequencies ranging from 400 to 70,000 Hz, have been standardized by the Inter Range Instrumentation Group (IRIG). These FM subcarrier frequencies are shown in Table 3.

Table 3. IRIG band frequencies.[†]

SUBCARRIER BAND					
Band	Lower Limit (Hz)	Center Frequency (Hz)	Upper Limit (Hz)	Subcarrier Deviation (percent)	Maximum Intel. Frequency (Hz)
1	370	400	430	±7.5	6
2	518	560	602	±7.5	8
3	675	730	785	±7.5	11
4	888	960	1,032	±7.5	14
* 5	1,202	1,300	1,398	±7.5	20
* 6	1,572	1,700	1,828	±7.5	25
* 7	2,127	2,300	2,473	±7.5	35
* 8	2,775	3,000	3,225	±7.5	45
* 9	3,607	3,900	4,193	±7.5	60
*10	4,995	5,400	5,805	±7.5	80
*11	6,799	7,350	7,901	±7.5	110
*12	9,712	10,500	11,288	±7.5	160
*13	13,412	14,500	15,588	±7.5	220
14	20,350	22,000	23,650	±7.5	330
15	27,750	30,000	32,250	±7.5	450
16	37,000	40,000	43,000	±7.5	600
17	48,560	52,500	56,440	±7.5	790
18	64,750	70,000	75,250	±7.5	1,050
OPTIONAL BANDS					
A	18,700	22,000	25,300	±15	660#
B	25,500	30,000	34,500	±15	900
*C	34,000	40,000	46,000	±15	1,200##
D	44,620	52,500	60,380	±15	1,600
*E	59,500	70,000	80,500	±15	2,100###

* Preferred Bands

[†] Reference: Inter Range Instrumentation Group of the Range Commander's Conference Document No. 106-60.

NOTES:

A. This band may be employed by omitting the 30-kHz band.
B. This band may be employed by omitting the 22- and 40-kHz bands.
C. This band may be employed by omitting the 30- and 52.5-kHz bands.
D. This band may be employed by omitting the 40- and 40-kHz bands.
E. This band may be employed by omitting the 52.5 kHz band.

\# For acceptable lower signal-to-noise ratio this figure may be increased to 3,300 Hz max.

\## For acceptable lower signal-to-noise ratio this figure may be increased to 6,000 Hz max.

\### For acceptable lower signal-to-noise ratio this figure may be increased to 10,500 Hz max.

Since the maximum permissible IRIG deviation is 7.5 percent of the subcarrier center frequency, the higher frequency subcarriers have increasingly greater signal carrying capacity. The lower frequency subcarriers are suitable only for modulation by signals that change relatively slowly with time, i.e., low data rates. The higher bands are employed for high-frequency data.

In FM/FM transmission systems, the electrical data signal from the sensor is used to frequency-modulate a subcarrier oscillator in one of the standard IRIG bands. The outputs of the subcarrier oscillators are mixed and used to frequency-modulate the transmitter. After transmission (by either a radio or wire link), the FM/FM output composite is separated into the various subcarriers by bandpass filters and the equivalent data signal is recovered by FM discrimination.

The FM/AM technique is basically the same as FM/FM with the exception that the FM outputs of the subcarrier oscillators modulate the amplitude of the transmitter, rather than the frequency. At the receiving terminal, the AM receiver output feeds the composite subcarriers into standard bandpass channel filters and discriminators, whose output is the equivalent data signal.

The time-division multiplexing systems, such as pulse amplitude modulation (PAM), pulse code modulation (PCM), and pulse duration modulation (PDM), which are popular in space telemetry, are not used in blast and shock research. Data rates are lower and equipment tends to be more complex and costly than for FM/FM. The newest solid-state commutation equipment used in pulse systems is capable of about 50,000 samples per second; this may prove adequate for blast studies. The data is converted from analog (voltage) to digital form (usually binary coded) and can be made directly suitable for data reduction in a digital computer. The PAM, PCM, or PDM signals may be transmitted via either AM or FM; the latter is usually preferred.

Data Transmission

Two classes of schemes may be used for relaying data in electric current or voltage form (analog or digital) to the recording equipment:

1. High-quality cable
2. Broadband telemetry.

The cable has the advantages of being simple, hard, and dependable, but it does necessitate physical connection of a continuous long metallic conductor to the sensor, and its consequent penetration of the explosive environment is potentially a source of severe (local, at least) perturbation. In addition, in a nuclear environment such a cable can pick up spurious EM signals in the manner described below.

Broadband (microwave) telemetry tends to become complex, voluminous, unreliable, and lacking in dynamic range; but it does, in principle, eliminate the long conductor penetration. For close-in nuclear measurements, it would be seriously attenuated (probably to cut-off) by the ionized medium at all but the earliest times.

Current developments in millimeter wavelength techniques offer promise for overcoming this obstacle. Even more promising is the possibility of going to optical wavelengths. Laser schemes for this purpose are being developed. Some of these use a flexible fibre optics light plant to eliminate the need for a precisely aligned optical path.

HARDWIRE TRANSMISSION. Recording equipment is usually situated far enough from the burst point to minimize explosion effects, but close enough so that transmission effects do not interfere with reliable recording. In practice, an upper limit of cable length between gage and recorder is about 8,000 feet; some sensing elements require shorter spans. Higher carrier frequencies, which accommodate higher data rates, are somewhat more difficult to transmit because of the cable losses and greater bandwidths involved. Hardened recorders partially offset this restriction by permitting the recorder to be placed closer to the gage.

In addition to the normal problems of hardwire cable, such as the possibilities of moisture or dirt affecting connections or inadvertent breakage, the explosive nuclear environment imposes rather severe forces on any cable transmission system. Three basic effects may be recognized: physical damage by the shock wave, transient radiation-induced effects, and electromagnetic effects.

Physically, a cable may be broken by ground motion or crushed by a pressure pulse. The crushing effect may degrade the signal or it may destroy it.* The importance of these effects depends on the

* This crushing effect can, in fact, be used as a method of determining the speed of shock propagation. See the section on SLIFER cables in Part 4 of this report.

time when destruction occurs in relation to the time of interest of the parameters being measured.

Intense pulses of radiation can produce significant perturbation in electrical cables and wiring, especially coaxial signal cables. Even with no voltage applied, a cable may exhibit a signal when exposed to a radiation pulse. These "TREE" effects on cables are discussed on page 200 in Section 6 of this report.

In addition to the radiation-induced effects on the hardwire transmission system, a detonation will produce a low-frequency electromagnetic pulse which can be transmitted along the wire. The EM pulse has been responsible for a great number of instrument failures during nuclear tests.

A section of this report dealing with the effects of these radiations on entire measurement systems and methods used to counter these effects begins on page 48.

RADIO TELEMETRY. It is often impractical to recover an instrument canister or to use hardwire transmission of data. In such cases radio telemetry is employed.

Usually the measured quantities are telemetered in real time as the actual measurement is being made. Timing information generally is added at the receiving station. However, when the instrument package, or the data link, is exposed to the highly-ionized region, or other disturbances caused by a nuclear blast, it sometimes is desirable to record the data locally for later transmission. When data is transmitted in this manner, timing must be added at the time of recording.

A typical FM telemetry transmitter is crystal stabilized, has an average power output of 2 to 5 watts, and utilizes a carrier frequency in the 215- to 260-MHz range. An RF amplifier may be added to increase the power. High-gain antennas often are used for transmitting, receiving, or both. Not only is the signal strength increased, but interference is reduced. Antenna arrays for increasing the gain are relatively simple structures if great physical strength is not required. Multiple receiving stations are sometimes used to insure an unobstructed line of sight.

The 215- to 260-MHz band is more susceptible to signal loss due to atmospheric ionization than are the higher-frequency bands. The factors affecting propagation disturbances are covered in Electromagnetic Blackout Handbook (U), DASA 1580-1, Volumes I and 2 (SRD).

The receiver is usually of a tunable design which can receive any frequency within the telemetry band being utilized. When better stability is required, the receiver frequency can be fixed and controlled by a crystal oscillator. The receiver system separates the composite subcarriers from the carrier signal through a filter and discriminator network.

The telemetry ground station, in addition to the ground-based components of the RF link mentioned above, usually contains equipment for processing and recording data. The subcarrier signals are still in a multiplexed state at the receiver output and must be separated and demodulated in order to recover the data.

RECORDING

The output from the sensors can be preserved by a variety of methods. Recording galvanometers, photographic reproduction of the raster display of a cathode-ray oscilloscope, and magnetic tape recording have been used, either singly or in combination, to record the output from electromechanical gages. Scratches on glass, plastic, or metal make a permanent record from mechanical gages.

The recording systems used by most laboratories are commercially available, augmented by special equipment to fit a particular need. Normally the cost of a recording system is so high that an agency is committed to its use for a number of years with only certain modifications and renovations being financially feasible. The availability of a specific recording system often dictates the types of other components selected in a measurement system.

Electromagnetic Oscillograph

There are two basic types of oscillographs using galvanometers: the direct writing and the light beam type. The basic component in both forms is a moving coil galvanometer. In concept, the galvanometer employs the principle that like magnetic poles repel each other. If a wire coil is energized with electric current, a magnetic field is developed. When this coil is suspended in the field of a permanent magnet, it tends to orient its field with that of the permanent magnet. If the coil is energized by the output of the sensing element, its deflection will be proportional to the energizing current.

In the direct-writing type of oscillograph, a pen attached to the moving coil traces an ink record on a continuously moving paper strip. The time dimension is usually determined by a known speed of paper movement and is accurate to ± 5 percent. When the frequency of the wave being recorded exceeds about 100 Hz, the required speed of the pen is too high for accurate readings.

The light-beam type of oscillograph is more accurate and records frequencies as high as 5,000 Hz. In this device the coil, with an attached mirror, is suspended from a copper or gold ribbon a few thousandths of an inch wide and less than 0.0001-inch thick and serves as an optical pointer to indicate the coil position by reflecting a light beam. The recording is accomplished by the effect of the light on a sensitized paper strip. Manufacturers have reported galvanometer resonant frequencies as high as 20,000 Hz;* however, the galvanometer resonant frequency must be considerably higher than the highest frequency of the waveform being detected.

It is common practice to duplicate the recorders for better reliability. Dual-channel galvanometers, of different sensitivities, are used to provide a wide dynamic range. A separate timing backup system may be used.

Oscillographic recorders may have as many as 36 data channels per recorder. Paper speed may be varied from 1/4 inch to 160 inches per second. Normally Eastman Kodak type 809 photographic paper in 250-foot rolls is used. This paper is reasonably good as far as radiation effects are concerned. A 10-roentgen exposure will produce some fogging, but readable records have been produced with radiation exposures of between 50 and 100 roentgens. The susceptibility of the recording medium to radiation exposure and the consequent requirements of shielding and early recovery are major drawbacks of this type of recording system.

In addition to being radiation sensitive and having rather low frequency responses, galvanometers are extremely fragile and can tolerate only low levels of shock and vibration. This limits their application in field tests unless special shock-mounting techniques are used.

Care must be taken to prevent galvanometer burnout from the electromagnetic pulse. This can be accomplished by extremely

* This may be wishful thinking. The highest galvanometer response that BRL has heard of is about 13,000 Hz.

careful shielding or by electrical disconnection of the gage and gage cable from the recorder at zero time for a few milliseconds. The EMP effect has been the greatest single factor contributing to data loss during nuclear field experiments.

Cathode-Ray Oscilloscopes

The high-frequency limitation imposed by the mechanical inertia of the sensing element of an electromagnetic oscillograph is largely overcome by use of the electronic cathode-ray oscilloscope. These devices have improved remarkably in recent years. A typical upper limit of frequency response for continuous display of repetitive waveforms is about 50 MHz, with 1,000 MHz possible through the use of special sampling techniques which systematically measure very short samples of the signal voltage and display them as a series of dots to reconstruct the waveform. Very low frequency signals can be conveniently observed by the use of storage tubes, with adjustable persistence of the trace, so that the entire waveform can be "painted" on the CRT (cathode-ray tube) phosphor and retained for as long as desired—several minutes, or even an hour. Accuracy has been improved, so that vertical and horizontal displacement, corresponding to signal voltage and time, can be measured to ± 3 percent with standard built-in circuitry, and accuracy can be improved with special calibrating devices. Some designs eliminate parallax errors by placing the graticule on the CRT face in the same plane as the phosphor, or by mixing calibrating markers with the signal so that they are subjected to the same distortions as the signal and displayed with it. Ruggedness has been increased and size, weight, and power consumption reduced by the use of designs utilizing solid-state circuitry. Photographic attachments are available which make the recording of either repetitive or transient phenomena much more convenient.

The upper frequency limit of a CRT oscilloscope is determined by the characteristics of the amplifiers and other circuitry associated with the CRT, and by the brightness of the trace produced on the phosphor. That is, a signal cannot be usefully displayed if it cannot pass through the amplifiers and cause deflection of the electron beam in the CRT, or if it causes the beam to move so rapidly that insufficient light is produced when the stream of electrons excites the phosphor. If the signal is repetitive, the phosphor integrates the effect of successive writings of the electron beam, and substantially higher sensitivity results than in the case of single transient signals such as shock waves. However, transients may be recorded for later observation by automatically triggering a camera using very fast film, available as standard equipment.

A major use of CRT oscilloscopes has always been the design, trouble-shooting, and calibration of all kinds of electrical equipment and instruments, in both the laboratory and the field. With more rugged and compact designs and improved photographic techniques now available, the CRT oscilloscope is increasingly important as an instrument in its own right.

A major problem with the CRT oscilloscope in field recording of blast and shock data has been triggering the scope sweep to coincide with the arrival of the signal to be measured. One solution to this problem is given on page 215.

Magnetic Recording

Since about 1946, magnetic tape recording has advanced from a technique suitable only for audio work to a very high quality method for recording signals from scientific instruments. Although video tape is used to record television signals with frequencies up to 4 MHz, the recording method introduces distortion which, although acceptable to the television viewer, is intolerable for scientific purposes. Frequencies up to perhaps 1 MHz can be recorded on modern instrumentation-quality tape recorders. However, most instrumentation recorders are designed with multiple channels on one tape, typically 7 channels on a 1/2-inch tape or 14 channels on a 1-inch tape, and each channel is limited in upper frequency response to 100 to 250 kHz. Each channel may be used to record multiplexed signals. Hence, a very large number of measurements can be recorded simultaneously.

A magnetic tape instrumentation recorder includes three basic components. The magnetic head records information on the tape and recovers it from the tape. The tape transport system moves the tape across the magnetic heads smoothly and at a constant speed. The record and reproduce amplifiers process the input signals going to record heads and the output signals coming from the playback or reproduce heads.

A magnetic head consists of a coil wound on a magnetic core. The core is very carefully machined so as to form a ring which is closed except for a narrow non-magnetic gap. The tape is transported past the head, and against the gap, so that the iron oxide particles deposited on the plastic tape act as a part of the magnetic circuit. When electrical current representing a signal flows through the coil, magnetic flux is set up in the core and the tape. The oxide particles on the moving tape become magnetized in proportion to the flux strength. (The magnetization curve necessarily is far from linear, since the particles must retain induced magnetization.) During playback the magnetized tape passing the gap induces flux through the core, and thus a voltage in the coil.

The mechanical precision required of the tape, heads, and transport mechanism is difficult to maintain under field conditions; dust, temperature variation, moisture, etc., can cause difficulties.

To overcome the inherent non linearity of the magnetization of the tape, either d-c or high-frequency, a-c bias may be used, usually the latter. The process by which a-c bias causes the record characteristic to become linear is often described as quite mysterious; understanding of the phenomenon is not quite so uncertain as is implied, but is beyond the scope of this review.

Frequencies below about 50 Hz will not produce usable signals because the rate of change of flux is too low. When such low frequencies are to be recorded, an indirect method is employed. A carrier signal is frequency modulated with the desired signal, then recorded on the tape. Not only is the low-frequency limitation overcome, but the FM carrier is essentially insensitive to the nonlinearity of the tape if the recording signal is made strong enough to saturate the recording medium. Further, a number of AM, FM, or pulse signals may be placed on the same FM carrier, using IRIG or other multiplexing techniques (discussed earlier), and a number of carriers may be recorded on the same tape (using a separate head for each channel).

Blast and shock magnetic recording is accomplished almost exclusively in the FM mode; however, the direct recording of pulses on tape is more prevalent today in other scientific fields because of the popularity of computers. The data processing machines rely heavily on tapes for input, output, and storage. Simple yes-no binary pulse recording is the most reliable; tape vagaries which would disable an amplitude-sensitive system are ignored by a pulse system.* The equipment external to the tape recorder which is required for pulse recording is formidable, and is not yet in wide use for field records. However, since digital (pulse) records are compatible with automated data-processing techniques and offer great advantages over analog records in terms of the accuracy attainable, they are finding increasing use.

A decided advantage of multiple-channel recording on the same tape is that time synchronization between channels and events is more readily established than when separate records are made. The importance of the absolute time base is much reduced; the emphasis shifts to the calibration of electrical delays and mechanical imperfections, such as skewness of the recording and reproducing heads, tape stretching and flutter, etc. A 100-kHz sine wave often is recorded on one channel of the tape to serve as a time reference and, through use of feedback and frequency-measuring circuits, to assist in controlling the speed of the tape drive mechanism during playback.

Records from tape may be played back at speeds different from those at which records were made, so that the time base can be expanded or compressed. This feature may be very advantageous in producing paper tapes from the magnetic tapes, in making spectral studies, in searching for specific events, etc.

When periodic signals are immersed in uncorrelated (random) noise, the desired signal sometimes can be recovered from the masking noise by forming tape loops and playing the tape back into a memory device, such as a CRT oscilloscope, with a medium- or long-persistence phosphor. Although this technique will not work for single-transient signals, such as those usually encountered in blast studies, it may be applicable to structural-response studies or others in which resonance of a mass-spring system is being observed.

* A heavily-saturated FM recording is almost like a pulse recording, except that the precise width of the FM "pulse" (i.e., the time of zero crossing) is important, whereas in true binary recording only the existence or non-existence of magnetization within an allocated zone is important.

THE MEASUREMENT SYSTEM IN FIELD TESTS

A fundamental consideration for selection of instrumentation for field studies involves a tradeoff between complexity and reliability. This does not necessarily mean that all complex systems will be unreliable, but it does point out a primary difference between a laboratory experiment and a field experiment. In a field test there may be but one opportunity to obtain data; thus instrument reliability must be high. In the laboratory, however, an experiment may be repeated a number of times, and instrument malfunctions are usually annoying rather than disabling.

A system which performs poorly in the laboratory obviously should not even be considered for a field operation. But having a system which performs well in the laboratory is not, in itself, a guarantee of good, or even adequate, performance in the field. The problems of EM shielding, atmospheric dust, dirt, and moisture, in addition to the unavoidable rough handling in field transport and installation, may prove insurmountable to a laboratory system.

In selecting a particular system, six major factors should be considered. First, what is the physical quantity to be measured and which instruments are available for that measurement? Second, what is the accuracy requirement of the measurement? This dictates the dynamic response and the frequency response of the entire system. Third, how many separate measurements are required and what is the time period of measurement? Fourth, what is the environment which the system, or individual components of the system, must withstand? This must include a consideration of the normal environment as well as the test environment. Fifth, what are the human factors involved? The degree of instrument complexity, the placement of the sensors, and the procedures used to check out and maintain the system must be considered against the experience and motivation of the technical personnel involved in the project and the time available for these procedures.

The sixth factor, although frequently overlooked when designing a measurement system, is essential. To avoid burial under a mass of data, careful thought must be given to the various alternative forms of data output so that the necessary data processing can be handled quickly and accurately. Data reduction must be programmed <u>during</u> the design of an experiment, not afterwards.

TRANSIENT RADIATION EFFECTS ON MEASURING SYSTEMS

When attempting any measurement in an intense nuclear radiation environment, an investigator is faced with severe restrictions with respect to the choice and deployment of his instrumentation. Two radiation manifestations are noted: first, an effect on electronics due to transient radiation (TREE) caused by the direct interaction of the ionizing radiation with the measuring system, and second, electromagnetic pulse (EMP) effects whereby the measuring system acts as an antenna to receive a transient EM signal produced by the burst.*

For many systems, the problem of the effects of nuclear detonations cannot be clearly segregated into EMP problems, TREE problems, thermal problems, blast problems, etc. Rather, these effects can interact in a way such that the combined effect is much more serious than is any particular effect taken alone. A related design problem is that while it is often comparatively simple to protect a system from one particular effect, the protection can actually soften the system to some other effect. Thus, the systems designer must always keep in mind the necessity of obtaining a realistic balanced system hardness.

TREE

The TREE effects on electronic measuring systems can be both transient and permanent in nature. The permanent effects are usually due to displacement of atoms located in crystalline lattices and are produced by close collisions between incident nuclear particles and the crystal atoms. These permanent effects are normally of little concern in blast and shock measurements, for they degrade only such semiconductors (and quartz crystals) which depend upon a very high degree of crystal regularity for proper function.

* This EM signal is not unique to a nuclear detonation, but can also be observed in large chemical explosions.

Most transient effects result from the generation of ion pairs in the system by the incident radiation. These ion pairs ultimately cause either photocurrents in transistors, or diodes or leakage currents in dielectrics. Data indicating the magnitude of TREE effects in various cables are presented starting on page 200.

The radiation effect of major concern to blast and shock experimenters is EMP and will be dealt with in some detail below. The following paragraphs were adapted from unclassified portions of Electromagnetic Pulse Phenomenology and Effects (U), DASA 1731 (DASIAC SR-41), 1966 (SRD).

EMP

The EMP signal is characterized by high power but low energy, a consequence of its highly transient nature. Low-frequency components of the pulse may propagate both electric and magnetic fields to considerable distances from the burst and to considerable depths below the earth's surface (Reference 6). The signal peaks at about 10^{-8} seconds and lasts about 5 to 10 microseconds, but the effective fields are reduced to 1/10 peak magnitude within one millisecond.

EMP Generation

The chief agent for the production of electromagnetic fields from nuclear explosions is the gamma radiation. The γ rays produce a current of Compton recoil electrons which acts as a source of fields, and by ionization processes, makes the air a conducting medium. However, most of the detonation energy is ordinarily emitted in the form of x rays. By Compton scattering and photoelectric absorption in the air, these also produce electric currents and lead to effects similar to the γ-ray-induced effects, especially at high altitudes. The fields produced by these effects are generally smaller than those produced by γ rays.

The gamma radiation from the explosion of an atomic bomb may be subdivided into seven components which have a relative importance depending upon the time scale of interest and altitude of the explosion. These components are:

- Prompt—those gammas emanating from the bomb itself
- Ground and air inelastic—those gammas resulting from fast neutron int[illegible] in the ground and with the air

- Ground and air capture—those gammas from neutron capture after slowing down
- Isomeric—those gammas emanating from decay of isomers of the fission debris
- Fission product—those gammas resulting from beta decays of the fission products.

The descriptions of these various components may be made with varying degrees of assurance and, in general, are dependent upon calculations which have only partly been verified by experiments.

The electron current which initiates the nuclear electromagnetic pulse (EMP) and the conductivity which shapes the EMP pulse are products of Compton collisions of prompt gamma rays. The Compton current and the ionization rate are complicated functions of time at any point. These functions reflect the arrival times, angles, and energies of gamma rays. For use in a gamma-ray transport theory, the prompt gamma rays can be effectively considered as coming from an isotropic point source. The finite dimensions of this source can be neglected in calculation because of the much larger dimensions of the effective EMP-producing source region (on the order of hundreds of meters to several kilometers at sea level). Source isotropy is a reasonable assumption because the environmental anisotropies are usually more severe than the weapon anisotropies.

NEAR-SURFACE BURST. The gamma rays that enter the ground (or ocean) from a detonation slightly above the surface are absorbed in a very short distance, a few meters at the most. Thus, over most of the distances where there are sizable Compton currents in the air, there are none in the ground. We thus have a hemispherical distribution of Compton currents in the air. However, the ground is usually a better conductor than the air (except very near the burst), so that the current of conduction electrons, instead of flowing radially inwards, will flow partly to and in the ground (Figure 4). Thus current loops are formed, with Compton electrons flowing outward in the air, and conduction electrons returning in the air and ground. These current loops give rise to a magnetic field, which is largest at the surface of the ground, and which runs clockwise azimuthally around the burst point. The electric field is tilted near the ground so as to be roughly perpendicular to the ground, and is directed upwards so as to drive conduction electrons into the ground.

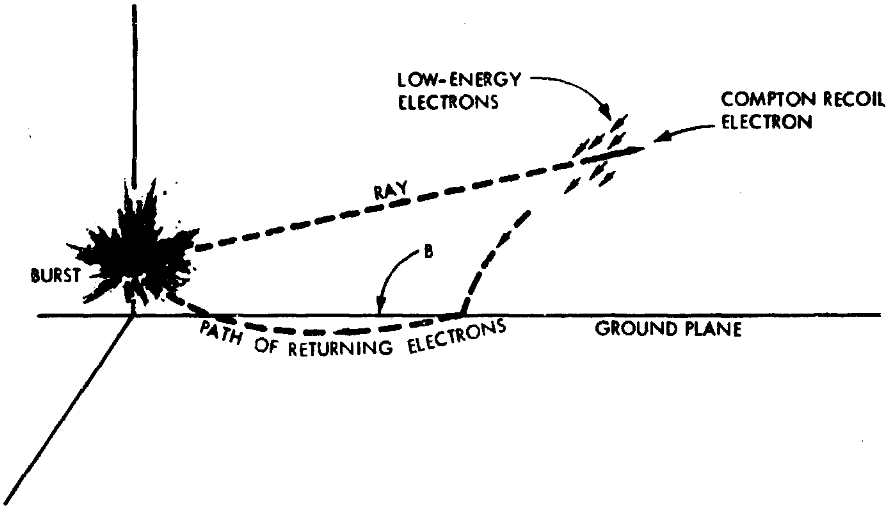

Figure 4. Influence of ground on return conduction current.

FREE AIR BURST. The previous paragraph discussed the fields produced by the gamma-ray induced Compton recoil electrons, neglecting the effect of the earth's magnetic field. In all cases the asymmetries (ground, air, and bomb) were in the gamma-ray flux and production of Compton electrons and ionization. The net electron motion was radial, and thus the source for the EM fields was a pulse, a radial current expanding with light speed from the burst point.

In the presence of the geomagnetic field, the Compton recoil electrons are deflected from their initially radial directions. The current pulse then contains transverse as well as radial components. Thus, even with complete symmetry of gamma-ray flux and electron production, there are sources for magnetic and non-radial electric fields. In fact, this mechanism generates very intense high-frequency EM fields and becomes increasingly important as the burst altitude is increased.

EMP Interaction with Systems

The EMP interaction with systems is singular among nuclear weapons effects in that the interaction is often with the configuration of the entire system and not necessarily with any subsystem by itself.

The complete system forms an antenna which responds as a whole to the EMP. Damage may occur at the gage, in the cable, or at the recording site.

GAGES. The major problem results from transducer inductance coils being short circuited. Damage has not been significant with balanced-reluctance gages. The most serious trouble has been permanent grounding of one circuit by flashover, causing disturbances on other traces.

The record for resistance-wire strain gages is much poorer, and reports show losses up to 100 percent.

Gages using inductive sensors generally flash over at about 1,500 volts, usually at the glass feed-through insulators in the gage case. Paper-base strain gages mounted on metal flash over at about 500 volts, through the paper base, with accompanying destruction of the gage. Bakelite-based gages flash over at 1,500 and 2,500 volts, and then only at the edge where the lead wires protrude, without destroying the gage. If the lead wires are positioned so that they extend vertically well inside the edge and are surrounded by a spot of insulating cement, they will withstand 5,000 volts, and final failure is at 7,000 to 10,000 volts. These bakelite-based gages appear to be satisfactorily rugged, but the effects of unbalanced currents resulting from flashover at a terminal cannot be ignored. The windings of a variable-reluctance transducer will survive a short current pulse of several watt-seconds, while a strain gage winding is destroyed by a short pulse of 0.1 to 0.2 watt-seconds, even though it will dissipate several watts continuously. The damage due to flashover at a terminal or elsewhere can be much greater, therefore, for a strain gage.

INDUCTION OF CURRENTS INTO CABLES. The influence of the electric and magnetic fields near the surface of the ground on electrical conductors depends on the configuration of the conductor. The manner in which the conductor is coupled to the electric field is affected by the presence or absence of insulation, the type of insulation, and the quality of contact between the conductor and the soil. The effectiveness of shielded cables depends on these factors and the manner in which the shield is terminated. In addition, the implications of a signal induced on a conductor are largely determined by the sensitivity of the system served by the conductor.

Thus, for example, a given pulse may cause serious malfunction if it is induced in a circuit designed for low-level signals, whereas the same pulse induced in a power circuit would be of no consequence.

Two theoretical models have been used to calculate the current induced in a conductor located in or near the ground by an electric field directed along the conductor. The first, called the wave impedance model, is applicable to groups of conductors that are so closely spaced that mutual coupling effects are significant. This wave impedance model was developed to study the currents flowing in the radial conductors of antenna ground systems. The wave impedance model considers the intrinsic impedance of the soil shunted by the wave impedance of the grid of conductors. The total current induced in the grid-soil complex by an electromagnetic wave propagating into the soil is divided by the soil impedance and the impedance of the grid of conductors. The wave impedance of the grid of conductors is determined by the conductor size and spacing. The wave impedance theory is applicable to conductors that are spaced less than two or three skin depths (in the soil) apart and are tightly coupled to the soil.

The second theoretical model, called the transmission line model, is applicable to conductors that are sufficiently far from neighboring conductors so that the electric field strength in the vicinity of the conductor of interest is not appreciably affected. In this model, the conductor is visualized as a coaxial transmission line, the ground serving as the return conductor. The line will have an impedance per unit length and an admittance per unit length that are determined from the electrical properties of the conductor, its insulation, and the soil. From these properties a propagation factor and a characteristic impedance can be determined. When a radial electric field is established in the ground, the field may be visualized as a distributed generator driving the line along its entire length.

The transmission line theory and the wave impedance theory provide methods of computing the current induced in either insulated or bare conductors. The problem of practical concern, however, is that of computing the current induced in the core wires of shielded or sheathed cables. Unfortunately, no detailed analysis of the coupling of the EMP-generated surge currents into the inner conductors of a cable is presently available.

INSULATED CONDUCTORS. Insulated conductors are defined here to be insulated wires and cables on or below the surface, and either insulated or bare wires above the surface. These conductors all have in common the characteristics that (1) the coupling between the conductor and the electric field in the ground is through the capacitance of the insulation, and (2) the attenuation of signals propagating along the conductor is relatively low. The capacitive coupling of the electric field to insulated conductors means that these conductors are affected most strongly by the high frequency (early time) components of the electric field in the ground. At very high frequencies, where the insulation reactance is negligible, the insulated wire behaves as a bare wire.

The propagation factor for the insulated conductor is very nearly equal to the propagation factor for the insulating material. Since the insulating material is in many cases almost lossless, currents induced in the conductor in high field regions can propagate great distances along the line with little attenuation. Furthermore, if the conductor is not terminated in its characteristic impedance, the induced signal will be reflected from the terminations and will travel back and forth along the conductor until it is dissipated in line and termination loss. Thus, under some conditions, a pulse of electric field will induce a train of pulses in the insulated conductor.

BARE CONDUCTORS. Bare conductors on or below the surface are generally characterized by tight coupling to the soil and high attenuation of signals propagating along the conductor. Since the conductor is in contact with the soil in which the electric field is established, the coupling is direct and strong at all frequencies. However, since the propagation factor for the bare conductor is almost equal to the propagation factor for the soil, currents induced on the conductor are attenuated very rapidly as they propagate down the conductor. In general, the currents induced on bare conductors in contact with the soil are determined by local fields in the soil, since the currents induced more than a skin depth or so away do not appreciably affect the magnitude of the current at a particular point of interest. Likewise, reflections are of concern only within a skin depth or so of the termination of the conductor, since the reflected current is attenuated to an insignificant value within a short distance of the end.

SHIELDED CONDUCTORS. The shield on shielded cables behaves in the same way as a conductor of the same configuration and relation to the soil; i.e., the insulated shield behaves as an insulated conductor, and the bare shield behaves as a bare conductor. The current induced in the core conductors is a result of the field that penetrates the shield. The core wires themselves are capacitively coupled to the fields penetrating the shield, however, and currents induced on these wires behave in a similar manner to those induced in the insulated conductors described above. Thus the currents in the core wires propagate for great distances without significant attenuation, and these currents may be reflected back and forth from the terminations several times before the current is dissipated in line loss or termination loss. One consequence of this characteristic of the shielded cable is that the current induced in the core wires, in the region where the field penetrating the shield is strongest, is propagated on the core wires to points quite remote from the high field region. Such currents are, of course, much smaller in the shielded case than they would be if no shield were present.

Two types of shielded cables are of special interest because of their wide use. These are the coaxial cables, such as RF transmission lines and shielded single conductors, and the larger, multiple-conductor shielded cables in which individual channels are carried on balanced, twisted pairs of conductors.

The coaxial cables are inherently unbalanced in both their transmission line properties and their coupling properties. The current induced in the outer conductor is much greater than the current induced in the inner conductor, since the outer conductor acts as a shield for the inner conductor. The consequences of this unbalanced coupling to the coaxial conductors depend tc a great extent on the way the circuit is terminated. If the outer conductor is terminated on a conducting housing that completely encloses the terminal equipment serviced by coaxial line, the large current in the outer conductor enters the system directly only to the extent that it penetrates the conducting housing, and the only signal seen by the terminal equipment is that induced in the center conductor and propagated along the interior of the line. If, however, the coaxial pair is used to service unshielded terminal equipment, so that the large signal propagating on the outer conductor can combine with the signal propagating along the interior, the relatively large undesired signals propagating on the outside of the outer conductor can enter the terminal equipment. This latter method of terminating the coaxial line compromises one of the principal advantages of the coaxial geometry and should be avoided if possible.

The above remarks on coaxial conductors are also applicable to certain characteristics of multiconductor shielded cables, particularly when the shield is insulated. It is conceivable, for example, that improper termination of the shield of a cable which has an insulated shield could completely negate the effect of the shield by allowing the current induced in the shield to propagate along the outside of the shield into the terminal equipment. The shield termination at the point of entry into the terminal equipment should be a completely enclosing connection (as opposed to a pigtail or ground strap) to the shield of the terminal equipment. On buried cables with bare shields, the current induced in the shield does not propagate over large distances, so that the problem is less severe on these cables. In doubly shielded cables in which the inner shield is insulated from the outer shield, current induced in the inner shield will propagate in the same manner as on cables with insulated shields. In the doubly shielded cables, current induced in the inner shield will be much smaller, but if full advantage is to be taken of the double shield, the inner shield must be just as carefully terminated as is the outer shield.

The currents induced in the balanced, twisted pairs in shielded cables are, in principle, common mode currents that are exactly equal in each conductor of the twisted pair. If the terminal equipment is also balanced and has adequate common mode rejection, these currents are of no consequence.

It is important to note that a balanced termination for the twisted pair implies that both conductors, each viewed as a transmission line, are terminated in the same impedance. If the individual conductors of the pair are terminated in different impedances, the reflected currents will not be common mode currents, and part of the incident current will affect the terminal equipment. Stray capacitance at the termination can be particularly troublesome in that it can cause an unbalance which is most severe for the high frequency (fast rise time) components of the signal.

CABLE TERMINATIONS. The most common method of terminating both the bare cable and the insulated cable is to attach the outer shield directly to a large buried metallic structure, such as a buried shielded room. When the transverse dimensions of the metallic structure are comparable to a skin depth in the ground, then the termination impedance is much less than the impedance of the cable and acts like a short circuit. This means that signals are reflected without loss in energy and the current at the termination can be as much as twice the cable current far from the termination.

Another common termination is made with a grounding rod driven vertically into the ground and attached to the outer conductor of the cable. Rods commonly used for this purpose are 1 to 2 meters long and 1 to 2 centimeters in diameter.

A theoretical study has been performed on the impedance of various grounding arrangements. The short length of the rod insures that its inductive effects are small. For an insulated cable in extremely high conductivity soil, the resistance of the rod is an order of magnitude less than the cable impedance. However, for average or low conductivity soil, this grounding arrangement does not reduce the termination impedance appreciably below the cable impedance. In particular for bare wires, the wire itself may be a much better grounding arrangement than the vertical grounding rod.

RECORDING SYSTEMS. Whereas in the case of long cable systems, the EMP coupling was principally through the electric field, the EMP coupling into compact recording systems is principally a magnetic field interaction. Time-varying magnetic fields induce circulating currents in conducting loops found in compact systems. Associated with these circulating currents are voltages determined by a characteristic impedance of the loops. These voltage differences appear to systems as signals and may cause severe disruption in system operation.

Magnetic cores, tapes, and tape heads have been found relatively insensitive to pulsed magnetic fields. In experiments, typical selections of these components have withstood pulsed fields of over 10 gauss with no detrimental effect to either the component or the system. Thin-film memory devices, however, are expected to be more sensitive to transient magnetic fields.

The importance of the EMP interaction with a recording system is determined by (1) the magnitude of the induced signal; (2) the normal signal levels in the system; and (3) the filtering and noise rejection properties of the system. Methods for minimizing the EMP interaction with recording systems are discussed below.

EMP Protection

The preceding paragraphs have shown that the nuclear EMP penetrates into a system principally in two ways. First, the EMP fields can penetrate through shields into the recording portion of a system and induce spurious, disrupting signals. Second, the EMP can induce current surges on the cables which tie a system to the measurement environment. These spurious signals can seriously impair the operation of the system.

In this section, methods of reducing the field penetration into a system and surge induction into cables are described. Techniques to minimize the EMP effects on the electronics of the system, once the system has been penetrated by the EMP, are also discussed. Finally, a summary is given of many methods employed in the past to increase the EMP "hardness" of systems.

REDUCTION OF EMP FREE FIELD PENETRATION INTO SYSTEMS. In blast-hardened systems, which must be located near the detonation, circuitry and instrumentation are usually enclosed within relatively small volumes. Often the easiest method of protecting them from the direct effects of the EMP fields is to shield the entire volume where the instrumentation is located. Localized shielding around separate sensitive units might in special cases be a more economical technique than maximum sensitivity shielding for the whole volume; however, the primary interaction of EMP with the system usually is through interconnecting wiring and not through effects on components or small subsystems.

If analyses indicate a high degree of EMP susceptibility, it may be possible to reduce the problem by redesigning certain circuits and introducing more durable components. For instance, vacuum tube circuits (depending on the type of tube and how it is being used) can withstand hundreds of volts in short surges without damage, while 50 to 500 volts or less is sufficient to permanently damage many transistors. On the other hand, transistor circuits are far more compact than tube circuits and therefore are more economical to shield. Tradeoffs between increased shielding and subsystem redesign with consideration of the operational functions of the individual circuits and components may make it possible to design a less vulnerable system with no loss in capability.

PROTECTION AGAINST CURRENT SURGES. It is necessary to protect cables and associated equipment from nuclear electromagnetic pulse-induced current surges to preserve their measuring capabilities. In general, methods used for protection against lightning surge effects afford a good guide for EMP protection. A significant reduction in vulnerability is obtained by reducing to a minimum the number of conduction paths entering the system. All conducting pipes and conduits entering both recording and instrument facilities should be grounded at two points: to the main outside ground point and to the point where pipes or conduits enter the shelter. These simple precautions in design will keep to a minimum the number of external conducting paths which can carry high-surge currents and fields to the system instrumentation.

In the preliminary shelter design, all nearly closed conducting paths formed by water pipes, rebar, steel I beams, etc. (but not by signal, power, cr ground cables), should be completely closed. This provides added system shielding and prevents possible arc-over (with subsequent RF noise harmful to many systems).

A loop of heavy conductor called a guard ring may be used to increase the L/R time of a loop system to a value which is large compared with the EMP field duration time. A large part of the energy stored in the guard ring may be put back into the magnetic field after the EMP transient has passed.

For protecting cable runs external to shielded instrumentation centers, a continuous metal conduit surrounding the cable provides maximum shielding. Continuous steel conduits, 1/4- to 3/8-inch thick, reduce the high electromagnetic fields and the induced cable currents to a level at which typical circuits would not be disrupted. Moreover, supplementary low power protection devices could easily control any residual currents.

A significant amount of induced current protection can also be provided by the cable sheath. The cable sheath is normally a conduit of aluminum, lead, or steel, about 50 to 100 mils thick, built into the cable for the purpose of preventing structural damage to the inner wires. To maximize the shielding effect, insulation of the cable sheath should be avoided, or at least the sheath should be grounded as often as possible, since insulation prevents rapid spatial and temporal decrease of the induced currents. Insulation over the sheath also produces higher core-to-sheath voltages and increases the opportunity for high-voltage insulation puncture. If insulation is necessary, an insulation should be used which is lossy and which will not char and become conductive when punctured by high voltage.

A third technique of cable protection from EMP-induced currents is the use of guard wires. A guard wire is a low-impedance wire (such as a low-gauge copper wire, AWG 1/0, or a larger diameter wire), placed a few inches over the cable to be protected. For buried cables protected by overhead guard wires, the currents induced in the guard wires create magnetic and electric fields which oppose the incident fields. The cable and guard wires share the induced current approximately as the inverse ratio of their impedances. However, to take advantage of this shielding effect, the cable must be within a few inches of the guard wire (or additional guard wires on the sides are necessary) to prevent the fields from circumventing the shielding effects of the top wire. The guard wires should also be bare, so that the electric field is effectively shorted.

An important point to consider when designing or specifying conduits, guard wires, and cable sheath armor is the maintenance of electrical continuity throughout the length of these devices. Discontinuities cause the induced current to produce high voltages, which may cause insulation breakdown. Multiple guard wires provide some insurance against this, particularly if they are connected together at intervals. Guard wire protection is especially important at the termination of the cable sheaths and conduits. To prevent arcing over to the inner conductors, place protection devices at the terminations, ground the shield to the chamber which the protected cable enters, and/or connect the ends of all conduits, sheaths, and guard wires with low-impedance grounded metal sheets outside the installation. The conduits and guard wires protect in two ways: they offer a path other than the signal and ground lines to the earth currents, and they carry these currents away from the internal instrumentation connected to these signal and power lines. Consideration of both of these points is essential in providing adequate system protection.

The first step in reducing voltage from several thousand volts down to the order of a hundred volts may be handled by lightning arresters such as the carbon block and the gas diode. The carbon block device is essentially a spark gap with two blocks of carbon as the electrodes. These devices can fire on signals as low as 400 to 500 volts; however, below this level the gap becomes too small and leads to the possibility of a short circuit. The principal advantages of a carbon block arrester are its fast response time, i.e., less than 1 microsecond, and relatively low cost.

Gas diodes are spark gaps within a closed container filled with some inert gas at a fixed pressure. This spark gap may be set to spark as low as 70 to 80 volts. Unfortunately, gas diodes are more expensive and larger than the carbon blocks, a fact which may limit their applicability for complete system protection. Furthermore, if the tube leaks, the spark-over voltage may increase by an order of magnitude. The greatest disadvantage of the gas diode is its slow response time. For a moderate-to-fast rising surge current, the gap may hold off voltages 4 to 5 times its d-c arc-over voltage. However, a new type of gas diode employing a pre-ionized gas may eliminate these disadvantages. The main advantage of the gas diode over the carbon block is the elimination of any possibility of short circuits from residue buildup. To use arresters as current surge limiters, attach them to a ground in conjunction with a heavy-duty inductance in the line. This produces the high voltages necessary to short out the abnormally high currents in the lines even if the line itself has too low an impedance to generate sufficient voltage.

When set up in proper staging, voltage and current limiters have proven to be protection against lightning-induced surges and, when selected to give sufficiently fast response and recovery time, should also protect against an EMP-induced surge.

RECORDER PROTECTION. To raise the susceptibility level of a system, the following requirements should be incorporated into the design and installation of the system.

1. Insure that the wiring between gage and recorder conforms to a "tree" or radial wiring scheme as shown in Figure 5. Using such a scheme, the system susceptibility level can be greatly improved. To be effective, the tree system must include all signal, power, and ground cables and have a single ground point.* If two or more systems are involved, they must be either electrically isolated at all points other than at this single ground point or combined in a single tree configuration.

2. Resistance checks should be performed both during the initial equipment installation phase and during any system or equipment modification phases to insure that there are no violations of the tree wiring scheme. Violations of the tree configuration can occur by introduction of loops formed by:

Signal cables

Chassis-to-chassis grounding

A-c power conduits

A-c safety (3rd wire) grounds

Equipment-to-floor or equipment-to-wall contact

Signal grounds

Telephone system grounds

Building construction grounds

Accidental contact of grounding elements.

EMP Protection Summary

In most cases, instrumentation surge tolerance rather than cable tolerance will be the determining factor in specifying system protection. Vacuum tube circuits can probably survive the 500 volts remaining after carbon-block arresters fire. However, over 50 volts

* It should be noted that some investigators prefer to "float" the entire system, i.e., have no ground at all.

