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TITLE: MEASUREMENT OF GROUND SHOCK IN EXPLOSIVE CENTRIFUGE MODEL TESTS

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MEASUREMENT OF GROUND SHOCK IN EXPLOSIVE CENTRIFUGE MODEL TESTS

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ABSTRACT

Los Alamos National Laboratory has begun a project to simulate the formation and collapse of underground cavities produced by nuclear explosions using chemical explosions at much smaller scale on a large geotechnical centrifuge. Use of a centrifuge for this project presents instrumentation challenges which are not encountered in tests at similar scale off of the centrifuge. Electromagnetic velocity measuring methods which have been very successfully applied to such models at 1 g would be very difficult, if not impossible, to implement at 100 g. We are investigating the feasibility of other techniques for monitoring the ground shock in small-scale tests including accelerometers, stress gauges, dynamic strain meters and small, mutual-inductance particle velocity gauges. Initial results indicate that some of these techniques can be adapted for centrifuge applications.

INTRODUCTION

Los Alamos National Laboratory recently began a project to investigate some of the phenomena which are associated with the containment of underground nuclear tests. The experimental goal is to use small chemical explosive charges buried in simulated rock and soil on a centrifuge [1]. Although the ultimate objective of this project may be outside the scope of this conference, many of the experimental techniques that will be used are directly applicable to the simulation of the effects of non-nuclear munitions using centrifuge models. Because this program has just begun, this paper will focus on general considerations regarding the measurement of ground shock on the centrifuge; however, we will briefly discuss the results of some preliminary tests.

Explosives have been used for many years on centrifuges. One of the most extensive applications has been the investigations of explosively produced craters by Schmidt and various co-workers [e.g., 2-5]. One of us has also been involved in this and similar studies [6,7]. However, almost all such investigations have involved no *in situ* measurements of the ground shock that is the mechanism by which the explosive does its work. We have found only one report of a centrifuge investigation in which the ground shock amplitude has been measured [8]. In order to have confidence in the fidelity of scaled model simulations of explosive effects on structures, it is essential that the ground shock be measured in the free field and in the immediate vicinity of the structure. Only if we are correctly simulating the source of the loads on the structure can we be assured that measured structural responses will be similar to the responses of the full-scale structure.

BASIC GROUND SHOCK MEASUREMENT TECHNIQUES

Numerous techniques have been developed to measure many parameters of ground shock in a variety of environments including nuclear explosions, large high explosive (HE) field tests and smaller HE tests in a laboratory environment. In this section we review some of those methods without direct consideration of their adaptability to centrifuge testing; that adaptability will be discussed in the next section.

Accelerometers have been successfully applied to the measurement of ground shock from large scale explosive events for many decades. In their most straightforward application, the acceleration is the measured quantity, but it is possible to integrate the basic output of the transducer to obtain both velocity and displacement. The integration can be done as a data reduction step after the experiment or in real-time, either in a circuit packaged with the transducer or in a separate package removed from the ground shock environment. Real-time, close-coupled integration to velocity has the advantages that the signal to be transmitted is lower frequency (which will usually be easier to separate from noise) and that the velocity is frequently the ground shock parameter most needed in the application. Experience shows that, unless the accelerometer and its cabling are extremely stiff, accelerometers follow the motion of the surrounding medium faithfully.

One difficulty of accelerometers is that they do not return good data when the inverse of the ground shock rise time is near or above the resonant frequency of the transducer. Typically, accelerometers capable of measuring very high accelerations are small and have high resonant frequencies (e. g., Endevco 2291 rated at 1×10^7 m/s^2 with a resonance at >250 kHz). Accelerometers are designed to be sensitive to motion in a particular direction, but packages can be obtained with three devices mounted so that their sensitive axes are mutually perpendicular. They typically have a sensitivity to transverse acceleration of a few percent of their nominal sensitivity. Another difficulty with accelerometers is occasional occurrence of drift and zero shift. Finally, accelerometer housings must be able to withstand the pressure that accompanies the acceleration in a ground shock pulse. However, despite their difficulties, accelerometers are unquestionably the mainstay of ground shock instrumentation for large scale events.

