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TITLE: PRESSURE MEASUREMENTS OF NONPLANAR STRESS WAVES

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ABSTRACT

Measuring the pressure of non-planar stress waves using thin piezoresistive gages requires correcting for induced strain parallel to the sensing elements. A technique has been developed that permits such measurements, making use of a dual element gage. One element, Manganin, is sensitive to stress both parallel and perpendicular to the sensing element; the other element, Constantan, is primarily sensitive to stress parallel to the sensing element. The change in resistance in the Constantan element is thereby used to correct for the strain effect parallel to the Manganin element axis.

Individual and combined Manganin and Constantan elements were subjected to controlled gas gun impact tests in the pressure and strain ranges of 0-50 kbar and 0-7%, respectively. From planar wave tests, the piezoresistivity of Constantan was found to be positive but negligible in comparison with Manganin. From combined stress and strain environments, the compression and tension strain factors of Constantan were found to be constant and equal to 2.06. The strain factors of Manganin were found to increase from 1.2 to 2.0 asymptotically in the range of 0 to 3% strain.

It was experimentally demonstrated that, because of the closeness of their strain factors, the Manganin-Constantan dual element gage could be used in the differential recording mode to yield pressure directly. In this mode the gage is a strain compensating gage. Analytical techniques have also been developed for more accurate strain compensation.

I. INTRODUCTION

We often need to measure the pressure generated by small projectiles as they penetrate complex structures. Small projectiles in complex structures inherently cause nonplanar pressure waves, and nonplanarity causes severe problems in pressure measurements.

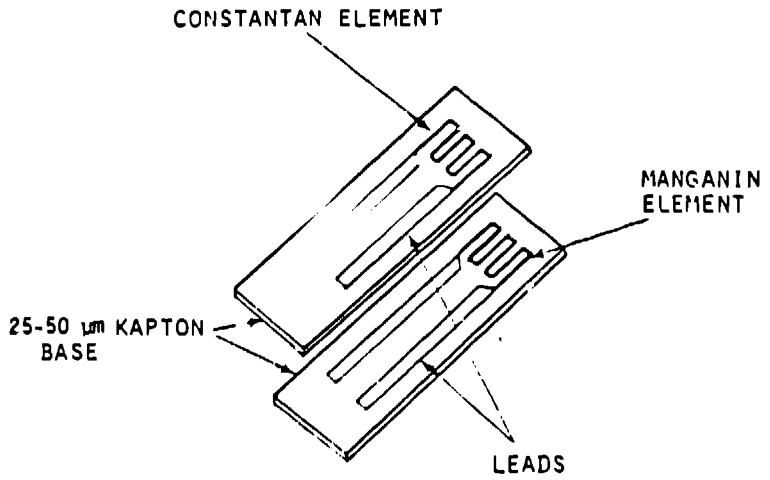
Thin carbon, ytterbium, and Manganin gages have been used successfully to measure planar waves. In planar measurements, the gage element is placed normal to the incident stress wave. The stress wave compresses the gage normal to its face, changing the gage material resistivity and the resistance of the 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.

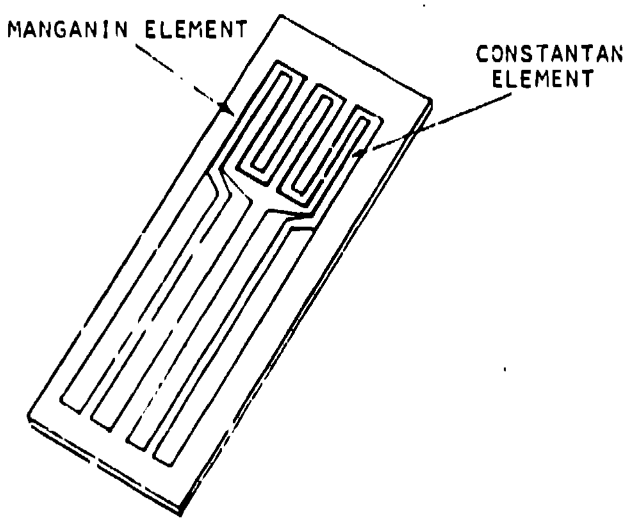
Nonplanar measurements have been made in the past. The simplest technique is to place a Constantan strain gage near the pressure sensing element and measure the strain. The resistance change of the Constantan strain gage is subtracted from the resistance change of the pressure sensing element to give the resistance change caused by 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 (94% copper and 6% nickel). 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 requirements, Manganin appeared to be more useful than ytterbium because of its greater pressure capacity. To develop a Manganin compensated gage, we measured the piezoresistivity and strain factors of Manganin and Constantan foils over a wide range of combined pressures and strains and developed manufacturing procedures for superimposed and interlaced gage combinations as shown in Fig. 1.



A-SUPERIMPOSED ARRANGEMENT



B-INTERLACED ARRANGEMENT

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

II. PRESSURE-STRAIN ANALYSIS

It is first useful to determine mathematically how pressure and strain combine to affect the resistance of a gage element. 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 Eq. (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 ΔP.

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

or

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

For small $\Delta L/L$

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

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

In practice we define an effective resistance change of the gage caused only by the pressure component.

$$\left(\frac{\Delta R}{R}\right)_{P\ \text{effective}} = \frac{1 + (\Delta R/Ro)\text{Total}}{1 + GF\ (\Delta L/Lo)} - 1.$$

Instead of using the natural logarithm of this function, we use the calibration curve for Manganin or carbon to determine the strain-corrected pressure.

For small strain this equation can be approximated by

$$\left(\frac{\Delta R}{R}\right)_{P\ \text{effective}} = \left(\frac{\Delta R}{Ro}\right)_{\text{total}} - GF \left(\frac{\Delta L}{Lo}\right)$$

The difference between the more exact equation and this approximation defines the amount of error introduced when direct subtraction schemes are used. This amount of error is often tolerable.

III. GAGE TESTING PROGRAM

Figure 2 shows the four main experimental arrangements we used in this program. Arrangements A, B, and C were tested with the Dynasen 63.5-mm-diam gas gun 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 and 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.