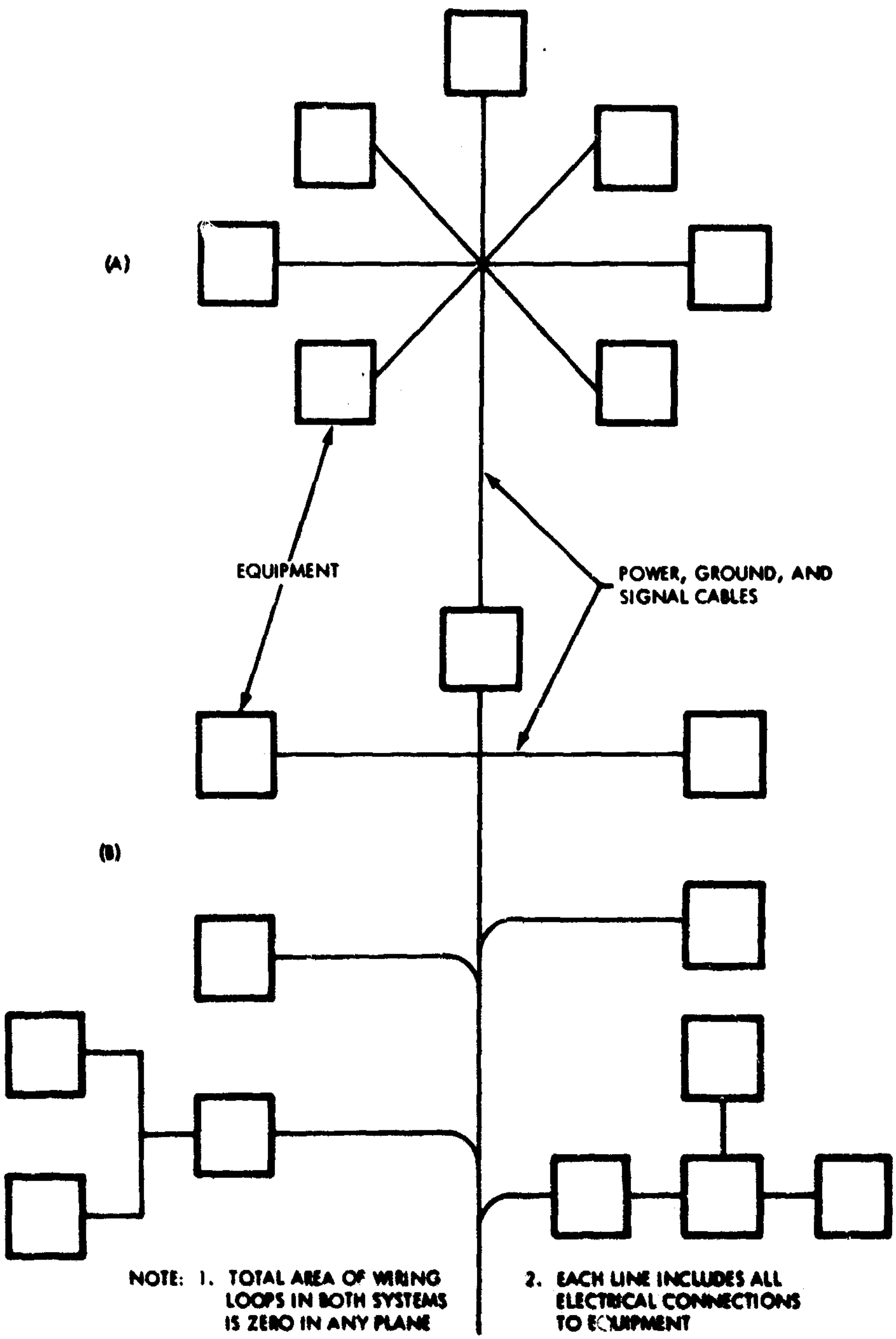

Figure 5. Wiring to reduce EMP susceptibility (A) Radial, (B) "TREE" wiring system.

will permanently damage many transistors and semiconductor diodes. and signal/noise levels of 0.6 volt can cause data degradation. These low tolerance levels require the use of Zerner diodes or other low power protection devices in the circuitry.

The following is a partial list of recommended construction practices which have proven effective in reducing problems of EMP interference and/or damage of instrumentation on nuclear tests.

1. Isolate power by either using internal motor-generator sources or putting lightning arresters on lines.

2. Put wires in boxed, grounded conduits.

3. Use a grounded screen over shelter air-conditioning outlets and ground all ducts.

4. In hardened shelters and instrument locations, ground the rebar (steel reinforcing bars in reinforced concrete), especially if it is tack welded.

5. Use largest available lightning arresters on power station transformers.

6. Put spark gaps on telephone lines from the recording shelter.

7. Ground cable outer shields and make them continuous; splicers often do not solder the shielding.

8. Insure that signal cable shields are well grounded at their point of entry to the shelter. Large transients inside screened rooms have been traced to poorly-grounded coax shields.

9. Bury cables as deeply as is economically feasible (> 3 feet) to reduce current surges.

10. Tie water pipes and other entries into the grounding system.

11. Equip any antennas and input leads which cannot be directly grounded with lightning arresters.

12. Adopt protection procedures to fit requirements of particular areas. Shield only the critical areas.

13. When a lead is tied into a coaxial cable, do not interrupt the shielding provided by the outer conductor. A grounded copper plate mechanically crimped to the cable shield has been used effectively.

14. Ground all seemingly nonessential equipment, such as elevator hoist cables.

15. Because natural grounds are often unsatisfactory, use a counterpoise at each site. Note that counterpoise requirements will vary with geographic location, since earth conductivity varies greatly from place to place.

16. Insure that the entire conduit system is well grounded.

17. Avoid use of nonconducting lubricants when putting conduit pipes together.

18. Insure that electrical contact exists between conduit and terminal box. Frequently the conduit is pushed against the box but insulated from it by paint.

19. Install a grounding strap from terminal box to door of box.

20. Use lightning protection techniques on all above-ground lines.

21. If power equipment supplies several sites, install lower-value fuses at the equipment end rather than the power end of a system.

22. Use circuit breakers rather than fuses, since breakers can be set more closely and reset more quickly. Check fuses periodically for deterioration.

23. Do not use slow-blow or delay fuses or breakers.

24. Design breakers (where feasible) to take no more than the largest expected load.

25. Put single-phase protection on each phase of three-phase power systems.

26. Use passive L.C. radio interference filters on signal, control, telephone, and power lines.

27. The EMP fields in the corners of a shielded structure are usually higher than in other parts of the structure, so that corner areas should be avoided or used with caution.

28. Insure that the intrasystem wiring conforms to a tree or radial wiring scheme. Include all cables, power, signal, and ground, in this scheme.

SECTION 3

AIRBLAST MEASURING SYSTEMS

SECTION 3
AIRBLAST MEASURING SYSTEMS

The pressure range of current primary interest in airblast measurements extends from fractions of a psi to over 10,000 psi. Environmental conditions range from ambient (which, under some field conditions are quite severe) to those encountered well within the nuclear fireball (see Appendix B).

Gages for use in field tests have incorporated reluctance elements, strain elements (bonded, unbonded, and solid state), resistive and piezoelectric transducers. The earliest gages and recording systems were not required to withstand deleterious environmental conditions since they measured relatively low overpressures and were thus located at some distance from the detonation. Since the data recording bandwidth was about dc to 500 Hz, these early systems were not suitable for accurate measurement of high-frequency phenomena. This was a particular problem for short-duration shock waves. The present higher-frequency response systems, with better recorders and faster gage rise time, follow more closely the forcing function, and provide better fidelity of the data acquired.

In atmospheric nuclear tests, the variable-reluctance-type elements have proved to be the most successful for obtaining meaningful data; however, the techniques of production and use of other sensors have progressed to the point where they will increase in usefulness.

In the following paragraphs, various gages in current use are described. In these descriptions, instruments used to measure stagnation and incident pressure are listed first, followed by a discussion of gage mounting, then the methods and instruments used to measure dynamic pressure. Within this framework the various gages are grouped by principle of sensing element and are presented in the same order as the discussion of sensing elements in Section 2.

OVERPRESSURE AND TIME HISTORIES

Electromechanical Gages

Wiancko

The Wiancko 3-PAD* is, in terms of years of continuous use, one of the oldest nuclear-blast pressure-measuring instruments. The 3-PAD is a variable differential inductance gage. The sensing mechanism, a bourdon tube flattened and twisted about its long axis, is contained in a heavy brass canister to minimize the effects of short-term temperature changes. One end of the tube is open to the atmosphere and rigidly held to the gage frame, while the other end is closed and attached to an armature held in close proximity to an E-shaped coil. Overpressure tends to untwist the bourdon tube; this rotation changes the air gaps in the electromagnetic circuit, thereby changing the circuit inductance. The inductance change can be used to modulate a carrier voltage to produce a signal as a function of pressure.

The Wiancko has a high output, is very rugged, and has been proven under field conditions. It is relatively insensitive to accelerations and ambient temperature change. The low impedance reluctance bridge allows the signal to be fed to the recorders on long pairs of wire, and does not require coaxial cable. The usual field practice has been to record the output signal on Consolidated Electrodynamics Corporation System-D equipment. The gage can be used to measure pressures as high as 10,000 psi; however, its response time of several hundred microseconds is too slow for short-duration, high-pressure measurements. The gage exhibits a limited frequency response and proximity to magnetic objects or fields causes erratic performance. It is rather insensitive to EM pulse and radiation.

Stanford Research Institute reported (Reference 7) results of tests of acceleration sensitivity of the Wiancko. Acceleration forces are generally assumed to act on both arms of the rocking-armature similarly with respect to both coils and thus maintain balanced conditions. However, a change in the relative geometry between the force and the gage will seriously affect its response. Figure 6 shows typical results from 30-psi gages tested on a spin table with radial accelerations to 90 g. There was found to be a considerable variation between gages of the same pressure range. Higher range gages (100

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*Reference to commercial products in this report does not imply approval or criticism by the DASA Information and Analysis Center or the United States Government.

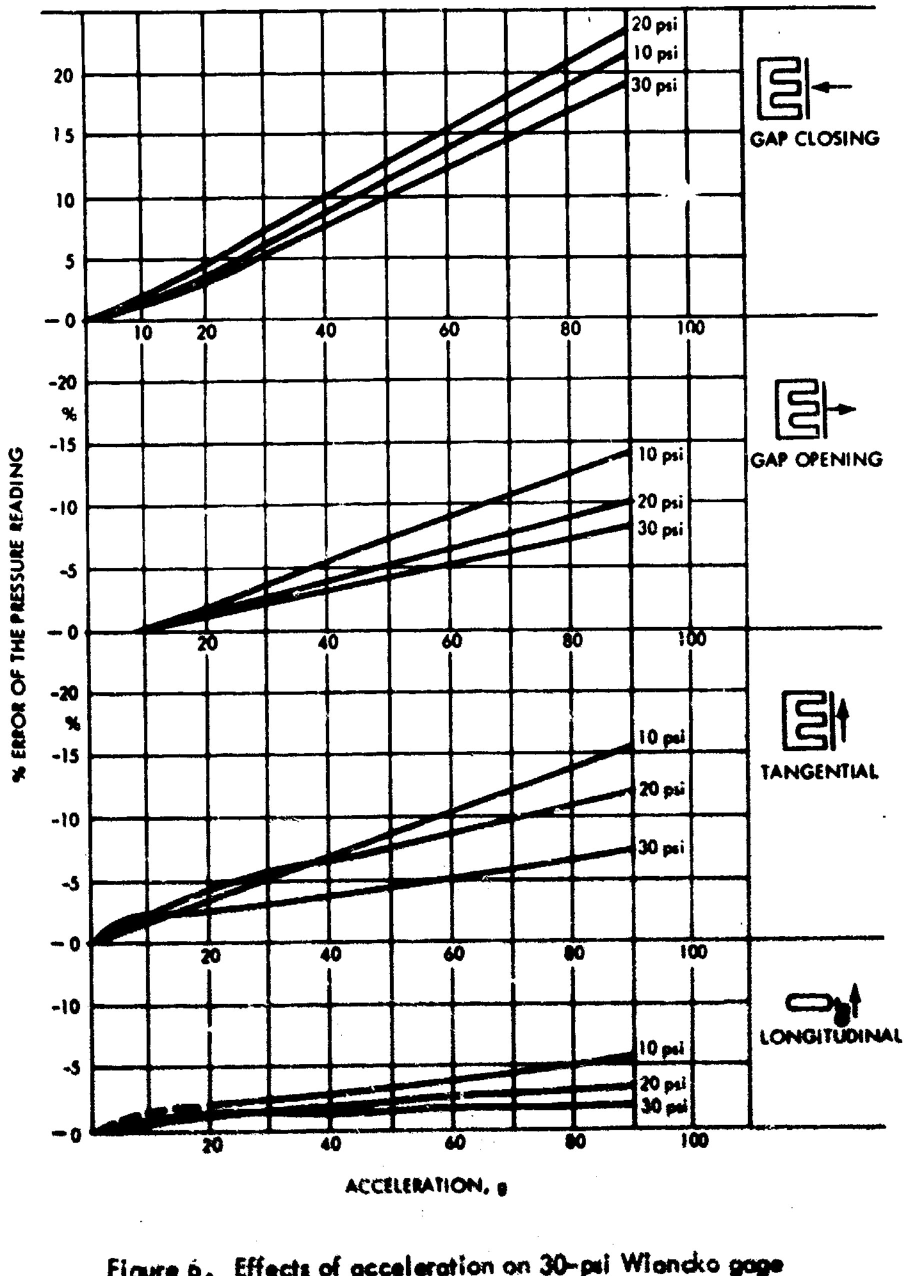


Figure 6. Effects of acceleration on 30-psi Wiancko gage (data from Reference 7).

to 300 psi) showed smaller errors while the 10-psi gages have slightly larger errors.

Ultradyne

The Ultradyne Engineering Laboratory of Albuquerque, New Mexico, makes a gage similar in principle to the Wiancko but differing in construction details. It has a reported rise time of 750 microseconds (Reference 8). The gage is a variable-inductance-type diaphragm about 1 inch long and 1 inch in diameter. The displacement of an Invar diaphragm flexing under the applied pressure produces changes in the inductance of coils situated just behind the diaphragm. A remote oscillator, incorporating the coil as circuit elements, generates a signal whose frequency is proportional to the pressure. Stanford Research Institute used this gage in a nuclear test and obtained data at levels above 200 psi (Reference 9).

CCC

The Consolidated Controls Corporation produces an electromechanical differential gage, the PFS400NA, which also utilizes the variable reluctance principle. Overpressure is converted to frequency variation by use of a clamped plate diaphragm moving in a magnetic field. This gage is made to measure pressures up to 300 psi.

The Naval Ordnance Laboratory has successfully used this gage at pressure levels below 15 psi with the gage coupled to either a Genisco No. 10–110 or Leach No. 800 miniature recorder with an Electromechanical Research No. 189 FM Plug-in discriminator (Reference 10). The gage was considered adequate by NOL—its accuracy and reproducibility were above average. The principal shortcomings, non-linearity and a 2-kHz limit to high-frequency response, are balanced by the instrument's ease of use—direct FM output and valid static calibration.

Two problems were noted in field use. First, the gage occasionally exhibited a decrease in sensitivity, probably caused by mechanical changes in the diaphragm-coil relationship due to atmospheric corrosion (the field use was near salt water). Secondly, care was required in interpreting the output records. Since the gage measures a pressure difference across a diaphragm between two chambers, conditions of blast loading may deform or displace the diaphragm and thus cause appreciable deviations of the pressure in the reference chamber. These deviations become significant, greater than +1 percent for side-on pressures below 5.0 psi. This deviation must be accounted for during data reduction by correction factors based on overpressure.

Photocon

The Photocon Research Products Corporation manufacturers the Model 352 Dynagage System which has been used in a nuclear environment to obtain surface level pressure and time history data at about 1500 psi, but a gage at 500 psi failed—presumably because of radiation effects (Reference 11). The sensor operates on the variable capacitance principle utilizing a double diaphragm. The outer diaphragm is connected to the inner sensing diaphragm by a central stud so that high thermal temperatures do not arrive at the sensing element in time to affect the measurement. Gage ranges are available to about 90,000 psi. In the nuclear field test further protection was provided by a perforated metal blast shield which prevented direct radiation from reaching the outer diaphragm. The gage had a high natural frequency, 60,000 Hz, and was used with a tuned system operating at a carrier frequency of about 1 MHz, but the company rates the system output as flat to 10 kHz only. Stanford Research Institute recommended that, in view of the success of this gage in the field (at least to 1500 psi), it be used as a primary instrument for obtaining high-pressure data from nuclear tests.

Kaman Nuclear

The gages listed thus far have been standard pressure-measuring devices that were adapted to measuring nuclear blast waves. The Kaman Nuclear Corporation radiation-hardened blast pressure transducers, along with the accessory K-5000 oscillator-demodulator, were specifically designed for pressure measurements in high-radiation level nuclear bursts. The Kaman gage has been tested in very severe simulated environments (References 12 and 13) and has been found to be relatively insensitive to the effects of radiation, acceleration and temperature. Tests have included:

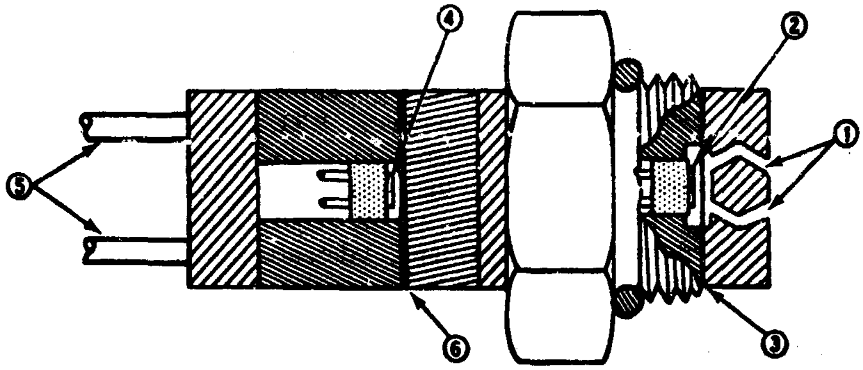
1. Neutrons

Total dose	1.0×10^{13} Nvt (> 10 kev)
Flux	2.0×10^{17} n/cm^2 - sec
Integrated flux	1.0×10^{14} n/cm^2

2. Gamma	
Dose rate	1.0×10^8 rads/sec
Integrated dose	1.0×10^5 rads
3. EMP	
Electric field strength	1×10^5 volts/meter
Magnetic field strength at pulse frequencies near 30 kHz	1×10^4 ampere-turns/meter
4. Temperature	
Ambient	-65 to +300°F
Transient	4000°F for 200 milliseconds
5. Shock and Vibration	
Shock	700 g for 2 milliseconds
Vibration	50 g (rms) for 20 to 5000 Hz

The Kaman transducer, shown in Figure 7, utilizes the effect of eddy current loss in a metal diaphragm on the impedance of a nearby small air-core inductor. The flat, stiff metal diaphragm, moving in an air gap between two stationary air core coils, is the only moving part of the gage. There are no magnetic components. Two air core coils and diaphragms are contained in a stainless steel housing. The two coils are connected as two arms of a Wheatstone bridge, which is completed by two resistive arms contained in the oscillator-demodulator. The active coil is in such close proximity to the non-magnetic pressure sensing diaphragm that small deflections of the diaphragm result in sufficient eddy current loss to significantly change its impedance. When the coils are properly phased, electrical pickup or radiation-induced noise sensed simultaneously by both coils is cancelled out in the electrical bridge circuit, of which the transducer forms a part, and thus reduces or eliminates the sensitivity to high-flux nuclear radiation effects.

All organic materials have been eliminated from the coil assembly. The coils are wound on ceramic coil forms made of 99-percent aluminum oxide with ceramic insulated magnet wire. The coil and coil forms are embedded in the gage case with a special, boron-free encapsulant. The standard transducer is build with both an active and an inactive coil-diaphragm assembly mounted in the same housing (or with minimal separation).



1. PRESSURE PORTS
2. ACTIVE COIL
3. DIAPHRAGM
4. DUMMY COIL
5. OUTPUT CABLE
6. DUMMY DIAPHRAGM

Figure 7. Kaman K-1205 radiation hardened pressure gage.

The bridge is driven by a 1-MHz carrier at 5 volts rms. The pressure to be measured is admitted to the diaphragm through a main inlet port. The overpressure causes a deflection of the diaphragm which unbalances the bridge. The 1-MHz bridge output is rectified through a ring demodulator, amplified, and filtered to produce a 1-volt full-scale dc output, proportional to the applied pressure, with a frequency response from dc to 10 kHz. Since small deflections of the diaphragm may be resolved, it can be unusually stiff with a natural frequency that is high when compared with the 10-kHz data output response. No mechanical damping is attempted; electrical filtering of the amplifier output reduces any ringing signal from the diaphragm. The output of the demodulator is fed directly to a voltage-controlled oscillator and amplifier and thence to a magnetic tape recorder. The cable length between the gage and the demodulator must be less than 50 feet. For greater distances, only certain cable lengths can be used without introducing cable effects because the cable must be cut and tuned to specific wave lengths. *

*A recent development is an instrument-cable matching device which permits the use of long cables.

A Kaman gage has been used to measure airblast pressures as high as 75,000 psi in an underground nuclear test (Reference 14), and has produced excellent data from high-explosive simulation experiments. In one HE field test, however, BRL reported situations in which the pressure orifice became plugged with dust and did not function properly. The major drawback to the Kaman gage appears to be its cost. Unless a measurement requires a gage with special radiation-hardened design features, laboratories use the less expensive unhardened gages.

Strain gage sensing elements are finding increasing use in airblast measuring instruments. Bonded and unbonded wire and the newer solid state and deposited strain elements are all represented in currently stocked gages.

Norwood

The Norwood gage (Models 111 and 211 used by AFWL) is a flush-mounted transducer manufactured by the Detroit Controls Division of the American Standard Products Corporation (Figure 8). A flush catenary diaphragm, when exposed to the pressure input, loads the end of an internal tube and axially compresses it. The wire strain elements are bonded both circumferentially and longitudinally to the internal cylinder, and the dimensional change of the strain tube is reflected by an equivalent change in the resistance of the bonded strain elements. Use of the catenary diaphragm results in a minimum volume change within the pressure vessel and also somewhat minimizes the effects of temperature changes on the output signal. The

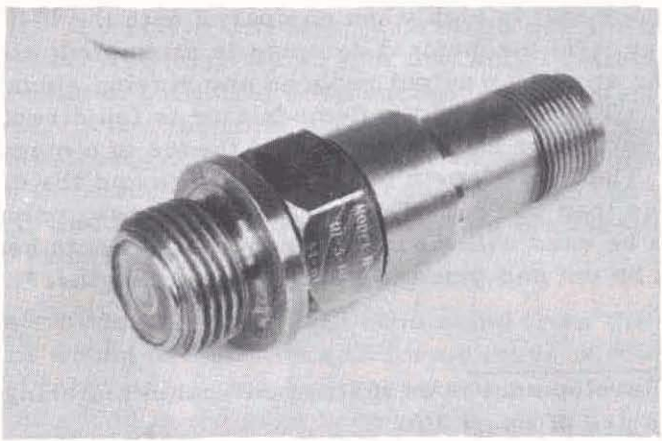


Figure 8. Norwood controls transducer.

gage has a natural frequency of 45 kHz and can be excited by either ac or dc.

AFWL reports that at high pressure levels there is a tendency for a zero shift to occur, probably caused by structural deformation of the strain tube. The temperature sensitivity can be compensated for with an ablative coating of 1/16 inch GE or Dow Corning silicon rubber without affecting output response. The gage is not damped and, thus, rings. The Air Force Weapons Laboratory is experimenting with oil damping but is experiencing leakage problems because the Norwood is not a sealed gage; however, some success has been achieved with a dual column damping system.

Dynisco

The Dynisco PT 76 and PT 136 are almost identical to the Norwood gage except for external configuration (Figure 9). Conventional 4-active-arm strain elements are bonded to a thin cylinder which has one end secured to the case and the other attached to the diaphragm.

Figure 9. Dynisco RC transducer PT 76.

The small mass and minute deflection resolution result in very-high-frequency response characteristics, but the low sensitivity of the bonded strain-wire gages—output about 2 to 4 mv/v full scale—requires signal-conditioning equipment and dc amplification for compatibility with voltage-controlled oscillators used in wide-band FM recording. The design and assembly of the gages make them insensitive to vibration and acceleration. Bonding the strain gages to the tube rather than directly to the diaphragm delays the effects of thermal transients, and the two passive arms of the bridge circuit are used for temperature compensation which further reduces thermal effects.

BRL has conducted a number of tests on the Dynisco gage (Reference 15). They performed a limited test on the response of both the Norwood and Dynisco gages to thermal transients on a special thermal pulsing device that exposed the gage diaphragms to a 1550°F propane torch flame for about 90 milliseconds. These test conditions produced voltages corresponding to about a 3-percent error in the Norwood and 0.3-percent error in the Dynisco. The particular gages tested were for different pressure ranges (the Dynisco, 2000 psi, the Norwood, 500 psi), but it does appear that the Norwood is more temperature-sensitive.

In an attempt to reduce the temperature response, BRL tested Dynisco transducers fitted with special diaphragms. The normal stainless steel diaphragm was replaced with others of various materials intended either to reflect, insulate, or evenly distribute the heat. Nickel, copper laminated with stainless steel, stainless steel covered with Teflon, and stainless steel coated with flame-sprayed aluminum oxide were tested. Only the aluminum oxide significantly reduced thermal shock. For very high pressure studies near the detonation point of underground nuclear blasts, BRL protects the diaphragm with a baffle consisting of a heat shield with eight double-angle inlet ports and a small cavity between the inlet holes and the diaphragm, as well as the aluminum oxide (Figure 10).

A model PT 76 tested for leakage in a vacuum showed a creep in zero balance (about 0.1 percent after 45 minutes in vacuum). This unbalance remained after return of the pressure to ambient. It is believed that all-welded construction would be required to give a better seal.

BRL notes that although the Dynisco is well-suited to laboratory use, a number of electronic difficulties have been experienced in HE field tests. Current BRL plans include use of the Schaevitz-Bytrex gage for future high-pressure field work. However, a Dynisco Model PT 136 was used successfully to obtain very high air pressure data in a recent underground test (Reference 14).

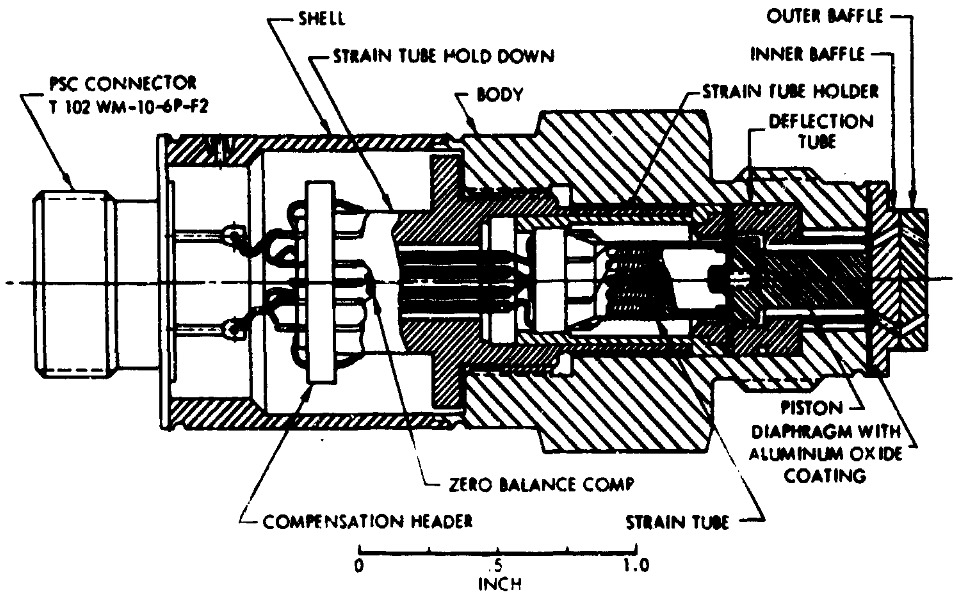


Figure 10. BRL high pressure airblast gage using the Dynisco pressure transducer.

CEC

Unbonded strain-gage windings connected in a four-arm bridge comprise the sensing element of a number of Consolidated Electrodynamics Corporation variable-resistance type transducers. Pressure against the flush diaphragm produces a displacement of the sensing element, thus changing the resistance of the two active arms and producing an electrical signal proportional to the applied pressure.

According to the manufacturer, acceleration and vibration have little net effect on the bridge output, as they are cancelled by the geometry and winding arrangement of the star-spring-type sensing element. Compensation for the effects of wide ambient-temperature variations is provided by the location of the two inactive arms in close proximity to the active windings.

Unbonded wire strain gages can be produced with excellent resistance to both neutron and gamma radiation; however, they are usually so sensitive to shock that they are used at pressure levels where the radiation is no problem.

Statham

The Statham Instrument Company manufactures a line of deposited strain gage pressure transducers. A strain-sensitive film is vacuum-deposited on a diaphragm and arranged electrically in a conventional, balanced four-active-arm Wheatstone bridge. Applied pressure causes tension stress in one pair of the arms and compressive stress in the opposite arms. The pressure is measured by the resistance change in the bridge circuit.

Theoretically, this gage should have excellent resistance to shock and vibration. The all-metal and ceramic construction should be very radiation-resistant; however, tests of a Model PA 801 exposed to the radiation from a nuclear test (Reference 16) indicated a recorder (Genisco) saturation after zero time. Further analysis of both the gage and the data from this test are required to determine if the observed effect was caused by the transducer or by the associated cables and instrumentation.

Micro Systems

Piezoresistive elements replace the conventional strain gage elements in a four-arm bridge circuit in Micro Systems gages. These piezoresistive elements produce an electrical resistance change with pressure that is about 15 times that produced by the metallic bonded strain-gage.

The elements are bonded to the back of a 1/4-inch diameter flush diaphragm. Pressure ranges to 500 psi are available. Shock tube tests at BRL indicated a base line shift due to thermal effects after about 20 milliseconds, but more recent gages are reported to be thermally protected. The solid state elements used may be a poor choice for field measurements in a nuclear environment unless the elements are doped to withstand radiation. The Micro Systems gage is very small and would be a good choice for model target-response studies.

Schaevitz-Bytrex

The Schaevitz-Bytrex Corporation also manufactures semiconductor strain-gage pressure gages with various pressure ranges. The silicon element is mounted in a stainless steel case. Overpressure applied through a diaphragm produces strains and resistance changes in the semiconductor members. The resultant current change in a modified Wheatstone bridge circuit produces a voltage which varies directly with pressure.

The Model HGF 2000 is used by AFWL for non-nuclear laboratory high-pressure work. The gage has a high natural frequency, 100 kHz, and a high output, 200 Mv full scale, but low pressure ranges are not available in this model—2000 psi is the lower pressure limit.

Either an ac or a dc recording system may be used, but high bridge impedance will cause cable noise problems. AFWL has experimented with plate-damping this gage. An ablative coating is applied to a thin steel plate placed over the sensing element. This tends to increase the general ruggedness of the gage; further work may eventually make it available for field use. The plate also reduces temperature sensitivity; however, the natural frequency is reduced to 60 to 75 kHz.

Although AFWL has reservations about using the HGF 2000 in field studies, BRL, as noted in the discussion of the Dynisco gage, has used the gage in underground airblast studies to obtain very high-pressure data (Reference 14). In the BRL version, the diaphragm is protected with a heat shield. Eight small, double-angle inlet ports lead to a small cavity between the sensor diaphragm and the heat shield. The shield allows for an even distribution of the initial thermal pulse, prevents debris from damaging the diaphragm and, to some degree, shields the gage from EM pulse (Figure 11).

At present, the HGF 2000 suffers the same limitations to a nuclear environment as do all the silicon semiconductors. However, Schaevitz-Bytrex makes a special silicon element for Sandia that is reported to be radiation resistant. These elements could probably be adapted to the high-pressure gage.

A model HGF 25 gage was subjected to a nuclear environment (Reference 16), and after the test the gage exhibited a shift in zero-pressure dc output level; when ac excitation was applied, no change in operating characteristics was observed.

MIT Pancake

The Department of Aeronautics and Astronautics at Massachusetts Institute of Technology has designed a pancake pressure gage, utilizing (at the present time) two Schaevitz-Bytrex HF-100 sensing elements. The gage is used in rocket sled blast studies. The 4-inch diameter by 1/2-inch thick probe uses the strain-gage elements on opposite faces. The Schaevitz-Bytrex elements were selected because

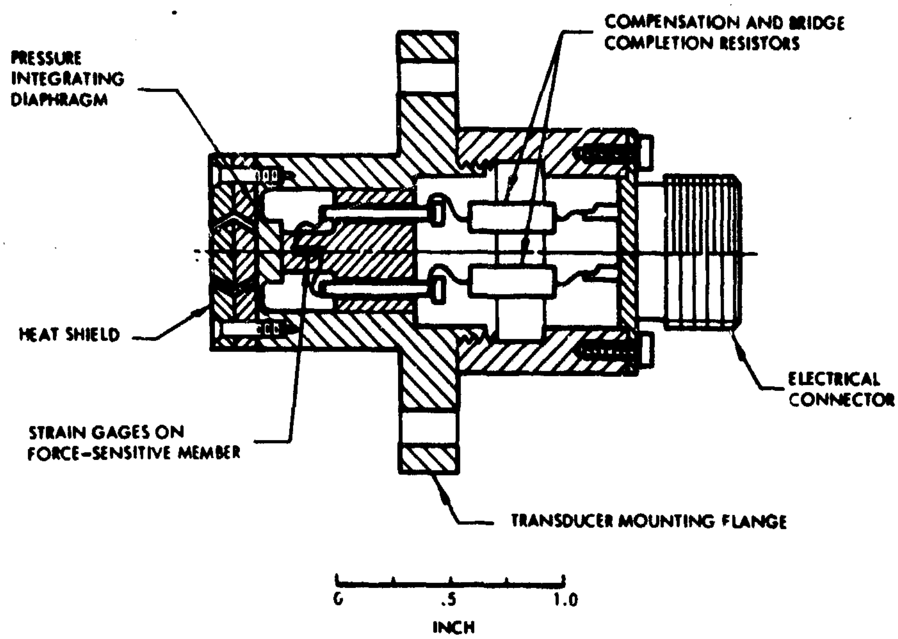


Figure 11. Bytrex pressure transducer used by BRL.

they had exhibited high degrees of accuracy, stability, and repeatability in MIT blast work (Reference 17). In field use, the plane of the probe is oriented vertically, with the axis through the stem directed toward the blast. Recording is on a Tektronix No. 551 dual-beam oscilloscope in the laboratory and on a 14-track Leach No. MTR 1200 in the field.

Extensive testing of the probe in a laboratory shock tube and later HE trials gave the investigators confidence in the overpressure data in the region of the blast between the shock front and the contact surface up to a flow of Mach 0.75.

Two modifications were suggested for possible improvements. First, a reduction of probe thickness was proposed to help reduce gage oscillation. The oscillation, with a period of about 0.6 millisecond, was observed in the record immediately after shock arrival, particularly at higher Mach numbers. The magnitude of the oscillations was found to be proportional to the thickness of the probe and was attributed to the diffraction of the initial shock and successive shocks and rarefaction waves. The second modification proposed was a reduction of probe size. Since the aerodynamic response time of the probe is expected to scale with probe size, it would seem worthwhile to reduce probe diameter. However, this must be tested carefully; when the diameter is reduced, the thickness ratio increases, which increases the ringing of the gage.

There are many systems using piezoelectric sensing elements. It is interesting to note that investigators using identical equipment on similar projects may express widely divergent opinions on the worth of a particular gage.

General Atomics

The General Atomics Division of General Dynamics offers several standard-item bar gages, all of which operate on the principle of conducting the pressure pulse down an elastic bar to a sensor which is shielded from the environment affecting the bar. Reference 18 discusses theoretical aspects of bar gages and the different configurations possible.

Gen Atom Quartz Pressure Bar Gage

In General Atomics Quartz Pressure Bar Gage, the pressure pulse induces a strain in a 1/4-inch by 24-inch tungsten rod which in turn loads the quartz sensing element. Beyond the sensing element is a magnesium rod. The rods and the quartz are securely cemented together with an epoxy cement. In theory the contrast between the acoustic impedances of the two rods causes the stress applied to the quartz sensor to be much lower than that in the tungsten rod, so that measurement of pressures up to 5 kilobars (about 75,000 psi) will not shatter the crystal.

The time duration which can be measured by this bar gage is 260 microseconds. This duration is determined by the time required for the reflected stress waves to return to the sensor from the ends of the two rods and perturb the output of the sensor.

When tested by MIT (Reference 19), the gage exhibited an extremely fast response to the pressure wave (about 3 microseconds); however, there was a slower rise in the signal above the initial jump to a peak about 80 percent higher in 80 microseconds. It was believed that the overshoot was due to an impedance mismatch between the quartz crystal and the tungsten rod; however, when an aluminum rod was substituted the overshoot was not eliminated. Swift at SRI (Reference 20) points out that the basic assumption of any bar gage, i.e., that the stress wave is transmitted down the rod without distortion, is not true. The speed of initial loading can cause oscillations and produce overshoot.

SRI Quartz Bar Gage

The Stanford Research Institute proposed a simplified bar gage suitable for high pressure studies, capable of handling a signal of longer duration than the 260 microseconds of the General Atomics gage (Reference 13). The SRI design would sacrifice resolution by accepting a rise time of about 10 microseconds. This would allow the use of a continuous rod with one or more sensors located 4 feet or more from the sensing end for better shielding, and with at least 6 feet of rod beyond the sensor, allowing an operation time of some 750 microseconds. It may be possible to extend the bar much further, or to terminate it to avoid reflection, but the limit is probably 1 or 2 milliseconds of useful measurement time.

SRI felt that there was some advantage in using two types of sensors on the same gage. A high-impedance piezoelectric sensor can be made to deliver a large signal, but it is sensitive both to the EM signal at zero time and to the nuclear radiation. A low-impedance strain sensor puts out a smaller signal, but its sensitivity to outside sources is low, so its signal-to-noise ratio may be better.

Sandia Quartz Pressure Gage

The quartz pressure gage designed by the Sandia Corporation and described in the section on earth strain gages (page 127) would possibly prove adaptable to extremely high peak-pressure measurement in a nuclear environment.

Kistler

The Kistler Corporation produces a line of quartz wafer pressure gages which have been used with considerable success in shock tube and laboratory work but with less satisfactory results in field studies.

Both the 600 and 700 series gages have been tested in the field, principally the 601 and 603. The output from the Kistler gages is usually fed through a Kistler No. 503 electrostatic charge amplifier to convert the signal to a low impedance compatible with long cables and ordinary recording equipment.

The 601 accommodates pressures from 10 to 300 psi and is physically small, thus well adapted to mounting in dynamic probes and stingers. MIT (Reference 21) reports a 10-microsecond response time using optimum electrical filtering, but there was a large oscillation in the signal. Using a 44-kHz second-order filter (3 db down), the overshoot was reduced to 5 to 10 percent, but the response time increased to 12 microseconds.

The 603 is slightly smaller and should have a higher natural frequency, a faster rise time and should be less responsive to acceleration. AFWL reports a temperature sensitivity which can be corrected by an ablative silicon rubber coating (this is now a standard feature available on Kistler gages). MIT (Reference 21) tests show a response time of about 7 microseconds, but the gage output, like the 601, oscillates. With a lower frequency filter, the response time was reduced to 10 microseconds, but a 15-percent overshoot remained; the oscillation of the signal was about ±10 percent from the mean to the peaks.

SRI Pressure Probe

Poulter Laboratories of the Stanford Research Institute has designed a pressure probe for measurement in the 200 to 50,000 psi range (Reference 22) which uses the piezoelectric principle in a unique way. A radially polarized piezoelectric ceramic (PXT-4) ring is fixed around a cylindrical sapphire rod. Overpressure stresses one end of the rod, and a pressure pulse is propagated along the rod which stresses the sensing element in a radial direction. Transient temperatures as high as 150,000°K for 100 microseconds can be tolerated. Static and dynamic calibration in a hydraulic press (to 36,000 psi) and by a dropping rod (to 10,000 psi) indicates a linearity of response of about 2 percent. A cathode follower is required to isolate the gage from the high capacitance associated with long cables.

Atlantic Research Corporation

Three Atlantic Research Corporation piezoelectric gages, the LC33, LC71, and the LD80, have been used in blast work. The LC33 is a high pressure pencil-type probe about 1/2 inch in diameter and 10-inches long. Its rated maximum pressure is 1000 psi; however, the 2-percent linear range is about 100 psi.

MIT (Reference 21) measured the dynamic response of an LC71 mounted on a 1-3/8-inch thick steel plate at the end of a shock tube at 100 psi. The gage proved to be linear within 2 percent of full scale. Its sensitivity varied between 85 and 130 picocoulombs/psi. The measured rise time was 5 microseconds. However, the signal exhibited a large oscillation. Electronic filtering to produce an optimum compromise between signal response time and oscillation resulted in a 6-microsecond rise time and about a 7-percent overshoot. The measured axial acceleration sensitivity was 0.025 psi/g, somewhat higher than the 0.005 psi/g listed in the manufacturer's specifications.

In tests of the LD80, NOL has obtained rise times of about 1 microsecond. This was without damping and oscillations were noted. Since the LD80 has a natural frequency of 500 kHz, second-order filtering should be able to produce response times of about 3 microseconds. It was found that a single layer of black electrical tape, used as a thermal shield, helped to reduce the overshoot.

Susquehanna

The Susquehanna ceramic piezo-gage is used by AFWL as the standard for low-pressure (i.e., < 1000 psi) shock tube work. Because of the poor dc response and temperature sensitivity, the gage is not suitable for field use. MIT shock tube tests (Reference 21) of the ST 4 at 2000 psi and 3100°K showed a 3-microsecond response with no overshoot or oscillations. On one test the rise time was 1 microsecond, but the limiting factor apparently was the bandwidth of the electronics employed in the system; the rise time actually may be much less. Black electrical tape was used as a thermal protection with no indication of degradation of response. The gage was linear within 1 percent, and the sensitivity was within 3 percent of the manufacturer's specifications. Of six different piezo-gages tested, MIT preferred the Susquehanna for shock tube work.*

*The six were Susquehanna ST4-10K, Atlantic Research LC71, Atlantic Research LD80-M1, Kistler 603M101, Kistler 601A, General Atomic Pressure Bar 108.

Endevco Corporation

The Endevco Corporation of Pasadena, California, offers a high-frequency piezoelectric gage capable of measurement under severe environmental conditions. The Model 2501 is available in two pressure ranges, 0 to 500 and 0 to 2000 psi. As in any high-impedance gage, radiation effects are to be expected. These effects should be manifested as a rapid voltage rise, followed by a slow decay depending primarily on the input impedance of the associated charge amplifier.

In a radiation exposure test (Reference 16), the actual behavior of the gage was obscured due to an amplifier saturation. This same saturation condition could exist in a field nuclear test. As a corrective measure it was suggested that either the shorting relay/charge amplifier circuitry be modified to prevent amplifier saturation or (preferably) the charge amplifier eliminated in favor of a radiation-resistant voltage amplifier located near the transducer.

BRL Piezoelectric

BRL designs and manufactures their own piezoelectric gages to meet a number of requirements. Under the supervision of Mr. Ben Granath, the BRL approach has been to construct a special gage to do a specific task. There is some transfer of use, however, and gages originally designed for shock tube work are sometimes utilized in field studies. Two basic gage types are made: (1) Bar gages, where a sensing element is coupled to an acoustic wave guide in such a manner that crystal resonance is dissipated within its backing, and (2) "Commercial" type gages. Table 4 lists some of the pressure ranges and sensing elements for representative BRL piezoelectric gages.

In general, the bar gages use a wafer of tourmaline or quartz that is bonded to a metal bar. The gage uses either 0.125- or 0.25-inch crystals in a 0.5- or 0.75-inch stainless steel case. Since the sensing element area is the governing parameter for signal output, the larger gage is used in the lower pressure region. The lengths of the bar were chosen experimentally to minimize ringing. The bar gage has a high frequency response, but its useful measuring time is only a few milliseconds, due to transient thermal effects. The shorter bar is used for gages making incident pressure measurements in order to minimize stresses due to unsymmetrical loading. The gages can be used to flow velocities as high as Mach 20 without ringing.

Table 4. BRL piezoelectric airblast gages.

Gage	Measurement	Range (psi)	Sensor	Element Diameter (inches)
2 megacycle bar	Reflected pressure	50–10,000	Tourmaline or quartz disc on 1.5-in. brass cylinder	0.125
2 megacycle incident	Incident pressure	50–10,000	Tourmaline or quartz disc on 0.75-in. brass cylinder	0.125
1.5 megacycle bar	Reflected pressure	10–2,000	Tourmaline or quartz disc on 3-in. brass cylinder	0.25
1.5 megacycle incident	Incident pressure	10–2,000	Tourmaline or quartz disc on 1-in. brass cylinder	0.25
Yellow dot	Incident pressure	1–500	Lead zirconate (GE 488A) on 0.625-in. lead cylinder	0.21
Field Pickup	Incident pressure	0.1–100	Lead zirconate (GE 488A) on 1-in. lead cylinder	0.375
Red dot	Incident pressure	0.1–100	Lead Zirconate (GE 488A)	0.21

The Yellow-dot and Red-dot gages have a lower frequency response than do the bar gages and are used in lower pressure areas where response is not so critical. The Yellow-dot gage is limited to shock front velocities of Mach 4 and lower. Velocities in excess of Mach 4 excite the gage to ringing.

In lower pressure areas, an enlarged version of the Yellow-dot, using a 3/8-inch diameter element, is used. This gage, called a Field Pickup, provides a greater signal to compensate for the increased length of cable that is often required in field experiments.

A cathode follower is required to couple the high impedance gage to a low-impedance amplifier. Recording in the lab is on a Tektronix 543 oscilloscope with 53–54D preamplifier. Field recording is on a variety of instruments; CEC System D and the Leach and Weber recorders have been used.

Mechanical Systems

The Ballistic Research Laboratories have carried on the development and improvement of self-recording mechanical systems since the early 1950s. Many variations have been constructed, using various combinations of sensing diaphragms, recorders, and timing elements, to reduce the size of the system while increasing its reliability and ruggedness.

In all the gage types, a deflection of the sensor diaphragm is recorded on a glass or stainless steel element as a scratch by an osmium-tipped phonograph needle stylus arm linked to the center of the diaphragm. A separate timing scratch is provided by an oscillator.

BRL Self-Recording System

The latest model of the BRL system (Figure 12a) has seventeen interchangeable sensors providing pressure ranges from 0.03 to at least 1000 psi with a rise time of approximately 0.2 to 0.5 millisecond when critically damped (Table 5). Damping, to minimize overshoot and oscillation, is adjusted by the size of the orifice which admits the pressure pulse to the diaphragm. The single-diaphragm sensors are constructed of NiSpan C stainless steel in a convoluted flexure disc welded to a mounting ring for ease of interchange (Figure 12b). The stylus and its spring arm are attached to the diaphragm by

Table 5. Characteristics of BRL mechanical self-recording diaphragm sensors.

