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KILOBAR BLAST PRESSURE TRANSDUCER--
3.4 KILOBAR PIEZORESISTIVE BLAST PRESSURE SENSOR USING SILICON LOAD CELL TECHNIQUE

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June 1982

Final Report

Approved for public release; distribution unlimited.

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Air Force Systems Command
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Measurements of blast pressures in high-explosive experiments require highly specialized transducers. This report describes development of a resistance-based transducer for measurements to 3.4 kilobars. A unique transduction scheme employing a silicon cylinder incorporates diffused transverse piezoresistive elements to respond as a load cell to compressive stress. Considerations for hardening against blast thermal and shock accelerations are reflected in design of the unit. Five prototypes were fabricated and test results are presented.

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I. INTRODUCTION

Highly specialized initiation and detonation of masses of high explosives is the basis for creating blast and shock environments scaled to simulate those of nuclear weapon detonations. Specimen strategic structures sited in the scaled environment are tested to enable assessment of survivability. Critical to accurate assessments is the acquisition of valid field test measurement data, especially blast pressure data. Only with high quality reliable blast pressure data can the degree of blast simulation be determined and the test input stimulus to the specimens be defined. This report describes the development of a variable resistance type silicon integrated sensor transducer for the measurement of blast pressure in the range to 3.4 kbar. This effort was undertaken because conventional clamped-edge, deflecting diaphragm silicon-integrated sensors are unsuitable for use above approximately 2 kbar. Such transducers are limited in their upper range because the thickness-to-diameter ratio of the sensing diaphragm becomes such that undesirable shear stresses are created if the fabrication of diaphragm-type transducers for ranges above 2 kbar is attempted. Specifically, these high shear stresses adversely affect the normal radial and tangential stress levels at the edge of the diaphragm in such a manner as to provide a highly nonlinear response. The approach taken in this contract was to replace the integrated sensor diaphragm with a two-piece silicon load cylinder utilizing piezoresistive elements in a transverse mode. Such a technique minimizes thermal response and results in a rugged, highly sensitive blast pressure transducer with a fast response.

Silicon integrated sensor transducers of the diaphragm type have been used very successfully over the last 15 years for measuring blast pressures in high explosive testing in the range to 69.0 MPa (10,000 lb/in^2). Integrated sensor technology using a silicon disc force collector and integral diffused silicon strain elements is ideally suited to this type of application for a number of reasons, including small size, ruggedness, low shock acceleration, fast response, high resonant frequency, sensitivity, high reliability, static calibration capability (DC response), and compatibility with low noise strain gage signal conditioning.

Specifically, this report describes a transducer development effort to extend the useful measuring range of this class of pressure transducers by employing a novel integrated sensor as the transduction element for a blast load cylinder pressure transducer. As a result of this effort, a number of prototype transducers were designed, evaluated and tested. The results are quite positive and this new transducer is deemed to be suitable for production and field testing. However, further improvement is possible and extension of the transducer range to 6.8 kbar is deemed feasible. The conceptual and theoretical framework, design, and experimental data are covered in subsequent sections.

II. DESIGN GOALS

A new basic sensing technique was employed to produce a blast pressure transducer with superior performance in the range of 3.4 kbar. Specifically, the subject transducer was conceived and designed to meet the following design goals.

Range	3.4 kbars
Housing Material	17-4 stainless steel
Envelope	Maximum dimensions per Figure 1
Sealing	34.5 MPa - Oil
Shock	50,000 G half-sine; 0.15-ms duration
Resonant Frequency	>700 kHz
Electrical Configuration	Wheatstone bridge
Full Scale Output	300 mV F.S.
Electrical Lead Out	Four-conductor shielded cable
Isolation	1,000 MΩ(min.)at 50 VDC
Environmental	Suitable for use in HE environment with thermal barrier and flash protection

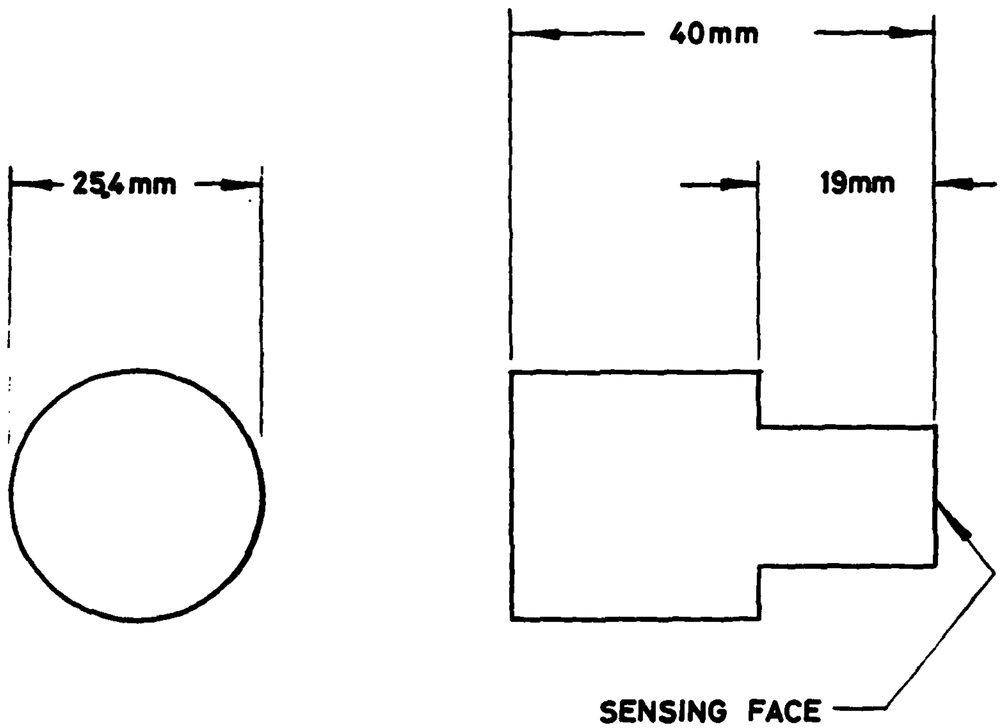

FIGURE 1. MAXIMUM TRANSDUCER ENVELOPE

III. CONCEPTUAL AND THEORETICAL DESIGN

1. INTRODUCTION

The basic integrated sensor approach is shown in Figure 2.

The approach employs an integrated sensor disc force collector which is mounted and conventionally loaded as a clamped-edge diaphragm. On the undersurface of the diaphragm a fully active diffused piezoresistive Wheatstone bridge is formed by conventional transistor processes of oxidation, photolithography, solid state diffusion, chemical etching, and vacuum metalization. A small centrally located void in the mounting allows the classic deflection with applied pressure.

This concept has evolved over the last 20 years into a transducer technology which is on the leading edge of test instrumentation sensor design.

The reason for the success of this approach lies in a number of factors inherent in the use of silicon as a diaphragm and in the solid state process by which the piezoresistive elements are manufactured.

Silicon is an excellent transducer material combining a high elastic modulus with a low density to yield a stiff sensor with a high resonant frequency. Moreover, silicon is a perfectly elastic material which will not deform in a plastic manner. Thus, silicon-based sensors allow the fabrication of pressure transducers of low hysteresis and superb static performance.

The piezoresistive strain sensitive elements are formed integral to the silicon diaphragm by a process of solid state diffusion. This technique eliminates the organic epoxies conventionally used to bond strain gage elements to diaphragms or flexures and is the basis for the superior performance of these devices.