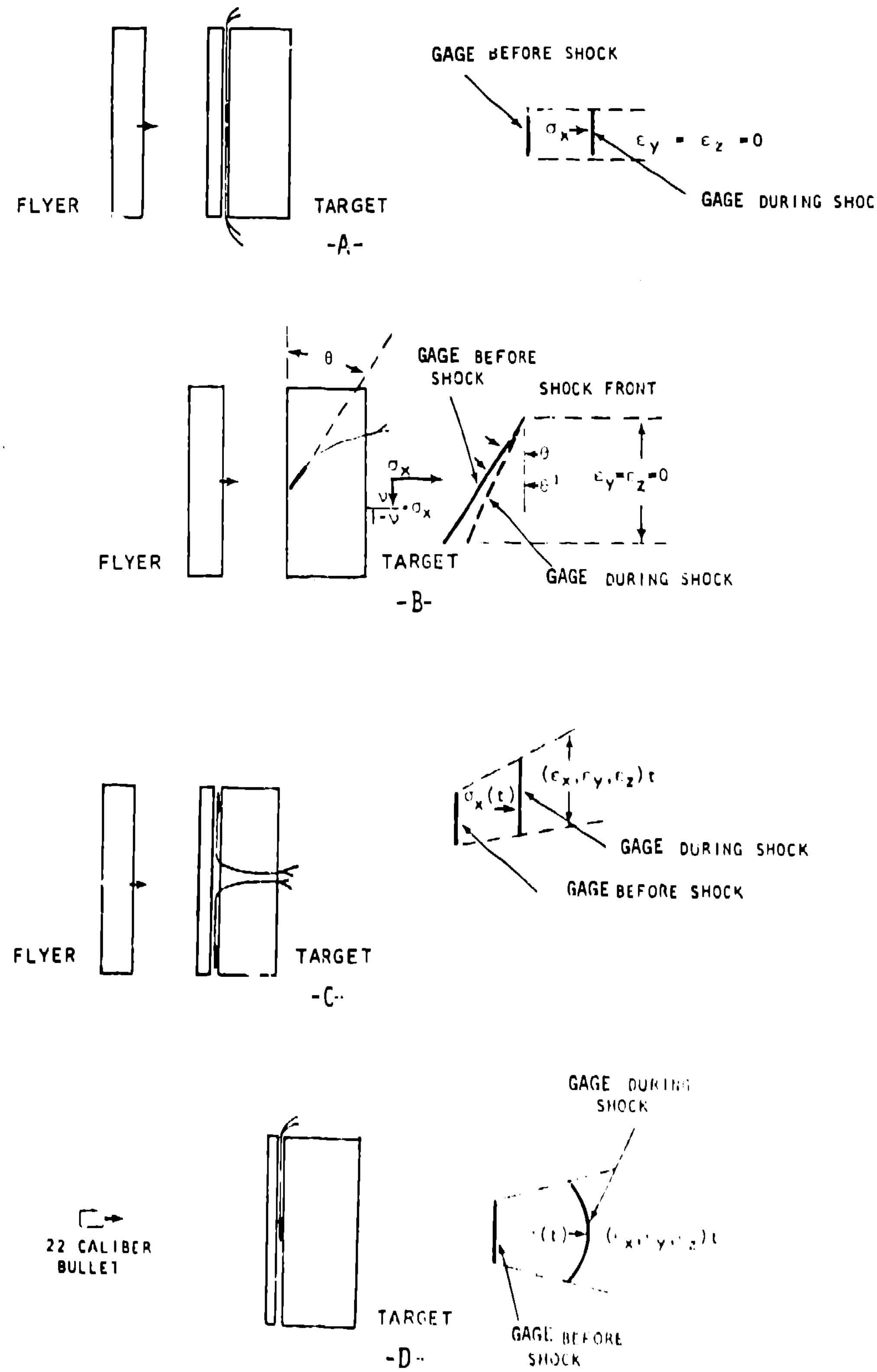


Fig. 2. Experimental arrangements for measuring stress and strain outputs.

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. 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

We 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 and 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 dots are the experimental data points from the various tension tests; the solid curves follow the mean values of the experimental points. The tension data vary over a considerable range at

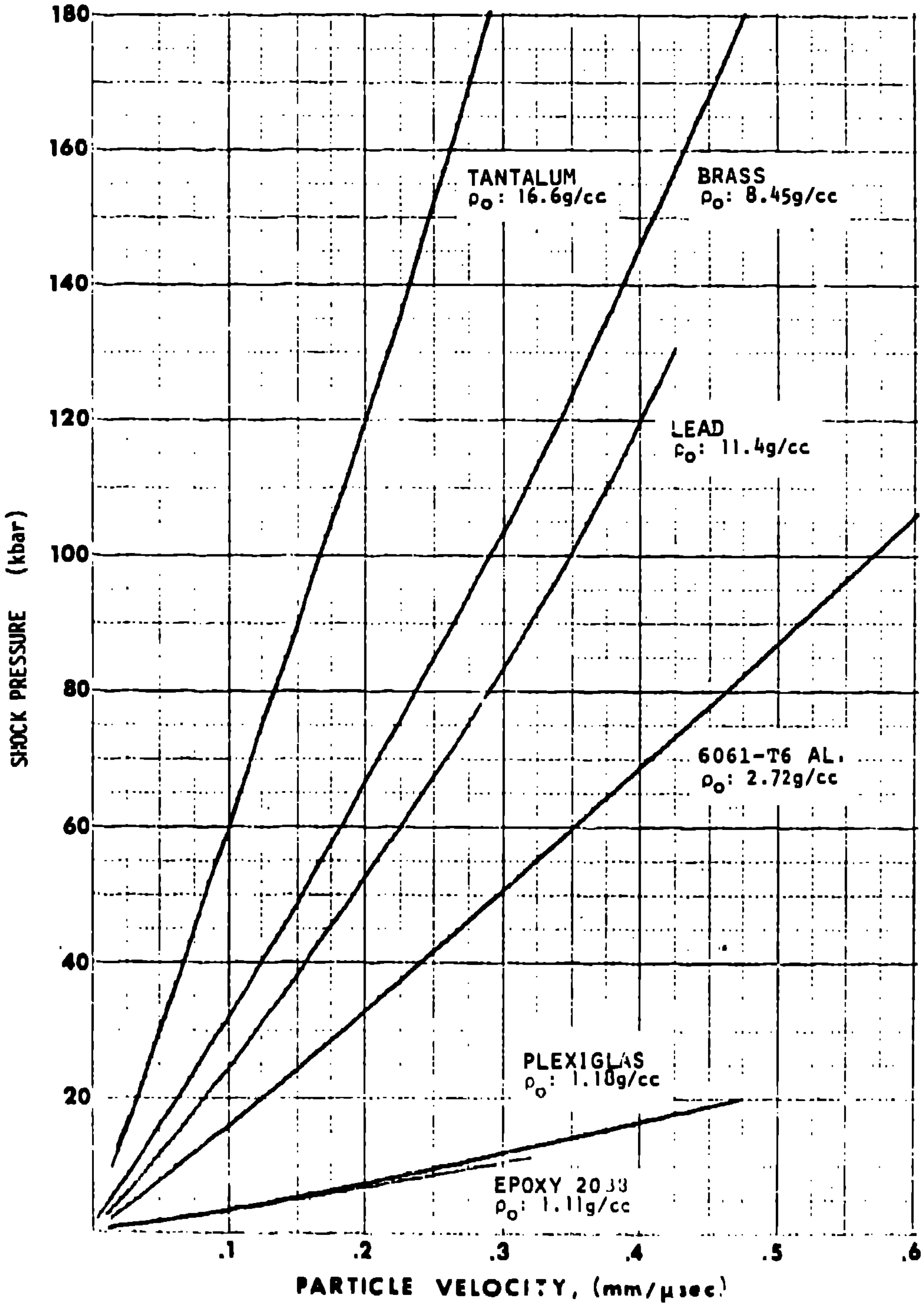


Fig. 3. Hugoniots of materials used in current work.