Induced electromotance is the basis of most techniques which directly measure the particle velocity in ground shock. The Lorentz force on electrons in a conductor moving in a uniform magnetic field was used by Zaitsev et al. [9]. When a large electromagnet is used to produce a uniform magnetic field perpendicular to the direction of the anticipated motion, the Lorentz force produces a current in a wire perpendicular to both the field and the motion. The current is proportional to the velocity of the wire which is small enough that it moves with the surrounding medium. More recent experiments have employed a cylindrical version to measure the azimuthal average of the radial velocity produced by a spherical charge [10]. This azimuthal averaging can be very useful in reducing the scatter of ground shock data caused by the inevitable variability of geologic materials. An electromagnetic particle velocity gauge has been developed in which the field is produced by a small permanent magnet rather than by a large electromagnet [11]; but the response of this gauge is highly non-linear, and it has not been employed in divergent flow.

Mutual inductance has also been used to measure particle velocity. Using two coils, both with their axes parallel to the direction of expected particle motion but separated in that direction, the velocity can be measured if a current is supplied to the upstream coil and the current is monitored in the downstream one. If the ground shock enveloping the source coil will sever the leads providing the current, a conductive plate can be placed inside the source coil to trap the flux for a duration dependent on its skin depth and thus prolong the useful life of the gauge [12]. After the shock envelops the outer coil, this gauge will only give a record of the relative velocity of the two coils.

Yet another electromagnetic velocity gauge consists of two long, thin coils wound together with the long direction being the expected direction of particle motion; a constant current is put through one of the coils and the current in the other is measured. As the end nearest the source begins to move, the area of the two coils decreases which produces a current in the pickup coil proportional to the rate of change of the area. If the flow is not significantly divergent, the result will be a measure of the particle velocity of that end of the gauge. As in the previous example, when the ground shock arrives at the end of the coils the gauge measures the relative velocity of the two ends [13].

The FDR displacement gauge is a gauge which directly measures the dynamic displacement in ground shock and has been used in large HE and nuclear tests. The gauge is essentially a coaxial cable aligned parallel to the direction of measurement; a frequency domain reflectometer is used to determine the length of the cable [14]. If the cable is very long and the upstream end is well coupled to the flow in the ground shock, the change in the length of the cable is the Lagrangian displacement at that end of the cable. For shorter cables, the gauge will measure displacement until the wave has encompassed both ends, and will measure the relative displacement of the two ends thereafter.

Almost all of the above described displacement, velocity and acceleration measuring systems have the potential of measuring strain, strain rate or strain acceleration as well. In some cases, such as the mutual inductance types of velocity gauge and the FDR displacement gauge, the potential can be achieved by using a smaller gauge and/or modifying the orientation. In most of the other cases, two separate gauges must be used and the strain derived by dividing the difference in their displacement by their separation.

In addition to parameters directly describing the flow field, measurement of the stress driving it is also desirable. Most measurements of stress in ground shock are accomplished with Lagrangian gauges which have transducers that are either piezoresistive or piezoelectric. The most common piezoresistive materials are foils of manganin, ytterbium or carbon-loaded polymer. Piezoelectrics include quartz, ceramics like lead zirconate titanate (PZT), lithium niobate, and recently polyvinylidene flouride (PVF_2).

In order to use these transducers successfully to measure ground shock, they must be packaged and emplaced to survive the flow and to deliver the proper stress to the transducer. The foil materials (the piezoresistives and PVF_2) can be made into very survivable flat-pack designs which will transmit the stress at the gauge surface to the transducer. Unfortunately, for the metals there is a considerable sensitivity to shear stresses which may also be delivered to the transducer. Carbon gauges have been shown to be sensitive only to the component of stress normal to the foil [15], so they should give reliable results in a flat-pack design.