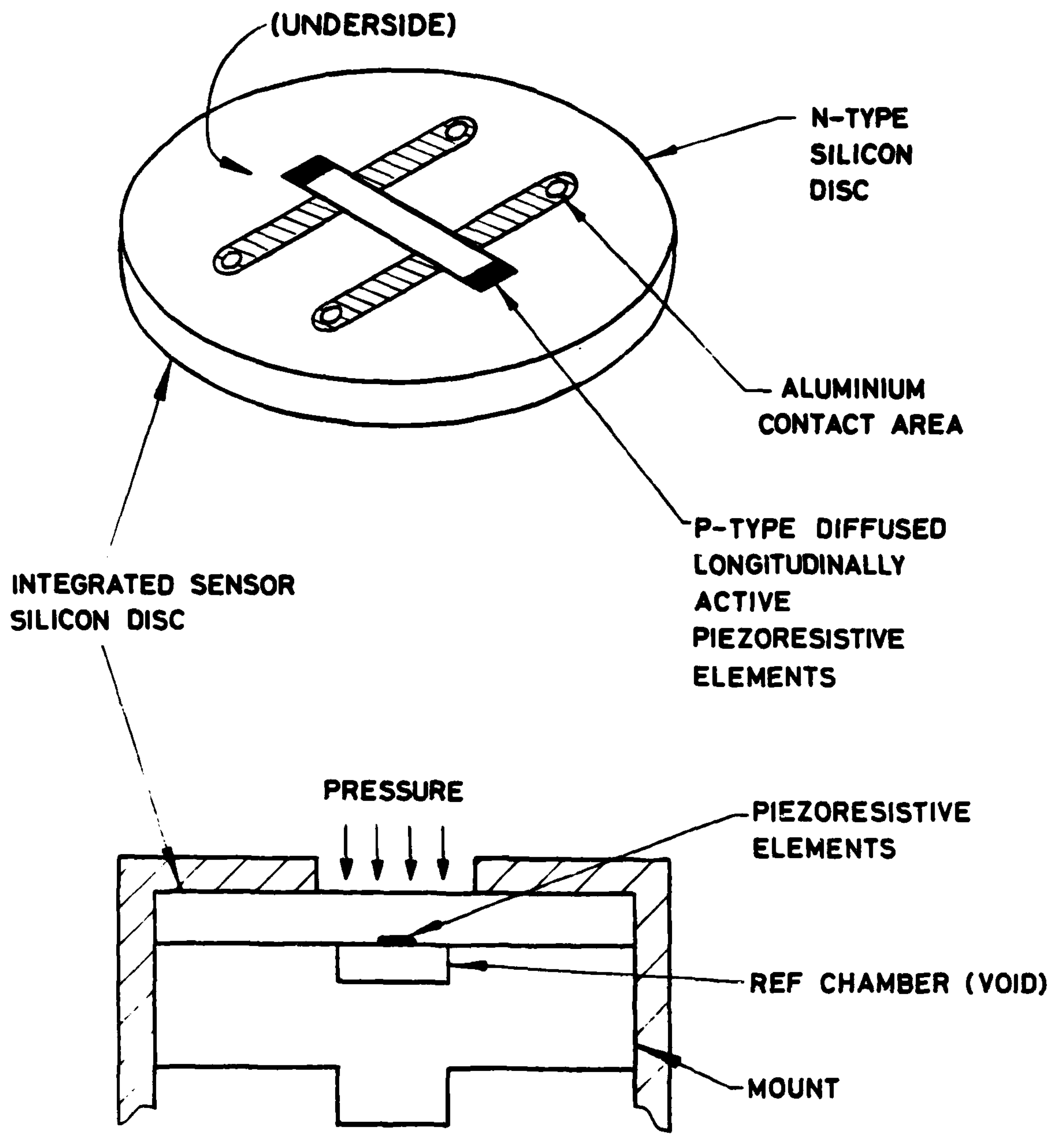

FIGURE 2. DIAPHRAGM TYPE INTEGRATED SENSOR PRESSURE TRANSDUCER

Because the four piezoresistive elements comprising a Wheatstone bridge are formed simultaneously, their temperature coefficients are closely matched. Moreover, the silicon elements formed on a silicon diaphragm result in a minimum of stress due to thermal expansion mismatch of materials.

The small sizes obtainable with this class of devices are possible because of the microlithographic process employed. This process is similar to that used in the manufacture of silicon integrated circuits. The desired pattern is first produced at 100x scale and then precisely reduced and stepped and repeated to form a number of images on a glass mask. These images are oriented along crystallographic axes transferred to the silicon wafer by the technique of photoresist imaging, oxide formation, and chemical etching. The result is that these devices can be batch fabricated, with typically 50 to 100 devices manufactured simultaneously on a 5-cm silicon wafer. The resulting sensors are thus nearly identical in their performance characteristics and are virtually operational pressure transduction elements as diced from the wafer, requiring only suitable packaging, thermal compensation, and calibration to become a finished, high performance instrument. Of particular relevance to the class of transducers used in blast and shock measurements is the ability to fabricate a very small active area of typically less than 1 mm in diameter for the HKS-375 series pressure transducers.

The resonant frequency for a clamped-edge diaphragm is given by

$$f_n = 9.66 \sqrt{\frac{ET^2}{\rho R^4}} \tag{1}$$

where

E is Young's modulus of elasticity

T is the thickness

R is the disc's active radius

ρ is the density of the disc material

When silicon is used as the diaphragm material, the density (ρ) is about a fourth that of the value for most metals. Consequently, the resonant frequency of a silicon disc used as a diaphragm is normally twice that of a metal diaphragm of identical dimensions.

Combining the constants in (1) allows f_n to be expressed as

$$f_n = K_1 \frac{T}{R^2} \tag{2}$$

where K_1 is a constant.

The radial stresses at the center of the diaphragm are given by

$$S_{rc} = K_2 P \frac{R^2}{T^2} \tag{3}$$

where

K_2 is a constant

P is the pressure

In order to study the effect of the reduction in transducer size, assume that the transducers have the same pressure range and are designed to have the same radial stress, S_{rc}, and thus a comparable output under these conditions. The relationship between the thickness and the radius of the element is

$$T^2 = \frac{K_2 P R^2}{S_{rc}} \text{ or } T = K_3 R \tag{4}$$

where K_3 is a constant.

Substituting for T in equation (2), the relationship describing the natural resonant frequency is

$$f_n = K_1 \frac{K_3 R}{R^2} = \frac{K_4}{R} \tag{5}$$

where $K_4 = K_1 K_3$.

This indicates that the natural frequency for transducers of the same pressure range and the same radial stresses in the center is inversely proportional to the clamped or active radius.

Thus, miniaturization plus the use of silicon for diaphragm material provides a substantial increase in the natural frequency. For example, going from a 2.5-cm-diameter metal diaphragm pressure transducer with 2.0-cm active diameter to a 3.2-mm diameter with 2.0-mm active diameter silicon diaphragm results in an increase of 10 x 2 = 20 times in natural frequency; and going to a pressure transducer with an 0.75-mm diameter and an active diameter of 0.25 mm results in an increase of 2 x 80 = 160 times in natural frequency.

The importance of the marked increase in natural frequency is the extension of the frequency response and the ability of the pressure transducer to respond to the very rapid rise time phenomena encountered in high explosive blast testing.

2. LIMITATION OF DIAPHRAGM APPROACH

The diaphragm approach, however, begins to show serious limitations above the range of 207 MPa This is because, as the diameter-to-thickness ratio of the disc becomes sufficiently small, undesirable shear stresses become a significant part of the total stress situation at the undersurface of the disc when loaded. These shear forces, in general, subtract from the bending stresses which represent the normal mode of operation of the device, and tend to create an unacceptably high nonlinear response.

When the diaphragm thickness-to-diameter ratio for a clamped-edge circular disc under normal pressure loading is about 0.1 or less, the theory of small displacements based on pure bending effects is quite accurate for practical calculations. The pertinent results for deflection (D) and radial bending stress (σ) as a function of radial distance (r) are as follows:

$$D\ (r) = D_o \left[1 - \left(\frac{r}{R}\right)^2\right]^2$$

$$\sigma\ (r) = \sigma_o \left[\left(\frac{3+\nu}{1+\nu}\right)\left(\frac{r}{R}\right)^2 - 1\right]$$ (Center in Compression)
(ν is Poisson's ratio)

$$D_o = \frac{3}{16}\ (1-\nu^2)\ \frac{P}{E}\frac{R^4}{T^3}$$

$$\sigma_o = \frac{3}{8}\ (1+\nu) P\left(\frac{R}{T}\right)^2 \quad (6)$$

D_o and σ_o are the deflection and radial stress at the center of the diaphragm, respectively.

