Final Report

on

Pressure Measurements in Basalt

(13 June 1966-13 February 1967)

Contract No.: NAS5-9354

Prepared by

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San Leandro, California 94577

for

Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

Experiments are reported in which manganin-wire piezoresistive pressure transducers have been imbedded in basalt rock and used to measure the pressure profiles resulting from the impact of hypervelocity projectiles. The experiments demonstrate the feasibility of making two-dimensional, non-perturbing, in-depth measurements of the pressure profiles resulting from such events. The gauges were imbedded in a thin layer of epoxy and sandwiched between two flat pieces of basalt. Explosively driven hypervelocity gas guns developed at Physics International Company were used to accelerate the projectiles (lithium-manganin alloy) to a velocity of 4.6 km/sec. Good agreement was obtained between the predicted peak pressure and that recorded by a manganin gauge located one-quarter of an inch below the impact surface, on the projectile axis.

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SECTION I

INTRODUCTION

Physics International has recently completed a study of pressure measurements in basalt under Contract NAS 5-9354 for the National Aeronautics and Space Administration. This study was concerned with demonstrating the feasibility of making two-dimensional, non-perturbing, in-depth measurements of the pressure profiles resulting from the impact of a hypervelocity projectile. In particular, the work dealt with the development and testing of a manganin-wire piezoresistive pressure transducer imbedded in basalt rock.

A basic manganin gauge-imbedded-in-epoxy configuration was modified for the hypervelocity work. The gauge was imbedded in a thin layer of epoxy that was sandwiched between two flat pieces of basalt. Initial experiments that utilized in-contact explosives to simulate hypervelocity impact were conducted to determine the effectiveness of the gauge design.

When a satisfactory gauge design had been developed, a series of hypervelocity impact shots were instrumented using basalt targets containing gauges. The results of these experiments indicated that the manganin gauge imbedded in rock is indeed a useful tool for in-depth studies of hypervelocity impact.

Section II presents a description of the gauge design and construction and a discussion of the experimental work performed and the results obtained. Section III presents a summary of the study and recommendations for further developmental work on the manganin piezoresistive pressure transducer.

SECTION II

TECHNICAL DISCUSSION

A. BACKGROUND

Most hypervelocity impact studies concentrate on relating projectile characteristics (shape, material, velocity, etc.) to target damage in terms of crater size and shape. A better understanding of the process, however, can be derived from detailed measurements of the pressure-time profile in the target. Such a pressure-time profile (after impact in the two-dimensional impact geometry) can now be obtained as a result of the development of the manganin-wire pressure transducers (Refs. 1, 2).

The transducer can be physically small and can be imbedded in the target material; thus it does not greatly perturb the shock propagation. In this way, the duration of meaningful recording is limited by target size and gauge integrity.

The peak pressure at the gauge is proportional to the percentage change in resistance of the manganin-wire transducer. The percentage change in resistance is obtained by passing a constant current through the wire before and during the shock pulse. Thus, the resistances corresponding to zero pressure and shock pressure are displayed on the same oscilloscope trace. The peak pressure calibration for these transducers is determined by the standard streak camera techniques developed for equation of state measurements.

The calibration of points on the relief side of the pressure profile is more complicated. It requires subjecting a transducer to a shock pulse of known shape and recording the change in resistance. The technique used for some calibration experiments of this sort is described in Reference 2. At present the profile calibration is probably accurate to about 20 per cent.

Under other programs, including Contract NASW-978 for the National Aeronautics and Space Administration and Contract DA 04-200-AMC-796(X) for the Defense Atomic Support Agency, Physics International Company has developed explosive hypervelocity gas guns for accelerating intact projectiles to velocities of 6 to 8 km/sec (Ref. 3). Projectile masses have been varied from 0.1 to 2360 gm. It is thus possible to generate peak pressures in rock targets well in excess of 400 kb, which is currently beyond the range of calibration of the manganin transducer. However, the position of the wire and the velocity of the projectile can be varied for observing any peak pressure desired.

B. GAUGE DESIGN AND CONSTRUCTION

It was originally intended that the study should involve manganin gauges imbedded in granite. However, available data indicated that piezoelectric output from the quartz led to noisy signals (Ref. 4). As a result, a change in target material from granite to basalt was agreed upon.[1] High density (2.82 gm/cm^3), homogeneous basalt rock was obtained from a quarry near Napa, California.

The basic gauge configuration used throughout this work is illustrated in Figure 1. This two-piece configuration was initially employed because of its simplicity and the success of this simple design led to its continued use. Placing a number of gauges in a single target would require a more advanced design; experiments with more complicated gauge configurations were conducted but additional work is required (see Appendix I).

Generally, each target was constructed with two imbedded gauges, one directly beneath the impact point and one off-axis, but at the same depth in the basalt. Figures 2 and 3 show the details of the gauge assembly. The gauges were pre-cast, centered in a 0.009-in.-thick layer of epoxy

[1] See Supplemental Agreement, Contract No. NAS 5-9354, Modification No. 1, August 26, 1966.