The most critical requirement of stress gauges is that they be emplaced in such a manner that the free-field stress is also the stress measured by the transducer. This was discussed in a paper delivered at the first symposium in this series [16]. The flat pack design was specifically selected for this quality. However, that design only guarantees that the stress measured is that in the medium immediately outside the gauge package. If the gauge has been emplaced in a hole drilled into the free-field medium, stress bridging may still occur around the emplacement hole and its contents.

CONSIDERATIONS FOR CENTRIFUGE IMPLEMENTATION

Not all of the above-described types of gauge will be usable for measuring ground shock in a centrifuge test and others may require substantial modification. The centrifuge environment differs from the field and static laboratory environment in that there are limitations on the mass and physical dimension of the test, the entire experiment is rotating about the axis of the machine, and the initial accelerations are much greater than 10 m/s^2. These differences will make some of these methods impossible to deploy and will degrade or invalidate the performance of other techniques.

Use of accelerometers to measure ground shock in centrifuge model tests is very appealing because of the long history of their successful application to full scale measurements. However, their use in the centrifuge environment will necessarily involve some effort. Integration of acceleration records to get velocity and displacement is obviously sensitive to any initial acceleration; thus care must be taken that the test acceleration not interfere. Use of ac coupling schemes should permit the dynamic signal to be recorded without interference from the test acceleration. This consideration will apply to accelerometers in any orientation because of the transverse sensitivity of the transducers. The small scale of the model experiment can also present problems. First, because the experiment dimensions are small, risetimes will be proportionately shorter if hydrodynamic similitude is maintained. This may lead to accelerometers approaching their resonant frequencies. Second, the size of the accelerometer package may be large enough to perturb the flow field. For comparison to the same problem at full scale, consider a half-centimeter accelerometer encapsulated in a 2 cm package for a 100 g test. This would be equivalent to a 2 meter package at full scale.

All electromagnetic velocity gauges may be affected by the rotation of the centrifuge if the ambient magnetic environment is poor. The earth's magnetic field *per se* is probably so weak as to be no problem for gauge response, but the presence of large masses of magnetic steel moving either relative to the test or relative to the earth's field may prove troublesome. Sensitivity to this possibility will have to be determined on a case by case basis. If the rotation produces a problem of varying background field large enough to compromise gauge performance, ac coupling may be useful in eliminating the spurious signal.

Some of the electromagnetic techniques will not be useful in centrifuge experiments because of their requirement for large electromagnets. For example the coils used to produce the magnetic field for a recent series of meter-scale tests with explosive sources in soil conducted at Livermore National Laboratory [17] employed a pair of coils about 3 m high and weighing several tons. We feel confident in predicting that these coils will not be used in any centrifuge testing program; in view of the considerable success of this technique for measuring ground shock in model tests at 1 g, this is unfortunate.

Fortunately, particle velocity gauges of the mutual inductance type seem to offer excellent potential for application to the centrifuge environment. The only anticipated difficulty is that scaling them down will entail the use of thinner gauge wires which will be more fragile. Nonetheless, this type of gauge will almost certainly figure prominently in future centrifuge modelling programs.

The FDR displacement gauge also seems to be a likely candidate. The most apparent difficulty also seems to be the trade-off between size and fragility.

Stress gauges should experience little difficulty due to either the static acceleration or the rotation of the centrifuge. Size may be some problem, but both carbon and PVF_2 are available in very small (< 3 mm) sizes. Obtaining the desired sensitivities from small transducers of other types may not be possible.

PRELIMINARY TEST RESULTS

The objective of our work so far has been to test various gauge designs that may be adaptable to the centrifuge environment. We have tested various package designs for manganin and carbon stress gauges and have identified several potential problems for obtaining good records. We are currently testing accelerometers to identify design considerations. The goals have been to develop stress gauge packages that (1) create a minimum of reflected waves by good impedance matching with test materials, (2) ensure a gauge life that is greater than that of stress signals associated with shock waves, (3) are easily emplaced in heterogeneous materials such as alluvium and grout, and (4) can protect the gauge element from the test material.