For thick plates, however, the effect of shearing stresses becomes significant. The deflection D(r) due to combined shearing of the middle surface and bending of the plate is given by

$$D(r) = D_o \left[1 - \left(\frac{r}{R}\right)^2\right] \left[1 - \left(\frac{r}{R}\right)^2 + \frac{4}{1-\nu}\left(\frac{T}{R}\right)^2\right] \qquad (7)$$

$$D(o) = D_o \left[1 + \frac{4}{1-\nu}\left(\frac{T}{R}\right)^2\right] \quad \text{AT THE CENTER} \qquad (8)$$

And the effect of shearing on the bending stress is to translate the shape of the radial bending stress vs. radial distance to more negative values, namely

$$\sigma(r) = \sigma_o \left[\left(\frac{3+\nu}{1+\nu}\right)\left(\frac{r}{R}\right)^2 - 1 - \frac{2}{1-\nu}\left(\frac{T}{R}\right)^2\right] \qquad (9)$$

The additional term $\frac{2}{1-\nu}\left(\frac{T}{R}\right)^2$ in the stress equation indicates that when the thickness is about one-third the diameter, the edge strain becomes zero and the center strain becomes more negative. As a result of this shear effect, the total net stresses at the gage elements are reduced and the output of the transducer is correspondingly reduced. To achieve a given output, higher stresses must be employed resulting in a more nonlinear response. Thus, the well-behaved linear response of a flat diaphragm is lost as the thickness-to-diameter ratio is increased beyond 0.1.

3. LOAD CYLINDER APPROACH

a. Introduction—The above considerations dictate that for measurement of blast pressures above 2 kbar a new conceptual approach is needed. The concept developed in this effort is shown in Figure 3.

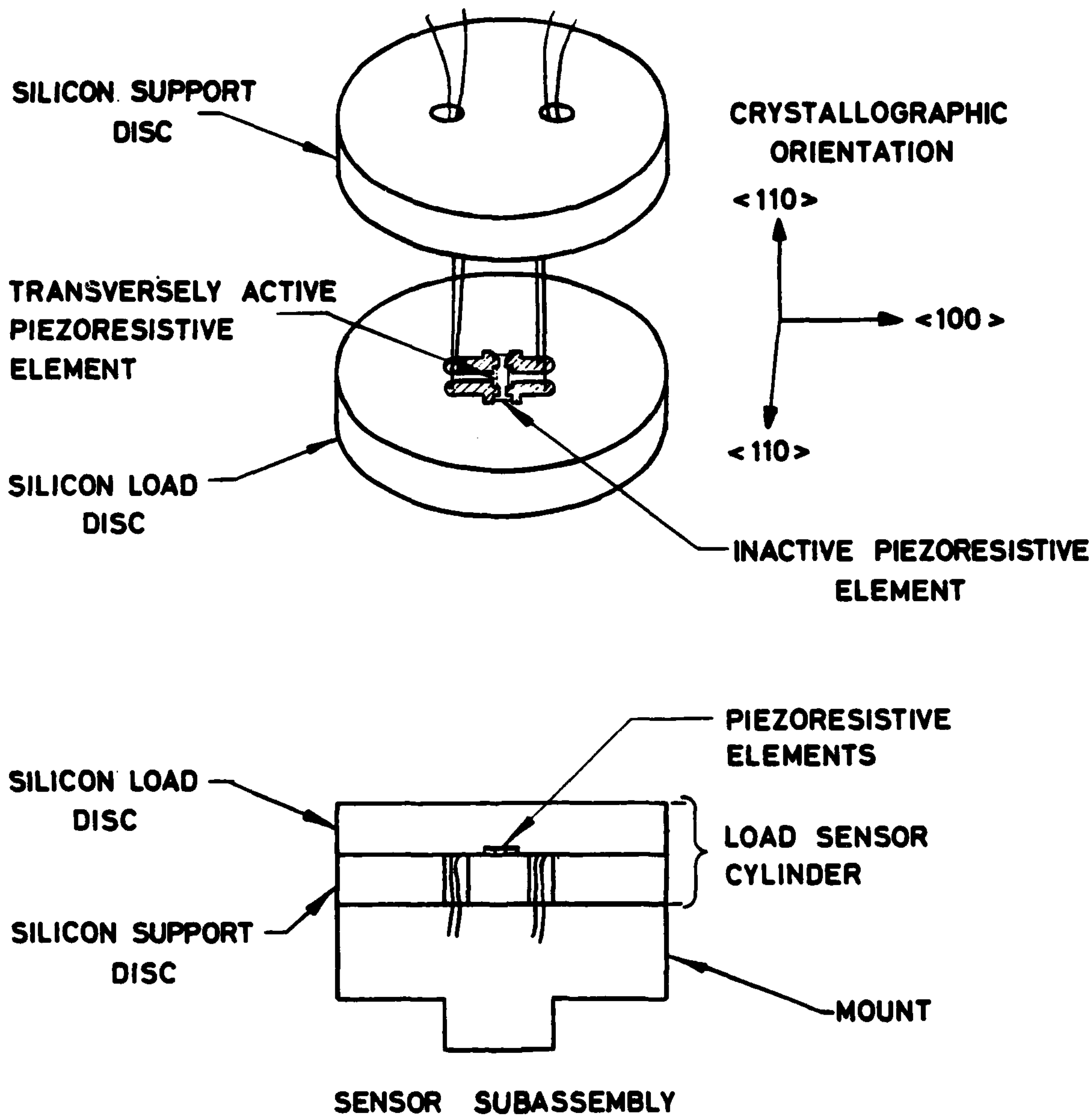

FIGURE 3. LOAD CYLINDER TYPE INTEGRATED SENSOR PRESSURE TRANSDUCER

The sensing element or silicon load cylinder is composed of an integrated sensor load disc and a silicon support disc. These two pieces are joined together with an epoxy bond, thus forming a silicon load cylinder. The piezoresistive elements are effectively embedded in the silicon load cylinder, and compressive loads may be readily applied to the piezoresistive elements in a uniform manner without undesirable stress concentrations by the application of a normal load.

A silicon disc 0.76 mm thick by about 0.44 cm in diameter is employed as a support disc. This second piece of silicon, having approximately the same overall dimensions but containing two small through-holes for lead exits, is joined to the sensor disc with a thin epoxy layer.

It is clear that a silicon load cylinder loaded uniaxially may be considered as a "load cell." This suggests an attractive technical solution.

The approach implemented makes use of the transverse piezoresistive properties of silicon to compressive load. When the load cylinder is appropriately mounted in a transducer structure, an applied pressure results in a compressive load on the load disc; this in turn results in compressive stress in the load disc. Since the piezoresistive elements are in the plane of the load disc, a normal compressive stress is exerted on these elements. If an appropriate crystallographic orientation is chosen, a significant resistance change is observed in the active piezoresistive elements due to the transverse piezoresistive effect. Rather than a clamped-edge deflecting disc, the structure is an integrated sensor load-disc wafer bonded to a solid silicon support plate and loaded in uniaxial compression.

The theory of such a device was discussed in a 1968 paper by Dr. Anthony Kurtz and Charles Gravel entitled, "Semiconductor Transducers Using Transverse and Shear Piezoresistance", which is listed in the bibliography.

