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TITLE: PRESSURE MEASUREMENTS OF NONPLANAR STRESS WAVES

MASTER

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PRESSURE MEASUREMENTS OF NONPLANAR STRESS WAVES

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I. INTRODUCTION

The Los Alamos National Laboratory is interested in the pressure generated by projectiles as they penetrate different weapon materials. Small projectiles in complex structures inherently cause nonplanar pressure waves, and nonplanarity causes severe problems in pressure measurements.

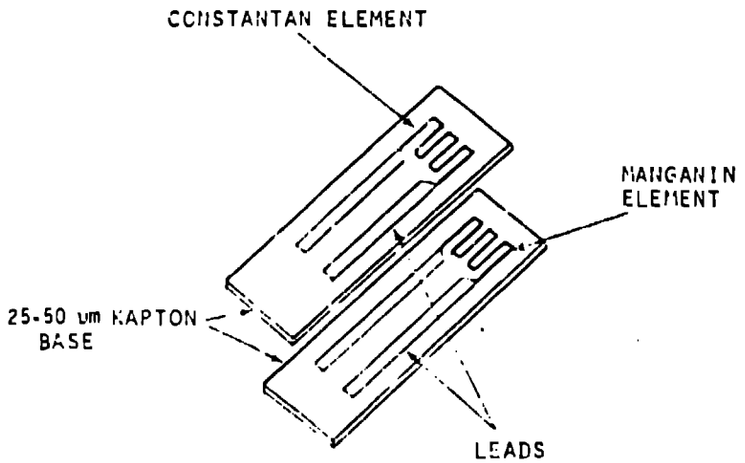
Thin carbon, ytterbium, and Manganin gages have been used successfully to measure planar waves. In planar measurements, the gage element is placed normal to the incident stress wave. The stress wave compresses the gage normal to its face, changing the gage material resistivity and the resistance of the gage. This change in resistivity has been well established and can be used to determine the amplitude of the stress wave.

Nonplanar waves add another dimension to the problem. The nonplanar wave compresses the gage normal to its face and compresses or stretches the gage parallel to its face. The gage responds to this second distortion as would a strain gage. The resistance of the gage is changed by both types of distortion. In nonplanar stress wave measurements, the strain component must be unfolded from the total resistance change to determine the resistance change caused by only the stress perpendicular to the gage face.

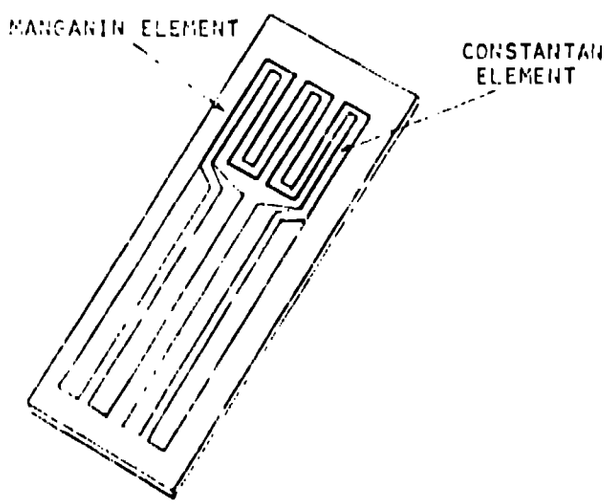
Nonplanar measurements have been made in the past. The simplest technique is to place a Constantan strain gage near the pressure sensing element and measure the strain. The resistance change of the Constantan strain gage is subtracted from the resistance change of the pressure sensing element to give the resistance change due to pressure. One problem with this technique is that it assumes that the pressure sensing element has the same strain gage factor as Constantan.

A more sophisticated technique was developed by Dynasen, Inc., for Lockheed.[1] They developed a gage consisting of two elements, ytterbium and Lohm. They found Lohm to have practically no pressure sensitivity and a strain sensitivity equal in amplitude but opposite in sign to ytterbium. By combining a 25-Ω ytterbium element in series with a 25-Ω Lohm element, strain was intrinsically cancelled. Any change in resistance was due to the pressure sensitivity of the ytterbium element. The problem with this gage is the limited pressure range that it covers.

For our measurements, Manganin appeared to be more useful than ytterbium because of its greater pressure capacity. To develop a Manganin compensated gage, Los Alamos let a contract to Dynasen, Inc., to derive the piezoresistivity and strain factors of Manganin and Constantan foils over a wide range of combined pressures and strains. We also asked Dynasen to develop manufacturing procedures for superimposed and interlaced gage combinations as shown in Fig. 1. Most of the work



A-SUPERIMPOSED ARRANGEMENT



B-INTERLACED ARRANGEMENT

Fig. 1. Strain-compensated shock pressure gage arrangements.

reported in Section II of this report was done by Dynasen, and most of the work reported in Section III was done by Los Alamos.

II. GAGE TESTING PROGRAM

Figure 2 shows the four main experimental arrangements Dynasen used in this program. Arrangements A, B, and C were tested with their 63.5-mm diam gas gun facility, operating at approximately 100 microns Hg. Arrangement D was tested with a 22-cal. rifle at atmospheric pressure. The projectile velocities were measured within 1% deviation using an electrical contact probe technique and time interval counters.

A. Piezoresistivity Tests

Dynasen measured the piezoresistivity of Manganin and Constantan foils with arrangement A. Three Manganin and three Constantan gages were mounted in the center of a target and subjected to a quasi-rectangular plane stress wave induced by the symmetrical impact of a free-rear-surface, projectile-mounted flyer disk. The targets and flyers were 6061-T6 aluminum, brass, and tantalum. The pressure ranged from 0 to 200 kbars. The pressure is obtained from the Hugoniot of the material and the particle velocity. In the case of symmetrical impact, similar target and flyer materials, the particle velocity is one half the impact velocity. The Hugoniots of materials used in these tests are shown in Fig. 3. The results of the piezoresistivity tests are shown in Fig. 4. The piezoresistivity of Constantan is positive, but its amplitude is practically negligible compared with Manganin.

B. Compression Strain Tests

The arrangement B in Fig. 2 was used to induce combined states of stress and strain on Manganin and Constantan elements. The targets were made by stretching six gages at 15°, 30°, 45°, 60°, 75°, and 90° with respect to the impact face and filling them with a slow-curing epoxy. The epoxy resin used was Hysol 2038, and the curing agent was HD0099. The Hugoniot of this epoxy, shown in Fig. 3, is close enough to the Hugoniot of Plexiglas that Plexiglas flyers were used to produce symmetrical impacts.

The technique consisted of imposing a sufficiently long quasi-rectangular plane wave upon the epoxy target that each gage was totally engulfed by the wave for at least several microseconds. The plane wave produces a component of compressive stress acting normal and parallel to each element. The component parallel to the element compressively strains the element. The change of resistance of the gage can be calculated knowing the material Hugoniot, the material density, the flyer plate velocity, the gage angle, Poisson's ratio, and the strain factor of the gage. Conversely, by measuring the change of resistance, the compressive strain gage factor was calculated from these tests.