Sensor Ranges (psi)	Sensor Natural Frequency (Hz)	Sensor Characteristics		
		Deflection at Rated Pressure (mils)	Hysteresis (percent)	Linearity (terminal based)
0–1	820	15.30	0.7	1.60
0–2	1085	19.60	0.87	1.68
0–5	1570	20.20	0.00	1.60
0–10	1895	26.80	0.67	2.69
0–25	2726	23.90	0.20	0.70
0–50	2995	24.20	0.30	2.40
0–100	3615	28.60	0.35	0.87
0–200	4351	31.35	0.73	3.57
0–400	5105	23.17	0.86	3.75
0–600	5955	20.82	0.52	2.16
0–1000	6990	20.10	0.59	0.45
0–2000[a]				
0–3000[a]				
0–10 Negative	1915	25.70	0.2	0.7
0–0.50	430	18.15	0.55	1.7
0–0.125	250	17.4	0.60	4.9
0–0.030	250	18.2	1.10	4.2

NOTE:
[a] No data at this time.

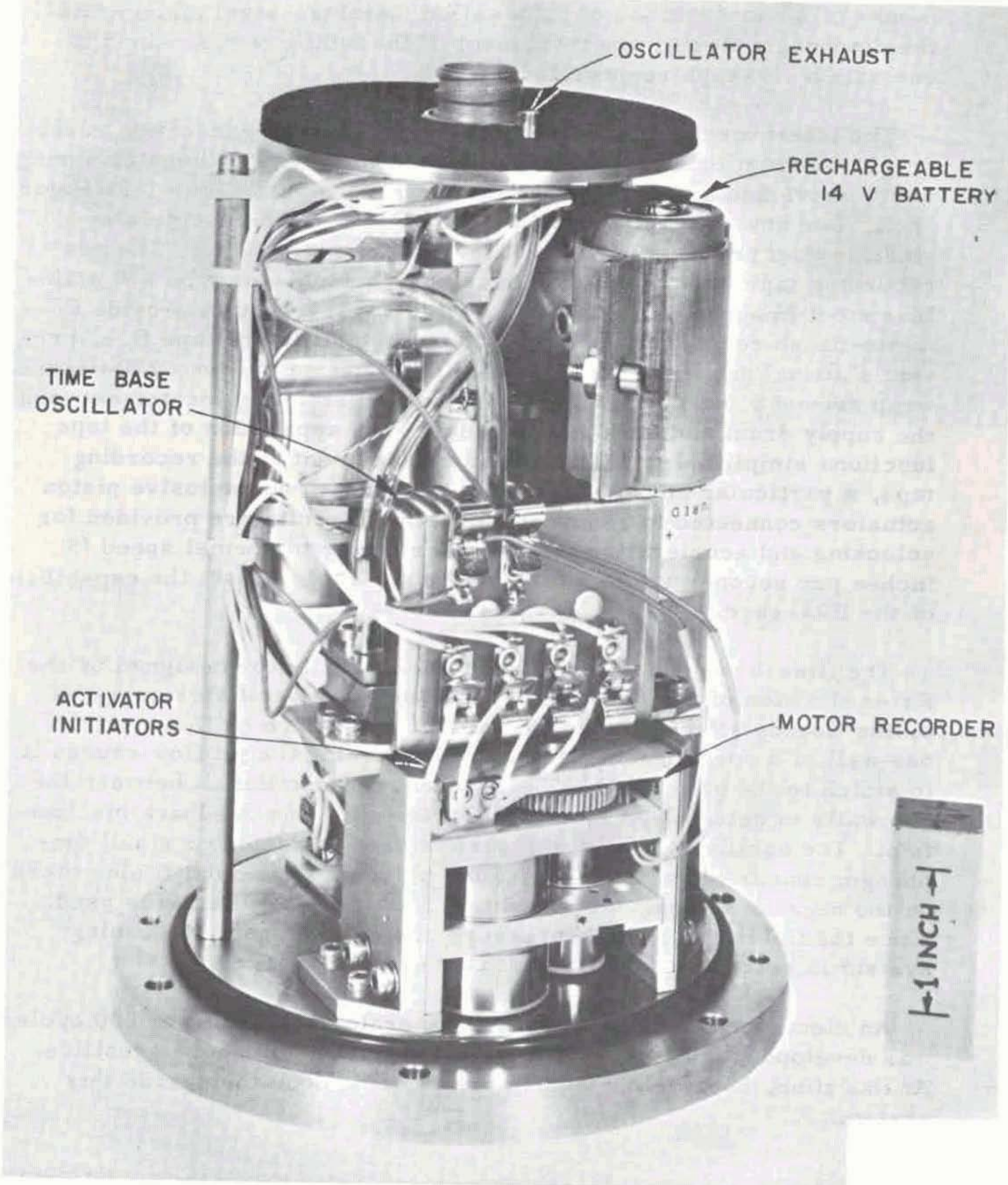


Figure 12a. BRL self-recording system.

means of a short section of thin-walled stainless-steel tubing. As the diaphragm flexes, the movement of the tubing is restrained to one axis by a sapphire-jewelled bearing.

The latest mechanical recording device, a third generation recorder developed from original BRL patents, uses a governed negator spring motor drive and a separate tape for the recording medium (See Figure 12c). The new recorders, Exline Model 245, were considerably smaller than previous units, and the frames more rigid. The new recording tape was 0.001 inch thick by 3/8 inch wide type 410 stainless steel (magnetic) strip with one side vapor-honed to provide a matte-finish recording surface. To help stabilize the tape (i.e. prevent shifting) during shock, the magnetic tape was given a 270-degree wrap around a magnetized recording pulley (an idler) located between the supply drum and the take-up drum. The separation of the tape functions simplified installation and replacement of the recording tape, a particular advantage in field service. Two explosive piston actuators connected to redundant initiation circuits are provided for unlocking and accelerating the recorder motor to normal speed (3 inches per second) within 5 milliseconds. Table 6 lists the capabilities of the BRL gage.

The time-base generator is an all-fluid oscillator designed by the Friez Division of the Bendix Corporation. The oscillator operates by the Coanda effect by which a fluid jet will attach or flow next to one wall of a specially shaped tube. Disturbing the jet flow causes it to attach to the other wall. The frequency of oscillation between the two walls is determined by the characteristics of a feedback mechanism. The oscillating fluid pressure is used to perturb a small diaphragm sensor whose attached stylus places a sinusoidal timing mark on the negator spring. At present, a 500-cycle oscillation is used. Since the fluid used is high-pressure compressed gas, the timing system is relatively insensitive to acceleration forces.*

An electromechanical time-base generator oscillating at 200 cycles was developed, but it proved to be acceleration and shock sensitive. At this time, no developmental work is being done to upgrade this system.

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*A discussion of another fluidic device designed for blast and shock work begins on page 100.

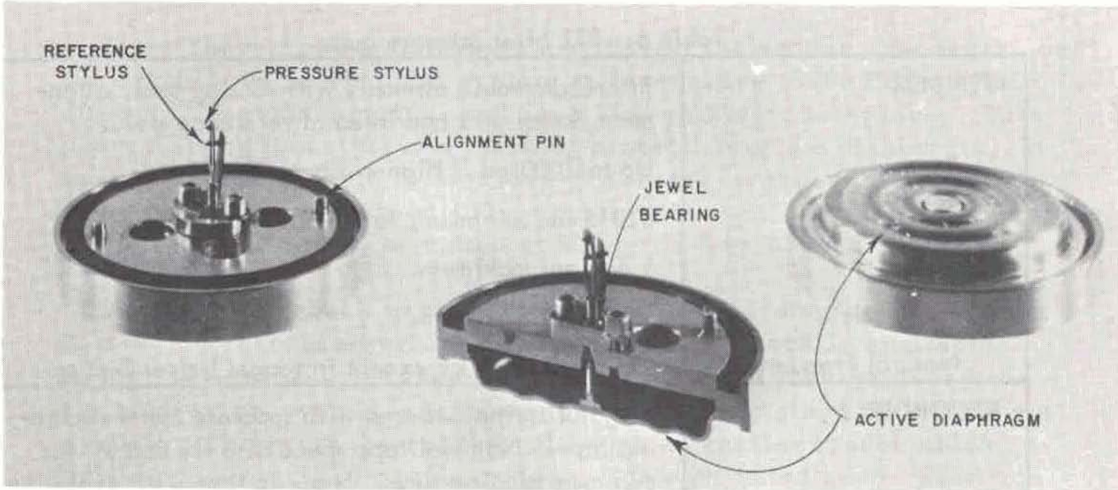

Figure 12b. BRL self-recording system.

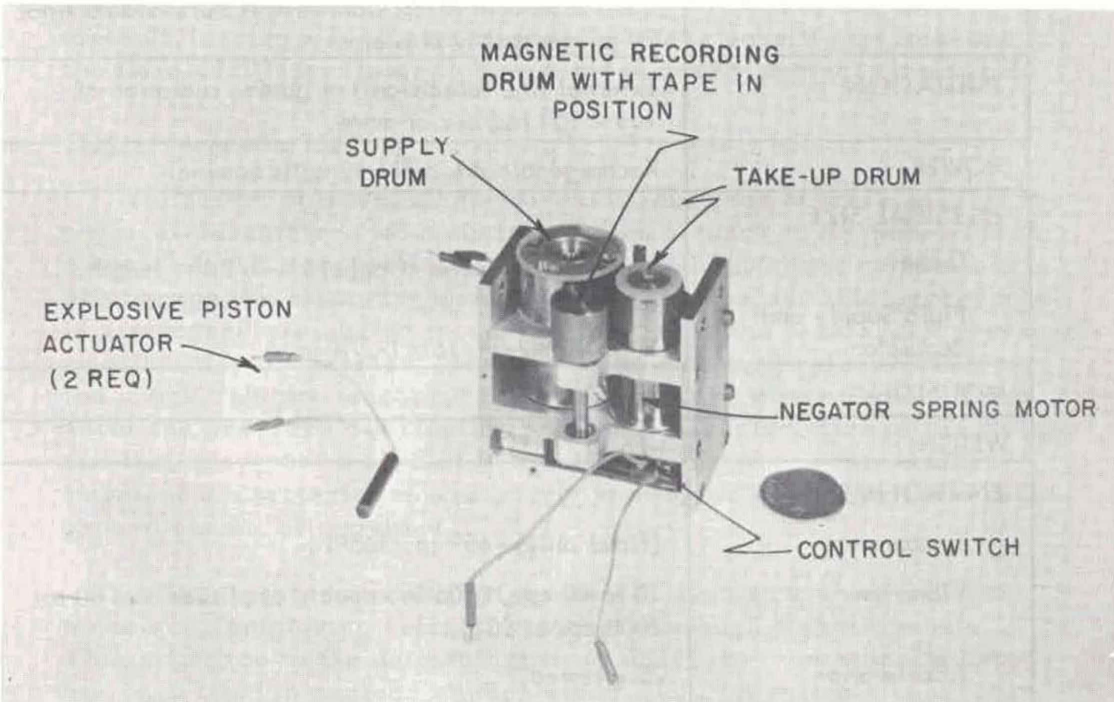

Figure 12c. BRL self-recording system.

Table 6. BRL blast pressure gage.

SENSOR	Interchangeable assembly with O ring seal, alignment dowel pins and integral reference stylus.
Range	Up to 1000 psi. Higher ranges feasible.
Deflection	0.015 in. minimum, full scale each range.
Linearity	5 percent maximum.
Hysteresis	1 percent maximum.
Natural Frequency	Greater than 1 kc except in ranges below 0–2 psi.
RECORDER	Negator spring powered with separate metal recording tape. Nominal tape speed of 3 ips and 20 sec minimum running time. Start-up time with explosive piston actuator: 0.5 ms.
Recording Tape	Magnetic stainless steel, 3/8 in. width × 0.001 in. thick x 60 in. maximum length.
TIME BASE	Fluidic type time marker, nominal frequency 475 cps ± 1 percent at constant temperature and nominal 20 psi gas supply pressure.
INITIATION	External line (electrical) or gamma radiation of 1.5×10^4 rad/sec or more.
POWER	Rechargeable dry cell, 12 volts nominal.
PHYSICAL SIZE	
Gage	4 3/4 in. diameter (flange) x 4-1/2 in. length.
Fluid Supply and Regulator	4-11/16 x 2-11/16 x 1-3/4 in.
MOUNTING	Flange.
WEIGHT	4.6 lb.
ENVIRONMENTAL	
Temperature	(Timer only) -65° to +165°F.
Vibration	10 to 80 cps, 0.06 in. double amplitude and 80 to 2000 cps at 20 g.
Acceleration	75 g tested.
Shock	100 g, 10 ms. At shock levels of 300 to 500 g, the pressure trace is subject to an error of ±3 to ±7 percent.

Since there are no electronic circuits in the sensor, recorder, or time base, the mechanical system is insensitive to TREE and EMP effects. The components used have high radiation tolerance. With proper shock mounting and thermal protection of the diaphragm, the system should be able to measure pressures in excess of 1000 psi. The system has withstood 100 g acceleration without affecting response. Tests are now being conducted at 500 g for 8 to 10 milliseconds.

A major drawback to a mechanical self-recording system is that it must be recovered before the record of the shock is available. In high pressure-level areas of nuclear tests, it may be days before the gage is recovered. At present there is no method of obtaining a zero-time mark on the record, although an earlier model which recorded on a disc had provision for a light-activated zero-reference trace.

BRL is continuing to improve the existing gage. Some of the proposals for change are: use a porous stainless steel in place of the orifice to improve damping characteristics; improve the frequency response of the sensor (which is evidently limited by its existing diameter); develop a fluid amplifier to increase sensitivity; improve the fluid oscillator timer to give a more nearly perfect sine curve.

Optical Measuring Methods

Application of the Rankine-Hugoniot equations of state enables the physical parameters immediately behind a shock to be derived from a knowledge of shock velocity. The use of high-speed cameras to photograph the expanding shock bubble against a suitable background is a standard measuring tool for determining the peak shock pressure as a function of distance. However, the standard calculations from the shock velocity technique for peak pressure give no information about the pressure distribution and flow characteristics of the wave, and they may not be applied to measurements where the Rankine-Hugoniot characteristics are poorly known, or when a suitable background cannot be provided.

Moulton and Simmonds (Reference 24) discuss a photo-velocity technique, employing refraction of light through a shock bubble. This approach to the determination of pressure from velocity data has been used in nuclear studies since 1950. A suitable background is prepared either by firing a group of smoke rockets to form a grid, or emplacing a canvas painted in a grid pattern. A high-speed camera, positioned so that the shock wave travels between the camera and the grid, photographs the expanding shock bubble. The edge of the shock is easily visible on the photographs as a distortion in the image of the grid caused by the effect of the refraction of light passing from the grid to the camera through the density discontinuity of the shock. Since the framing speed of the camera and the geometry between the grid, shock wave, and camera are known, accurate values of velocity may be obtained. Table 7 lists selected characteristics of some of the cameras used in this type of measurement.

The photo-velocity technique is suitable for pressure determinations at very high pressures, and good agreement with analytically determined curves has been obtained to about 150 atmospheres; however, the system is subject to large errors at low overpressure values.

Recently BRL, particularly Mr. Noel Ethridge of the Terminal Ballistics Laboratory, has been conducting feasibility studies on other optical techniques and methods of optical data analysis. These techniques are intended to provide a comparatively inexpensive yet accurate means of measuring shock parameters at high altitudes where direct measurement methods are both difficult and expensive.

The BRL method applies the Gladston-Dale relationship to relate the index of refraction to air density (Reference 25). By shadowgraph photography using a point light source, a refraction profile of the shock is obtained from which it is possible to calculate a density profile of the shock bubble and determine the pressure profile of the shock. Experiments have been performed using the solar disc and point light sources (Reference 26). In an HE field test using the solar disc as the light source, the density profile converted to an overpressure-time profile was found to be in agreement with the BRL self-recording gage results (Reference 27).

For a point light source, the density profile can be determined only for the region immediately behind the shock front. For an extended background light source, information can be derived over a correspondingly larger portion of the blast wave. During the Sailor Hat HE tests, cameras recording the event fortuitously viewed the earth's horizon; examination of the photographs showed an effect as from a solar disk of infinite radius, so it may be possible to use the horizon to record the density profile of a shock during most of its time history.

Table 7. Camera characteristics.

Camera	Frame Rate (frames/sec)	Frame Size	Film Capacity	Remarks
Photosonics 4C	to 3,250	35 mm	500 and 1,000 ft.	Uses a rotary prism for image compensation on film continuously in motion.
Photosonics 10B	180 and 360	2-1/2 in x 2-1/4 in.	400 and 1,000 ft	Can be converted to half frame 70 mm for higher framing rate.
Dynafax—Mod 36	200 to 26,000	0.28 in. x 0.39 in.	224 frames	Three discrete shutter speeds, 4.1, 2.1, and 1.0 microsec and 8.6 millisec record time at maximum frame rate.
Fairchild HS-100	100 to 3,000	16 mm	100 ft	Uses rotating prism and moving film.
Mitchell	to 128	35 mm	400, 1,000, 2,000 ft	Registers film during each exposure in the same position in the film gate.
GSAP-16	16 to 24	10.4 x 7.4 mm	50 ft	Originally designed as an Air Force gun camera
Wollesenak, FASTAX WF-3	to 4,500	16 mm	100 ft	

The lower limit to which this technique may be extended is a function of both the magnitude of the density discontinuity behind the shock and the resolving power of the camera and film. Potentially the method may extend measurements into very low overpressure levels.

It is suggested by BRL that the concept of observing the passage of a shock from a nuclear blast against the solar disc may have other applications. Since the sun provides a background radiation source with a wide range of frequencies and spectral emission and absorption lines, a measure of air, or shock, temperature may be possible by recording the extent to which nitrogen spectral lines are absorbed.

BRL is also conducting studies to apply laser mapping techniques to the determination of blast parameters. Various tracking systems, doppler shift measurement, and interferometric methods are being considered. It is suggested that the radius versus time, density profile, particle velocity, and velocity profiles may be obtained.

SPECIALIZED AIRBLAST MEASUREMENTS

Both mechanical and electronic gages are used singly and in combination to obtain blast data at high altitudes or at great distances from the detonation.

Low Pressure Measurement

Microbarographs may be divided into two general classes: the very sensitive "absolute" dc instruments, and "high-pass" instruments. Absolute instruments have a flat response from zero to cut-off frequency, and high-pass instruments measure the difference between the present pressure and a weighted average of the prior pressures. This weighted average is determined from a reference volume of air which is connected to the atmosphere by a slow leak. Often an acoustic low-pass filter—a leak in series with the volume—is included to filter out turbulence and high-frequency noise. An equivalent electrical circuit may be constructed in which the leaks are represented as resistances and the volumes as capacitors.

Most meterological measurements are made with absolute instruments using an aneroid bellows or bourdon tube sensors. The data obtained relate to very very low frequency atmospheric fluctuations, i.e. cycles/hour. Atmospheric deviations as small as 0.04 mb (0.0006 psi) may be measured, and ranges of 500 mb (7.25 psi) are available.

Since each microbarograph is designed and constructed to operate in a particular frequency range, the sensitivities are correspondingly selected. At the present time any single instrument cannot be used over a large range of frequency and signal levels. Table 8 indicates the response characteristics of three commercially available high-pass microbarographs which might have application to blast measurement (Reference 22.A).

Table 8. High-pass microbarographs.

Type	Manufacturer		
	Globe	Teledyne	Columbia-Pace
Sensor	Capacitor microphone-amplifier	Variable capacitance oscillator	Variable reluctance bridge and amplifier
Flat frequency range	0.1-400 Hz	0.002-1 Hz	0.0003-1 Hz
Maximum pressure	≈500 μb	±100 μb	±2500 μb
Linearity	<5 percent	≈5 percent	0.5 percent
Output	Voltage, 20 v peak to peak, 0.5 v/μb	FM signal 7 Hz/μb	Voltage, max ± 10V dc, 0.0004 v/μb

A few low-level measuring instruments have been specifically designed for blast measurements.

The low-pressure range sensors for the BRL self-recording gages are intended for measurements of minute pressure changes at great distance from the blast and have made earth-based measurement of high-altitude detonations.

For very low-level measurements, the Sandia Corporation (Reference 23) uses a Wiancko 3-PBM-2 twisted bourdon tube microbarograph sensor capable of recording blast waves of 1-microbar to 48-millibar overpressure. An amplifier and a two-channel Brush pen-type recorder, with difference in sensitivity of 4:1 between channels, complete the unit. The recording paper speed most often used is about 1 inch per second, but faster and slower speed settings are available. A time-marking trace is provided on the edge of the recording paper. This equipment has been used for years, with some minor modernizations, for recording distant waves from nuclear tests. It gives about 95-percent amplitude response to a square-wave pressure input in about 30 milliseconds. It has an adjustable bleed plug which can be set to allow a compression to bleed off to 1/3 of the initial amplitude in 20 to 50 seconds. This equipment is considered to be satisfactorily accurate for recording acoustic waves from yields ranging from 100 pounds to about 20 megatons. Calibration and linearity checks have shown that these sets will record within a ± 20-percent amplitude accuracy about 85 percent of the time without on-the-spot recalibration. This is comparable to most blast-wave recording systems, unless very detailed and careful calibrations are performed for each usage.

ROCKET AND BALLOON-BORNE MEASUREMENTS

Two systems will be discussed: The BANSHEE instrumentation used on high-altitude HE simulation tests and the proposed Blue Rock system. Both systems are self contained with the sensor, recorder and power supply located within the instrument canister. In each system the canister also contains instruments measuring other phenomena.

During the BANSHEE tests, a single balloon carried both the measuring instruments and the HE charge. Two types of gage were contained in the instrument canister; the BRL self-recording mechanical gage and piezoelectric gages.

The canisters used to house the electronic and mechanical gages were metal cylinders approximately 5 feet in length by 4-3/8 inches in diameter. The end of the canister that faced the charge ended in a right circular cone; the opposite end of the canister was flat. The canister at Station No. 1—the gage station closest to the detonation—was made of steel. The remaining three canisters were made of aluminum. Each canister consisted of a number of individual cylinders that were fastened together to form the complete canister cylinder. Joints were sealed with rubber "O" Rings and the interior of the entire canister assembly was bled to ambient pressure through a 1/8-inch diameter bleed hole located on the flat base of the canister during the balloon ascent to altitude. During the ascent and floating phases, each canister was encased in a polystyrene thermal jacket designed to maintain the interior of the canister at approximately 70°F. The thermal jackets were jettisoned approximately 2-1/2 minutes prior to charge detonation or missile interception.

The mechanical gage was constructed as a complete sub-assembly of the instrument canister, and the gage housing became a cylindrical section of the canister.

Kistler MIC and BRL lead metaniobate electronic gages were recorded on Leach MTR-500 14-channel miniature tape recorders. The sensing surface of one lead metaniobate gage was covered with a protective cap so that it would indicate effects on the gages which might not be directly related to blast pressures.

After the detonation, the instrument string was parachuted to earth and recovered.

Two problems were noted with this system.* First, there was a shock induced through the suspension system which caused the electronic gage pre-amplifiers to saturate. Evidently, the pre-amps were sensitive to both the mechanical shock and the induced accelerations. Secondly, there were often failures with the thermal jackets. It is believed that gage sensitivity was reduced due to cooling of the gages.

The Blue Rock system is designed by NOL to measure blast pressures from high-altitude explosions. Magnetic tape recorders inside parachute- or balloon-supported canisters record pressure-time data from sensors located in the noses and at four uniformly spaced positions about the mid-sections of the canisters.

The pressure sensor used is an aluminum piston supported by a thin aluminum tube operating within a steel cylinder. Two active semiconductor strain gages are bonded to the outside of the thin tube and react to stresses induced in the tube by pressures exerted on the piston face. Two additional identical strain gages, which comprise the remainder of the bridge, are packaged within the aluminum tube. A full-scale pressure applied to the sensor piston face produces an unbalance of 12 mv/v in the strain gage bridge. The lowest mechanical resonance of the sensor assembly is approximately 30 kHz.

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*Sub-system and component malfunctions were also noted, but, since these are almost normal for a field operation, only those problems unique to the balloon-borne system are discussed.

Bridge controlled oscillators associated with the sensors produce signal frequencies proportional to bridge unbalance. These FM signal frequencies, proportional to applied pressures, are then recorded on the internal tape recorder.

Fluidic Devices

In addition to the fluid oscillator time-base generator described (on page 90) and the contemplated development of a pure fluid amplifier, Bendix-Friez developed for BRL a liquid mass, self-damping, triaxial self-recording accelerometer which merits mention. Although the device has not yet performed to specifications, it holds promise of evolving into a reliable, radiation-resistant field instrument.

All components of the prototype gage except the high pressure gas supply and pressure regulator were housed within an aluminum alloy cylinder with a stainless steel cover and mounting plate. The overall dimensions were 11-1/2-inches long by 4-3/4-inches diameter at the mounting plate. The gas supply and pressure regulator were housed in a separate cylinder 5-1/2-inches long by 3-1/4-inches diameter. The two containers were connected by pneumatic tubing and an electrical cable.

The following were principal components in the accelerometer housing:

1. A liquid mercury seismic mass, housed within a roughly cubical cavity, with a Ni Span C membrane mounted on each of the six cavity walls

2. Six conduits containing the silicone fluid coupling liquid, starting at the outer surface of each of the six membranes and terminating at a Ni Span C diaphragm in each conduit

3. A metal tube, carrying a stylus, connecting the outer surfaces of the diaphragms, in pairs, for each of the three orthogonal axes of the seismic cavity

4. A spring-powered tape recorder in which a negator spring supplied the motive power and the recording surface

5. A fluid oscillator timer operating a stylus at a calibrated frequency of approximately 500 Hz

6. A fixed or reference stylus
7. A battery
8. An explosive piston actuator
9. A manual arming switch.

In operation, a remote initiating switch is closed to fire the explosive piston actuator to accelerate the tape recorder to normal tape speed within five milliseconds and start the regulated gas to flow to activate the fluid timer. The recorder tape runs at about 3 inches per second for 20 seconds. Accelerations sensed by the instrument appear as deflections in the traces scribed on the tape by one or more of the three sensing styli. At the same time the fixed or reference stylus and the timer stylus scribe respective traces on the tape.

The principle of operation of the sensing system may be described as follows: when the accelerometer is subjected to acceleration, the liquid mercury tends to move in the direction of the resulting force. Motion of the mercury deflects one or more pairs of membranes on the cavity walls and thus imparts motion to the silicone fluid in the coupling lines. The coupling fluid transmits motion to the diaphragms which, acting in pairs, deflect the attached styli.

Data is obtained from the instrument by removing the tape from the recorder and examining the traces under magnification. Acceleration values are determined by comparing the observed deflections with calibration data. Time intervals are determined from the number of cycles of known frequency traced by the timer stylus. The reference trace serves as an indicator of tape stability. Table 9 lists the characteristics of this device.

Two major drawbacks to field use exist. First, the use of mercury as the sensing mass produces a very heavy instrument. Second, undesirable cross-talk was prevalent in drop tests. Cross-talk in these triaxial accelerometers may be roughly defined as a recorded response in one or both axes at right angles to the direction of the input acceleration.

GAGE MOUNTING

The gage systems described in the preceding section may be used to measure either stagnation or incident pressure, depending on the method of mounting the gages and their orientation with respect to the direction of blast wave propagation.

Table 9. Triaxial accelerometer capabilities.

Range	0—75 g and 0—150 g built and tested, ranges up to 0—1000 g are feasible.
Stylus Deflection	0.010 in. minimum for 75 g (tested).
Natural Frequency	Approximately 60 Hz for 75 g unit.
Damping Ratio	0.35 for 75 g unit.
Recorder	Negator spring powered with separate metal recording tape. Nominal tape speed of 3 ips and 20 sec minimum running time. Start-up time with explosive piston actuator: 0.5 ms.
Recording Tape	Magnetic stainless steel, 3/8 in. width x 0.001 in. thick x 60 in. maximum length.
Time Base	Fluidic type time marker, nominal frequency 475 Hz $\pm$ 1 percent at constant temperature and nominal 20 psi gas supply pressure.
Initiation	External electrical line or gamma radiation of 1.5×10^4 rad/sec or more.
Power	Rechargeable dry cell, 12 volts nominal.
Physical Size	
Accelerometer	3-3/4 in. x 4-1/2 in. x 9-1/2 in.
Fluid Supply and Regulator	4-11/16 x 2-11/16 x 1-3/4 in.
Mounting	Bulkhead
Weight	12 lb.
Environmental	
Temperature	Timer only −65° to +165°F.
Vibration	0–2000 Hz at 20 g
Shock	250 g, 11 ms.

For stagnation measurements the pitot tube is usually employed (Figure 13). Pitot tubes for both subsonic and supersonic flow have been designed (Reference 9).

Care in gage orientation is required to insure that incident pressures are actually measured. Two methods are currently standard. The first uses a side-on baffle, consisting of a 1/2-inch thick aluminum disc, 18 inches in diameter, with the gage mounted flush with the center of the disc (Figures 14 and 15). The baffle allows the blast wave to develop a steady laminar flow past the inlet port of the gage. Orientation of the baffle is critical; the face of the disc must be parallel to the direction of the shock propagation. Yaw angles of 10 degrees can produce a 5-percent error in the blast record. In regions of supersonic flow, above-ground mounting of the side-on baffle is not desirable because of the difficulty of constructing a rigid support structure; therefore, the second mounting method places the gage face flush with the earth's surface, usually in the center of a large mass of concrete, and often attached to an aluminum baffle which is, in turn, mounted flush with the concrete.

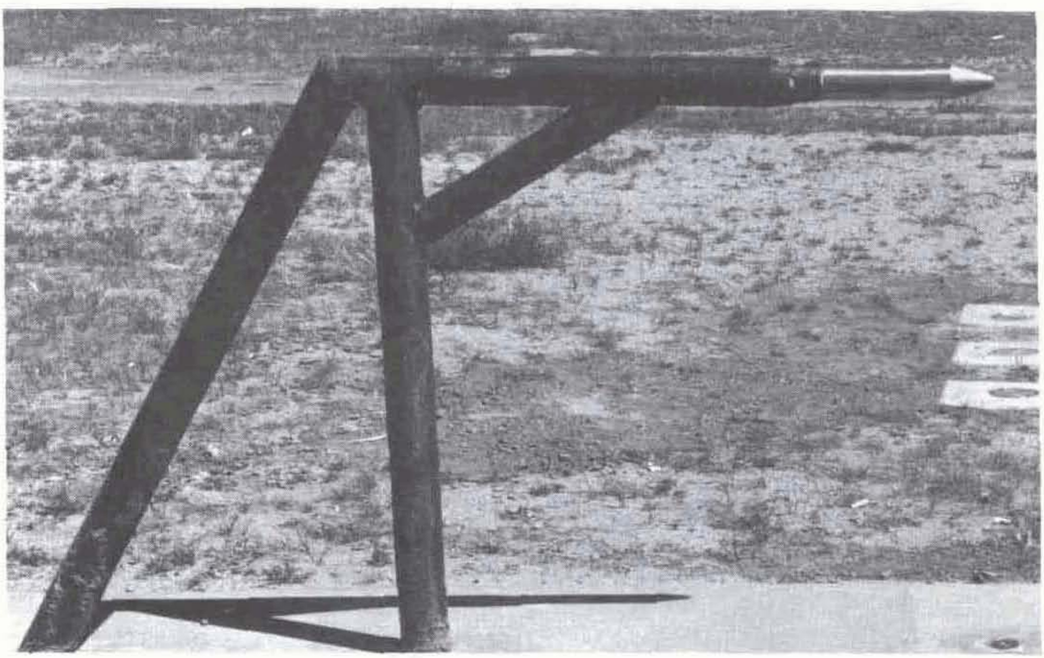


Figure 13. Pitot tube gage mount.

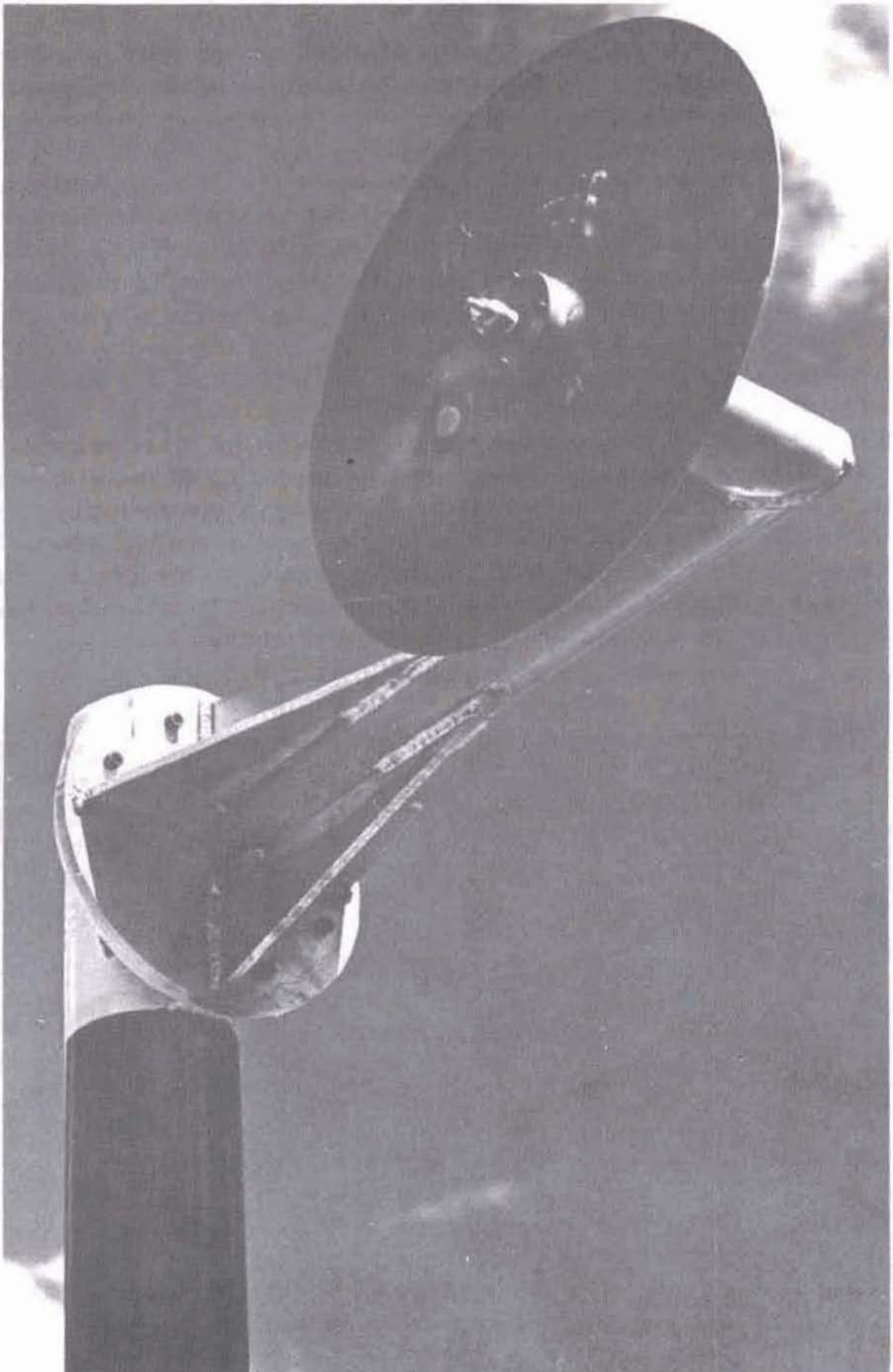


Figure 14. Side-on baffle for an airblast gage.

Figure 15. Underground flush-gage mount.

NOL has designed and used a hemispherical baffle (Figure 16) with a single inlet port for situations where no stable mounting is available (Reference 28). The gage within the hemisphere does not measure true incident pressure. However, this parameter can be calculated from the measured gage response if the aerodynamic characteristics of the baffle and its orientation with respect to the shock front are known. The aerodynamic characteristics may be determined by theoretical calculations while photo-triangulation is used to interpret gage orientations with respect to the blast waves.

BRL has adapted its basic self-recording system to a non-directional gage which will measure pressure pulses irrespective of the orientation of the gage (Figure 17). Such a system will have great usefulness when used on anchored barges or balloons where the position of the gage cannot be fixed. In the non-directional gage, the self-recording system is positioned within a 12-inch diameter, 1/2-inch thick aluminum spherical shell. Overpressure is admitted to the sensing element through 24 holes 1-1/2 inches in diameter spaced equally around the surface of the sphere.

For airblast measurements in the underground cavities used to contain nuclear detonations, special methods of gage mounting are

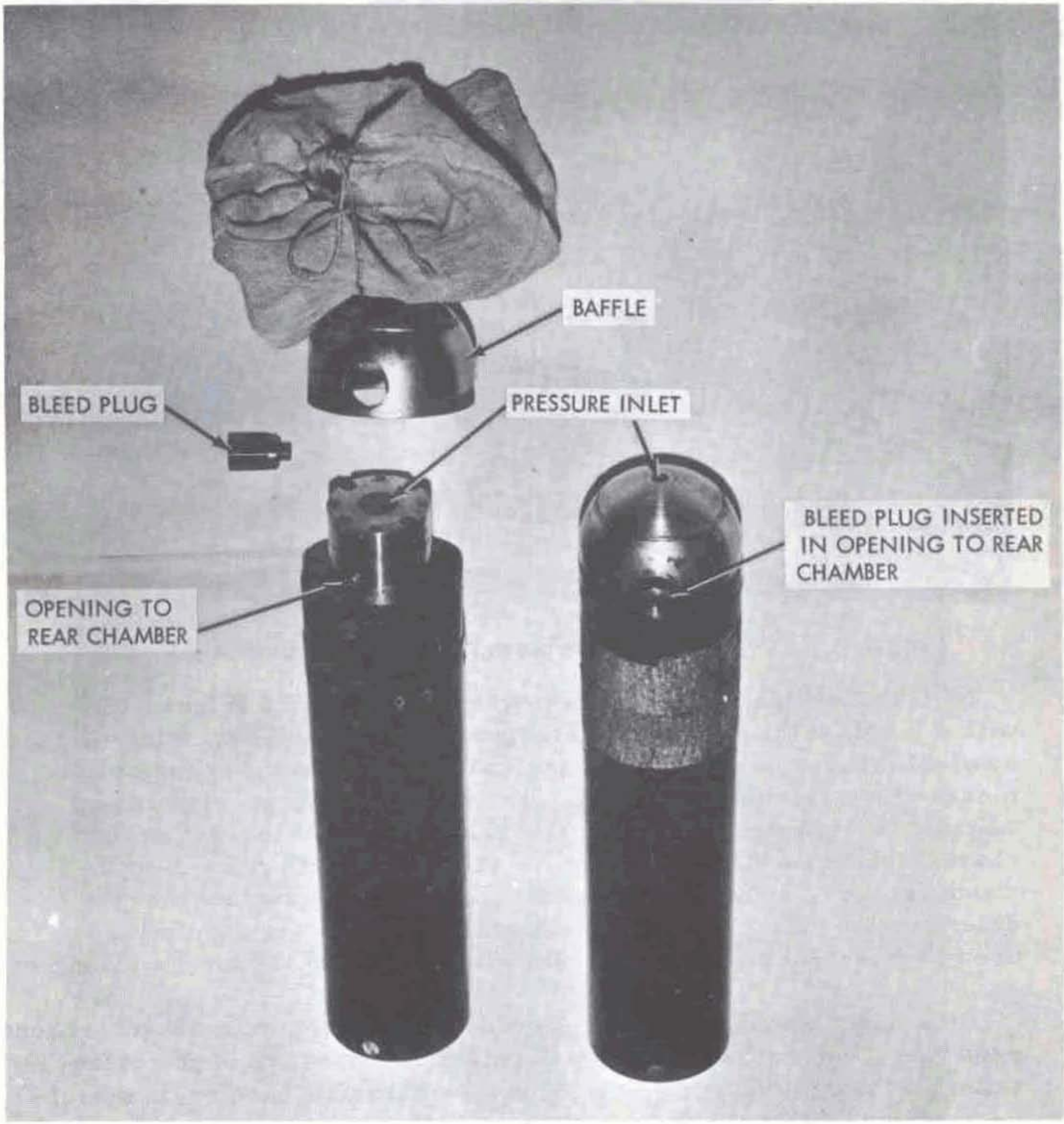


Figure 16. NOL airblast gage with hemispherical baffle.

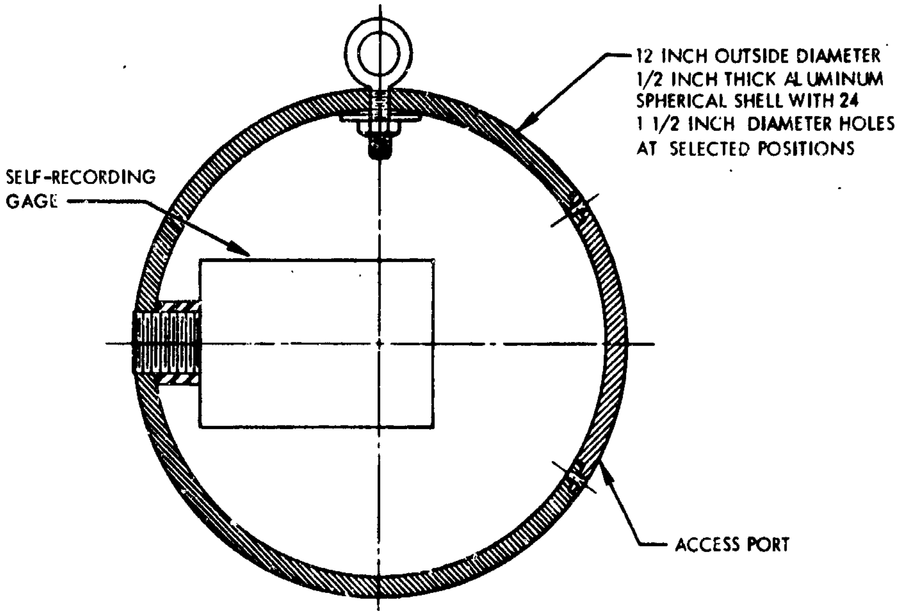


Figure 17. BRL non-directional gage mount for the BRL mechanical self-recording gage.

required. The main consideration is survival of the gage (and its transmission line) for the duration of the pressure pulse. The important functions of the gage mount are:

1. To absorb as much as possible of the energy imparted to the gage by the blast pressure loading

2. To shield the gage and its associated input and output cables from the intense electric and magnetic fields generated near a nuclear explosion

3. To protect the gage from the thermal pulse and radiation produced by the device

4. To protect the gage output lines from crushing.

Solutions to these problems exist (Reference 14).

In general, special gage canisters are designed using soft metals, silicon rubber, and plastics such as polyethylene and polycarbonate (Lexon) to protect the gage. Recording times of 3 microseconds at pressures in excess of 4000 psi have been obtained.

DYNAMIC PRESSURE

Dynamic pressure may be calculated from the separate measurement of stagnation and incident pressures; it may be obtained from a special gage configuration employing a sensor, or two or more sensors, to record the differential pressure between the stagnation and incident measurement; or it may be derived from the calibrated response of drag-sensitive targets.

Calculation

In the calculation method most often used, the stagnation and incident pressures, as functions of time, are obtained from separate instruments. A correction factor, which is a function of the Mach number of the particle flow behind the shock, is applied to the stagnation pressure value in order to determine the true pressure in the absence of the probe. For a clean (e.g., non dust- or water-loaded) blast wave which can be expressed mathematically in terms of isentropic flow, the Rankine-Hugoniot equations which relate the incident overpressure, the air flow and the ratio of specific heat of air at constant volume and constant temperature are used to find dynamic pressure. The calculation of the correction factors for Mach compressibility, the factors required, and methods used for dynamic pressure determination in dusty air are found in References 29 and 30.

Since two measurements of pressure are made, the cumulative errors in calculated dynamic pressure are multiplicative, not additive. To help reduce error, it is important that the separate gages be placed close enough together to simultaneously sense the shock wave, yet far enough apart so that neither gage perturbs the flow around the other gage.

Direct Measurement

A logical refinement to the method of obtaining data from separate gages is to obtain both required measurements from a single gage either by using a single sensor to register the difference in pressure between the head of the probe and an entry port along the probe body, or by two or more sensors to make these measurements. Usually the single probe is used only in regions of subsonic flows because the use of side ports on a supersonic pitot tube requires a rather long span between these ports and the nose of the instrument in order to assure unperturbed flow at the side ports. This requirement leads to a mechanically weak probe.

Three gages have been considered "standard" for dynamic pressure measurement in nuclear tests. Although not used today in high-explosive testing, these gages, perhaps with newer-type sensing elements, would probably be used in an atmospheric nuclear test if testing were resumed. Their general features are described below. Reference 30 discusses the relative merits of each gage.

Sandia Corporation Pitot Static

The Sandia Pitot Static Differential Gage is a snubnose probe, 2 inches in diameter and about 18-inches long. Pressure entry ports are located at the tip and about 6 inches from the tip. Two Wiancko variable-reluctance sensors measure the difference between the stagnation and the incident pressures and the incident pressure, respectively.

BRL "q"

The BRL "q" Gage is similar in external appearance to the Sandia Pitot Gage but is about 3 inches in diameter. Normally, only the stagnation pressure is measured, but one model, called the QGS, measures both stagnation and incident pressure (Figure 18). The sensing element is a BRL self-recording gage.

The Sandia and the "q" gages were designed to measure dynamic pressure at rather low dynamic pressure levels. The hemispherical shape of the probe tip and the location of the side ports cause the correction for Mach number to become large at flows above Mach 0.9.

SRI Total Head

SRI developed a Total Head, or "Z" gage specifically to gather data used to calculate dynamic pressure in regions of supersonic flow. The probe has a sharp tapering nose, a dust vent, and a filter to prevent sand and dust from reaching the sensing element. Only stagnation pressure is measured.