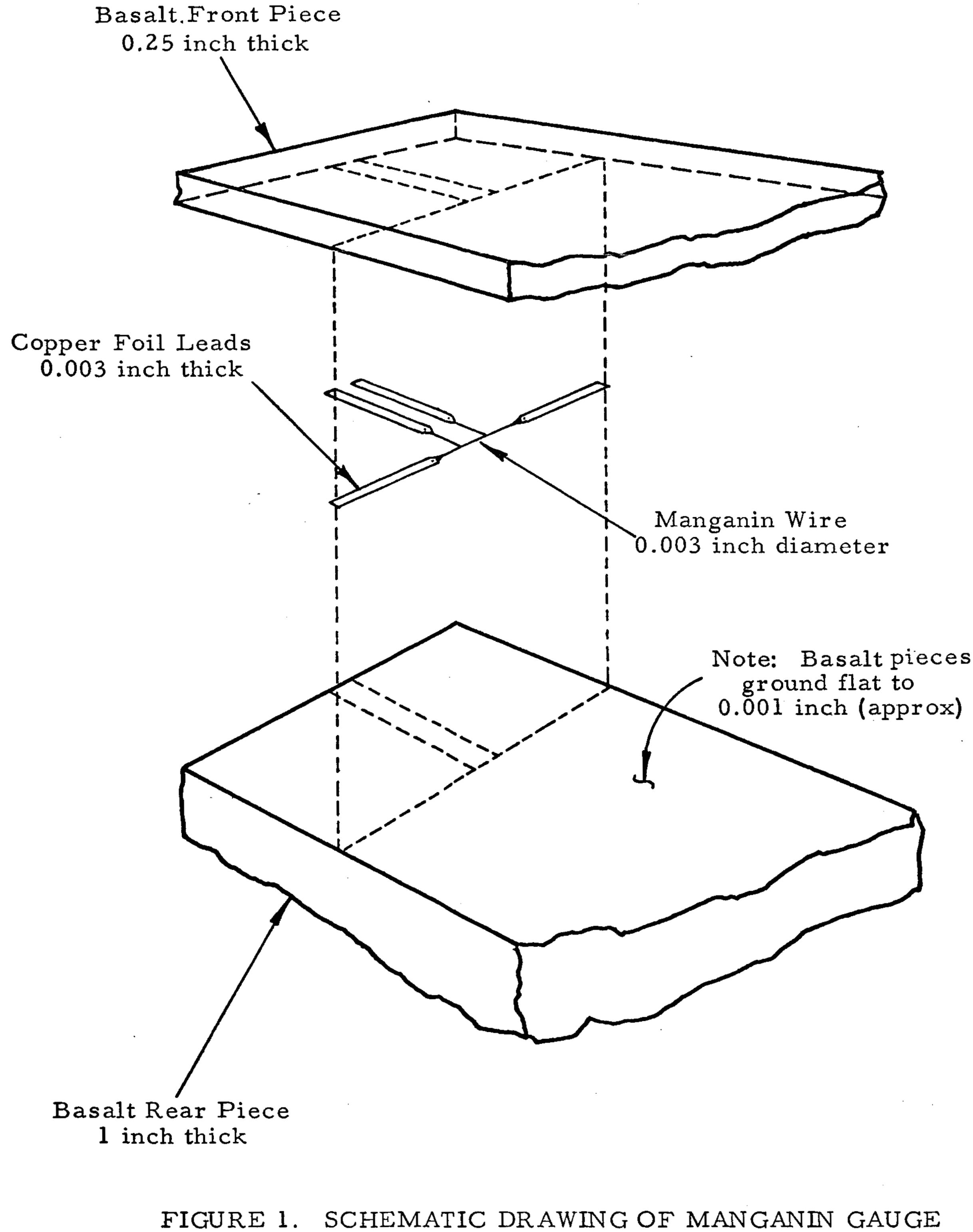

FIGURE 1. SCHEMATIC DRAWING OF MANGANIN GAUGE IMBEDDED IN BASALT

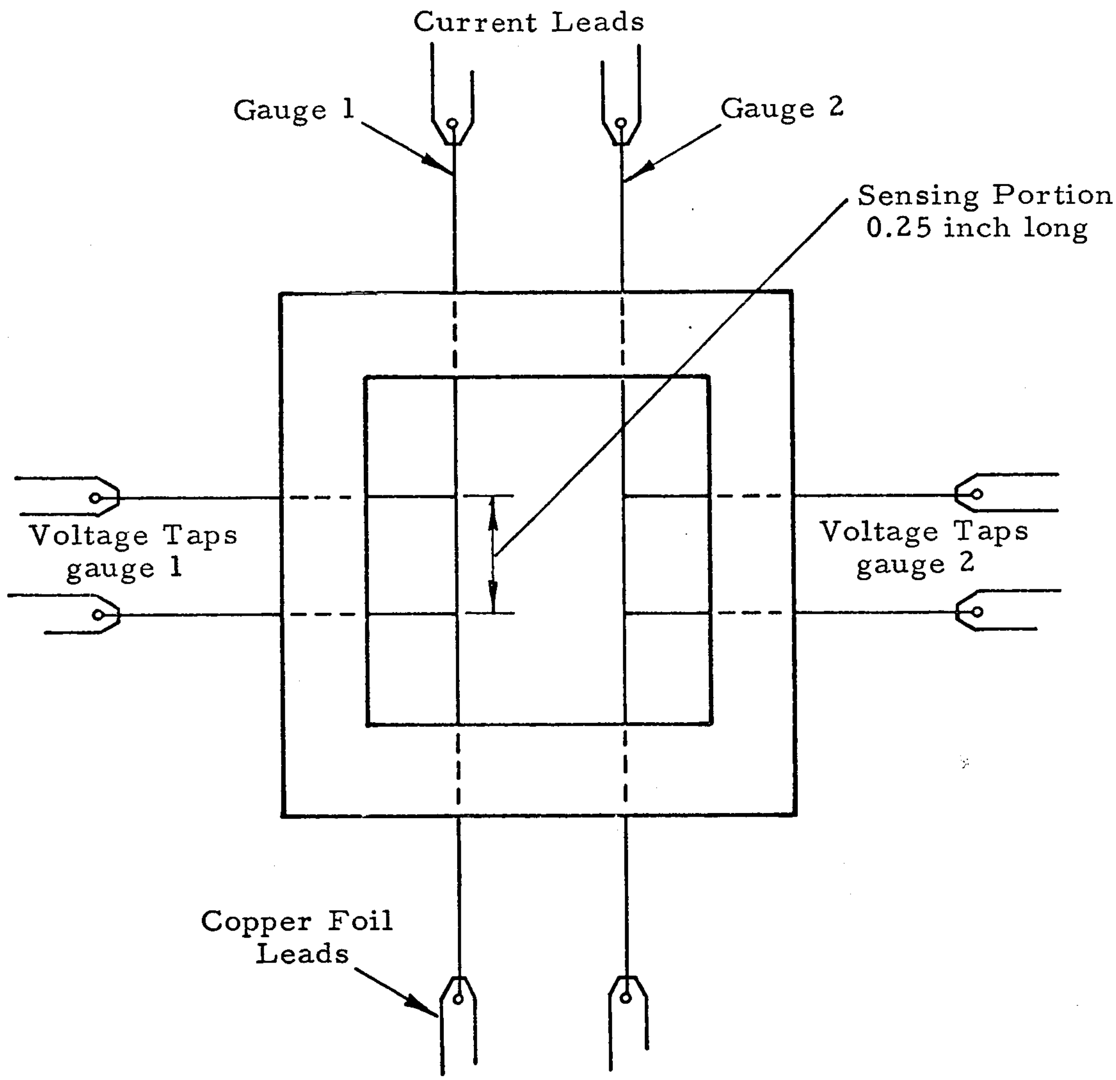

FIGURE 2. TYPICAL TWO-GAUGE ASSEMBLY FOR IMBEDDED MANGANIN GAUGE

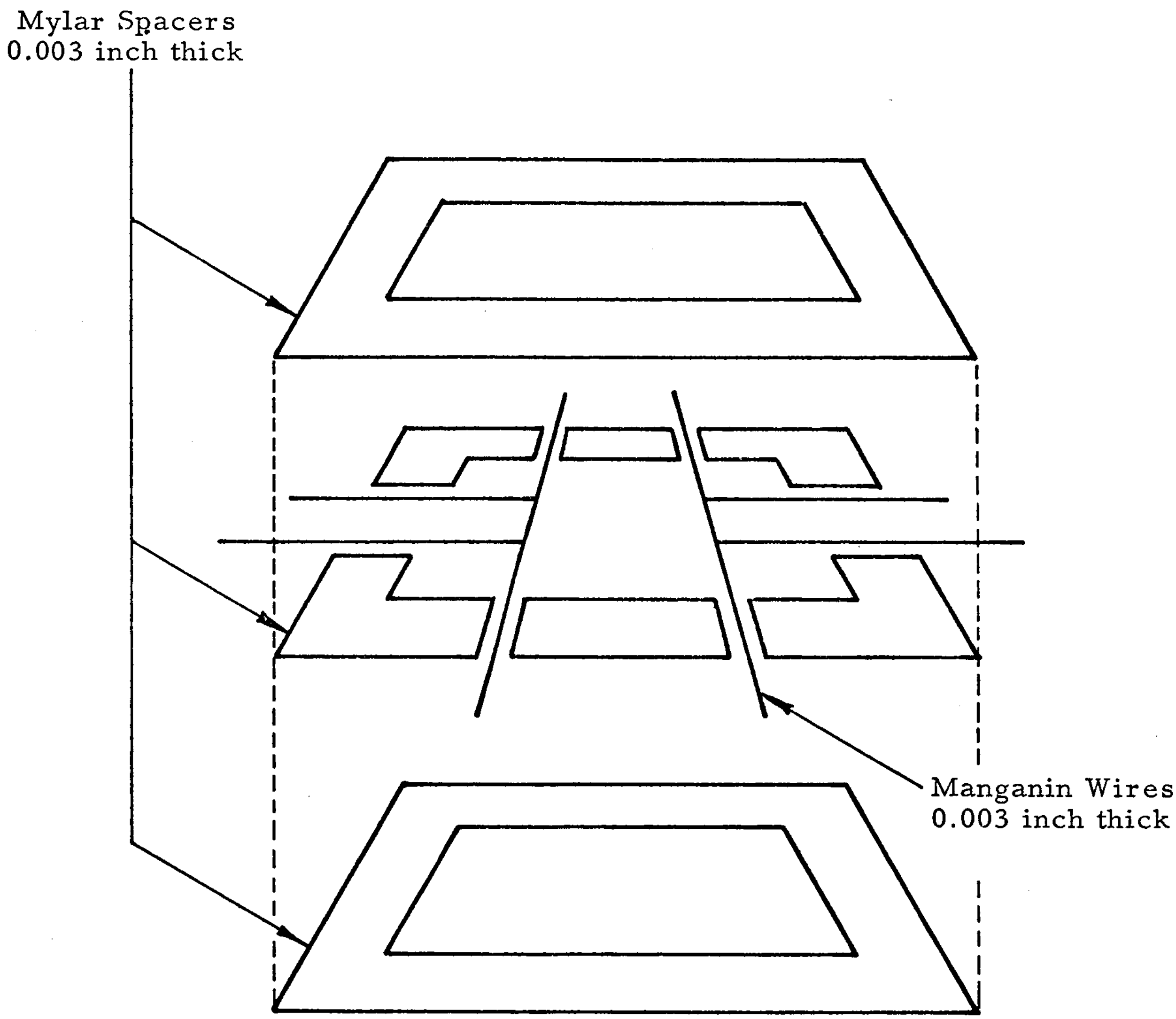

FIGURE 3. EXPLODED SCHEMATIC DIAGRAM OF PARTS OF MANGANIN GAUGE ASSEMBLY

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with the aid of mylar spacers as shown in the figures. (The equation of state of mylar is not unlike that of epoxy, and no apparent problems were encountered due to the presence of the mylar.) Thin copper-foil leads were soldered to the end of the manganin wires. The entire assembly was then cast in a 0.010-in. layer of epoxy between the two flat pieces of basalt. In this case 0.010-in.-thick mylar spacers were used, and care was taken to avoid trapping air in the casting.

The time required for the epoxy and wire to come to pressure equilibrium with the basalt is determined by the thickness of the epoxy, since the equilibration process involves multiple wave reflections in the epoxy. We made the layer of epoxy as thin as possible, compatible with maintaining gauge continuity for a reasonable recording time. Previous experience indicated that epoxy layers of about 0.005 to 0.010 in. would give recording times of the order of 5 μsec. (This is for a 0.003-in.-diameter wire.) In practice it was found that a 0.010-in. layer of epoxy gave adequate results, and so it was used throughout.

C. SIMULATED HYPERVELOCITY IMPACT EXPERIMENTS

In-contact high explosives were used to generate a pressure pulse in a basalt target in experiments that were designed to approximately simulate the impact of a hypervelocity projectile. The only purpose of these experiments was to determine the effectiveness of the gauge design chosen.

For these experiments an RDX pellet (with a 1/2-in.-diameter and 1/4-in.-thickness) was detonated at the center of the front face of the basalt. The front piece of basalt was 1/4 in. thick, and the rear piece was 1 in. thick. The lateral dimensions of both pieces were 4 in. by 4 in. Two manganin transducers were imbedded in the epoxy layer: one on the centerline and one displaced approximately 0.8 in. from the axis.