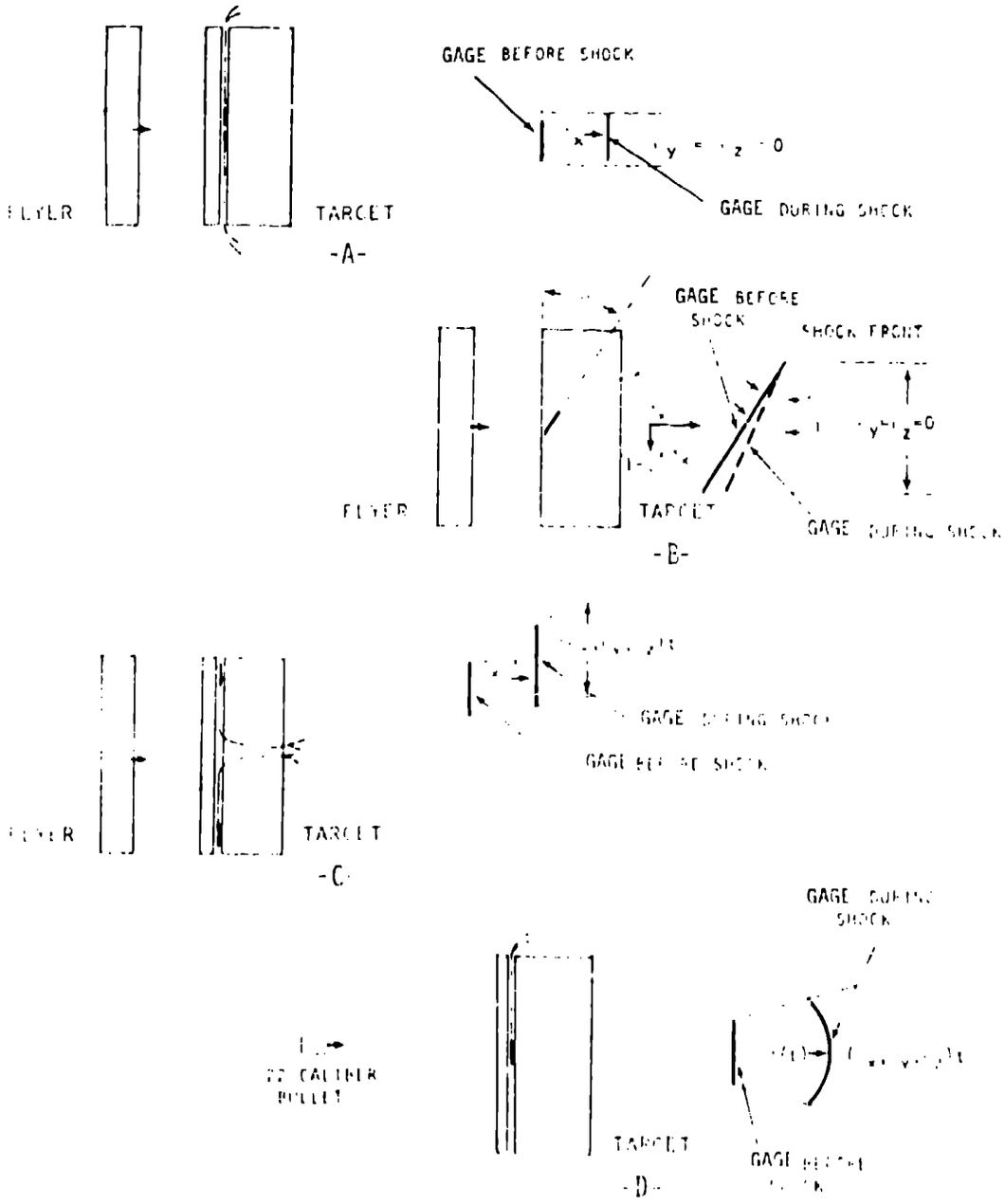


Fig. 2. Experimental arrangements for measuring stress and strain outputs.

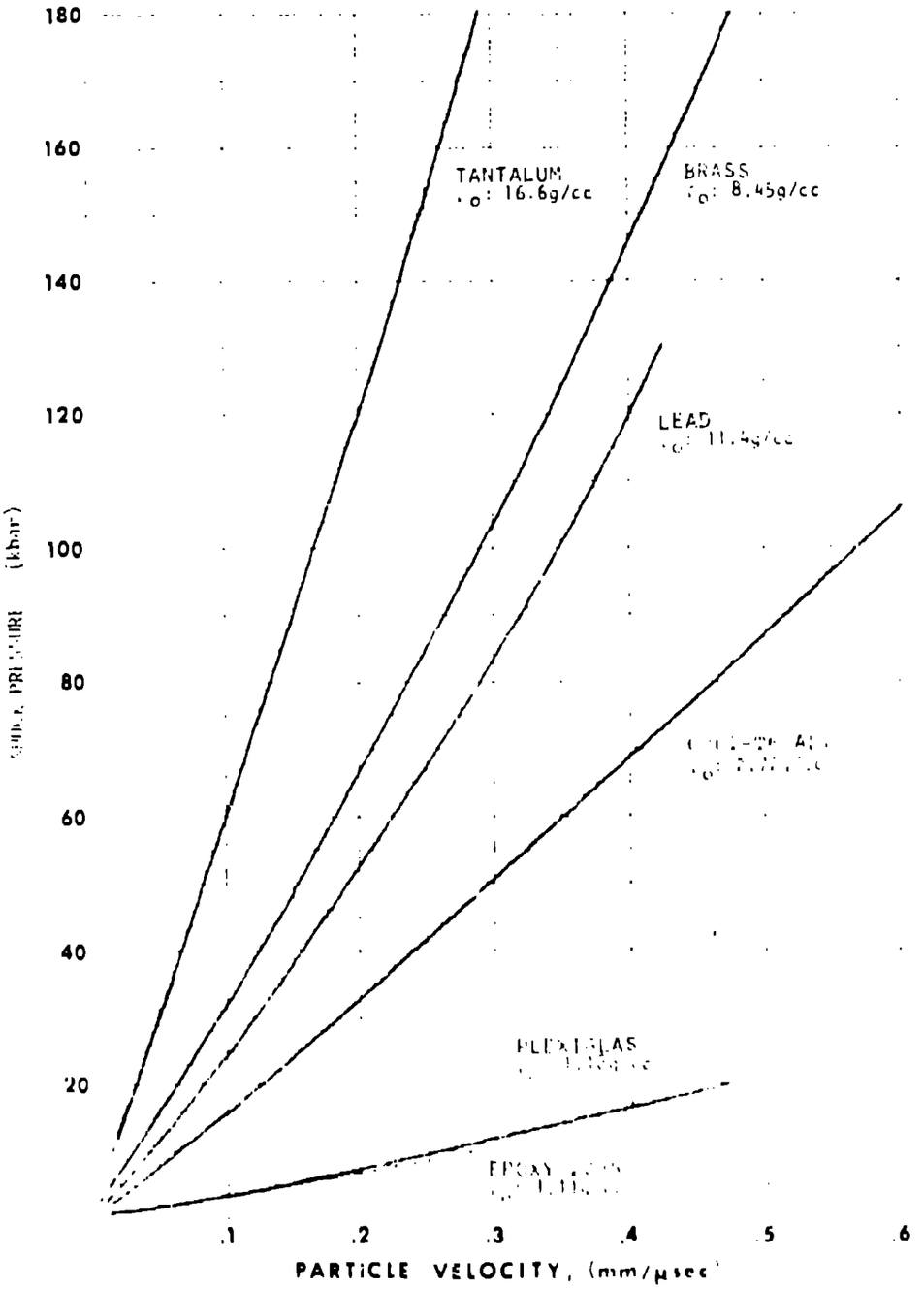


Fig. 3. Hugoniots of materials used in current work.

