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BALLISTIC MISSILE OFFICE NORTON AFB CA J V QUINTANA
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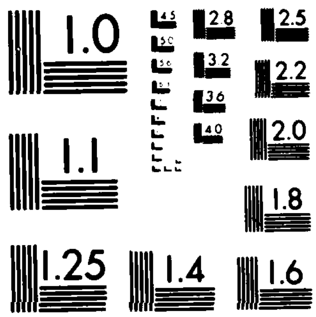

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PHYSICAL MODELING TECHNIQUES FOR MISSILE AND OTHER PROTECTIVE STRUCTURES

Papers Submitted for Presentation During the
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Review of Material for Public Release

Mr. James Shafer
Defense Technical Information Center
DDAC
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The following technical papers have been reviewed by our office and are approved for public release. This headquarters has no objection to their public release and authorizes publication.

1. (BMO 81-296) "Protective Vertical Shelters" by Ian Narain, A.M. ASCE, Jerry Stepheno, A.M. ASCE, and Gary Landon, A.M. ASCE.

2. (BMO 82-020) "Dynamic Cylinder Test Program" by Jerry Stephens, A.M. ASCE.

3. (AFCMD/82-018) "Blast and Shock Field Test Management" by Michael Noble.

4. (AFCMD/82-014) "A Comparison of Nuclear Simulation Techniques on Generic MX Structures" by John Betz.

5. (AFCMD/82-013) "Finite Element Dynamic Analysis of the DCT-2 Models" by Barry Bingham.

6. (AFCMD/82-017) "MX Basing Development Derived From H. E. Testing" by Donald Cole.

7. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Experimental Program" by J. I. Daniel and D. M. Schultz.

8. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Specimen Construction" by A. T. Ciolko.

9. (BMO 82-017) "Testing of Reduced-Scale Concrete MX-Shelters-Instrumentation and Load Control" by N. W. Hanson and J. T. Julien.

10. (BMO 82-003) "Laboratory Investigation of Expansion, Venting, and Shock Attenuation in the MX Trench" by J. K. Gran, J. R. Bruce, and J. D. Colton.

11. (BMO 82-003) "Small-Scale Tests of MX Vertical Shelter Structures" by J. K. Gran, J. R. Bruce, and J. D. Colton.

12. (BMO 82-001) "Determination of Soil Properties Through Ground Motion Analysis" by John Frye and Norman Lipner.

13. (BMO 82-062) "Instrumentation for Protective Structures Testing" by Joe Quintana.

14. (BMO 82-105) "1/5 Size VHS Series Blast and Shock Simulations" by Michael Noble.

15. (BMO 82-126) "The Use of Physical Models in Development of the MX Protective Shelter" by Eugene Sevin.

*16. <u>REJECTED</u>: (BMO 82-029) "Survey of Experimental Work on the Dynamic Behavior of Concrete Structures in the USSR" by Leonid Millstein and Gajanen Sabnis.

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SESSION 22EM

PHYSICAL MODELING TECHNIQUES
FOR
MISSILE AND OTHER PROTECTIVE STRUCTURES

ABSTRACT

INSTRUMENTATION FOR PROTECTIVE STRUCTURES TESTING

Joe V. Quintana

Selected stress and motion parameters associated with test input stimulus, free-field response, and specimen structure responses are identified as measurands in simulation testing of Air Force (AF) protective structures. For each measurand the corresponding sensor and sensing technique used by the AF is illustrated and briefly described. Observed performance is noted and other factors reveal implementation guidelines.

INSTRUMENTATION FOR PROTECTIVE STRUCTURES TESTING

JOE V. QUINTANA[1]

INTRODUCTION

Critical to the success of efforts to develop survivable protective structures is the data acquired in experimental field tests. Real-time measurements characterizing the test input stimulus, free field responses and structure responses are indispensable for accurate empirical assessments of structure survivability and verification of physical models.

This paper is an overview of instrumentation used in simulation testing by the Air Force Civil Engineering Research Division of the Air Force Weapons Laboratory (AFWL/NTE). The techniques presented have evolved over several years and have been used in a number of programs for nuclear blast simulator development and subsequent survivability testing. In this paper selected stress and motion parameters in the areas of stimulation, free field response, and structure response are identified as specific measurands of interest. A description of the corresponding sensor (transducer and its mounting hardware) and the sensing technique is presented with pertinent considerations and observed performance parameters. Emphasis is on the sensing end of the measurement channel although a brief description of system topics such as signal conditioning electronics and cabling schemes is included. The techniques described generally represent current approaches at the Civil Engineering Research Division. However, they do not reflect ongoing instrumentation development efforts toward utilizing the latest in transducer materials technology, electro-optics, semiconductor devices, fiber optics, and others to enhance fieldability, accuracy and survivability of the instrumentation.

It is hoped that the descriptions will enable readers to assess the techniques in view of their own current practices or interests and enter a technical dialogue with the author toward optimizing the instrumentation for specific applications. Only with such information exchanges can the experimental community realize mutual benefit in fielding instrumentation to obtain the necessarily high quality of field test measurement data required.

TEST INPUT STIMULUS

Blast Pressure

Considering that large masses of high explosives are used to create the tailored blast environments for simulation testing it follows that a most

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significant parameter to characterize test input stimulus is the blast pressure time history. The hostility of the total test environment and the stringent characteristics of the measurand require a highly specialized transducer. The unit developed to AFWL/NTE specifications specifically for use in simulator applications is designated the HKS-11-375-10K. The resistance-based transducer incorporates a silicon integrated sensor (IS) disk with diffused semiconductor strain gages in an essentially monolithic construction to provide outstanding shock hardness. The silicon IS enables extremely high resonant frequency, and thermal barrier provisions minimize flash thermal responses in the use environment. Evaluation testing and successful applications of the HKS-11-375-10K since 1975 have demonstrated shock acceleration hardness to greater than 50 Kg (indicated), natural resonant frequency greater than 700KHz, on-axis acceleration sensitivity less than 0.4μv/g , and less than 0.2 mv response from flash thermal stimulus applied per NBS Bulletin 905 to the sensing face of the transducer. The basic unit is available in various performance ranges from 3.4 MPa (500 psi) to 137.9 MPa (20,000 psi) from Kulite Semiconductor Products, Inc., originators of the IS silicon disk element for pressure transducers. Figure 1 is a representation of the unit.

For events using the HEST simulator the specific measurand is the blast overpressure loading the ground surface directly under the explosives array. To measure blast overpressure sensors are installed flush in the testbed surface. Normally sensors are located throughout the total area to observe propagation of the blast wave front. To provide stable sensing platforms concrete masses on the order of 0.2m^3 are poured at the sensing locations. Steel mounting hardware and provisions for cable protection are embedded in the pour. After concrete cure, the cable and the plug-in sensor module (with transducer) are installed to complete the stable flush-mount installation. Figure 2 shows the AFWL/NTE blast pressure sensor hardware. Figure 3 shows a typical HEST blast pressure sensing installation. HEST cavity pressures to 35 MPa (5 K psi) have been measured using the concrete high mass scheme.

Time of Arrival

A parameter used to cross-correlate blast pressure data, monitor HE detonation rate, and characterize detonation wave front symmetry is the time of arrival (TOA). The specific measurand is the time lapse between the explosives initiation at T-zero and the time the detonation front arrives at uniquely predetermined precisely established positions throughout the explosives array. Up to 300 sensors (depending on size of the simulator explosives area) may be fielded to acquire the TOA data with a TOA digitizing system designated as TOADS II. TOADS II is the second generation of a system developed to AFWL/NTE requirements specifically for simulator applications. Typically, a TOA sensor consists of a relatively inexpensive 1 cm dia X 5 mm thick ferroceramic (PZT-5) disc secured directly to the explosive element at the established location. Each sensor is assigned a unique identifying number, and each is cabled directly to the TOADS forward system (FS) electronics unit usually within 50 meters of the HE array. The TOADS, totally independent of the instrumentation system, functions as an electronic stop-watch with all channels starting to count simultaneously at T-zero and stopping when a pulse is generated by the piezoelectric disc on arrival of the detonation wave front. All elapsed time data is stored on receipt during the event. After the test the FS is retrieved and the data is dumped, digitized,