MEASUREMENT IN DUST-LADEN AIR. Dust loading of air by a blast wave influences the dynamic forces. Special instruments have been devised to determine the characteristics of a dust-laden blast. Two instruments, the Snob and Greg gages, have been used extensively to obtain dynamic pressure data from atomic tests. They

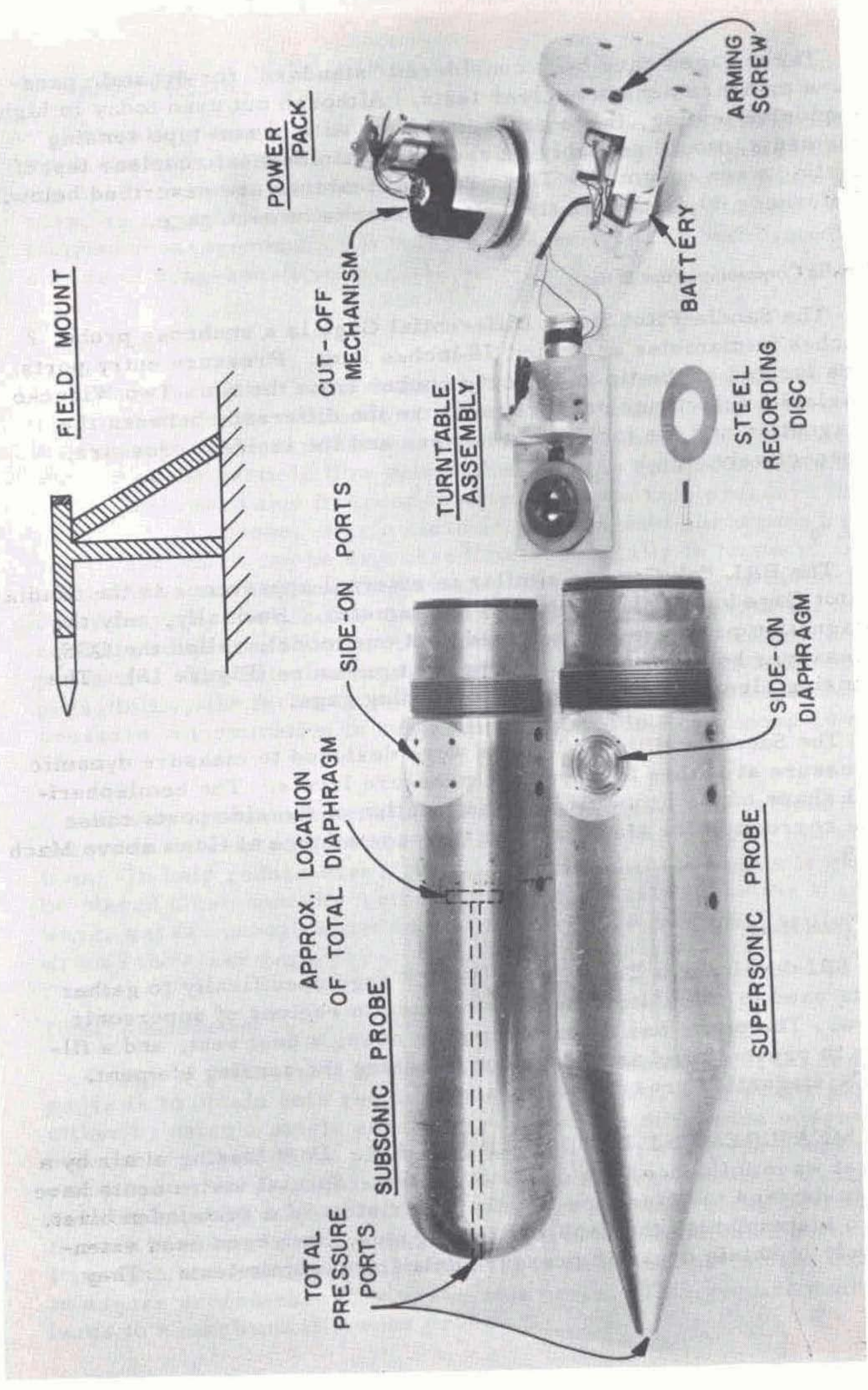


Figure 18. BRL QGS gage for dynamic pressure measurements.

supplement each other in field use. Reference 30 gives a detailed account of these gages as well as the standardized procedures for the reduction of their data.

Snob

The Snob, so named because it is intended to ignore the dust, obtains incident pressure- and dynamic pressure-time measurements in clear or dusty air. The gage diameter is made so small, compared with the average distance traveled by a dust particle to reach stagnation, that the dust loading is insignificant. The Snob has a very small-diameter nose with a streamlined tip. The stagnation pressure is transmitted from a point close to the probe tip through a set of small holes, and then to the forward pressure sensor which is located near the middle of the probe. A long cylindrical cavity designed to decelerate and capture dust particles also opens to the probe tip. The incident pressure is sampled through eight ports and is fed to the rear of the sensor to obtain a differential pressure. There is also a sensor to measure independently the incident pressure. The response time of the stagnation sensor is about 3 milliseconds. The overall response time is dependent on the difference in fill time between the two cavities and is about 4 milliseconds. Some error, about 4 percent, was noted in the pressure levels recorded by the incident pressure sensor; this was assumed to be due to flow perturbations, introduced by the gage support and mount (Reference 30).

Greg

In the Greg gage, a different concept is involved. By stopping the flow completely on a surface, the total momentum flux can be determined. The gage thus needs to measure only stagnation pressure. The gage consists of a flush diaphragm sensor, mounted on a probe with a hemispherical tip. The diaphragm is protected from abrasion or puncture by several layers of silicon rubber. The Greg, like the Snob, employs an Ultradyne variable-reluctance sensor.

By comparison of the measurements of the two types of gages, both the clear air dynamic pressure and the effect of dust loading can be determined.

BRL Self-Recording Gages

BRL has constructed self-recording versions of both the Snob and Greg gages by replacing the normal sensing element with a self-recording gage (Reference 31). After this modification, the Snob gage measured only stagnation pressure and it was necessary to use the incident pressure determined nearby to calculate dynamic pressure. The Greg gage was further modified by placing a free piston in a sliding fit in the pressure port. The piston sensed the pressure and transmitted the combined air- and dust-stagnation pressure to the self-recording gages. Hydraulic brake fluid was used to fill the pressure sensor, the small volume behind the piston, and the connecting passage.

SRI-MAD

A modern descendant to the Snob and Greg is the Stanford Research Institute MAD (Measurement of Air and Dust) gage—a total pressure probe which measures the dynamic pressure of the air phase and the momentum flux of suspended dust almost independently, and can extend the measurement into the 500-psi region. The basic element in the latest version of the SRI-MAD system is a vented pitot tube about 6 inches long with ports for measuring the local pressure at two locations along the tube length (Figure 19). Pressure is measured as near the forward end of the tube as possible and again as near the rear as possible. Free stream incident pressure is measured through static taps in the wall of the gage body. Venting of the pitot tube (to avoid plugging with dust) is controlled by a metering orifice at the rear of the tube.

As the stream of dust-laden air encounters the nose of the tube, the air phase decelerates almost immediately to the velocity of the metered airflow within the tube. The dust particles, being considerably more massive, decelerate gradually due to air drag, slowly transfer momentum to the air, and cause a corresponding increase in pressure with distance along the tube length. The pressures from the front and rear ports are transmitted through separate passages to variable-inductance pressure sensors (at present, Ultradyne Model S-30). Data from the front port and the static port are used to compute the air dynamic pressure, while the difference in pressure between the front and rear port is a measure of the dust momentum flux.

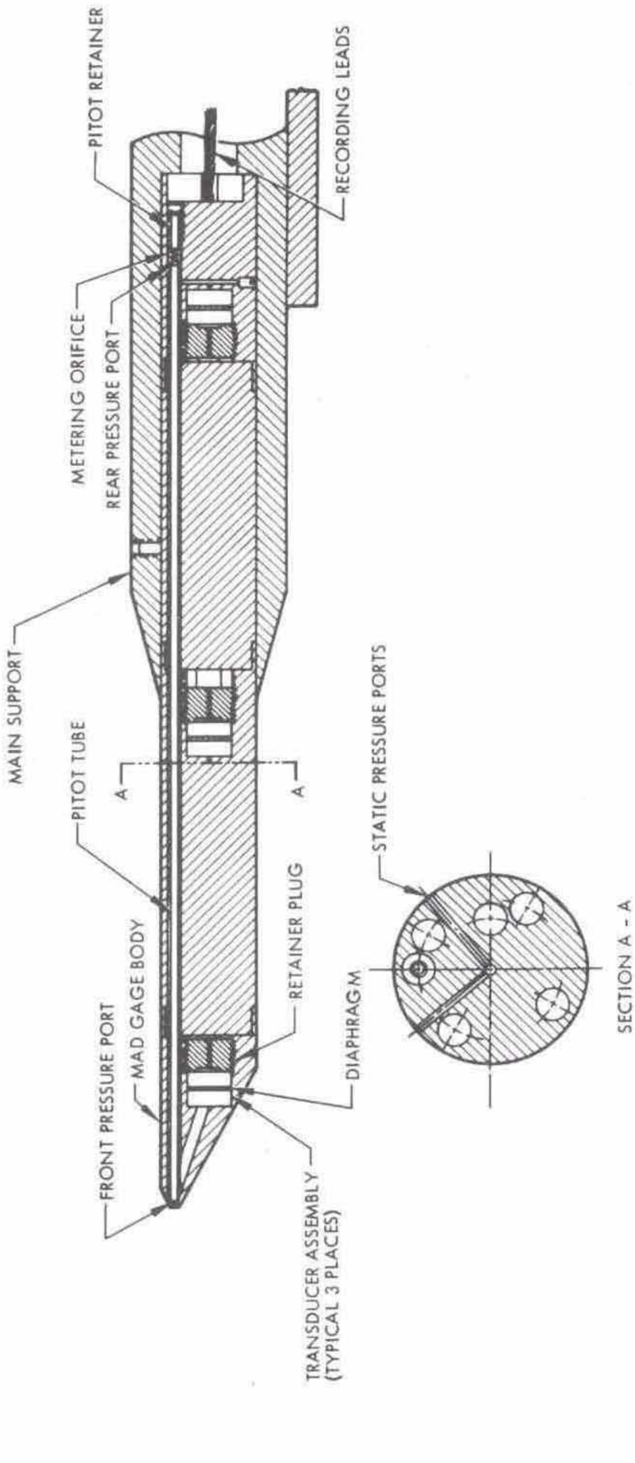


Figure 19. SRI-MAD gage.

An inductive frequency-modulated-multiplex (FMX—[the X stands for experimental]) system is used to transmit signals from the MAD gage. Each of three sensors in the gage (measuring front port pressure, incident pressure, and rear port pressure, respectively) consist of a diaphragm sandwiched between two coils, with a sealed cavity between diaphragm and coil on each side. As the cavity on one side is pressurized, the diaphragm is displaced, causing a change in the inductance of each of the two coils—an increase in one and a decrease in the other. The coils are active members of tank circuits of two separate oscillators; therefore, as the inductance of the coils changes, the frequencies of the two oscillators also change, one increasing and the other decreasing. The oscillators' basic frequencies, when subtracted, provide a frequency which falls in one of the bands of a standard ±4-kHz constant-bandwidth carrier system. This FM signal is combined with other FM signals in the carrier system and is transmitted to the data collection center on a single pair of wires. The composite signal is conditioned for the correct level and transmitted to a magnetic tape recorder. The signal-conditioning system is also capable of separating each band from the composite for quick-look evaluation.

The interpretation of data from the MAD gage requires a knowledge of the dust particle size. Therefore, a dust sampler is always used in conjunction with the MAD gage to obtain samples for laboratory determination of particle size distribution.

The dust sampler is a 2-inch I. D. tube, open fore and aft, and equipped with two explosive closing devices in tandem and about 30 inches apart (Figure 20). When the advancing dust cloud interrupts a light beam, the devices fire simultaneously, pinching off a section of the tube and capturing a sample of dust-laden air. In supersonic flow, isokinetic sampling can be achieved if the shock wave attaches to the forward end of the tube and if velocity equilibrium between dust and air is re-established before reaching the location of the first closing device. Therefore, the leading edges of the samplers are sharp, to minimize shock detachment distance, and, although it is estimated that velocity equilibrium is re-established within about three diameters, the first closing device is placed about six diameters aft of the nose. It is estimated that the closing signal lags the dust cloud arrival by not more than 5 or 6 milliseconds; simultaneity of of closure is assured to within ±1 or 2 microseconds. Field experience has indicated that the explosive closure devices on the dust sampler require redesign or modification.

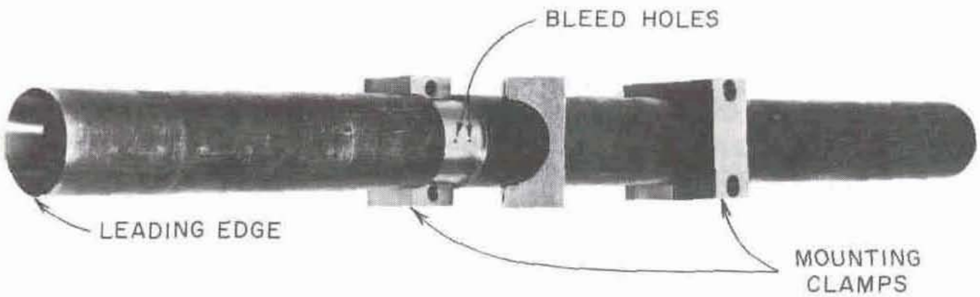


Figure 20. Dust sampler (explosive closures not shown).

Indirect Methods of Measurement

Drag-sensitive targets may be used in two ways to determine dynamic pressures: (1) as an active gage where the pressure-time response is recorded; and (2) as a passive gage where only the effect of the dynamic force is noted.

DRAG GAGES. Total-drag probes which directly measure the drag force on a specifically shaped body are representative of the active gages.

NOL Three-Component Force Gages

NOL developed and used three-component force gages in a number of nuclear tests (Reference 63). These gages measured the blast-wave-induced forces on a small target in three mutually perpendicular axes.

The targets were 4-inch and 10-inch diameter spheres, 4-inch and 10-inch cubes, 6-5/8-inch diameter cylinders, and 6-5/8-inch parallelepipeds (the last two measured in two axes only).

The NOL system consisted, basically, of a variable-inductance sensor, a FM multiplexer, and magnetic-tape signal recording. The sensing elements contained within the target responded to the excitation produced by the blast wave and modulated the frequencies of oscillator units located in close proximity to the gage. Each component, in conjunction with its associated oscillator, operated on a different frequency. The signals from each gage were multiplexed and transmitted as a single FM signal on up to one mile of field telephone wire to an instrument shelter where multichannel magnetic tape recorders received the signal. Calibration and timing signals were recorded simultaneously.

The sensors were supplied by Schaevitz Engineering Company and Ordnance Engineering Company. Both manufacturers used the same basic design for the mechanical and electrical systems of the gage; however, construction details differed. The principal features of the mechanical system were the three independent and orthogonal axes which restrained the target motion to translational displacements only. The restraining force of each axis was provided by a pair of springs which could deflect only in a direction perpendicular to the plane of the springs and only when a force or a component of force was in this same direction. Because of great stiffness of the springs to forces in directions other than the one just mentioned, springs themselves were used as rigid supports for the structural members of the other two axes. In this way, the orthogonal components of a vector force acting on the gage influenced only the respective rectilinear axes of the gage.

The points of difference between sensors supplied by each manufacturer were in the type of springs used, the material employed in the electromagnetic circuit, and the maximum translational motion the model allowed.

Each axis of the force gage had its own natural frequency. The frequencies were limited by the mass of the moving parts of the gage and the spring constants required to allow this mass to move only as far as necessary to generate the required electric signal. These frequencies ranged from 85 Hz to 550 Hz. This relatively low frequency response prohibited the use of these gages for measuring short-duration diffraction forces; hence, their usefulness was limited to the long-duration drag phase of the shock wave interaction.

SRI Total Drag Probe

The drag-sensitive target in the SRI Total Drag Probe is a hollow 3-inch long section of a 3-inch diameter mounting cylinder, 33 inches in total length (Figure 21). The mounting cylinder is rigidly positioned with its long axis parallel with the ground and at right angles to the direction of air flow (Reference 32). The target element is at the center of the mounting tube in order to minimize the effects of flow around the end of the element. The target section is restrained axially by set screws to avoid binding at the interface with the mounting cylinder.

The sensing elements are strain gages attached to an octagonal proving ring within the hollow target cylinder. Blast-induced drag forces produce a small displacement of the target cylinder, which is measured by the strain gages on the proving ring.

The initial design was for four different maximum overpressure ranges varying from 50 to 500 psi. The natural frequency of these gages varied from 4 kHz to 5.5 kHz. The sensitivity was adequate for measurement from as low as one percent of the predicted maximum loading to a dust-loaded force up to five times the predicted air loading.

SRI-BRL Drag Force

SRI constructed for BRL a number of special cross-section drag gages which used the same sensing element as the SRI Total Drag Probe (Reference 33). The main design features of these gages are listed below and are shown on Figure 22.

SRI-BRL Square Cross-Section Total-Drag Force Gage

A cylinder of square cross-section was used in place of the original cylindrical target.

SRI-BRL Cubical Total-Drag Force Gage

A cube of the same edge dimensions as the cylinder of square cross-section was located at the end of the mounting tube.

SRI-BRL Circular-Plate Total-Drag Force Gage

Similar to the cubical gage except that an 8-inch diameter plate was fastened to the surface of the target facing the blast.

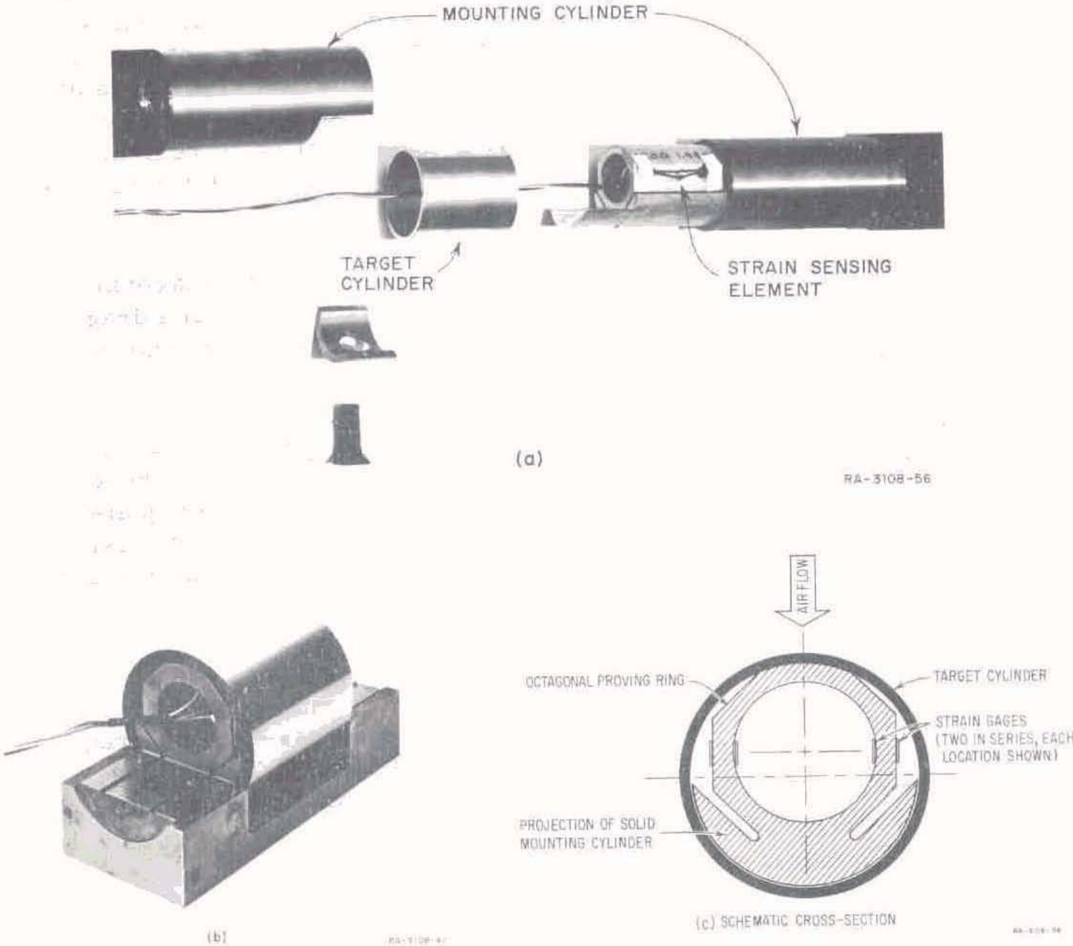
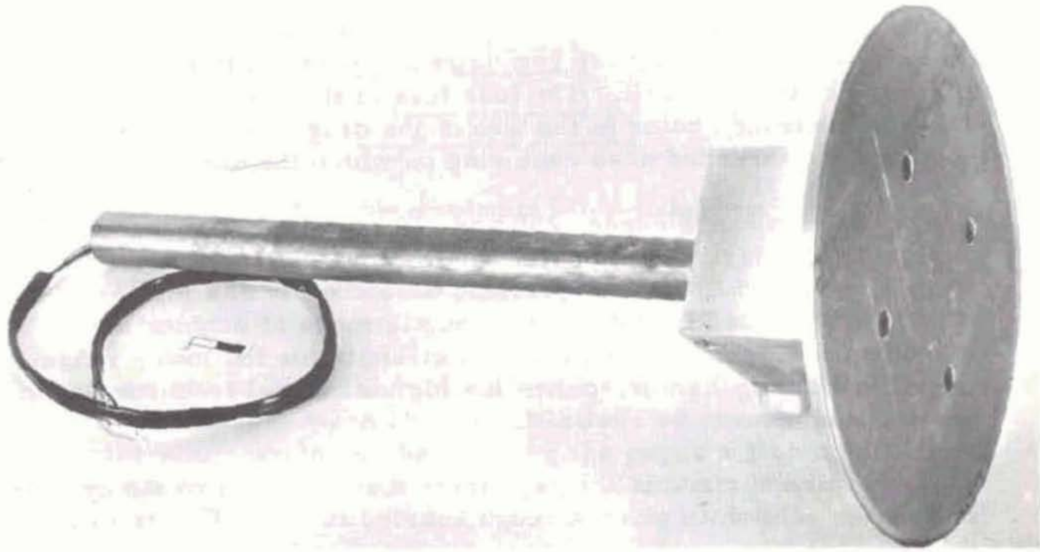


Figure 21. Total drag probe assembly: (a) exploded view—drag probe shown is for 50 psi overpressure region, (b) 500-psi probe shown on calibrating jig, (c) schematic cross-section.

a. SRI-BRL cylindrical drag force gage of square cross-section.

b. SRI-BRL cubical drag force gage.



c. SRI-BRL circular plate drag force gage.

Figure 22. Drag force gages.

In an HE simulation test, all the gages except the cubical one showed severe initial oscillations. Since the cubical and the circular plate gages both contained a high-viscosity silicone oil for gage damping, it is difficult to assess the significance of these oscillations.

BRL Bi-axial

BRL has constructed a bi-axial drag gage for measuring the magnitude and direction of dynamic blast pressure. The sensing element is a load cell in a target area that behaves approximately like a section of a cylinder of infinite length.

The Schaevitz-Bytrex Corporation provided BRL with a special load cell 1-inch square by 1-1/2-inches long that would sense forces in two cross axes. A cylindrical drag gage was designed around this load cell. Figure 23 is an assembly drawing of the completed probe.

The conical base was designed to give rigid support to the active elements and to provide easy mounting in a 3-inch O. D. by 2-inch I. D. tube. The base is firmly held in the tube by a series of set screws and the bi-axial load cell is affixed to this base. The center section encloses the load cell and provides support for the nose cone. A minimum clearance is allowed between the center section and the load cell to allow for the flexing of the cell. The drag cup is the sensitive section and provides a frontal area of 1 inch by 1-5/8 inches. The central web of the drag cup is firmly screwed to the top (moving element) of the load cell. The four legs of the center section fit through clearance holes in the web of the drag cup. To these legs is mounted the threaded nose cone ring on which the nose cone is screwed.

On the high range gages, 250 and 750 pounds force, the components are made of a high strength aluminum alloy 7075T6. On the low ranges, 25 and 50 pounds force, the base cone is of a milder aluminum alloy 2024T3, and the drag cup is made of magnesium. The magnesium drag cup is of sufficient strength for the lower ranges of gages, and being lighter, permits a higher natural frequency of the moving elements to be realized.

The entire surface of the gage from the nose cone to the cylindrical center section is given a rough knurled finish. This is to promote

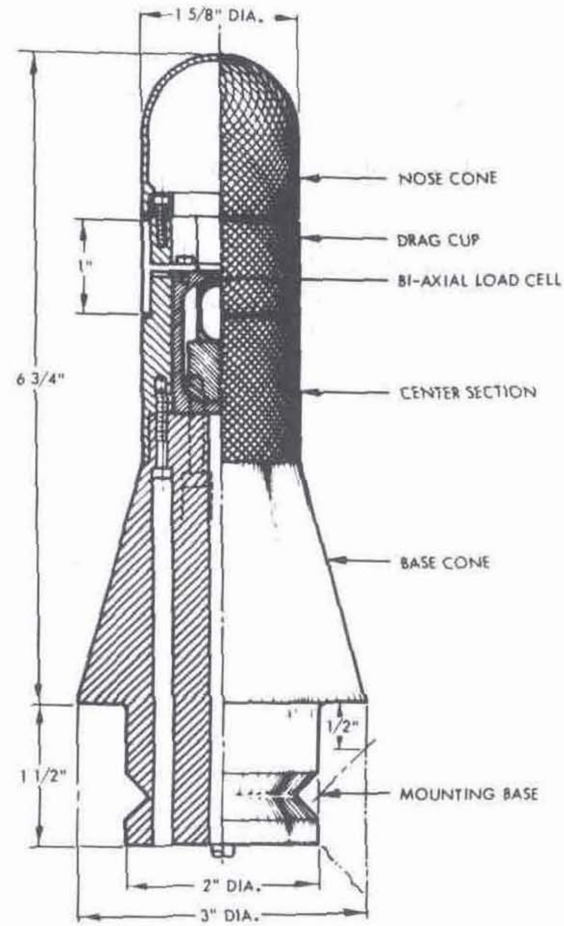


Figure 23. Assembly drawing of BRL bi-axial drag gage.

turbulent flow about the body and minimize variations in drag coefficient in the transition region of flow.

Four ranges of bi-axial load cells were made for BRL by Schaevitz-Bytrex. The ranges were 25, 50, 250, and 750 pounds. All ranges used solid-state strain patches, giving the gages a high output signal of approximately 20 millivolts per volt full scale. The input signal was 5 volts. With the drag cups mounted, the load cells had natural frequencies which varied with the rated range:

25-pound gage	=	2.5 kHz natural frequency

50-pound gage	=	3.5 kHz natural frequency
250-pound gage	=	5.0 kHz natural frequency
750-pound gage	=	5.0 kHz natural frequency.

One would expect the 750-pound gage, having naturally a more rigid member, to have a higher natural frequency than the 250-pound gage. The 750-pound element, however, is made of tool steel, while the 250-pound element is made of aluminum alloy. The increase in mass of the steel element over the aluminum element apparently nearly cancels the advantage of the increase in spring rate, resulting in similar natural frequencies.

GATC Tri-axial

The General American Transportation Corporation has proposed the construction of a tri-axial aerodynamic drag gage. The gage would consist of a hollow, 3-inch diameter sphere, mounted by means of a unique omnidirectional spring to the tip of a stinger. Blast-induced displacement of the sphere in each of three mutually perpendicular directions would be measured directly by three linear variable differential transformers (LVDT). The transformer signals would then be proportional to the three components of drag force acting on the sphere.

The preliminary design was for a gage capable of withstanding a 100-psi incident pressure (with a generous overload allowance), and having a natural frequency of about 20,000 Hz. Schaevitz-Bytrex would provide an LVDT radiation-hardened to 3×10^{20} n/cm^2 and 10^{13} ergs/g of gamma. The status of this proposed gage is unknown at this time.

PASSIVE DYNAMIC PRESSURE GAGES. Passive gages are little used today because they indicate only total force and specify nothing of the time histories which are so important in formulating predictive damage schemes.

DPI

The Australian DPI gage has been used in HE nuclear-simulation studies. It is representative of the passive gage. The DPI consists of a rigid stem and cylindrical target supported by a flexible aluminum hinge (Figure 24). The blast loading on the target causes it to de-

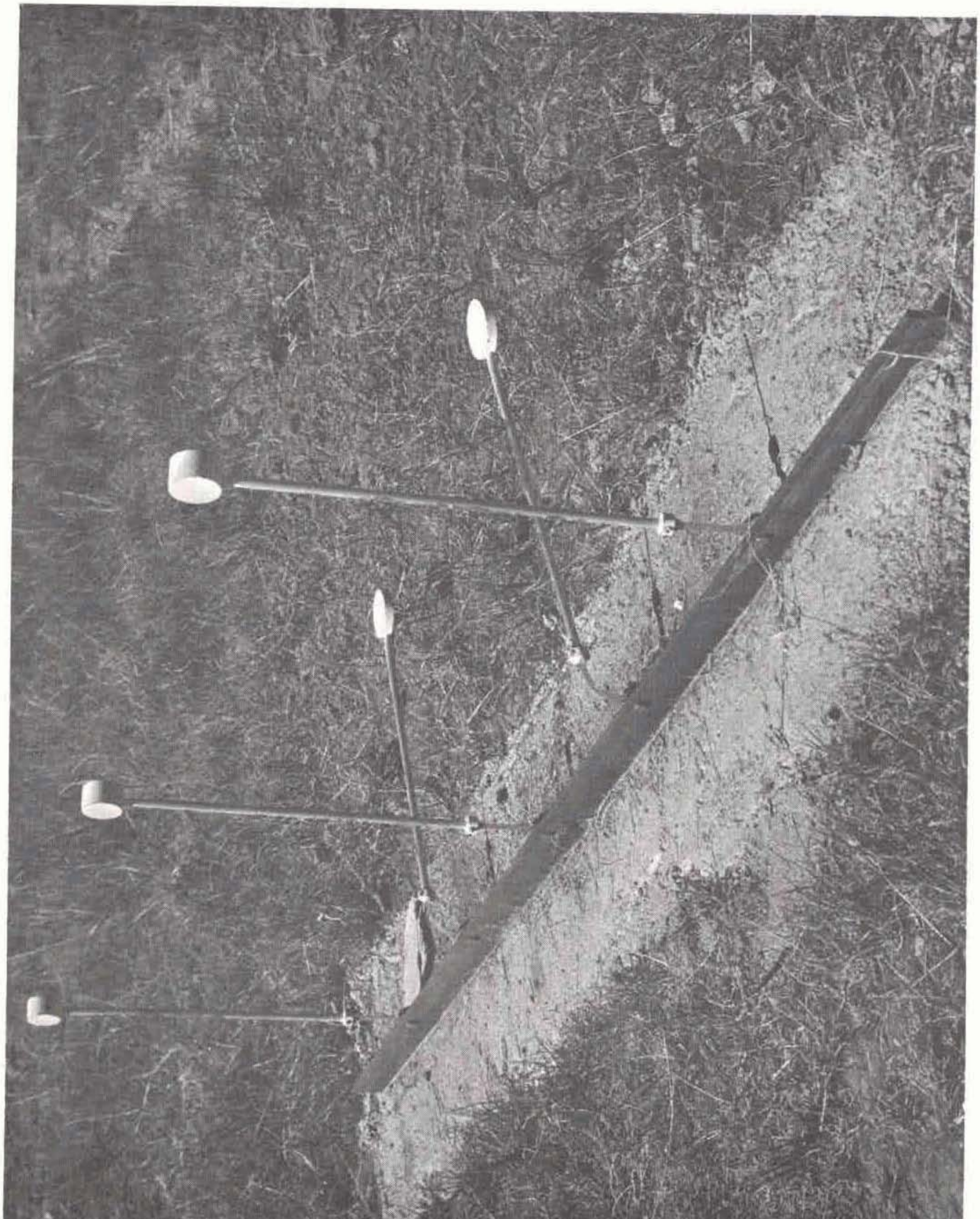


Figure 24. Australian DPI gages shown after being exposed to a blast wave.

flect away from the blast until the energy imparted to the gage is lost in plastic deformation of the hinge. Measurement of the angle of deflection, when applied to a calibration curve obtained in a shock tube, is a measure of the dynamic impulse of the shock wave.

Targets with different frontal areas are available to measure a wide range of overpressures. The gage is rugged, insensitive to radiation and EMP effects, and easy to install and maintain in the field. There is, however, some problem of interpreting the results when reflected blast waves from nearby objects deform the hinge, and the lack of a time history is a handicap.

Other passive methods have been used to determine response to dynamic pressure. One is the very pragmatic approach, where a piece of military equipment, such as a tank or jeep, is placed in the path of the blast wave, and its response to blast pressures is photographed. Often, only the total final damage is assessed without use or analysis of the motions recorded photographically. High-speed photography of the motions of simple objects of different size and shape in the blast wave is also used.

SECTION 4

UNDERGROUND MEASUREMENT SYSTEMS

SECTION 4

UNDERGROUND MEASUREMENT SYSTEMS

INTRODUCTION

Three major divisions exist in the types of measurement required of underground shock phenomena: first, a determination of the earth stress and pressure attenuation as the shock wave propagates through the soil or rock; second, a measure of strain; and third, a recording of ground motion, either as acceleration, particle velocity, displacement, or shock spectra. All of these parameters are determined as functions of time, distance from burst, and depth of burial. In addition, the strain and ground motion measurements require specification of both the horizontal (radial) and the vertical components.

In theory, only the stress measurement and one determination of ground motion are required, since acceleration, velocity, and displacement may be derived from each other by differentiation or integration with respect to time, and strain may be found by differentiation of displacement with distance (or vice versa). However, the accuracy of the calculations is dependent on an assumed perfect medium which is not encountered in field tests—or in laboratory tests, for that matter.

Studies of stress, strain, and ground motion have been made in the three response domains described on page 13 . The earliest measurements were at stress levels within the region of elastic response; recent studies have obtained data from the plastic and even hydrodynamic zones at pressures of hundreds of kilobars.

It is believed that the most important loading imposed on an underground structure will be produced by direct airblast-coupled loading on the earth's surface rather than by energy transmitted through the ground from regions closer to ground zero; therefore, the greatest amount of effort has been to obtain underground measurements in the high-overpressure region, i.e., airblast overpressures greater than about 100 psi, where the air shock outruns the ground shock. Measurements in the hydrodynamic domain are required to improve understanding of the mechanisms of energy coupling into the medium, in order to design super-hard installations.

Since the interpretation of the data from underground measurement is intimately connected with an understanding of soil mechanics, the normal problems of gage design and adequate matching of gage response to the type of measurement being made are compounded by two other factors which must be considered. They are:

1. The properties of the soil or rock medium where the measurement is made
2. The interaction of the medium and the gage.

Soils and rock are nonhomogeneous, anisotropic, and non-linearly elastic. The stress-strain relationships are dependent upon many natural factors such as soil or rock type, particle or grain size, porosity, water content, local voids and inhomogeneities, shear strength and past pressure experience.

Since the gage is, in effect, an inclusion within the medium, care must be taken that neither the gage nor the techniques used in emplacing the gage alter the local free-field stress-strain conditions. The degree to which a gage and its placement can achieve this goal determines the accuracy and repeatability of the measurement. The gage should assume the modulus and density of the medium in which it is placed, and its size and shape, relative to the size of the sensing area, should not be responsible for arching effects. In placing the gage within the medium, care must be taken to assure that the gage is mechanically coupled to the medium by seeing that no voids exist between the gage and the medium and that the material placed around the gage is impedance-matched with the medium. Various methods of gage placement have been attempted. They generally fall into two categories:

1. Compacting soil around the gage
2. Grouting.

Neither method has been shown to be clearly superior in field tests. The choice of method is usually made for other reasons. For example, grouting is the only possible method when placing a gage in rock, and it is the only reasonable method when the gages are located far from the surface in a bore hole.

In the sections that follow, only instruments for measurement in the hydrodynamic and the elastic regions are considered as separate categories. A load which causes a plastic deformation of an instrument (especially a non-linear plastic deformation) will distort that portion of the output signal generated during the deformation; thus most investigators prefer to use instruments designed for the elastic domain and disregard that portion of the time history which is distorted. Also, there is a great overlap in pressure ranges for elastic and hydrodynamic domain gages. Only those gages and systems of recent design or current use are discussed here; the reader is referred to Volume III of DASA 1285, Nuclear Geoplosics, for a presentation of the many different types of gages which have been used for underground measurement.

HYDRODYNAMIC ZONE MEASUREMENTS

In the hydrodynamic zone, stress is much greater than the strength of the materials used to construct gages. The problems of survival of gage and cable until the complete stress-time relation is recorded are formidable, and have not yet been solved. Only the peak values and early time histories of shock pressure and particle velocity, and a determination of shock position, are presently possible.

Shock Pressure

Piezoelectric and piezoresistive principles are applied to obtain pressure-versus-time data. The approaches have some overlap in their respective useful ranges, with piezoelectric quartz finding application in the 1- to 35-kilobar (kb) region. The piezoresistive technique utilizes different sensing elements to achieve ranges from 5 to 400 kb.

Quartz Gages

Quartz gages have fairly rapid response times. Rise times in the order of a few microseconds are possible. The accuracy of pressure-time measurements should be better than ±5 percent, with repeatability of 1 to 2 percent. These numbers are probably more a function of the knowledge of the properties of the material being subjected to shock than the gage per se. Some improvement might be expected for smaller area active electrodes with an attendant reduction in output signal level.

Sandia Corporation makes two different types of quartz gage, a thick-element gage and a thin-element gage. These quartz crystal sensors show linear response to at least 25-kb pressure. The gages are useful somewhat beyond this range, but tend to become non-linear up to about 35 kb. This latter figure is generally considered to be the upper limit for quartz gages.

Sandia Thick Quartz Gages

The Thick Quartz Gages are fabricated from synthetic-grown material (termed "stone") supplied, cut, and polished to very close tolerances by the Valpez Corporation, Massachusetts. The thick gages were designed to measure shock propagation in metal plates and require a flat surface for bonding. Their use in field studies will depend on either finding a method of obtaining an adequate bond, or using an impedance-mismatch technique where the shock input into the quartz is from a material with a known Hugoniot.

The X-cut crystals have a diameter which varies from 2 to 4 inches and a thickness of 0.5 to 1 inch. Since the speed of shock propagation in quartz is about 0.23 inches per microsecond (or 4.4 microseconds for a 1-inch gage) the thinner gages produce shorter usable records before the signal is obscured by reflections from the back face of the crystal due to impedance-mismatch effects.

The latest model gages are 4 inches in diameter and 1 inch thick. The ratio of diameter to thickness is important in determining the accuracy of the gage because of shock reflections from the side surface of the disc. A ratio of 4:1 results in an accuracy of about 1 percent.

The polished crystals have metallic electrodes vapor-deposited on the front and back faces as thin (100 microinches) films. The most common electrode material is silver over a sublayer of chrome.* A guard ring or groove 0.003- to 0.004-inch wide is cut through the back surface electrode. The diameter of the circle formed by the ring is 1-1/2 times the thickness of the gage. The guard ring is electrically connected to the front surface electrode through a low value bleed resistance (50 to 100 ohms) to match the electrical impedance of the center, or active, electrode. The active electrode

*Gold over chrome is available but appears less desirable, since during later soldering operations the gold tends to form an amalgam with the lead in the solder, leading to poor bonds.

is attached to the center conductor of a coaxial cable. The outer shield of the cable is connected to the junction of the front surface and the bleed resistor. The gage is pressure-bonded to the sample under test with a thin layer of epoxy.

A high output signal level is realized whose magnitude is a function of the area of the center electrode. As an example, a 3/4-inch electrode will result in an output of approximately 50 to 60 volts for a pressure of 15 kb. Consequently, the gage can be used to produce a signal which can be transmitted over long wires directly, without need of amplifiers. Signals can be sent through over 2,000 feet of cable in this manner. Some form of equalizer is employed at the end of long cables to reshape the pulse before driving the scope or recorder. This technique has been used very successfully in reading out quartz data, although the signal strength may be reduced by approximately an order of magnitude in the pulse forming network.

Sandia Thin Quartz Gages

The Sandia Thin Quartz shock pressure gage uses one or two X-cut synthetic quartz discs 0.5 inch in diameter and 0.05-inch thick, mechanically coupled to the surrounding medium (invariably rock) with a matching grout. Figure 25 shows the two types of gages.

Unidirectional stress along the X-axis produces a piezoelectric charge proportional to the area of the quartz, the stress level, and the piezoelectric constant of quartz. This charge is integrated by accumulation on a capacitor, and a voltage-controlled oscillator located near the transducer is used to provide an amplified signal for recording.

The quartz delivers a net positive charge; thus, should a negative charge from some other source be stored in the capacitor, the voltage out of the emitter follower could indicate a stress lower than the actual stress because a portion of the positive charge from the quartz would be required to destroy the negative charge stored on the capacitor.

In one application in HE simulation (Reference 34), the presence of an EM-like disturbance triggered the recording oscilloscopes and the data were either obscured in the disturbance or arrived following the oscilloscope sweeptime. Fortunately, the data were also being recorded on FM tape so the pressure records were not lost. If nothing

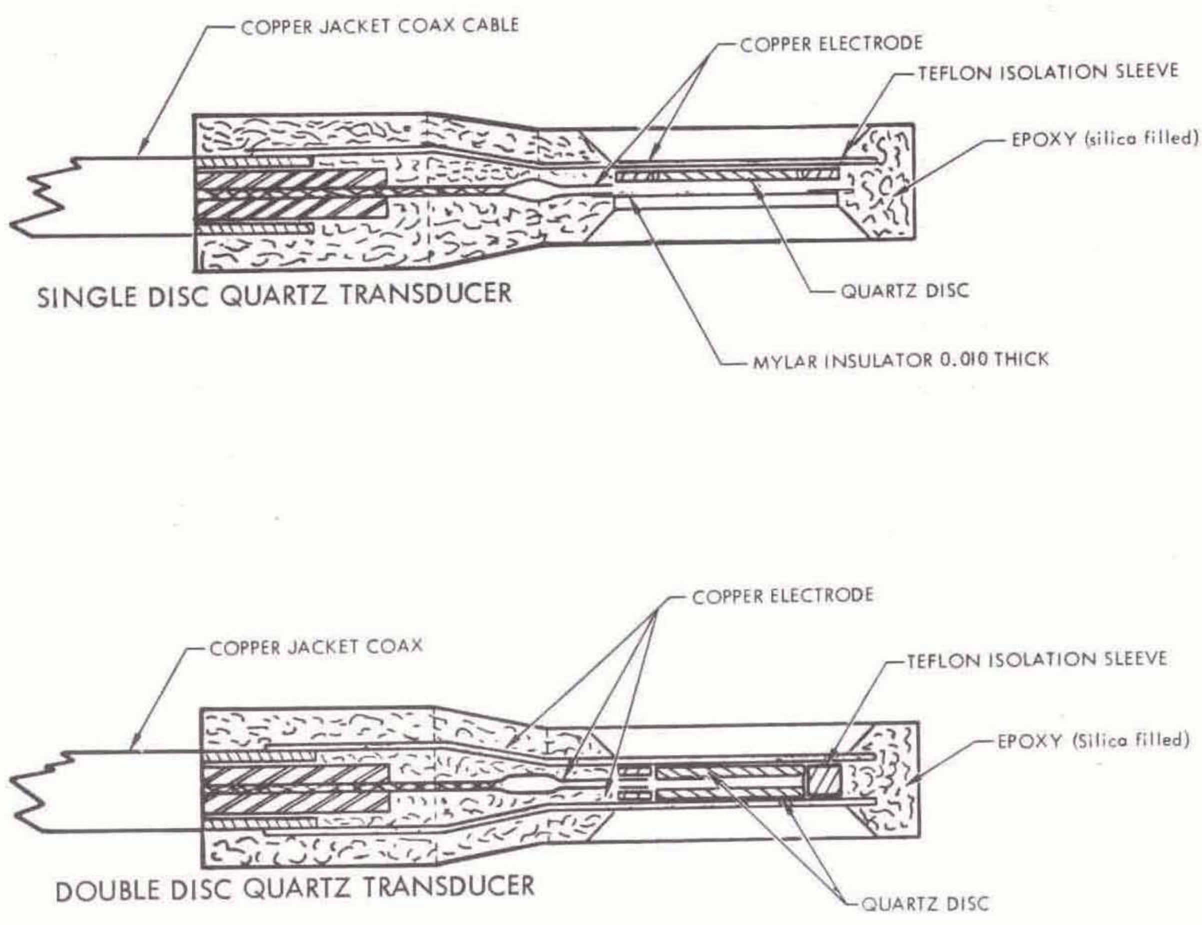


Figure 25. Sandia thin quartz pressure gages.

else, this experience should indicate the value of dual recording and show that even in chemical explosions, precautions must be taken to avoid the bias of recorded data from electrical disturbances resulting from the detonation.

Manganin Gages

Manganin gages to measure pressures of 20 to 450 kb have been produced by a number of organizations, e.g., Harry Diamond Laboratories, Stanford Research Institute, Sandia Corporation, and the Illinois Institute of Technology Research Institute.

A typical pressure gage is fabricated from 3-mil (0.003-inch) diameter manganin wire which undergoes piezo-resistive changes when subjected to pressure. To bias the gage, a constant-current supply is triggered by an external sensor, located in the area of measurement, just prior to the production of the pressure pulse to be measured. The power supply delivers from 0.2 to approximately 2 amperes of current in a pulse about 50 microseconds wide (or longer if greater recording time is feasible). The actual change in resistance of the manganin due to the pressure pulse is detected as a change in voltage occurring between two voltage probes. The timing of triggering the constant current supply is obviously critical since it must coincide with the arrival of the pressure pulse.