The pressure sensor makes use only of the transverse piezoresistive coefficient. If a cylinder of silicon containing properly oriented embedded piezoresistive stress sensing elements is subjected to uniaxial compression, an output proportional to body stress is obtained. This configuration shown in Figure 3 uses two arms of a Wheatstone bridge having a large negative transverse stress gage factor as active bridge elements and two arms having essentially zero gage factor as inactive or dummy bridge elements. A suitable orientation for p-type silicon to achieve this is the plane of disc (110), direction of active elements (110) and direction of dummy or inactive elements (100). The sensitivity of such a device used in a Wheatstone bridge configuration is given by

$$\frac{\Delta V}{V} = \frac{1}{2} GF_t \varepsilon \tag{10}$$

where

GF_t is the effective transverse gage factor

ε is the strain

For the orientation and doping levels chosen

$$GF_t = -50 \tag{11}$$

So for an output of 30 mV/V, the required stress can be calculated as follows:

$$\frac{\Delta V}{V} = \frac{1}{2} (-50) \varepsilon \tag{12}$$

$$\frac{\Delta V}{V} = \frac{1}{2} (-50) \frac{\sigma}{E} \tag{13}$$

$$\sigma = -\frac{2E}{50} \times \frac{\Delta V}{V} \tag{14}$$

$$\sigma = -248.2 \text{ MPa} \tag{15}$$

Thus compressive stresses of the order of 248.2 MPa on the load cylinder are required. Such a stress level is well within the compressive strength of silicon, which is on the order of several thousand MPa.

Frequency response for such a device is inherently high. The frequency response of the silicon load cylinder is given by

$$f_n = \frac{1}{2\pi} \sqrt{\frac{Kg}{m}} \tag{16}$$

where

$$K = \frac{\pi R^2 E}{T} \tag{17}$$

$$m = \pi R^2 \rho T \tag{18}$$

where

R is the radius of the disc

E is Young's modulus = 1.93×10^5 MPa

T is the thickness of the disc

ρ is the density of silicon 2.3 gms/cm^3

Therefore

$$f_n = \frac{1}{2\pi T} \sqrt{\frac{Eg}{\rho}} = \frac{1.47 \times 10^5}{T} H_z \tag{19}$$

With thicknesses of 0.51 mm to 0.75 mm, the theoretical natural frequency is 2 to 3 MHz.

Two sensor configurations were developed and fabricated during this effort. The initial design uses an integrated sensor load disc type SQ33-350-163. A computer generated diffusion program is presented in Table 1 and a mask drawing of the device is shown in Figure 4. The program of Table 1 calculates relevant performance parameters and appropriate diffusion times for elements of various diffused line widths. The program is based on the classical diffusion equations. Initial measurements on transducers fabricated with this sensor indicated that the contract sensitivity goals could not be met.

A redesign of the sensor to achieve a higher gage factor and a bridge resistance increase from 350 to 750 Ω was accomplished as part of this effort. The higher gage resistance allowed the excitation level to be increased from 5 V to 10 V. The new configuration, which uses an integrated sensor load disc type C11-750-175, was a very successful design which allowed the contract sensitivity goals to be met. See Table 2 and Figure 5.

b. Device Fabrication--For proper stress transmission, the transversely active piezoresistive elements must essentially be embedded in the silicon load cylinder. This is accomplished by making the load sensor a two-piece structure. The first piece is a disc containing the piezoresistive element, and the second piece is a silicon support disc rigidly bonded to the first by the use of an epoxy adhesive.

TABLE 1. DIFFUSION PROGRAM FOR SQ33-350-175

INTEGRATED SENSOR SILICON LOAD DISC

DEVICE TYPE NUMBER: SQ33-350-175

MASK NUMBER: 700-B-18222

LINE WIDTH	OHMS/ SQUARE	SURFACE ATOMS/CC	TIME MINUTES	TEMP DEG-C	DEPTH MILS	%/100F TCGF	TCR	SPAN RATIO	GF (111)	GF (110)
0.11	1.58	0.764E 21	14.	1200.	0.163	4.1	9.8	0.7	60.	45.
0.12	1.72	0.764E 21	12.	1200.	0.150	4.1	9.8	0.7	60.	45.
0.13	1.86	0.764E 21	10.	1200.	0.139	4.1	9.8	0.7	60.	45.
0.14	2.01	0.764E 21	8.	1200.	0.128	4.1	9.8	0.7	60.	45.
0.15	2.15	0.764E 21	7.	1200.	0.120	4.1	9.8	0.7	60.	45.
0.16	2.30	0.764E 21	6.	1200.	0.112	4.1	9.8	0.7	60.	45.
0.17	2.45	0.764E 21	6.	1200.	0.105	4.1	9.8	0.7	60.	45.