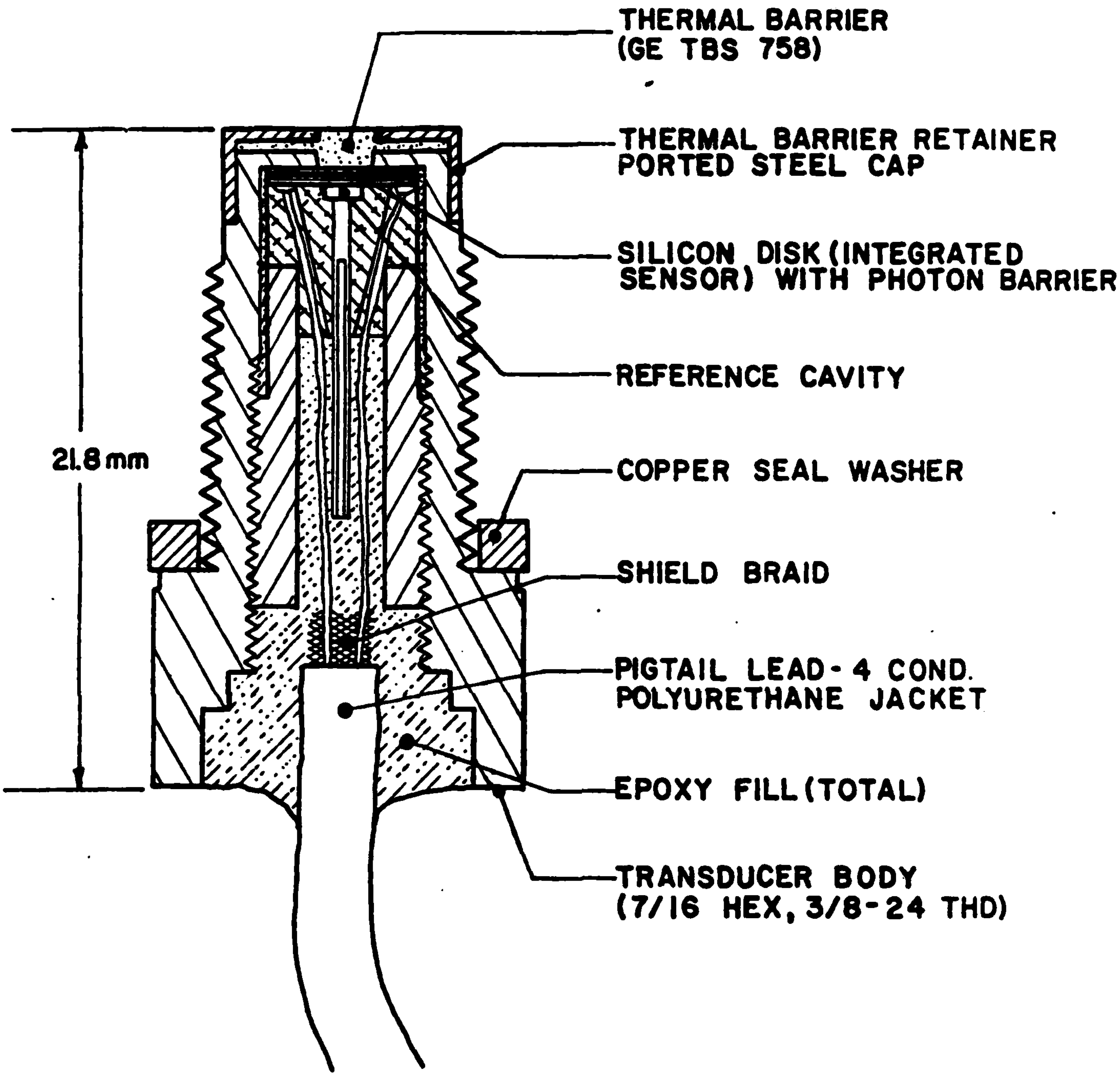


FIGURE 1. HKS-11-375-10K BLAST PRESSURE TRANSDUCER

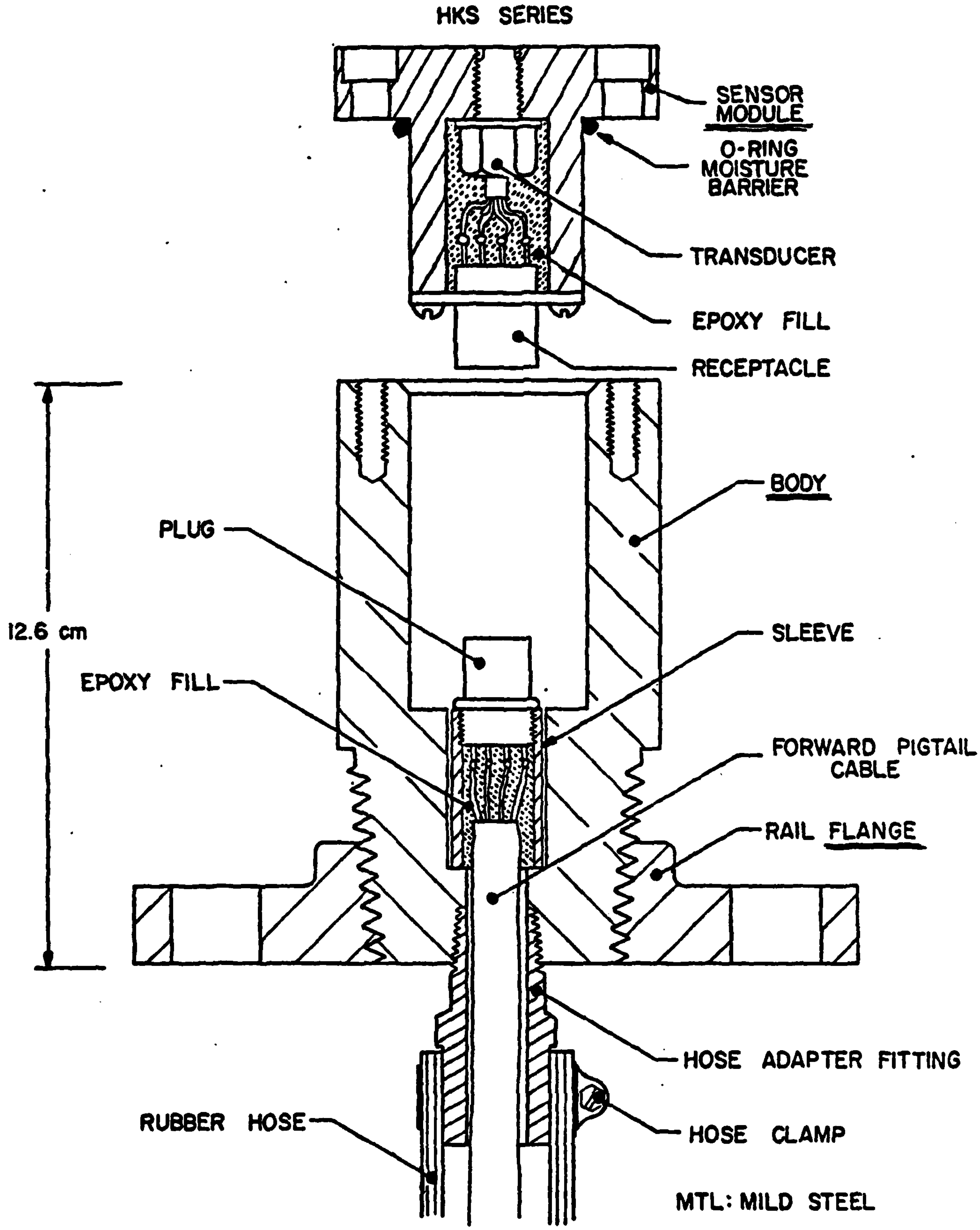


FIGURE 2. AFWL BP SENSOR HARDWARE

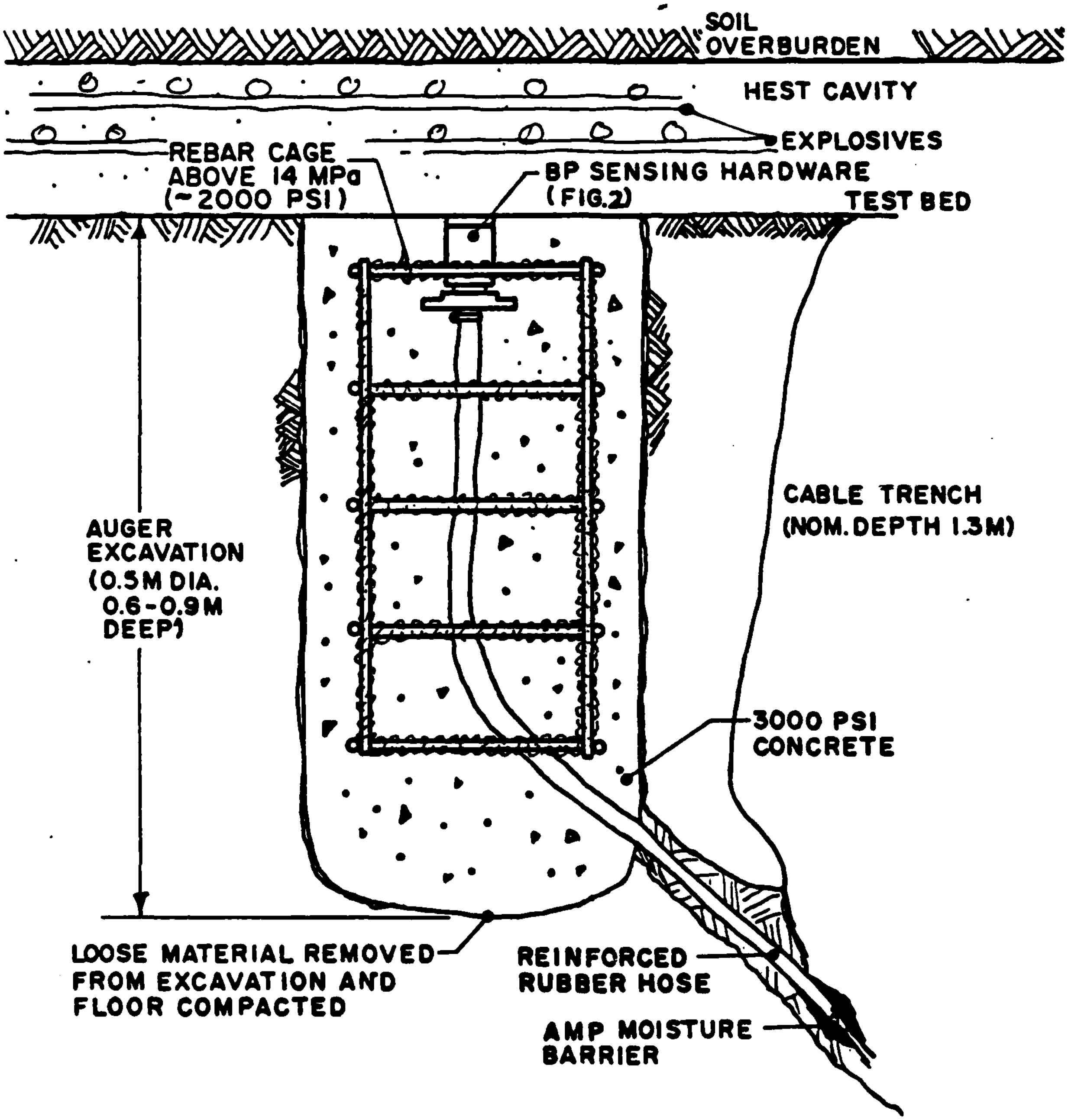


FIGURE 3. HEST CAVITY BP SENSING INSTALLATION.

and printed on paper tape by a central control (CC) unit in the control van. Each channel is uniquely listed with its corresponding elapsed time in microseconds. Data accuracy, a function of the internal clock, is on the order of ± 0.2 μs. Resolution is ± 0.4 μs, and data yield is consistently above 95%. Figure 4 shows a typical TOA sensing installation.