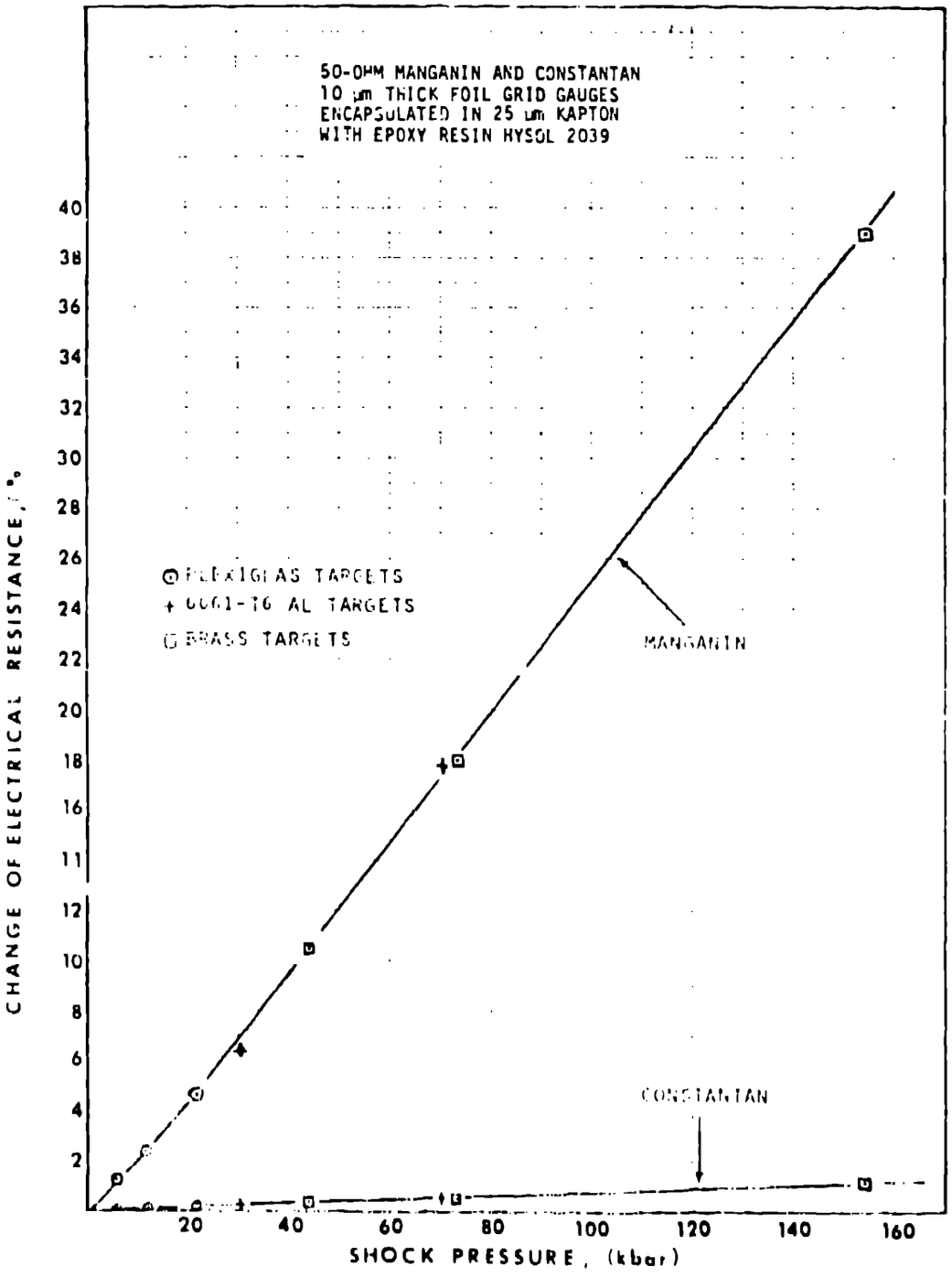


Fig. 4 Change in electrical resistance for Manganin and Constantan foils.

Figure 5 shows six oscillograph traces from these tests. Only in the first trace is the pressure component greater than the strain component. In the other traces, the strain component is greater producing a negative output. Figure 6 summarizes the results from the compressive strain tests for Manganin and Constantan. The Manganin strain factor varies between 0 and 4% strain. The Constantan strain factor appears to be unaffected by the pressure field.

C. Tension Tests

Dynasen used arrangement C shown in Fig. 2 to measure the state of combined stress and tensile strain. Carbon, Manganin, and Constantan elements were imbedded near the outside radius of cylindrical Plexiglas and aluminum targets. When the flyer struck the target, a stress wave was transmitted through the target, applying a stress normal to the gage. The target then expanded radially as relief waves formed, straining the gages. The strain was measured with the Constantan gage, and the pressure with the carbon gage. The strain sensitivity of carbon and Manganin are comparable, but the pressure sensitivity of carbon is almost 20 times greater than Manganin. This difference in pressure sensitivity makes the relative strain error introduced in the carbon gage much smaller than in a Manganin gage, and easier to correct. Knowing the pressure and the piezoresistivity of Manganin, the pressure component of the output can be unfolded, leaving only the strain output. The strain component, along with the measured strain, were then used to calculate the strain gage factor for Manganin. Figure 7 shows six oscillograph traces from these tests. The upper two traces are from carbon elements that undergo the greatest change of resistance. The center two traces are from Manganin elements. The first step in the Manganin record is due to the pressure wave; the later slope is due to strain. The lower two traces are from Constantan elements that respond only to the strain. The tensile strain results are summarized in Fig. 8. The tensile strain factor falls slightly under the compressive strain factor. We are not certain whether this results from a true strain effect or a bias in the experiment.

III. EXPERIMENTAL USE

A. Strain Correction

The strain gage factor of Manganin is variable making the strain correction difficult, but fortunately the strain factor is single-valued making the correction possible.

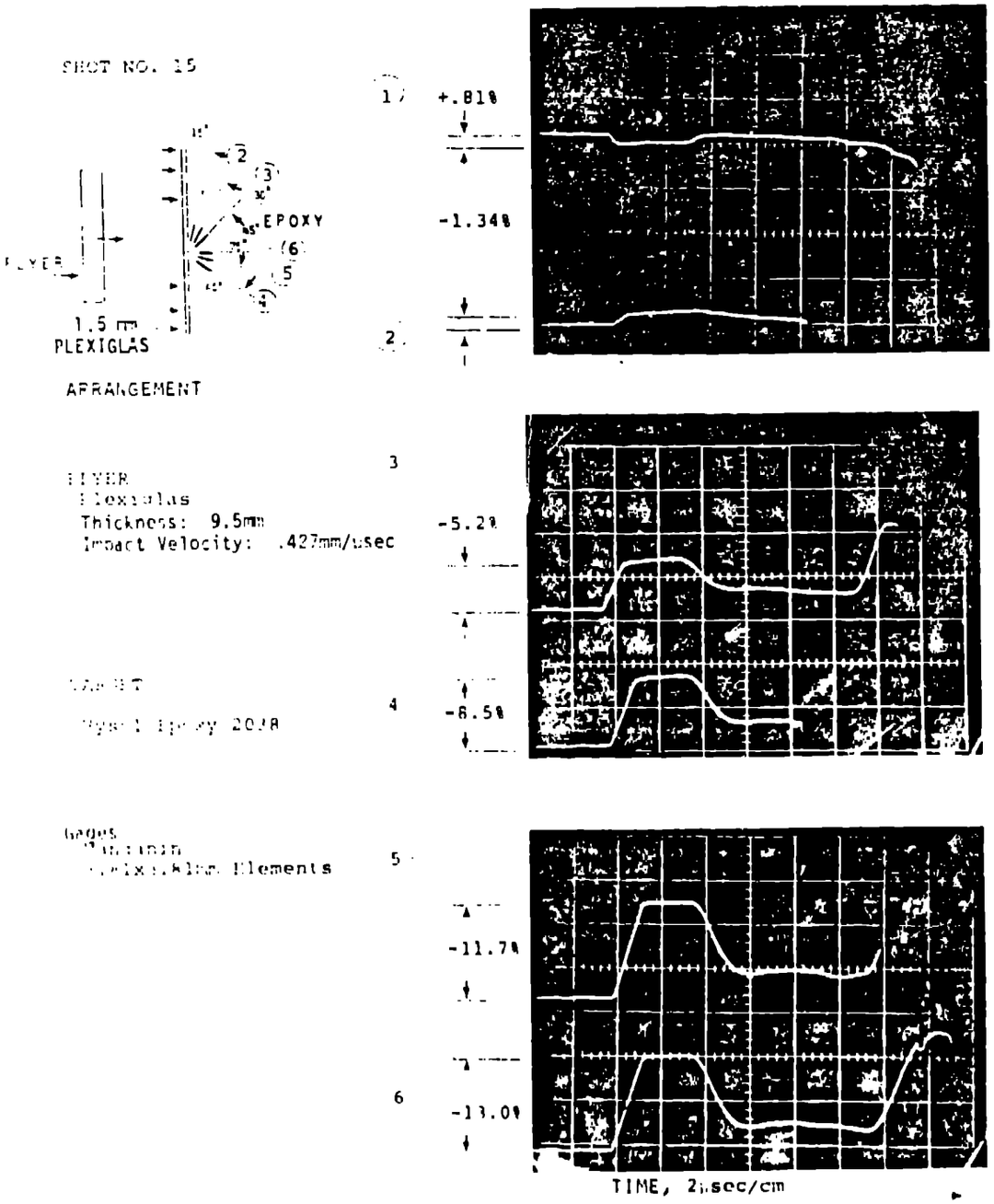


Fig. 5. Representative outputs for Manganin gages.

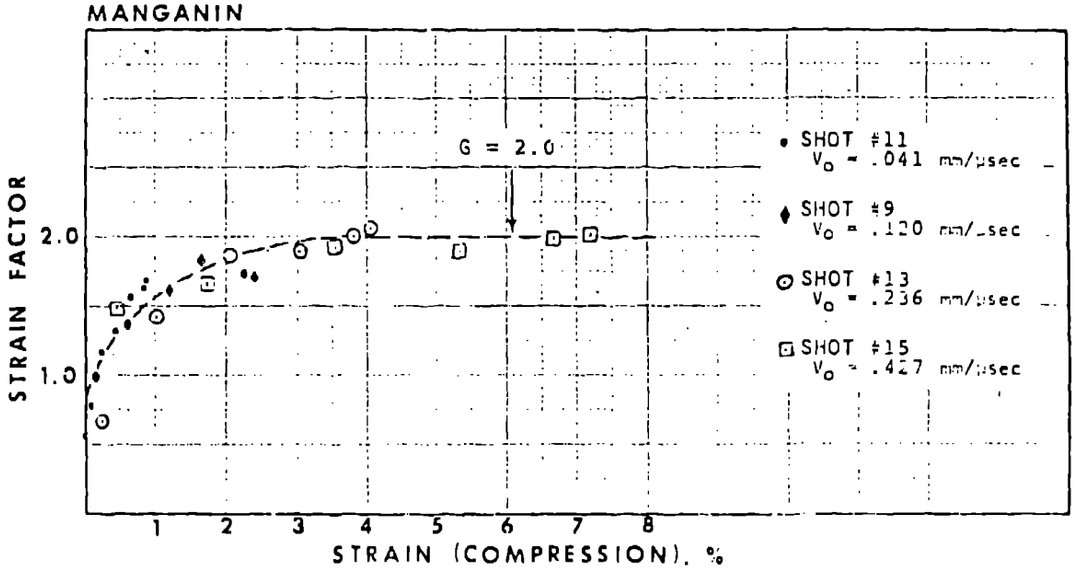


Fig. 6. Compression strain factors derived from gas gun tests.