The output of the on-axis transducer is shown in the oscillogram in Figure 4. The upper sweep is the gauge output with a sensitivity of 1 V/cm.

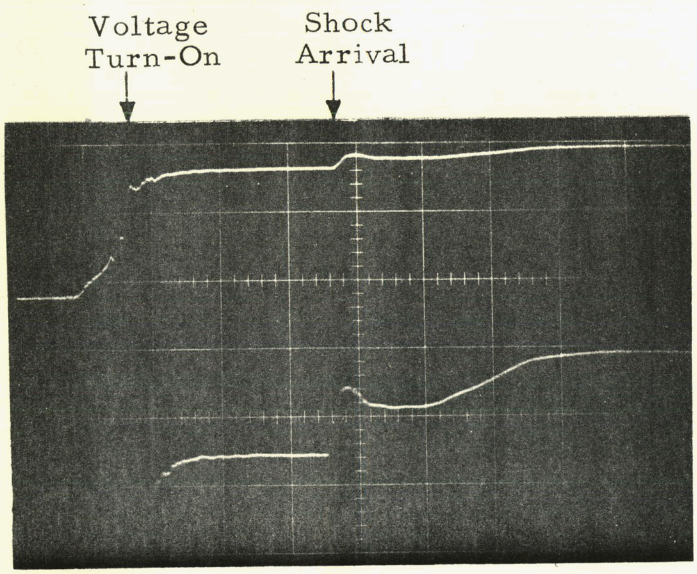


FIGURE 4. GAUGE OUTPUT, IN-CONTACT EXPLOSIVE EXPERIMENT.
Sensitivity Upper Beam: 1 V/cm
Lower Beam: 0.2 V/cm
Sweep Speed: 1 μsec/cm

The first voltage step (proportional to the initial wire resistance R) is the power supply turn-on, and the second rise (proportional to ΔR) corresponds to the shock arrival. The lower sweep is the gauge output at a sensitivity of 0.2 V/cm, with the baseline suppressed to display the shock signal on an expanded scale.

The measured peak $\Delta R/R$ of 10.3 per cent indicates a peak pressure of 35.5 kb, based on the calibration given in Reference 4 and independently verified at Physics International under Contract AF 29(601)-7182. (For peak pressure $P < 150$ kb, $\Delta R/R$ (%) $= 0.29$ %/kb $\cdot$ P (kb).) The output of the off-axis transducer was at least an order of magnitude less than that of the on-axis gauge. Calculations indicate that for a spherical shock wave in granite the peak pressure attenuates as $\frac{1}{r^2}$ (see Ref. 5). For our experimental geometry there is also an angular dependence of the attenuation, but the $\frac{1}{r^2}$ dependence alone predicts that the peak pressure at the off-axis gauge location will be less than 10 per cent of that at the on-axis gauge.

It should be noted that the output signals are extremely noise-free, which is the result of careful placement of the cables and power supply as well as the use of differential pre-amplifiers. Further, there are more than 5 μsec of gauge recording with no indication of gauge break-up. The rise-time of the signal is about 0.2 μsec, which is consistent with the thickness of the epoxy layer. From these results it was concluded that the gauge design chosen was suitable for the hypervelocity impact shots.

The oscillogram shows an initial shock rise and subsequent decay. However, following this the trace levels off and rises again to a higher peak value. This behavior is not indicative of the shock pressure. It has been shown that this rise in wire resistance is due to an increase in length and a decrease in cross-sectional area of the wire caused by sideward stretching of the gauge wire. Thus this signal is partially an indicator of the non-planarity of the shock wave front.

D. HYPERVELOCITY IMPACT EXPERIMENTS

1. Initial Series--Nylon Projectiles

Instrumented basalt targets were used in conjunction with experiments conducted under other contracts to develop hypervelocity guns. This was done to avoid fabricating hypervelocity guns and conducting experiments for the impact data alone. These experimental guns employed nylon projectiles and typically yielded velocities of about 5 km/sec.

To provide reliable synchronization of the gauge power supply turn-on and the projectile impact, we developed a reliable thin foil contact switch. In addition, it was important to insure that the gauge instrumentation was compatible with the other types of instrumentation used in the hypervelocity gun experiments, in particular flash X ray.

No useful data were obtained on these initial shots either because of instrumental difficulties or because the experimental gun did not deliver an intact projectile.

2. Lithium-Magnesium Projectile--First Shot

Rather than continue to place gauge targets on experimental guns associated with other Physics International programs, we decided to build a small, inexpensive explosive gun specifically for this program. The gun chosen had previously delivered an intact projectile of lithium-magnesium which was 0.75 in. in diameter and 0.8 in. long (the projectile material is a magnesium alloy of 13 to 15 per cent lithium and 1 per cent aluminum).

The basalt target had a front piece 1/4 in. thick and a rear piece about 1 in. thick. The lateral dimensions of both pieces were approximately 5 in. by 5 in. The epoxy layer contained one gauge approximately on projectile axis and a second gauge about 1 centimeter off-axis. The target was placed 1 meter from the muzzle of the gun to allow for taking radiographs of the projectile in flight.