Our initial tests used gauge packets placed in a tank of water with spherical high explosive charges. The charges were 1 and 2 inch (25 and 51 mm) diameter spheres of C-4 high explosive initiated by Reynolds RP-87 detonators. This approach allowed experiments to be setup easily and provided a harsher test for most gauges than would soil. Use of C-4 permitted quick molding of the charge to the desired size while saving expense. Presently we are experimenting in a sand bed, which is also relatively simple for experimental setup. Simple design encourages the repetition of many shots in preparation for the limitations imposed by the centrifuge.

Figure 1 illustrates a design for the manganin gauge package that, so far, has met our goals. The manganin gauge is mounted on a polycarbonate support with the sensitive element at right angles to the Kapton-coated leads. A coaxial cable is attached to the back of the gauge. A shorting pin extends about 1 mm in front of the sensing element; this pin is also attached to a coaxial cable. The whole assembly is potted in epoxy, which can be doped with corundum powder to obtain the desired density. The package is placed perpendicularly to the shock front. Upon contact, the shorting pin triggers an oscilloscope trace. The wave, with reflections of minimum amplitude, will then pass through the gauge along the axis of the wire leads. In this manner, the wave must travel several centimeters before it can shear the gauge leads; hence a relatively long record is achieved. A desirable feature of using the oscilloscope trigger is that the scope can be set to a fast measuring window, which allows detail of the wave profile to be obtained. With other recording techniques this pin might be redundant. Figure 2 shows two typical records for different charge sizes and different gauge ranges in water. Note that the gauge orientation affects the shape of the measured signal.

We have also used carbon gauges in a flat pack design. Figure 3 shows the gauge sensitive element and leads encapsulated between two 1 mm thick sheets of mica. The gauge leads and mica plates are strengthened by potting in epoxy well away from the sensitive element. This design allows us to place the gauge perpendicular to the direction of stress wave propagation. The lifetime of the gauge is maximized by its tangential length, which determines the amount of time the shockwave must travel to reach the leads after hitting the gauge element. Figure 4 is a typical stress record obtained with a flat pack gauge in water.

Since the carbon gauge placement we employ is much different than that used for manganin, different geometrical problems (e. g., reflections, gauge motion and bridging across the gauge altering the free-field stresses) arise for each gauge. Shear strength in tuff and grouts used to simulate it is expected to be a major problem to overcome in achieving good stress records. The radial versus tangential arrangements described above are hoped to give us maximum gauge life.

We have experienced problems with electromagnetic noise from the detonator because it produces over 100 millivolts of moderate frequency (5 to 10 MHz) noise in unshielded leads. This noise may be an artifact of our simple charge design. However, we have found that by using coaxial leads wherever possible and aluminum foil shields around the gauge packages, the noise can be reduced to less than 10 millivolts. With further grounding of the shielding and use of better, cast charges, we are certain that the noise can be reduced to negligible levels.

FUTURE PLANS

Our program to measure ground shock produced from small HE explosions on a centrifuge has just begun. There is still much to be done at 1 g in the line of selecting and perfecting proper techniques before moving onto the centrifuge. As mentioned above, we are beginning to conduct tests in soil-like material. We expect to conduct tests in grouts designed to simulate the porous tuffs which occur at the Nevada Test Site. However, the primary thrust of these early experiments is upon measurement techniques, not on materials. During the coming months we plan to try several other stress and velocity gauges. In particular, we will investigate the feasibility of using the long electromagnetic particle velocity gauge and stress gauges using PVF_2 sensitive elements. Other plans include attempts to measure hoop stresses (with the carbon gauge described) and strains (with the FDR gauge and a strain-rate version of the long electromagnetic gauge). We hope that within the next year we will begin testing with fully confined bursts on a centrifuge.