To give some feel for the sensitivity of the manganin gage, a 30-percent change in resistance might be expected for a peak pressure of 100 kb. The gage is linear between about 25 and 400 kb. Up to 50 microseconds of write time can be obtained with the manganin wire gage. Rise times of 5 shakes (5×10^{-8} seconds) are possible with 3-mil wire and some work has been accomplished using 1-mil wire, or ribbon, with a somewhat faster response time. The gage is considered to be very good for peak pressure measurements, although long pressure tails might be somewhat difficult to measure accurately.

Manganin gages respond to the pressure in the medium in which they are embedded. Thus, if the embedding material material replicates the properties of the earth (or rock) in which shock propagation is being studied, the gage output is proportional to the earth pressure. However, when the gage is embedded in a medium different from the surrounding earth, the gage output must be corrected for impedance mismatch between the embedding material and the earth. The correction can be calculated if the equation-of-state of both the soil and the embedding material is known.

When used as a pressure gage, the wire is embedded close to the surface of an insulating material and the gage placed in contact with the surface to be sensed. As long as the wire is insulated properly, a variety of materials may be used to mount the gage. For example, the wire may be attached, with an epoxy, directly to a granite core. The gage may be used to sense pressure in curved surfaces.

The lower limit of usefulness of the manganin wire pressure-time gage is generally considered to be approximately 20 kb. However, examination of static pressure data seems to indicate that, with some further development effort, the range of the gage might be extended to as low as 1 kb.

HDL and IITRI Manganin Gages

Both the HDL and the IITRI gages use a manganin spiral about 3/8 inch in diameter, embedded in either plexiglass or epoxy insulator, and oriented so that the plane of the spiral is parallel to the shock front. The manganin measures the shock profile existing in the insulator. The corresponding peak pressure in the adjacent medium depends on the shock impedance and the equation-of-state of the two media.

The HDL gage, designed for material response studies, uses three coplanar spirals embedded so that their centers lie along radii 120 degrees apart and 1 inch from the center of the gage. By determining the arrival time at each spiral, the obliquity of the shock front may be determined. Sandia (Reference 35) uses a similar technique with their impedance-mismatch gage.

SRI Manganin Gage

The SRI Manganin Gage (Figure 26) uses a grid of 3-mil wire embedded in a C-7 epoxy insulator. The manganin wire is an active resistive element of an electrical four-arm bridge circuit. Up to at least 150 kb, the C-7 behaves ideally, i.e., as a fluid of low electrical conductivity. The initial goal of the gage design was a 0.1-microsecond rise time, >50-microsecond recording time and a ±10-percent accuracy in the range from 10 to 500 kb. These goals are gradually being met. Durations of about 30 microseconds at pressures of about 30 kb, and 20 microseconds at 100 kb, have been achieved with a gage 4 inches thick and 6 inches in diameter. Pressures have been recorded at temperatures up to the melting point of manganin, 1020°C (Reference 36).

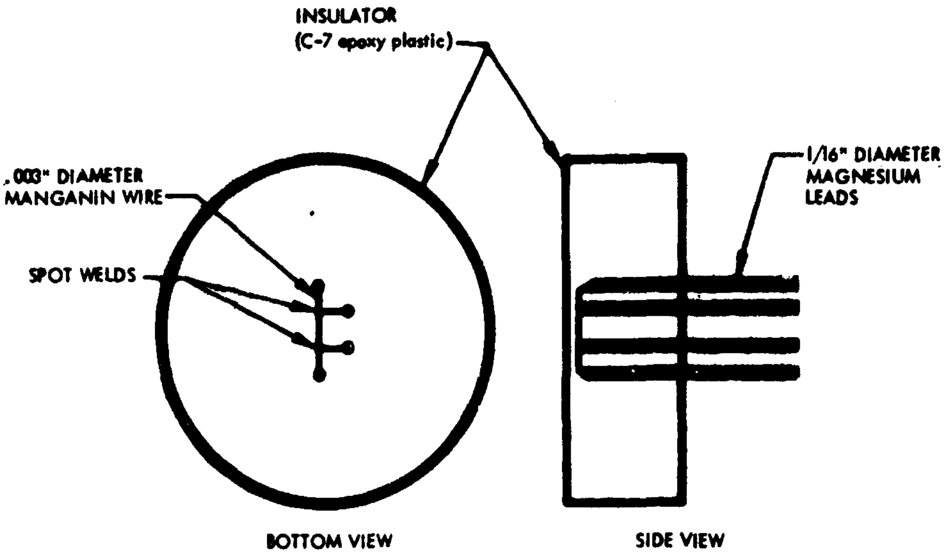


Figure 26. Configuration of SRI manganin gage in C-7 epoxy gage.

In addition to the G7 epoxy, SRI has successfully constructed manganin gages using aluminum, granite, limestone and highly-compacted tuff as the embedding medium. Studies are now being performed to determine methods of embedding the sensor in playa (earth) material which has the same density and water content as the soil where the measurement is to be made.

Sandia Manganin Gage

The Sandia Manganin Gage, similar to the SRI gage, uses both a grid of wire and the C-7 epoxy insulator. The gage is larger, 6-inches thick and 8 inches in diameter, and has achieved a recording time of 50 to 60 microseconds before the gage fails and the wire breaks.

Other materials besides quartz and manganin are used in high-pressure gages. BRL has constructed a gage which depends on the change in electrical conductivity of sulphur subjected to pressure; SRI uses the piezoresistive properties of calcium; an IITRI gage depends on electrolytic properties of solutions; and the UCRL plastic gage depends upon the depolarization of a solid.

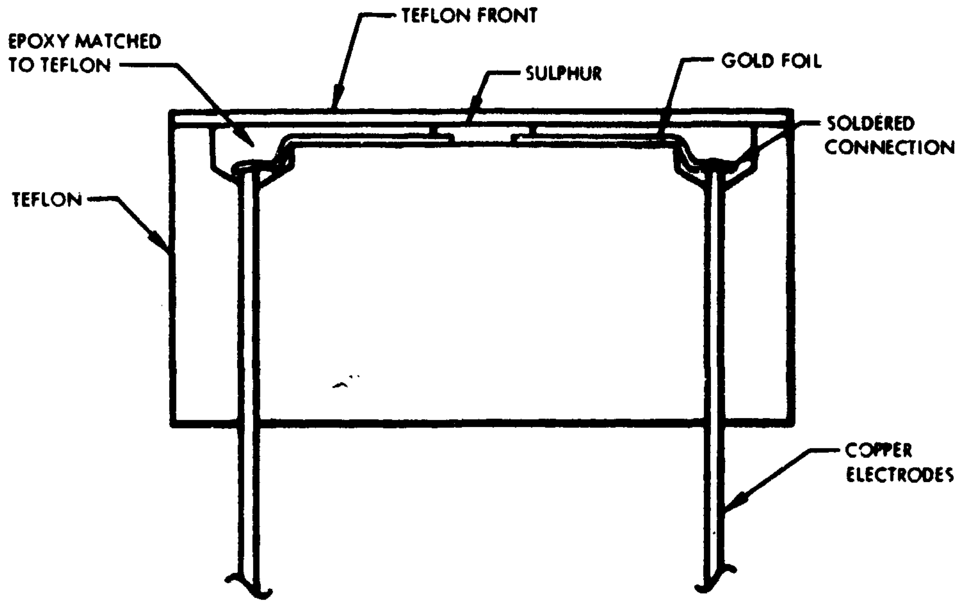


Figure 27. BRL sulphur gage.

BRL Sulphur Gage

In the BRL Sulphur Gage (Figure 27) the main body of the gage is made of Teflon, which was selected because it is non-polar and does not generate spurious signals when shocked, does not conduct at pressures below several hundred kilobars, and is a close match to the shock impedance of sulphur. The gage is prepared by machining a shallow cavity in the Teflon base. The Teflon is drilled and copper electrodes are pressed into place. Gold foil, 0.001-inch thick, connects the copper electrodes to the cavity region where the sulphur is placed. Vacuum-melted sulphur is cast into the cavity. After it solidifies, the excess is ground away, leaving a thin layer of sulphur, 0.007-inch thick, to bridge the gap between the gold foils. The 0.007-inch sulphur thickness permits adequate time resolution for most measurements. Teflon front-insulation, usually 0.010-inch thick, is bonded to the surface with an epoxy matched to the density of Teflon by the addition of inert filler. The 0.010-inch thickness of the Teflon front permits the sulphur to be close to the point where the measurement is desired and minimizes attenuation (Reference 37).

While some degree of success has been achieved using this gage in the laboratory, no attempt has yet been made to use it in field tests. Some possible shortcomings should be pointed out. First, the influence of temperature on conductivity has been neglected, in that the compression-temperature relationships associated with the shock jumps used for calibration have been assumed to be the same as the compression-temperature relationships existing under conditions of the pressure profile measurements. Second, although compressed sulphur is assumed to be an intrinsic semiconductor, impurities may influence the conductivity and could introduce reproducibility problems. Both of these shortcomings will be considered in further investigations.

SRI Calcium Gage

The SRI Calcium Gage is designed for measurements in the 5- to 25-kb range. A thin film of piezoresistive calcium is vacuum vapor deposited on an optically flat substrate. The general configuration of the sensor is shown in Figure 28. The piezoresistive element is located within the insulating medium and lies in a plane which is

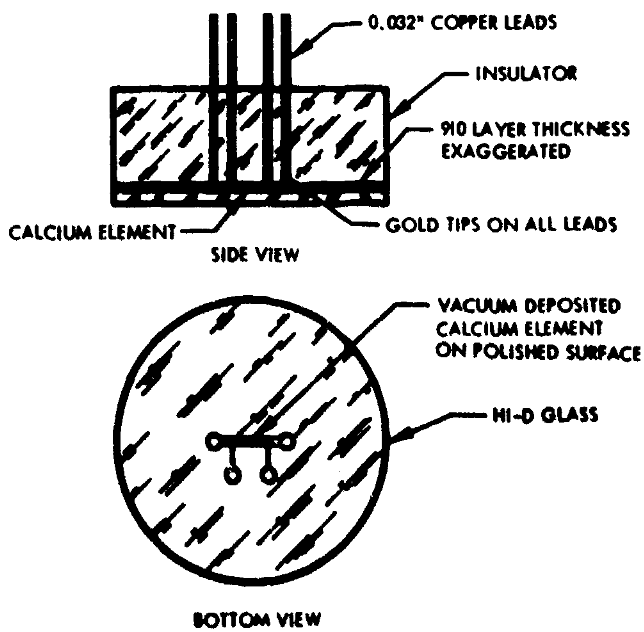


Figure 28. SRI calcium pressure gage.

parallel to the shock front. It is in the form of a four-terminal network which permits resistance measurement of only its central portion, thus avoiding effects due to contact resistance between the leads and the element. Electrical connections to the piezoresistive element are by means of four leads embedded in the insulator and oriented perpendicular to the plane of the shock front. When the shock crosses the element, it produces simultaneous compression and acceleration. The result is a fast transducer response with preservation of electrical continuity. A rise time of 20 nanoseconds and a 10-microsecond recording time have been achieved (Reference 38).

IITRI Electrolytic Cell

The IITRI Electrolytic Cell utilizes a piezoresistive liquid (Figure 29). Two platinum spheres act as electrodes in an electrolyte, whose composition varies according to the pressure to be measured. The cell constant, ion concentration, and ion mobility of the electrolytic cell each undergo reproducible changes during shock loading. The net result of these changes is a change in the electrical resistance of the cell. The gages are calibrated in an explosively loaded water column. Three solutions are presently used to provide three pressure ranges:

1.	Carbon tetrachloride	150 to 350 kb
2.	Paraffin	50 to 150 kb
3.	Ammonia	5 to 50 kb.

Recording times of from 5 to 200 microseconds have been achieved, depending on the peak pressure level and the distance from the burst.

Like the manganin gages, the IITRI cell is subject to the triggering problem for oscilloscope recording, but this purely electronic problem can be solved with the present level of technology. There is the possibility that the EM pulse and initial radiation in a nuclear burst will produce changes in the cell that will result in a false determination of pressure. The developers of the gage at IITRI feel that this is not the case and are now testing the gage in simulated nuclear environments.

UCRL Plastic Gage

The UCRL Peak-Pressure Plastic gage is shown schematically in Figure 30. A 30-mil thick Lucite shell is coated on both sides with a conducting silver paint, which also forms the ground connection

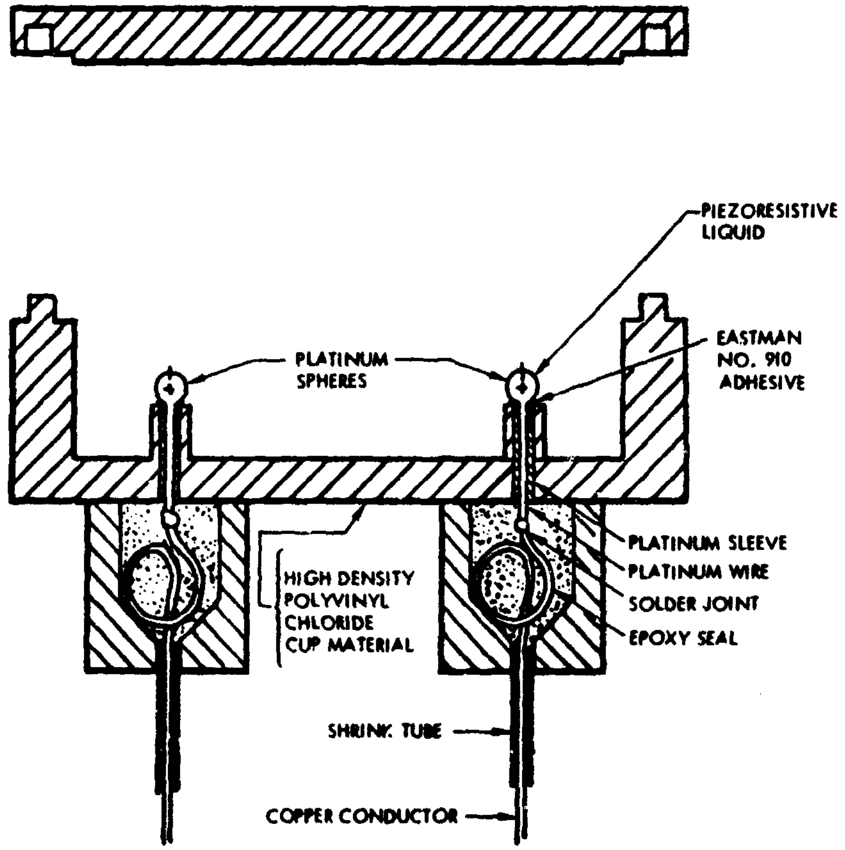


Figure 29. IITRI high-pressure electrolytic cell shock pressure gage.

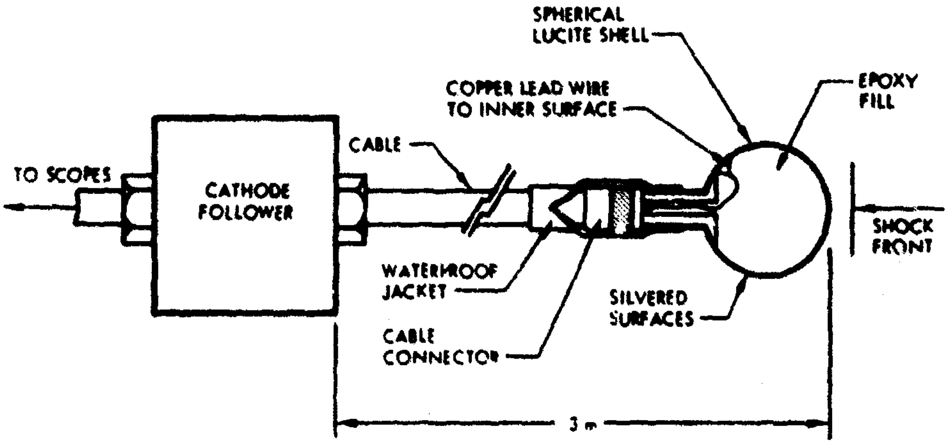


Figure 30. UCRL peak-pressure plastic gage.

to the cable shield. The Lucite globe is filled with epoxy for increased mechanical strength. When a stress front traverses the thin wall of the gage, a current whose amplitude is proportional to the peak stress flows through a load resistor connected to the inner and outer surfaces. It is postulated that, since the lighter components of a molecule have higher mobilities, the passage of a shock will preferentially align the molecules in the direction of the shock travel. For materials whose molecules have a permanent dipole moment, the charge liberated varies linearly with the peak stress over a region bounded by a threshold pressure and a saturation value. It is linear over the stress range, which is 50 to 180 kb in Lucite. The corresponding range in the detonation medium depends on the impedance mismatch between it and Lucite (Reference 39).

Sandia Impedance Mismatch Gage

Sandia (Reference 35) has developed an impedance mismatch gage to measure pressures up to 1000 kb, with rise times of less than 1 microsecond. The gage measures shock transit times in samples of known Hugoniot. When a strong shock wave propagates through a medium whose equation of state is unknown and then meets two or more materials whose Hugoniots are known, these materials acquire, from the shock, a pressure-particle velocity which can be determined by measuring the transit time of the shock. By applying the conservation equations to the system of waves resulting after the shock passes the interface, the pressure and particle velocities in the reflected wave, (which must lie on the reflection Hugoniot—or mirror image of the Hugoniot—of the medium), may be calculated.

In the field use, a core sample from the emplacement hole is cut into a flat disc about 8 inches in diameter and 1 to 2 inches thick. On this disc are mounted three smaller discs, 1-1/2 inches in diameter and 0.394 inches thick. Two of these smaller discs are mismatch material and one is of the rock medium. Centers of these discs lie at 120-degree intervals on a circle of 1-1/2-inch radius. A shock detector is positioned on each disc, and three more are placed in a circle of 3/4-inch radius inside the small discs. The shock detectors are small wafers of PZT (Clevite Corp., Cleveland, Ohio), 0.120 inch in diameter and 0.020 inch thick, sandwiched into a small brass housing to which a standard Microdot coaxial cable is connected. The signal from the detectors is fed into a delay-time coding mixer circuit which can identify the direction of shock propagation.

Speed of Shock Propagation—Peak Pressure

A numerical solution for pressure and particle velocity may be obtained from time-of-arrival data combined with the equation of state of the propagating medium. The complications in this numeric solution lie in the mathematics to handle the divergence of the cross-sectional area with increased radial distance from the burst point, and in the accurate determination of the in situ Hugoniot of the propagating medium. Unfortunately, only the peak pressure and peak particle velocity may be determined using this technique.

Pressure Switches

The earliest method of obtaining shock wave time-of-arrival and velocity data in the hydrodynamic zone utilized the leading edge of the shock front to crush specially-designed, normally-open pressure switches. The switches triggered a pulse generator whose output was presented on an oscilloscope, along with a crystal-controlled time reference signal, and photographed by means of a high-speed camera.

The switches were placed at known distances from the center of the burst and were sequentially crushed. Each switch had its own individual pulse generator which produced a characteristic pulse so that each switch could be identified on the film. Reference 40 gives a complete description of the pulse system and coding used.

The major shortcoming of the pressure switch system was its susceptibility to multiple triggering. This phenomenon usually resulted from the alternate opening and shorting of the switch cables which occurred as the shock wave traveled along their length. In an installation requiring the use of cables several hundred feet in length, the number of extraneous pulses generated could easily be several times as great as the number of useful pulses and thus seriously complicate the analysis of data. A number of different electronic triggering systems have been devised to minimize the extraneous pulses (Reference 41).

Sandia Shock Detector

Sandia Corporation has developed a shock wave detector which is a modification of the pressure-switch (Reference 39). Two lead-zirconate-titanate piezoelectric rings detect the stress wave arrival

(Figure 31). The local shock velocity can be calculated from the time difference in triggering the two elements if the emplacement geometry of the gage is accurately known.

UCRL Pin Gage

UCRL (Reference 39) has modified a pin gage, originally designed for laboratory measurements, to obtain field data. Small electrical contactors, or pins, are placed at accurately measured positions within and near the upper surface of an aluminum block located at the bottom of the gage and oriented toward the direction of shock propagation (Figure 32). The time sequence of pin closures is recorded, yielding both shock and free-surface velocities. Since it has been shown that to a good approximation the free surface velocity is just twice the particle velocity, the peak pressure in the aluminum may be calculated. If the shock compression curve of the medium is known, graphical mismatch calculations can be used to calculate a medium pressure. It should be noted that the free-surface information is actually not required since the relation between shock and particle velocity is well known for aluminum. This redundancy is nevertheless desirable in a field instrument. Peak pressures from nuclear detonations in granite and volcanic tuff have been successfully measured with this gage.

Variations of this gage exist where the aluminum is replaced by salt, the medium being measured, in order to reduce the complexity of the calculations. (The gage must be adequately coupled to the medium.)

Sandia Plexiglass Gage

Sandia (Reference 35) uses plexiglass, which closely matches the Hugoniot of Nevada desert alluvium, as a matrix in which they embed small PZT shock detectors (or a double PZT ring). The gage consists of a pair of PZT wafers 0.125 inch in diameter by 0.020 inch in length separated by 2.23 inches of plexiglass. The equation-of-state of plexiglass is well known so the time difference between the PZT signals indicates the shock velocity. They have obtained a pulse of 300 volts from the PZT rings at a pressure level of 150 kb, with a rise time of 1 microsecond. SRI has recorded the output from this gage on a dual-beam oscilloscope (Tektronix-555) using the signal received from the front PZT wafer to trigger the scope sweep.

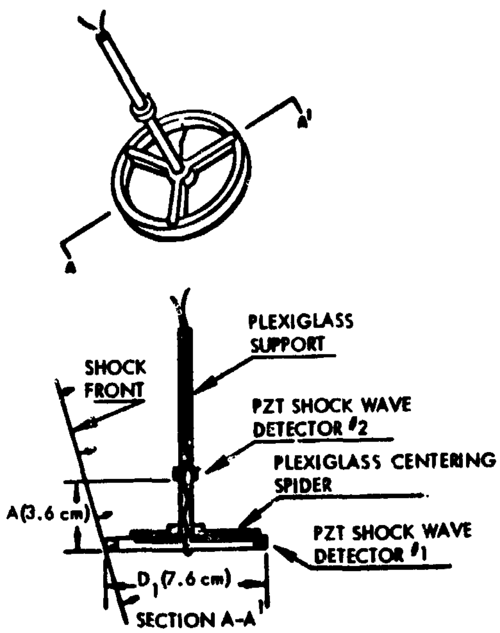


Figure 31. Sandia shock-wave detector.

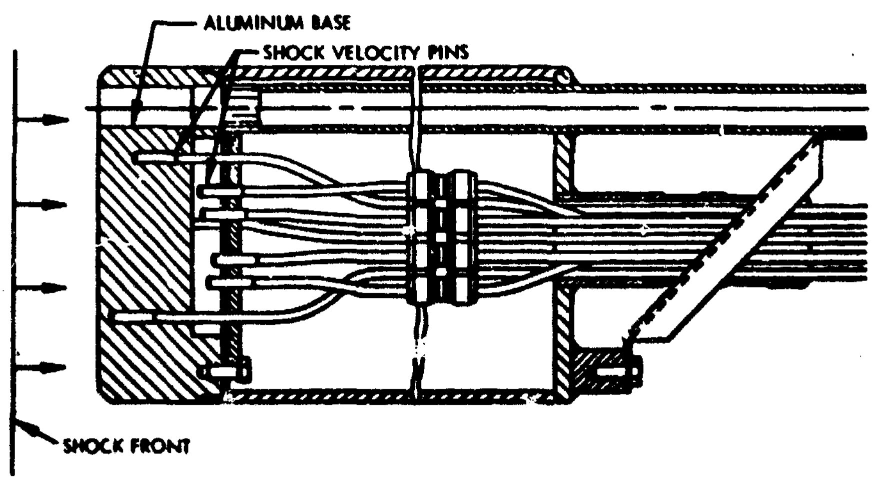


Figure 32. UCRL pin gage.

SLIFER Cable

The gages discussed above give only discrete determinations of shock velocity at specific locations. The effect of the shock crushing a cable may be utilized to obtain a continuous measure of shock front position. The Doppler or SLIFER (Shorted Location Indicator by Frequency of Electrical Resonance) gage used by Sandia is an electrical transmission line—embedded in the earth so that the stress wave will move along the length of the cable—which is physically weak in comparison with the stress produced by the shock front and will thus be shorted at the shock front by crushing. This short will move with the local shock velocity in the medium.

The transmission cable constitutes an inductive impedance in a tuned circuit of a Colpitts oscillator, its inductance being related to the cable length. As the shock front continuously shortens the buried cable, the frequency of the oscillator is increased in direct relation to the shock front position along the line. The output of the Colpitts oscillator is heterodyned with a crystal oscillator and the difference frequency recorded on magnetic tape.

The derivative of the relation of shock front position versus time provides a measure of shock velocity versus distance. If the equation of state of the shocked medium is known, the shock pressure versus distance can be inferred.

In field operations, 1/2-inch air-dielectric coaxial Telcon cables are installed radially from ground zero at various depths, and attached to the oscillator. The Telcon cable has been found to crush at pressures above 1 kb. A solid-dielectric coaxial cable, RG-8, has been used when it was necessary to guard against the possibility of water penetration into the Telcon, or where there was danger of damage by the backfill operation. The RG-8 crushes at pressures above 10 kb.*

Calibration of a resonance cable requires two measurements of the oscillator frequency, one with the cable shorted at its extreme end and the other with the cable shorted at the oscillator. For a cable 100 feet long, typical frequencies will vary from about 500 kHz at full length to 700 kHz at zero length. The frequency can be adjusted

*After-the-detonation retrieval of the cable and a measurement of the distance of crushing serves as a check on the SLIFER technique since the distance to a pressure level of 1 kb (or 10 kb) can be directly measured.

by changing lumped values of capacitance and inductance in the oscillator circuit.

Errors in shock position using this technique, arising from the measurement method and from the survey of initial cable placement, are believed to be no greater than about 6 inches. The accuracy of the pressure calculated from these positions is determined by how well the backfill matches the impedance of the undisturbed medium. In HE field tests it is common to position the cable three to six months in advance of the test to allow for natural settling and compaction.

Particle Velocity

In the sense that pressure-determining instruments rely to some extent on calculations of impedance mismatch between the shocked medium and the gage material, they may all be termed particle velocity instruments, for they establish a point on the pressure-velocity curve. The pin gage, using a slab of the medium in place of the aluminum, measures the free surface velocity directly, but can be used in only a few media. The basic fault of the pin gage is that it measures only the spall velocity at a single instant. At best, this is only the peak spall velocity; nothing can be inferred about conditions in back of the shock front.

The Engineering Physics Company (EPCO), Rockville, Maryland, conducted a literature survey and analysis of the various methods used for close-in particle velocity measurement, together with their respective advantages and disadvantages (Reference 42). They considered the application of

1. Pin gages
2. Impedance mismatch
3. Radar doppler
4. Laser doppler
5. Magnetic induction

and concluded that

1. Contact pairs of pin gages and impedance mismatch devices do not afford a time record of the particle velocity. This provision is considered to be essential in any new gage design. In addition, data reduction to particle velocity in the case of the impedance-mismatch concept involves debatable assumptions,

requires a trained interpretation, and is inherently accurate only to within approximately 5 percent.

2. Although the doppler radar gage is claimed to be capable of time recordings, it was pointed out that any interferometric (doppler) concept is prone to gross error in data interpretation unless a transmission medium is employed whose dielectric constant is unaffected by pressure. Since no material, save a vacuum, satisfies this requirement, the doppler concept is deemed unreliable for the measurement of particle velocity except when the transmission medium is free space (vacuum), in which event the device serves as a free surface or spall velocimeter. The doppler radar and laser methods are too expensive and complicated to supplant the contact pair concept for such a free surface or spall application. As a result, the doppler radar and laser concepts are considered unsatisfactory for the field measurement of particle velocity.

EPCO Velocimeter

EPCO designed and constructed two gages using the effect of mutual induction to measure particle velocity (References 43 and 44). An electrical conductor moving in a magnetic field will have an electronic potential developed across its terminals. Specifically, if a wire conductor is buried in the soil near an explosion, in the presence of a magnetic field, a voltage will be generated at its terminals when it is caused to move through the magnetic field by the impinging shock wave.

EPCO Faraday Gage

In the Faraday induction velocimeter (Figure 33), a deformation of a wire by the shock wave, in the presence of the earth's magnetic field, gives rise to the measured voltage.

EPCO Self-Inductance Gage

In the self-inductance velocimeter, shown schematically in Figure 34, a strong magnetic field is established by passing a large current through a parallel wire system. As this electrical configuration is deformed by the shock wave, the voltage generated is used to measure particle velocity. The mutual inductance per unit length between the two circuits is measured as the shock front shortens the circuits along the X-axis. The device was designed to measure veloci-

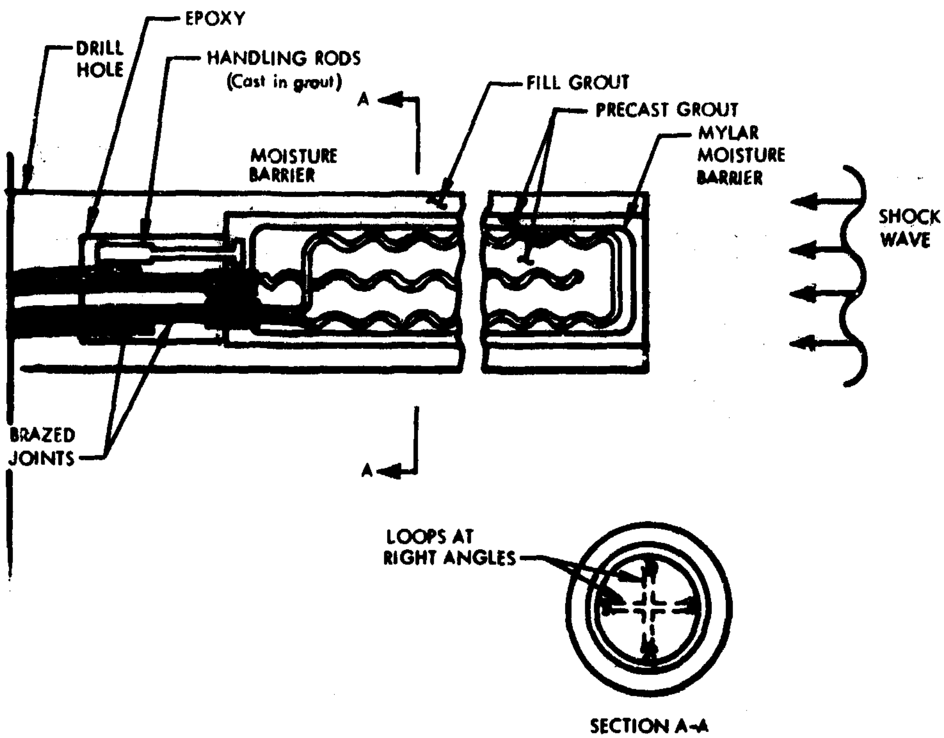


Figure 33. EPCO Faraday induction velocimeter.

ties as high as 1000 ft/sec. The limiting factor in recording time is the technical problem of keeping the conductor in one piece in the presence of the shock wave, as times of up to 100 microseconds are anticipated.

Since the EPCO analysis of methods of particle velocity measurement was made, laser technology has undergone a tremendous advancement. It is probably technically possible, using a vacuum light pipe or perhaps fiber optics, to determine the particle velocity. The advantages of a laser technique would be considerable in that EMP would be less of a problem.

Swift of SRI (Reference 20) has suggested using a velocity pickup gage to determine particle velocity. A velocity pickup is a mass-spring system operating at frequencies above its undamped natural frequency, so that the relative displacement between the mass and its case is essentially the same as the displacement of the case (the mass

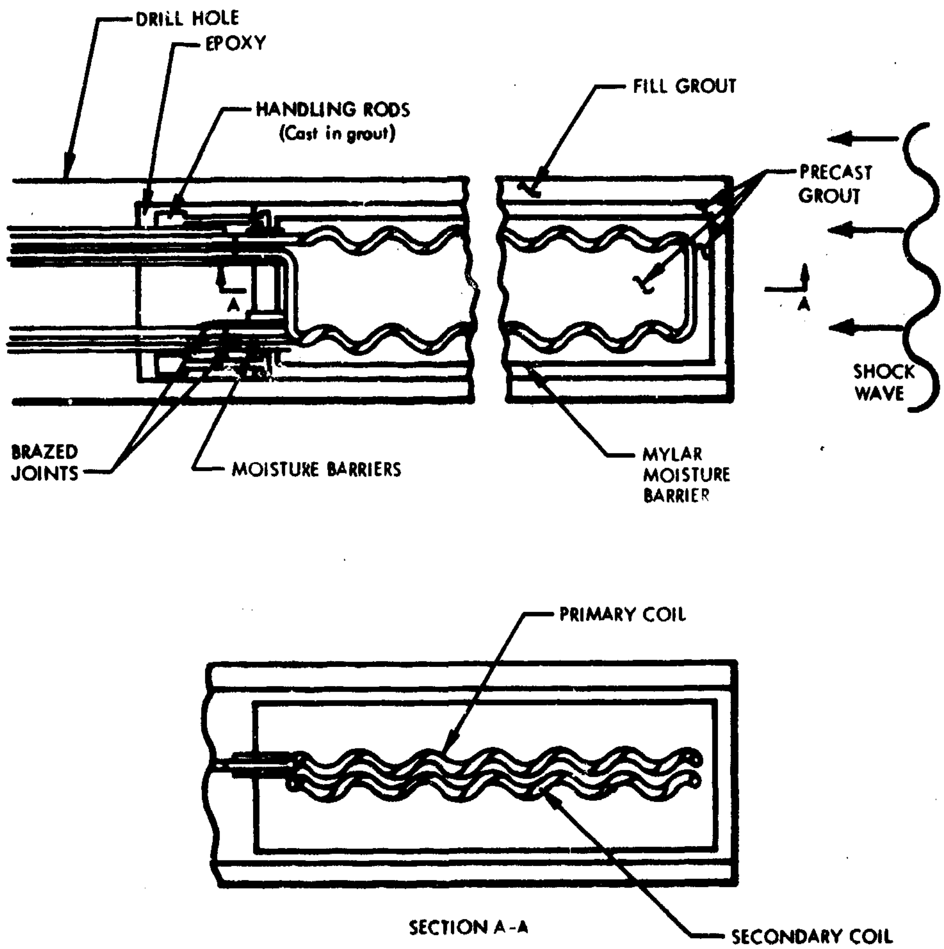


Figure 34. EPCO self-inductance particle velocimeter.

remains essentially stationary). The output is usually the voltage produced by the relative velocity of motion between a coil and a magnet, of which one is attached to the case and the other is a part of the seismic mass. The output, then, is proportional to the velocity of the case for frequencies well above the natural frequency and amplitudes less than the limit of travel of the mass with respect to the case.

CEC Velocity Pickup

One type of velocity pickup which Swift considered was the Consolidated Electrodynamics Corporation (CEC) Model 4-106H. This device is a spring-magnet type with a total travel of 0.5 inch. A spring-magnet type was chosen because it needs no unsupported leads from the coil to the terminals.

The gage was modified by rewinding the coil with a larger wire and fewer turns to produce a voltage in the 500-ohm load of about 40 mv per inch per second of velocity. If subjected to a velocity of about 500 in/sec, the peak signal would be a very respectable 20 volts. The low-frequency response limit is set by the natural frequency of 5 Hz which permits satisfactory operation at 10 Hz and above. The gage was tested on a shake table and found to be operative at 4000 g. Swift concluded that it was probably that the first peak could be obtained with the instrument, and possibly a portion of the time history.

Crescent Velocity Pickup

The Crescent Manufacturing Company velocity gage is self-generating and consists of a solenoid and a magnetized plunger. The solenoid is composed of two coils mounted end-to-end within a nonmagnetic tube. Motion of the magnetized plunger induces a voltage in each winding proportional to the particle velocity. The gage is arranged as a closed cylinder with the magnetic plunger resting at the lower end. Earth motion causes the cylinder to move relative to the plunger, creating an electrical output. Motion of the plunger compresses the air, which damps the motion of the plunger relative to its case. Output of the VE-200 series was determined by SRI to be 100 mv/in/sec with the two windings connected in series adding.

The CEC gage and Crescent Manufacturing Company gage (Model 101258, in which the magnet moves inside the coil rather than on the outside) were used in an underground nuclear test and recorded particle velocities in excess of 8 ft/sec (Reference 45).

Acceleration

At present no adequate method exists to measure directly acceleration in the hydrodynamic zone. In a recent underground nuclear test (Reference 45), SRI attempted the measurement with two different gages—a commercial piezoelectric accelerometer and a specially constructed gage—and obtained questionable data. Since the problem appears to be in the transmitting and recording systems, it will be worthwhile to describe the gages used.

Endevco Accelerometer

The Endevco Corporation manufactured the lead-zirconate-titanate piezoelectric units, which were calibrated to 15,000 g. These gages are nearly undamped resonant systems with natural frequencies to about 80 kHz. The gage, amplifier, and an active calibration unit were incorporated in a single canister. Mechanical protection for the electronics was provided by flow-coating them with hard epoxy and potting them in the canister with a resilient silicone rubber.

During the test the acceleration rise time evidently approached or exceeded the frequency response of the recording system and resulted in a degraded record.

SRI-FMX Accelerometer

The SRI-FMX accelerometer is a variable-reluctance diaphragm-type gage. Acceleration orifices deflect a stainless steel diaphragm supported between two coils (Figure 35). As the diaphragm and its associated ferrite discs (used to achieve a high frequency response) change position relative to the coils, the change in inductance changes the frequency of each of two FMX oscillator circuits.

The ultimate range of this accelerometer is stated to be dependent only on the material of the gage body, which at about 125,000 g begins to yield under its own inertia. The range of the gage is set by varying the diaphragm thickness. Since these gages are essentially undamped resonant systems, and are expected to ring and overshoot if excited at frequencies near their natural resonance, every effort is made to make the natural frequency as high as possible.

During the test, EMP effects seriously affected the FMX multiplexing system used to transmit the data.

Strain

SRI (Reference 45) constructed a strain gage designed to measure the strain in a grouted hole in a direction radial to the shot point. The gage was designed to withstand a 20,000-g shock load.

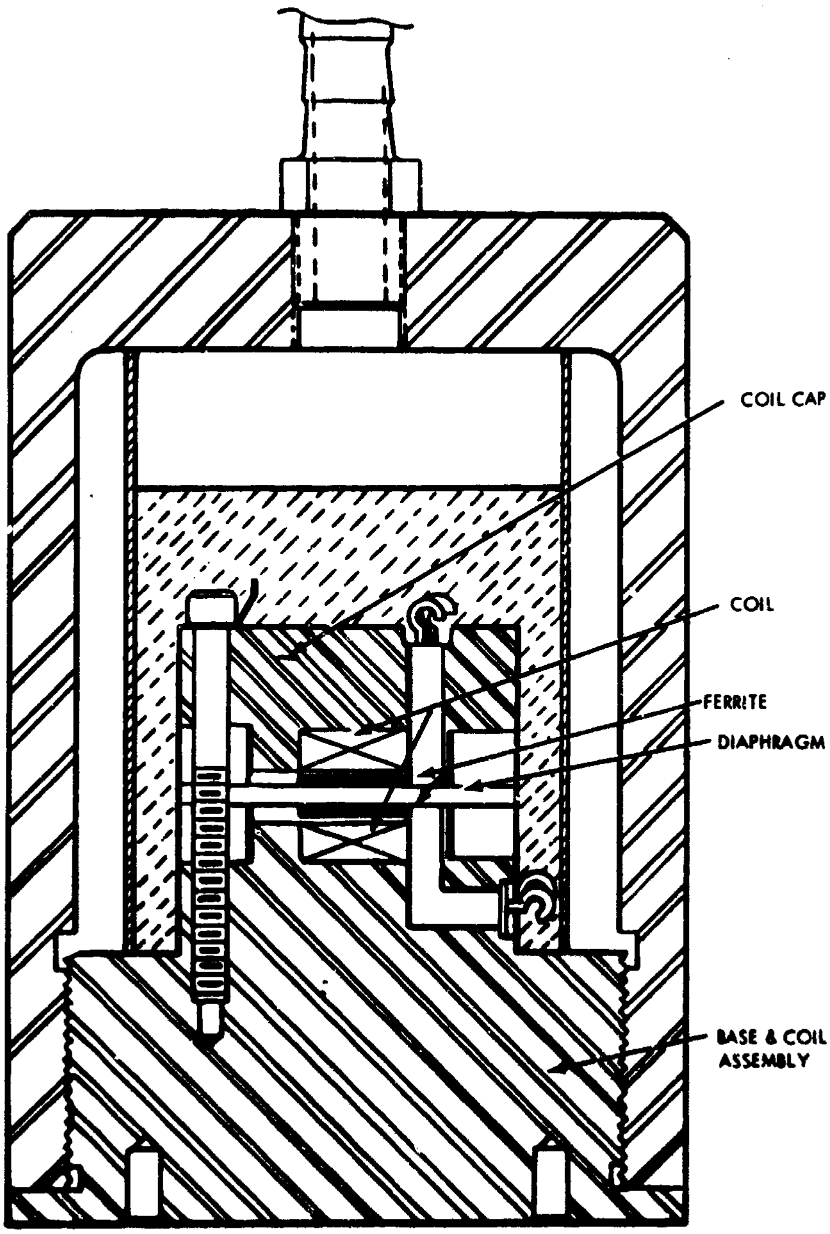


Figure 35. Cross-section of a typical SRI–FMX accelerometer.

SRI-FMX Strain Gage

The SRI-FMX strain gage (Figure 36) was constructed of a 3-inch long piece of 1-1/2-inch diameter stainless steel tubing (the strain element) capped with stainless steel reference-point caps at each end.

Inside the tubing were two coils assembled so as to face each other, on the longitudinal axis of the gage, 1/4- to 1/2-inch apart. The coils were mechanically fixed relative to each other and one reference flange. A ferrite-disc steel-disc ferrite-disc assembly was placed between the coils and was mounted on a steel shaft which slid through center holes in each coil assembly; the shaft was fixed to the other reference flange.

Compression or extension of the strain element due to forces on the caps caused the disc assembly to move relative to the two fixed coils. Movement of the disc assembly relative to each coil changed the inductance of each coil, which in turn changed the frequency of each of the two FMX oscillator circuits. For calibration, the shaft on which the disc assembly was mounted was made a threaded connection to the flange to permit disc-to-coil relative motion. The shaft was fixed in position and waterproofed upon completion of the calibration sweep.

The steel strain element tubing was designed to give the same strain for a given force as did the grout slug which was displaced.

As with the accelerometer, failure to obtain data was due to EMP effects rather than malfunction of the gage.

ELASTIC ZONE MEASUREMENTS

The instruments used for elastic zone measurement are not as specialized as those used in the hydrodynamic zone, and some are available as off-the-shelf items from industrial manufacturers. Emphasis has shifted from new designs to the analysis of the performance of existing equipments.

Soil Stress

There is an ambiguity in the terminology used by both investigators and gage manufacturers to describe shock in earth. The particular term used depends both on the viewpoint of the investigator and the use which is to be ultimately made of an individual measurement.

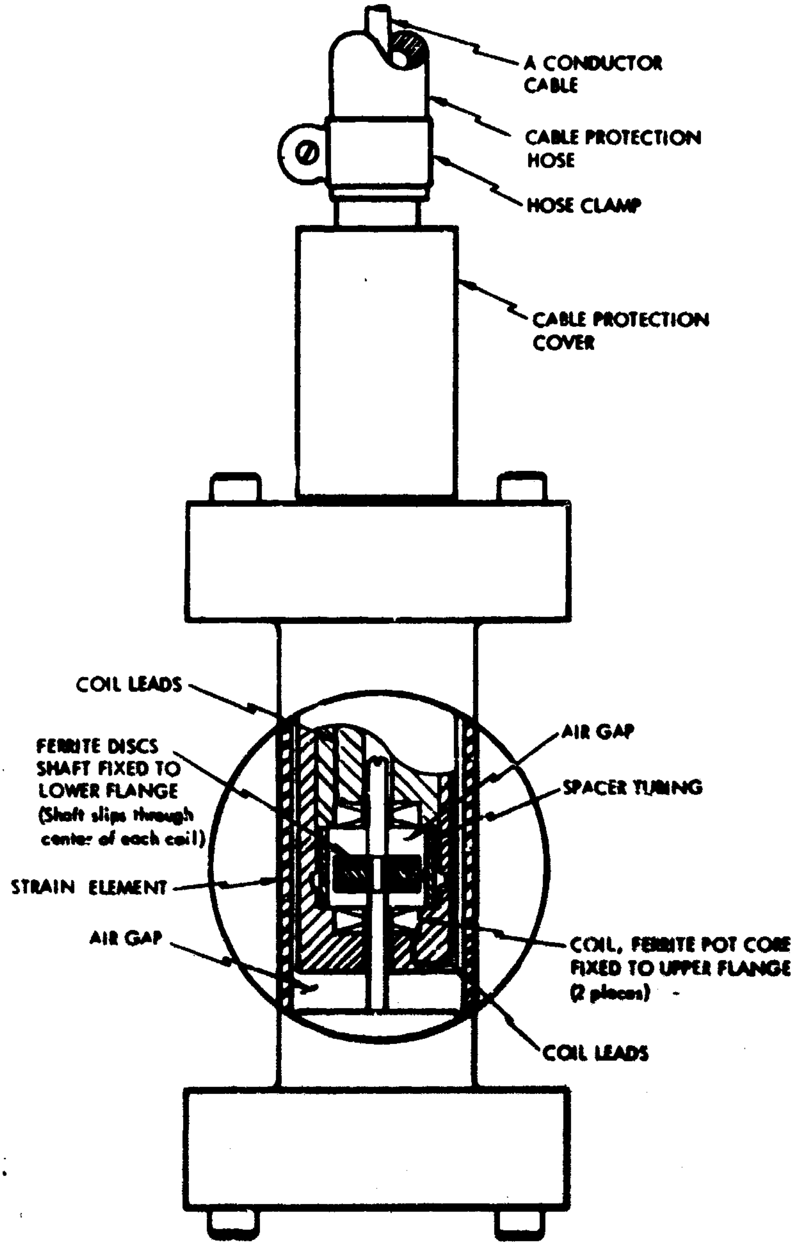


Figure 36. Cross-section of SRI-FMX strain gage.