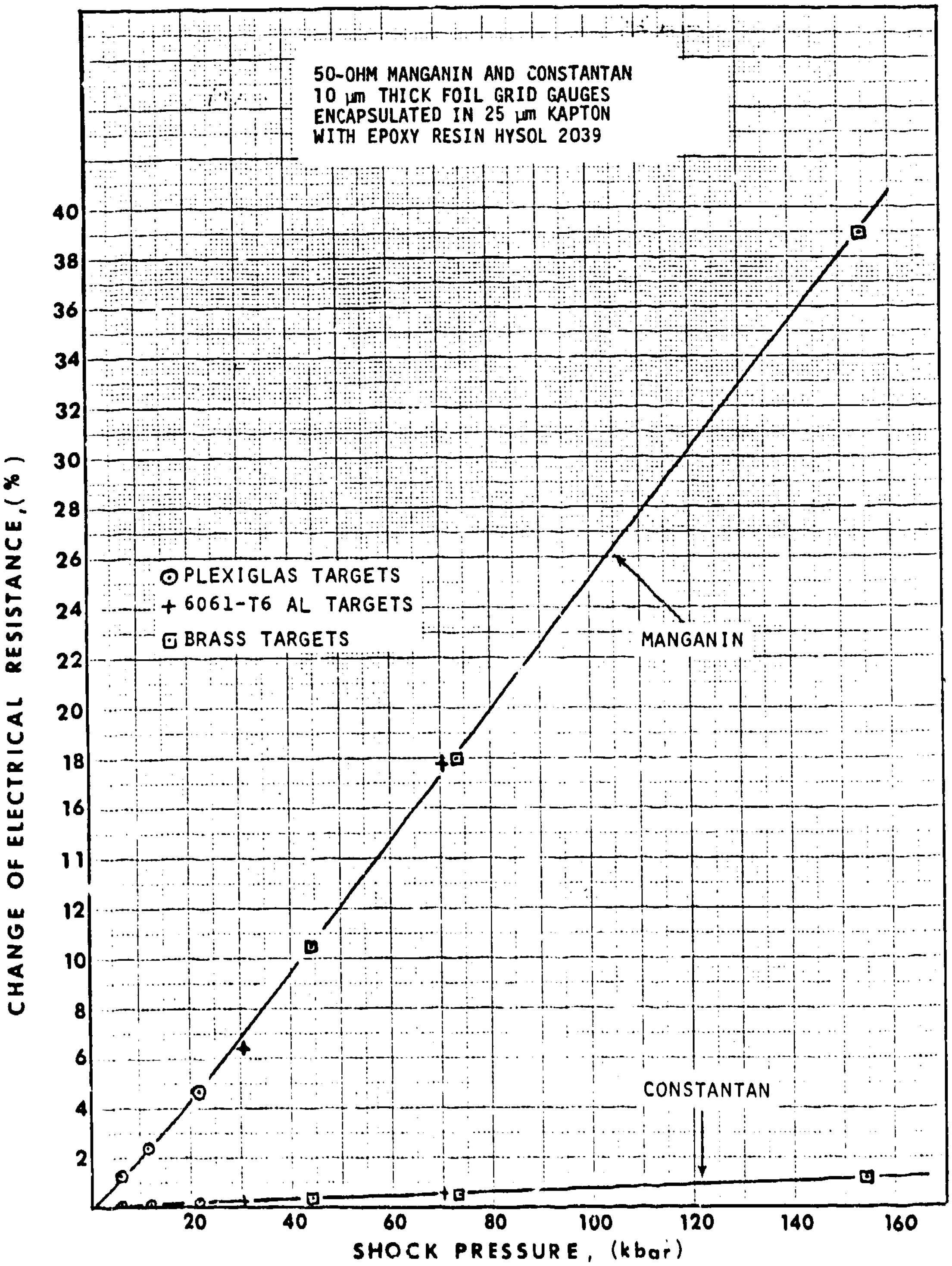


Fig. 4. Change in electrical resistance for Manganin and Constantan foils.

