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76-65

# DEVELOPMENT OF PIEZORESISTIVE BAR GAGE

CERF, University of New Mexico
Box 25, University Station
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December 1976

Final Report

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the adaptation of pressure bar techniques for pressure measurement to the development of a more reliable, useable, and rugged pressure gage for measuring pressure (up to 10,000 psi) in blast chambers and shock tubes. The pressure bar gage, used for years as a piezoelectric transducer, was converted to a piezoresistive transducer for easier use in field tests. Preliminary evaluation tests in the laboratory indicate that this gage combines the good dynamic response of damped pressure (over)

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ABSTRACT (cont'd)

bar gages (fast rise time with little overshoot and ringing) with the static response capabilities and reliability of the more common diaphragm pressure gages. Initial use in a field test indicated that the gage can survive high-velocity debris impact, although usually with some zero offset. This offset can probably be eliminated by using soft debris shields.

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# ILLUSTRATIONS

# SECTION I
# INTRODUCTION

## BACKGROUND

Blast-effect simulation of nuclear weapons has generally been accomplished with explosive-filled chambers designed to generate specified blast pressures and durations. These simulations are generally conducted as disposable (i.e., one shot) field tests. Pressure pulses within these chambers are usually characterized by large pressure spikes, high temperatures, and large amounts of debris flying about the cavity. Measurement of pressure under these conditions is usually more difficult than that under cleaner environments, such as in a gas-driven shock tube. Usually, in the past, these measurements were accomplished with piezoresistive (i.e., strain gage) diaphragm-type pressure gages. However, these gages can be damaged by the large pressure spikes, which can cause diaphragm resonance and possible overranging of the gage, as well as by debris impact. Another class of pressure gage that could be used is the pressure bar gage. Since pressure bar gages are usually built as piezoelectric gages, their use in the field has been limited because of cable-noise problems. However, if the principle of pressure bar gage operation could be applied to explosive-chamber pressure measurements, significant improvements in pressure-data recovery might be realized.

Piezoelectric pressure bar gages were developed a number of years ago to measure pressures in gaseous detonation waves and in shock tubes. A small metal bar was used to transmit the pressure to a piezoelectric sensor. The metal bar and the piezoelectric sensor were acoustically matched to prevent reflections at the interface. (This was usually accomplished with aluminum bars and quartz disks.) In early versions, a backup bar of similar size and acoustic impedance was used to delay the reflection time from the end of the bar (ref. 1). This resulted in a gage with a relatively short recording time, depending on the length of the backup bar. The primary advantages of piezoelectric pressure bar gages are their very fast rise time and very little resonance.

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1. Edwards, D. H., Journal of Scientific Instruments, Vol. 35, 1958, p. 346.

A significant improvement in piezoelectric pressure bar gages is reported in reference 2. In these gages a tapered backup bar encased in wax is used. The wax sheath acts to absorb the stress pulse transmitted into the backup bar and thus prevents unwanted reflections and greatly extends the recording time. It has been demonstrated both analytically and experimentally that if the piezoelectric crystal cannot be placed on the pressurized end of the bar (considered impractical because of sealing and bar support problems), the optimum crystal location is somewhere between two and four bar diameters from the input end (ref. 2). This crystal location is the best compromise between fast rise time and minimized ringing due to wave dispersion in the metal pressure bar.

A further development of the piezoelectric bar gage (fig. 1) was made at the Ballistics Research Laboratory (BRL) (ref. 3). This development overcame the sealing and bar support problems. The piezoelectric sensor is located on the input end of the pressure bar to achieve a very fast rise time. The pressure bar, which is acoustically matched to the sensor, is embedded in an absorptive material (a relatively hard epoxy) to dissipate the stress pulse into the surrounding material. The electrical circuit is completed by a thin silver plating between the exposed face of the sensor and the gage case. This gage (Model ST-4) is commercially available.* The ST-4 gage probably has the fastest rise time of any commercial pressure gage. If properly used, the ST-4 gage has a rise time of about 0.2 μsec. It also has very little overshoot (less than about 10 percent) and essentially no resonance. It is, however, very temperature-sensitive because of the exposed piezoelectric sensor.

Because of piezoelectric circuitry problems in field tests and the temperature sensitivity of commercially available pressure bar gages, an effort was undertaken at the Civil Engineering Research Facility (CERF) several years ago to

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2. Edwards, D. H.; Davis, L., and Lawrence, T. R.; "The Application of a Piezoelectric Bar Gage to Shock Tube Studies," <u>Journal of Scientific Instruments</u>, Vol. 41, 1964, pp. 609-613.
3. Granath, B. A., and Coulter, G. A., <u>BRL Shock Tube Piezo-Electric Blast Gages</u>, BRL Technical Note No. 1478, Aberdeen Proving Ground, Maryland, August 1962.

*Susquehanna Instruments Company, Rt. 2, Box 228, Havre de Grace, Maryland 21078.

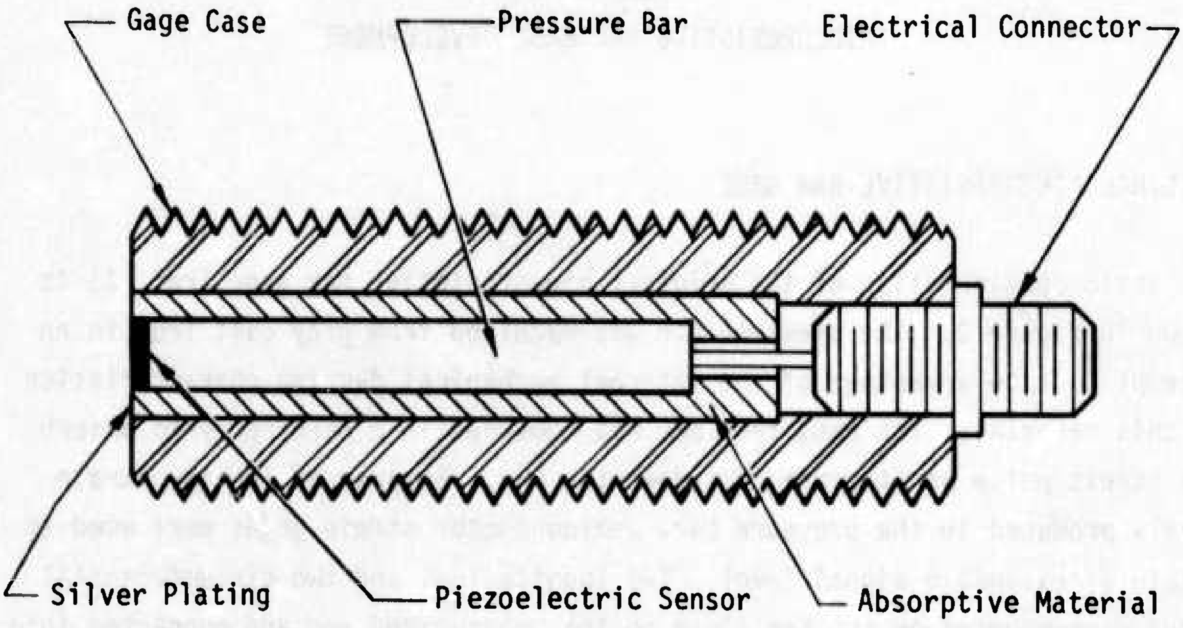

Figure 1. Piezoelectric Pressure Bar Gage (Model ST-4)

develop a piezoresistive bar gage. It became apparent that if the sensing elements were changed from piezoelectric to piezoresistive (i.e., strain gages) and placed a small distance from the end of the bar, both of these problems could be reduced, while retaining the advantages of pressure bar gages (fast rise time and low resonance). In addition, such a gage should be much less likely to be damaged by debris. Initial development work on a piezoresistive bar gage was described previously (ref. 4). That development is summarized in this report and subsequent developments at CERF are presented.

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4. Crist, Robert A. and Simmons, Kenneth, Dynamic Economical Large Testing Apparatus--A Blast Pressure Loading Technique, AFWL-TR-71-151, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, June 1972.