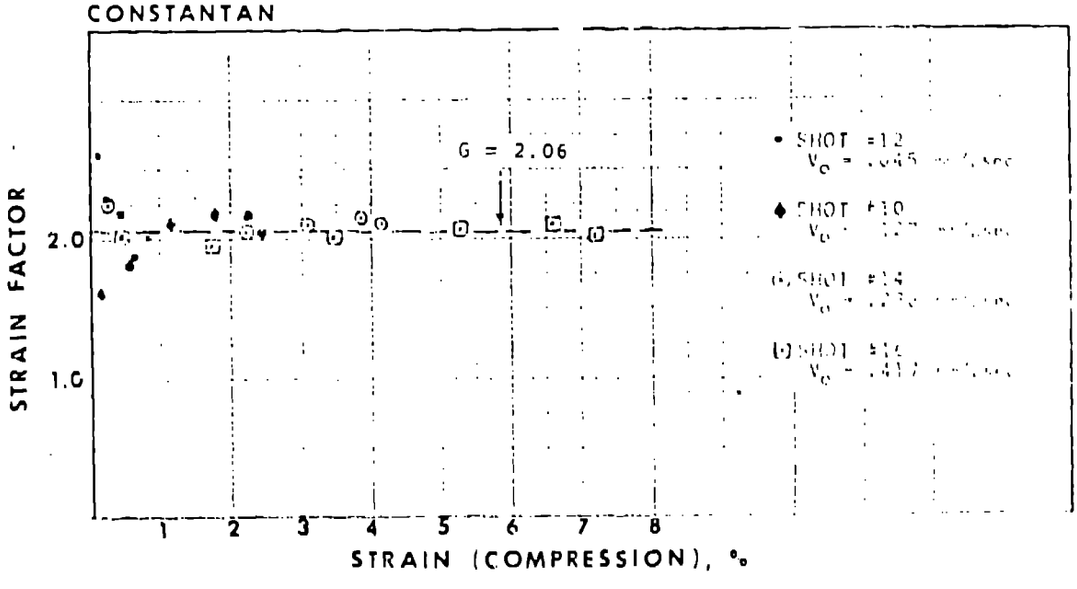


Fig. 6. Compression strain factors derived from gas gun tests.

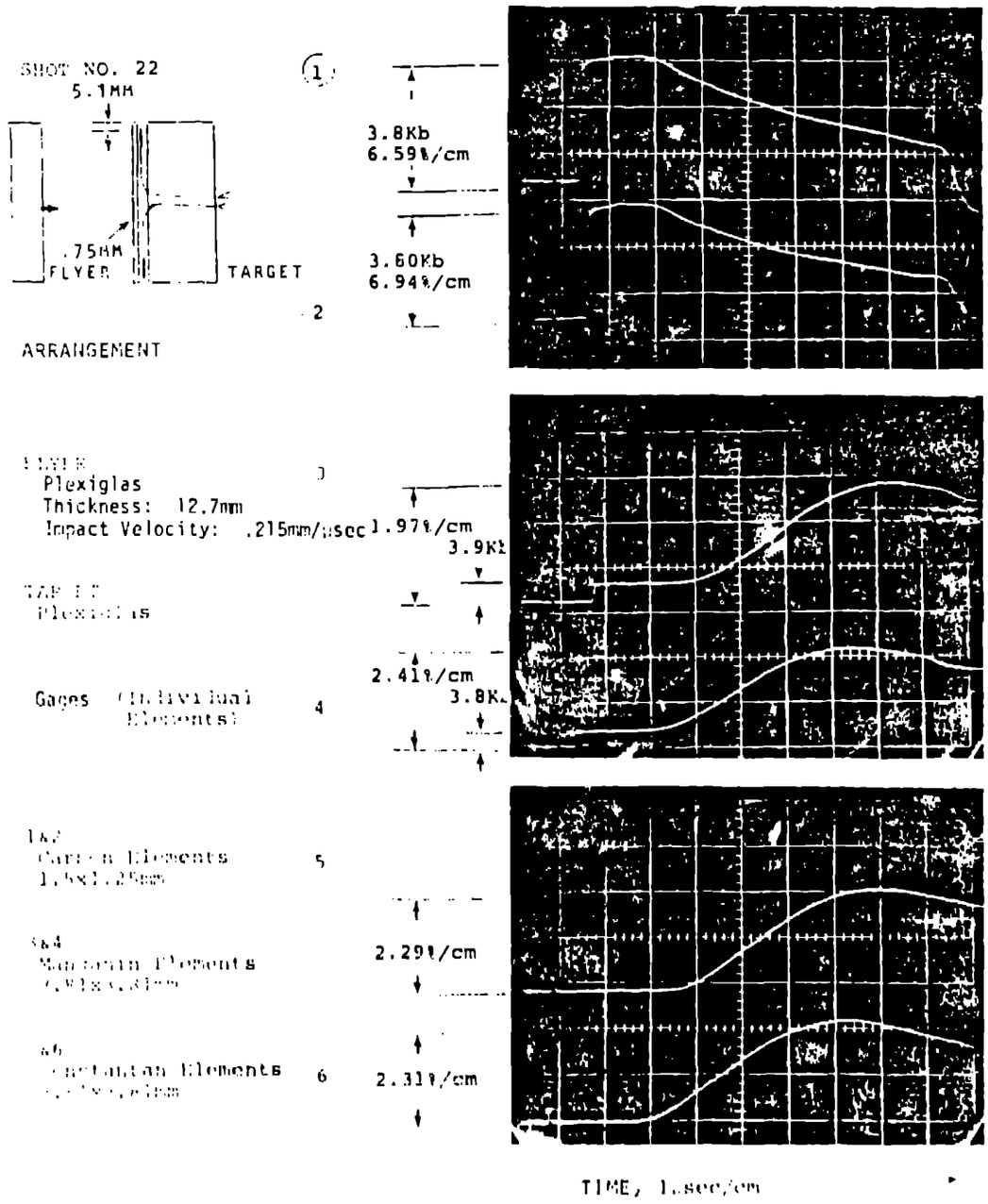


Fig. 7. Representative output of gages subjected to combined stresses and tension strains