REFERENCES

[1] E. S. Gaffney and J. A. Cheney, Containment science on a centrifuge. Proc. 2nd Symp. Containment of Underground Nucl. Expl., Kirtland AFB, NM, 2-4 Aug, 1983, Vol. II, 365-378, CONF-830882, Defense Nucl. Agency, Kirtland AFB (1983).

[2] Holsapple, K. A., and R. M. Schmidt, On the scaling of crater dimensions, 1, explosive processes. J. Geophys. Res. 85, 7247-7256 (1980).

[3] Holsapple, K. A., and R. M. Schmidt, On the scaling of crater dimensions, 2, impact processes. J. Geophys. Res. 87, 1849-1870 (1982).

[4] Housen, K. R., R. M. Schmidt and K. A. Holsapple, Crater ejecta scaling laws: Fundamental forms based on dimensional analysis. J. Geophys. Res. 88, 2485-2499 (1983).

[5] Schmidt, R. M., "Gravity Effects in Cratering", Bimonthly Prog. Rep. 2, January 13 1983, Boeing Aerospace Company on contract DNA001-82-C-0301 (1983).

[6] E. S. Gaffney, Effects of gravity on explosion craters. Proc. Lunar Planet. Sci. Conf. 9th, 3831-3842 (1978).

[7] E. S. Gaffney, H. K. Brown and J. A. Cheney, Explosion craters in ice at large scaled yields. Lunar and Planet. Sci. XIV, 233-234 (1983).

[8] P. L. Rosengren, Jr., Centrifuge modeling techniques. Symp. Proc., Pt. 2, Interaction of Non-nuclear Munitions with Structures, U. S. Air Force Academy, CO, 10-13 May, 1983, 25-28 (1983).

[9] V. M. Zaitsev, P. F. Pokhil and K. K. Shvedov, An electromagnetic method for measuring the velocity of detonation products. Doklady Akad. Nauk SSSR, 132 (6), 529-530 (1339-1340 in Russian) (1960).

[10] A. L. Florence, J. C. Cizek and C. E. Keller, Laboratory experiments on explosions in geologic materials. Shock Waves in Condensed Matter--1983, J. R. Asay, R. A. Graham and G. K. Straub, eds., Elsevier, New York (1984).

[11] J. N. Fritz and J. A. Morgan, An electromagnetic technique for measuring material velocity. Rev. Sci. Instr. 44, 215-221 (1973).

[12] P. L. Coleman, Development of the Krata particle velocity gauge. Conf. on Instr. for Nucl. Weapon Effects, Mar 30-Apr 1, 1982, DNA-TR-82-17, pp. 137-148, Defense Nuclear Agency, Washington (1982).

[13] SRI mutual inductance gauge

[14] T. O. Summers, The FDR particle displacement gage electronics. Proc. 30th Intern. Instrum. Symp.-Denver, Colorado, 647-654, Intrum. Soc. Am. (1984).

[15]. W. D. Williams, D. J. Fogelson and L. M. Lee, Carbon piezoresistive stress gauge. Shock Waves in Condensed Matter-1983, J. R. Asay, R. A. Graham and G. K. Straub (eds.), 121-124, Elsevier, New York (1984).

[16] C. W. Smith, D. E. Grady, L. Seaman and C. F. Petersen, Constitutive relations from in situ Lagrangian measurements of stress and particle velocity. DNA-2883I, Defense Nuclear Agency, Washington (1972).

[17] Don Larsen, personal communication (1984).

Figure 1. Sketch of manganin gauge assembly.
Figure 2. Pressure histories recorded from manganin gauges. (a) Charge diameter, 25.4 mm; gauge range, 50.8 mm. (b) Charge diameter, 50.8 mm; gauge range, 50.8 mm.
Figure 3. Carbon flat pack gauge assembly.
Figure 4. Pressure trace measured by carbon gauge at a range of 127 mm from a 50.8 mm diameter charge of C-4.