Soil Stress infers only a solid medium of shock propagation. The term is adequate for rock but not for unconsolidated soils.

Soil Pressure implies a hydrodynamic medium—which may describe rock and saturated soils at higher pressure levels.

Soil Shock infers the propagation of a discontinuous shock front—this may be the case at high pressure levels from hydrodynamically compelled blast energy, but does not describe airblast-coupled energy or lower pressure phenomena.

Pore Pressure refers to the hydraulic pressure in the interstices between small soil masses and is usually used only to describe soil properties, but is occasionally used as a measure of blast energy and coupling.

Carlson-Wiancko

One of the earliest gages used to measure soil stress in the elastic zone, the Carlson-Wiancko gage, is still occasionally used. The basic gage is a modification of an instrument designed by Dr. R. W. Carlson for the measurement of static stress in foundations and grades. The gage consists of two flat rigid circular metal plates connected at their periphery by narrow annular diaphragms and separated by a thin circular space filled with viscous silicone oil. One plate is concentric, the inner face in contact with the fluid, and responds as a diaphragm to a fluid pressure developed by a loading normal to the parallel faces of the gage. A Wiancko variable-reluctance sensor generates a signal proportional to the diaphragm deflection.

The Wiancko sensor is used at pressure levels below 300 psi and is replaced by the smaller Ultradyne unit for pressures from 300 to 500 psi (see page 68 and page 70 for descriptions of these sensors). The mismatch between the gage and typical soils limits the usefulness of this gage.

The United Electrodynamics Corporation has constructed for AFWL two types of stress gage: a Spool Gage and a Sand Dollar Pancake Gage (References 46 and 47).

UED Spool Gage

The spool gage, which measures pressures up to 5000 psi, is made up of two sections. Each section consists of a thin circular disc, 4 inches in diameter, attached to an aluminum tube or stem. The stem of one section fits inside the other section, sliding freely on ground and lapped cylindrical surfaces. The sensing element in the latest version is either a Micro Systems or Schaevitz-Bytrex semiconductor strain gage; however, gages using both variable capacitance and LVDT sensors have been constructed.

The gage is installed in soil with the stem along the axis of stress to be measured; a pressure applied to one of the discs strains the central aluminum column. The sensors on the column produce an output proportional to the strain. The gage is installed with the sliding stems extended, and soil from the gage location is replaced at its original compaction between the end plates.

The gage has an output of 100 mv full scale. It is very stiff and has an aspect (height/diameter) ratio of about 1.5:1; thus, there is an effect due to shock transit time over the gage which stresses the soil and the gage differently, and perhaps some effect due to shock focusing. The density of the gage is about that of aluminum, or twice the density of sand. AFWL has determined that, in dry sand, the gage over-registers the pressure by factors of 1.1 to 1.2 for static loads and 1.3 to 1.4 for dynamic loads.

The placement of the gage is a major problem especially when it comes to backfilling between the discs to attain original soil density.

UED Sand Dollar Pancake Gage

The Sand Dollar pancake gage was designed for AFWL but apparently was never used in a field test. This UED design was a very thin disc incorporating a capacitance type of transducer.

The Sand Dollar gage attempts to minimize the effect of mismatching the modulus of deformations between the soil and the gage by reducing the thickness of the gage. The differential strain between the gage and soil is a function of their respective moduli of deformation and the aspect ratio of the gage. As the aspect ratio is made to approach zero, the differential strain also approaches zero although the relation between the moduli of deformation remains unchanged.

BRL Pancake Gage

Both BRL and WES use thin pancake-type gages. The BRL gage has a 4-arm bonded strain gage as a sensor. Its range is from 0 to 60 psi with a 30-mv output at full scale and a frequency response of 0 to about 200 Hz. The gage is 3 inches in diameter and 0.4 inch thick, with an aspect ratio of about 0.13:1. The total weight is 115 grams with a density of 3 grams per cc. The sensitive part of the gage consists of a single diaphragm which takes up the central 65 percent of the total area of one side. The diaphragm thickness controls the flexibility or stiffness of the gage. Since the outer edge of the gage is insensitive to pressure, arching effects concentrating near the rim should be minimized. BRL has constructed a somewhat smaller gage, a type J-2, 2 inches in diameter which measures soil stress to 90 psi.

WES-SE

The WES-SE gage (Figure 37) is a double-diaphragm gage using semi-conductor strain-gage elements as sensors. It records pressures to about 1000 psi. The gage design is based on the principle of a deflecting, rigidly clamped, circular diaphragm. The gage is wafer-shaped with an active diaphragm in both the top and the bottom surfaces. The semiconductor strain-gage sensors (Micro Systems Inc. PEI-16-350, P type) are bonded to the diaphragms. The aspect ratio of the gage is about 0.1:1 but is adjustable by the addition of an epoxy ring or baffle around the outer edge of the disc. Table 10 lists the main gage characteristics. AFWL has found the SE to be a rugged, dependable and repeatable instrument; however, they doubt its value at zero depth of burial because of the difference in stress distributions in air and soil, e.g., a uniform distribution in air and a non-uniform distribution in soil. The overregistration factor was determined by AFWL to be 1.1 static and 0.85 dynamic in dry sand.

IITRI Pancake

IITRI makes for AFWL a single diaphragm gage that is very similar to the WES-SE. The gage uses a 2-arm-bridge, semiconductor strain-gage as a sensor. Since there is but one diaphragm, the gage records the stress at zero depth of burial. AFWL reports a tentative overregistration factor 0.9 static and 1.1 dynamic; these values are based on few data, however, and may change. The present gage records pressure from 0 to 500 psi.

Filpip Gage

The Spitz Laboratories, Inc., manufactures a thin wafer-shaped variable capacitance gage, the Filpip, which is used to measure soil

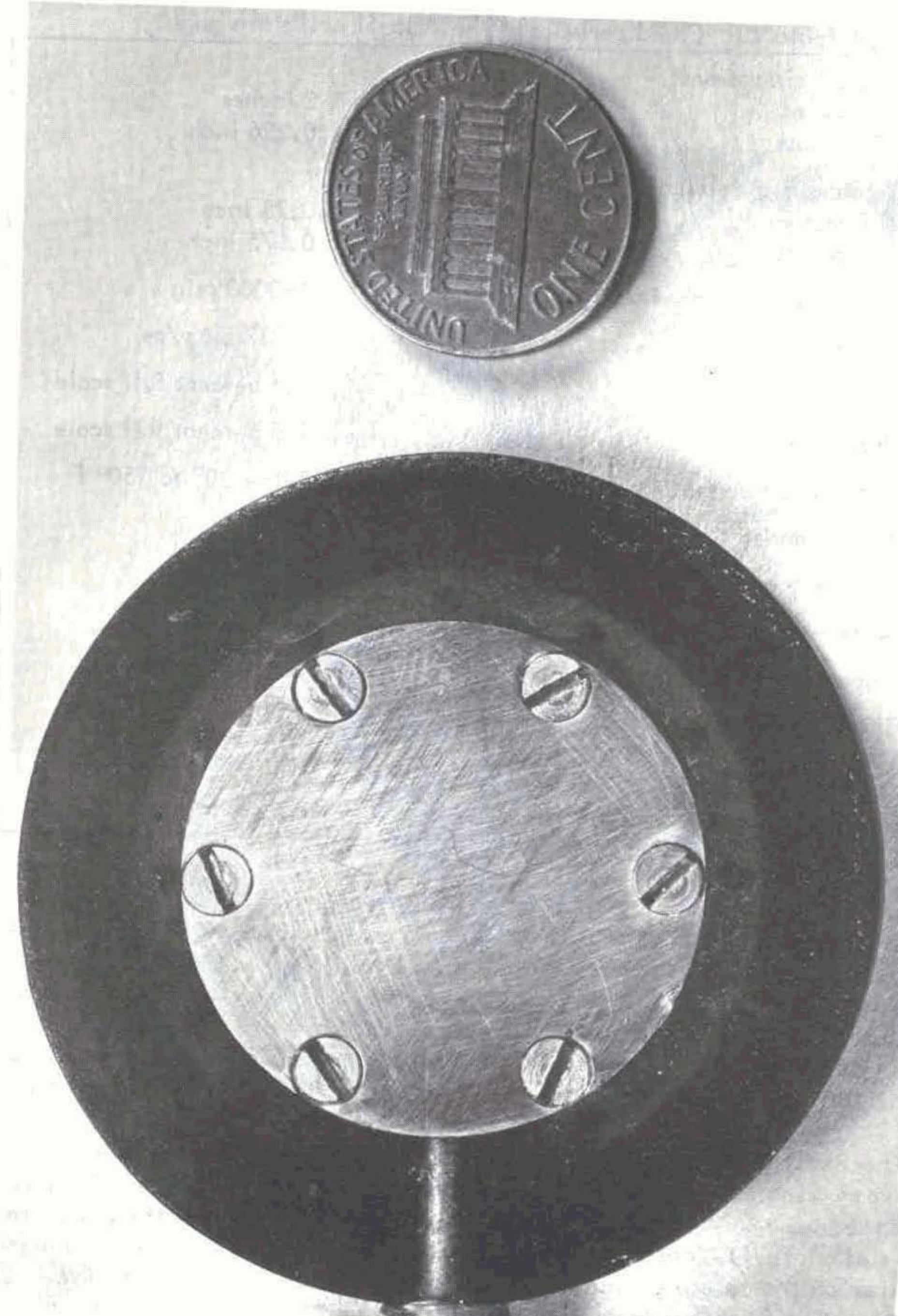


Figure 37. WES-SE soil stress gage.

Table 10. Characteristics of the WES-SE soil stress gage.

Overall dimensions	
Diameter	2 inches
Thickness	0.226 inch
Diaphragm dimensions	
Diameter	0.75 inch
Thickness	0.075 inch
Linear range (approximate)	0–2000 psig
Output	0.017 μv/v/psi
Linearity	0.4 percent full scale
Hysteresis	1.6 percent full scale
Temperature range	Below 30° to 150° F
Recommended excitation	10 volts
Maximum excitation	21 volts
Acceleration sensitivity normal to diaphragm	0.04 psi/g
Apparent strain sensitivity	20 to 30 μin/in/psi
Thermal sensitivity	1 psi/°F
Natural frequency	>40 kHz
Response time (to a step input)	$<6 \times 1\ 10^{-6}$ sec

pressure in laboratory work. Two ranges are available: -10 to +10 psi and -10 to +100 psi. The gage is constructed of Saran plastic with stainless steel plates and mica dielectric. The diameter is 1 inch, and the thickness is 0.035 inch. Static tests show the gage to be linear with applied pressure and a static overregistration factor of about 1.1 to 1.2. The variable capacitance sensor is probably not the best available for a nuclear environment but the gage might find use in HE field tests.

The Stanford Research Institute constructed a Surface Shear Gage to measure airblast-induced surface shear forces in the 0- to 200-psi overpressure region (Reference 32). The gage (Figure 38) consists of a flat plate, 1-foot square, supported on two octagonal half-rings similar to the moving ring used in the SRI Total-Drag Probe (see p 117). The strain rings in turn are fastened to steel mounting plates which are attached securely to a massive concrete base. The top

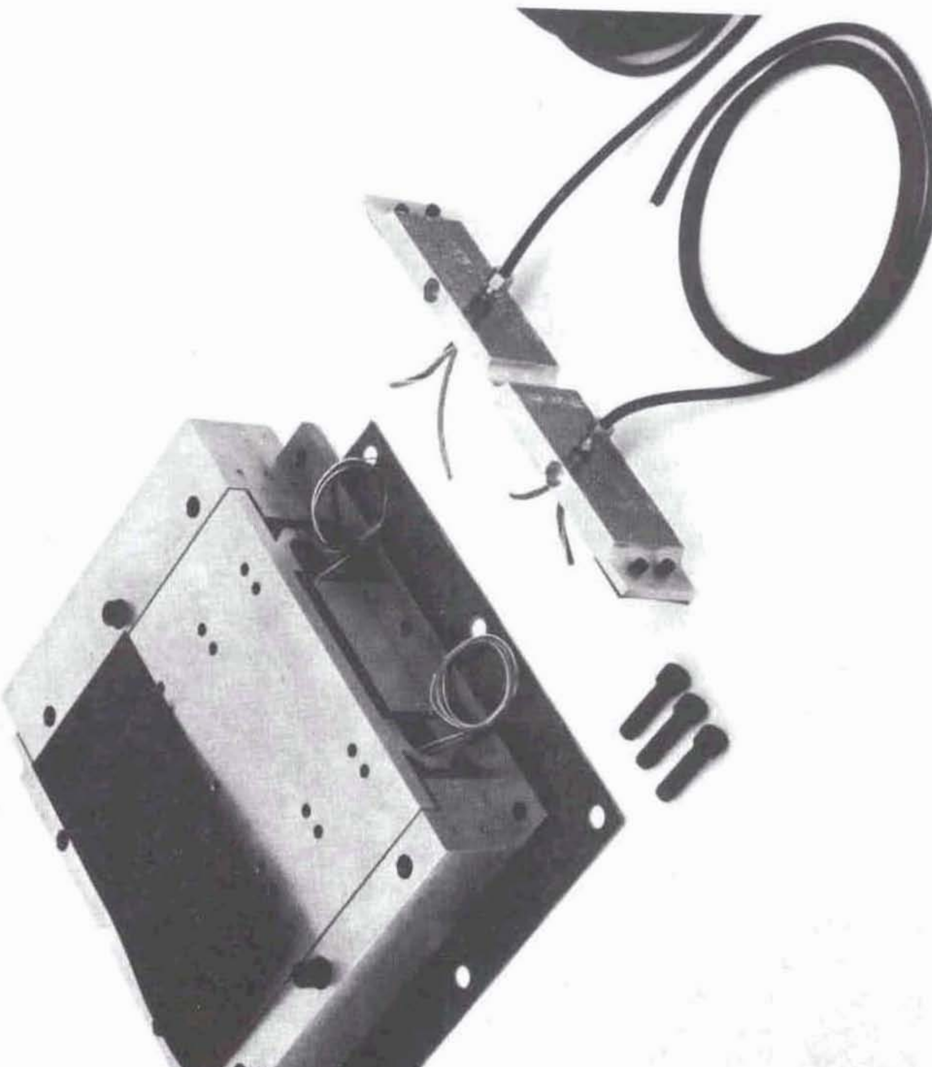


Figure 38. SRI surface shear gage.

surface of the gage is covered with ordinary stair tread material providing a sandpaper-like finish in contact with the soil.

Two strain gage bridges are used in the shear gage to obtain independent measurements of normal and shear forces. Each leg of the bridges contains two strain gages in series, one mounted at each end of the strain-sensing element. Damping is obtained by filling the gage enclosure with polybutene-20 which has a viscosity of about 6,500 centistokes at 90°F.

Rensselaer Tri-Axial Gage

The Rensselaer Polytechnic Institute, Troy, N. Y., has constructed for NCEL a tri-axial soil pressure gage to measure 0 to 100 psi with a 1-millisecond rise time. The shape of the gage is spherical, which makes it independent of both the directions of the soil properties and the directions of the stress field in the soil. The shell of the gage, 3 inches in diameter, is divided into 8 equal segments obtained by one equatorial and two longitudinal planes of intersection at right angles to each other. These segments are made sufficiently rigid to act as curved beams, each triangular segment being supported at 3 points. Six strain-gaged spokes extend from the center of the sphere to the points of intersection of the covering segments. The system of measurement is based on the requirement that the 3 space components at each point of intersection can be measured separately. In total, 18 force components are required to establish the magnitude and direction of the force acting on the gage in space.

A placement technique has been developed to minimize the effects of the presence of the gage in the soil. Placement is accomplished by surrounding the gage with a flexible elastic medium. The diameter of this elastic medium is sufficiently large to exclude the possibility that the stress concentration effects, due to the rigid inclusion of the spherical gage, will prevent significant displacement at its boundary. Transfer of stresses acting on the outer boundary of the elastic medium then occurs through the intermediary of a material with known properties and dimensions.

The prototype gage exhibited undesirable characteristics of non-linearity and hysteresis which were attributed to imperfect bonding between the gage and the elastic medium. It is unknown whether developmental work is continuing on this gage.

Soil Strain and Displacement Measurement

Since strain at any point is the space derivative of displacement, these two classes of instruments will be grouped together. Usually, a long-span gage is termed a displacement gage and a short-span gage is used to determine strain, although this is not a universal distinction.

Long-period displacement produced by underground nuclear explosions may be measured by relative displacement devices, both fixed-base and variable-base, and by inertial displacement. In addition, electronic analog circuits (Reference 35), for single and double integration of other measures, have yielded displacement data.

FIXED REFERENCE DISPLACEMENT MEASUREMENT. In order to measure absolute ground motion directly, a reference point must be chosen which remains fixed with respect to the earth. This reference point is, in general, located at a great distance from the point of motion. Usually the reference point is selected to be at some distance below the earth's surface. Both rigid rods and stretched wire have been used to measure gross ground displacement.

Sandia Rigid-Rod Gage

The Sandia Rigid-Rod, Long-Span Displacement Gage consists of a solid 1/2-inch aluminum rod 10 feet long, one end of which is anchored through a plate to the earth. The opposite end of the rod is free and carries the magnetic core of a Schaevitz linear variable differential transformer. The transformer is anchored to the earth through its canister. Hence, the LVDT output is an index of the relative displacement of the two anchors.

The rod is protected and decoupled from the surrounding medium by placing it inside a corrugated, flexible 3/4-inch metal tube which also provides a watertight assembly. Tests have shown that the corrugated tubing would withstand over 1000-psi external pressure before starting to collapse and bind the rod.

Since the relative earth motions are generally small (0.01 to 0.5 inch in a 10-foot span) and the rod must be free to move, a means had to be provided to zero the unit after it was embedded in the medium by tamping or grouting.

During installation, the rod is clamped in the canister by a pin-and-slot arrangement. After the installation, a motor turns the sleeve containing the slot, thereby freeing the rod to move longitudinally.

A second motor then turns three jack screws which hold a cage carrying the LVDT transformer, thereby zeroing the assembly.

Sandia also makes a 3-foot gage. It is similar to the preceding gage in that one end of the rod is terminated in a flat plate and the Schaevitz transformer is in a canister at the opposite end of the rod. The size of the canister is greatly reduced, the locking motor eliminated, and locking of the rod for installation is accomplished by cutting a groove near the end of the rod, in which a bar is placed. When the zeroing motor is operated in either direction, a cam pushes the bar out of the slot and a spring catch holds the bar out of the way. Two motor-driven jack screws move the LVDT transformer back and forth to zero the unit. (See also the SRI Soil Strain Gage, page 165.)

In a third model, the LVDT transformer is stationary in the canister. The end of the rod is threaded for several inches and carries an internally threaded cap. Mechanical stops permit the rod to move freely over a limited range, but the rod is not locked as in the previous models. After the gage is embedded in the earth, a motor-and-gear arrangement screws the cap, which carries the LVDT core, back and forth until the unit is zeroed or balanced. In this position, the rod has at least a 50-percent overtravel, the actual amount depending upon the size of the LVDT being used. This unit is smaller in size, is more rigid, and should be simpler to build, adjust, and operate than the previous models. The canister, about 4 inches in diameter, has a 12- to 15-inch diameter anchor plate at one end. The cylindrical portion is covered with a soft sleeve to decouple it from the earth. These features give more precise reference points for gage length. This model may be used with either the 3-foot or the 10-foot rods.

Sandia Wire Gage

Where relative earth displacements of several inches are anticipated, the rigid-rod transducer becomes so unwieldy and large (hence perturbing the medium) as to be impractical. Also, long rods (over 10 feet) have a tendency to buckle and resonate when shocked, thereby introducing noise into the record. Sandia developed long-span wire gages using a spring-loaded wire, one end of which is anchored to the earth while the opposite end is wrapped around a spring-loaded drum. A multiturn rotary potentiometer coupled to the drum-shaft indicates any motion of the drum. A spiral clock-spring placed inside the drum maintains 10 to 25 pounds tension on the wire. In some applications, an external spring is anchored to the wire to provide tensions of

50 to 150 pounds. The 0.026-inch music wire is encased in 3/16 inch bronze corrugated flexible metal tubing to decouple it from the medium and to keep water out of the gage housing.

Most of the gages of this type are made by Sandia. Wire lengths of 25 to 50 feet are most commonly used. Three- and ten-turn 500-ohm potentiometers are used, with a 2-inch drum for the wire. The chief drawbacks of these gages are the difficulty of adjusting both the spring tension and the potentiometer position, the high spring gradient, and the ease with which the potentiometer may be damaged if the wire and tubing are overstretched during installation. The gage is limited to locations where the potentiometer may be manually adjusted after installation.

For gages operating at greater spans, with displacements up to 3 feet, the upper anchor end of a 0.060-inch stainless steel wire is anchored to the drum of a motor-driven winch in a canister at the bottom of the hole. These springs maintain an initial tension of 100 to 130 pounds on the wire, and were designed to provide at least 60-pounds tension at the maximum displacement. Where the total displacement is 12 inches or less, the 2-inch drum-and-potentiometer assembly (previously described) has the 0.026-inch wire fastened to the 0.060-inch wire in the bottom canister. Where the displacement is more than 12 inches, a drum-and-potentiometer unit is used in which two turns of the 0.060-inch wire are wrapped directly around the 3.86 - or 4.77-inch drums, giving 12- or 15-inches displacement per turn of the shaft.

This gage is quite difficult to install, has poor mechanical reliability, deteriorates badly in the ground and does not reproduce high frequency components of strain and displacement. However, it has been used successfully in field tests.

ACF Inc. and Sandia have modified the long-span wire gage. The sensing element in the new gage uses a light beam interrupter rather than a rotary potentiometer. The new system has a higher frequency response and is easier to install, but has a lower shock tolerance.

NON-FIXED REFERENCE VARIABLE DISPLACEMENT. The direct, absolute measuring methods are impractical for most dynamic measurements of strain. Measurement of differential displacement may be accomplished by two methods:

1. A coupled strain gage where the gage connects two points

2. An uncoupled strain gage with no physical connection between the gage points.

UNM-AFWL Spool Gage

The Spool Gage* consists of two semi-rigid thin discs, connected by a thin, sliding, hollow stem. The sensing element is either a linear variable differential transformer or a linear potentiometer. Relative movement between the discs is measured directly.

In a study of the methods involved in relative displacement measurements in soil, Baker and Lynch (Reference 48), concluded that for accurate measurement a spool gage should incorporate the following features:

1. The ratio of the area of the end plate to the cross-sectional area of the coupling shaft should be at least 60
2. The shaft should be in a segmented configuration to carry no load and allow freedom of motion
3. The lateral surface of the shaft should have a low coefficient of friction and less than 5 percent of flexible material
4. The gage should be quite short compared to the length of an input pulse
5. Data within increments of time smaller than those required to assume a nearly uniform strain state between end plates are not valid
6. End plates should be rigid, as thin as possible, and of low mass.

The major problem with spool gages is their placement within the soil mass in such a manner as to minimize arching effects and impedance mismatch caused by the gage and by possible voids in the backfill. In general, spool gages have poor accuracy and poor resolution. It is almost impossible to construct one that is waterproof.

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*There is no commercial manufacturer of this gage. A number of laboratories have constructed modified versions of the gage [see DASA 1285-3]. The gage described here is used by AF WL and was designed by W. J. Baker, University of New Mexico (Reference 48).

IITRI Coil Gage

In the IITRI Coil Displacement Gage, the direct measurement of differential displacement, is between two gage points which are not mechanically coupled (Figure 39). The gage points are wire coils encapsulated in 3/4-inch diameter by 1/16-inch thick discs embedded in the soil, oriented to be parallel and concentric. A second set of coils is positioned at a convenient location. The principle of operation is that of an air core differential transformer with a null balancing system to permit accurate measurements of small strains (Reference 49).

In operation, the drive-coil circuit is composed of a 50-kHz oscillator and drive-coil power amplifier. The pickup coils are connected to an amplifier, which in turn is connected to a synchronous detector, filter, and meter. When the spacing of the two coil sets is different, a small differential voltage appears at the input of the amplifier. Once amplified, the signal is the envelope of this high-frequency carrier. The synchronous detector (a conventional ring demodulator) separates the envelope from the high-frequency carrier. The demodulator output is zero when the carrier input is zero or nulled, and is either positive or negative in polarity when the two pickup coil voltages are not equal. The polarity depends on which coil has the larger voltage, thereby indicating whether the coils embedded in the sample have moved closer together or farther apart. The response time of the gage, defined as the time from 10 percent to 90 percent of peak output, was determined experimentally to be approximately 0.01 millisecond.

There are no mechanical coupling effects, as in the spool gage, but the output is to some degree sensitive to lateral and rotational misalignment.

IITRI has used coils up to 6 inches in diameter which allow gage lengths up to 18 inches, and hence are less sensitive to local discontinuities in large soil samples. The system consists of two sets of coils with a driver coil and a pickup coil in each set. A 10-Hz oscillator is used to power the driver coils. The pickup coils from each set are combined in two arms of a balanced reactance bridge. The relative displacement between two coils of one set serves to unbalance the bridge. The amplitude modulated signal is then demodulated to obtain a dc signal proportional to the relative displacement between the two embedded coils. A full-scale output of 0.3 volts (at maximum sensitivity) can represent 1.4 percent strain in the 18-inch gage span. The cross-talk between adjacent sets of coils near each other is limited to 1 percent when a common oscillator is used and a separation of nine coil diameters is maintained between coil sets.

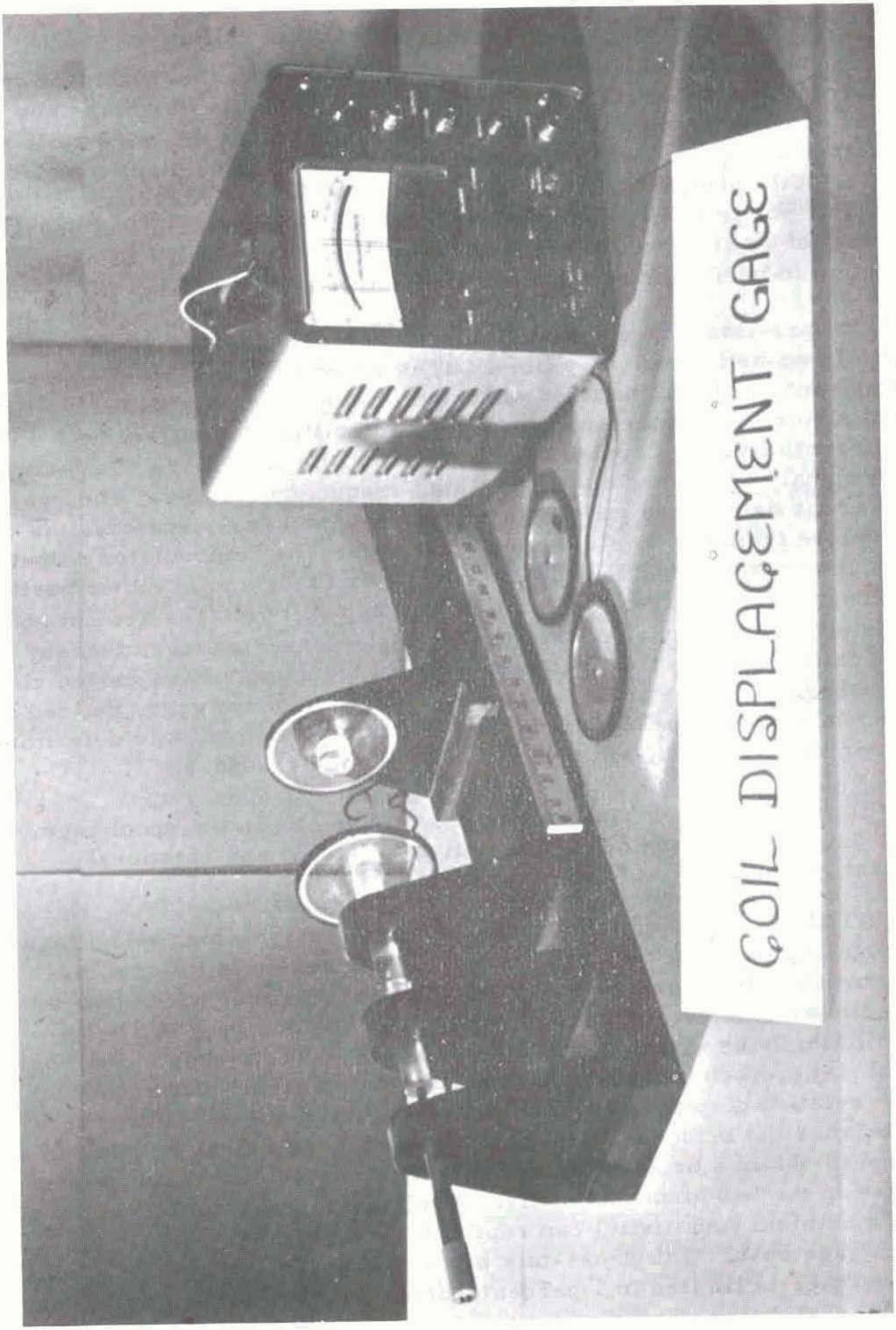


Figure 39. IITRI soil displacement gage shown in laboratory.

In the IITRI gage, waterproofing is not a problem and AFWL reports very good accuracy. Placement without disturbing the soil is still a problem, however. At present, the IITRI system is strictly a laboratory tool, still in the developmental stage.

SRI Soil Strain Gage

The SRI-designed soil strain gage (Figure 40) consists of a long tube, whose ends are securely fastened to the medium. The relative displacement of the ends is sensed by an LVDT attached to one end piece. The plunger, an armature, is extended by a rod which varies in length, depending on the strain range for which the gage was designed. The LVDT displacement range was ±0.25 cm, and strains of 0.6 to 4 ppk could be realized with gage lengths of 60 to 300 cm.

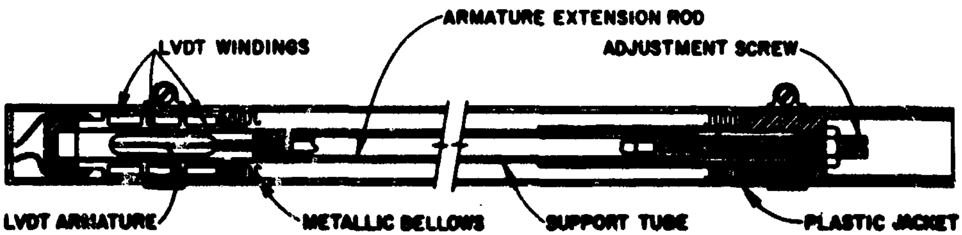


Figure 40. SRI strain gage.

INERTIAL DISPLACEMENT GAGES. Both Sandia and SRI have constructed gages using inertial principles.

In two types of gages designed by Sandia, the relative motion between sensing mass and case is reduced by coupling the linearly moving sensing mass to a flywheel. This is accomplished by a rack-and-pinion gear in one gage and by a recirculating ball nut in the other. In the SRI gage, a pendulum geared to a flywheel acts as the inertial element.

Sandia Rack and Pinion Gage

In the Sandia Rack and Pinion Gage (Reference 35), a moving rack is fastened to a mass carried on a ball bushing which rolls on a splined shaft. The signal output is generated by a rotary differential transformer. The maximum displacement measured is about 4 feet; the rise time of the gage is about 0.5 second, and the sensitivity of the gage is 0.04 g.

SRI Inertial Displacement Gage

The gage is housed in a 6-inch diameter sphere. A dc motor and solenoid are included in the case to permit calibration and leveling of the inner cage after grouting.

The SRI gage (Reference 50) measures either horizontal or vertical soil displacements of up to 36 inches for time periods of 2 seconds, with an accuracy of about 1 inch. Angular deflection of a geared pendulum is sensed by an E-shaped Wiancko variable reluctance sensor fastened to the gage case. The effective length of the pendulum, and therefore its natural period, is substantially increased by gearing it to a flywheel. The flywheel rotates through an angle of 15.6 degrees for 1 degree of rotation of the pendulum, resulting in small pendulum motions for large earth motions. This arrangement results in the instrument having a long natural period, i.e., 3 to 5 seconds. A steel vane attached to the pendulum shaft passes over the Wiancko core and balances the inductances when the pendulum is in its neutral position. The vane may be adjusted so that the electrical unbalance of the coil varies linearly with pendulum angle. In the vertical component gage, the pendulum is held in a horizontal position by a weak spring.

A number of other concepts and methods have been investigated for strain and displacement measurement. They are listed in the SRI report, DASA 1285, Nuclear Geoplosics.

Two devices, although not today incorporated in soil strain or displacement measuring gages, are worthy of further study.

The Kaman Radiation-Hardened Eddy-Current sensor, described in the section on airblast measurements, is essentially a displacement measuring device. It can accurately measure the distance between a 20-turn sensing coil and almost any metallic surface. Ranges of from 0–0.002 inch to 0–0.500 inch, with continuous resolution, are available. Frequency response is about 100 kHz. The sensor output is repeatable to within 0.1 percent and linear with 2 percent of full-scale output. The high impedance of this gage allows the use of relatively long cables between the sensor and the recorder.

Gulton Industries, Metuchen, New Jersey, has proposed using flexible strain devices (which they manufacture) to construct a triaxial strain gage. The flexible elements, potted in RVT silicone rubber, could be mounted in almost any solid matrix.

PERMANENT SUBSURFACE DISPLACEMENT. Slope indicators and scratch gages, used in vertical cased drill holes, can record the change in slope, the peak transient displacement and the magnitude of permanent displacement as a function of depth.

Slope Indicator

Two methods are used; both are standard well-logging procedures. One method uses a single, specially constructed tube or casing. A slope indicator, called a mouse, which consists of a simple pendulum with electrical contacts for determining the pendulum position, is lowered into the casing to define the slope of various sections of the cased hole both before and after the blast. The casing is constructed in such a manner that each 2-foot section can partially telescope to offset the effects of the ground motion.

Scratch Gage

In the other method, a second tube, coated with machinists' bluing, is placed inside the casing and anchored to the bottom of the hole. A scribe on the casing responds to the ground motion marking the inner tube. After the test, the inner tube is rotated, so as not to obscure the scribe marks of the transient motion, and removed to expose the record of peak transient displacement.

These methods are relatively cheap and reliable but are poor in accuracy and, of course, give no time histories. The tube must survive the ground motions in order to produce data.

Reference 51 records the use of these instruments during an HE field test.

Soil Particle Velocity

Vertical and horizontal particle velocities are measured directly with gages designed by SRI and by Sandia-modified SRI gages.

SRI Mark I

The SRI Mark I vertical particle velocity gage (Reference 52) uses a linear differential transformer as the sensing element (Figure 41). A solenoid in the gage holds the transformer core in a raised position. The core is released and allowed to fall under the influence of gravity in a highly viscous oil. The motion of the core mass is opposed by flow of the oil around the moving core. The core attains an approximately

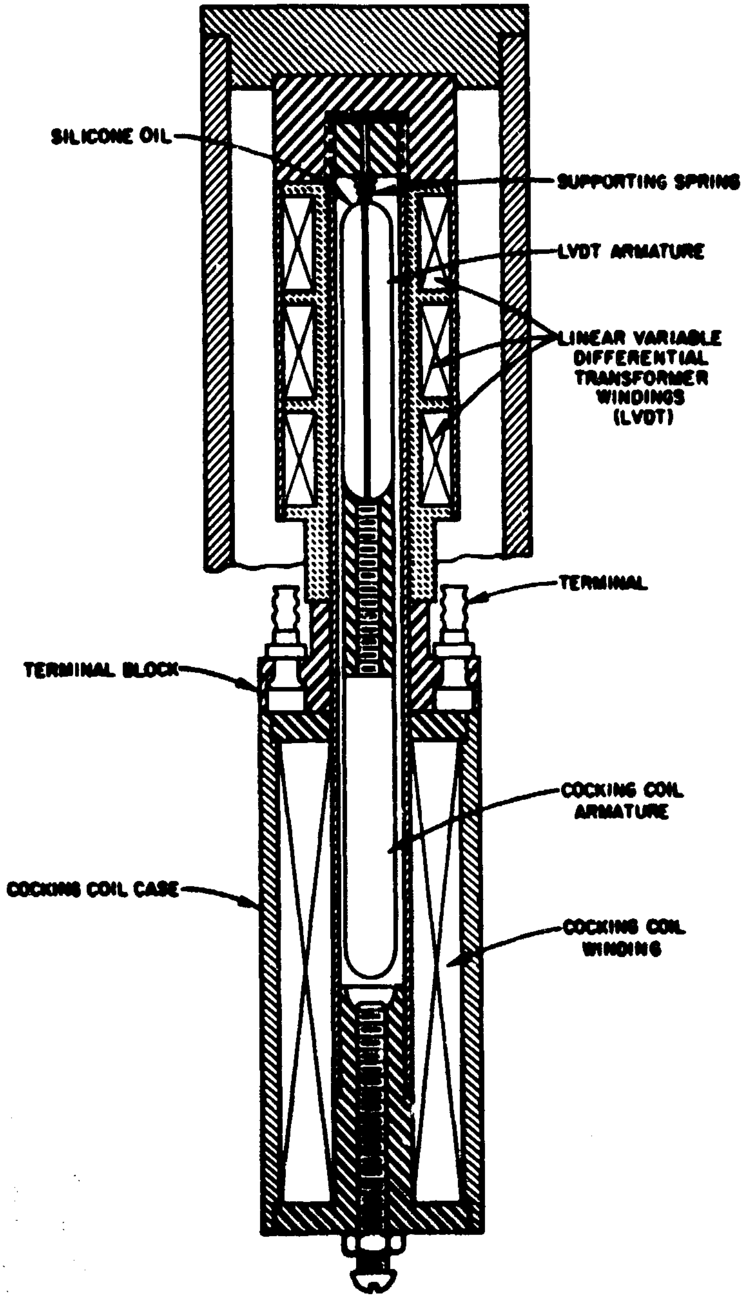


Figure 41. SRI Mark I velocity gage.

constant velocity for a fall time of about 2 seconds with a total travel of 0.3 inches. The flowing oil exerts a force on the core that is proportional to the velocity of the mass relative to the case of the gage. This force is equal and opposite to the inertial force on the moving mass. The gages have a finite bandwidth over which displacement of the transducer in its case is proportional to the particle velocity. The core release is synchronized so that the ground shock (hopefully) arrives at the gage while the core is falling at a uniform velocity and while sufficient fall time remains to measure the velocity. The response of the gage is within 5 percent from 0.2 to about 200 Hz. The maximum range is about 64 fps. This range can be increased by using a more viscous oil; however, this would decrease the gage sensitivity.

The basic Mark I gage measures 1.2 inches in diameter and is 3.3-inches long (3.0 × 8.2 cm). Normally, a mounting flange 2.5 inches in diameter is attached to one end of the gage.

SRI Horizontal Gage

The SRI horizontal gage uses the concept of an overdamped, low-natural frequency, pendulum accelerometer (Figure 42a). The maximum range of measurement is about 100 fps. The sensor is the coil assembly of a Wiancko variable reluctance element and a cantilevered mass in the form of a pendulum. The pendulum is flat in cross-section and is surrounded with a heavy silicone oil to allow extreme damping. With the pendulum hanging vertically, the undamped natural frequency is about 5 Hz (this varies somewhat between individual gages). When the pendulum is oil-damped, the frequency is lower due to the mass of the oil which moves with the pendulum.

The deflecting coil assembly, which (when energized) pulls the moving elements off-scale to one side, serves several purposes. When the gage is mounted for true horizontal measurement, energizing and then releasing this coil provides a record from which the low-frequency time constants may be directly derived. When it is necessary to measure at some angle other than horizontal (up to 30 degrees from the horizontal), this coil serves to trigger the release of the moving element in a fashion similar to that of the vertical gage. Finally, for field calibration, the coil is energized, the gage is turned on its side, and a record is taken as the coil is released.

SRI Mark II

When positioned to measure vertical particle velocity, the coil of the horizontal gage described above is unable to lift the armature. SRI redesigned the gage to measure vertical motion by the addition of a weak spring which supports the pendulum in a neutral position (Figure 42b). This gage, called the Mark II, has a greater flexibility than the Mark I but is more susceptible to damage from severe shock.

SRI Mark III

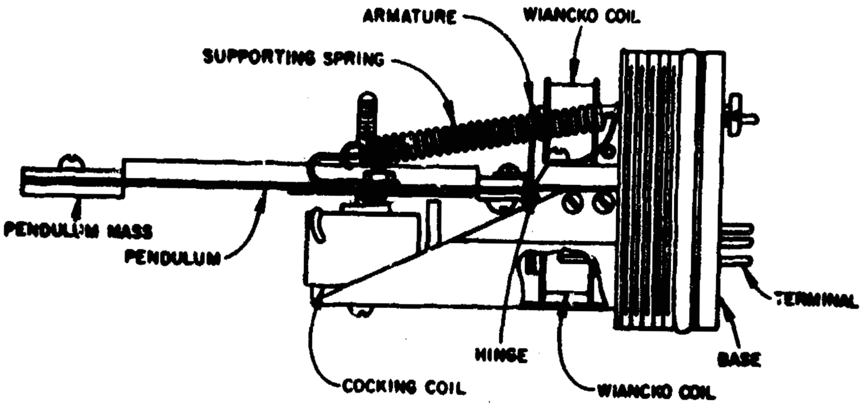
The Mark III Vertical Velocity Gage was developed by SRI especially for an HE test in limestone to meet the need for a gage with an increased frequency response (Figure 43).

The plunger in Mark III is the armature in the LVDT, instead of being a separate part coupled to the transducer as in Mark I. This reduces the mass of the moving parts of the gage. At the same time clearances are smaller than in the similar Mark I gage to increase the viscous force, and the length and oil volume are reduced to minimize false response to acceleration by compression of the oil. The gage is aperiodic, that is, no spring is provided to maintain it in the null position. A cocking coil is provided to lift the plunger to the top of its travel before the shot. Gage response is from 0 to >3000 Hz and measures velocities of 110 feet/sec.

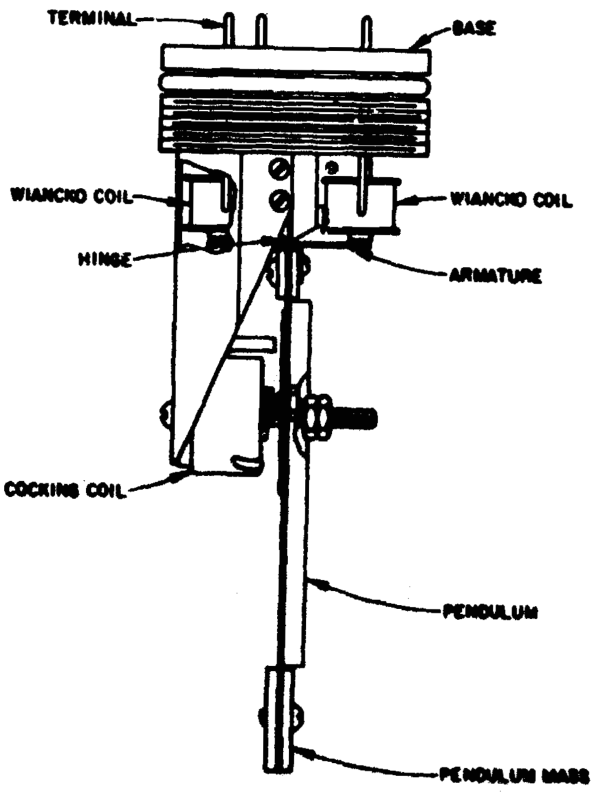
Like the Mark I, provision was made to release the plunger at a predetermined time before the shot so that the plunger would be falling during arrival of the signal. This feature produced much difficulty. The precise timing of the release was a matter of considerable importance. Since the rate of fall of the plunger is a function of the viscosity of the oil, which is temperature-dependent, release times had to be adjusted after the gages were in place and had come to thermal equilibrium with the surrounding rock.

Sandia DX

The Sandia DX is a modification of the SRI design. The DX is specifically designed to extend the range of particle velocity measurements into the 300 fps region and to withstand shock loads in excess of 1200 g. Sandia redesigned the pendulum suspension, the pendulum and the armature assembly. They designed a system for filling the gages with damping fluid (DC 200 silicone oil) under vacuum to eliminate the possibility of air mixing with the damping fluid and causing



(a)



(b)

Figure 42. Horizontal and vertical Mark II velocity gage.

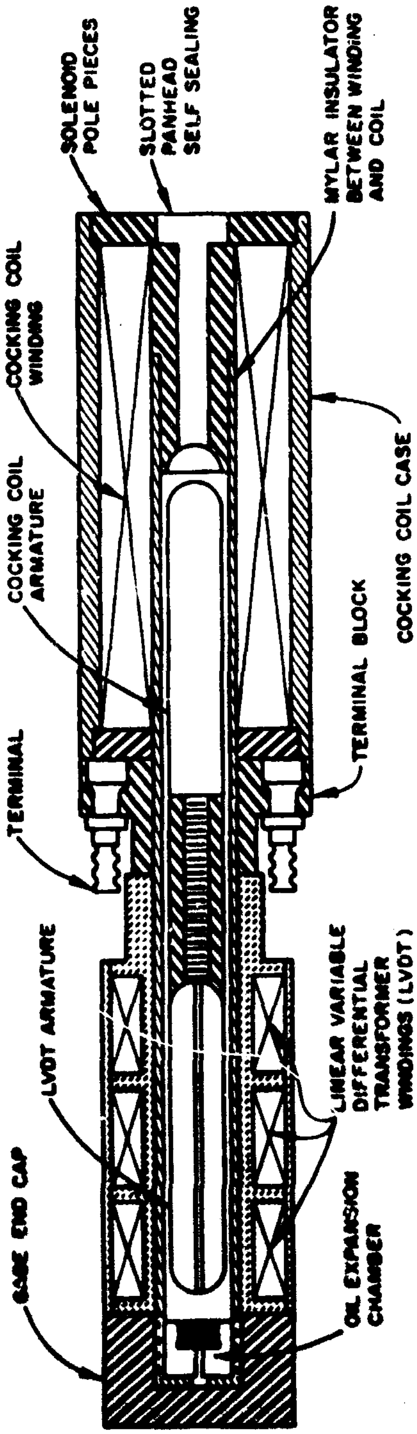


Figure 43. SRI Mark III velocity gage.

changes to the damping ratio, and they used a flexible bellows to accommodate temperature expansion of the damping fluid. Two models of the gage are produced. One, with a brass pendulum, is designed to measure velocities in the 0.1- to 25-fps range, while the other, with an aluminum pendulum, is for the range of 10 to 300 fps.