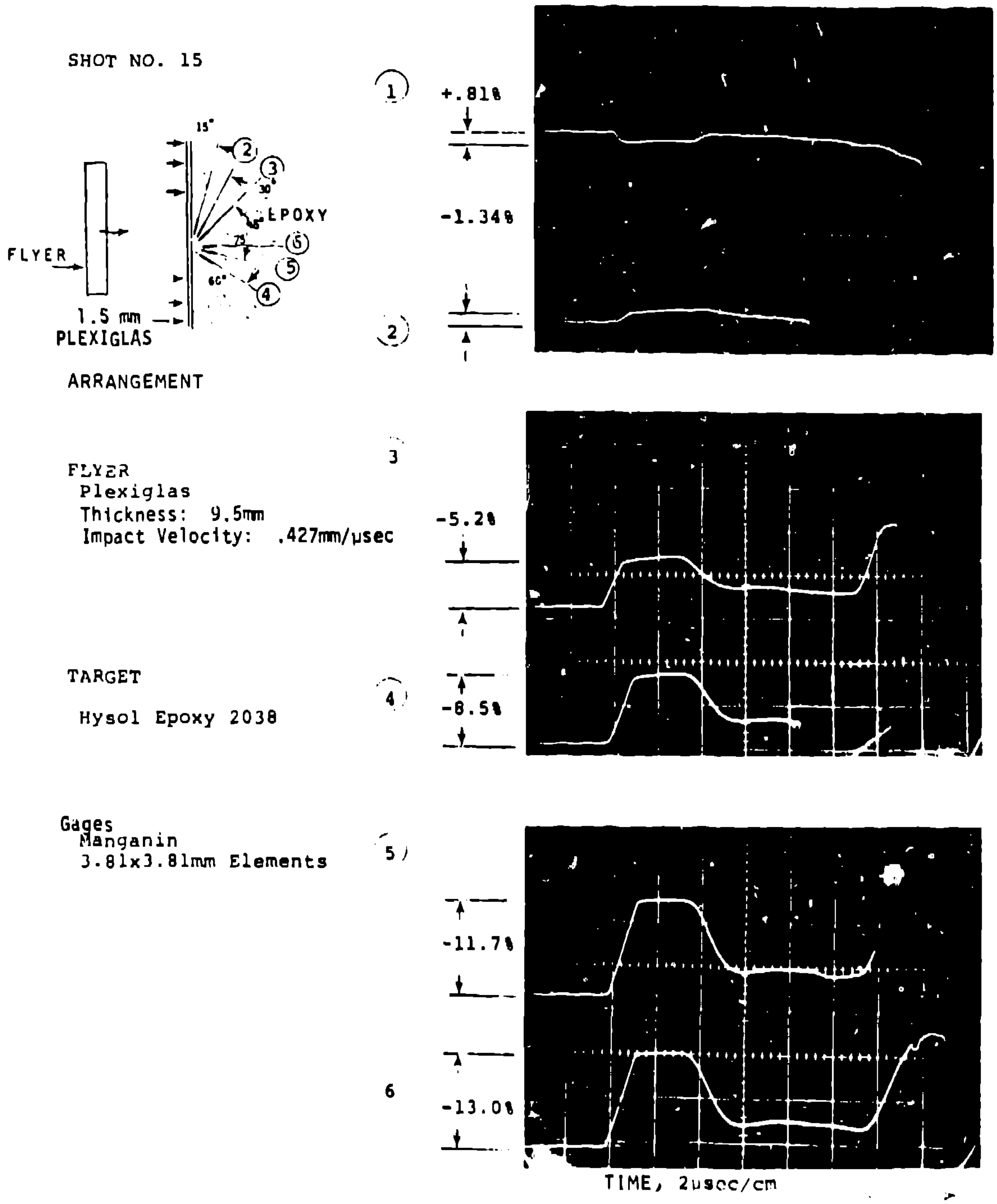


Fig. 5. Representative outputs for Manganin gages.

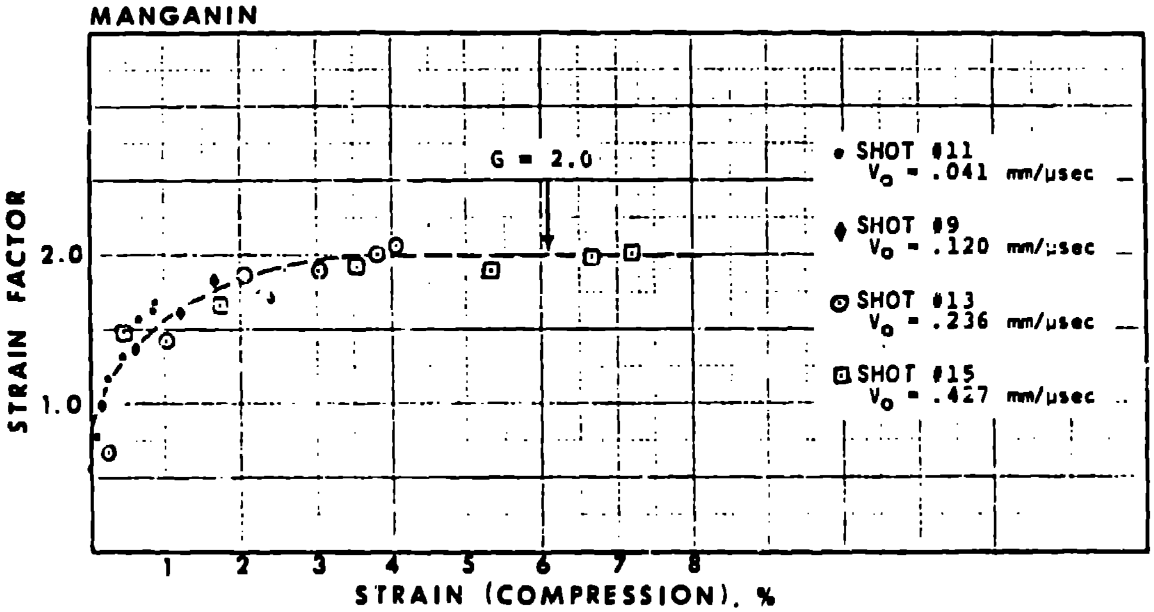


Fig. 6a. Manganin.

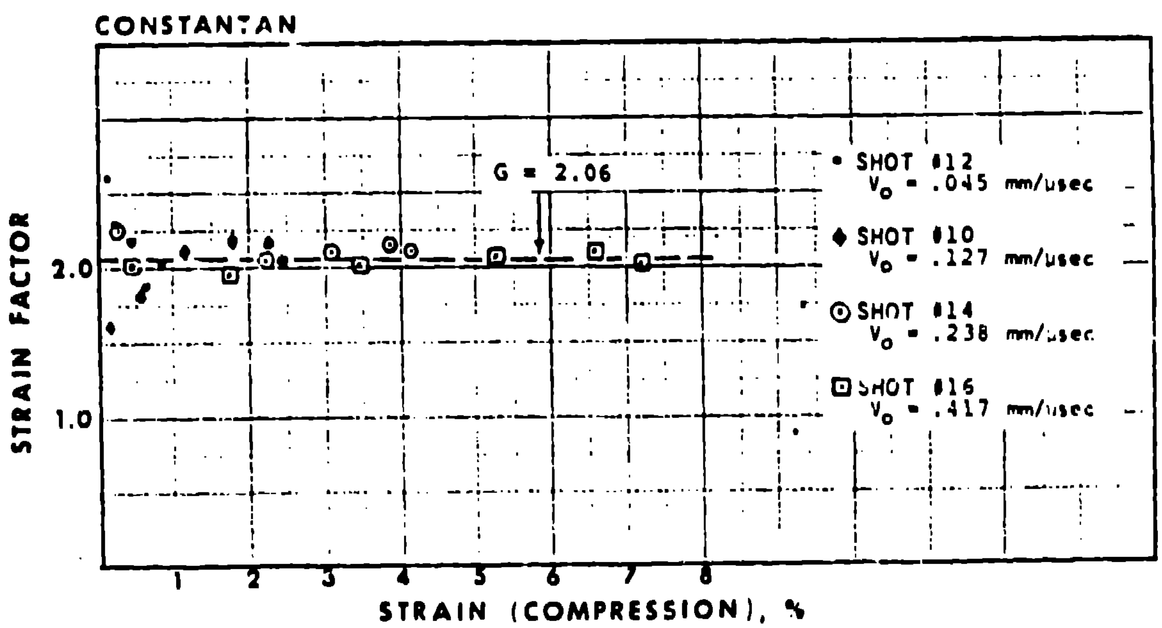


Fig. 6b. Constantan.