Manganin Gauge Assembly

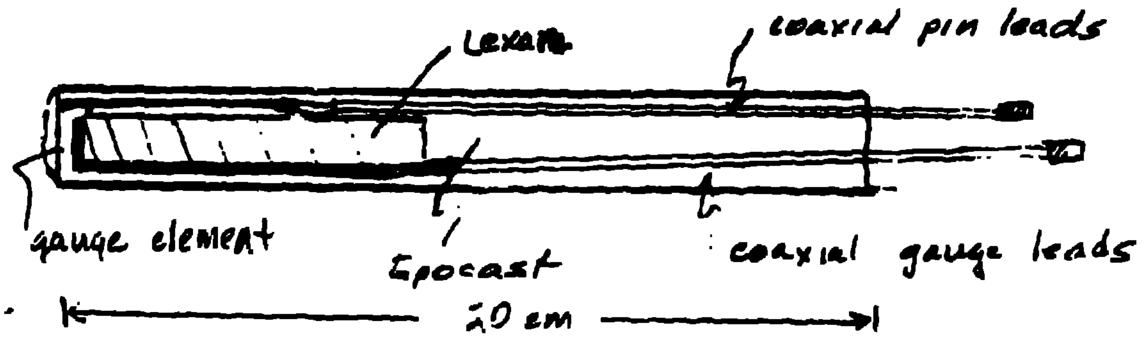

Fig.1 Sketch of manganin gauge assembly

Fig 1

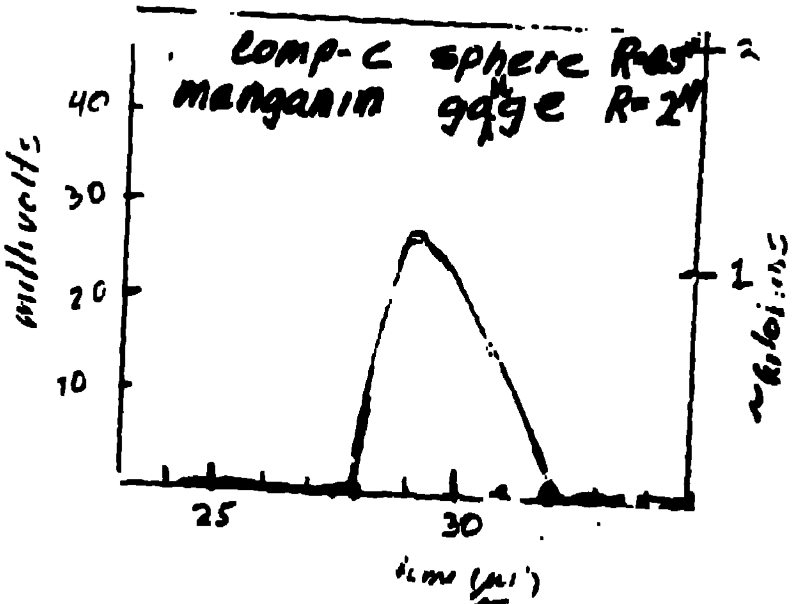

Fig 2a. Pressure trace in water measured by manganin gauge placed 2 inches from center of 1 inch