Total Pressure

For applications in shock-tube-like simulators, such as the Dynamic Airblast Simulator (DABS), a prime parameter toward characterizing input stimulus is total pressure. Again, considering the masses of HE used to drive the simulator and the resulting hostility of the test environment, highly specialized instrumentation is required. Considering that total pressure must be sensed with the transducer oriented head-on into the oncoming flow, and considering presence of blast driven debris particles, the primary concern is protecting the transducer with minimum perturbation of the measurand. The design of the HKS-11-375 sensing face is such that only particles impacting a 2 mm diameter area at the center can cause transducer failure. Thus, protecting the central area is all that is necessary for survivability against blast driven particles. The method used was to design a cap which could be threaded down over the transducer face. The flat surface of the cap was then machined to provide the necessary central area protection and apertures for enabling blast flow to the transducer face for total pressure sensing minus debris effects. Thus an effective "debris shield." Figure 5 shows the debris shield configuration designated the Mod VI "church-window" as used in conjunction with the HKS-11-375 transducer. The design features the maximum aperture area to offer minimum restriction to blast flow thus minimizing effect on rise-time and peak amplitude. The aperture configuration also precludes definition of a cavity which could support acoustic oscillations. The principle of deep beams theoretically enables the thin webs to support the critical protective area against hypervelocity impact of 1 mm^3 mild steel particles. Originally designed for use up to 69 MPa (10,000 psi) measurements to 100 MPa (14,500 psi) have been performed by using hardened (heat-treated) debris shields and thermal barrier retainers on the face of the transducer. Numerous successful head-on sensing applications in a variety of blast environments has demonstrated adequacy of the technique. Signal analyses of acquired data verifies the antiresonance of the "cavity". However, during the shock tube evaluations in developing the shield it was found that at levels of reflected pressure in the range to 20.7 MPa (3000 psi) a perturbation of early time data profile was noted such that validity of the first $\sim$50 μsec by comparison with an unshielded reference measurement was questionable. Thus selective application of the technique is required as for all measurement applications.

Incident Overpressure

In applications where structures are tested with blast wave stimuli generated by "point-source" explosives simulating nuclear surface burst weapons, the principal parameter (and the measurand) is incident overpressure (IOP). IOP measurements are made with the sensor surface flush in the free field and oriented side on to the direction of blast wave front propagation.

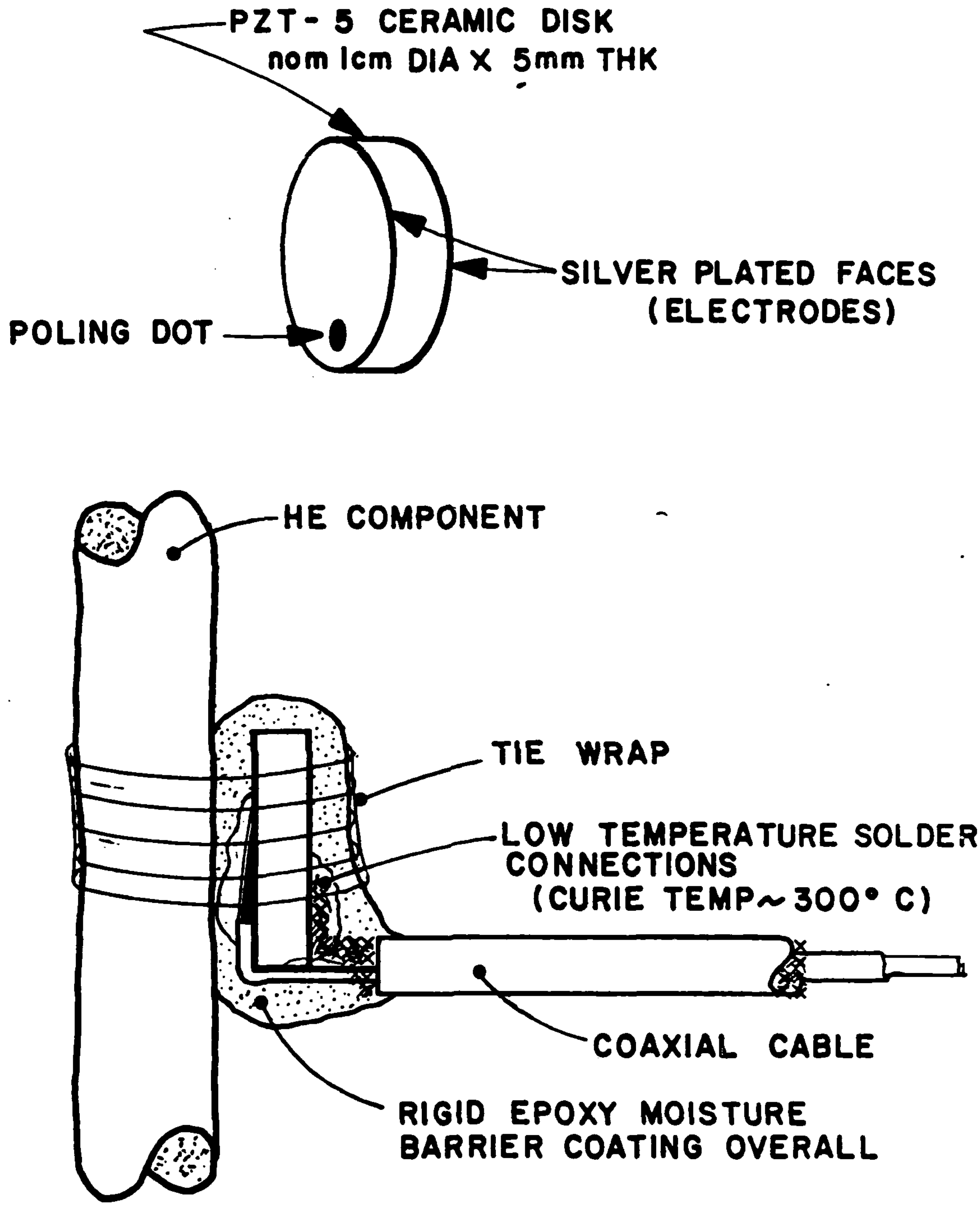


FIGURE 4. PIEZOLECTRIC TOA SENSOR

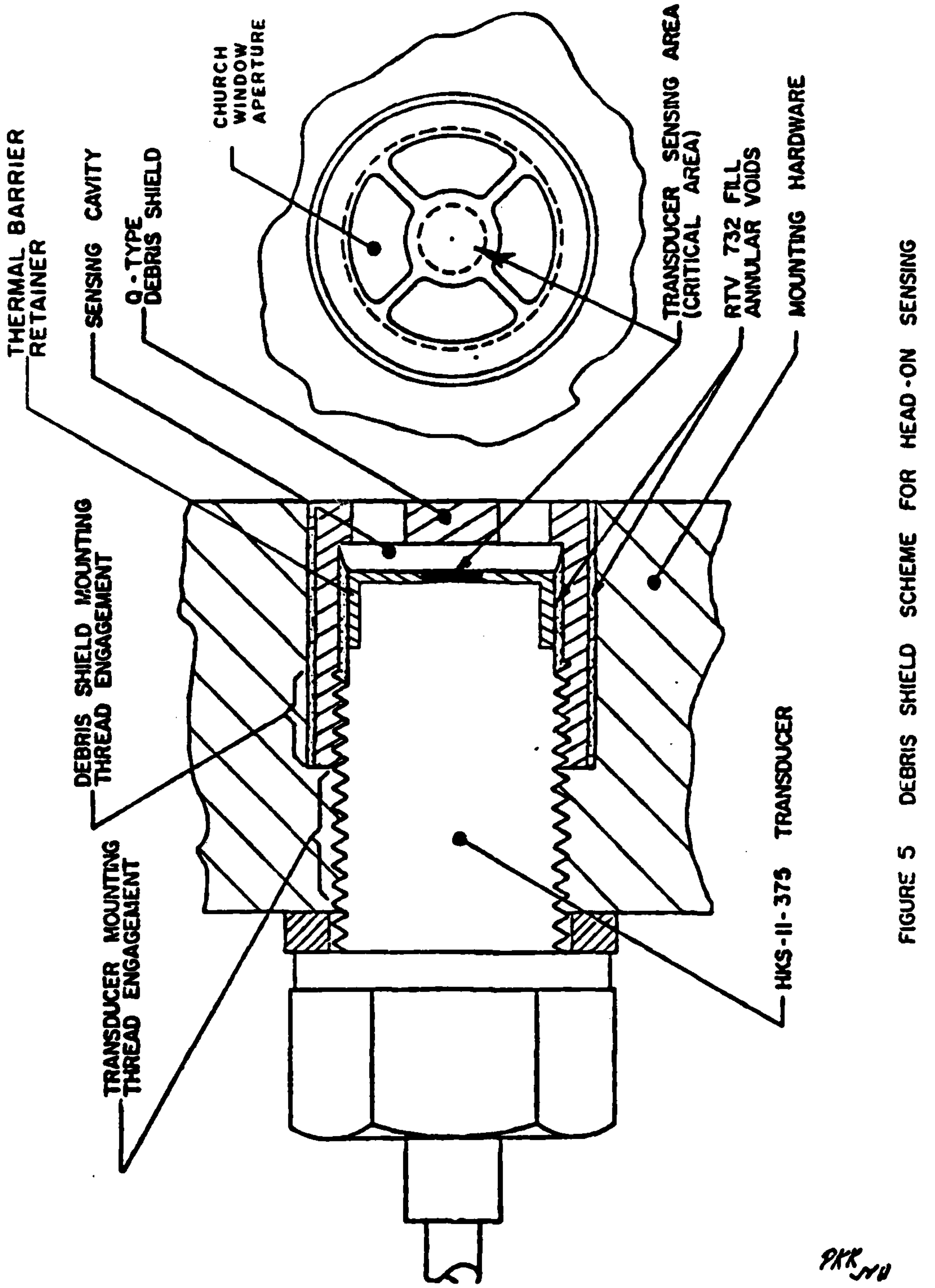


FIGURE 5. DEBRIS SHIELD SCHEME FOR HEAD-ON SENSING.

In this orientation the sensor experiences a relatively mild shock acceleration environment compared to that in the HEST. Consequently, it was established that the concrete high mass sensing technique would also work in IOP sensing applications. Thus the IOP sensing technique has been the poured-in-place concrete mass with embedded hardware as described earlier for the HEST. However, because of the wide range of IOP magnitudes possible in a given test event (typically from 35 MPa "close-in" to the HE stack to .035 MPa at "far-field" locations) transducers other than the HKS-11-375 series are required. For gage pressure measurements down to .03 MPa the Kulite XTS-1-190 series transducer has been used in suitably modified plug-in sensor modules.