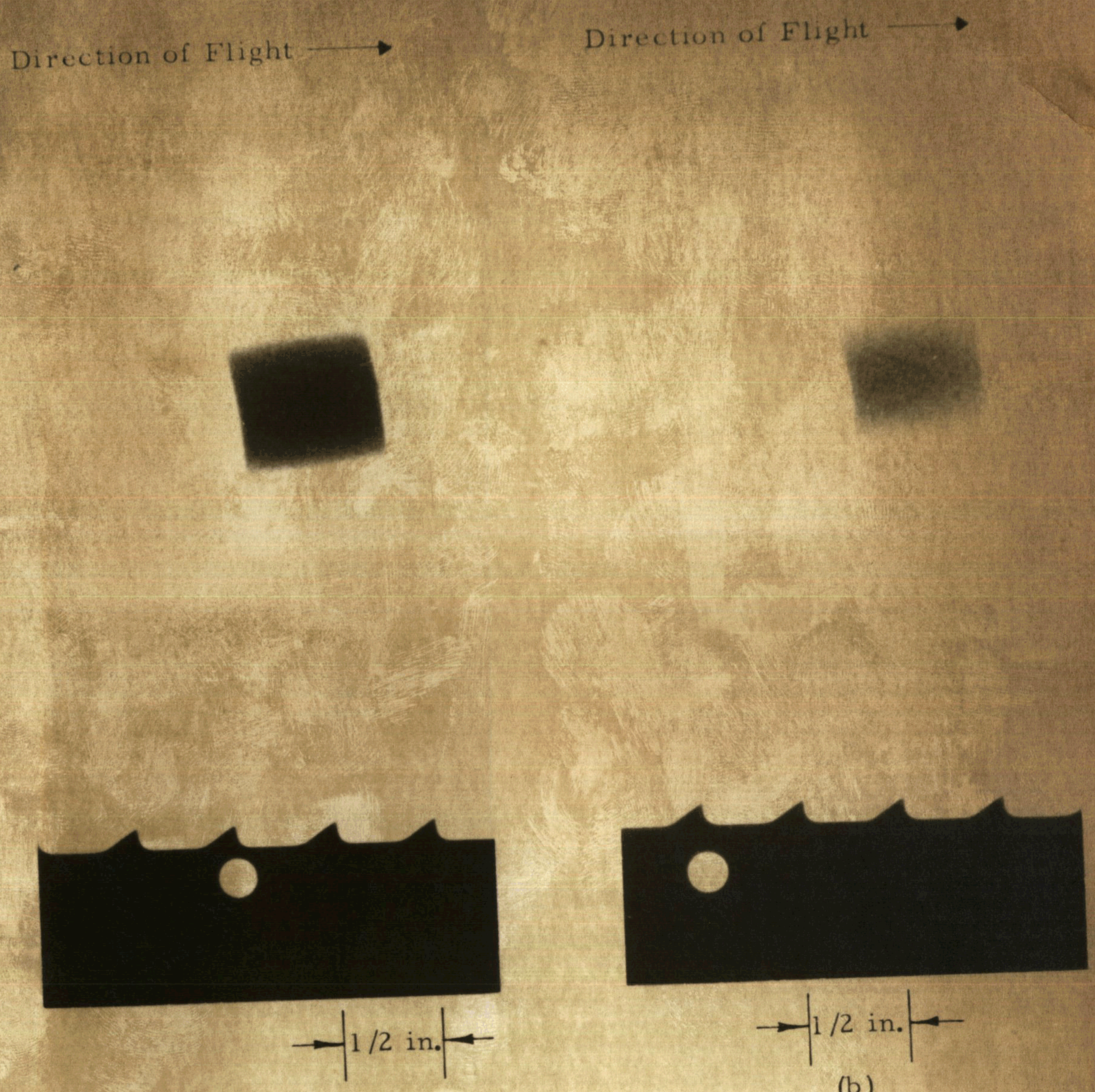
Figure 5 shows the radiographs of the projectile, indicating that it was slightly canted but intact. From these radiographs the velocity of the pellet was determined to be 4.6 km/sec.

The gauge outputs are shown in Figure 6(a) (the on-axis gauge) and Figure 6(b) (the off-axis gauge). The upper beams in both cases are the respective gauge outputs at a sensitivity of 1 V/cm, and the lower beams are the same outputs at 0.2 V/cm. In both cases the lower beams are partially obscured because of the high signal amplitude. In all cases the sweep speed was 2 μsec/cm.

The measured peak $\Delta R/R$ is 46.0 per cent for the first gauge and 45.0 per cent for the second gauge. These correspond to pressures of about 167 kb and 161 kb, respectively. (From Reference 4, pressure $P > 150$ kb gives $\Delta R/R$ (%) $= 16.0\% + 0.18\%/\text{kb} \cdot P$ (kb).)

For purposes of comparison with experimental results we calculated the expected peak pressure from a lithium-magnesium projectile traveling at 4.6 km/sec impacting basalt. The results are shown in Figure 7, which shows a basalt Hugoniot together with a lithium-magnesium cross-characteristic for a velocity of 4.6 km/sec. The basalt data (Ref. 6) were obtained from a high density ($\rho_o = 2.82$ gm/cm^3) basalt that came from the same area as the basalt used for the gauges. The lithium-magnesium Hugoniot was obtained by a synthesis of magnesium and lithium Hugoniots using volume weighted averages of compression. The indicated interface pressure is about 290 kb. Although this is only an approximation, it is clear that the projectile did not strike the target directly above the on-axis gauge. The two gauges give similar enough results to indicate that the projectile probably hit the target more or less centered between the two gauges. Thus it struck at least 1/2 cm off of intended center.

In Figure 6, the ramp-type decay of the "off-axis" gauge indicates that the gauge probably broke almost immediately. The "on-axis" gauge appears to have recorded for over 1.5 μsec, but the decay profile seems



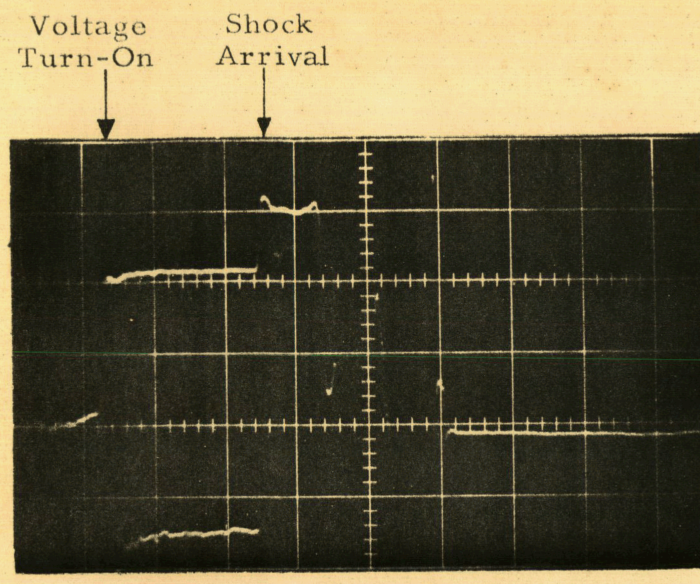
(a)