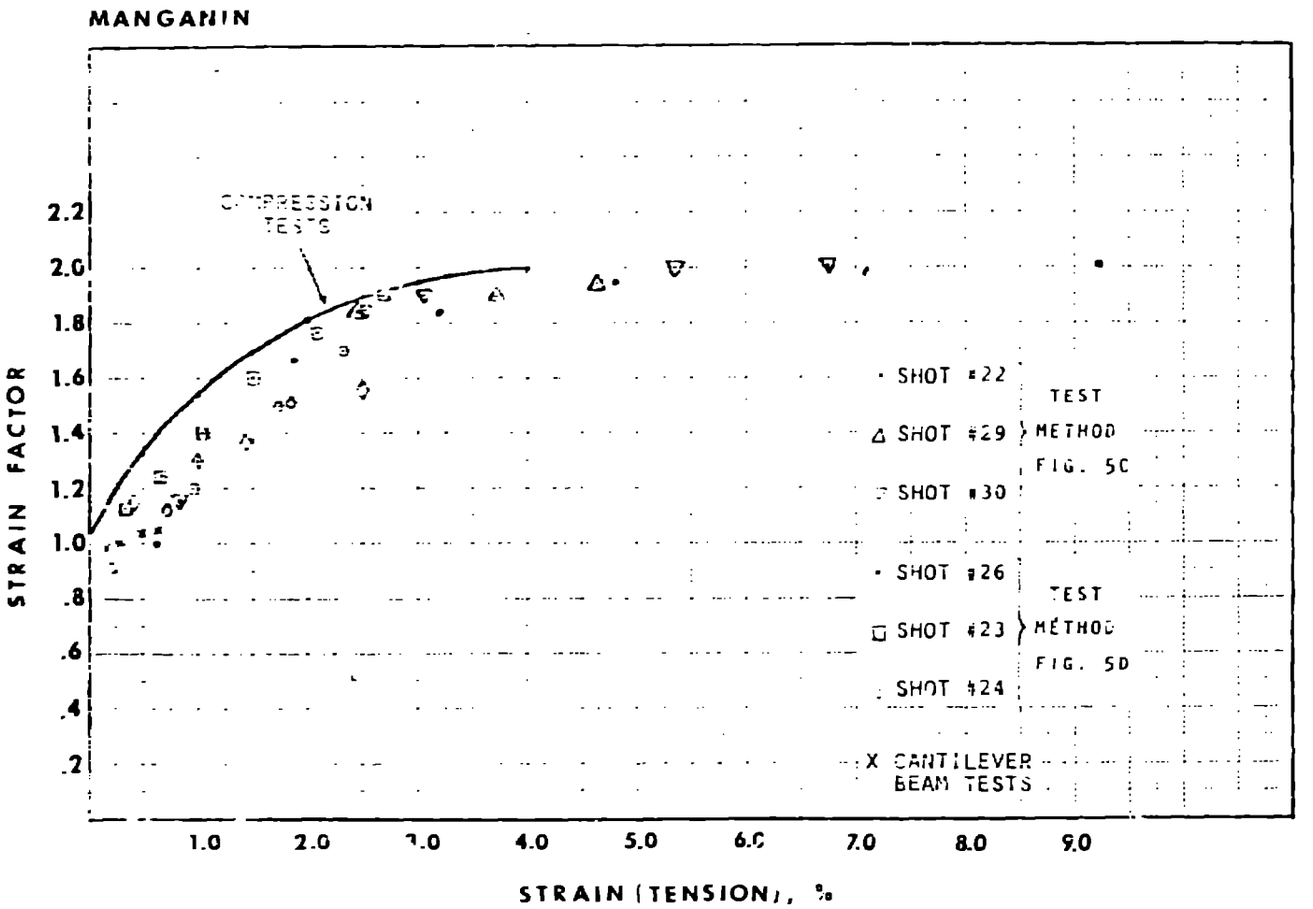


Fig. 8. Strain factor of Manganin foil in tension.

The resistance of a piezoresistive gage is a function of its length and the surrounding pressure.

$$R = R(P,L)$$

The change of resistance when the length and pressure change is:

$$dR = (\partial R/\partial P)dP + (\partial R/\partial L)dL \qquad (1)$$

Over a limited pressure and strain range the partial derivitives are given by:

$$\partial R/\partial P = aR \text{ and } \partial R/\partial L = GF(R/L)$$

where a is the piezoresistivity of the gage and GF is the strain gage factor. Substituting these into equation 1 gives:

$$dR/R = adP + GF(dL/L)$$

Integrating this equation gives

$$\ln(R/Ro) = a\Delta P + GF\ln(L/Lo)$$

This can be solved for P.

$$\Delta P = (1/a)\ \frac{\ln(R/Ro)}{\ln(L/Lo)^{GF}}$$

or

$$P = (1/a)\ \frac{\ln(1 + \Delta R/Ro)}{\ln(1 + \Delta L/Lo)^{GF}}$$

for small $\Delta L/L$

$$P = (1/a)\ \ln\left[\frac{1 + \Delta R/Ro}{1 + GF(\Delta L/Lo)}\right]$$

For Manganin $a = 0.00218\ \text{kbar}^{-1}$ reproduces the known resistance change versus pressure curve very well. For carbon $a = 0.035\ \text{kbar}^{-1}$ reproduces the curve fairly well. If the gage factor is known the pressure can be determined by measuring the strain with a Constantan gage and the total resistance change of the pressure sensing element.

B. Frequency Response

The 0.1 mm thick combination gage is capable of measuring planar stress waves with an approximate rise time of 50 ns. For nonplanar or obliquely incident measurements, we do not approach this capability. We are limited by the area of the gage face; our gages are typically 5 mm on

a side. A nonplanar or obliquely incident wave subjects different portions of the gage to different pressures. The gage output is a function of the average pressure over the gage. For example, a plane shock front traveling parallel to the gage face at 8 mm/μs takes 0.6 μs to transverse the gage. Stress waves traveling at lesser angles take less time; stress waves traveling at lower velocities take more time. This effect needs to be considered when looking at the rise time of a stress wave.

C. Field Tests

We have used these Manganin-Constantan combination gages on several field tests with fair success. We have seen lower pressures in these experiments than we had expected; most of the measured pressures have been under 10 kbar. In this range the strain correction would be much easier with carbon or ytterbium pressure sensing elements. We plan to do further development on one of these materials in the near future.

To cover the full pressure range and to add duplication, we have used carbon and Manganin elements together in many of our measurements. The Manganin element is normally part of a Dynasen Manganin-Constantan combination gage developed in this program. A carbon gage is epoxied directly over the combination gage. The thickness of the package is satisfactory because the rise times of the pressure waves that we are measuring are relatively slow.

Most of our pressure measurements have been in mock high explosive (HE) or lithium hydride (salt). Figure 9 shows what we call a mock HE pressure instrumentation package (PIP). The PIP is in the center, and the various gages that go into the PIP are on the sides. Four pressure sensing devices are present in this PIP: a Manganin-Constantan combination gage, a carbon gage, a piezoelectric pin, and a twinning pellet. A Dynasen Manganin-Constantan combination gage is shown in Fig. 10. The piezoelectric pin gives a signal when the pressure wave arrives at the pin. This helps to sort out actual pressure at the carbon and Manganin gage elements from other induced noise. It also provides an arrival time if the other gage elements are lost. The twinning pellet is made of ingot iron, which twins when it is subjected to a pressure greater than 7 kbar. Twinning is a slippage of the crystalline structure within grain boundaries, and can be seen with a microscope after the sample is cut and polished.

Figure 11 shows a salt PIP used in the same test. In this case only a carbon gage was used along with the pin and twinning pellet. Figure 12 shows results from these PIPs. Although the first pressure pulse of approximately 3 kbar is low for the Manganin gage sensitivity, the agreement with the carbon gage is good and strengthens the credibility of the measurement. The agreement at later times is poor, but a larger pressure is measured by both gages. The salt pressure traces were correlated in time with a slightly higher pressure seen in the outer PIP, as expected.