Fig 2

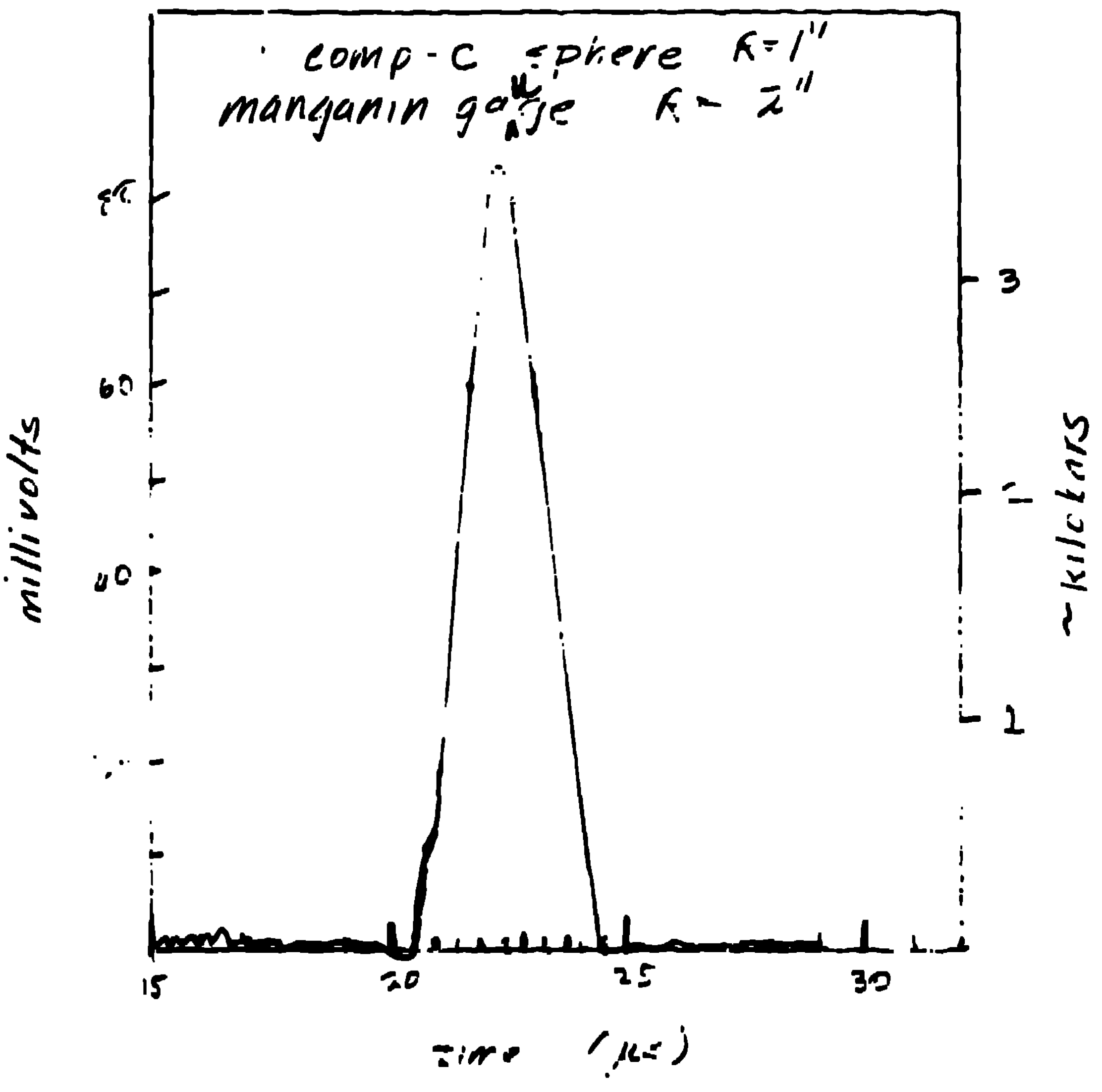

Fig. 2b. Pressure trace in water measured by manganin gauge placed 2 inches from center of a 2 inch diameter comp C-4 charge