Lithium-Magnesium Projectile
8.8-in. from Muzzle

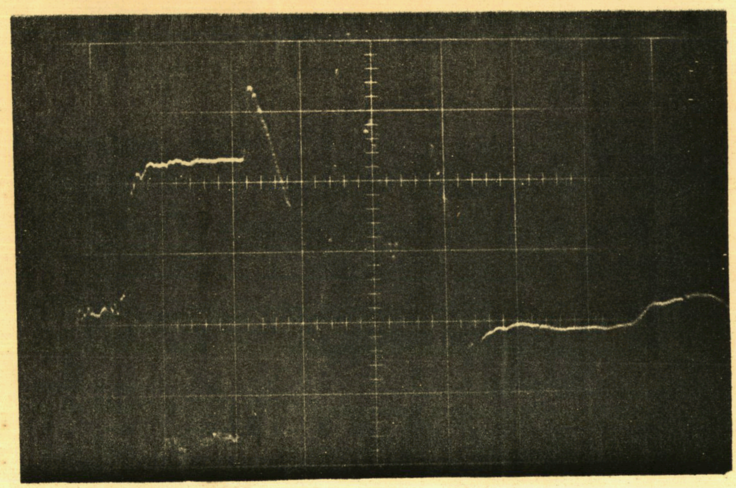
(b)

Lithium-Magnesium Projectile
25.5-in. from Muzzle

FIGURE 5. RADIOGRAPH OF LITHIUM-MAGNESIUM PROJECTILE IN FLIGHT



(a)



(b)

FIGURE 6. GAUGE OUTPUTS, FIRST GUN SHOT WITH LITHIUM-MAGNESIUM PROJECTILE.
Sensitivity Upper Beam: 1 V/cm
Lower Beam: 0.2 V/cm
Sweep Speed: 2 μsec/cm

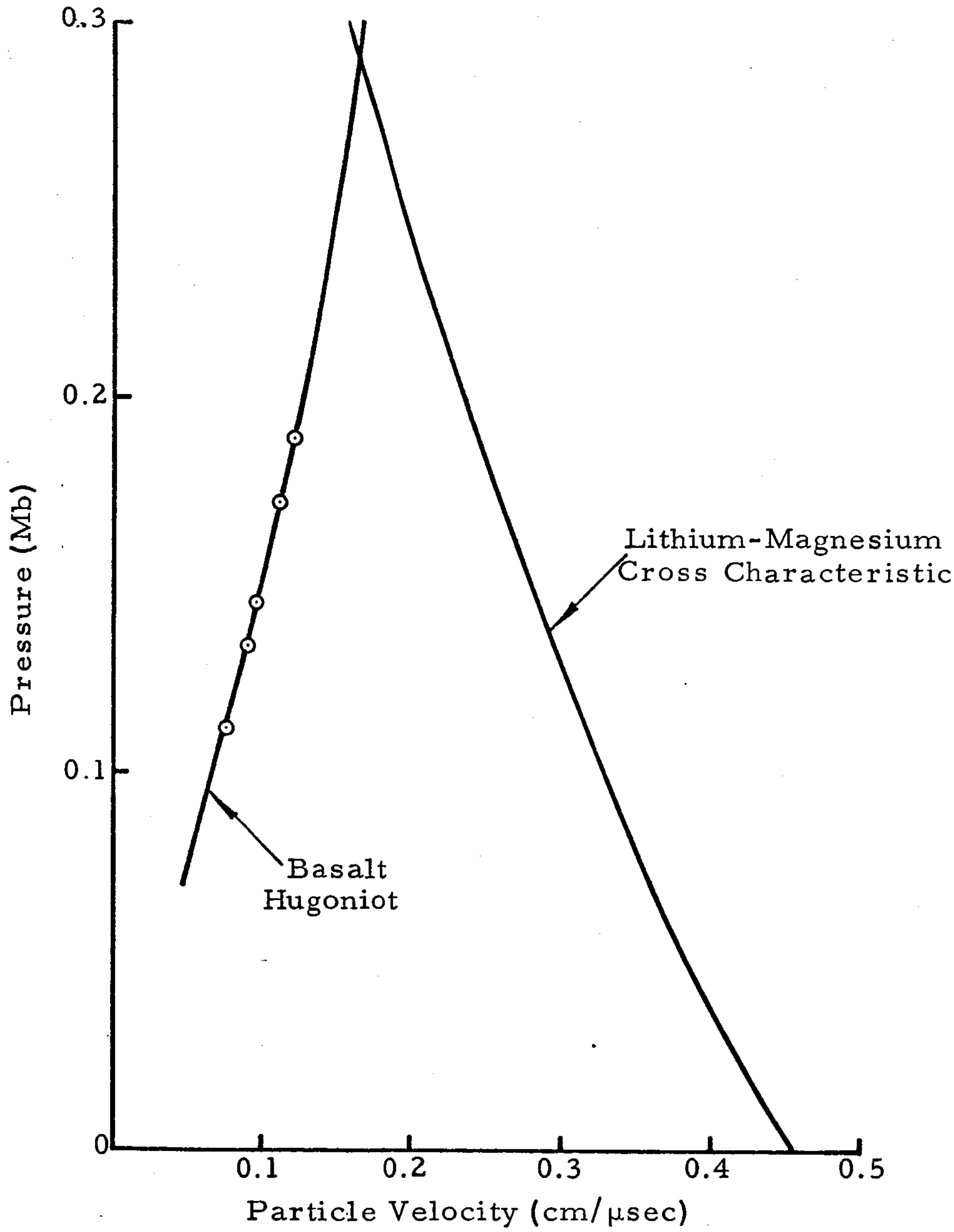


FIGURE 7. CURVES OF PRESSURE VERSUS PARTICLE VELOCITY FOR LITHIUM-MAGNESIUM PROJECTILE IMPACTING BASALT

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to be indicative of sideward stretching of the wire superimposed on the actual pressure profile.

3. Lithium-Magnesium Projectile--Second Shot

We built and fired a second hypervelocity gun patterned after the first one. The projectile was again a cylinder of the same lithium-magnesium alloy, 0.75 in. in diameter and 0.8 in. long. The basalt target again was made with a 1/4-in.-thick front piece and a 1-in.-thick rear piece. The target contained two gauges 1 cm apart. Great care was taken in lining up the gun with the target so that the projectile would hit directly above the on-axis gauge.