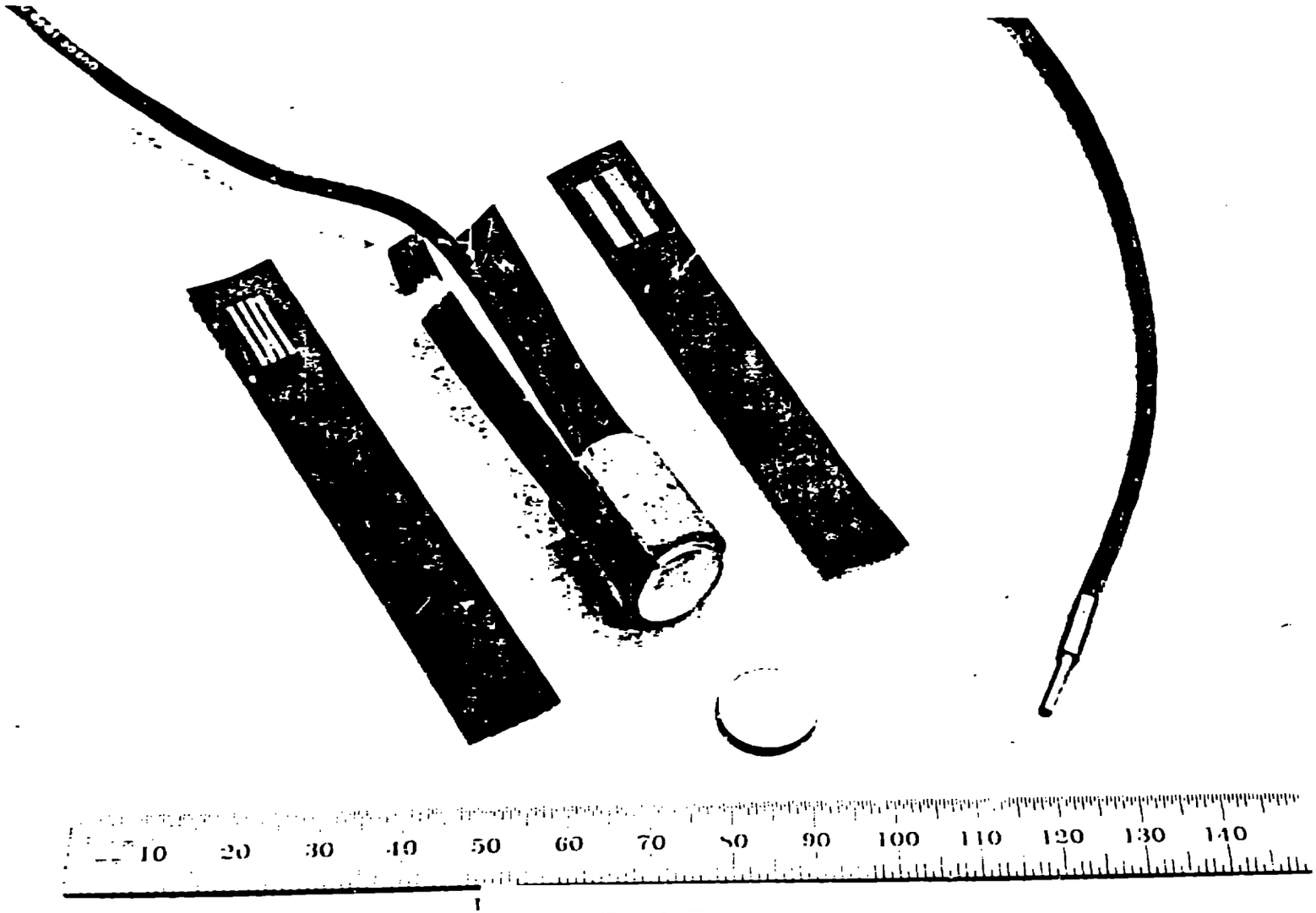


Fig. 9. Mock HE pressure instrumentation package used in NRL tests.

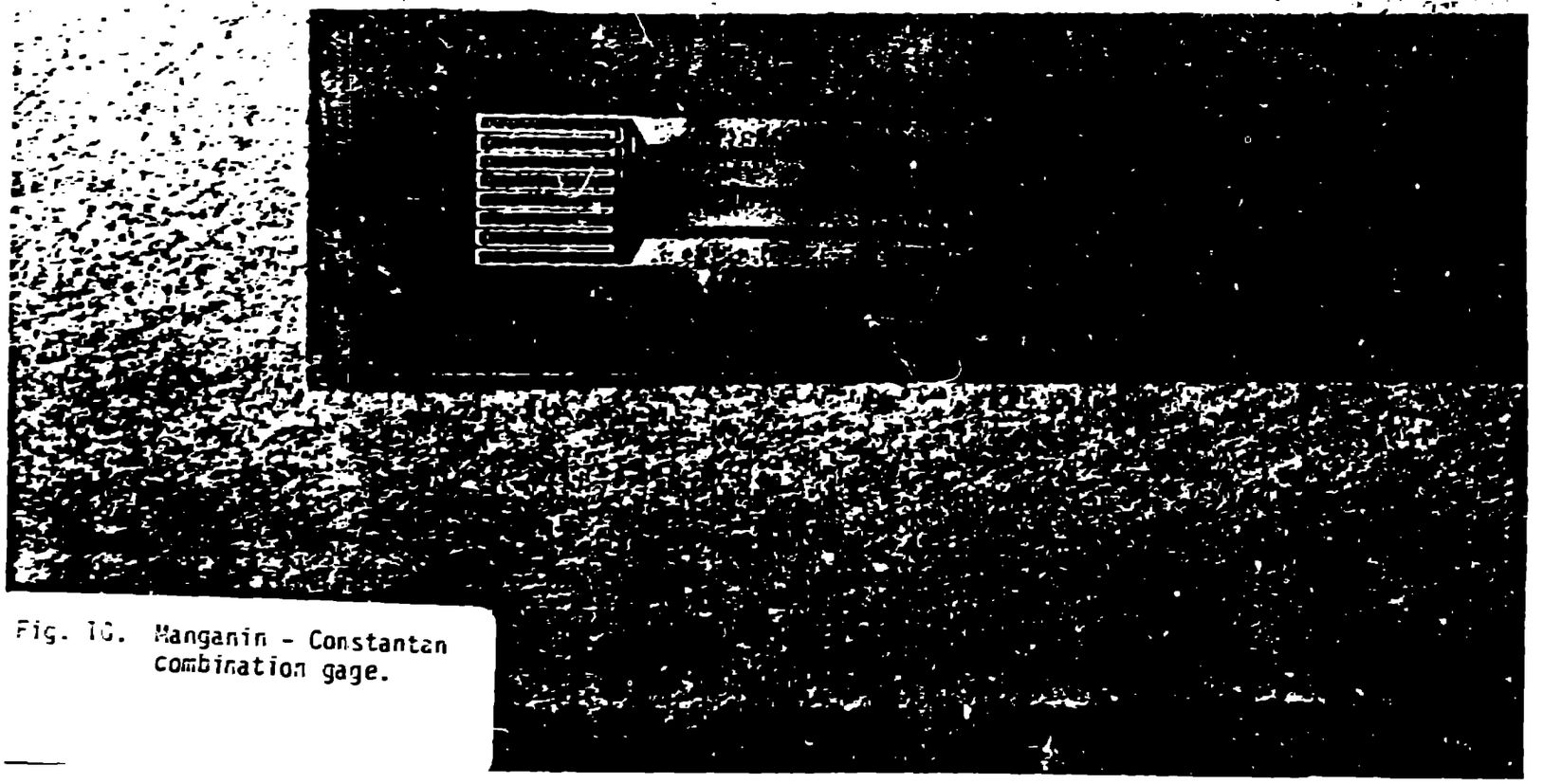


Fig. 10. Manganin - Constantan combination gage.

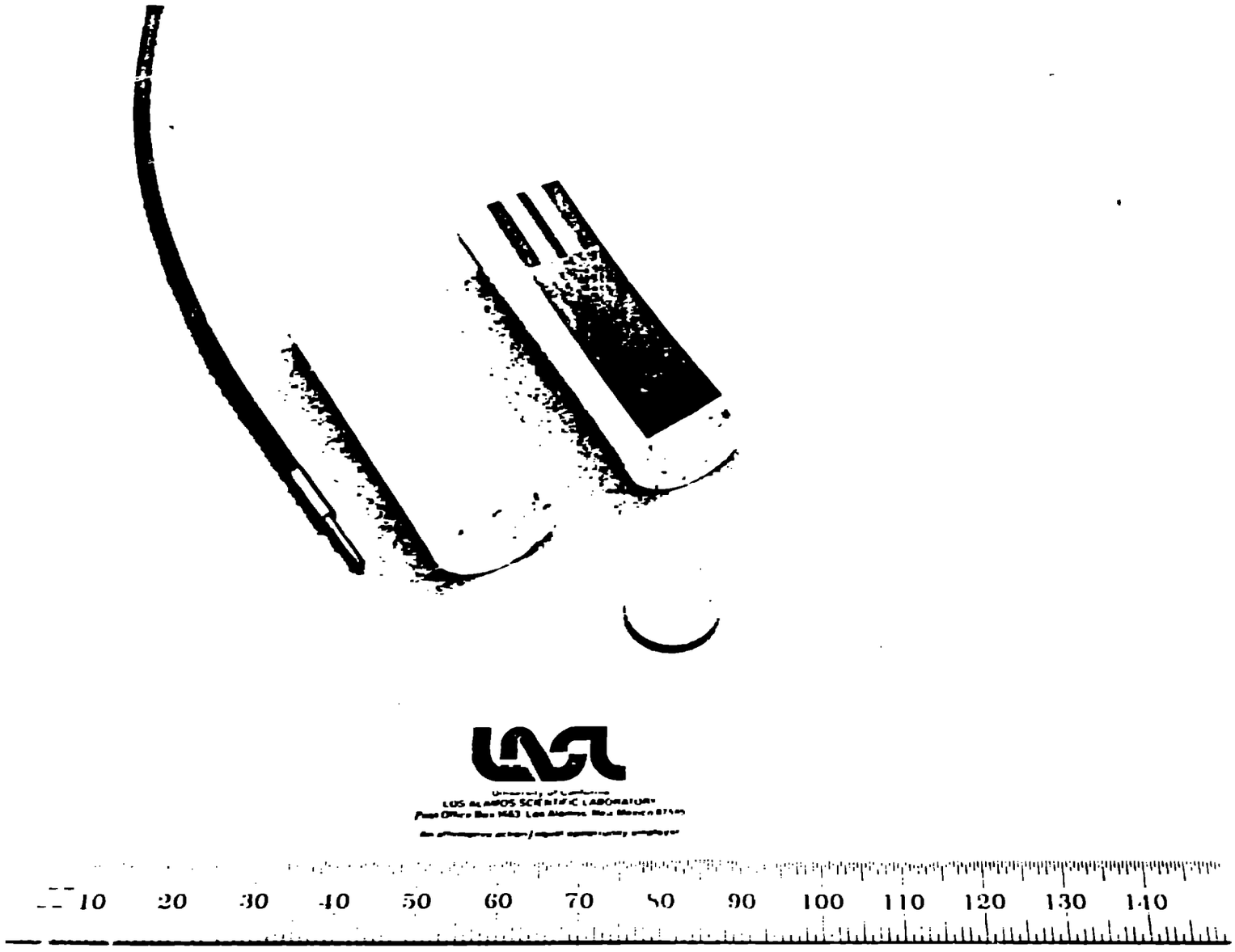


Fig. 11. Salt pressure instrumentation package used in NRL tests.