For IOP and HEST measurement applications where constraints preclude use of the concrete mass, an alternate sensing technique has been devised. Designated the "pipe mount", the technique consists of standard rigid pipe and pipe fittings in an in-line assembly with the regular plug-in module mounting hardware at the sensing end. Figure 6 is a typical assembly. Subject to properties of the free field geology the assembly, with a "driving head" in place of the sensor body, is impact driven vertically into the free field at the sensing location. At proper depth the driving head is removed and a regular sensor body is threaded into the upper coupling. A hand excavation is made to enable routing the cable downward and out into the cable trench. With the cable in place and covered over the plug-in sensor module is installed, a minor backfill and surface compaction effort is performed, and the low mass blast pressure sensor is ready. The pipe mount has been fielded in a number of HEST and non-HEST applications in a wide range of environment severities and has demonstrated highly satisfactory performance. Pre and post test optical surveys of sensor location and orientation together with analyses of acquired data have indicated as good, if not better performance than the high-mass concrete in terms of maintaining an established sensor location and orientation. The consideration is that if the sensor is the same post-test as it was pre-test, there is reason to believe that the sensor did not displace with respect to the free field and did not become disoriented from perpendicular with respect to the propagating overpressure wave: two critical factors in acquiring valid pressure measurement data.

FREE FIELD RESPONSE

Particle Acceleration

Of critical importance in characterizing free field response to test input stimuli is particle acceleration. Fortunately there are many makes of accelerometers which will very accurately sense the magnitude of acceleration which it has experienced. The difficulty here is to couple the transducer to the free field such that it will experience the average accelerations that a typical soil particle experiences as a result of a specific stimulus. Historically, the accepted method has been to enclose the accelerometer in a package whose selected physical properties closely approximate those of the specific free field and comply with the free field motion response. A variety of metal canisters (usually aluminum) has been devised and used by experimenters in many free field measurement applications. However, due to

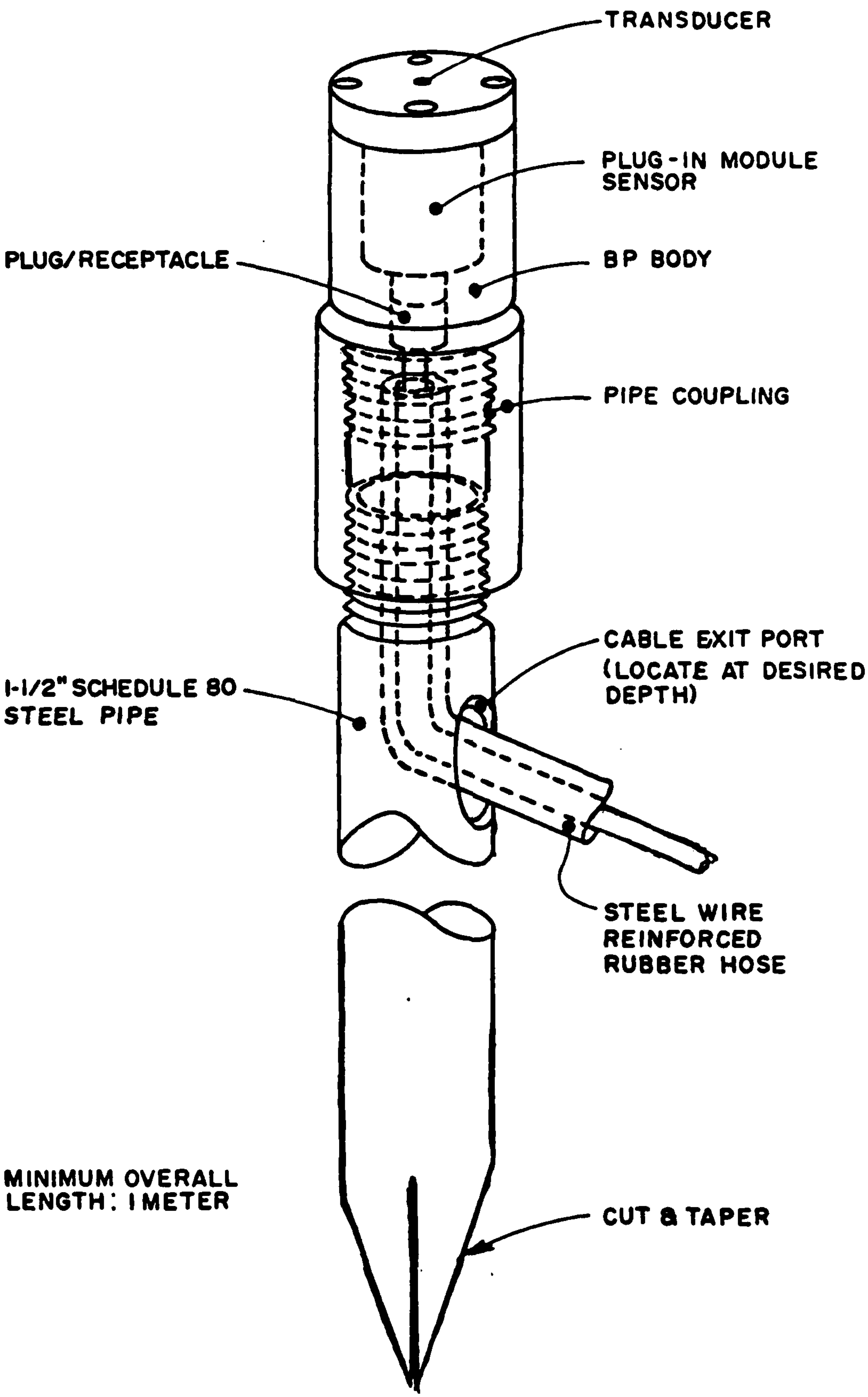


FIGURE 6. AFWL BP PIPE MOUNT

the propensity to ring when shock excited and a number of problems inherent in fabricating, waterproofing, and fielding metal can packages, the AFWL developed the castable canister sensing technique. Main feature of the technique is that the package containing the accelerometers is of cast epoxy. With epoxy of suitable properties and with re-useable molds, cost effective mass production methods are easily implemented. Normally, a sensor package is made in two pours. The first forms the base and the pillar for mounting the accelerometers on 3 mutually perpendicular surfaces. Accelerometers are then bonded to the surfaces with cyanoacrylate resin to sense along the axes as desired. Wiring transition from the very small transducer wire to the larger forward landline cable is effected without tedious splicing activity by using miniature terminal strips also bonded to the pillar. The second pour completes the cylindrical geometry and effects total encapsulation. After overnight cure, the resulting miniature package is a moisture impervious, 3-d sensing, essentially monolithic cylinder with relatively high natural frequency for sensing free field accelerations. Figure 7 shows the AFWL/NTE epoxy micro-canister. For placing the sensor in the free field an NX-size 7.6 cm (3in) diameter vertical hole is drilled at the desired location. An indexed and graduated placement rod is connected to a fastener cast into the upper face, and the sensor assembly is lowered to the desired depth. Vertical orientation and azimuth are carefully established and maintained while soil-matching expansive grout is injected to effect coupling of the sensor to the free field. After a suitable cure time the placement rod is unfastened from the sensor and a final injection of grout completes the coupling for the sensing installation.

Soil Pressure

To observe load stresses in the free field as well as in backfill regions around emplaced structures, measurements are made of a principal axis stress or "soil pressure". The transducer used is the "SE" gage developed to specifications of the U.S. Army Corps of Engineers, Waterways Experiment Station. The transducer is wafer-like with sensitive diaphragms forming the central area of each surface. A flat ring encircles and is soft coupled to the central area to isolate it from transverse stresses. The ring also functions to provide the proper diameter such that the central area registers true stress and is not affected by arching in the soil media. Figure 8 shows the transducer. Most critical in sensing soil pressure is the placement of the transducer such that intimate coupling with the media and accurate sensing orientation are established and maintained. In backfill areas and in near-surface free field applications careful hand placement in sieved soil beds with strict attention to reconstituting the soil around the transducer has yielded correlatable data to 14 MPa. Various placement schemes for vertical and horizontal sensing at depths greater than 1 m in the free field have been only partially successful due primarily to the inability to establish and verify intimate coupling to the unknown in-situ media conditions at the deep (6 m) sensing location. Vertical boreholes to partial depth have somewhat alleviated the placement problem for sensing the horizontal component. However, more development is needed for deep placement of the sensor.