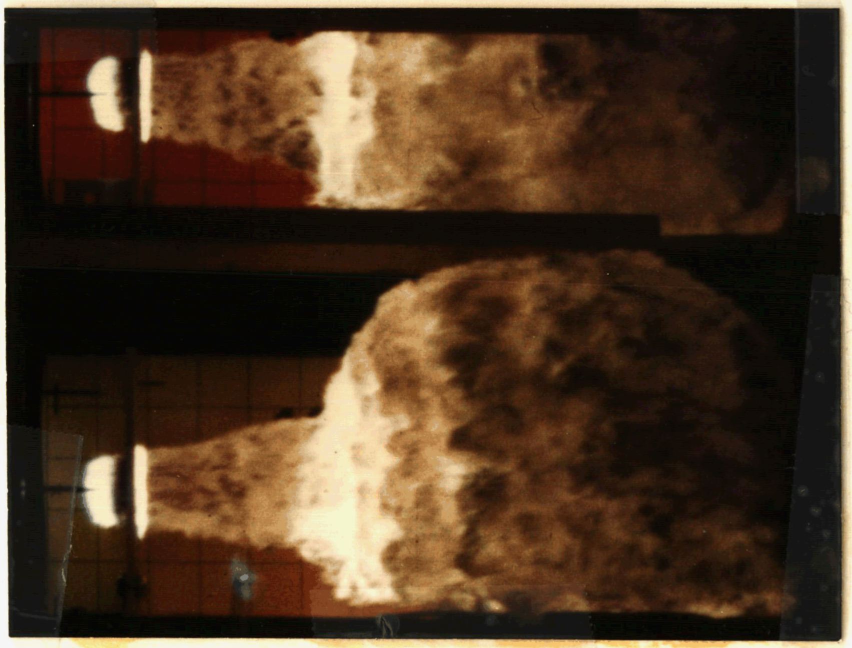
The target was placed 30 cm from the muzzle of the gun, and this time the flight of the projectile was monitored with a high-speed framing camera. The projectile was observed in two views at right angles to each other to verify that it struck the target on-axis. Figure 8 presents two frames showing the pellet in flight. In Figure 8(b) the pellet has just passed through the thin-foil contact switch that triggers the oscilloscopes and gauge power supplies. Figure 9 presents two frames showing impact. Figure 9(a) was recorded immediately after impact, and the two rods extending from the target indicate that the pellet had indeed struck the target on-axis. From the framing camera record the velocity of the pellet was again found to be 4.6 km/sec.

The gauge outputs are shown in Figure 10(a) (the on-axis gauge) and Figure 10(b) (the off-axis gauge). The upper beams in both cases are the respective gauge outputs at a sensitivity of 2 V/cm, and the lower beams are the same outputs at 1 V/cm, with the baseline suppressed to display the shock signal on an expanded scale. In all cases the sweep speed was 2 μsec/cm.

The measured peak $\Delta R/R$ is 72.8 per cent for the on-axis gauge and 30.3 per cent for the off-axis gauge. These correspond to pressures of about 315 kb and 104 kb, respectively. It should be noted that the

(a)

10.5 μsec Before Impact



(b)

4.5 μsec Before Impact

FIGURE 8. TWO FRAMES FROM HIGH-SPEED FRAMING CAMERA RECORD SHOWING THE LITHIUM-MAGNESIUM PROJECTILE IN FLIGHT

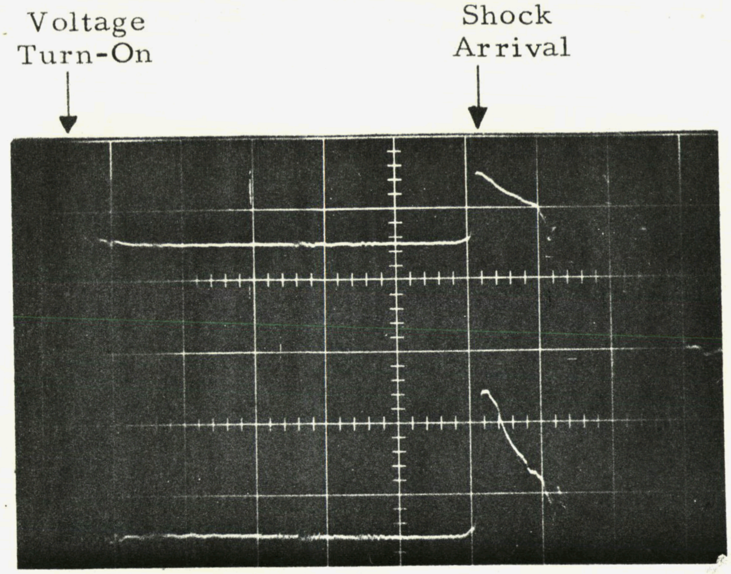
(a)

1.5 μsec After Impact

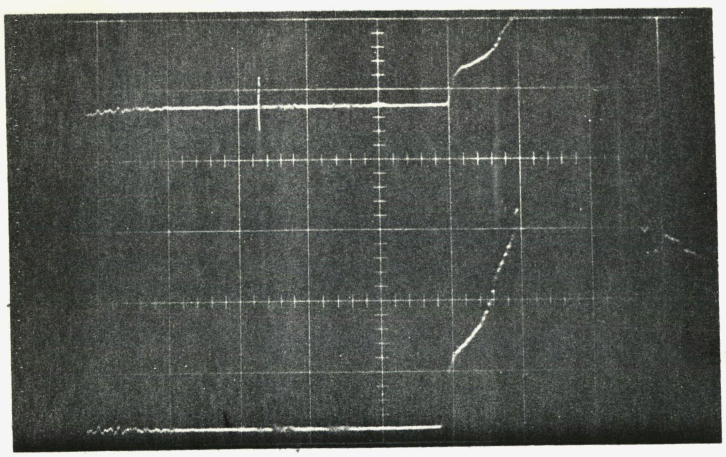
(b)

7.5 μsec After Impact

FIGURE 9. TWO FRAMES FROM THE HIGH-SPEED FRAMING CAMERA RECORD SHOWING THE LITHIUM-MAGNESIUM PROJECTILE IMPACTING THE BASALT TARGET



(a)



(b)

FIGURE 10. GAUGE OUTPUTS, SECOND GUN SHOT WITH LITHIUM-MAGNESIUM PROJECTILE.
Sensitivity Upper Beam: 2 V/cm
Lower Beam: 1 V/cm
Sweep Speed: 2 μsec/cm

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manganin gauge calibration is not precise for pressures above 150 kb. With this in mind, and considering the approximate nature of the lithium-magnesium Hugoniot, the agreement with the calculated peak pressure of 290 kb is good.