# SECTION II
# PIEZORESISTIVE BAR GAGE DEVELOPMENT

## ORIGINAL PIEZORESISTIVE BAR GAGE

The basic configuration of the original piezoresistive bar gage (ref. 4) is shown in figure 2. The pressure bar was machined from gray cast iron in an attempt to take advantage of the internal mechanical damping characteristics of this material. The cast iron bar was embedded in a hard epoxy to absorb the stress pulse as it propagates down the bar. Because of the low strain levels produced in the pressure bar, semiconductor strain gages were used to obtain a reasonable signal level. Two longitudinal and two circumferential gages were mounted on the bar close to the pressurized end and connected into a full bridge for temperature compensation.

Results of preliminary evaluation tests on the original piezoresistive bar gage are shown in figure 3. The tests were conducted in a 2-in-diameter, air-driven shock tube with the gages mounted end-on in the tube to measure reflected pressure. A reflected pressure of about 250 psi was used. The upper trace in each record is from the piezoresistive bar gage and the lower one is from an ST-4 gage. The first record (fig. 3a) shows that the piezoresistive bar gage maintained most of the fast rise time associated with pressure bar gages. Both gages show a rise time of about 2 μsec. The second record (fig. 3b), at a slower sweep rate, shows that the piezoresistive bar gage is much less temperature-sensitive than the ST-4 gage. As the shock wave reflected back and forth through the closed-end shock tube, the pressure built up to the static chamber pressure. The piezoresistive bar gage followed that static pressure reasonably well; whereas, the ST-4 gage began drifting fairly rapidly because of temperature sensitivity.

Tests of original piezoresistive bar gage models (fig. 2) involving long-duration pressure steps indicated drift problems after several seconds (fig. 4). It was suspected that the drift was due to creep within the epoxy potting compound used to encase the pressure bar. As the epoxy creeps it loads the side of the bar and reduces the longitudinal strain thus decreasing the

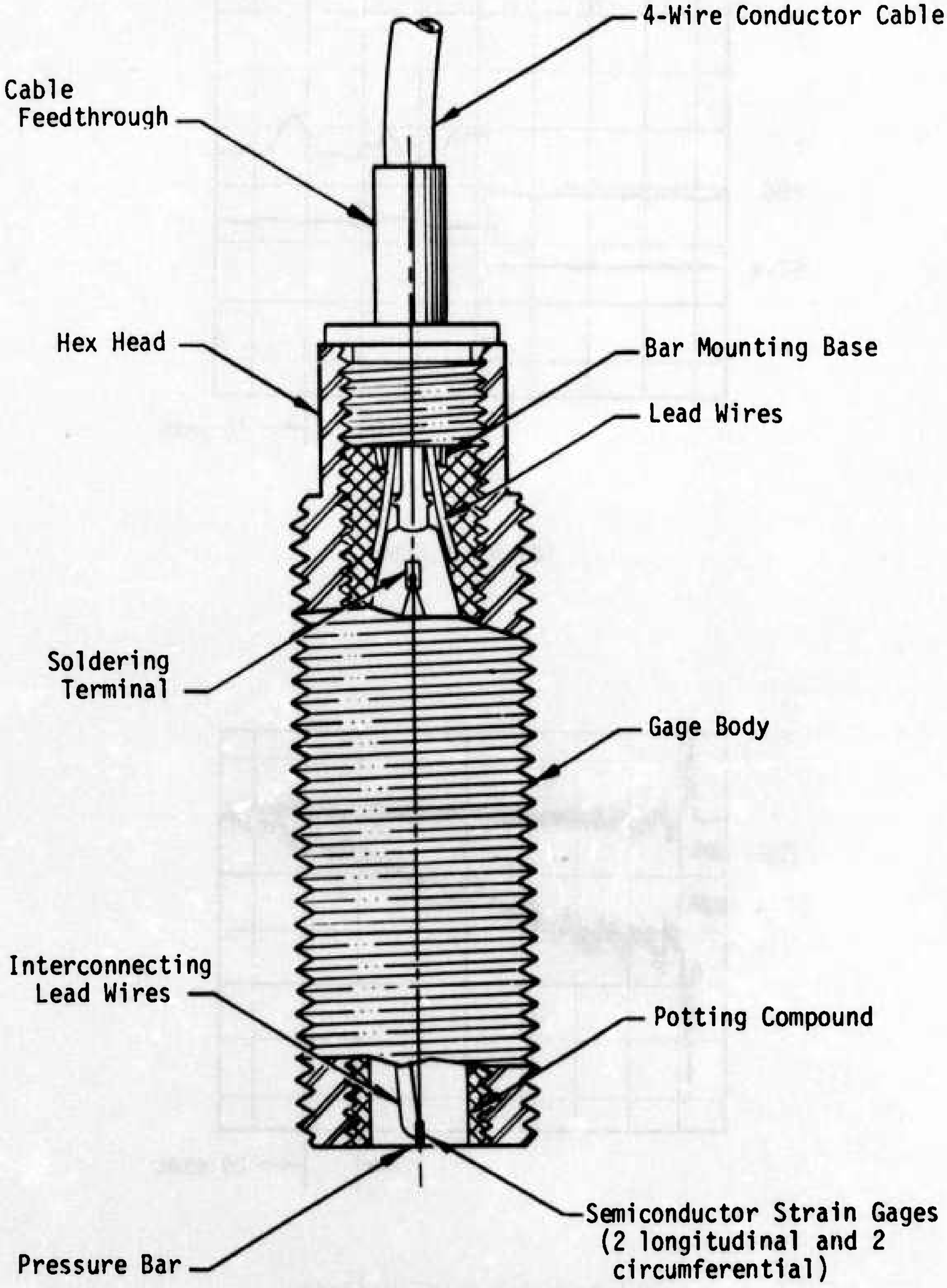
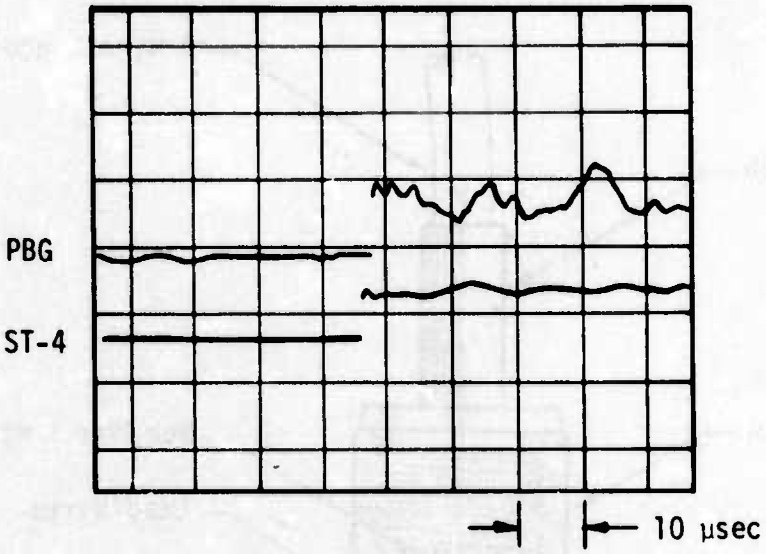
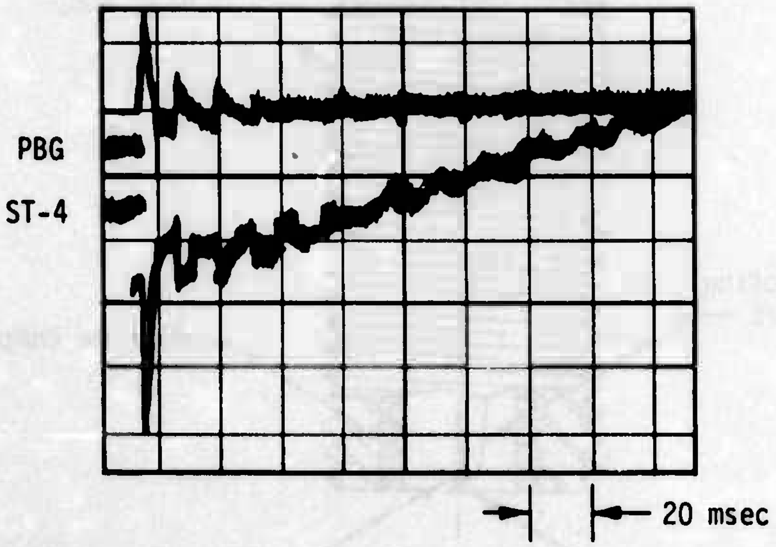