EPOXY MICROCANISTER

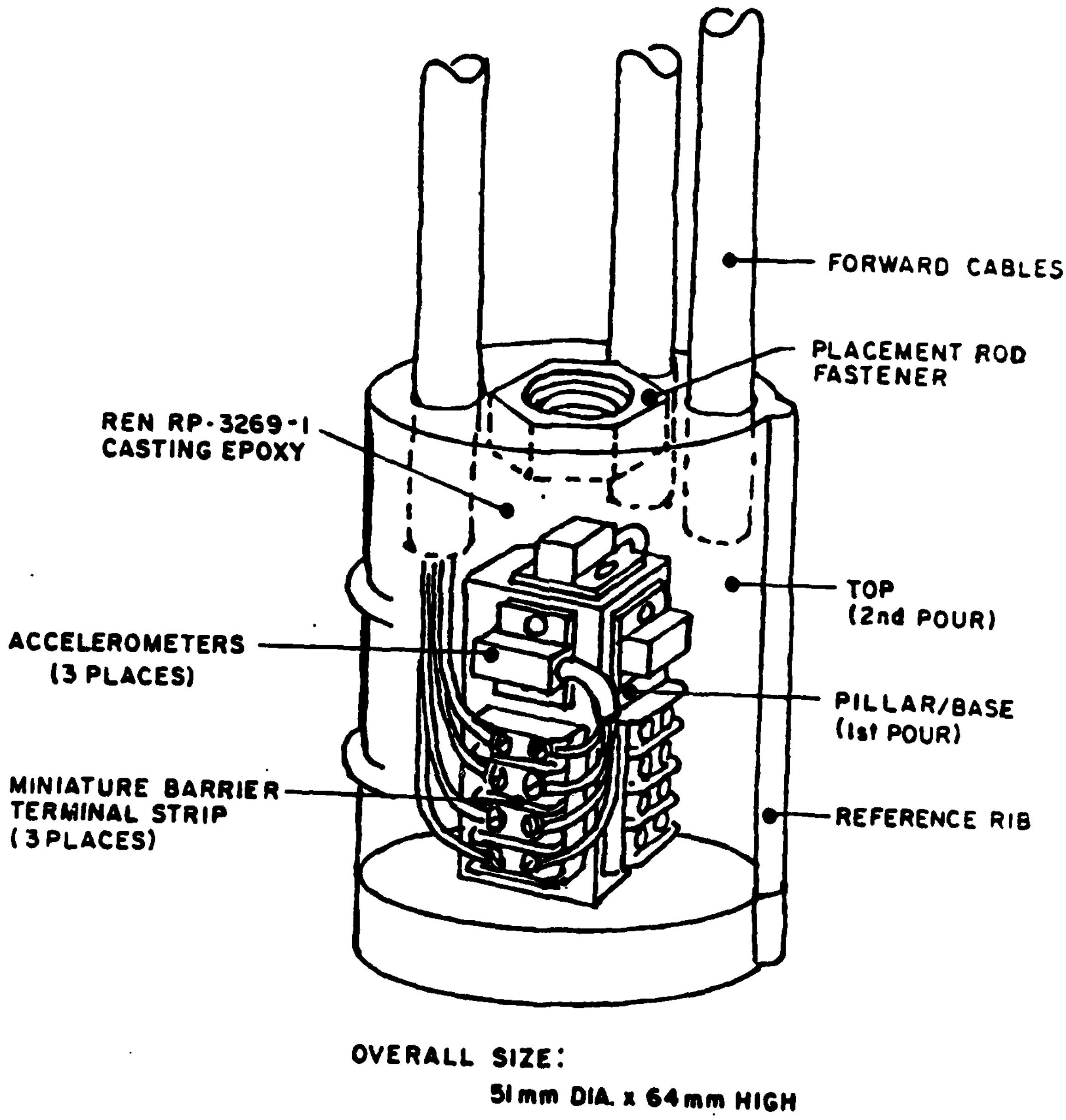


FIGURE 7. FREE FIELD ACCELERATION SENSOR

WES SE GAGE

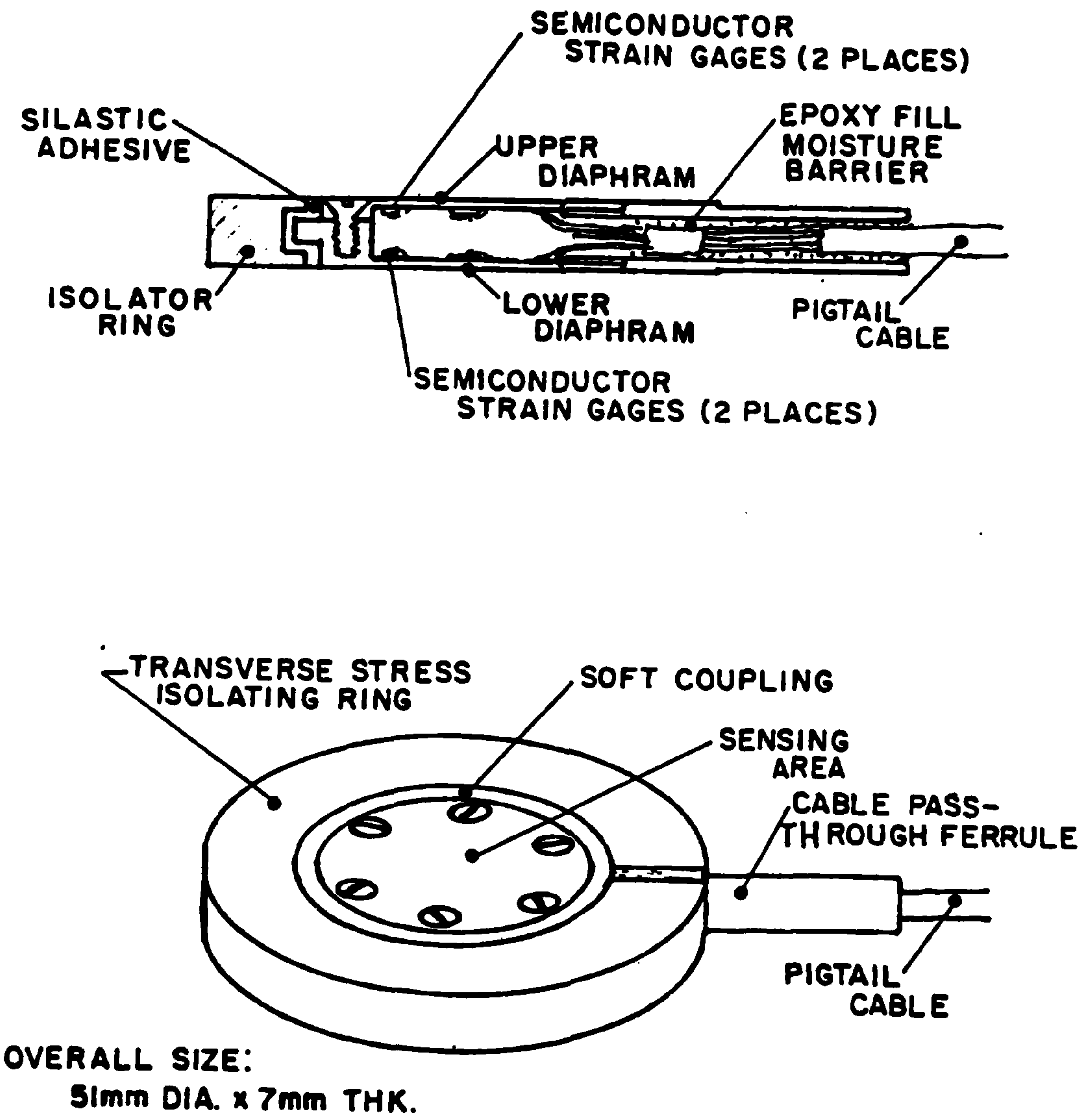


FIGURE 8. SOIL PRESSURE TRANSDUCER

STRUCTURE PARAMETERS

With a specific test input stimulus characterized by blast pressure data and propagation through the free field revealed by particle motion and stress data, the bottom line is to determine specimen integrity as characterized by structure data. Comprehensive and accurate determinations require knowledge of real time blast and ground shock induced loads as well as the resulting response parameters. Thus a variety of types of measurements is normally fielded such that data is acquired on specific measurands and cross-correlations may be enabled with other related parameters.

Blast Induced Load

Basically 3 modes of airblast loading occur in simulation testing. Depending on simulator configuration these are (1) downward direct as in HEST (2) total loading horizontally as in DABS (3) incident loading as from "point-source" HE. Although the transducer used for all blast load measurements is the HKS-11-375, each sensing environment is unique. Thus each measurement channel must be designed only after careful consideration of all information pertinent to the environment and each sensing location.

(1) Direct Loading

The sensing technique used for measuring airblast loading of the exposed surface in HEST environments is similar to free field blast pressure measurements i.e. a high mass concrete mount with embedded gage mounting hardware. However, in this case the high mass concrete is the structure itself. The most competent, stable location in the structure surface is selected and gage mount hardware is placed prior to concrete pour. Normally, care is taken to isolate all transducer mounting hardware from rebar or other structural steel components in the structure. Thus, shock stresses are not directly coupled into the transducer, and a possible source of shock-induced noise is eliminated. Rigid plastic or metal tubing leads from the mount to the interior of the structure. Thus the cable is locally protected against cable noise induced by shock stress and gross motion. Ultimately the cable exits the structure via a cable penetration provision through the structure wall at depth into the free field. For measuring blast loading the sensor is flush with the structure surface which in turn is flush with the testbed. Thus, blast load measurements on structures in HEST simulators register the same measurand as the free field blast pressure measurements, and the data is directly correlatable.

(2) Total Loading

Sensors to measure loading in DABS-like simulators experience a somewhat different environment. Total reflected pressure magnitudes tend to be higher with generally higher attendant shock environment. The thermal environment is driven by hypervelocity compression in addition to HE detonation and burn.

Large quantities of debris, especially soil particles and explosives residue, are driven down the simulator and impact specimen surfaces. The sensing technique for full duration measurements of blast load on surfaces is to employ the church window debris shield as for DABS free-stream total pressure measurements. Again, the blast load sensor hardware is cast into the structure such that the sensor is surface flush. The regular plug-in sensing module face is simply counterbored and the debris shield is threaded on to the transducer. With the debris shield in place full duration data yield for measurements of blast loading in debris-laden environments has consistently been above 95% of the channels fielded. Measurements to 68.9 MPa (10,000 psi) have been made using the technique.

(3) Incident Loading

Load measurements in field tests driven by point sources such as HE stacks are generally of the incident overpressure type sensed side-on. The sensing environment associated with this measurement is by far the least severe of all. The regular blast pressure sensing hardware is cast in at the desired sensing location such that the plug-in module is surface flush. The HKS-11-375 transducer is installed and the sensor is complete. For measurements less than 1.7 MPa (250 psi) the plug-in module is modified to accommodate the Kulite XTS-1-190 series transducer. Measurements to 0.03 MPa (5 psi) are enabled such as those in the far field.