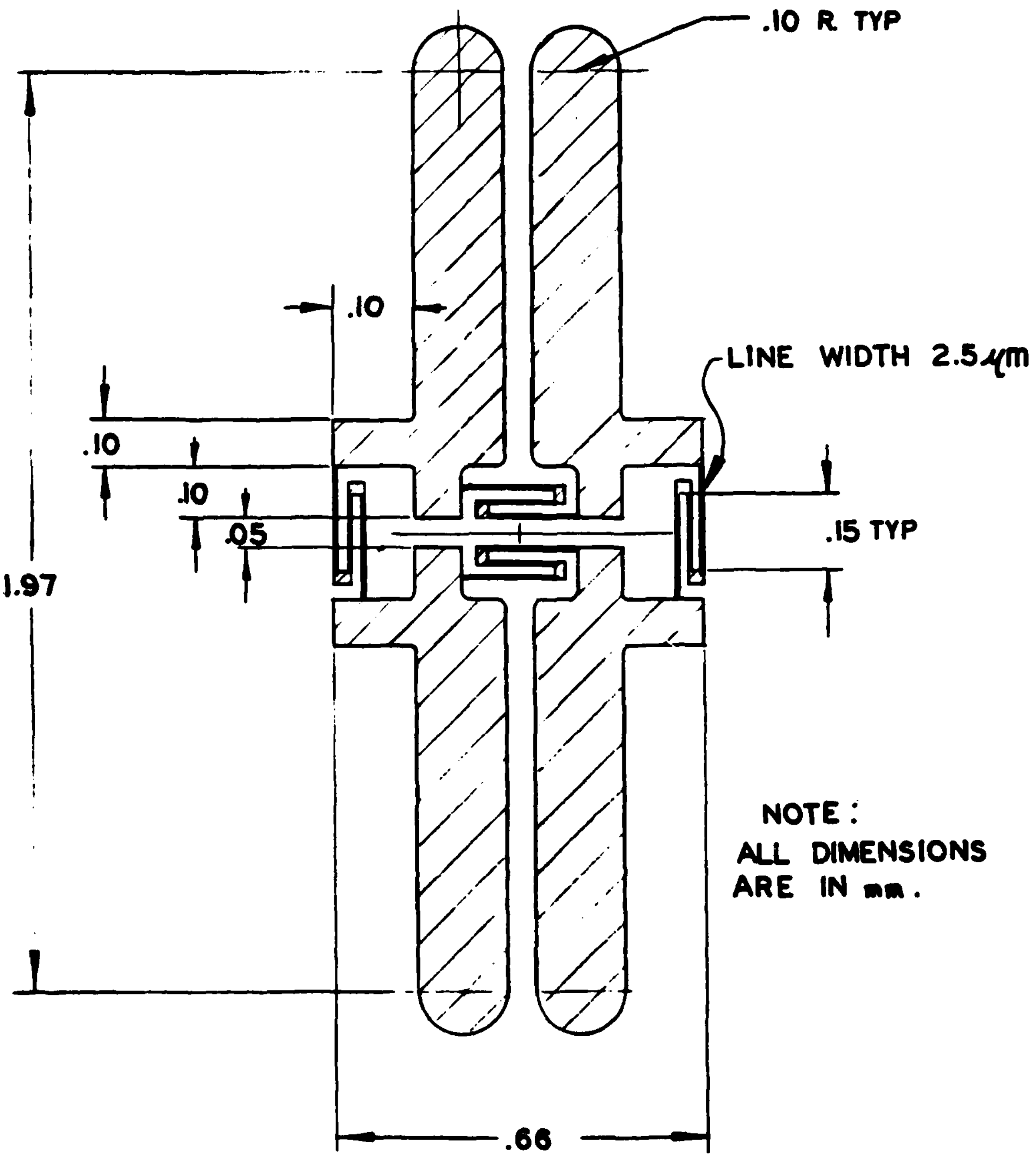

FIGURE 4. SC33-350-175 DIFFUSION MASK

TABLE 2. DIFFUSION PROGRAM FOR C11-750-175

INTEGRATED SENSOR SILICON LOAD DISC

DEVICE TYPE NUMBER: C11-750-175

MASK NUMBER: 700-B-21396

LINE WIDTH	OHMS/ SQUARE	SURFACE ATOMS/CC	TIME MINUTES	TEMP DEG-C	DEPTH MILS	%/100F TCGF	TCR	SPAN RATIO	GF (111)	GF (110)
0.66	50.30	0.245E 20	51.	1150.	0.160	10.8	5.5	-2.0	108.	81.
0.67	51.12	0.245E 20	49.	1150.	0.157	10.8	5.5	-2.0	108.	81.
0.68	51.93	0.245E 20	48.	1150.	0.155	10.8	5.5	-2.0	108.	81.
0.69	52.75	0.245E 20	46.	1150.	0.152	10.8	5.5	-2.0	108.	81.
0.70	53.57	0.245E 20	45.	1150.	0.150	10.8	5.5	-2.0	108.	81.
0.71	54.39	0.245E 20	44.	1150.	0.148	10.8	5.5	-2.0	108.	81.
0.72	55.21	0.245E 20	42.	1150.	0.146	10.8	5.5	-2.0	108.	81.

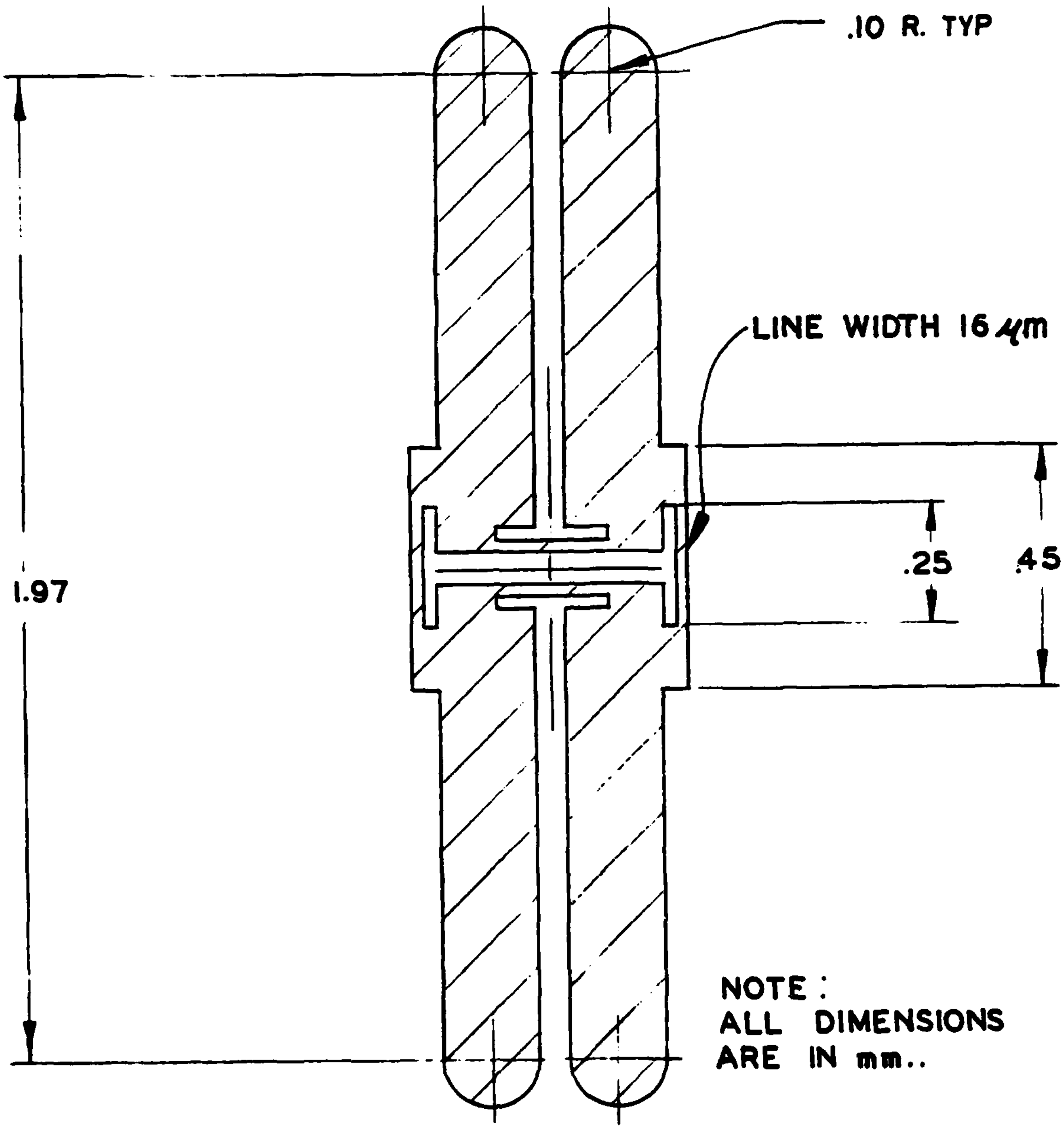

FIGURE 5. C11-350-175 DIFFUSION MASK

The load sensor disc is fabricated using standard photolithographic techniques to obtain the diffused pattern. The approximate depth of such a diffused layer is about 1 μm.

4. MECHANICAL DESIGN

The basis for the mechanical design of the transducer is the HKS-11-375. This transducer has proven rugged and reliable through many years of production at Kulite and field test use by the Air Force Weapons Laboratory and other agencies. The evaluation of this design has been well documented and will not be repeated here.

Figure 6 shows the mechanical construction of the HKS-11-375. The construction is essentially monolithic with no moving parts, allowing extremely high shock acceleration hardness; the measurand is coupled to the silicon disc through a small port in the sensing face of the unit via the thermal barrier material, TBS-758. This transducer employs an integrated sensor silicon disc using a conventional clamped-edge diaphragm. The techniques of construction were chosen and developed to meet the requirements of survivability and performance in the high explosive test environment. Preliminary testing of the load cylinder was done in this configuration. A two-sided clamping arrangement is accomplished when the load cylinder in Figure 3 is employed with the HKS-11-375 hardware of Figure 6. The load cylinder is clamped between the transducer body and the subassembly housing. It became apparent, however, that this mechanical configuration was inappropriate for this type of sensor. Test data given in a subsequent section show that this dual-sided clamping configuration interferes with the proper response of the silicon load cylinder.