Figure 2. Original Piezoresistive Bar Gage



(a) Rise Time



(b) Temperature Sensitivity

Figure 3. Original Piezoresistive Bar Gage Responses

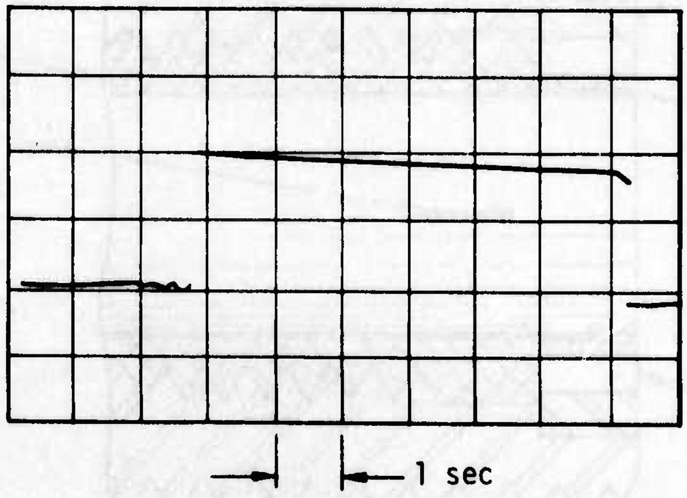


Figure 4. Response of Original Piezoresistive Bar Gage to Pressure Step

gage output. To eliminate this long-duration drift, a pressure relief ring (fig. 5) was installed in the end of the piezoresistive bar gage. This ring prevented the fluid pressure being measured from acting on the potting compound. A Teflon film was installed between the pressure relief ring and the pressure bar to reduce friction. The results of the pressure relief ring modification (fig. 6) indicates that the drift was essentially eliminated.

Both static and dynamic high-pressure tests on the piezoresistive bar gage are reported in reference 4. The static tests indicated very good linearity up to about 5,000 psi and less than 4 percent nonlinearity up to 10,000 psi (fig. 7a). The dynamic test results (fig. 7b) were obtained with a high-pressure helium/freon shock tube. The piezoresistive bar gage reproduced the ST-4 trace reasonably well, with respect to both amplitude and waveform.

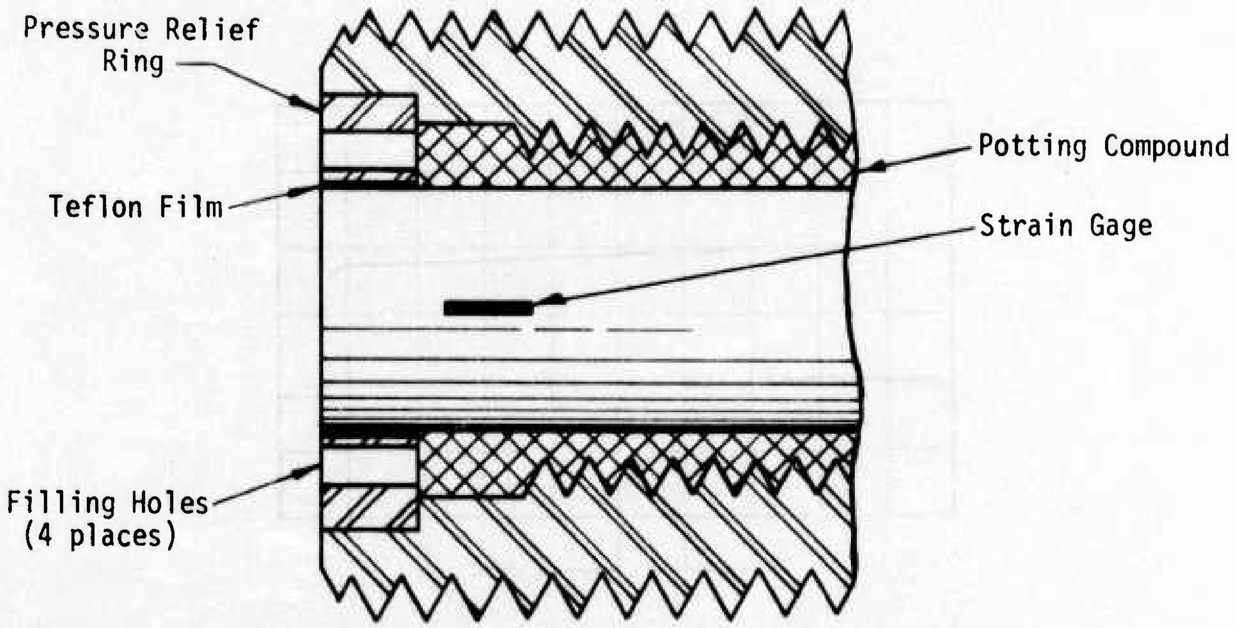


Figure 5. Original Piezoresistive Bar Gage with Pressure Relief Ring

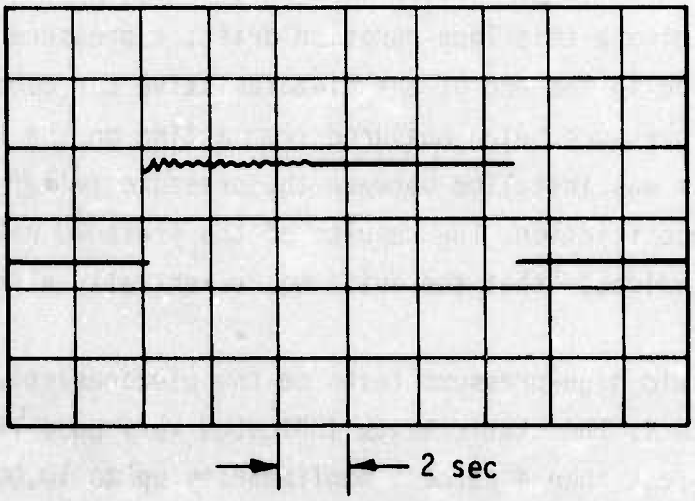
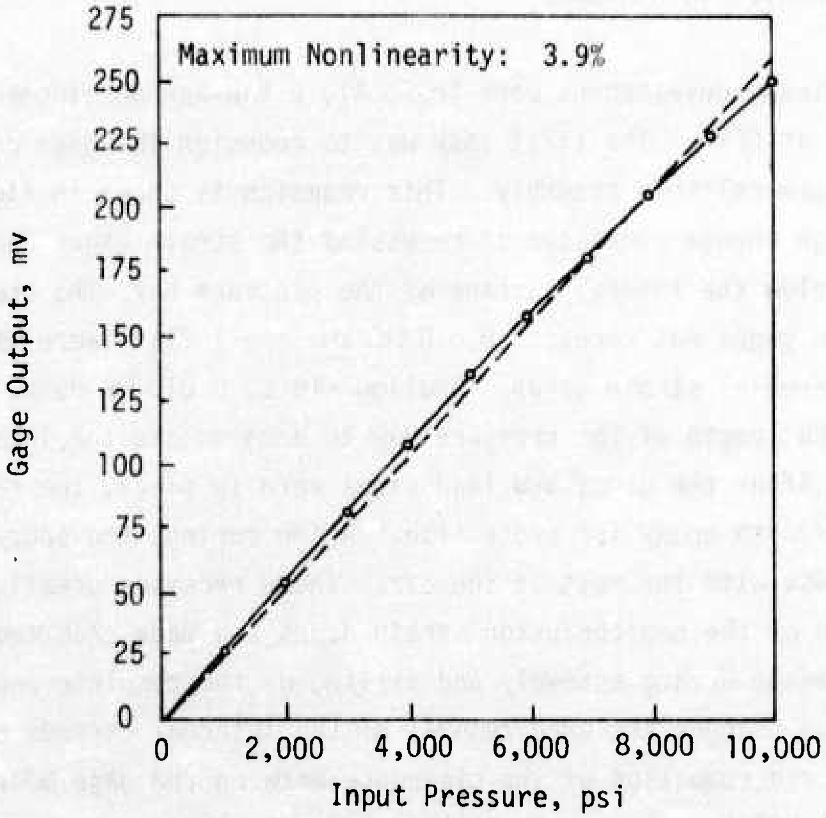
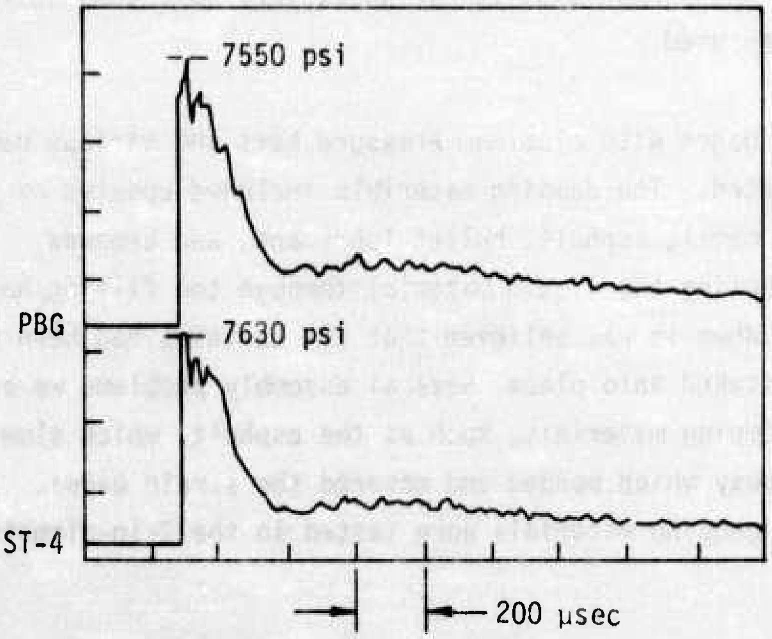