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

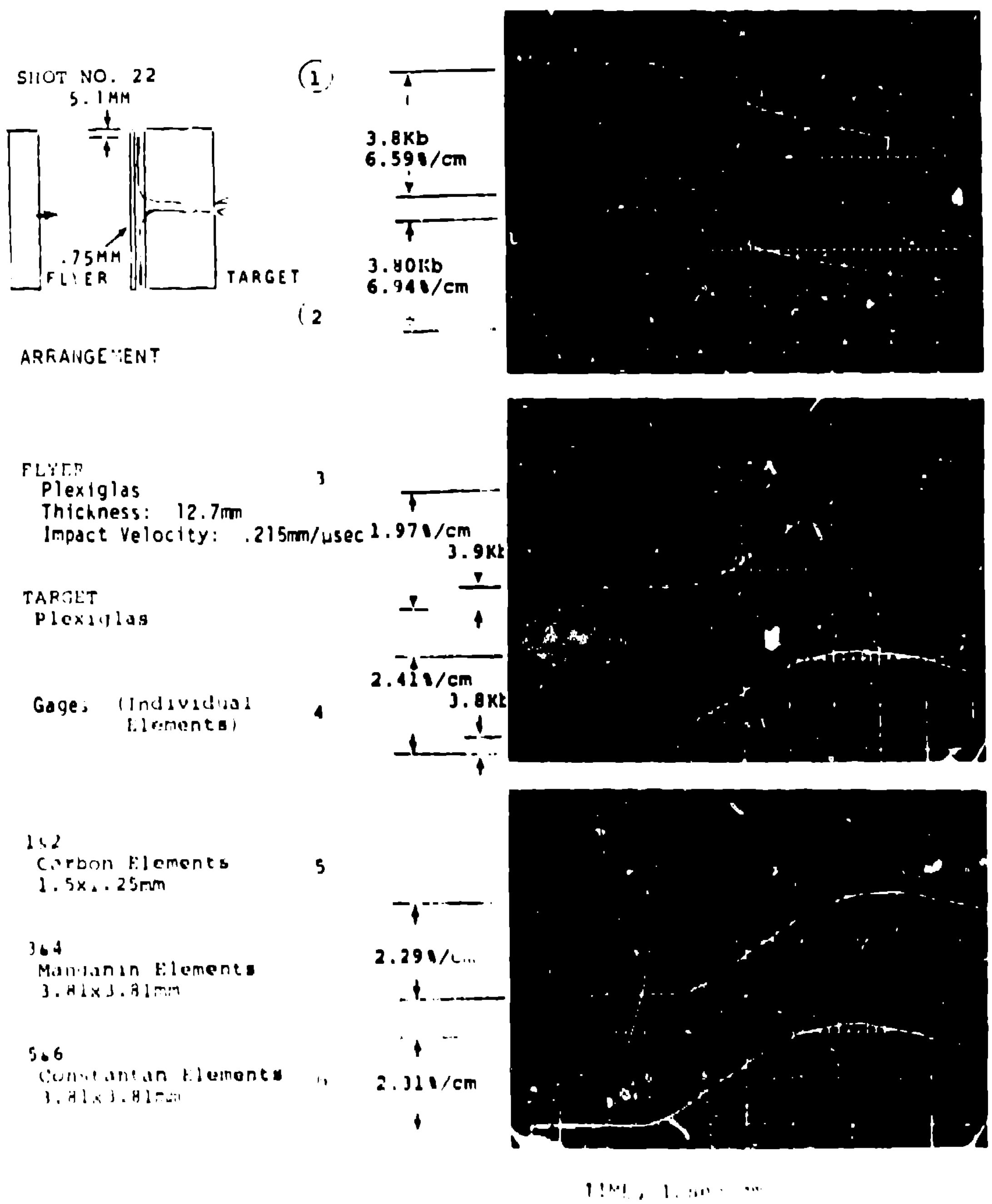


Fig. 7. Representative output of gages subjected to combined stresses and tension strains.

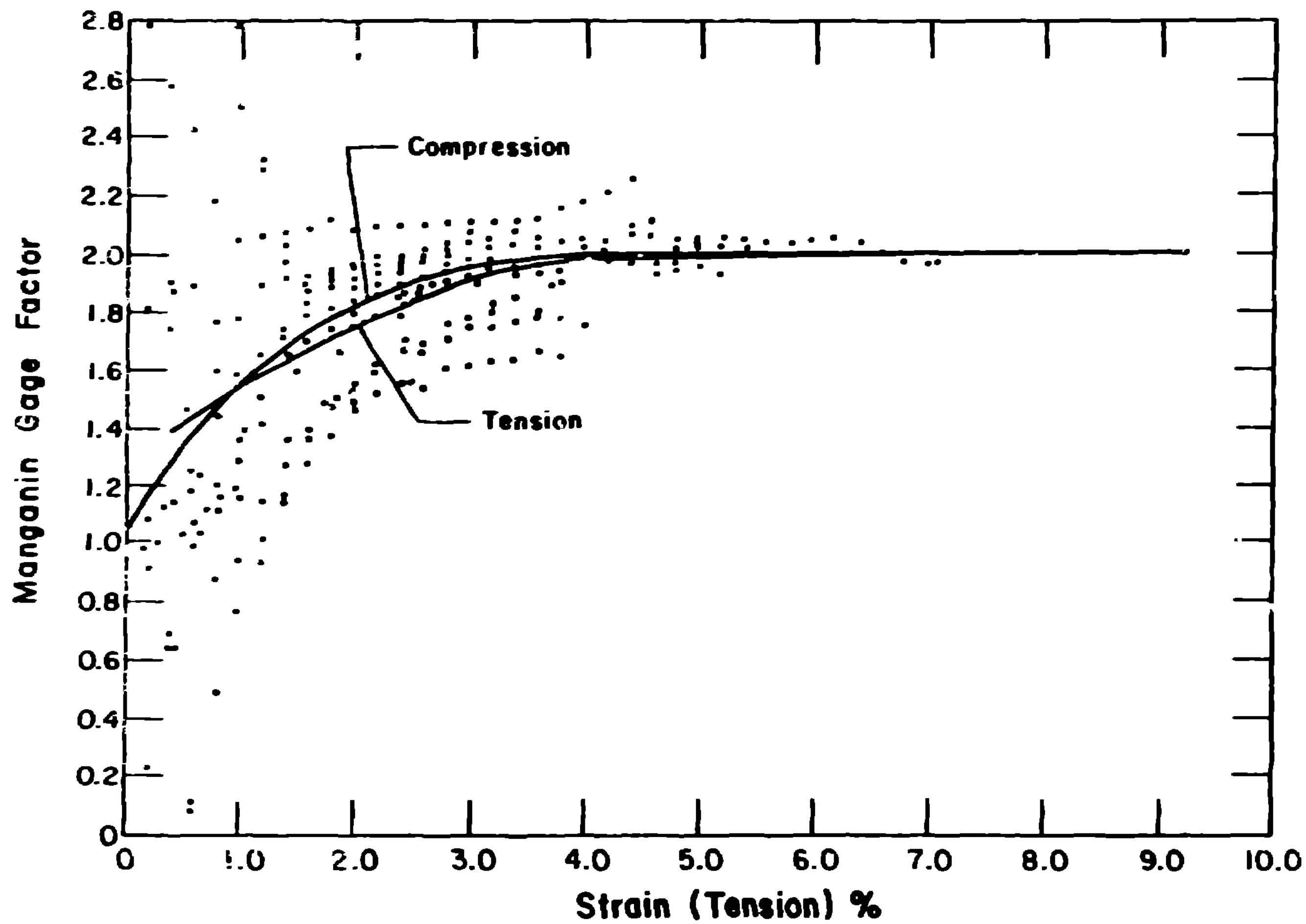


Fig. 8. Strain factor of Manganin in tension. The dots are the experimental data points from the various tensile strain tests; the solid curves follow the mean values of the experimental points.