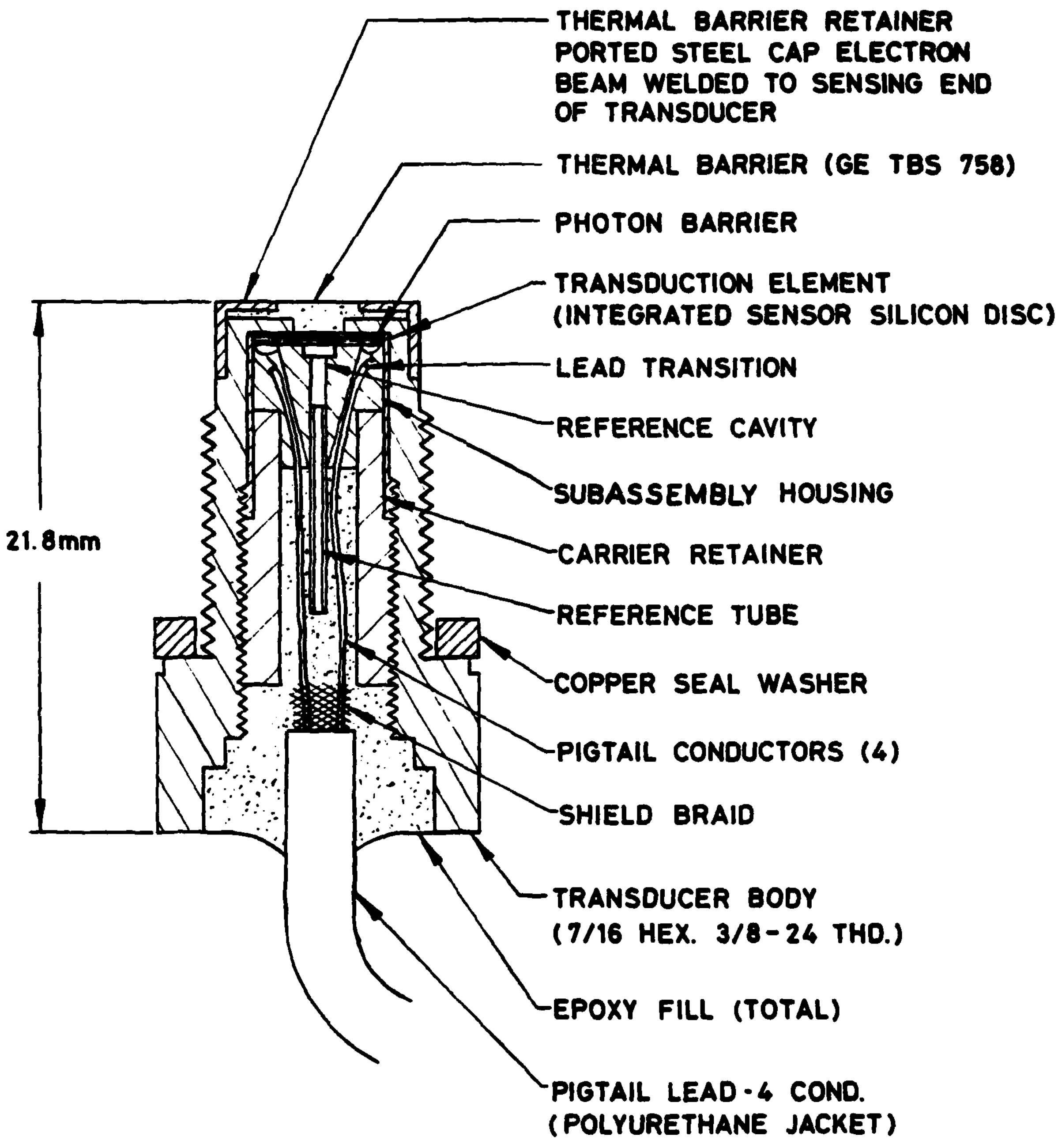

FIGURE 6. HKS-11-375-10K BLAST PRESSURE TRANSDUCER

The configuration shown in Figure 7 was investigated; several aspects of this design are noteworthy. The silicon load disc is mounted to a thick silicon support disc to form a silicon load cylinder. This technique insures a perfect thermal match between the sensor and its mounting. This is quite important for thermal and mechanical stability. The silicon load cylinder is epoxy mounted to a two-piece metal support housing to form a load sensor subassembly. The sensor subassembly is electron beam welded to the transducer threaded body. This technique insures the mechanical stability of the transducer. Proven techniques of construction are employed, including the leadwire interconnection system used in the HKS-11-375 and the combination of the GE TBS-758 thermal barrier and aluminum photon barrier employed in that transducer. The aluminum photon barrier precludes undesirable flash thermal responses.

Measurements showed that the configuration of Version I did not respond to static pressure. Essential to the operation of the device is the coupling of the measurand uniaxially to the sensor. The structure of Figure 7 allows the applied pressure to distribute itself hydrostatically through the low modulus TBS interface layer. An analysis shows that all crystallographic orientations for P-type silicon are insensitive to hydrostatic pressures. In fact, the configuration responded well to transient blast pressure wave fronts but could not be statically calibrated. The ability to effect matching static and dynamic calibration is a major advantage of the piezoresistive approach.

The structure of the HLC-1-375 Version II, shown in Figure 8, was developed to address this lack of static response by the use of an alternative coupling technique.