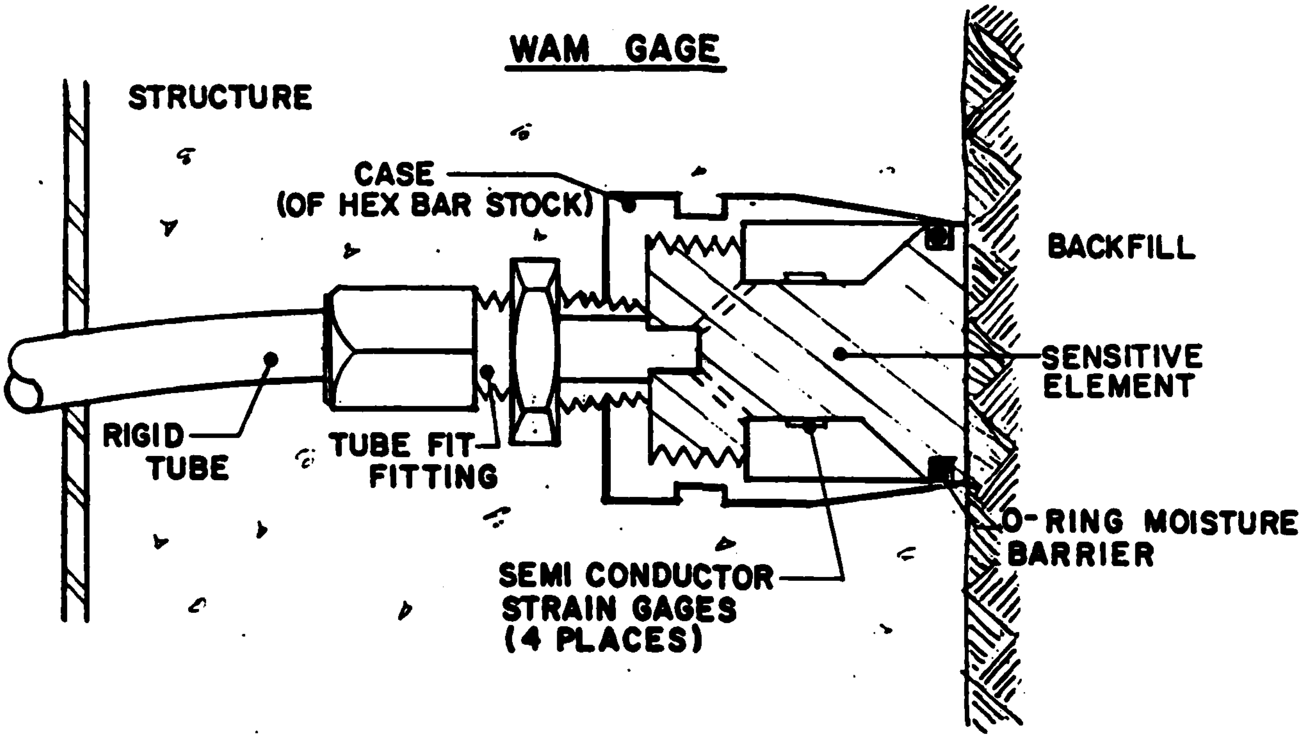
GROUND SHOCK LOADING

Overall loading on the specimen structure cannot be characterized without knowledge of the load stresses transmitted to the structure through the geologic media. Although a wide variety of interface stress and motion measurements has been fielded to measure interface parameters toward characterizing structure-media interactions, measurements of normal and shear stress at the interface are required to provide the necessary structure loading data.

Interface Stress

Characterization of load stresses in AFWL simulation testing has been from information of normal stress and biaxial shear stresses. Currently two sensors are employed to measure normal stress, and one is used to sense shear and normal stresses at the interface. The two configurations of normal stress sensors are the WAM gage and the NS gage. Both employ similar steel cases cast into the structure at the sensing location and strain-gaged aluminum elements installed from the outside to effect a surface-flush normal stress sensor. Figure 9 shows typical installations. With total moisture impervious strain gage installations both sensors have yielded comparable data for a given environment. The NS gage geometry is better suited to use in transverse shock acceleration environments above 2 Kg. The lower mass, stiffer element produces less noise response from transverse shock accelerations and transverse load stresses acting on the sensing face. For sensing shear stresses and normal stress with one transducer the TRIAX gage is used. As for

WAM GAGE



OVERALL SIZE: 44mm DIA. x 50mm LGTH.

NS GAGE

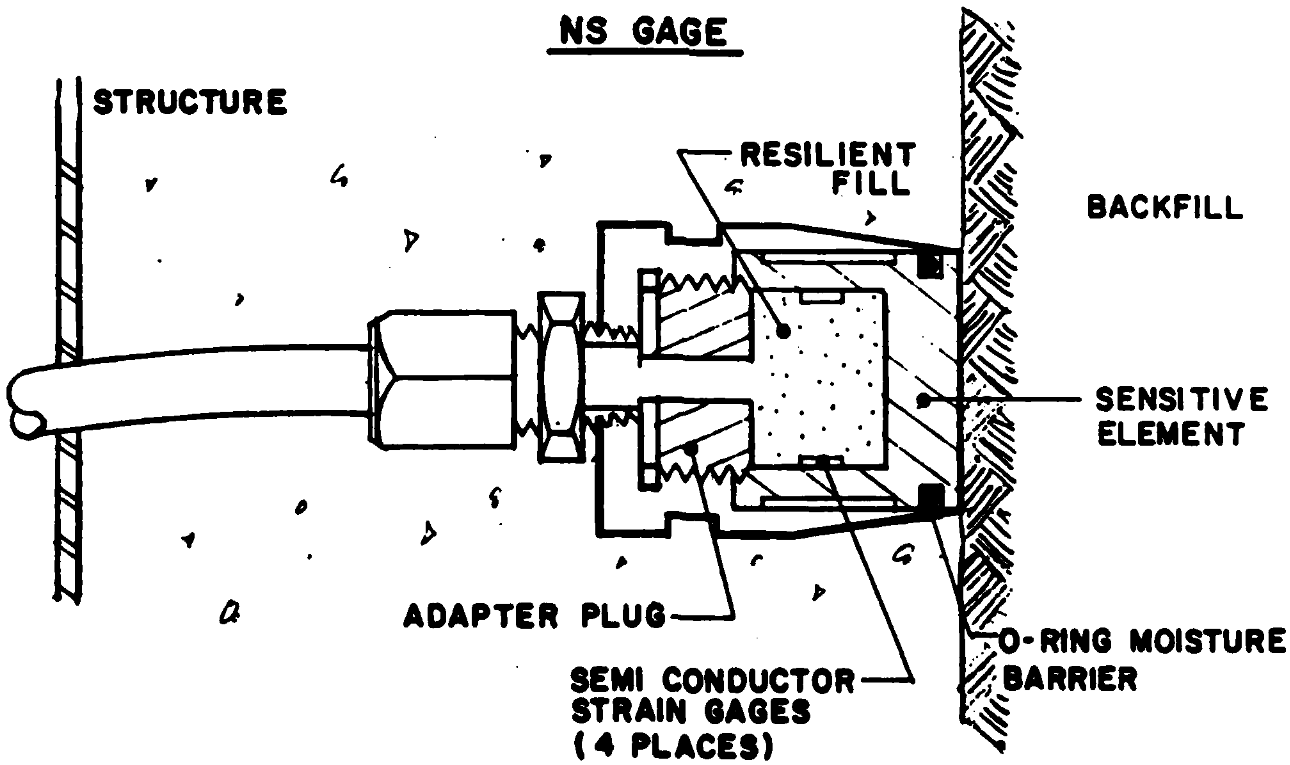


FIGURE 9. NORMAL STRESS SENSORS

the normal stress gages, a steel case is first cast into the structure and the sensitive element installed after concrete cure. However, the triax case is carefully oriented such that the sensitive element will be properly indexed and sensing axes will be correct. The triax element is installed from the inside. The geometry of the element with its strain gaged cantilever beams is such that, in addition to sensitivities in three axes, there is an acceleration compensation effect in the transverse axes. Sensing end of the case is tapered to the sensing face diameter for minimum surface texture perturbation. Additionally, the face of the element is filled with a concrete/epoxy mix to duplicate the actual concrete texture for required shear coupling with the soil media. Figure 10 shows a typical triax gage installation.