low strain where the measurement is very sensitive to small errors in strain. At higher strain values the data spread is much less. The mean of the tension data follows the compressive data curve well, and it appears that the strain factor of Manganin is the same in compression and tension.

D. Effect of Pressure on the Tensile Strain Factor of Constantan

We made two tests to measure the tensile strain factor of Constantan in a pressure field to determine whether Constantan could be used under pressure to measure strain in the tension tests. To check the pressure effect, Dynasen developed two new gages. These gages were designed to measure radial strain close to the cylindrical surface and at the surface on cylindrical targets. Figure 9 illustrates the target, flyer plate, and gage types.

The internal gage is subjected to the shock pressure shortly after the projectile strikes the front surface of the target. Relief waves then form and the target expands radially. The radial expansion produces nearly equal strain on the internal and external gage. If the Constantan strain factor is pressure independent, the two strain measurements would be identical. Actually, the external gage is on a radius 5% larger than the internal gage so a slightly larger signal was expected from the external gage.

Three internal-external pairs of gages were placed in two targets, making six comparisons possible. Of the six pairs, three of the data records terminated before meaningful data were obtained. Figure 10 shows the other three pairs of oscillograph traces. The trace for the internal gage number 1 is almost identical to the trace for the external gage number 2 on both shots. The traces for gages 3 and 4 on shot 24 are not as close. To analyze these data, we redrew the traces on transparent graph paper and placed the trace from the inner gage over the trace for the outer gage. We shifted the zero time for the inner trace to match the outer trace. The shift was necessary because the expansion occurs at slightly different times for the two gages. We also applied a 5% correction for the difference in radius at which each gage was located and a correction for a slight difference in amplification of the two gage outputs.

The strains measured on gages 1 and 2 in both shots were very close. The ratio of strain measured internal to external was 1.1 for shot 23 and 1.0 for shot 24. It was not so close for gage 3 and 4; the internal to external ratio for gages 3 and 4 was 1.3. This larger ratio could have been caused by some slippage in the outer gage. We believe that gages 1 and 2 more accurately represent the real case and that the strain factor of Constantan is nearly independent of pressure as found in the compressive strain tests.

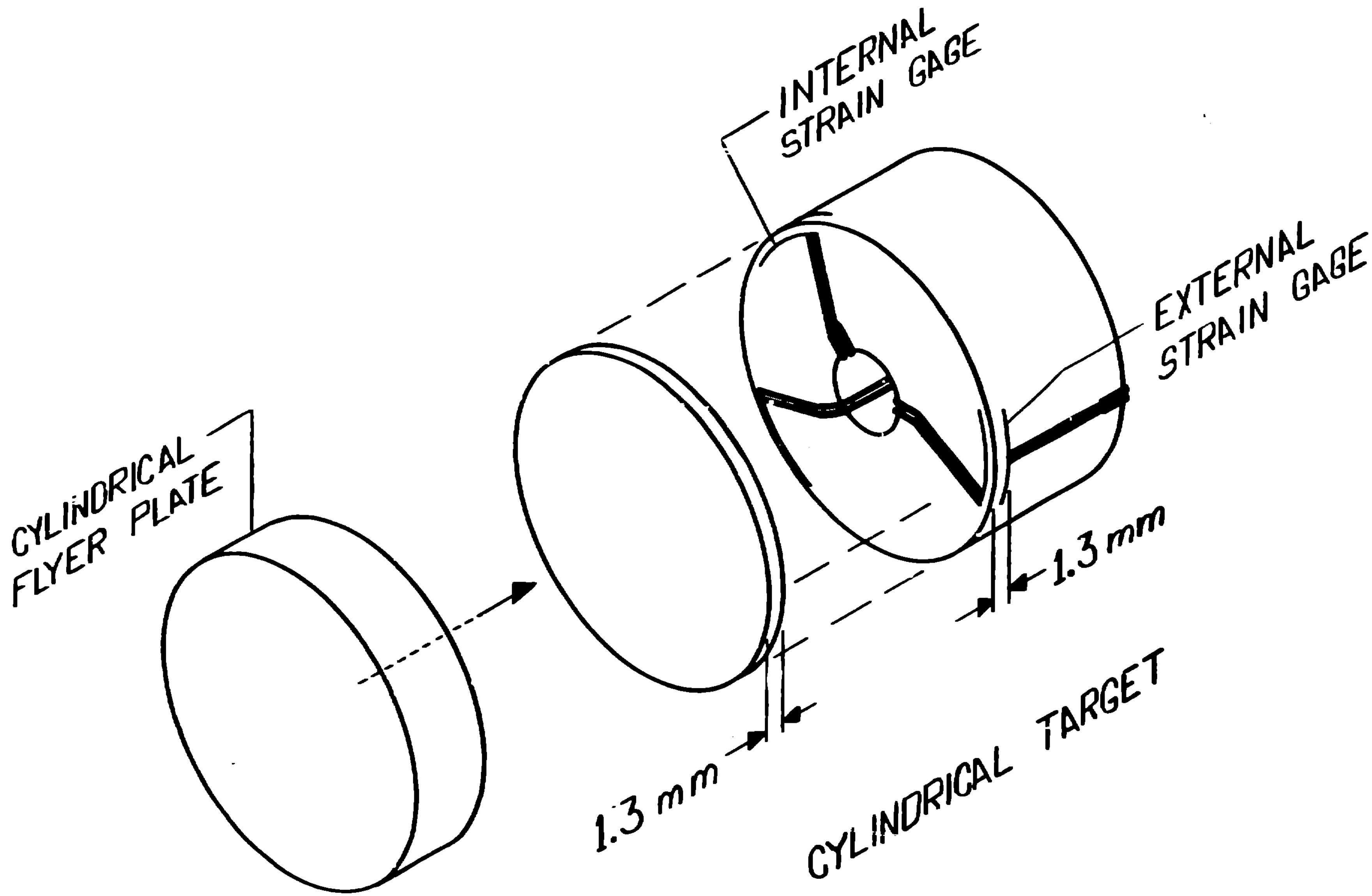
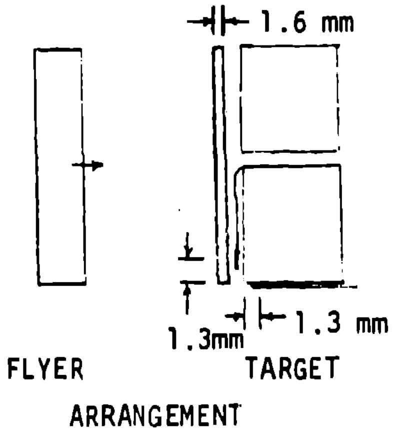


Fig. 9. Target for measuring how pressure affects the tensile strain factor of Constantan.