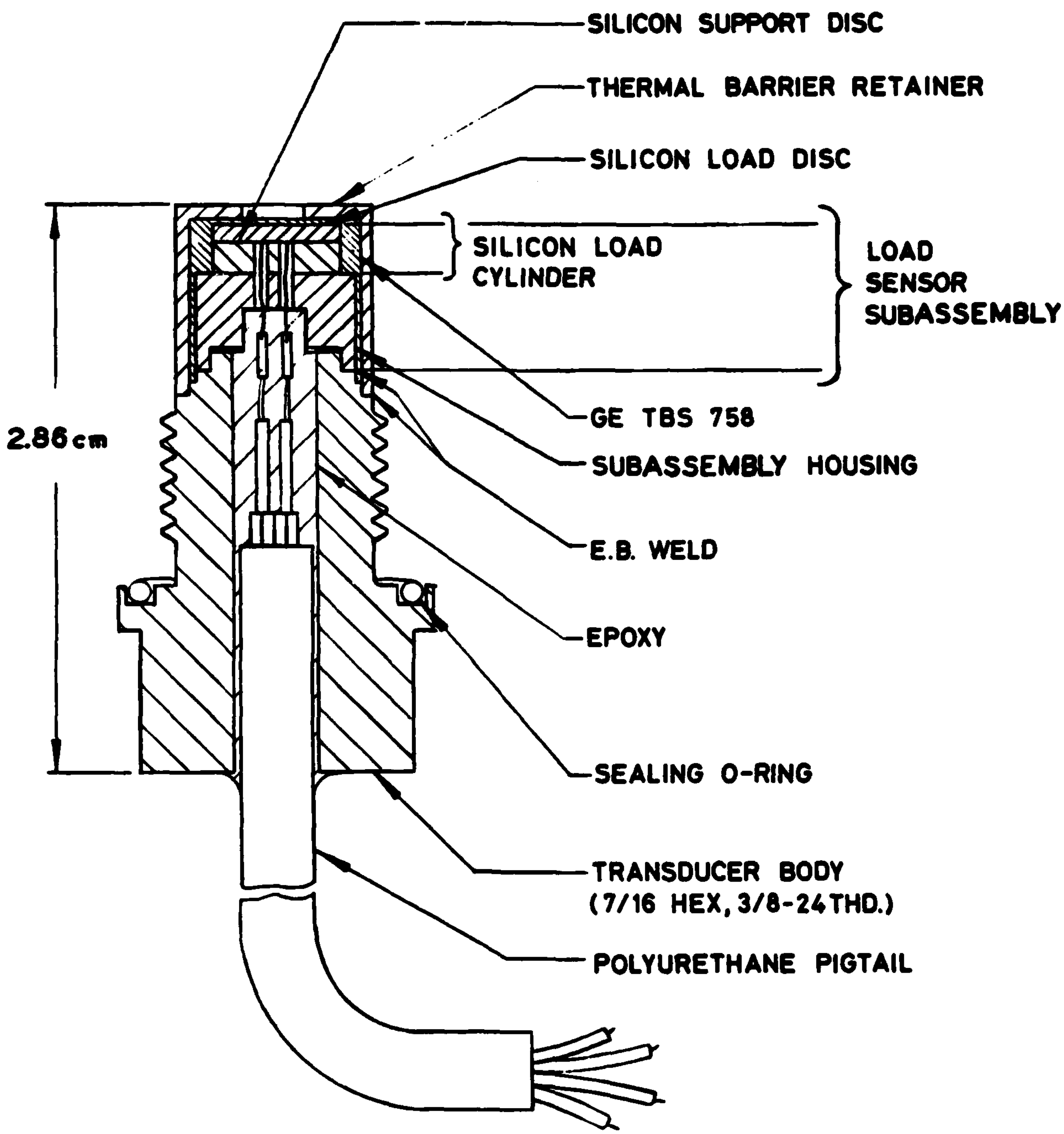

FIGURE 7. HLC-1-375-50K VERSION I LOAD CYLINDER TYPE BLAST PRESSURE TRANSDUCER

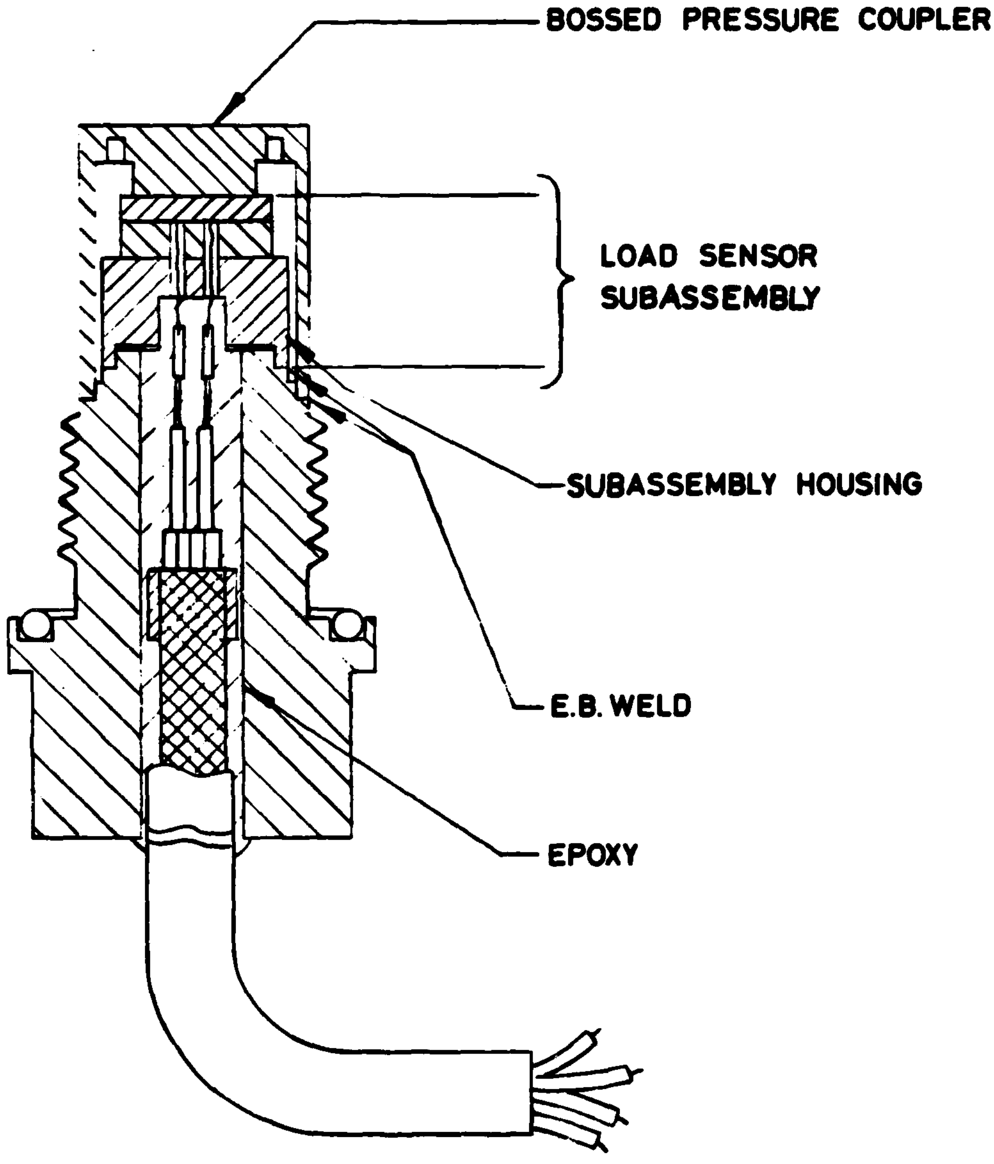

FIGURE 8. HLC-1-375-50K VERSION II LOAD CYLINDER TYPE PRESSURE TRANSDUCER EMPLOYING BOSSED PRESSURE COUPLER

The transducer of Figure 8 has a bossed metal force coupler to serve as force collector. This force coupler, which is integrally machined and electron beam welded, serves to couple the pressure measurand to the silicon load cylinder without need for a port. The metal face serves as an excellent photon barrier and supplies enough thermal and mechanical protection to the silicon load cylinder so that the Thermal Barrier Silicon layer normally employed is not required. If the TBS is found to be desirable for any reason, it may be added to the structure in the usual manner. An additional benefit of the metal face is that the relative dimensions of the boss and the groove may be varied to adjust the transducer sensitivity and range.

Experimental data on the subject transducers have verified the performance of this design.

IV. PROGRAM RESULTS AND EXPERIMENTAL DATA

1. PROGRAM SUMMARY

The following was accomplished during the course of the contract:

a. A number of transducers employing SQ-33-350-175 load cylinders were fabricated.

b. Preliminary measurements were made on transducers fabricated with HKS-11-375 parts. The SQ-33-350-175 load cylinder did not possess sufficient sensitivity to meet the contract; and the HKS-11-375 construction was not suitable for use with the load disc.

c. Accordingly, redesigns of the load sensor disc and the transducer structure were initiated. A new sensor mask (C11-750-175) and a load sensor disc of a higher gage sensitivity and bridge resistance were fabricated. The HLC-1-375 transducer design was accomplished and a number of transducer assemblies were manufactured. This design was unsuitable; it responded properly in a dynamic mode but was nonresponsive in a static mode.

d. The final design emerged as the HLC-1-375 Version II. This design was quite successful. Two versions were fabricated: a long version with a relatively thick boss and a short version with a thinner boss. It was felt that the stiffer, thicker boss might be necessary even at the penalty of higher mass loading. In fact, both versions performed within the contract goals.

e. Five transducers of Version II were fabricated and shock tube tested at Kirtland.

2. TEST RESULTS

An initial evaluation was performed with standard HKS-11-375 hardware and an SQ33-375-175 load disc.

The sensitivity of several sensors with 5 VDC excitation is listed below:

TABLE 3. SENSITIVITY OF SQ33-375-175 LOAD CYLINDER

Unit No.	Sensitivity (mV/Pa)
1	14.5
6	27.5
7	26.2

The above represents an average full-scale output of 165 mV. This is substantially below the contract goal of 300 mV nominal.

During the testing, the units displayed substantial hysteresis (approx. 5% F.S.) and zero nonreturn. Figure 6 shows that the HKS-11-375 structure results in the silicon load cylinder held in a double-sided clamped arrangement with the load sensor cylinder held between the transducer body and the element carrier. The double-sided clamp arrangement substantially restricted the proper deflection of the load disc and appeared to be the cause of the hysteresis. Also considered was the fact that the sealing washer and the general contruction of the HKS-11-375 were deemed not suitable for 3.4 kbar service.

A new design was required, so the HLC-1-375-50K Version I was conceived. A new load sensor disc (C11-750-175) with a higher gage factor and bridge resistance of 750 Ω was incorporated in this design.

The Version I configuration incorporated a very rugged, substantially reinforced, all electron-beam-welded transducer subassembly structure. A metal O ring is incorporated in the design replacing the usual copper washer. This O ring was tested and found to seal adequately at 345 MPa.

The significance of the 750 Ω bridge resistance is that it allows an excitation of 10 VDC with a minimum self-heating effect.

Table 4 plots the zero balance and resistance as a function of bridge excitation for a typical transducer.

TABLE 4. BRIDGE EXCITATION EFFECT FOR HLC-1-375-50K

V In (VDC)	V Out (mV)	R (Ω)
0	0 VDC	0
1	+ 2.42	726
2	+ 4.85	728
3	+ 7.32	731
4	+ 9.91	739
5	+12.72	739
6	+15.69	746
7	+18.75	745
8	+21.94	747
9	+25.39	743
10	+29.35	744

Table 4 shows that the zero balance is approximately proportional to the excitation voltage. The relatively slight deviation from linearity observed is the result of self-heating of the transducer as a result of the applied excitation. The relatively small increase in bridge resistance indicates that excitations of up to 10 VDC are within the capabilities of the transducer.