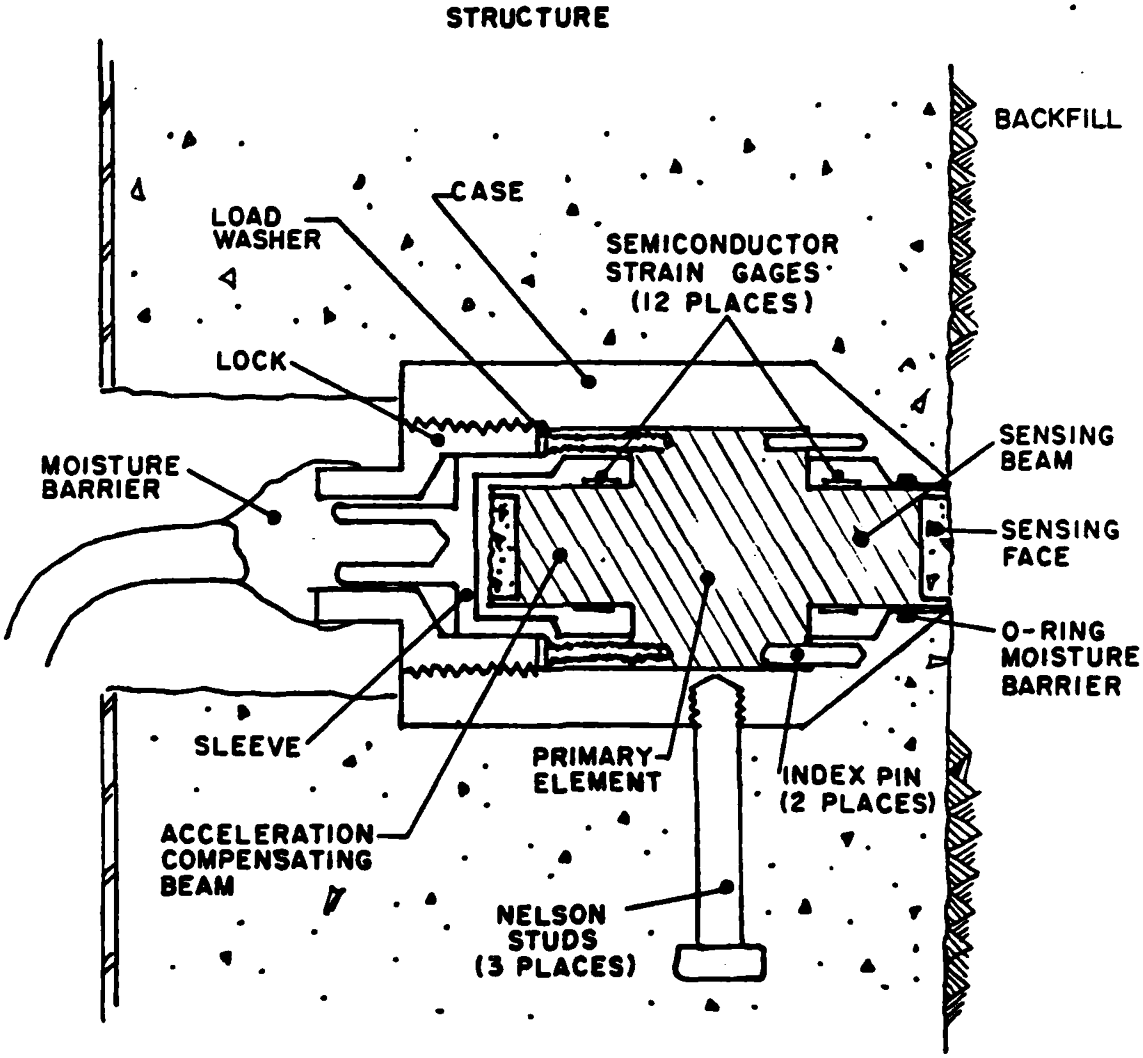
Rebar Strain

A prime parameter to assess structure response to loading stresses is strain in the steel reinforcing components, rebar strain. A successful technique for sensing rebar strain is the use of four separate foil strain gages all at the strain sensing location. Two are applied diametrically on the bar to sense tension-compression and the other two are on separate metal tabs as dummies. The tabs are mounted near the sensing location such as to be mechanically isolated from, but thermally coupled to, the rebar. Thus the tab-mounted gages are fully temperature compensating dummy gages in keeping with good strain gage instrumentation practice for high accuracy data. Strain gages are bonded with cyanoacrylate adhesive to enable a 15 minute cure time installation free of all adversities associated with 2 part-mix, long-time or heat accelerated cure epoxy adhesives. The complete installation is waterproofed and overlayed with a tough, two-part shrinkfit jacket against damage during concrete pour and vibrating. The inner layer of the jacket is a resilient waterproofing material which also serves to isolate the strain installation from back-side stresses. Leads connected to each strain gage are routed from the sensing installation to the structure interior. Figure 11 illustrates the technique. Maximum length for the completed installation can be around 38 mm. The strain gage bridge connections can conveniently be made, and all electrical parameters for defining sensitivity can be monitored essentially at the bridge with the circuit in the actual use configuration. The sensing technique with bridge excitation voltages to 30 vdc has demonstrated 50 $\mu\varepsilon$ resolution direct (i.e. unamplified) data and yields in the range above 90% of channels installed. (One test event used the strain sensors after a 7 month period during which the emplaced silo structure was from 1/3 to 2/3 full of water!)

Structure Acceleration

Gross structural acceleration responses are among the less troublesome measurements performed in survivability testing. Sensing techniques require embedding prepared metal mounting plates in the surface to enable attachment of the motion transducers. Pre-drilling, tapping, and welding Nelson studs facilitates proper orientation and ensures intimate coupling to the concrete mass. Figure 12 shows a typical sensor. Care is taken to isolate the mounting plates from rebar and other structural steel members to preclude

NMERI TRIAX GAGE



OVERALL SIZE:
~64mm DIA x ~89mm LONG

FIGURE 10. NORMAL AND SHEAR STRESS SENSOR

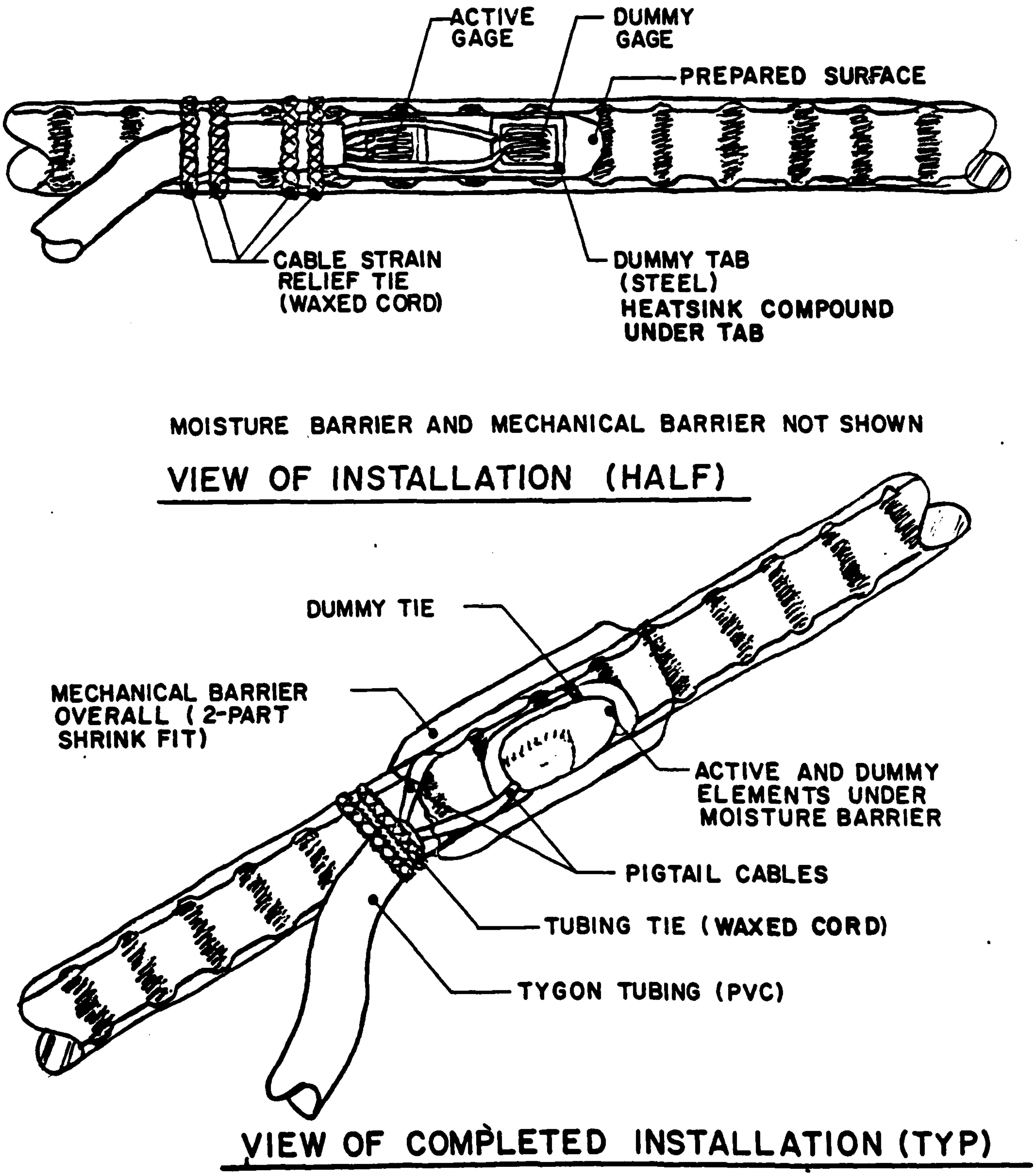


FIGURE 11. REBAR STRAIN SENSOR

BIAXIAL ACCELERATION

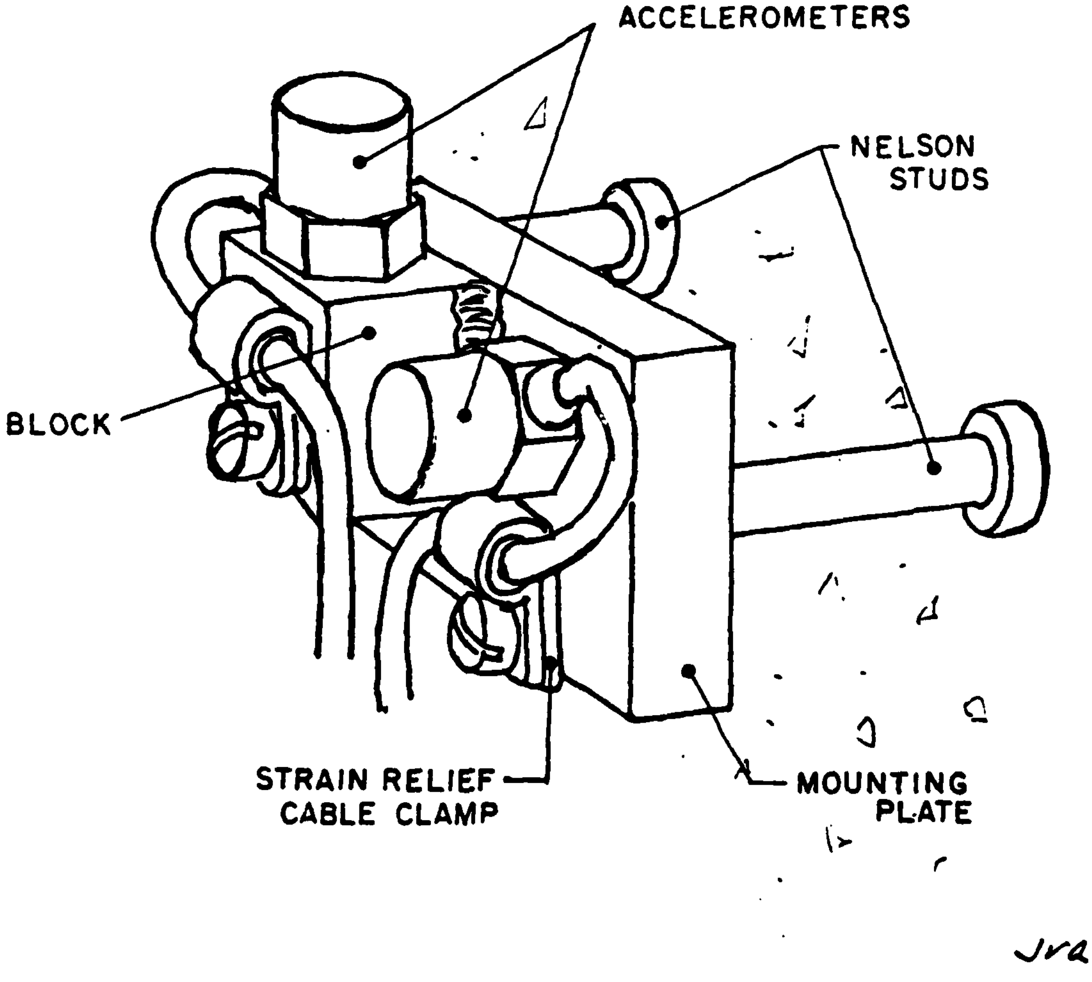
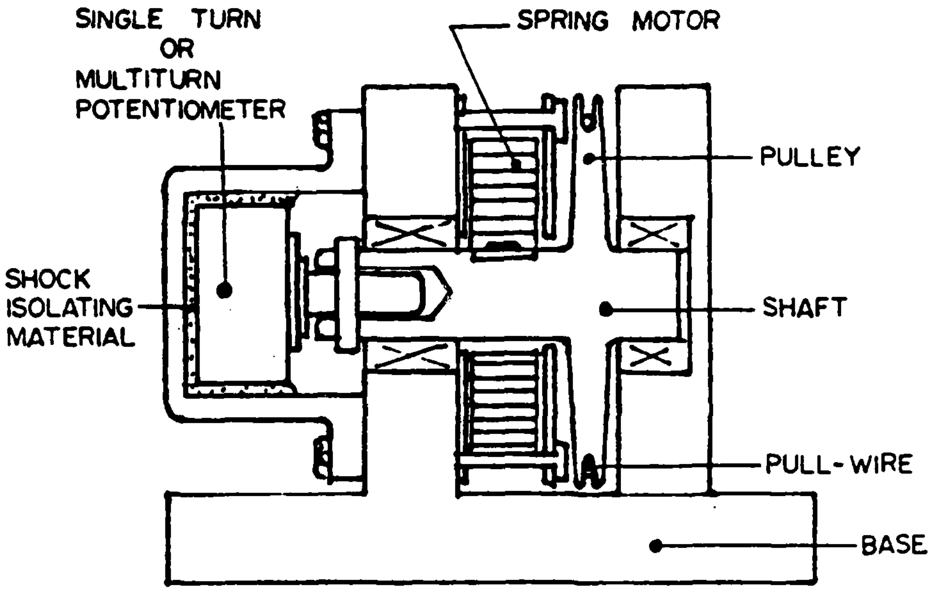