FLYER
- Material: 6061-t6 Al
- Thickness: 12.7 mm
- Velocity (23): 0.321 mm/μs
- Velocity (24): 0.233 mm/μs

TARGET
- Material: 6061-t6 Al
- Impact Pressure (23): 26 kbar
- Impacr Pressure (24): 19 kbar

GAGES
- 1 and 3 Imbedded Constantan
- 2 and 4 Surface Constantan

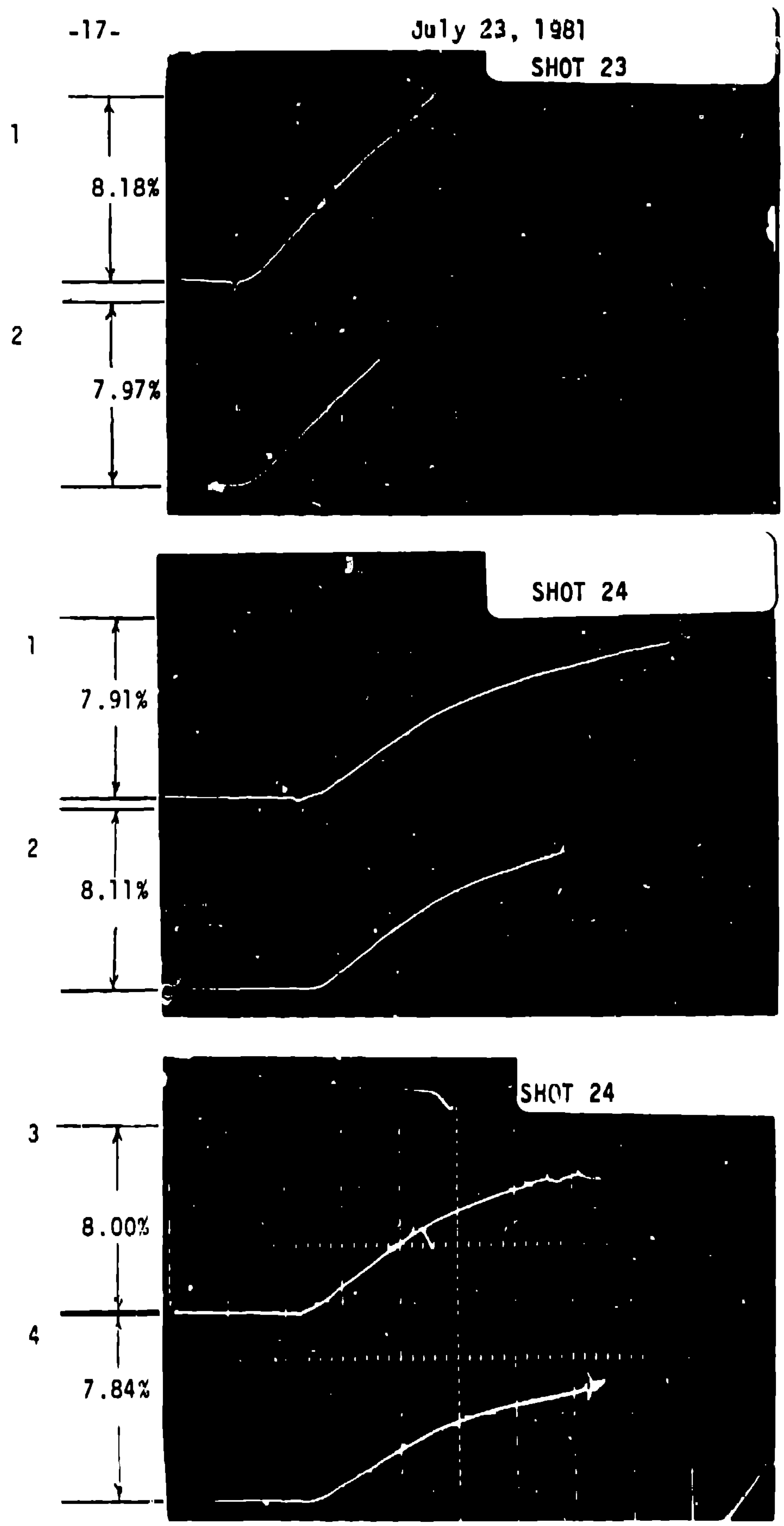


Fig. 10. Constantan gage outputs from free surface and imbedded gages.

B. Differential Recording

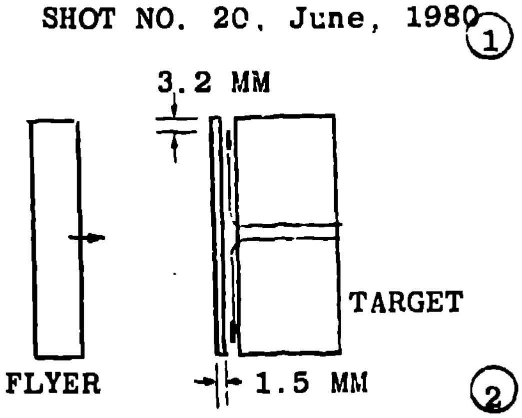
It is often burdensome to record two signals, Manganin and Constantan, to make a pressure measurement. Twice as many recording channels are required as for a single pressure measurement, and the data must be manipulated following the test to obtain the strain-corrected pressure. Initially, we hoped that the strain factor of Manganin would be close to that of Constantan, 2.0, to simplify the strain correction and allow a real-time correction to be made. The gage factor appears not to be constant but to vary from 1.2 to 2.0 over the range from 0 to 3% strain. It is still appealing to subtract the strain from the pressure in the recording process. As shown in the last section, correcting for strain is actually more complicated than simply subtracting the Constantan output from the Manganin output, but for many tests this method would be adequate.