Figure 6. Response of Original Piezoresistive Bar Gage with Pressure Relief Ring to Pressure Step



(a) Static Response



(b) Dynamic Responses

Figure 7. High-Pressure Results of Original Piezoresistive Bar Gage

## REDESIGNED PIEZORESISTIVE BAR GAGE

After the preliminary development work (ref. 4), a low-key developmental effort continued at CERF. The first task was to redesign the gage case for easier and more reliable assembly. This redesign is shown in figure 8. The primary design change consisted of recessing the strain gages and lead wires slightly below the lateral surface of the pressure bar. The area around the strain gages was recessed 0.010 in. and small flats were machined for the circumferential strain gages. Shallow slots, 0.010 in. deep, were machined along the length of the pressure bar to accommodate the interconnecting lead wires. After the gages and lead wires were in place, the recessed areas were potted with epoxy for protection. After curing, the epoxy was machined down flush with the rest of the bar. These recesses greatly facilitated application of the semiconductor strain gages and made them much less susceptible to damage during assembly and filling of the complete pressure gage. Other design changes included removal of the internal threads next to the pressure bar and reduction of the clearance between the gage body and the pressure bar to 0.008 in. Also, the filling holes in the pressure relief ring were sealed with brass pins, which were staked into place. By completely sealing the end of the piezoresistive bar gage, very soft damping materials such as wax could be used.

Piezoresistive bar gages with aluminum pressure bars and various damping materials were constructed. The damping materials included epoxies of various hardnesses, Wood's metal, asphalt, bullet lubricant, and beeswax. The gages were filled by injecting the liquid material through the filling holes in the front of the gage. When it was believed that all cavities had been filled, the sealing pins were staked into place. Several assembly problems were encountered with some of the damping materials, such as the asphalt, which slowly attacked and softened the epoxy which bonded and covered the strain gages. The gages with these various damping materials were tested in the 2-in-diameter, air-driven shock tube.

The results of the tests generally indicated that the beeswax was the best damping material. Results of tests with soft epoxy and beeswax are compared in figure 9. The soft epoxy allowed considerable ringing in the gage (fig. 9a); the beeswax essentially damped out all of this ringing (fig. 9b). However,

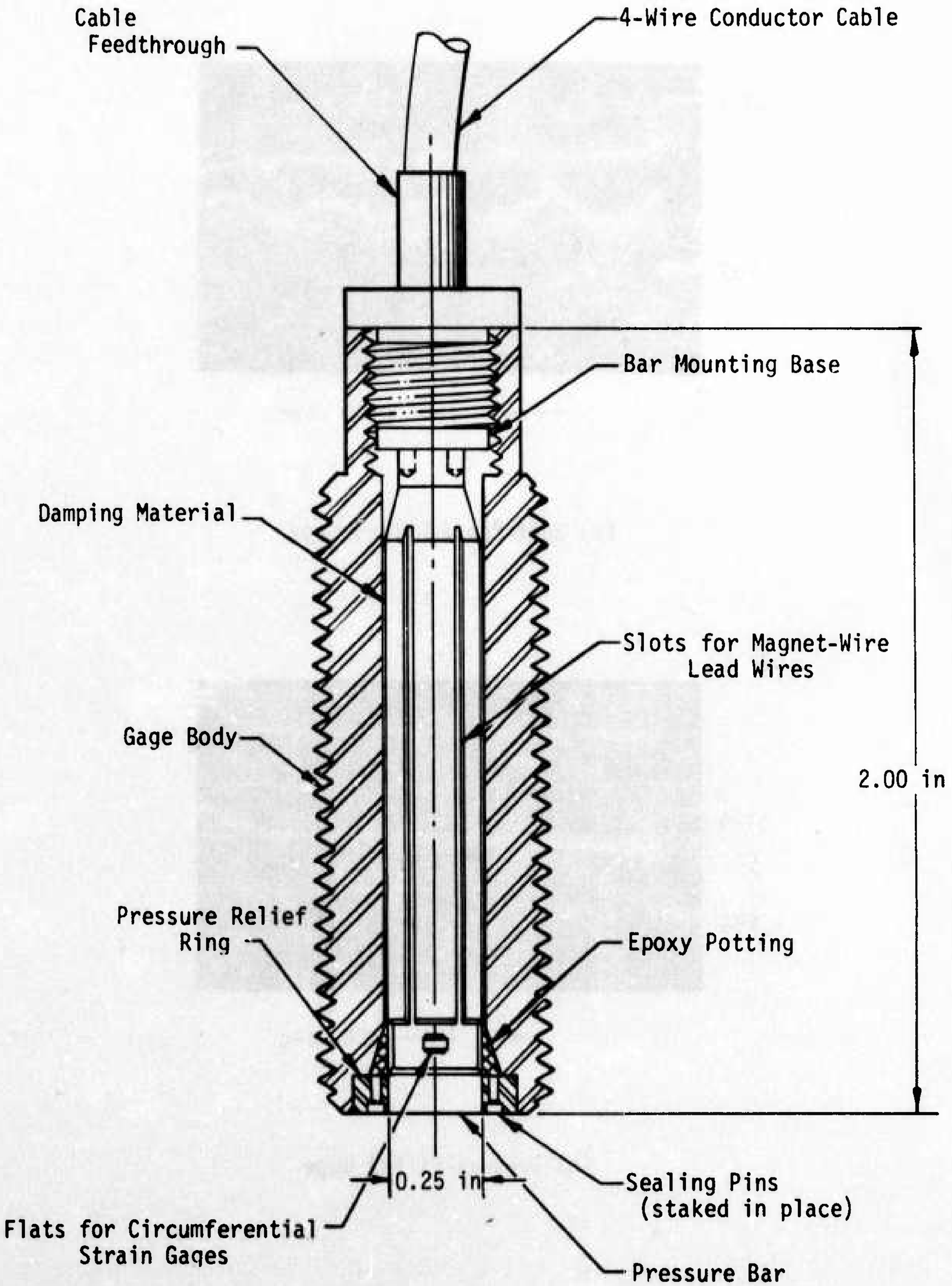
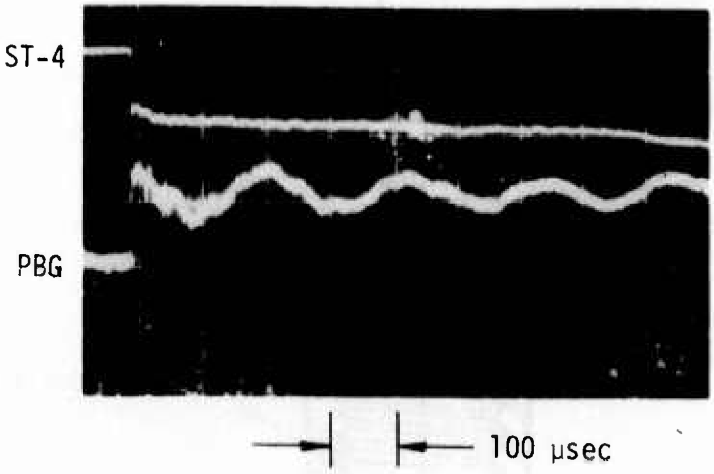
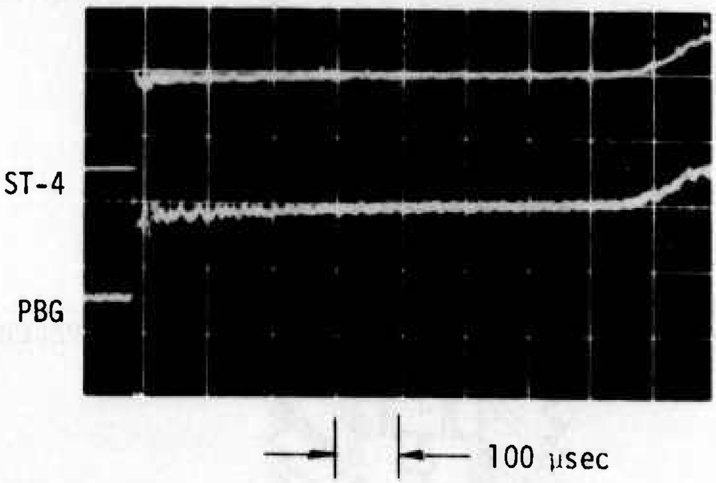