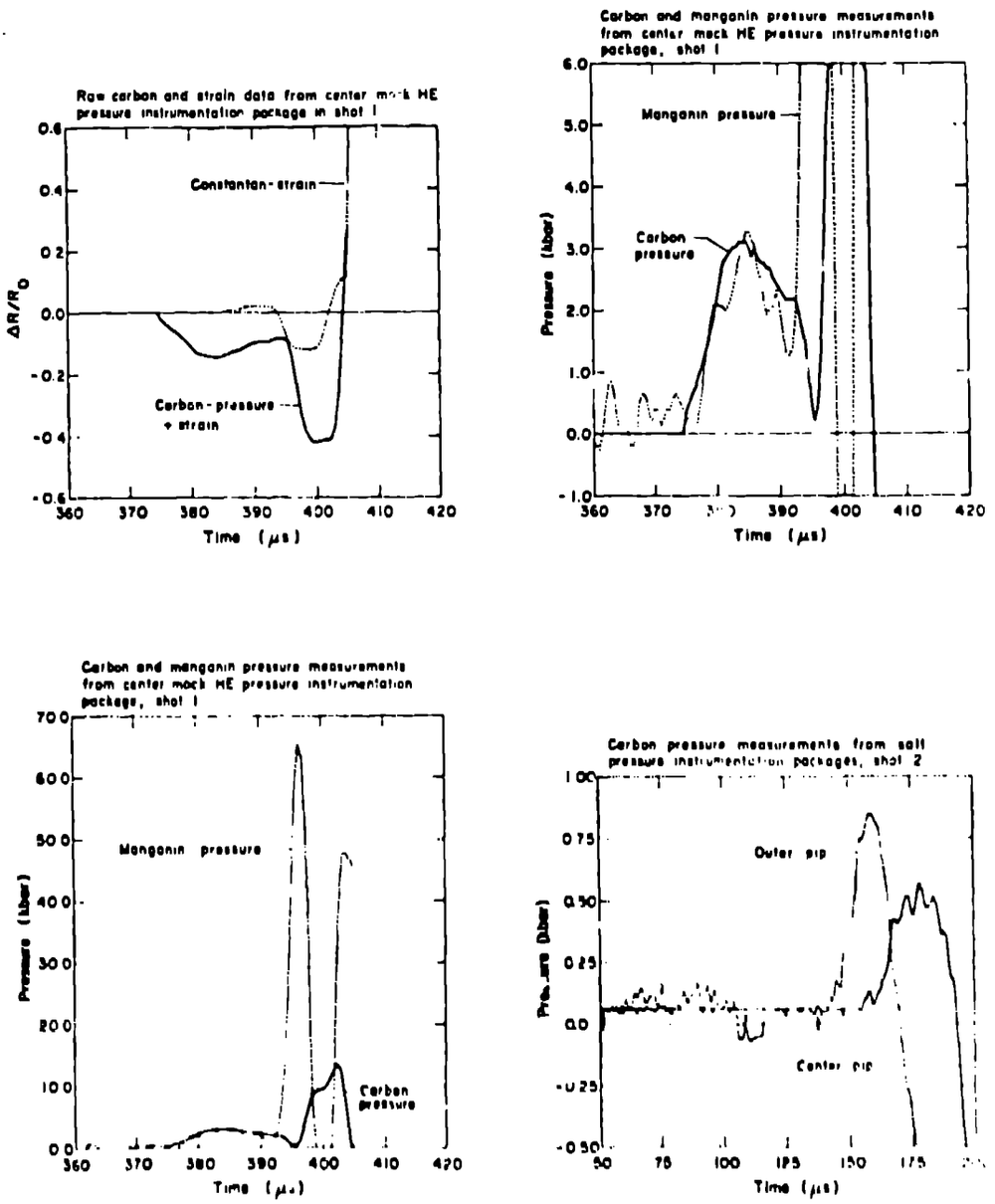


Fig. 12. NRL test results from mock HE and salt pressure instrumentation packages.

Another PIP design shown in Fig. 13 was used to measure pressure orthogonally. Two gages were mounted at right angles on the salt. These were superimposed gages with a folded carbon gage on one side and a 50-Ω Constantan strain gage on the other side. The gage is shown in Fig. 14; results from a measurement of this type are shown in Fig. 15. The strain on the axial gage is tensile from an expanding wave front. The strain on the radial gage is compressive as it should be because the gage is perpendicular to the pressure front.

The pressure is about equal on both axes at early times, indicating that the material is acting hydrodynamically. At later times as the strain increases, the pressure measurement is less certain.

IV. Summary

A useful gage has been developed for measuring pressure of nonplanar or obliquely incident stress waves. The measurements made with these gages are not as precise as direct strain gage measurements, but are very good considering the conditions under which these gages are used. We feel a need to further develop our ability to measure nonplanar stress waves in the 0-10 kbar range. Carbon or ytterbium will probably be chosen for the sensing element.

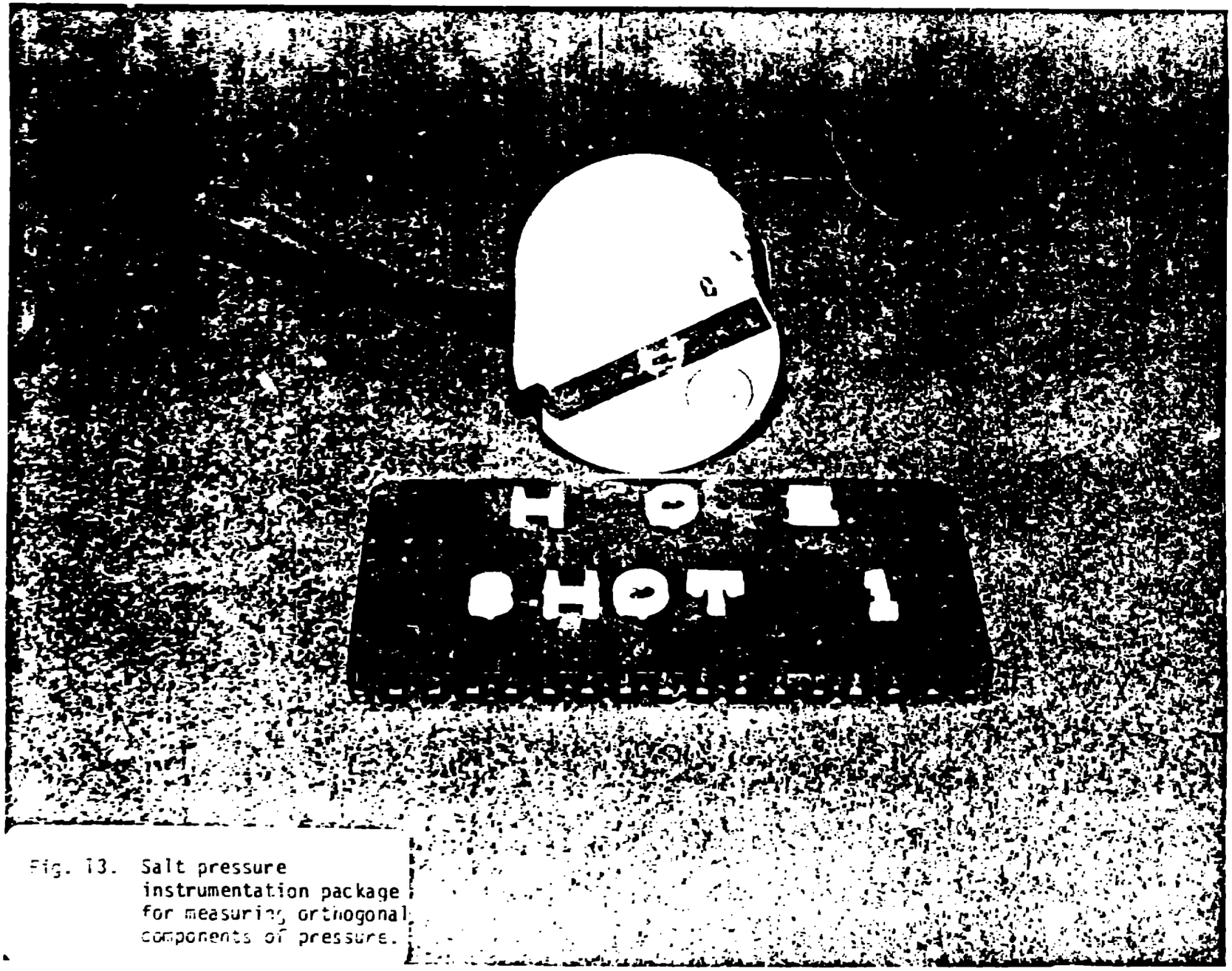


Fig. 13. Salt pressure instrumentation package for measuring orthogonal components of pressure.