However, there are problems with the DX gage:

1. With a 3-kHz carrier, the maximum frequency response is less than 600 kHz
2. The variable reluctance element can only be energized by an ac system (AFWL considers this to be a disadvantage—Sandia does not)
3. The mounting arrangement is poor, and a special housing is required, which increases the size and weight of the gage system
4. Any oil-damped gage is temperature-sensitive.

Even with these limitations, AFWL reports that the DX is the best available field gage. It is very rugged and has produced reliable results from field tests.

SRI-AFWL Miniature Velocity Gage

At the request of the Air Force Weapons Laboratory, SRI redesigned their Mark I velocity gage to decrease its size and weight and increase frequency response (Reference 62). The gage measures velocity transients from less than 2 cm/sec to above 600 cm/sec over a frequency range from 1 to 500 Hz. It senses velocity along one axis only and is not affected by crosswise accelerations up to at least 30 g. The sensitive axis may be horizontal or vertical or inclined, provided a small external adjustment is made to counteract gravity. The gage is nearly a cube of about 5-cm edge length and weighs 375 gm.

The gage works on the principle of a highly overdamped spring-mass system with its undamped natural frequency at the geometric mean of its range. The relative displacement between mass and instrument case is a direct measure of the velocity of the case.

In the present model the mass consists of a thin rod suspended between two parallel cantilevered leaf springs, as well as a damping cup and the core of a LVDT which are rigidly attached to the rod. The cup slides with a radial clearance of about 0.04 mm over a stationary piston and provides viscous damping by shearing a viscous oil film between cup and piston. The LVDT, whose coils are embedded in the stationary piston, records the relative motion between the piston and cup.

The gage has been vibration-tested at frequencies from 0.25 to 1000 Hz and appears to be flat in the range 1 to 500 Hz, to within 5 percent. The smallest velocity it will sense is below 2 cm/sec, and the maximum velocity is above 600 cm/sec. An over range of about 50 percent is tolerated before the gage hits rigid stops, but the gage is nonlinear in the over-range region. The gage appears to be unharmed by accelerations as high as 40 g and perhaps more, but its acceleration tolerance has not been determined.

Gage sensitivity is affected by temperature changes by about 1 percent per °F. The gage shows a tilt signal which, for a horizontal gage, is about 1.5 percent of full scale per degree of tilt. The gage is not affected by loads of up to 1,000 pounds on the case. It will withstand shocks of approximately 4,000 g along the sensitive axis and 1,000 g along the cross axis.

Tests of the gage in soil indicate that its presence disturbed the motion field to the extent that the measured velocities may have been considerably in error; however, this same problem undoubtedly exists with all other velocity gages used in soil. The results of these tests indicate the gage measures the input velocity of shock-loaded soils to within about 10 percent.

This version of the SRI velocity gage is probably easier to use in the field than any of its predecessors. The square case may be more easily mounted on a surface than could the older round, pendulum-type gages.

SRI calculations indicate that it may be possible to raise the upper limit of the frequency range to 2000 or 3000 Hz without extensive redesign. At the same time, the maximum velocity allowed would be increased from 600 to about 3000 cm/sec, but with a corresponding drop in sensitivity. Conversely, an increase in sensitivity may be achieved by weakening the springs. This could increase the sensitivity by as much as a factor of four and lower the effective frequency range.

Shock Spectra

The peak relative response spectrum of a mass-spring system provides a useful structural design tool. A shock spectrum is simply a graph of peak displacement, peak velocity, or peak acceleration of a mass-spring system plotted against the system's natural frequency for a specific forcing function.

DTMB designed a reed gage for analysis of vibration aboard ships which has been adapted to shock measurement. It will not provide a time history of underground shock but does provide an envelope of expected maximum ground motion.

TRW Reed Gage

TRW Systems produces the only reed gage currently in use in field studies. The TRW reed gages incorporate a number of masses on cantilever springs, or reeds, mounted on a rigid base (Figure 44). The masses and spring constants of the reeds are so designed that their natural frequencies cover the range between 2 and 300 Hz. There are two gage configurations with somewhat different ranges of frequencies. For higher levels of ground shock the standard gage configuration, which has ten nominal reed frequencies of 3, 10, 20, 40, 80, 120, 160, 200, 250, and 300 Hz, is used. For somewhat lower levels of shock, the modified or low-frequency gage configuration having eight nominal frequencies of 2, 3, 5, 10, 20, 40, 80, and 120 Hz is used.

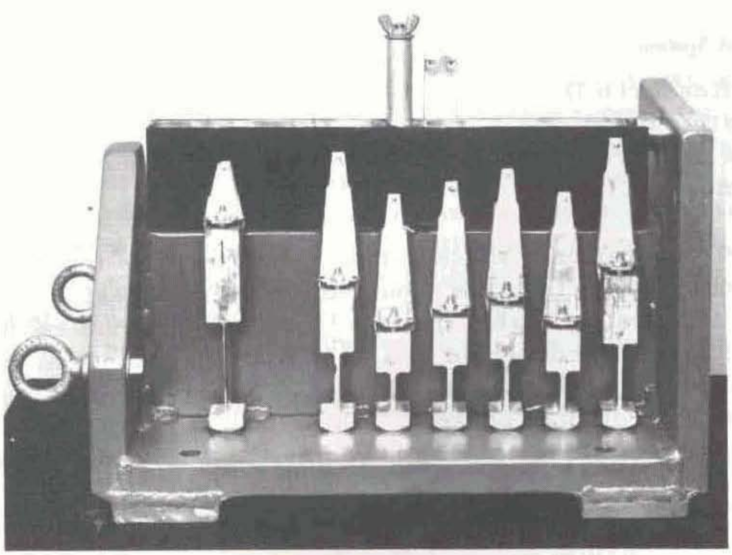


Figure 44. TRW reed gage.

The masses, which move in one plane, have scribers in contact with a polished metal record plate. A thin layer of lamp black is deposited on the record plate prior to preshot installation, by smoking it with a candle. When the gage base is subjected to ground shock, the reeds vibrate and the scribers record their maximum displacements on the record plate. After recovery of the record plates following the test, the displacements are measured. These measurements are converted to mass displacements by use of calibration factors which take into account such things as the location of the scriber with respect to the center of the mass, the fact that the mass is distributed rather than a point mass, and slight variations in reeds due to manufacturing tolerances. This then provides the frequency-displacement data used to plot the shock spectra.

The gages may be positioned in such a manner as to record either vertical or horizontal ground motion.

Time of Stress Arrival

It was indicated on page 125 that some of the characteristics of the shock wave in soils and rock could be calculated from an accurate time-of-arrival measurement. The measure of stress arrival time at known locations may be made with the various gages and recording systems which have already been described; however, the cost per data channel is very high.

AFWL TA System

The Research Division of the General American Transportation Corporation developed a 100-channel inertial time-of-arrival system for AFWL to provide a low-cost-per-channel measuring system (Reference 53).

In field operation a shock pulse associated with the dilatational and distortional waves triggers a buried omnidirectional inertia-switch sensor and a pulse is sent through high-level transmission lines. The switch closure is converted to a unidirectional standard pulse by a monostable single-shot multivibrator. This pulse energizes a neon glow tube on a display console. The total optical display consists of a matrix of glow-tubes having a geometrical relation to the sensor locations. The glow tube output is photographed by a high-speed framing camera. Timing is obtained by Beckman type 605A decade counting units on the console.

A group of these sensors, distributed throughout the depth of vertical holes, yields the time history of the waves at a given distance from ground zero. By combining the data from a number of vertical arrays, a two-dimensional time history of the waves may be found.

The sensors from each vertical array are connected to a transmission cable through a junction box containing an EM pulse overvoltage protection device. The system junction combines the two functions by utilizing a printed-circuit spark gap for both the connection of the sensor leads to the transmission cable and overvoltage protection. The electronic input circuitry requires only the overvoltage be held to 50 to 100 volts. Thus, the printed-circuit gap and a conventional NE-2 neon glow lamp across the input of the electronics are sufficient.

The sensor consists of a heavy mass in the form of a ball suspended on springs inside a light fluid-filled spherical shell. Changes in velocity or acceleration of the shell result in relative displacements between the mass and the shell. When the relative displacement equals the clearance between the ball and the shell, contact is made, a circuit is closed and the signal generated. Preliminary laboratory tests have indicated sensor closure rise times were less than one microsecond.

The response threshold of the sensor can be varied by changing the springs which support the mass, or by changing the viscosity of the damping oil, or both. Thresholds as low as 0.5 g and as high as 20 g may be obtained; thus, the system can record times of arrival of pulses of different magnitudes.

The system may also record the arrival of different waves since the recovery time of the system is about 1 microsecond (somewhat higher for the stiffer gages). The indicator on the optical display is lighted for one multivibrator period each time the sensor is activated, but a complete open-close-open cycle must be exhibited by the sensor or no further multivibrator action will occur. High-frequency ringing of the sensor will not result in more than one operation of the multivibrator since the oscillations will occur during the dead time of the one-shot multivibrator (i.e., the time during which the glow-tube is lit). A low-frequency ringing may be identified by the repetitive pulse train and can be accounted for during data analysis.

By using a quasi-digital display and high-level transmission lines, susceptibility to electromagnetic disturbances such as the EM pulse is materially reduced. Converting the data to pulses gives more freedom from background and permits data gathering under conditions impossible for conventional analog systems. Since the time-of-arrival sensor operates as a switch sending a 12- or 24-volt signal to the system, the signal level is sufficiently high to overcome the background noise which normally results in almost total signal obscuration in the case of conventional analog systems operating at millivolt levels.

AFWL has reported only one difficulty using the system. In one test the sensors were pressure-grouted within deep emplacement holes. The grout, under pressure, displaced the oil between the shell and the ball mass and immobilized the ball.

AFWL believes that larger systems with 200 or 400 channels could easily be made. This would further reduce the cost per data channel.

ANCILLARY EQUIPMENT FOR UNDERGROUND MEASUREMENTS

The usefulness of data obtained from instruments positioned underground is often dependent upon a precise location and orientation of the individual instruments. The following section, adapted from Sandia Corporation Report SC-M-65-330, by Ted B. Morse, (Reference 54) describes some of the instrumentation accessories and techniques Sandia has developed to assure that a sensing device is properly emplaced.

Assembly and Instrumentation Shelter

Instrumentation arrays are frequently 20 to 35 feet long. Transportation and handling problems require that the various units of the array be shipped separately and assembled at the site. As many as five or six arrays may be required at one hole and all must be ready to go down-hole at the same time.

Field experience necessitated the development of a transportable assembly, checkout, and installation shelter with the following characteristics:

1. Skid-mounted so as to be movable from hole to hole by truck or tractor
2. High enough so that the whole array could be assembled and checked out both mechanically and electrically
3. Removable end bracing so that the shelter could be skidded

over the hole casing which may extend 2 to 3 feet above the ground surface

4. Protection from the weather

5. A cable trough on the roof so the cables from the reels could be inspected for mechanical damage as they are fed vertically down-hole; also a provision for snubbing the cables

6. Safe working platforms at convenient heights over the hole

7. Light and power outlets

8. Exhaust fans

9. A monorail and chain hoist for each array

10. Movable work benches.

As the arrays are lowered, an observer on the roof monitors the dynamometer and footage counter. Another observer inspects the cable jackets as they pass over the roof. Tension in the cables is maintained by a workman braking each reel to maintain an appropriate sag between the shelter and reel.

Recent installations have used balanced-torque cable which has a twist of less than 10 degrees per hundred feet under load. Ordinary cable may twist several hundred degrees under similar conditions.

After the arrays have been lowered to the desired depths, a tie-off stand is placed over the hole with the hoist cable clamped to it, and the instrument cables are supported from it with Kellum cable grips. A 3- or 4-foot steel sawhorse is satisfactory.

The shelter may or may not be skidded away from the hole before the grouting is done.

A typical installation is a 12 × 24 × 20-foot high shelter with an I-beam or 6 × 6 timber framework and plywood or canvas sides. A 4 × 4-foot hole in the roof is provided about 6 feet from one end for the steel messenger cable, instrument cables, and grout hoses. Along one edge, a sheet-metal trough (3-foot radius) provides a snubber and guide for the cables. At the far end, 2-foot diameter wooden sheaves guide each cable from its reel which is placed on the ground, 50 to 100 feet from the shelter.

Inside, two platforms over the hole provide a safe working area. A trap door permits the arrays to be moved over the hole on the monorail while still allowing walking space all around the array.

After all sensor arrays are ready, a crane is positioned over the hole in the roof. The steel messenger cable is wound on the drum of the crane. The side of the shelter is removed so the operator can see the workers around the hole casing and receive their signals.

Lead ballast weights, connected to the steel line by means of two small steel plates, are lowered into the hole until a 1-inch bar placed through the center rests on the top of the casing. This bar supports the weights while the cable is disconnected and the array (from the monorail) transferred to the steel line and bolted to the top holes of the steel plate. The grout hoses and instrument cables are clamped and taped to the steel cable as it is lowered into the hole. (Power wrenches are used for attaching the clamps to the cable.)

Instrument Canisters

Very few end instruments are designed to be buried directly in soil or grout; hence, they must be protected from the elements. At the same time, they must be well-coupled to the earth or environment they are to measure. Instrument canisters in deep holes may be subjected to high hydraulic pressures caused by the head of water and grout when they are installed.

Aluminum tubing has proven to be a satisfactory material for canisters, since the sonic velocity nearly matches that of many surrounding media, and its high damping coefficient reduces ringing when subjected to shocks. In early tests, accelerometers were mounted on blocks or angles bolted to the canister. As the instrument ranges were increased, these had a tendency to ring or deflect.

More recently, an aluminum tube is machined with a 2-degree (per side) internal taper on each end, leaving about 1/2-inch aluminum thickness. Matching tapered solid plugs have holes bored for the various accelerometers and velocity gages in the proper relative orientations in respect to locating pins and grooves in the plugs and shell. After the gages are installed in the plugs and wired, the two plugs are inserted and wedged together in the tapers by tightening two 3/8-inch bolts. The plugs may include a tilt mechanism for the velocity gages.

Some difficulty was experienced in fishing through the wires from the lower plug during final assembly, so the latest design has just one plug. An increase of 1 inch in diameter and 2 inches in the length of the plug permit the installation of all the gages in it. This change decreased the overall length of the canister by several inches.

For locations where only one or two gages are required, solid aluminum blocks are machined to provide space for the gages and accessories. A 1/2- to 1-inch cover is bolted over the assembly.

Canister Sealing

Sealing to exclude deep hole water is a problem in buried canisters. Covers can be sealed with O-rings if the tolerances of mating parts are maintained and the proper O-ring diameters are used for the working pressure expected. Covers with a 1/4- to 1/2-inch step to guide them into the canister tube, and with 0.005- to 0.0010-inch radial clearance and an O-ring groove to give axial compression as the cover bolts are tightened, have withstood 4000- to 5000-psi external pressure, provided the O-ring grooves are made according to the manufacturer's recommendations as to proportions and surface finishes.

Radial compression designs (piston-ring style) were tried, but were ruled out because of the difficulties of assembly and removal, the ease of damaging the O-rings and mating surfaces on assembly, and the very close radial tolerances required of the parts. The same troubles were encountered with the 45-degree corner O-ring designs. Both types had a tendency for the O-ring to extrude into the crack under high pressures.

Sealing of cable entrances has required the development of special high-pressure cables and connectors. The basic sealing element is a neoprene O-ring clamped in axial compression. (See the section on Recorders for cable termination methods.)

Manual Installation of Gage Canisters

The installation of gage canisters near the surface does not present a great problem. In general, these are within 10 feet of the normal ground surface and are installed in open cuts.

The latest style Sandia surface canisters have an 8- to 10-inch spike in the bottom and a 2- to 4-foot rod or handle on the top. An index mark on the case is oriented toward ground zero. The spike is driven into the undisturbed earth, and the top rod is manipulated as the grout is poured (or as the earth is tamped) around the canister, to maintain the gage's level.

In canisters containing a pendulum-type velocity gage, the gage itself is monitored and used as the level indicator. In other cases, spirit levels are used on the rod extending from the top of the canister.

In holes from 10 to 150 feet deep, where the canisters are not readily accessible, several other means are employed. In general, spring spiders are included in the array to keep the canister centered in the hole so that the grout can flow completely around it. If the canister is to be turned after insertion, the spiders are free wheeling. If the canister does not have to be turned, or if it contains a mechanism to rotate another canister, the spider grips the walls to resist the torque.

The actual insertion is done with rigid rods. If the presence of a rod or pipe will not perturb the medium and influence the records, thin-wall conduit from 1/2 to 2-1/2 inches in diameter is fastened to the canister and grouted into the hole. (This conduit may also contain the instrument cables and serve as some mechanical protection for them.)

If it is felt that such a tube would perturb the medium, the rods must be removed before the grout sets. Originally, 20-foot sections of 1-1/2-inch-square aluminum tubing were coupled and bolted together, and used to push the canister into the hole and to rotate it. After the grout was pumped in, and before it started to set, a locking mechanism (Bal Lok) was actuated by a cable running inside the tubing This disconnected the rods from the canister without disturbing its position, and the rods were withdrawn.

Considerable time was spent in coupling and uncoupling the rods. The 20-foot lengths were difficult to maneuver in cramped underground tunnels and they were quite susceptible to damage. Handling and storage were also problems. Sandia developed a pin and tongue-and-groove quick-disconnect coupling of 1-inch (1/8-inch wall) aluminum tubing in 5-foot (±0.1-inch) sections using a Bal Lok disconnect on the lead rod. The pull wire was permanently threaded through all the rods, which were kept in a partitioned carrying case to prevent tangling of the pull wire.

In use, the first rod with the locking unit is fastened to the canister and pushed into the hole so the trailing end protrudes a few inches.

The next section is coupled to it by holding the latter at right angles to the first rod, pushing the two sections together (being guided by the pin and tongue-and-groove), and straightening the rod to be in line with the first rod. It is then pushed into the hole, and the process repeated.

The distance the canister is pushed into the hole is measured by counting the number of 5-foot sections used. The rods and couplings are rigid enough so the canister can be accurately located longitudinally and can also be rotated. Thirty rods are in a set, giving a working distance of 150 feet. The carrying case is 4 × 24 × 64 inches, and can readily be carried by two men.

In vertical holes, compass units (described below) are generally used to determine the azimuth orientation. If the holes are large and the depth shallow, the compass unit may be omitted and a stripe on the canister top, illuminated by a lamp, may yield sufficient accuracy for orienting the canister. In other cases, two lamps on the top of the canister have been surveyed-in with a transit at the surface.

In horizontal holes, visual methods (stripe on the can), electrolytic potentiometers, contact-making pendulums, or the gages themselves have been used to indicate when the canister was properly positioned.

Instrument-Leveling Devices

Some inertial instruments, such as the mechanical displacement gage and the pendulum velocity gage, which depend upon gravity to null them, require rather precise leveling after they are installed in the earth.

The double-integrating mechanical displacement gage consists of a free mass on a guide shaft which must be maintained level within ±5 minutes. A motor-driven worm-and-gear sector tilts the frame supporting the gage proper, after the canister has been tamped or grouted into place. An electrolytic potentiometer level (Hamlin Model EP 10-12), mounted on the gage proper, is used to indicate when the gage frame is level.

Pendulum-type velocity gages have an operating range of ±5 degrees from true vertical. To cover a reasonable span, the pendulum should be zeroed within ±1/4 degree of the center position. This can only be done by leveling the instrument case. Velocity gages on the ground surface are leveled manually as they are tamped or grouted into position.

Since deep-drilled holes can vary 2 or 3 degrees from the vertical, some means must be incorporated in the instrument canister to level the gage after the grout has set.

The first leveling device consisted of a solid block in which the velocity gage was mounted, and which was tilted by a motor-driven worm and gear. A few preliminary tests showed that the gear backlash introduced excessive play when the unit was shocked.

The second version consisted of pivoting the gage and block through the center of gravity and using a motor-driven screw to compress an opposing spring to about 200 pounds force. These forces, reacting through spring-loaded (300 pounds) ball pivots on the block, provided a gage mount capable of transmitting 100 g to the gage, with very little distortion in the sensitive axis.

Compass Indicator Units

In order to position a gage canister in a vertical hole at known azimuth, some fixed reference is necessary. Gyroscopic compasses were first considered, but the cost per unit and the drift over a period of hours, makes them unattractive for this application. In addition, it is often desirable to check the orientation of the unit months after the installation. Various radio compass devices were considered, but the power and electronics required became rather excessive. Magnetic compasses were the reasonable answer.

Sandia constructed a 1-1/4-inch compass card with a 0.028-inch hole drilled 0.475 inch from its center. A light source above the card illuminates a photodiode below the card when the hole is in alignment. This assembled section is placed in a cage on a shaft so that it can be rotated by a motor in the top section of the canister. Geared to the cage-shaft is a 10,000-ohm,10-turn potentiometer for indicating the position of the light-and-diode with respect to the canister.

The early-model canisters consisted of several machined sections welded and bolted together. All joints were potential sources of leaks when submerged. Extensive pressure tests of O-ring configurations developed a canister in which there were only two possible sources of leaks, i.e., at the cap and at the cable entrance. Later developments combined the instrument canister and the compass canister, thereby eliminating the cable entrance as a possible leak.

The first models contained two sets of carbon-zinc batteries, two relays, and miscellaneous hardware, including a slip-clutch. Zinc-carbon batteries, operable to 100°F, are useless in deep holes with high temperatures. However, mercury batteries are usable to 185°F. The slip-clutch and mechanical stops required considerable machining and were replaced by pins in the potentiometer-gear and small micro-switches. The switches also indicate when the compass-cage has reached the end of the travel. Magnetically shielded permanent magnet motors are used for ease of reversibility over a single pair of wires. The limit switches are shunted by diodes to reverse the motors when the limit has been reached.

In the control box, two independent 28-volt dc power supplies are included, one for the motor control and the other for the potentiometer bridge circuit or the photodiode circuit. A zero center 100-micro-amperes meter serves as a galvanometer and an indicator for the photodiode circuit. Two diodes, back-to-back, control the galvanometer sensitivity and avoid pegging the meter. A single two-position switch changes all circuits to either function. One two-gang, 200-ohm potentiometer in each lead of the lines to the compass unit below compensates for line resistance in the bridge circuit. All controls are over five conductors, one of which may be the shield of a four-conductor cable.

Practically all of Sandia's work has been in media (soils, granite, salt, and alluvium) which are relatively free from magnetic materials of pockets. Experience by oil-field-logging companies has indicated that there is relatively little change in the direction of the earth's magnetic field from the surface to several thousand feet down. Whatever error exists is small compared to the accuracy required for this work.

However, if steel cables are used to suspend the ballast or weight below the instrument arrays, the spurious magnetism of the steel cables would affect the compass and cause unpredictable errors. Therefore, it is the practice to use phosphor bronse cables of 1/2- or 3/4-inch diameter when the array is to be bypassed. Originally, two cables were used, but it was found that there was a tendency for the cables to twist around the array and to bind the canisters when an effort was made to rotate them.

Canister Rotating Units

Three types of devices have been used for rotating the instrument-and-compass canister assemblies.

The first unit used consisted of a Bodine KC-22 115-volt, 60-cycle, condenser-run, induction motor (0.001 hp, 0.9 rpm) stepped down through a 1:3 gear ratio to drive a shaft from which the instrument-compass assembly was suspended. A slip-clutch and mechanical stop permitted 370 degrees of rotation. The output torque was about 20 ft-lbs. Spring fingers on the outside of the canister prevented rotation of this unit in the hole. Gear trouble led to the development of a sturdier assembly.

The second-generation rotating unit consisted of a Borg 11-watt, 4.7-rpm, 15-inch-ounce torque, 115-volt, 60-cycle, condenser-run induction motor driving a planetary reduction gear and an output shaft having a torque output in excess of 50 ft-lbs.

Both these designs used motors whose output torques were voltage-sensitive and which required three conductors for operation. As holes became deeper, both these factors became undesirable.

The third version of the rotator adopts a Globe Industries 115-volt, 1/30 hp, dc permanent-magnet motor with a 5700:1 integral gear box, requiring only two conductors for bidirectional operation and whose torque is proportional to current (which can be monitored from the control box at the ground surface).

In past operations, difficulties were experienced with the canister sticking and the springs slipping, bending, and taking a permanent set, thereby imparting erratic motion to the instrument and compass canisters as they were rotated. To overcome these difficulties, a scissor jack and motor were added to the rotating canister to lock it more effectively to the hole walls to counteract the torque of the rotating mechanisms. However, the jacking mechanism recently was found to be unnecessary on long strings where the ballast (lead weights) exceeded 1000 pounds; consequently, it was eliminated, and the canister was shortened appreciably.

Cable Dynamometer and Footage Counter

When an instrument array is being lowered into a drilled hole, it is desirable to continuously monitor both the length of cable installed and the total weight on the cable. The length of cable installed indicates the elevation of the instrument array with respect to the shot elevation. The weight on the hoist cable is an index to the smoothness and alignment of the hole, blockages, or the height of water in the hole. Erratic tensions may indicate spalling of sufficient severity to justify removal and inspection of the array for possible damage or to bail out the debris in the hole.

Some drill hoists include a tension indicator but these are not always readily accessible. The sensitivity of these indicators often leaves something to be desired.

A clamp-on, three-sheave dynamometer was developed to monitor the cable tension and the footage. This unit may be located anywhere on the cable that is convenient. A Dillon 5000-pound dynamometer measures the force on the center sheave. The assembly may be calibrated statically with any known weight or force. The range of the instrument may be varied by changing the spacer on the take-up rod which is removed when the dynamometer is installed around the cable.

The lower-sheave shaft operates a bi-directional revolution counter. The diameter of this sheave is such that its effective circumference is exactly 2 feet when used with 3/4-inch steel cable. Calibration is effected by moving the dynamometer a known distance along a cable stretched along the ground under a tension approximating the average load to be expected. Accuracies achieved in the field have been better than 20 percent on installation and removal. Some error was probably due to stretching of the cable under load.

Touch-down Indicators

In holes where spalling is severe, it is desirable to know whether the debris has risen in the bottom of the hole sufficiently to prevent lowering the array to the desired depth.

A waterproof touch-down indicator was developed to indicate when solid bottom was reached. It consists of a canister (of the array diameter) attached to the bottom of the lead weight through-rod by means of a coupling and plunger rod. The plunger rod is sealed with O-rings and spring-loaded to 300- or 400-pound force with automobile valve springs.

When an obstruction is encountered, the spring is further compressed and the plunger rod operates a microswitch to give a signal at the surface.

The heavy spring preloading prevents operation of the switch by hydrostatic pressure (when there is water in the hole) or by minor obstructions which fall away.

Lead Weight Ballast

Since the canister assemblies are hollow, their effective densities are often less than 1.0; hence, they would float if water were in the hole. When grout with a density of 2 to 3 is introduced, most canisters definitely would float, or the tension in the array would be insufficient to maintain the array in a vertical position. It is therefore necessary to add weights to the bottom of the arrays to maintain tension in the hoist cables under all conditions.

Originally, lead slugs of the required weight were cast in one piece, but because of handling problems the lead slugs were redesigned into 4-foot units of 600 to 700 pounds each which are coupled together to obtain the total weight required. Handling problems are greatly simplified.

SECTION 5

UNDERWATER MEASUREMENT SYSTEMS

SECTION 5
UNDERWATER MEASUREMENT SYSTEMS

There are no fundamental innovations recently developed for use in underwater shock research. This is because fundamental measurement ideas developed ten to twenty years ago appear to be adequate for today's measurement objectives. Advances are being made by using modern solid-state techniques to increase reliability and flexibility of instrumentation. Adaptation to the deep ocean environment with its tremendous hydrostatic pressure is being successfully made.

Two distinct types of underwater pressure measurements are discussed here. One is a determination of the phenomena directly associated with the shock and bubble pulse produced by an underwater explosion, or by the water loading from an air or underground shock, and the other is measurement of the surface wave motion produced by the explosion. The pressures represented by these two measurements are several orders of magnitude apart. It is difficult to design a gage which will withstand the first and still measure the second.

The shock pulse from an underwater burst is much greater than that observed at an equal distance from an equal-yield burst in air or underground. The pulse also shows a more rapid decay. Thus, all electronic instruments used underwater should have the fast response characteristics that are required of air or underground instrumentation, only close to the detonation.

SHOCK-WAVE PRESSURE MEASUREMENT

Pressure measurements of the initial shock and the bubble pulsations are generally performed. In addition to peak pressure, a measure of the time-of-arrival of the various direct and reflected shocks, the positive duration, the total positive impule and the energy flux are desirable. Measurement of negative impulse is important for some studies, but it is usually an item of minor interest which is obtained only if it does not interfere with the other measurement.

Mechanical Systems

Ball crusher gages, diaphragm gages, and other mechanical gages have been extensively used in underwater work. Since most mechanical systems do not supply a time history of the shock, but merely a measure of the peak pressure or energy of the wave, they are usually employed today only as back-up instrumentation.

Ball Crusher Gage

A Ball Crusher Gage consists of a steel piston, a soft metal ball and a steel anvil. One end of the piston is in contact with a copper sphere which rests on the anvil; the other end of the piston is exposed to the shock wave. The amount of deformation of the ball is proportional to the shock impulse. The response of the gage up to the time of maximum deformation is equivalent to that of a mass-spring system subjected to a force applied to the mass; the motion of the piston can be described by the differential equation of a linear oscillator. In order to integrate this equation to determine the maximum pressure, it is necessary to know the shape of the pressure-time curve.

The NOL Ball Crusher Gage is a representative instrument. It has either a 5/32- or a 3/8-inch copper sphere as the deforming element and can measure pressures from 300 to 1,500 and 700 to 6,000 psi, respectively (Reference 55).

Modifications of the NOL gage were made before the 1958 Hardtack nuclear tests in order to waterproof the gage. Experience with the system had indicated that the original gage would leak after a few hours at rather moderate depths, and would leak almost immediately at depths greater than 100 feet. Water inside the gages causes a low, erratic response. Waterproofing is obtained by O-ring seals on all screw joints and a rubber diaphragm over the piston. NOL reported success with this system to 500 feet, the maximum depth they instrumented.

NOL Self-Contained Gage

NOL has experimented with self-contained mechanical systems which produce pressure-time data. In the last system modified by WES for use in a nuclear test (1958), the shock pressure pulse entered a damping orifice and lead-in tube, causing rotation of a Wiancko twisted bourdon tube pressure sensing element. A diamond-tipped stylus fastened to the sensing element scribed a pressure-time trace on a rotating, coated-glass drum which was driven by a spring-powered clock motor activated by an explosive escapement release level. The amplitude of the scribed mark was linearly proportional to the pressure. Timing marks were produced by a separate electromagnetically driven stylus. The response time of the system was 0.3 milliseconds and pressure ranges from 50 to 3,000 psi were available (Reference 55).

This instrument is remarkably similar to the BRL mechanical airblast system which was in use in 1958.* The newer BRL system, with its more reliable drive and timing mechanism, is waterproof and could be used under water; however, the maximum range of 3,000 psi and a rise time of 0.2 to 0.5 milliseconds in the BRL system offer no measurement improvement over the older NOL gage. The shock resistance of the mechanism is not known.

Electronic Systems

One of the major disadvantages of mechanical systems, even those which record time histories, is that they must be recovered in order to provide a measurement. This restriction does not apply to electrical systems where the signal may be transmitted to a safe recording location.

NOL-Wiancko

Attempts have been made, with varying degrees of success, to encase an airblast gage in a waterproof housing to adapt airblast sensors for underwater work. NOL (Reference 55) has used a Wiancko P-9-1005 sensor with a Hartley oscillator (modified to increase the base frequency to 25 Hz) within a ball-like waterproof case. This system measured overpressures of from 300 to 3,500 psi at 1,000 feet below the water surface. A cable is used to deliver power from a surface station to the oscillator and to transmit the FM signal to the recorder on the surface.

*In fact, low range BRL gages were modified by Scripps Institute of Oceanography for use in shallow-water wave measurement (Reference 56). A compliant bladder on the ocean floor, connected to the surface supported by a hose, was pressurized with air until the bladder began to fill. The air volume change caused by the bladder expansion and contraction in response to wave pressure was recorded by the BRL gage.

Piezoelectric Gages

The standard piezoelectric sensing elements used today are tourmaline and some of the ferroceramic elements. Tourmaline is preferred because it is sensitive to hydrostatic pressure, and thus no mechanical protection is required to insure that strain acts in a particular direction. Any such protective housing increases the effective size of the gage which is a distinct disadvantage for an underwater gage because of the rapid decay of the underwater pulse. As shown in Figure 45, the smaller the gage, the more nearly the gage output will follow the applied dynamic pressure. It is the usual practice to use the smallest gage possible in order to reduce this crossing error. It must be noted, however, that for nuclear detonations, the duration of the shock waves are long enough so that the crossing error becomes negligible and easily corrected.

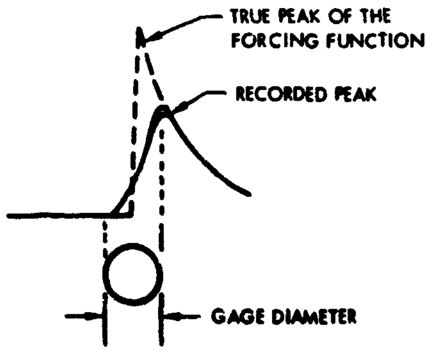


Figure 45. Crossing-time error.

Tourmaline Gages

The tourmaline gages used by NOL, WES, and DTMB are prepared by Crystal Research Company, Cambridge, Massachusetts. Table 11 lists the output response of various sizes of tourmaline gages; all consist of a pile of four plates.

Table 11. Tourmaline gage characteristics.

Gage Diameter (inches)	Output ($\mu\mu$ coulombs/psi)	Rise Time (μ seconds)
1/4	2	6
1/2	8	13
7/8	25	25
1-1/8	40	37
1-5/8	90	47
2	140	60

Waterproofing is a problem with the tourmaline gages and their cable connections. NOL has attempted a number of different methods—lacquer, silicone rubber—but always comes back to one of the first methods used, that of coating the gage with a special wax mixture. There may be some impedance mismatch between the water and the wax but this is entirely negligible.

ARC PZT Gages

NOL has tested some of the lead zirconate titanate gages commercially available from Atlantic Research Corporation. The manufacturer reports that pressures up to 10,000 psi can be measured with some models, and a variety of frequency responses, rise times, and direction sensitivities are available. Most of the gages are waterproofed with a bonded neoprene rubber sheath covering the sensor and a monel mounting sleeve which connects to the transmission cable. For shock wave pressures of a few hundred psi or greater, NOL found these gages failed to yield reliable results, and failed readily when subjected to underwater shock. At very low pressures—a few psi—these gages may provide usable data.

Pace Variable Reluctance

WES has recently reported success using Pace Engineering Company Model P24A electronic water pressure gages (Reference 58). In this gage, a flush stainless-steel diaphragm moves a small mass whose motion is sensed by a variable reluctance sensor. Ranges of 0 to 200 and 0 to 500 psi are available with natural frequencies from 30 to 35 kHz.

SHOCK WAVE TIME OF ARRIVAL

Doppler Systems

Both pressure switches and the SLIFER, or Doppler, system (described in the section on Underground Measuring Systems) have been used to obtain time-of-arrival data. The pressure switch is essentially a crushable section of a coaxial cable. A small brass cylinder 1/4 inch in diameter and 1/2 inch in length is grounded electrically to the outer sheath of a coaxial cable. A central rod, which is an extension of the central conductor of the coaxial cable, is insulated by air from the outer case. A shock greater than 4,500 psi crushes the case (in less than 1 microsecond) forming an electric short in the cable. A pulse generator codes the signals for transmission and recording. The main problem in a field test (Reference 58) was waterproofing. The use of air-dielectric cables in a SLIFER system should end most of the waterproofing problems (a solid dielectric coaxial cable would not be susceptible to water leakage, but would measure only pressures above 10 kb).

Some of the gages developed for very high-pressure underground measurements could easily be adapted for high-pressure underwater work. Of particular interest is the IITRI electolytic cell which is not directionally sensitive and responds to shocks from 5 to 350 kb, and the manganin wire gages developed by SRI and Sandia.

WAVE MEASUREMENT

Measurements of low-frequency, water waves involve determination of the height of the crest above still-water level, the depth of the trough, and the surface velocity of the wave train. There is also a requirement to determine the distance of wave run-up on the shore.

Mechanical Systems

Mechanical self-recording, pressure-time gages, normally used for shock pressure measurements, may be positioned in shallow water to record the pressure change due to the passage of surface waves (see page 191). Both modified BRL mechanical gages and bourdon tube-driven stylus gages have been used (Reference 56).

Can Gage

The maximum wave amplitude can be determined by noting the high water mark on a vertical post or pole. Usually this measurement is made by attaching small cups on the pole at known heights and determining if water is in the cups after the passage of the wave. Similarly, open cans have been buried flush with the sand surface on a beach at various distances from the water. The presence or absence of water in the can is a measure of wave run-up.

Optical Systems

The absolute motion of a float on the water surface may be photographed from a fixed land station. The float motion is related to the motion of the wave passing beneath. Accurate elevation-versus-time curves derived from the photographs give data on wave position, period, and height.

WES Grid Board Gage

A more quantitative measure may be obtained by a photographic recording of the wave passage against a fixed marked staff or a grid board. A grid board gage used by WES (Reference 59) will be described as representative of this system. The WES grid gage consists of an 1/8-inch thick aluminum plate, 4 feet by 8 feet, painted to provide a contrasting background on which horizontal lines (at 0.2-foot intervals) are painted. The gage is positioned with the 8-foot length parallel to the water surface on a radial line from the point of detonation. The midheight of the gage is adjusted to be at the water surface. A motion picture camera records the wave action. A time reference is provided by an accurate electric clock within the field of view of the camera.

Aerial Photography

Aerial stereographic photography of a large segment of the wave train may be performed. Standard photogrammetric procedures on the stereo pairs yield data on the amplitude and location (and hence, the speed) of the various waves.

Electronic Systems

Inverted echo sounders positioned on the sea floor, resistance gages, and pressure gages (both commercial and specially constructed) are used to provide amplitude-versus-time records.

Two types of variable resistance gage are in current use; the wave rod and the parallel wire gage.

WES-Wave Rod

The wave rod is essentially a step resistance wired in series with an oscillographic galvanometer (Reference 60). The resistance rod is placed vertically in the water with the static water surface near the center of the rod. As the water surface changes level, the water conductor path along the rod between the resistors and a conduction strip changes the current flow to the galvanometer.

WES Parallel Wire Gage

The parallel wire gage (Reference 59) consists of two 20-mil diameter stainless-steel piano wires (about 5 feet long typically) spaced approximately 1/2-inch apart and stretched between two circular pieces of micarta. A steel rod also extends between the micarta to give the gage its necessary rigidity (and to enable the tension in each wire to be adjusted). The gage is connected to one leg of an ac bridge circuit which has a 10-volt, 60-cycle output. Changes in water level are reflected as changes in gage conductivity which, in turn, cause a change in the bridge circuit power output. The output is rectified, filtered and fed to a sensitive galvanometer for recording.

Tsunami Gages

Scripps Institute of Oceanography uses very specialized long period wave recorders (Tsunami recorders) for both open water measurements, on deep water taut wire mooring, and near-shore studies (Reference 60). A basic characteristic of these recorders is a hydraulic filter system (and a very deep-placed pressure entry port) which suppresses the effects of normal tide, wind-driven short-period swell, and surf beat.

Scripps Pitch-Angle Recorder

Scripps has also experimented with a self-referencing recorder (Reference 56). Since the pitch angle of a float, or vessel, follows the slope of the surface, a recording of the slope-versus-time curve can be integrated to yield the wave height history. A Minneapolis-Honeywell LABS gyro, designed to give pitch and roll information to an automatic pilot, was modified to record measurements of pitch to ±30 degrees and yaw to ±60 degrees. In actual use, there was a base line shift on the output record which complicated the problem of data reduction.

TRANSMISSION, SIGNAL CONDITIONING AND RECORDING

SECTION 6

TRANSMISSION, SIGNAL CONDITIONING AND RECORDING

Common to all measurement is the problem of accurate transmission and recording of the data signal. Most of the problems in transmission, signal conditioning, and recording are related to the need to record at a distance from the sensing device in a blast and radiation environment which is severe, unusual, and not very well understood in many respects. The output of most sensors is extremely low, and the signal requires amplification for transmission and recording.

Two basic philosophies, not mutually exclusive, have developed about methods of recording nuclear blast data. Each has its particular advantages.

The first method is to record on equipment which is essentially of a laboratory type by moving a portion of the laboratory into the field in an instrument bunker or a specially designed instrument van-trailer. Recording in this manner enables a researcher to use rather sophisticated equipment but he must usually locate the recorder at great distances from the source of the signal. The second method is to design a special hardened recorder which may be installed near the signal source. The simplicity of use and (hopefully) the reduction of cost with a hardened recorder must be traded off against the likelihood that the recorder cannot be recovered for some time after a nuclear test, due to radiation hazards, or the need to remove debris to gain access to the recorder emplacement.

RECORDING SHELTERS

Bunkers

Bunkers, usually of reinforced concrete, buried or located aboveground, can be large enough to house over 100 channels of recording equipment, or so small that they protect a single instrument. Usually, the larger installations have proved to be more useful because it is possible to maintain, by air-conditioning, the environment required by most laboratory instruments.

Vans

Most agencies have found it easier to use a van-trailer both to transport the instruments to the field and to house them while they are there. A trailer used in this manner will eliminate the field time required to mount the instruments in the bunker and reduce the time necessary for instrument checkout. The trailers may be buried or protected by sand bags or earth berms to guard against blast, thermal, and radiation damage.

AFWL Hardened Shelter

A unique portable hardened instrument shelter has been developed by AFWL. The shelter, approximately 12 feet long and 8 feet wide, is constructed of 3/8-inch corrugated steel plate. It is capable of withstanding a 50-psi overpressure. Signal conditioning and recording equipment for 100 channels is shock-mounted inside. The unit is self-contained with its own generator, air-conditioning and receiver for WWV timing signals. Its size and weight are such that it can be transported by air, if necessary; however, it is usually located on a flatbed trailer along with an equipment work shop.

CABLES

A great number of different types of cables are being used in field test programs. The actual cable selected depends on the type of signal, the number of signals to be transmitted and the type of recording equipment being used.

The NOL, for instance, uses Signal Corps field telephone cable (type WWD-1-TT) to connect ultradyne-type gages to the recorders. This cable has been used where gages were as much as 2 miles from the recorders.

Type AWG 20 four-conductor coaxial cable is used by many field groups for underground tests. AWG 20 is a twisted 96-strand, braided, shielded cable with a neoprene jacket. The cable is about 1/2-inch in diameter and weighs about 0.1 lb/ft. Laboratory tests have shown a tensile strength of about 700 pounds, with a 3- to 4-percent elongation. However, the anchoring strength of the Conax-type connector with which the cable is usually connected to the canister, or gage, is only 100 to 200 pounds. After one nuclear test, practically all the connectors examined showed evidence of the cables moving out of the canisters. Crushing tests at Sandia showed the cable withstood pressures of 1200 to 2200 pounds when compressed between 1/4- to 2-inch cylinders and a flat plate, and 18,000 pounds between two 6-inch flat plates. When the cable was placed inside a 3/4-inch garden hose, it did not fail at 20,000 pounds, the limit of the press.

Cable Survival

One of the problems of hardwire transmission has been the survival of the cables long enough for the major portion of the event to be recorded. This is especially critical in the plastic and crushing zones near an underground detonation. A gain of only a few milliseconds of recording time often justifies the expenditure of considerable effort and expense.

Most failures have been due to tension failure of the cable. At points where crushing of the jacket was evident, the conductors appeared to be intact.

A number of methods have been attempted to protect the cables mechanically from the effects of ground motion. To some degree they are all successful; however, no optimum method has been devised for mechanical protection. Among the cable-protection methods are:

1. Placing the cable inside a 3/4-inch garden hose—this inexpensive method seems to work as well as any other

2. Placing cables inside 2-, 3-, or 4-inch flexible Greenfield conduit or reinforced high-pressure rubber hose

3. Placing cables inside 2-, 3-, or 4-inch aluminum or steel tubing

4. Coiling the cables into a helix, inserting the helix into a steel tube, and filling the tube with grease to permit free cable movement after grouting

5. Back-filling trenches with sand or vermiculite after the cables are snaked in the trenches

6. Spiraling the cable around 3/4-inch Bungee cord or 3/4-inch garden hose and placing the whole assembly inside 3-inch Greenfield flexible metal conduit.

Sandia (Reference 54) reports success with special cables. For the Shoal detonation they obtained two different types from the Vector Cable Company, Houston, Texas. One was a 4-conductor AWG 20, shielded, double-armored, jacketed cable. A special connector anchored both layers of armoring strands by clamping; a tension of about 5,600 pounds was required to cause the wire strands to slip. The other cable consisted of six 4-conductor AWG shielded, jacketed cables spiraled around a 1/2-inch (1/16-inch wall) rubber tube, all of which was covered with a 1/10-inch neoprene jacket. The outside diameter was 1-1/4 inches. At locations of major earth movement, the cables were installed in 3-inch (1/8-inch wall) aluminum tubing for additional protection.