Figure 8. Redesigned Piezoresistive Bar Gage



(a) Soft-Epoxy-Filled Gage



(b) Beeswax-Filled Gage

Figure 9. Test Results of Redesigned Piezoresistive Bar Gage

it was often difficult to get the beeswax into the gage well enough to produce the damping shown in figure 9b. Also, once in and sealed, the beeswax would apparently separate from the pressure bar and damping would be reduced. This separation, which would sometimes take several weeks to occur, was probably caused by cavities inadvertantly left within the beeswax and by the high coefficient of thermal expansion of beeswax.

Since the piezoresistive bar gage was suspected of being sensitive to cross-axis acceleration, acceleration-sensitivity tests were conducted on several well-damped, beeswax-filled gages. The test setup consisted of a steel Hopkinson pressure bar loaded by a short steel striker bar (fig. 10). The piezoresistive bar gage was mounted close to the free end in a hole drilled and tapped into the bar. Acceleration was measured by an accelerometer mounted on the free end of the Hopkinson bar. Each test usually consisted of a series of five or six loadings at various acceleration levels (controlled by the striker bar impact velocity).

Typical data from the tests are shown in figure 11. The top trace indicates the acceleration level; the bottom trace shows the acceleration-induced signal from the piezoresistive bar gage. The results of one of the test series are plotted in figure 12. This plot shows a distinct leveling off of the pressure gage output with increasing acceleration levels. For this particular gage, the transverse acceleration sensitivity (defined as pressure gage output divided by acceleration level) at 4300 g was 0.032 psi/g, based on a faired curve through the data points. This acceleration sensitivity value was fairly typical for all the beeswax-filled gages; and although it is fairly high when compared to that for certain types of diaphragm pressure gages, this value is not so high as to discourage further development. These relatively high values simply mean that in high-acceleration environments, it may be advisable to use some sort of mechanical noise isolation when mounting the piezoresistive bar gage.

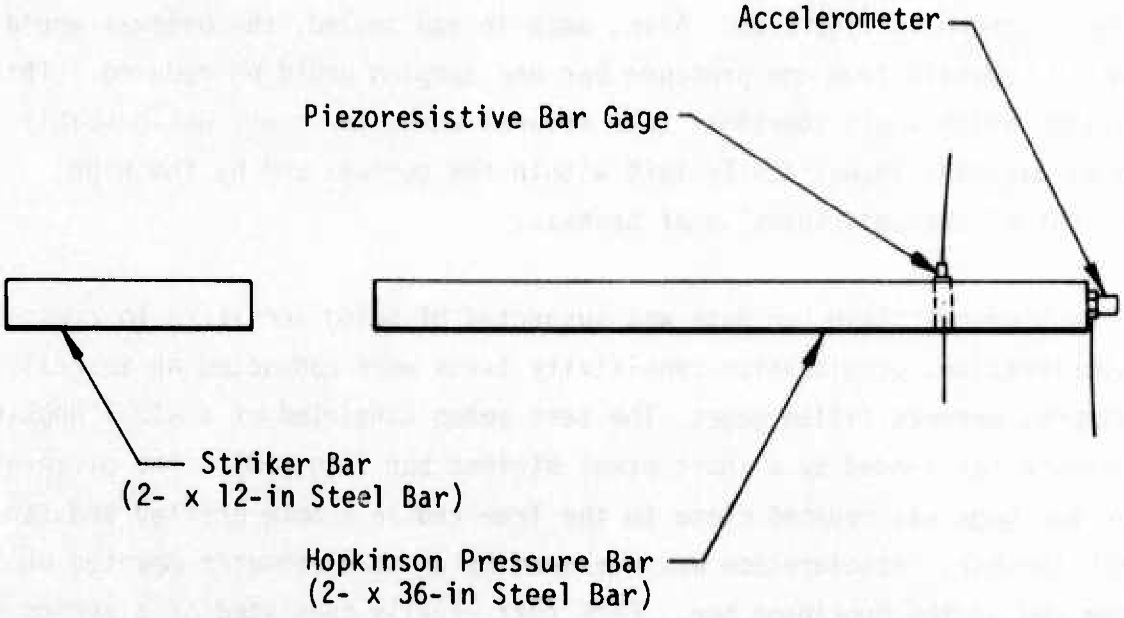


Figure 10. Test Setup for Cross-Axis Acceleration Tests

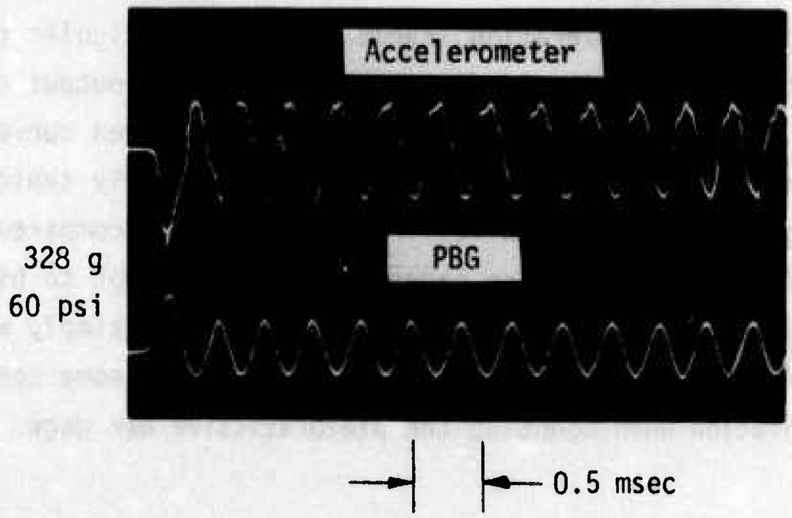


Figure 11. Typical Data from Cross-Axis Acceleration Tests of Redesigned Piezoresistive Bar Gage