Fig 3

Flat Pack Carbon Gauge

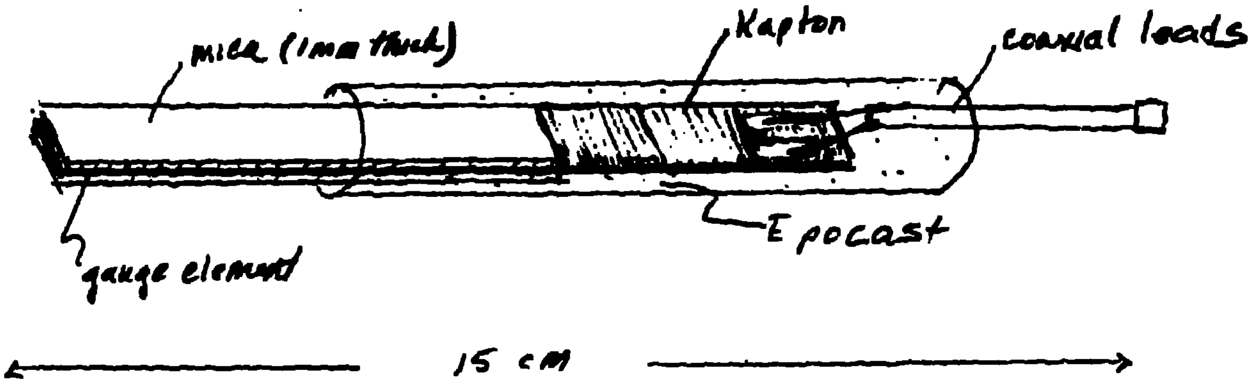

Fig. #3 Flat pack carbon gauge assembly

Fig 4.

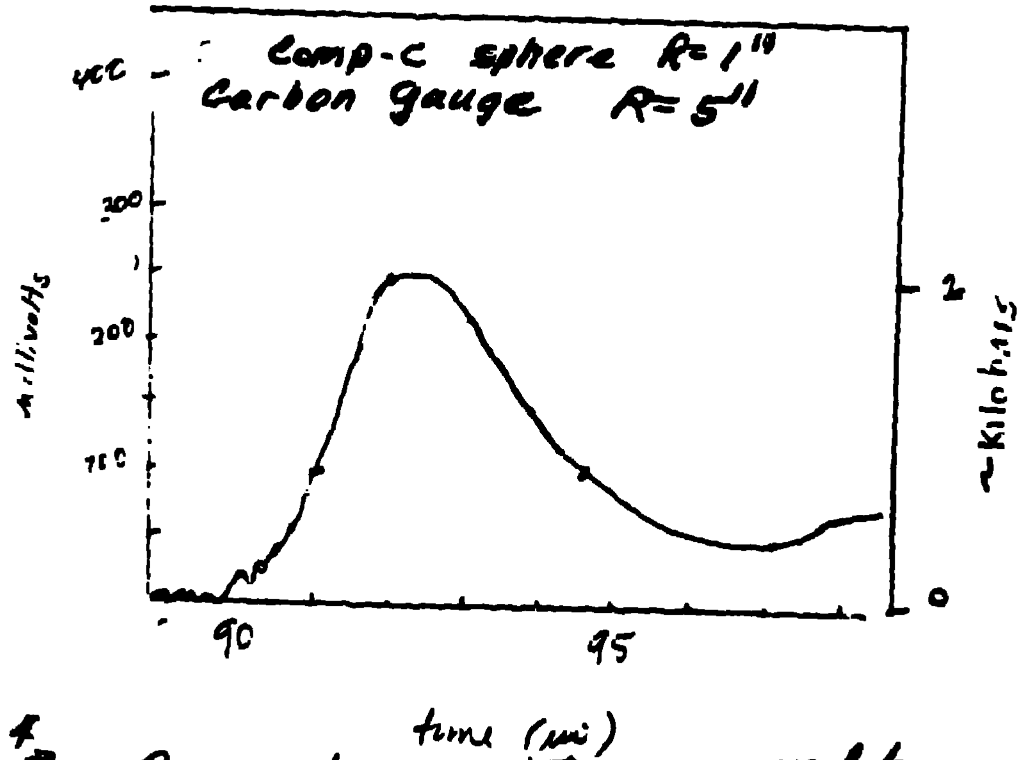

Fig. 4 Pressure trace in water measured by carbon gauge placed 5 inches from the center of a 2 inch diameter