Both gauges recorded for about 1.5 μsec. This was confirmed by a current monitor that indicated that an essentially constant current was maintained in the gauge wires for about 1.5 μsec from the first shock arrival. The on-axis gauge record appears to be a faithful record of the pressure profile including an initial flat-topped portion of brief duration. The off-axis gauge resistance, after initially rising and leveling off, rose again due to lateral motion of the gauge element.

SECTION III

SUMMARY AND CONCLUSIONS

A comprehensive study of hypervelocity impact phenomena requires information that can be derived from in-depth pressure profile measurements. We have developed a pressure transducer system capable of making such profile measurements. The transducer employs a manganin wire piezoresistive gauge, which is imbedded in the material to be studied in such a way that it causes very little disturbance of the shock propagation.

Initial experimentation using in-contact explosives to simulate hypervelocity impact validated the design of a simple two-piece, gauge-in-basalt configuration. This was followed by a series of hypervelocity impact shots wherein basalt targets were used in conjunction with Physics International experimental guns. Reliable instrumentation techniques were developed, but no useful pressure records were obtained partly due to the uncertain projectile integrities to be expected from new gun designs.

Two hypervelocity impact shots were performed using reliable gun designs. Peak pressures inside the target were measured at different locations with respect to the impacting projectile, and in one case a decaying pressure profile was recorded by the imbedded gauge. In addition, the measured peak pressure agreed well with the predicted value.

It has thus been shown that the concept of using imbedded piezoresistive gauges for measuring pressure profiles in hypervelocity impact work is a sound one. The gauge design developed is already a workable system for many applications. Some modifications would, of course, be needed for certain applications.

There are currently several problems that limit the flexibility of this transducer design. Fortunately, none of these are problems without a fairly straightforward solution. The amount of calibration data that currently exists for the manganin gauge is inadequate. In particular, for hypervelocity impact studies more information is needed on the decay profile calibration for the gauge as a function of both the magnitude and duration of the peak pressure. The necessary experiments and calculations are possible within existing technology.

The current gauge design will allow only two or at the most three gauges in close proximity in the target. Additional work is required to develop a reliable gauge design of a more sophisticated type, which will allow more gauges to be placed close together. This will involve choosing among the existing designs of such gauges, and will probably require little or no development work.

The two-dimensional nature of the shock waves associated with hypervelocity impact gives rise to stretching of the gauge wires along their length. This results in a resistance change in the wire not proportional to the pressure in the surrounding medium. In the limiting cases of high shock pressures and/or shock waves of large radii of curvature this effect can be reduced to negligible importance (however, lateral rarefactions will still result in pressure perturbations on a longer time scale). For intermediate cases it will probably be necessary to experimentally recalibrate the gauge, or to calculate the magnitude of the perturbation and apply a correction factor to the measured profiles. It should be emphasized that this effect is not a factor as far as peak pressure measurements are concerned. It has already been demonstrated that the peak pressure can be determined as a function of depth in the target material.

As a result of the present program one can now consider subsequent studies in which detailed measurements of the peak pressure, peak pressure attenuation, and pressure-time histories in the target would be correlated with the results of two-dimensional computer code calculations of the physical phenomena associated with particular hypervelocity impact events.

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APPENDIX I

ADDITIONAL EXPERIMENTS WITH GAUGE DESIGNS

Although the gauge design described in Section II was found to be adequate, other gauge designs that would allow for the placing of more gauges in close proximity to each other were later tested. Several designs were tried in two experiments with in-contact high explosives. In both cases the gauges were imbedded in modeling clay since this material is inexpensive and quite workable, although admittedly of much lower shock impedance than basalt.

While the previous gauge had the leads coming out the sides of the target, these gauges all had the leads coming out the rear of the target. On the first shot there were two gauges, each one having two sets of voltage taps. One set of voltage taps came out laterally and then bent up in a 90 deg bend. The other set of voltage taps came out laterally on the opposite side and bent up in two 45 deg bends. One of the gauges was imbedded in a 0.01-in. epoxy layer using mylar spacers as in the earlier gauge design. The manganin wires emerged from the epoxy and bent up as described, and the copper foil leads were then attached. The other gauge was imbedded directly in the clay with no epoxy insulation, and the copper foil leads were attached in the plane of the gauge and then bent up in the manner described.

Both gauges broke almost immediately upon arrival of the shock front. The gauge imbedded directly in the clay fared better and even may have recorded the peak pressure. The other gauge probably sheared at the place where the wire emerged from the epoxy and was surrounded by clay. At such an interface the discontinuity of shock flow could easily have caused the shearing of the wire. The different techniques of bending up the leads, whether copper foil or manganin wire, resulted in no apparent difference in gauge record.

On the second shot there were four gauges, each with a single set of voltage taps coming straight back. As in the previous shot the current leads came out laterally a short distance and then were bent up to emerge out the back of the target. One gauge had a 0.01-in. epoxy insulation, and the voltage taps were spot welded to the current loop, as had been done in all previous work. A second gauge had a 0.01-in. epoxy insulation, and the voltage taps were each looped over the current wire to form a double strand and were then spot-welded to the current loop. A third gauge had a 0.009-in. mylar insulation (epoxy bonding together two pieces of mylar) and the looped and spot-welded voltage taps. The fourth gauge had a 0.009-in. mylar insulation and looped voltage taps that were left un-welded.

All gauges appeared to have broken immediately upon the arrival of the shock pulse. The looped voltage taps were an attempt to provide more lasting continuity at what could be the weakest point in the gauge. There is no evidence to indicate that these taps helped.

It is felt that greater care in designing the gauge configuration and in building and emplacing the gauge will yield a successful gauge, that is, one that will record a pressure profile for as long as 5 μsec or more.