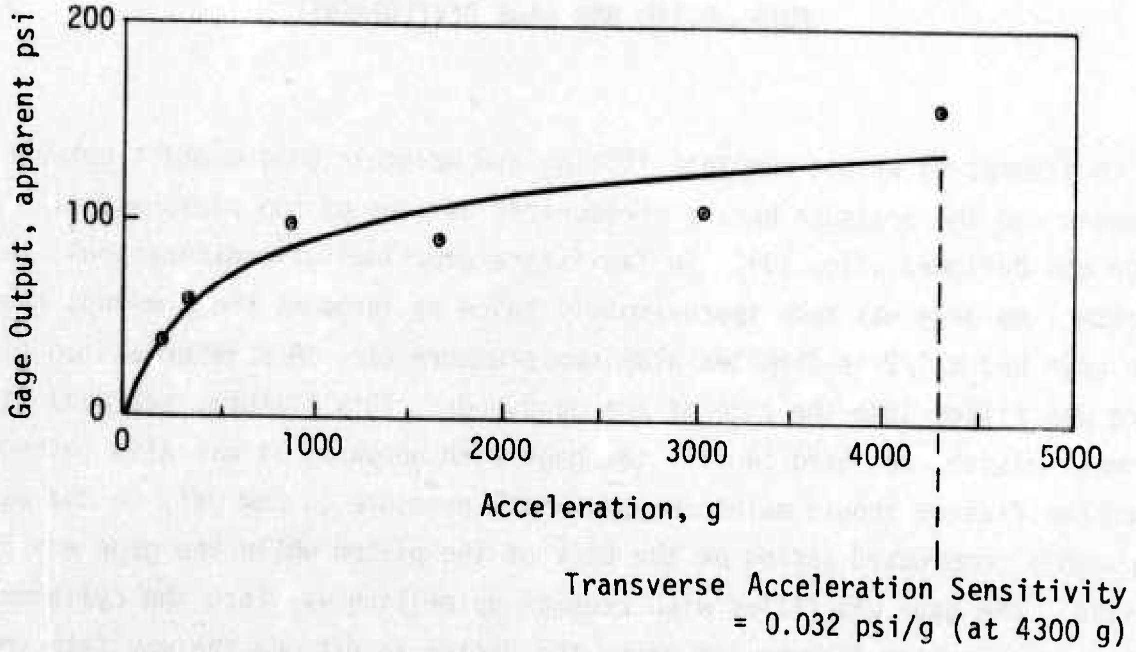


Figure 12. Typical Error Signal Versus Acceleration Level for Redesigned Piezoresistive Bar Gage

# SECTION III

# PRESSURIZED BAR GAGE DEVELOPMENT

In an attempt to assure complete filling and maintain good contact between the beeswax and the pressure bar, a pressurized version of the piezoresistive bar gage was designed (fig. 13). To facilitate experimental modifications, this pressurized gage was made approximately twice as large as the previous gages. The gage had a 1/2-in-diameter aluminum pressure bar. A pressurization fixture was fitted into the side of the gage body. This fixture, equipped with a small piston, was used to fill the gage with beeswax; it was also intended that the fixture should maintain some small pressure (a few psi) on the wax through a compressed spring on the back of the piston while the gage was being tested. The gage was filled with beeswax by melting wax into the cylinder of the pressurization fixture and using the piston to extrude the wax into the gage. The holes in the pressure relief ring on the front of the gage served as vents. Wax was extruded into the gage until continuous ribbons of wax came out all four vent holes, at which time the vent holes were sealed with small screws.

The first attempt to fill the pressurized gage resulted in the epoxy joint between the pressure bar and the bar mounting base being broken because of excessive extrusion pressure on the wax. The gage was disassembled and a new pressure bar was fabricated with the mounting base machined as an integral part of the pressure bar. The gage was reassembled and filling of the gage was accomplished with little difficulty.

The pressurized bar gage was first tested in an unpressurized mode in the 2-in-diameter, air-driven shock tube. The results indicated that good damping had been achieved by the extrusion-filling process. The gage was retested periodically for about a month with no apparent degradation of the damping characteristics. It then became apparent that if the gage was completely filled by the extrusion-filling process, continuous external pressurization of the wax during testing and use of the gage would be unnecessary.

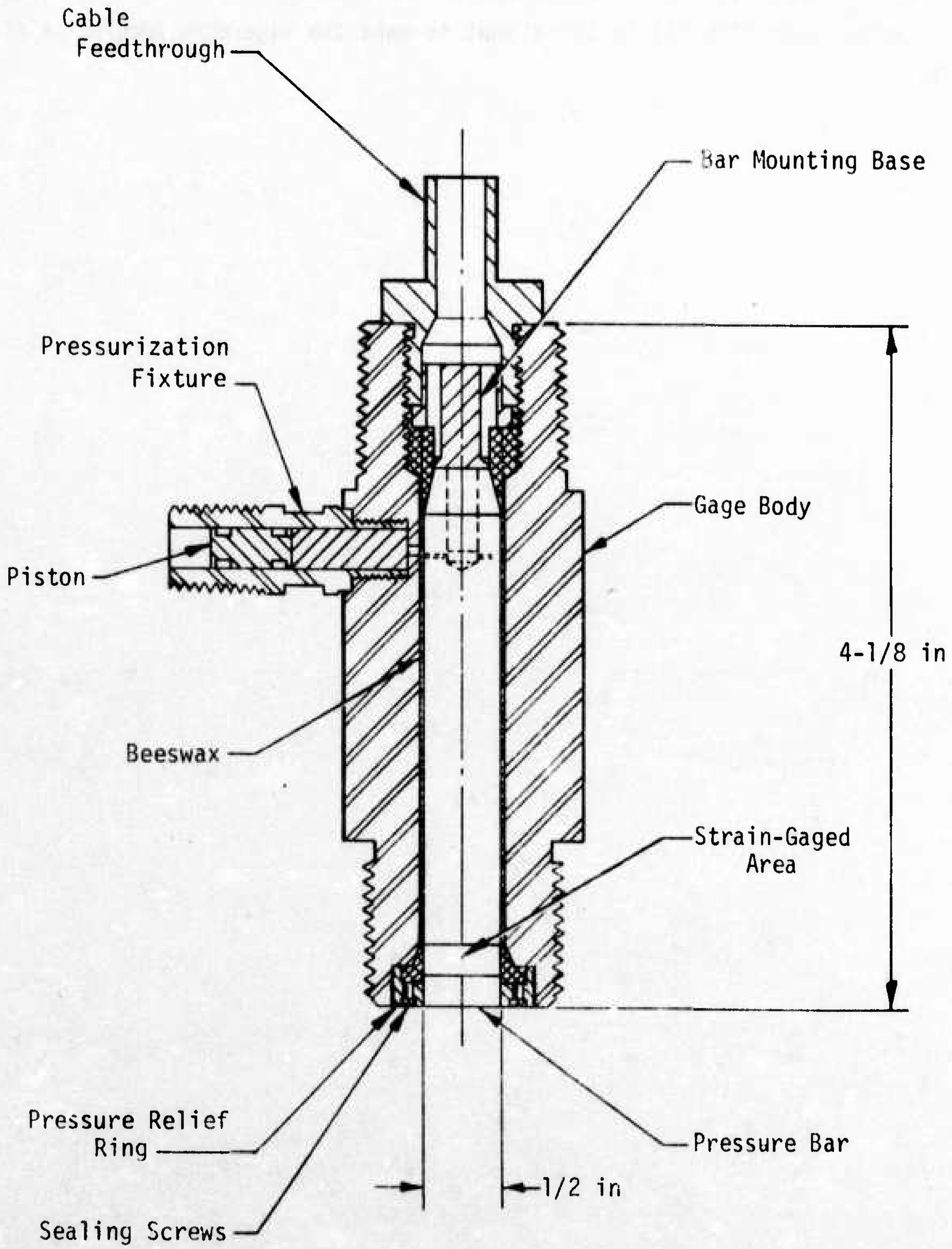


Figure 13. Pressurized Piezoresistive Bar Gage

With the apparent good results of the extrusion-filling process, the decision was made to apply this filling process to the smaller version of the piezoresistive bar gage (fig. 8) in an attempt to make the gage more usable in field tests.

# SECTION IV
# DEVELOPMENT AND EVALUATION OF FIELD GAGE

The gage shown in figure 8 (1/4-in-diameter pressure bar) was modified for use with the wax extrusion-filling process. The modified gage is shown in figure 14. A small filling hole was drilled in the side of the gage body toward the back end of the pressure bar. The external threads were removed from the gage body in this region to facilitate the fit into the filling fixture. The pressure bar and the mounting base were machined as an integral part, as with the pressurized gage.