FIGURE 12. STRUCTURE ACCELERATION SENSOR

possible noise inducing shock stresses. Design considerations for the plates include sizing to the minimum for the highest possible natural resonant frequency (at least 10 X the highest expected motion frequency) while accommodating the transducer. Where the requirement is for biaxial sensing at a particular location a block is welded or otherwise securely fastened to the plate to mount the orthogonal motion transducer. Generally, transducers can be any of a number of available accelerometers with small critically fluid damped units preferred for gross motion measurements. Such a unit is the Endevco 2262C-2000. Of extreme importance in such installations is the proper strain relief and retention means for cabling. If not properly implemented initial shock motions may easily cause cable failure at worst or cable slap and flexure induced noise at best. Pre-planned cable routing and anchors embedded in the structure surface for cable clamps enable adequate retention. Also, for successful installations total moisture imperviousness must be achieved at all cable splice connections. A combination of AMP sealing/dielectric compound overwrapped with Scotch 88 electrical tape has proven highly successful in structures as well as in all other field test locations.

Relative Displacement

A most difficult response measurement is the relative displacement between one point on a structure interior surface with respect to another during the violent transient test environment. Such measurements are required for characterizing deformations of structures under transient loading. Complicating the task is that generally the static distance (span) between points can be up to 2 m. The requirement to sense motion ranges to ± 13 cm with required resolution of 2 mm is not uncommon. Other troublesome aspects include shock-driven debris and blow-by combustion products (which preclude use of radiative sensing techniques) and the fact that the points on the structure move randomly with respect to each other while under up to 3 Kg shock loading. A sensing technique most suited to withstand the shock accelerations, remain intact during random shock motions of sensing points, and yield effective displacement data is to use a "pull-wire potentiometer" (PWP). The unit consists of a constant-tension clock spring motor whose shaft is common with a low-inertia pulley and the shaft of a rotary potentiometer. The PWP is fastened to a mounting plate embedded in the structure surface at the sensing point having the least severe initial shock environment. A pre-cut span length of low mass high strength 1 mm diameter braided steel cable (wire) is connected to an anchor at the other sensing point. The similar type cable wound on the pulley in the unit is now pulled out against spring tension and coupled to the span cable. The sensing points changing effective separation vary the length of cable which rotates the potentiometer shaft producing as proportional voltage. Figure 13 is a diagram of the PWP unit. Early (1973) applications of the technique used a commercially available unit from Celesco Transducer Products, Inc. in California. The ruggedized PT-101RX model was obtained and modified for special application. The units yielded smooth data profiles of displacements at indicated velocities to about 10m/s. Critical to using the technique is the proper tension in the spring motor and adequate shock hardness of the potentiometer. Tension of the spring motor produces corresponding tension in the pull-wire



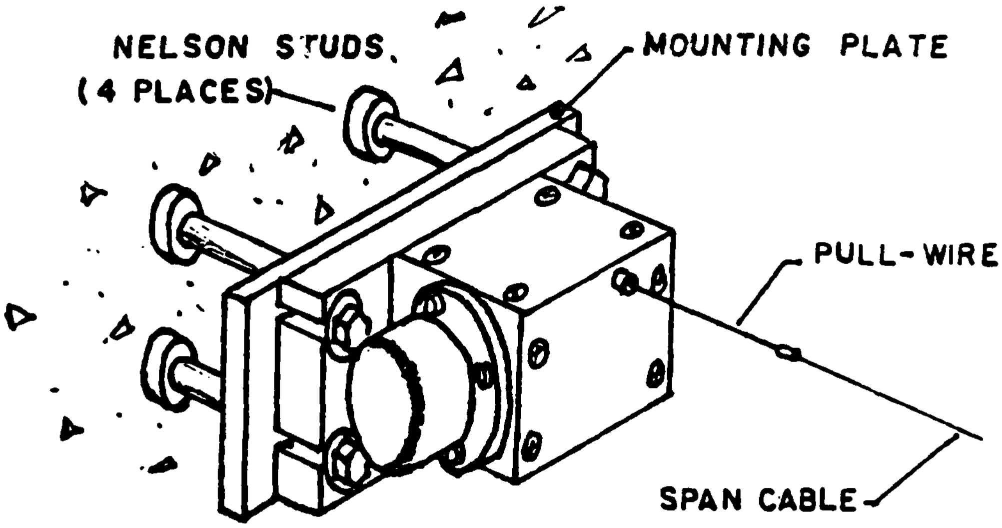


FIGURE 13: RELATIVE DISPLACEMENT SENSOR

which enables fast retraction with decreasing span and increases the fundamental vibrating frequency of the cable span. Shock hardness of the potentiometer establishes survivability with a minimum of shock-induced noise. Obviously careful consideration of these two parameters as well as the others is mandatory for the acquisition of accurate full duration relative displacement data.

SYSTEM TOPICS

Cabling

Extremely important is the requirement that the analog signal from the sensor be transmitted without alteration via landline cable to the electronics. Cabling considerations are separated into two general areas based on environment (a) the forward cable (typically 70 m) from sensor to the close-in ISC 230 signal conditioners (b) the trunkline cable (typically 600 m) from conditioners to the instrumentation vans in a remote location. The forward cable experiences ambient direct burial conditions and the blast induced stress and motion environment of the testbed. Thus, cable design must require a mechanical construction that will minimize stress induced piezoelectrical noise effects and flexure-induced triboelectric noise. Electrical design is to ensure minimum impedance at frequencies of interest. Cables must be properly placed in well-designed trench arrays to minimize broadside stress impingement and to accommodate differential motion of the free field. Slabs of 5 cm thick expanded polyethylene beadboard placed over the cables in the trench prior to backfill and compaction may be of benefit in testbeds especially where high stress (35 MPa, 5000 psi) will be applied. Expanded beadboard is also used in various designs at structure cable penetrations to the free field to mitigate the shear and tensile failure conditions occurring at initial motion. Trunkline cable, normally unburied, must withstand the ambient meteorologic and solar radiation environment and present the minimum possible electrical impedance at the frequencies of interest.

Signal Conditioning

Since all transducers normally fielded are resistance based and connected as Wheatstone bridge circuits, signal conditioning is simple and straight forward. Electronics providing transducer excitation and signal amplification is located in shelters as near as practical to the testbed. Design of the special AFWL/NTE ISC 230 conditioner includes electro-optic as well as electromagnetic techniques to provide signal isolation. Thus, flexibility in system grounding and shielding is enabled to effect highly favorable signal-to-noise ratios with dynamic performances of 60 db typical. Long term zero signal and gain stability over the temperature range -10°C to +50°C, a 26 KHz frequency response and remote shunt calibration capability are other features included to ensure fieldability and performance. Conditioned analog signals are recorded on magnetic tape in the single channel-per-track (CPT) FM mode or with FM subcarrier multiplex (multiple channels per track) in the direct mode. Data bandwidths can range to 80 KHz with CPT recording and up to

32 KHz with multiplex configurations. Thus, a wide range of data frequencies can be recorded; everything from the very rapid transient of a blast pressure to the relatively slow rigid body response of the specimen structure.

On completion of current upgrade activities sponsored by the USAF Ballistic Missile Office, the AFWL/NTE will operate and maintain six fully equipped instrumentation vans with a combined data channel capability of approximately 1600 channels. With two additional vans for timing, control, and communications, a major capability will exist for data acquisition in simulation development and field testing of protective structures in MX as well as other critical Air Force programs.

CONCLUSION

The foregoing overview has attempted to give some insight to instrumentation techniques successfully applied by the Air Force Civil Engineering Research Division in simulation field testing of protective structures. Although such descriptions tend to give a "no-problem" impression of simplicity, nothing is farther from fact! The author cannot overemphasize the importance of considering every known or suspected factor surrounding each measurement requirement as a uniquely definitive parameter extremely able to allow Murphy to prevail. Thus, the author hopes that if the descriptions stimulate any interest, pro or con, a telephone call will open the topic to the kind of indepth technical discussions which will hopefully defeat Murphy in all his guises and result in better techniques toward acquiring the highest quality field test data.

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