If a high-mechanical-strength cable is required, a type AGW 20 can be obtained which will not fail at a static load of 56,000 pounds pull. The armor consists of twenty-four 3/16-inch, 7 × 7 stranded steel cables spiraled at 23 degrees over the jacket. The strands are brought through a special connector, turned 180 degrees and clamped.

TREE Effects

Transient radiation (TREE) effects produce signals which have proven to be very detrimental to measurement systems. The current associated with this signal may be defined as a replacement current, since it is most likely to be a current in an external circuit which is necessary to replace electrons, or other charged particles, which are knocked out of their usual position by the radiation. The magnitude of the radiation-induced signal changes with the voltage applied to the cable. The change in current, relative to the current with no potential applied, is defined as a conduction current, since it is probably due to the conductivity induced in the insulating dielectric by electrons produced by the radiation.

Conduction in the insulator is frequently characterized by two components. For very short radiation pulses, there is a prompt component whose magnitude is a function only of the instantaneous exposure rate. At the end of the radiation exposure, there is a delayed component having an approximately expotential decay.

Radiation effects on selected coaxial cables exposed in a linear accelerator are summarized in Table 12 (from Reference 5).

Table 12. Radiation effects on coaxial cables exposed in a linear accelerator to 30-Mev electrons at $\approx 10^{10}$ roentgens/sec.*

Cable	Type	Replacement Current, 10^{-14} coul/cm-roentgen	Conductance, 10^{-17} mho-sec/cm-roentgens
RG-8/U	Solid	-70 (a)	0.5
RG-58/U	Solid	+ 3	$\lesssim 1$
RG-59/U	Solid	- 2.4	1.2 prompt ~2.5 to 1 ms
RG-62/U	Semisolid	- 2.4	50 (b)
RG-114/U	Semisolid	- 0.5	5
Teflon RG-62/U	Semisolid	- 4	16
Teflon RG-115/U	Solid	- 7	$\lesssim 1$
Teflon RG-141/U	Solid	- 4	$\lesssim 1$
Teflon RG-210/U	Semisolid	- 3	30
Foamed RG-8/U	Cellular	- 3	15
Foamed RG-62/U	Cellular	+ 8	25
Roamed RG 1-in special cable	Cellular	+34	15

NOTES:
- a May be too large due to stopping of a portion of primary beam.
- b Average over 4.5-microsecond pulse. Initial spike ($\approx$3 microseconds) about a factor of 10 larger.
- * Reference 5.

Thermal-neutron- and fast-neutron-induced replacement currents are opposite in direction to that of the gamma-ray components. The magnitude of these replacement currents are such that, in typical pulsed reactor exposures without selective shielding, the gamma and neutron contributions are almost equal and opposite.* Hence,

*It should be noted that the time sequence of the arrival of gamma and neutron radiation from a nuclear weapon may be different from that of a pulsed reactor; thus in a nuclear environment the magnitude of the replacement current may be greater than indicated in Table 12.

the net signal observed can actually represent a small difference between two large components.

The replacement currents appear to be independent of the integrated flux and exposure rate. The fast-neutron component of the replacement current, however, exhibits a saturation such that the current per unit of flux decreases by approximately a factor of 20 after an extensive irradiation.

Wiring with thin insulation is not expected to exhibit the radiation effects behavior observed in coaxial cables. In particular, the limited measurements reported in DASA 1420 (Reference 5) indicate that the replacement current is primarily a function of the gamma environment. To a good approximation, it can be assumed that the radiation environment will amount to the emission of between 1 and 5×10^{-3} electrons for each gamma photon traversing the object. A reasonable average value corresponds to about 3×10^{-13} coulomb/cm-roentgen.

The conduction current is a very sensitive function of the amount of insulation around a wire and its nearby environment. For a bare wire in air with a grounded plane nearby, the predominant conduction is due to the ionization produced in the air. This ionization current is a strong function of air pressure and also is a nonlinear function of the applied voltage, and the asymmetric dependence of current on applied voltage is due to the fact that most of the current is carried by free electrons.

Placing insulation around the wire would clearly reduce the conductance, but at the price of increasing the effective area of the wire, and hence, the effective replacement current. At present, the best information seems to indicate that a layer of insulation having a diameter a few times the wire diameter is optimum. A more detailed investigation of the dependence of radiation-induced current on the thickness of insulation around the wire is needed.

Cable Connectors

One of the weak points of the instrumentation systems is the entrance of the cables into the instrument canister. Cable sheaths are relatively free of pinhole leaks, and the heavy neoprene jackets withstand considerable mechanical abuse, but securely anchoring the cable to the canister continues to be a problem. Even though the cable jacket and shield may remain connected to the canister, the conductors inside are often pulled away from their terminals, or the conductors are broken inside the insulation, if the cable is disturbed sufficiently.

For surface canisters and shallow holes, Sandia has found that the Conax-type connecter is satisfactory (when properly installed) if the external hydraulic pressure is relatively low and movement of the earth not too great. This connector consists of a base, cap, rubber bushing, and pusher slug. The base has a 1/2-inch, -14 tapered pipe thread, which is screwed into a tapped hole in the canister. The cable is inserted through the cap, pusher slug, rubber bushing, and base, into the canister. As the cap is screwed down, the pusher slug compresses the rubber bushing so that the outside diameter expands to seal to the walls of the base. At the same time, the inside diameter compresses the cable to seal to the jacket. When the connector is properly assembled, the cable has a slipping strength of 100 to 200 pounds, and will seal to 100- to 200-psi external hydraulic force. However, if the cap is tightened too much, the cable jacket may be cut and the conductors actually broken.

Deep holes with high external pressures and canisters with 20 to 50 gages present different problems. The Vector Cable Company has developed a termination capable of withstanding 4000- to 5000-psi external pressure. A flange and O-ring are bolted to the canister to seal the connector. The cable passes through a sleeve in the flange. Each conductor is terminated on a feedthrough bushing on an insulating bulkhead. A neoprene boot is vulcanized outside the serrated brass sleeve (on the flange) and to the cable sheath. Since the cable contains no voids, external pressure tends to improve the seal between the boot and brass above.

During preliminary tests, it was found that the cable had a tendency to creep through the brass sleeve when externally pressurized. A positive-stop bulkhead and feedthrough bushings, and the filling of cable voids with a vulcanized rubber compound, eliminated this difficulty. This type of connector proved satisfactory at the Shoal and Dribble operations.

Mecca Cable and Service, Inc., of Houston, has developed a pin-and-jack type of connector which has also proven satisfactory under high pressure. The single-conductor type consists of a brass 1/16-inch, 24-NPT portion with an O-ring. This screws into the canister wall. A rubber jacket is molded around the brass fitting and has a half O-ring molded into the outside wall about 1/4-inch from the end. The conductor or pin extends through an insulating bushing through the brass tube fitting. The on-conductor cable terminates in a jack which is covered by a rubber boot vulcanized to the cable jacket. About 3/8 inch from the end of the boot, an O-ring groove is molded on the inside of the boot. When the pin and jack are engaged, the O-ring is engaged. External pressure increases the sealing pressure.

Sandia attempted to use glass-insulated feedthrough bushings manufactured by Fusite Corporation, Cincinnati, Ohio, Type 1/16-27NPT-FP. The bushings have maintained a seal to more than 25,000-psi oil pressure. These would have required insulating the exterior connections.

An attempt to waterproof these terminals by potting in RTV Silastic compound failed when 4000-psi water pressure caused a Conax connector rubber bushing to cut the cable jacket, permitting water to flow along the fiberglass cable filler to the terminals. Bonding of the silastic compound to the neoprene jacket was also unsatisfactory. Bonding to the aluminum canister, however, was good.

RECORDING EQUIPMENT

Most recorders in use today are off-the-shelf items of commercial manufacture; a few, notably the AFWL DAQ-PAC and Harry Diamond Laboratories WETR, were produced by special order. A great many combinations and permutations of recording, and signal condition system elements (off-the-shelf, specially designed and breadboard) are employed, according to the particular requirements of a test, equipment availability, past experience, and individual preferences of a test group.

A typical system might use a MOD CA10 Statham 10 KHz (or a Genisco 20 KHz or a Wiancko 3 KHz) carrier system; a Teledynamics Type 1270 subcarrier oscillator; and an Ampex CP-100 tape recorder and Tektronics No. 521 oscilloscope. FM carrier demodulation and compensation for speed fluctuations in recorder tape transports may be obtained with an Electro-Mechanical Research, Inc. discriminator.

CEC System D

The Consolidated Electrodynamics Corporation (CEC) System D carrier-amplifier system will be described in some detail because it appears to be frequently used by field groups.

The System D is a carrier-amplifier system that will record static and dynamic outputs between dc and 600 Hz. It uses an amplitude-modulated, suppressed-carrier signal, with the amplified gage signal transmitted to an oscillographic recorder. The system may be used with two- or four-arm bridge transducers operating on the resistance change or variable reluctance principle. A signal of ±1 mv will cause a full-scale deflection. Attenuators enable the system to operate with input signals in the range of +1 volt to -1 volt. The system includes an oscillator power supply for sensor excitation with an output of 10 volts at 3 Hz, an attenuator to vary the input signal levels, an amplifier to boost low signal levels, and a phase-sensitive demodulator to provide correct polarity to the signal output. Under the condition of zero stress on the sensor, the output signal amplitude is zero. The signal is amplified, transmitted, and admitted to the demodulator, where the carrier is decoded and the proper sign and magnitude given to the signal. This output is transmitted to a current-sensitive oscillographic recorder where a permanent graphic record of the signal is made on photosensitive paper.

The System D, although old, is still adequate for the needs of most investigators. There is always a requirement for a higher frequency response, but this is usually not critical except from gages positioned close to ground zero.

SYSTEM D MODIFICATIONS. Almost everyone who uses the System D has made modifications on the equipment to meet their own particular specifications. At WES, Mr. F. P. Hanes, in charge of all electronic instrumentation, has modified the System D to enable it to drive either a tape drive or a galvanometer, or both together.

A simple device has been designed at Sandia to mechanically change the attenuator setting of the input into a System D amplifier. In some studies, Sandia wanted to record a phenomenon during a shot and also for some period after the shot (e.g., the earth movement at the time of a shot and, later, the reflections and disturbances during the collapse of the crater or cavity). The intensity of the signals from these two events may differ by orders of magnitude. If the equipment is set to record the first event, the second event is so obscured in noise as to be of doubtful value. If the equipment is set to record the latter events, the initial signal saturates the system, and the electronic equipment may not recover in time for the latter event. Thus, it was necessary to change the sensitivity of the system between the two events. A motor, slip-clutch, gears, adjustable pinstop, etc., are mounted on the front of the panel of each amplifier. This does not interfere with normal balancing of the unit in setting up the system. After the system is balanced, the attenuator switch is left in the normal position for recording the main event. A pin is placed in a hole corresponding to the attenuator setting desired for recording the second event. A few seconds after the main event, a timing signal applies 27 volts dc to the motors for 3 to 5 seconds. The motor turns the attenuator shaft until stopped by the pin at the desired setting, then the clutch slips until the power is removed. The switching operation takes only a few milliseconds and few data are lost in this interval.

SYSTEM D SIGNAL CONDITIONING. Since the input signals required for System D use are relatively high, ±1 volt, a low signal conditioning and amplifying network is necessary. The Electro-Mechanical Research Corporation manufactures a unit with the following specifications:

1. A variable dc voltage transducer power supply for each channel, with a usable range of 5 to 20 volts

2. A balancing network for each channel to zero-null any transducer unbalance in the range of 0 to 60 mv

3. A dc amplifier for each channel with a gain of 1,000, thus allowing a ±1 mv signal input to give a ±1 volt output

4. A logic unit for complete remote control for all phases of the recording cycle.

CEC System E

The CEC System E, like the System D, operates on the AM-suppressed carrier principle, and functions in essentially the same way as the System D; however, the System E uses a carrier frequency of 20,000 Hz, with a bandpass of 0 to 3000 Hz, which permits recording of a much higher frequency from the gage.

Hardened Systems

Blast-hardened data acquisition systems are being employed with increasing frequency in order to eliminate lengthy signal cables.

The Leach, Model 800, and the Genisco Data Model 10–110 are both small 14-channel recorders constructed to withstand shocks of 100 g.

Leach Hardened Recorder

BRL at one time incorporated the Leach recorder into a self-contained system within a 10-inch diameter, 6-1/2-foot long cylinder which was buried in an augered hole in the earth. Internal batteries provided the necessary power for operating the electronics for 30 minutes and the tape transport for 2 minutes. Thirteen data channels were provided. The fourteenth channel was used for reference timing and time-zero recording. Transducer excitation voltage was provided by the system: dc, 3, 10, and 20 Hz at 10 volts. When dc excitation was used, 10 Hz data response was provided, by means of wide-band FM (±40-percent deviation) with 54-Hz center frequency. Noise levels were on the order of 10 percent, full scale. The one use of this system—to acquire nuclear blast data—failed.

Genisco Hardened Recorder

The Genisco Data 10–110 was designed for use in adverse environmental conditions. The 10–110 is small (7 × 8 × 12-1/2 inches), lightweight (28 pounds), and portable. The system uses a unique Cobelt tape drive and transport which eliminates many problems inherent in tape transports using reels and pinch rollers.

The Cobelt drive scheme was first applied to the Genisco recorder designed for use on a rocket sled. This recorder had several features designed to permit it to operate satisfactorily under heavy vibration and accelerations up to several hundred g. In the recorder, no conventional reels are used. Instead the recorder is constructed very rigidly on both sides of precision spaces only 0.0001-inch thicker than the tape width. The tape, instead of being supported between reel sides, is handled by the blocks of metal which form the body of the recorder. When the recorder is assembled, the entire tape guide function is carried out by these side plates. For withstanding shock, this construction is much superior to one using a reel of any kind since a reel side must necessarily be relatively flimsy.

The Cobelt drive, in order to maintain contact of the tape with the head, consists of an auxiliary plastic belt which presses the tape toward the heads. This belt also provides the drive normally supplied by the capstan and pinch roller. The tape is thus both pulled along by friction with the Cobelt and pressed by it against the heads. A disadvantage of the Cobelt drive is that the lateral guidance of the tape, unless it is severely constrained, is related to the straightness of the driving belt, and there is a tendency for the tape to wander. In the Genisco recorder, this is kept to a minimum by the body of the recorder.

The data channels are wide-band FM(±40-percent deviation) with 54-Hz center frequency, thus giving a frequency response of 0 to 10 Hz. The minimum input to the VCO for full-scale deviation is ±250 mv. Thus, a high output transducer may be used directly into the VCO and give full-scale deviation without the use of a preamplifier.

An advantage of this recorder is its ability to operate with the center frequency shifted, thus giving a much higher signal-to-noise ratio when using the extended frequency band. With Fairchild dc amplifiers, a signal of 2 mv will drive the system to full-scale deviation.

Two complete systems have been designed specifically for nuclear studies. They are the DAQ-PAC and the WETR.

Keltec Industries of Alexandria, Virginia, developed a hardened Weapons Effects Test Recorder for Harry Diamond Laboratories. Information on this equipment is not available at this time.

DAQ-PAC

The DAQ-PAC system, developed by the MRD Division of General American Transportation Corporation for AFWL, is a self-contained portable package to obtain measurement under severe shock, pressure, radiation and EMP environments. Table 13 lists the operating environmental specifications.

The DAQ-PAC (Figure 46) consists basically of two parts: (1) a signal conditioning section which provides excitation voltages for transducers, automatic calibration, bridge balance, bridge completion and a balanced differential preamplifier to provide adequate signal levels for recording; and (2) an analog magnetic tape recording system for recording in both direct and FM format per IRIG specification 106—60.

Table 13. Operating environmental specifications for DAQ-PAC.

Shock	100 g, 1/2 sine wave, 11 ms duration
Neutron Radiation	10^{13} NVT (preamps and record electronics—10^{14} NVT)
Gamma Radiation	10^{8} rad C/sec intermittent, recover 0.1 ms; 10^{6} rad C/sec continuous
EMP	16,000-ampere turns/meter magnetic field; 5,000 volts/meter electric field 5 kHz to 25 kHz.
Temperature	-20°C to +55°C
Overpressure	500 psi minimum
Moisture	Waterproof—150 psi hydrostatic pressure

All components of the system are plug-in modules, so that a wide variety of transducers can be used to obtain magnetic tape recording without additional circuitry. After recording, the tape is recovered and played back on any standard IRIG magnetic tape playback system. A total of twelve data channels plus two channels for flutter compensation and time reference data are provided.

The DAQ-PAC also contains a programmer, electromagnetic pulse (EMP) input circuit protection and internal power supply.. Upon activation by external control signals, the programmer automatically directs the DAQ-PAC through a series of operations including pre-test warm-up and calibration, shorting input lines for EMP protection, data measurement recording, and post-test calibration. Thus, the DAQ-PAC is a complete instrumentation system and requires no external support other than the initial activation. The high shock and nuclear radiation resistance has been obtained by an all solid-state design and the careful selection of components.

The DAQ-PAC uses a modular construction to achieve a broad flexibility for measurement purposes. A combination of modules or cards are provided which allow measurement of low frequency phenomena (dc-600 Hz) using a 3-kHz carrier for transducer excitation, or

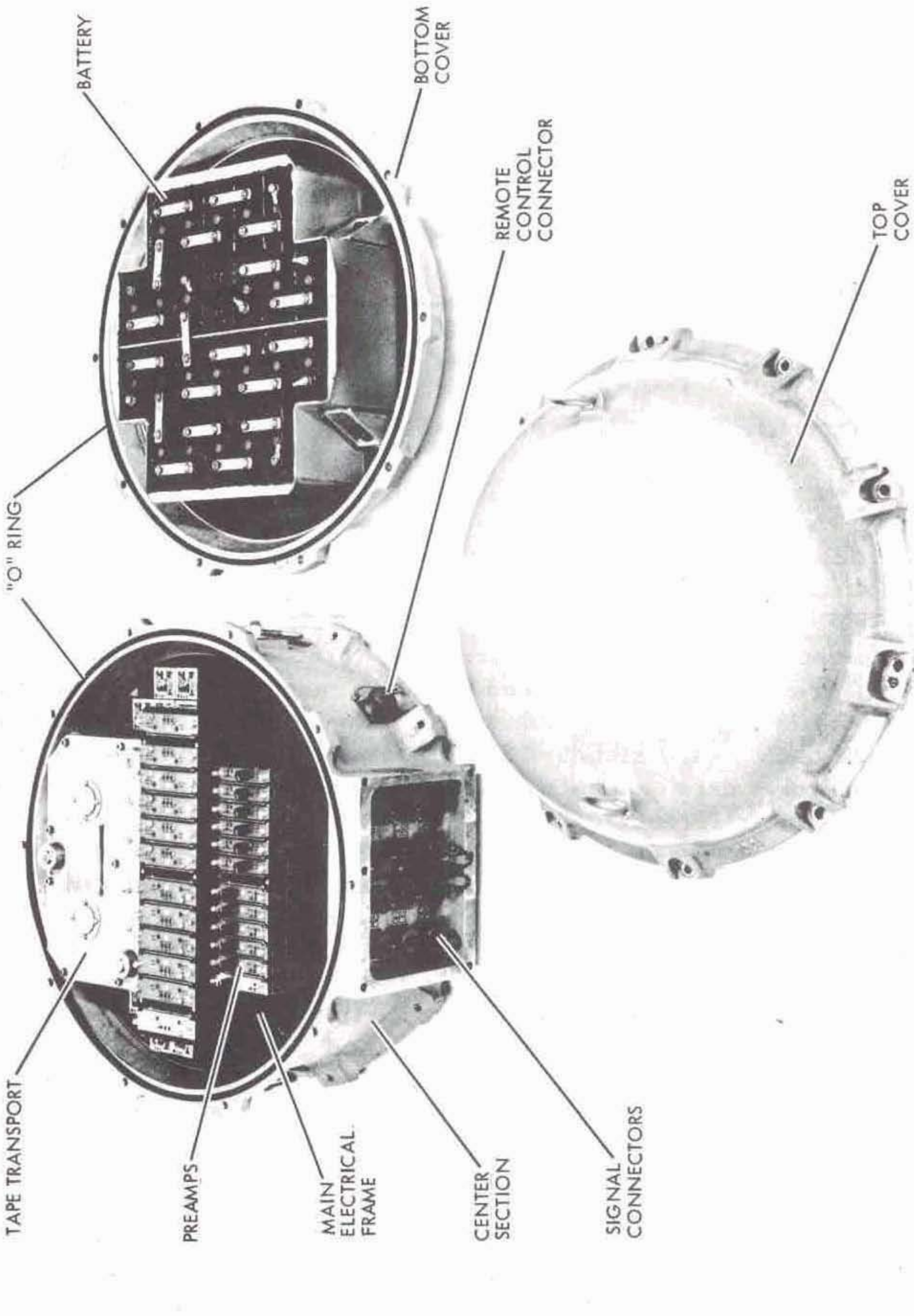


Figure 46. DAQ-PAC hardened recorder.

wide band linear (200--200,000 Hz) processing for applications requiring high frequency response. Wide band recording over the range of dc to 20,000 Hz is also available as an optional feature for those applications where both relatively high frequency response and dc levels must be recorded (see Table 14). Tape speeds of 3-3/4 ips to 60 ips can be provided, depending on the frequency response requirements. The corresponding recording times range from 60 to 4 minutes, respectively.

Table 14. DAQ-PAC specifications.

GENERAL CHARACTERISTICS	
Accuracy	± 2 percent of full scale FM mode; ± 5 percent of full scale FM mode under specified environment
Tape speed	Standard 3-3/4 through 60 inches/sec
Tape width	1 inch
Recording time	4 minutes at 60 ips
Track numbering and spacing	Per IRIG Specification 106-60 (analog)
Recommended tape	3M Tape 951-1
Start-stop time	1.0 seconds maximum
Tape speed accuracy	0.5 percent from nominal at 60 ips
Flutter	< 1.0 percent peak to peak dc to 300 Hz at 60 ips
Calibration	Automatic 0 and single shunt
Frequency response and input impedance	See plug-in modules
Transducer connection	Standard 4-wire system under environment. 6-wire remote calibration for long lines in absence of EMP

Table 14 (Cont'd.)

Size	24-1/4-inch diameter oblate sphere 20 inches high
Weight	275 pounds
PLUG-IN PREAMPLIFIERS	
Wide band preamplifier—model 1053	
Input voltage	1 mv rms for 1 volt output
Step attenuator	X0, X1, X10, X100
Input impedance	25,000 ohms, X0; 50,000 ohms all other settings
Signal-to-noise ratio	30 db
Frequency response	200 Hz to 200 kHz ± 1 db
Bridge excitation	0–10 volts dc 1 watt
Adjustments	Attenuation, amplifier gain, bridge voltage, and bridge balance
Carrier preamplifier—model 1054	
Input voltage	1 mv rms for 2.5 volts dc output
Step attenuator	X0, X1, X10, X100
Input impedance	1500 ohms minimum
Signal-to-noise ratio	30 db
Carrier frequency	3 kHz
Frequency response	0–600 Hz ± 1 db
Bridge excitation	3 kHz, 1–10 volts rms, 1 watt

Table 14 (Cont'd.)

Adjustments	Attenuation, amplifier gain, bridge voltage, and bridge balance
dc preamplifier—model 1062	
Input voltage	5 mv for 2.5 volts output
Maximum peak input voltage	± 2.5 volts
Gain stability	± 1 percent after 5-minute warm up
Step attenuator	X0, X1, X10, X100
Maximum source resistance	100 ohms
Frequency response	dc to 20 kHz
Bridge excitation	0–10 volts dc 1 watt
Adjustments	Attenuation, amplifier gain, bridge voltage and bridge balance
PLUG-IN ELECTRONICS	
FM Record—model 1067	
Input voltage	± 2.5 volts for ± 40 percent deviation
Frequency	108 Hz ± 40 percent (60 ips)
Frequency response	dc to 20 kHz (60 ips)
Signal-to-noise ratio	30 db from dc to 20 Hz at normal recording levels
Input impedance	50,000 ohms minimum
Adjustments	Signal amplitude, center frequency, heat drive current

Table 6-3. (Cont'd.)

Direct record—model 1057A	
Input voltage	1 volt P.P. for normal record level
Frequency response	± 2 db between 300 Hz and 200 kHz
Signal-to-noise ratio	30 db from 300 Hz to 200 kHz
Bias signal	10 mHz
Adjustments	Signal amplitude, bias amplitude, head tuning

The DAQ-PAC is physically comprised of four major sub-assemblies: the electronics compartment, the tape transport, the battery pack, and the external container. The container affords the necessary environmental protection against EMP, overpressure, and moisture as well as housing the other sub-assemblies.

A boss is provided to mount a cable strain relief to minimize cable breakage from motion of the DAQ-PAC due to ground motion. Shaped as an oblate sphere, the container is constructed of three pieces of 5/8-inch thick aluminum, a center section, and top and bottom covers. Each cover is bolted to the center section with ten studs which can be quickly removed for access to the inside or rapid data recovery.

The electronics compartment and tape transport, which form the heart of the system, are hard-mounted to the center section as a package. This assembly has been designed so that all the data channel modules such as the preamplifiers and record electronics are exposed at the top and are accessible for balancing, adjustment and replacement when the top cover is removed. Similarly, the entire tape transport can be quickly removed from the top for rapid recovery of the recording medium in the field.

The battery pack consists of a potted assembly of rechargeable nickel-cadmium batteries secured to the bottom cover. It is coupled to the electronics and transport through cables with connectors.

For airborne or space applications the electronics and tape recorder can be removed as a package from the central section of the container and mounted elsewhere with no reduction in shock and radiation resistance. This effects a savings in weight, particularly if the internal battery can be eliminated by substitution of the vehicle electrical power.

Raster Oscilloscopes

SRI has reported success recording transient blast and shock phenomena with a raster oscilloscope and camera. The raster oscilloscope used was Tektronix type 555 dual beam. The trailing edge of one sweep gate was applied to the trigger of the opposite sweep, producing alternating sweeps on the oscilloscope face. The sweeps have virtually no "dead time" between the end of one and the start of the other. The oscilloscope has a bandwith of 2 Hz to 13 MHz (26 nanoseconds) and a gain sensitivity of 0.05 volt/cm. The advantage with this system is that data will not be lost if a time-of-arrival switch fails to trigger a scope sweep, or if a timing signal is applied to the trigger at the wrong time.

AUXILIARY EQUIPMENT

Northrop

The Northrop Ventura Corporation has developed and tested a number of signal conditioning equipments in a nuclear environment. Reference 16 gives the specifications and operating characteristics of:

1. A vacuum tube voltage controlled oscillator
2. A tunnel-diode voltage controlled oscillator
3. A 100-kHz tuning oscillator
4. An amplifier and ac to dc converter.

Northrop is also developing methods and equipment for using fiber optics to transmit data.

Endevco Amplifier

The Endevco Corporation offers a small tube type amplifier, No. 2618B, with a gain variable from 4 to 17. It was designed for use with piezoelectric transducers under severe radiation environmental conditions.

GATC VCO

The MRD Division of General American makes a hardened voltage-controlled oscillator which employs RCA nuvistors as active elements and wire wound resistors and mica capacitors as passive elements to permit operation under nuclear radiation environments up to 10^{15} NVT. Potted construction is employed to allow operation under shocks exceeding 50 g.

The MRD-VCO provides a full-scale frequency shift (±40 percent carrier frequency) with an input of ±1 volt. Drift in frequency does not exceed 1 percent of double bandwith over a temperature range of -20 to +80°F. The unit contains its own voltage regulator and operates from an unregulated 90-volt power supply.

Calibration

Recorded data are useless for making amplitude measurements unless a known reference amplitude is recorded at the same time on the same record through the complete recording system. Primary input voltage and frequency, thermal effects on the cables, amplifiers, power supplies, etc., changes in sensitivity of the various components with time, and other factors, all tend to change the overall system recording sensitivity. However, if a known step input is inserted into the complete system just before shot time, the drift until the main event is recorded is generally insignificant. The relative amplitudes on the record remain constant.

Much of the recording is done by recording the unbalance produced in a two- or four-arm bridge circuit. If one arm is momentarily shunted by a fixed resistance (and capacitor) to give a finite deflection equivalent to a known output of the gages, a known calibration step is on the record. This step also may be used to determine direction of the initial event on the record, and is an index to the linearity of the whole system in the event actual amplitudes are greater than anticipated. If the gage records an event directly, without going through a bridge, a known voltage may be inserted into the recording system to give the calibration step.

Sandia Calibration

At one time, Sandia mounted their "Cal +" unit, which performs these calibration steps, in the instrument racks in the recording trailer, which was generally several thousand feet from the gage. Since some time would elapse between the time the system was set up and balanced and the actual time of the shot, temperature changes and drift in the equipment and cables introduced some error in the calibration step. Hence, it was decided to place the calibration unit at the end instrument so that it would see the same changes as the gage itself.

Sandia developed a unit to be placed in the instrument canister, consisting of transformers, ruggedized relays, resistors, and capacitors, all potted to further protect them from the environment. Two or four complete units are potted into a pancake 4 inches in diameter and 2 inches thick. These assemblies can withstand 1000-g shocks without malfunction (Reference 54).

APPENDIXES

APPENDIX A

GLOSSARY OF TERMS USED BY BLAST AND SHOCK INVESTIGATORS

ABSOLUTE PRESSURE—Pressure measured with respect to a vacuum.

ACCELERATION—Time rate of change in velocity and/or direction.

ACCELERATION SENSITIVITY—The difference between the sensor output at zero acceleration and the output measured at a given steady-state acceleration. Usually expressed in percent of full-scale output per g.

Acceleration, Dynamic Transverse Excitation Sensitivity—The change in output of a sensor observed when a dynamic acceleration, either sinusoidal or pulsating, is applied in any direction perpendicular to the sensitive axis.

Acceleration, Steady Transverse Excitation Sensitivity—The change of output of a sensor observed when a constant acceleration is applied in any direction perpendicular to the sensitive axis.

ACCURACY—Freedom from mistakes or errors. A measure of conformity to a specified value.

ACTIVE LEG—An electrical element within a sensor which changes its electrical characteristics as a function of the application of the forcing function.

ANALOG OUTPUT—Sensor output in which the amplitude is continuously proportional to the stimulus, the proportionality being limited by the resolution of the transducer. Distinguished from DIGITAL OUTPUT.

BLAST LOADING—The total force on an object caused by the air blast from an explosion striking and flowing around the object. It is a combination of diffraction and drag loading.

BLAST WAVE—The shock wave transmitted through the air, accompanied by winds, propagated continuously from an explosion.

BLAST SCALING LAWS—Formulas which permit calculation of the parameters describing a blast wave at any distance from an explosion of specified energy. The known variation with distance of these parameters for an explosion of known energy is the reference.

COMPRESSION PRESSURE—See DYNAMIC PRESSURE.

DAMPING—The resistance, friction or similar cause that diminishes the amplitude of an oscillation with each successive cycle.

Damping Factor—(1) The ratio of any one amplitude and the next succeeding it in the same sense or direction when energy is not supplied on each cycle. (2) The percent of critical damping in a gage. Represents a compromise between frequency response and overshoot. The theoretical optimum figure is a damping factor of 0.64 which corresponds to a frequency response flat ± 2 percent from zero (steady state) to 60 percent of the natural frequency of the transducer.

Optimal Damping—Damping ratio slightly less than unity which limits sensor overshoot to a value less than the specified uncertainty of the instrument.

Critical Damping—The value of sensor damping which provides the most rapid transient response without overshoot.

Damping Ratio—The ratio of actual sensor damping to critical damping. May be expressed as the ratio of output under static conditions to twice the output at the lowest frequency where a 90-degree phase shift is observed.

Fluid Damping—Accelerometer damping obtained through the displacement of fluid by the mass and the accompanying dissipation of heat.

Magnetic Damping—Damping obtained through the generation and dissipation of electromagnetic energy.

DAMPED NATURAL FREQUENCY—The frequency at which a single degree of freedom system will oscillate, in the presence of damping, upon momentary displacement from the rest position by a transient force.

DEAD VOLUME— The total volume of the pressure port cavity of a sensor with no forcing function applied.

DIFFERENTIAL PRESSURE— The measurement of the difference between two pressures under consideration.

DIFFRACTION— The deflection of waves around the edges of objects. For a blast wave impinging on an object, diffraction refers to the passage around, and envelopment of the structure by the blast wave.

DIFFRACTION LOADING— The force (or loading) experienced by the structure by the blast wave during the diffraction envelopment process. The force results from the differential between incident and reflected pressures of the blast wave in the early stages of target engulfment. See also DRAG LOADING.

DIGITAL OUTPUT—Sensor output that represents the magnitude of the stimulus in the form of a series of discrete quantities. Distinguished from ANALOG OUTPUT.

DIRECT SHOCK WAVE— A shock wave traveling through the medium in which the explosion occurred, without having encountered an interface.

DRAG LOADING— The force on an object or structure due to the transient winds accompanying the passage of a blast wave. See also DIFFRACTION LOADING.

DURATION— The time required for the shock wave to pass a given point. See also POSITIVE PHASE and NEGATIVE PHASE.

DYNAMIC PRESSURE— The air pressure which results from the mass air flow (or wind) behind a blast wave. It is equal to the product of half the density of the air through which the wave passes and the square of the particle (or wind) velocity behind the shock front as it impinges on the object or structure.

DRIFT— A change in measuring system output attributable to any cause.

"E" CORE or "E" COIL—The configuration of laminations used in certain inductive sensors which resembles the form of the capital Roman letter "E."

EARTH SHOCK—See GROUND SHOCK.

ERROR—The difference between the indicated value and the true value of a measured parameter.

FLAT FREQUENCY RESPONSE—Response of a measuring system to a constant amplitude function which varies in frequency. The response is flat if it varies within specified limits of amplitude.

FORCING FUNCTION—The physical phenomenon such as pressure, acceleration, velocity, or displacement which is measured by the sensor.

FREE AIR—A region of homogeneous air sufficiently remote from reflection surfaces or other objects so that the characteristics of the direct shock wave are not modified by reflected shocks or disturbances arising from scattering objects.

FREE AIR OVERPRESSURE—The unreflected pressure, in excess of the ambient atmospheric pressure, created in the air by the blast wave from an explosion.

FREE FIELD OVERPRESSURE—See FREE AIR OVERPRESSURE.

FREQUENCY RESPONSE—The portion of the frequency spectrum of the forcing function which is sensed by a system within specified limits of amplitude error.

FREQUENCY-MODULATED OUTPUT—An output which is obtained in the form of a deviation from a center frequency, where the deviation is proportional to the applied stimulus.

FREQUENCY RANGE—See FREQUENCY RESPONSE.

FULL SCALE—(1) The maximum value of forcing function the sensor was designed to measure. (2) The magnitude of the output of the sensor at the maximum forcing function.

GAGE FACTOR—A measure of the transfer function of strain-sensitive resistive materials. Numerically expressed as the unit change in resistance divided by the unit change in length.

GAGE PRESSURE—(1) A differential pressure measurement in which the ambient pressure provides the reference. (2) A pressure in excess of the standard atmospheric pressure at sea level and 70°F, e.g., 14.7 psia.

GAGE SENSITIVITY—See GAGE FACTOR.

GROUND SHOCK—The transmission of a vibratory energy as waves in rock or soil, causing a time-varying acceleration, velocity, and displacement.

HEAD-ON PRESSURE—The force resulting from the moving air mass in a blast wave coming to rest on a reflecting surface and transfering its dynamic momentum to static pressure.

HYSTERESIS (or HYSTERESIS ERROR)—The maximum difference between the readings of a sensor for a fixed value of the measured stimulus taken when the stimulus is increasing and when it is decreasing. Hysteresis error is usually expressed in percent of full scale.

IMPULSE—The product of the force from the blast wave and the time during which it acts at a given point. It is computed as the time integral of the variation of force at a given point, the integration being performed from the time of shock arrival to the end of the positive phase. It is generally convenient to use the concepts of overpressure impulse and dynamic pressure impulse.

INACTIVE LEG—An electrical element within a sensor which does not change its electrical characteristics as a function of the forcing function. Specifically applied to elements which are employed to complete a Wheatstone bridge.

INCIDENT PRESSURE—Pressure measured side-on to the advancing shock wave.

INDUCED SHOCK WAVE—The shock wave transmitted into a medium when a shock wave traveling in one medium meets the interface between the two media.

INFINITE RESOLUTION—The ability of a sensor to provide a stepless, continuous output over the entire measured range.

KILOBAR—A unit of pressure, 1 kilobar = 987 atmospheres = 14,509 psi.

LINEARITY—The relationship existing between two quantities such that the change in one quantity is exactly and directly proportional to the change in the other quantity. The quantities and ranges involved must be clearly specified.

LOCAL STATIC PRESSURE—See INCIDENT PRESSURE.

MACH STEM—The shock front formed by the fusion of the incident and reflected shocks from an explosion.

NATURAL FREQUENCY—The frequencies of free oscillations in an undamped body.

NEGATIVE PHASE—That portion of the blast wave in which pressures are below ambient atmospheric pressure.

NON-LINEARITY—The maximum deviation between a straight line joining the zero and full-scale plotted output points of a sensor. It is usually expressed in percent of full scale.

OUTPUT—The signal from a system or device which is a function of the applied stimulus or signal.

OVERPRESSURE—Pressure above ambient pressure, usually measured in pounds per square inch (psi).

OVERPRESSURE IMPULSE—See IMPULSE.

PEAK AMPLITUDE—The maximum deviation of a phenomenon from its average, or mean, position.

PITCH—Deviation of the direction of flow from a parallel to the surface. Upward is considered positive.

POSITIVE PHASE—That portion of the blast wave in which pressures are above ambient atmospheric pressure.

POSITIVE PRESSURE—See DYNAMIC PRESSURE.

PRECURSOR—A pressure which precedes the main blast wave.

psi—See OVERPRESSURE.

psia—See ABSOLUTE PRESSURE.

psig—See GAGE PRESSURE.

RANGE—A statement of the quantitative limits of a physical system.

REACTIVE BALANCE—The capacitive or inductive balance which is often required to null the output of certain sensors or systems when the excitation and/or the output are given in terms of alternating currents.

RAREFACTION WAVE—The wave which results as a shock wave encounters an interface of a less dense medium and imparts some of the shock energy into that medium. See TENSILE WAVE.

REFLECTED PRESSURE—The total pressure which results instantaneously at an interface when a shock wave traveling in one medium strikes another medium.

REFLECTED SHOCK WAVE—The wave propagating back into the transporting medium that results when a shock wave strikes an interface between two media.

REFLECTION FACTOR—The ratio of the total, reflected pressure to the incident pressure when a shock wave traveling in one medium strikes another.

RELIABILITY—A measure of the probability that a system or device will continue to perform within specified limits of error for a specified length of time under specified conditions.

REPEATABILITY—The ability of a system to repeat a measurement of a fixed stimulus to a specified accuracy.

RESOLUTION—The smallest change in applied forcing function that will produce a detectable change in the instrument output. Measures the degree to which small increments of a forcing function can be discriminated in terms of instrument output.

RESPONSE (SENSOR)—A quantitative expression of the output of a transducer as a function of the input, under conditions which must be explicitly stated.

RESPONSE (TARGET)—The action of an object under conditions of shock loading.

RESPONSE TIME—The time required for the output of a sensor to reach a stated value (usually 95 percent) of the full-scale output when subjected to a step function input under conditions of critical damping. For an oscillatory output the time is computed from the beginning of the initial variation to the first oscillation peak.

RINGING—The oscillatory behavior of an object in response to a rapidly applied load.

RINGING FREQUENCY—The frequency of oscillation of the sensor in response to a transient forcing function. The ringing frequency is a function of the mass and the spring constant of the system.

RISE TIME—Time interval from the shock arrival to the peak overpressure. (For instrumentation, see RESPONSE TIME.)

SENSOR—A device for converting one form of energy into a different form of energy to facilitate measurement.

SHOCK FRONT—Boundary between the pressure disturbance and the ambient environment where abrupt changes in velocity, pressure and temperature occur.

SHOCK STRENGTH—Ratio of the peak blast wave overpressure (plus ambient pressure) to the ambient pressure.

SHOCK WAVE—A steep-front pressure discontinuity propagating through a medium as the consequence of a sudden application of pressure in the medium.

SIDE-ON PRESSURE—See INCIDENT PRESSURE.

SPAN—That portion of a range over which a gage is used.

STAGNATION PRESSURE—See HEAD-ON PRESSURE.

STATIC PRESSURE—See INCIDENT PRESSURE.

STRESS—The force acting in a unit area of a solid.

STRAIN—The deformation of a solid resulting from a stress, measured by the ratio of the change to the total value of the dimension in which the change occurred.

TEMPERATURE RANGE—That range over which the temperature specifications of the gage are met.

Temperature Maximum Range—The absolute range without damage to the sensor.

Temperature Output Sensitivity Drift—The change of sensor sensitivity, expressed as a percent of full-scale output per unit of input, due to a change in temperature over a given range.

Temperature Zero Drift—The change in output due to temperature change with no forcing function applied. Expressed as a percent of full-scale output per degree temperature change from 70°F.

TENSILE WAVE—The wave reflected back into a medium at the interface of a less dense medium. See RAREFACTION WAVE.

TOTAL PRESSURE—See HEAD-ON PRESSURE.

THRESHOLD OF SENSITIVITY—The smallest change in forcing function that will result in a detectable change in sensor output.

TRANSVERSE SENSITIVITY—The ratio of change in sensor output to an incremental change in a given stimulus along any axis perpendicular to the sensitive axis. In accelerometers, it refers to the change in the sensor output at zero acceleration and at some other acceleration value applied along a plane perpendicular to the sensitive axis.

TRANSDUCER—See SENSOR.

YAW—Horizontal deviation of flow direction from a line joining ground zero and the gage.

ZERO UNBALANCE—The output of a sensor when no forcing function is applied. Expressed in terms of percent of full scale output.

APPENDIX B

THE NUCLEAR BLAST ENVIRONMENT

In order to obtain an adequate and meaningful measurement of some parameter of the shock wave, consideration must be given to the blast-produced environment in which the measuring device is expected to operate. Shown below are selected environmental parameters (obtained from a number of unclassified sources) for nuclear detonations. Due to the uncertainty of the scaling factors involved, the values given must be considered as approximate. A measured value from a given test may easily differ from a factor of 2 to over an order of magnitude from those listed.

BURST ENVIRONMENT AND MEASUREMENT	WEAPON YIELD			
	1 KT	10 KT	1 MT	10 MT
SURFACE BURST				
Fireball radius at break-away (feet)	110	275	1750	4400
Maximum fireball radius, (feet)	220	550	3500	8800
Distance from GZ for 100 psi (feet)	330	710	3300	7100
Incident overpressure at 1 mile (psi)	0.45	1.7	37	250
Positive duration at 1 mile (seconds)	0.36	0.32	0.15	0.14
Dynamic pressure at 1 mile (psi)	<0.1	.07	15	200
Time of shock arrival at 1 mile (seconds)	4	3.4	1.4	0.6
Shock front velocity at 1 mile (ft/sec)	1200	1200	2000	4600
Particle velocity at 1 mile (ft/sec)	900	900	1200	3500

BURST ENVIRONMENT AND MEASUREMENT	WEAPON YIELD			
	1 KT	10 KT	1 MT	10 MT
SURFACE BURST (continued)				
Prompt gamma at 1 mile* (rads)	7	70	15,000	500,000
Prompt neutrons at 1 mile (n/cm^2)	7×10^8	2×10^{11}	2×10^{14}	7×10^{14}
Thermal at 1 mile (cal/cm^2) (clear atm)	.5	5	500	5000
SHALLOW UNDERGROUND BURST**				
Peak stress, 500 yds lateral (kb)	.02–.08	.06–.1	.08–3	1.5–20
Peak stress, 500 yds below (kb)	.03–.1	.07–.2	.1–4	2–25
Maximum acceleration at 500 yds (g)	<.03	.03–.5	1–10	20–70
Displacement at 500 yds (inches)	$\approx 10^{-3}$	$\approx 10^{-2}$	.5–2	12–23
SHALLOW UNDERWATER BURST				
Peak air pressure at 1 mile (psi)	1	2.2	11	20
DEEP UNDERWATER BURST				
Water shock pressure at 1 mile (psi)	320	800	5000	12,000
Shock velocity at 1 mile (ft/sec)	5000	5000	6000	7400
Impulse at 1 mile (psi-sec)	55	250		

* 50–50 fission-fusion at sea level.
** Particular medium is important.

APPENDIX C
CONVERSION FACTORS

MULTIPLY	BY	TO OBTAIN
Atmospheres	.007348	ton/in^2
Atmospheres	76.0	cm Hg
Atmospheres	33.90	ft H_2O (4°C)
Atmospheres	29.92	in Hg (0°C)
Atmospheres	1.0332	kgs/cm^2
Atmospheres	10.332	kgs/m^2
Atmospheres	14.70	lbs/in^2
Atmospheres	1.058	tons/ft^2
Bars	.9869	atmospheres
Bars	10^6	dynes/cm^2
Bars	1.020×10^4	kgs/m^2
Bars	2.089	lbs/ft^2
Bars	14.50	lbs/in^2
cmHg	.01316	atmospheres
cmHg	.1934	lbs/in^2
in. Hg	.03342	atmospheres
in. Hg	.4912	lbs/in^2
kilobars	986.8	atmospheres
kilobars	1.45×10^4	lbs/in^2
lbs/in^2	.06804	atmospheres
lbs/in^2	2.036	in. Hg
microbars	1.45×10^{-5}	lbs/in^2
millibars	.0145	lbs/in^2

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13. ABSTRACT

Section 1 contains a summary of blast phenomena and includes descriptions of shock formation, air blast, ground motion, underwater phenomena, and target response to shock loading. Section 2 is an introduction to measuremen systems and describes the principles of the various sensing elements, gages, and transmission and recording systems used in blast and shock research. These brief summary sections are not definitive sourcebook presentations, but are intended to place both the measurement objectives and measurement methods in a meaningful order. The remaining sections discuss the existing types of measuring systems grouped by physical phenomena measured.

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