We made four tests where the Constantan gage output was subtracted directly from the Manganin gage output using differential inputs to the recording oscilloscopes. Good results were obtained on three of these tests. At early times the wrong gage factor is used, but the strain contribution is small so the resulting error is small. At later times when the strain is large, the gage factor of Manganin approaches that of Constantan so the correction is not bad. The Manganin minus Constantan, Constantan, and carbon traces for one of the shots are shown in Fig. 11. Table I summarizes the results from these tests. The Manganin differential pressure measurement follows the strain-corrected carbon pressure measurement very well. From these data the differential technique appears to be a viable technique to use for Manganin strain correction.

C. 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 traverse 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.

SHOT NO. 20, June, 1980



ARRANGEMENT

FLYER

Material: 6061-t6 Al
Thickness: 12.7 mm
Impact Velocity: .241 mm/μsec

TARGET

Material: 6061 t6 Al
Impact Pressure: 19.5 Kbar

GAUGES

1 & 2 Interlaced
Manganin: #1
Constantan: #2
Trace #1 Mang. Minus Const.
Trace #2 Const.

3 & 4 Interlaced
Manganin: #3
Constantan: #4
Trace #3 Mang. minus Const.
Trace #4 Const.

5 & 6 Carbon Single Elements

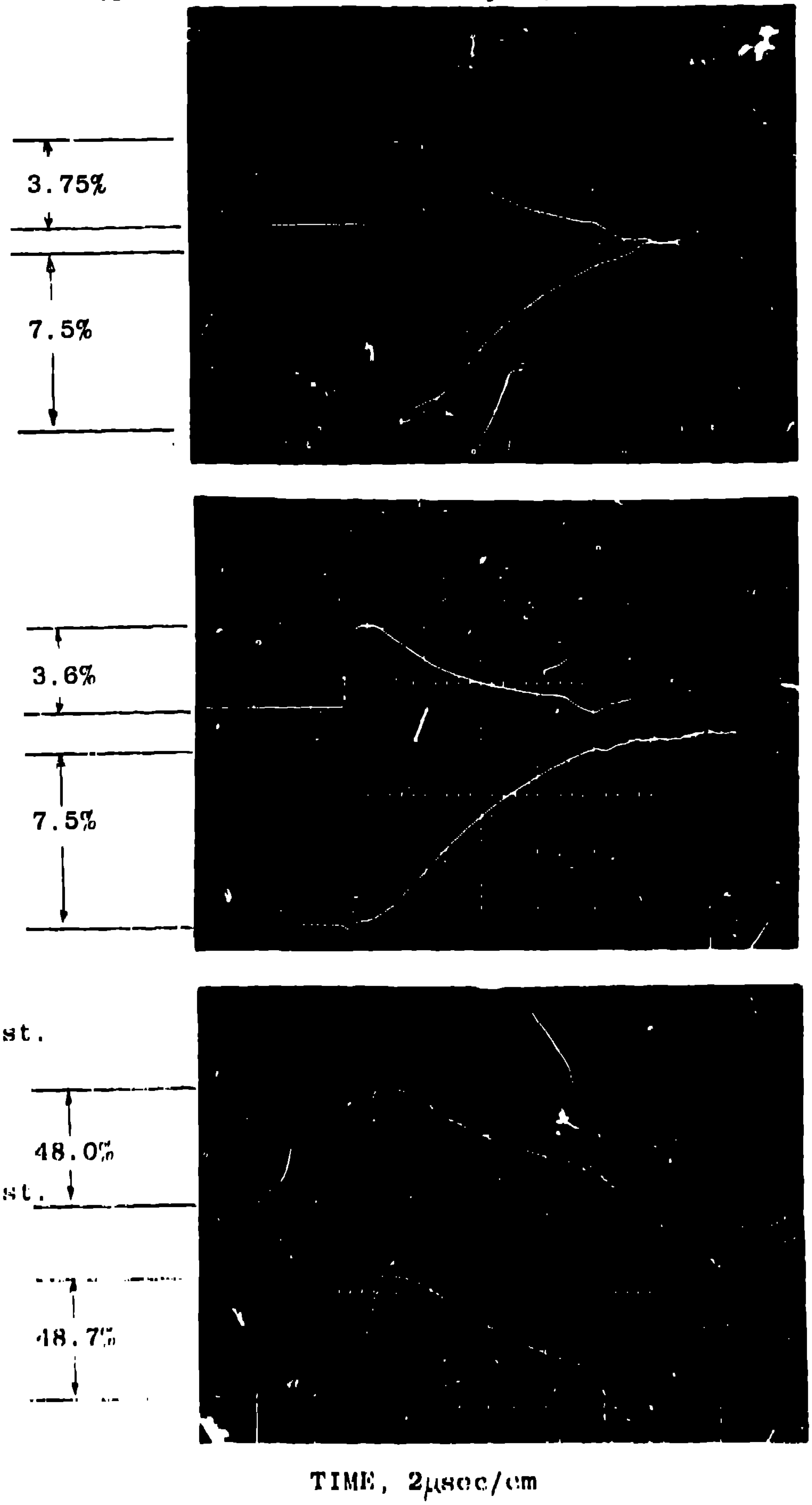


Fig. 11. Representative differential and direct outputs of gages subjected to combined stresses and strains.

TABLE I

COMPARISON OF DIFFERENTIAL MANGANIN MEASUREMENT WITH STRAIN CORRECTED CARBON MEASUREMENT

Shot Number	Calculated Peak Pressure (kbar)	Time After Peak Pressure (µs)	Measured* Strain (%)	Experimental Carbon* Pressure (kbar)	Experimental Manganin* Pressure (kbar)
20	19.5	0.0	0.1/0.1	23.4/21.4	17.5/17.4
		2.0	1.0/1.1	11.5/ 9.7	12.3/10.4
		3.5	2.0/2.0	5.8/ 5.7	6.6/ 6.5
		6.0	3.1/3.1	1.8/ 2.5	1.3/ 3.0
21	30.0	0.0	0.3/0.0	31.1/32.4	26.4/26.3
		0.5	1.1/0.3	23.8/28.5	22.1/22.9
		1.0	2.0/1.2	15.1/18.4	16.2/16.4
		1.6	3.1/2.4	8.6/ 8.8	11.4/11.0
		2.4	4.1/3.6	5.7/ 4.7	7.6/ 6.2
		3.4	5.0/4.6	2.9/ 1.4	5.0/ 3.0
22	41.5	0.0	0.2/0.2	35.1/41.2	44.8/43.8
		0.7	0.7/1.0	33.1/34.6	40.2/35.2
		1.3	1.6/2.0	28.2/24.0	31.2/25.6
		2.0	- /3.2	13.2/ -	20.7/17.3

* Data were recorded at two locations, A and B. Data from location A precede data from location B.

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. These gages have been used in several field tests with good results. Manganin-Constantan combination gages were used at the same locations as carbon gages, and the similarity of the results in the range covered by the carbon gages was encouraging. We now 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.

AKNOWLEDGMENTS

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