The filling fixture for the extrusion-filling process consisted of a gage holder block, a filling cylinder with a small tip machined to fit the filling hole in the gage body, and a piston with a weight platform (fig. 15). The gage was placed in the holder block with the filling hole aligned with the centerline of the filling cylinder. The cylinder (previously filled with wax) was screwed down until the tip engaged the filling hole. Weights were then placed on the weight platform to slowly extrude the wax into the gage. A pressure of about 200 psi was maintained in the filling cylinder until the ribbons of wax coming through the vent holes were continuous and no air bubbles were evident. The gage was then removed and all vent holes were sealed with brass pins staked into place.

The extrusion-filled piezoresistive bar gages intended for field usage were subjected to a number of preliminary evaluation tests including tests in the 2-in-diameter, high-pressure, helium/freon shock tube. The results of the shock-tube tests showed that good damping was achieved (fig. 16a) and the fast rise time was preserved (fig. 16b).

Cross-axis acceleration sensitivity tests were conducted on one of the field gages. The result was essentially the same as that shown in figure 12. This indicates that acceleration sensitivity was neither increased nor decreased by the improved filling process.

Fourteen piezoresistive bar gages like the one shown in figure 14 were built for the Dynamic Air Blast Simulator (DABS) IA Project (a large expendable shock-tube type of field test). Eleven of the fourteen gages had hardened

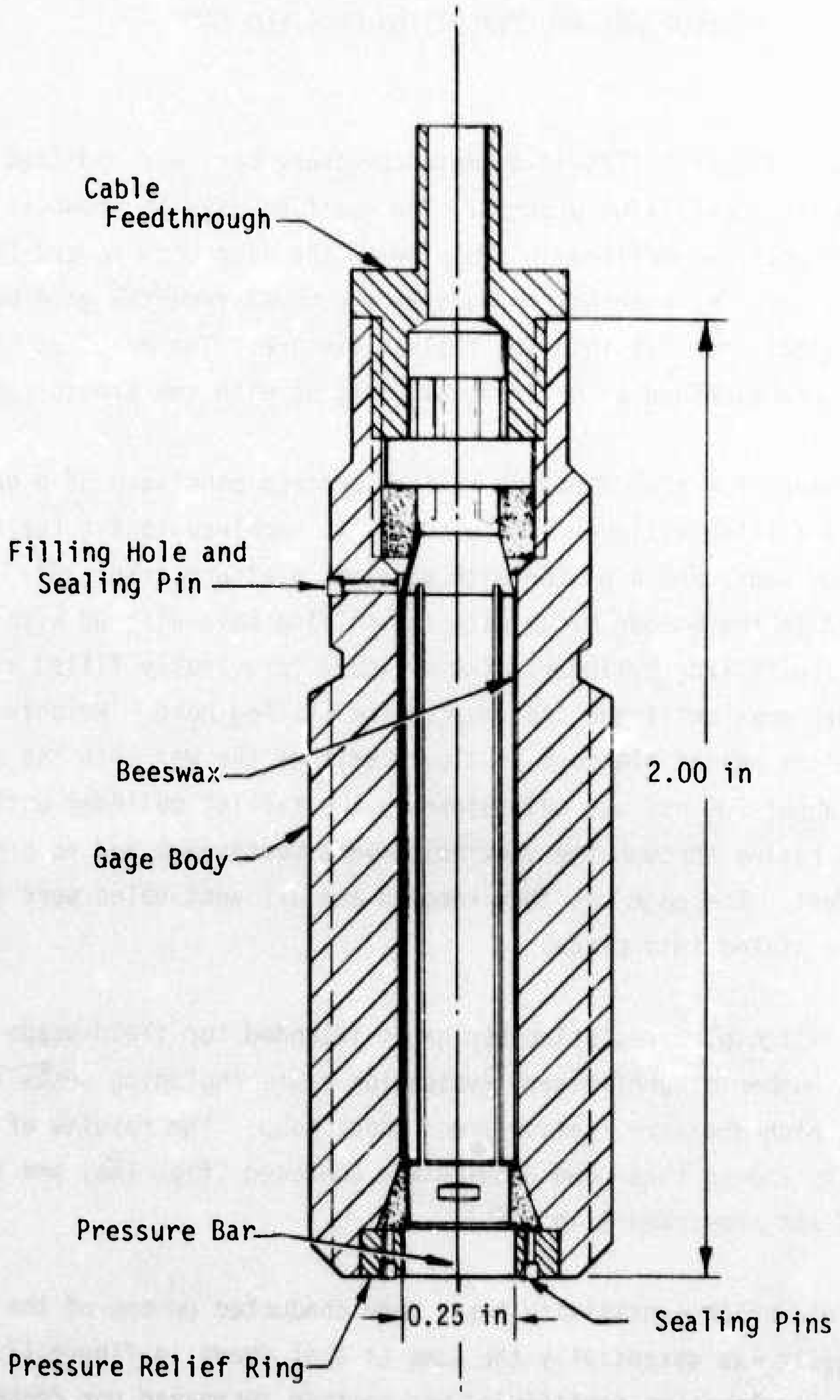


Figure 14. Redesigned Piezoresistive Bar Gage Modified for Extrusion-Filling Process