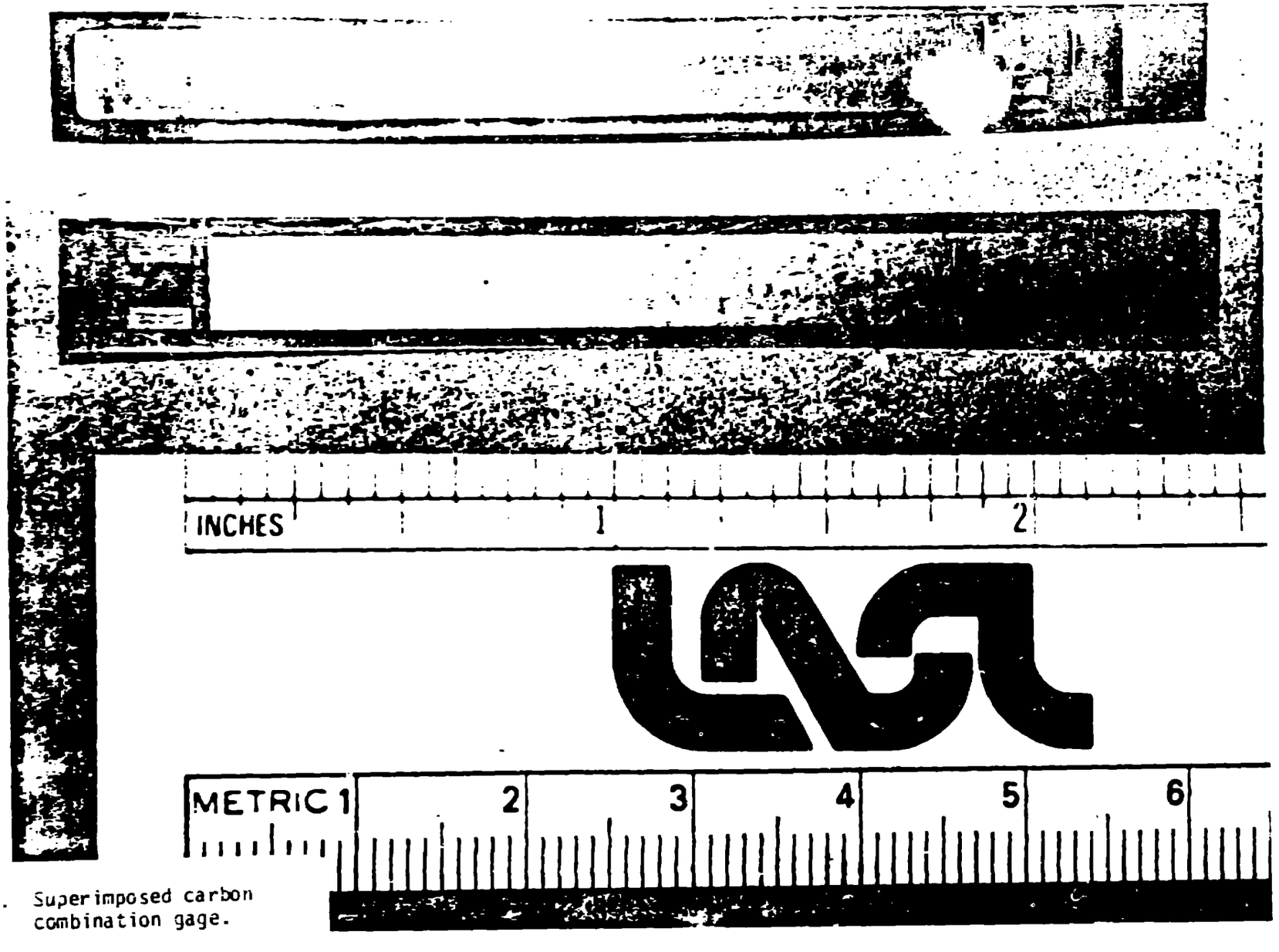


Fig. 14. Superimposed carbon combination gage.

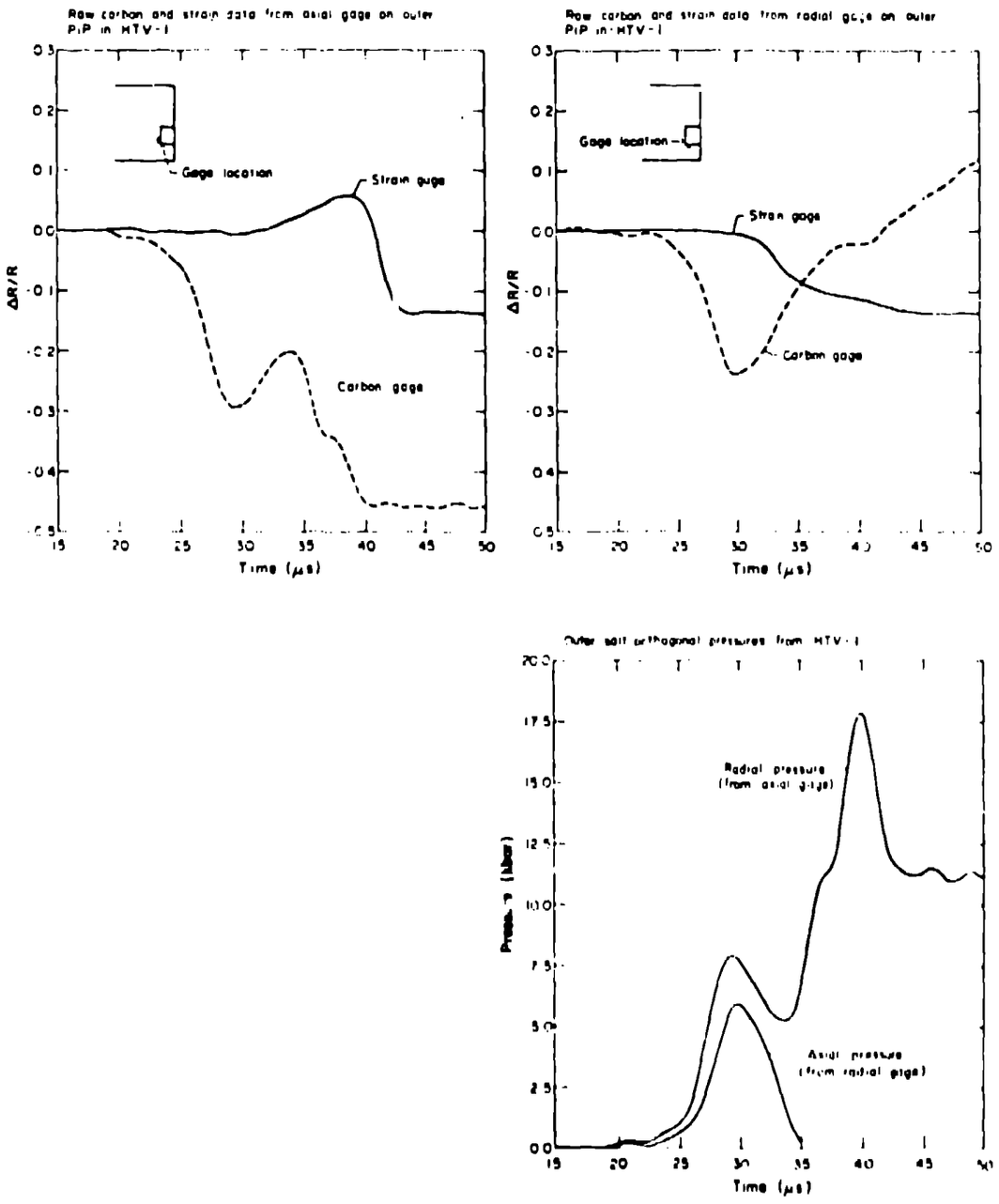


Fig. 15. Orthogonal components of pressure measured in HTV 1.

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1. "Strain-Compensated Stress Gage Development Final Report," Lockheed Missiles and Space Co. Report, LMSC-D506298, July 1976.

2. J. A. Charest, "Development of a Strain-Compensated Shock Pressure Gage," Dynasen Inc. Report, February 1979.

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