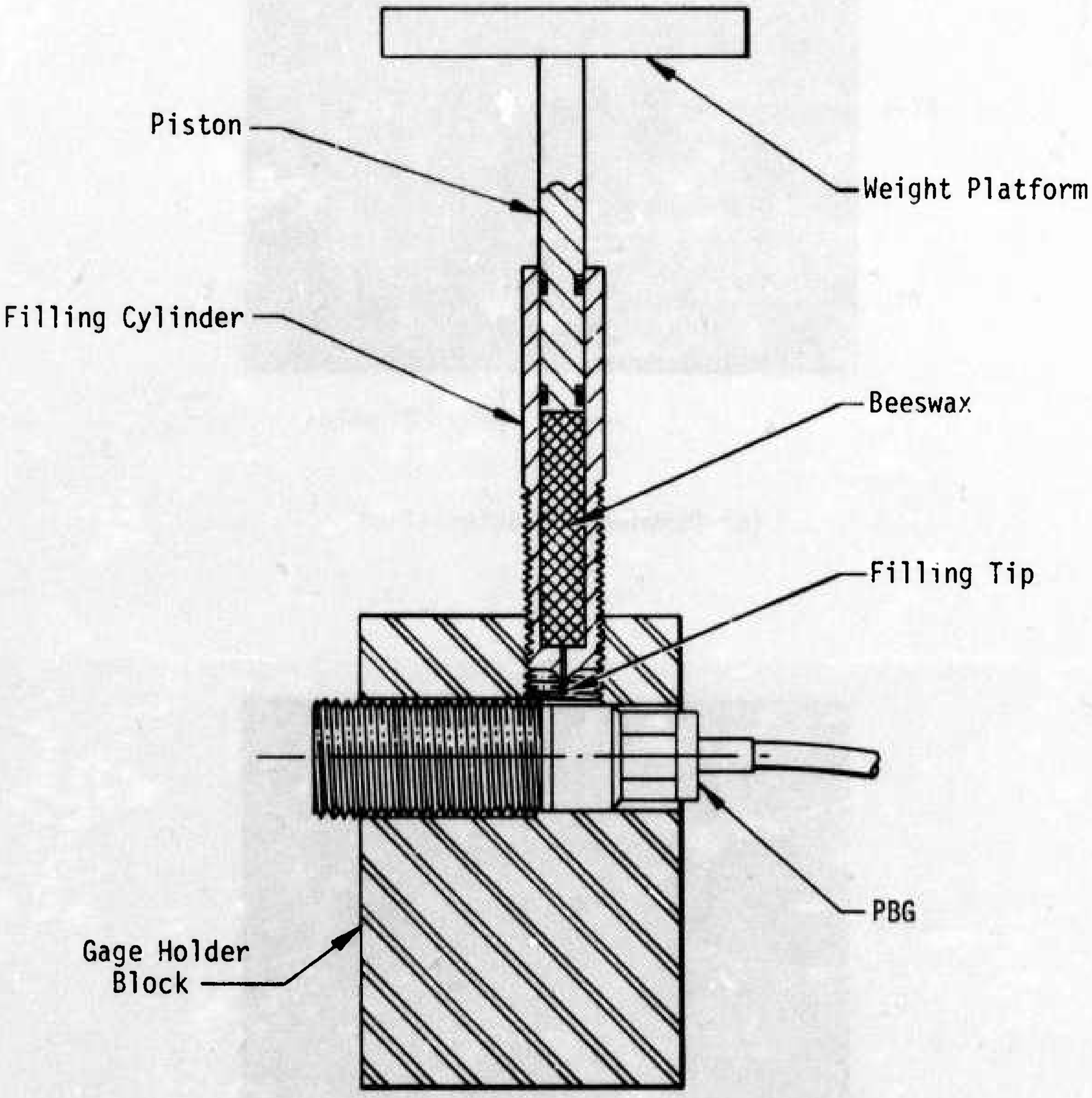
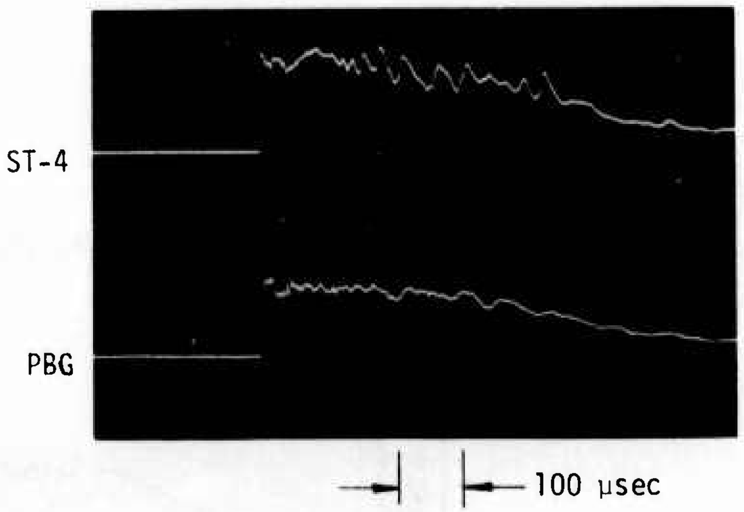
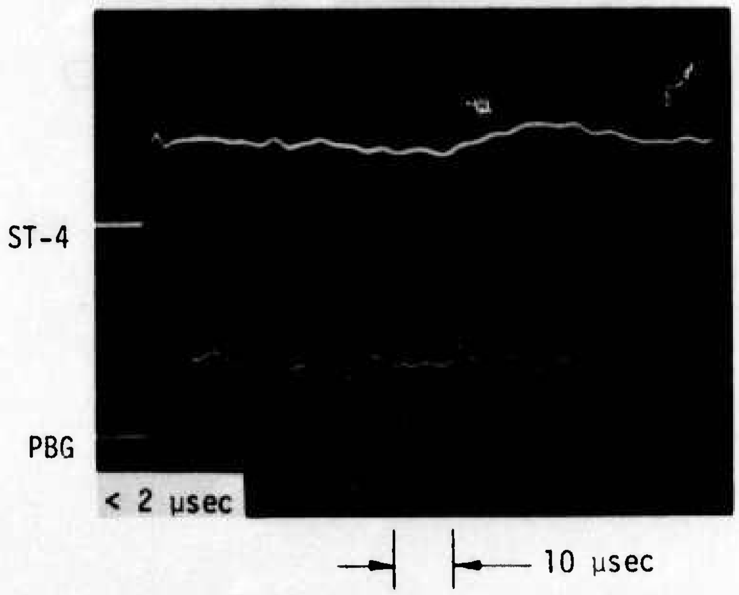


Figure 15. Filling Fixture for Extrusion-Filling Process



(a) Damping Characteristics



(b) Rise Time

Figure 16. Shock-Tube Results of Extrusion-Filled Redesigned Piezoresistive Bar Gage

steel pressure bars. This gave these gages an effective range of about 30,000 psi, with an overrange capability of about 100,000 psi. These higher-range gages were used because of the large pressure spikes and debris expected in the DABS IA Test.

The 14 gages were dynamically calibrated in the 2-in-diameter, high-pressure shock tube with an ST-4 gage as a reference. These calibrations were conducted at three different pressure levels (approximately 500, 1500, and 3000 psi). The result of one of these calibrations is shown in figure 17. This plot indicates reasonable dynamic linearity up to about 3000 psi.

The 14 gages were used in the DABS IA Test with reasonable success. Nine of the gages were placed in stagnation probes where they were subjected to particle impacts at about 5000 ft/sec and stagnation pressures of about 3000 psi. Six of the nine stagnation gages continued to read after debris impact, although sometimes with significant zero offsets. The zero offsets were probably caused by impact-generated inelastic deformation within the steel bar. It may be possible to reduce this offset by shielding the pressure bar with a softer material, such as lead. A soft shield should help to reduce the impact-generated stress levels before they are propagated into the steel pressure bar.

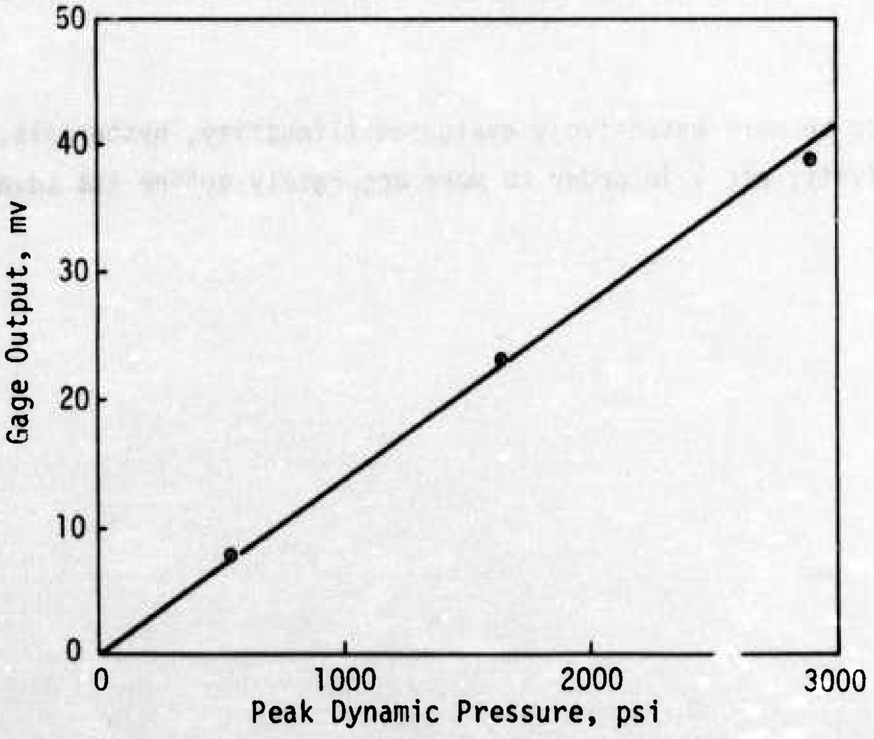


Figure 17. Shock-Tube Calibration of Redesigned Piezoresistive Bar Gage

# SECTION V
# CONCLUSIONS AND RECOMMENDATIONS

The piezoresistive bar gage damped with beeswax appears to work well, provided the beeswax maintains good contact with the pressure bar. It also appears that filling the gages by the extrusion-filling process assures good contact. The wax-filled bar gage developed here had a fast rise time ( ≈ 2 μsec) and little overshoot and ringing; and from DABS IA experience, it appears to be rugged and reliable.

The acceleration sensitivity of the piezoresistive bar gage is higher than that of some types of diaphragm gages, but not so high as to cause problems in most shock-tube experiments. No noise in the DABS IA data could be attributed to acceleration sensitivity. There may be construction techniques which would reduce the acceleration sensitivity, thus reducing the potential problem.

The zero offsets experienced in DABS IA (a result of the extremely harsh debris environment) can probably be reduced by shielding the pressure bar with a softer material such as lead. Reducing the impact stresses in this manner should reduce or eliminate the inelastic deformation within the steel pressure bar.

The gage needs to be more extensively evaluated (linearity, hysteresis, temperature sensitivity, etc.) in order to more accurately define its advantages and limitations.

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