The above resistance change at 10 V represents a self-induced heating effect of 20°F which, based on extensive previous experience, is comfortable for this class of transducer.

At the excitation of 10 VDC and with the increased basic sensitivity of the new sensor, the contract goals were reachable.

Testing on the HLC-1-375-50,000 Version I, however, showed essentially no static pressure sensitivity. This result was caused by the geometry of the Version I pressure sensor. The front end of the transducer is the load disc encapsulated by a TBS protective layer which results in the applied static pressure distributing itself as hydrostatic pressure; and this class of sensor is insensitive to hydrostatic pressure.

The above considerations resulted in the redesign of the transducer to Version II. This version incorporates a bossed metal pressure coupler bonded to the load disc, and eliminates the undesirable stresses caused by the side loads of the hydrostatic force. Two varieties were designed and fabricated, a long version and a short version. The longer version has a considerably thicker and stiffer face. A number of transducers were fabricated and a suitable fabrication process was developed.

Five prototype transducers were tested for a number of parameters. Table 5 lists the sensitivities for each of the transducers.

TABLE 5. PRESSURE SENSITIVITY OF HLC-1-375-50,000 II PROTOTYPES

Serial No.	Type	Sensitivity (mV/V/Pa)
3976-3-7	Short	4.1
4332-5-14	Short	4.6
3976-3-3	Long	2.8
3976-3-5	Long	3.6
3976-3-8	Long	5.4

For an excitation of 10 V, the above is an average full-scale output of 298 mV, which is very close to the contract goal.

A typical full calibration is given in Table 6.

TABLE 6. TYPICAL PRESSURE CALIBRATION OF HLC-1-375-50K - VERSION II

S/N 3976-3-3 - EXCITATION 10 VDC

Pressure (MPa)	mV Out	Deviation %
0.0	24.61	-0.74
70.0	91.95	-0.43
139.9	160.63	+0.29
206.9	226.51	+0.16
275.9	293.57	+0.39
344.8	356.11	-0.74
275.9	294.35	+0.64
206.9	227.71	+0.52
139.9	162.12	+0.74
70.0	93.85	+0.14
0.0	25.88	-0.36

The units were tested per NBS Technical Note 905 for thermal response with a Sylvania #22 flash source. The units were found to have a rather low flash sensitivity as indicated in Table 7.

TABLE 7. HLC-1-375-50K - VERSION II

FLASH SENSITIVITY

Serial No.	Maximum Deviation (mV)
3976-3-3	0.55
3976-3-5	0.80
3976-3-8	0.55

The largest observed sensitivity is somewhat larger than the contract goal of 0.3 mV.

The transducers were tested for convection response with a propane torch on the sensing face as required in the statement of work.

The results are listed in Table 8.

TABLE 8. CONVECTION RESPONSE OF HLC-1-375-50K - VERSION II

Serial No.	Maximum Deviation (% F.S.)
3976-3-3	0.5%
3976-3-8	1.0%

This is within the contract goal of less than 2% of full-scale convection sensitivity.

Five prototype units were submitted for shock tube testing. An HKS-11-375-10K was used as a reference. The small 10-cm shock tube at the University of New Mexico Civil Engineering Research Facility (CERF) was employed for the testing.

Accelerations were measured in the end-plate mounting fixture. Typical peak reflected pressure levels were 28 MPa and simultaneous acceleration levels of up to 56,000 G were registered during the testing.

A total of 10 shots with two test transducers, the reference, and the acceleration shot were fired. Data were acquired using B&F strain gage signal conditioners and a Nicolet Explorer Digitizing Storage Oscilloscope; all transducers survived the testing. Zero unbalance before and after each shot was recorded, and changes were typically less than 0.1 mV, indicating exceptional mechanical and electrical stability. The results of Shot VIII, which are typical, are shown in Figures 9, 10 and 11.

In general, a good correlation is seen between the HKS and HLC. The HLC does seem to show a slightly faster decay. Further testing is required to determine the cause of this more rapid decay; however, it is likely to be more representative of the actual pressure signal than the HKS reference.

Note that Specimen 3-5 decays slightly below the base line. This is a long version and it protruded slightly from the end-plate, thus experiencing a slightly different reflected pressure environment.

When the transducer was made flush, it decayed properly to the base line. An analysis showed that the effect was caused by side pressure on the sensing end of the transducer. The effect of the positive side pressure was to place the load disc under negative loading. The solution is to use the transducer in a flush mode. An alternate solution is to provide a peripheral groove on the top surface of the diaphragm to eliminate the side stresses.

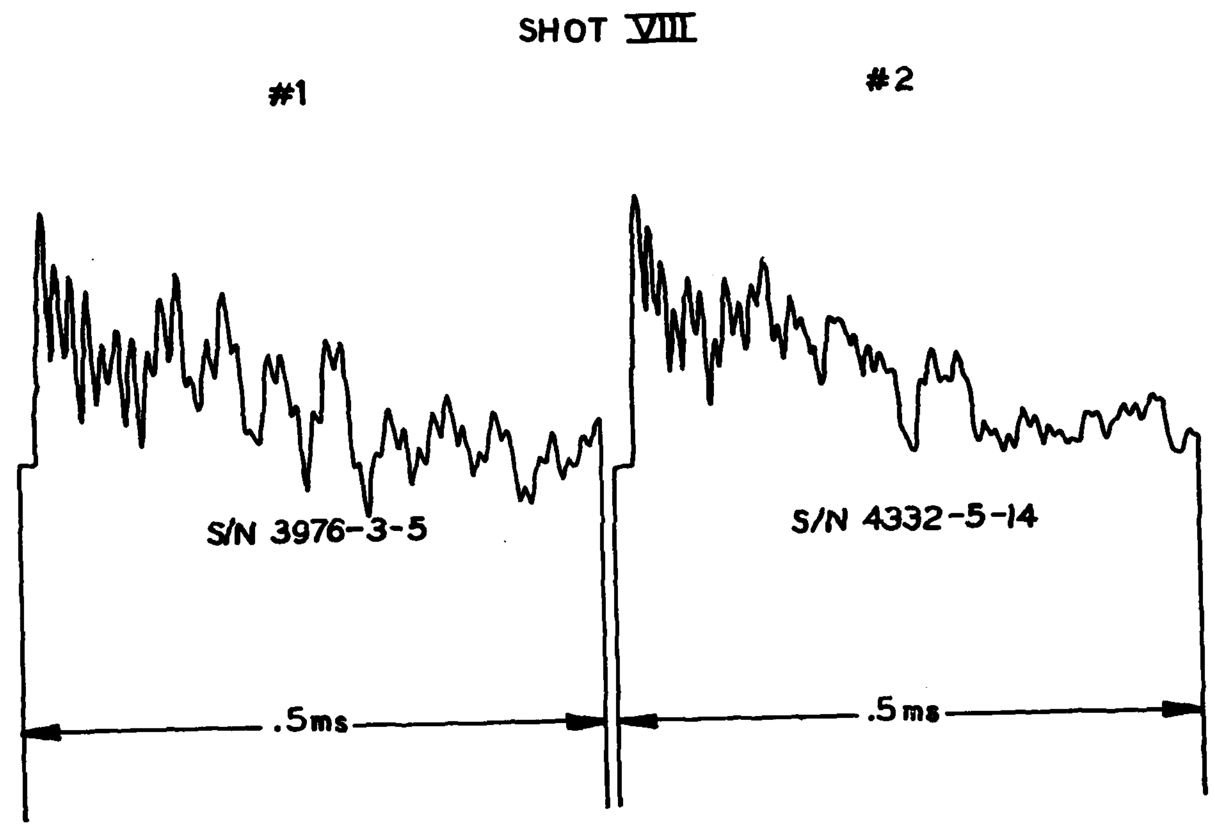

FIGURE 9. SHOCK TUBE TEST HLC-1-375-50K .5ms DURATION

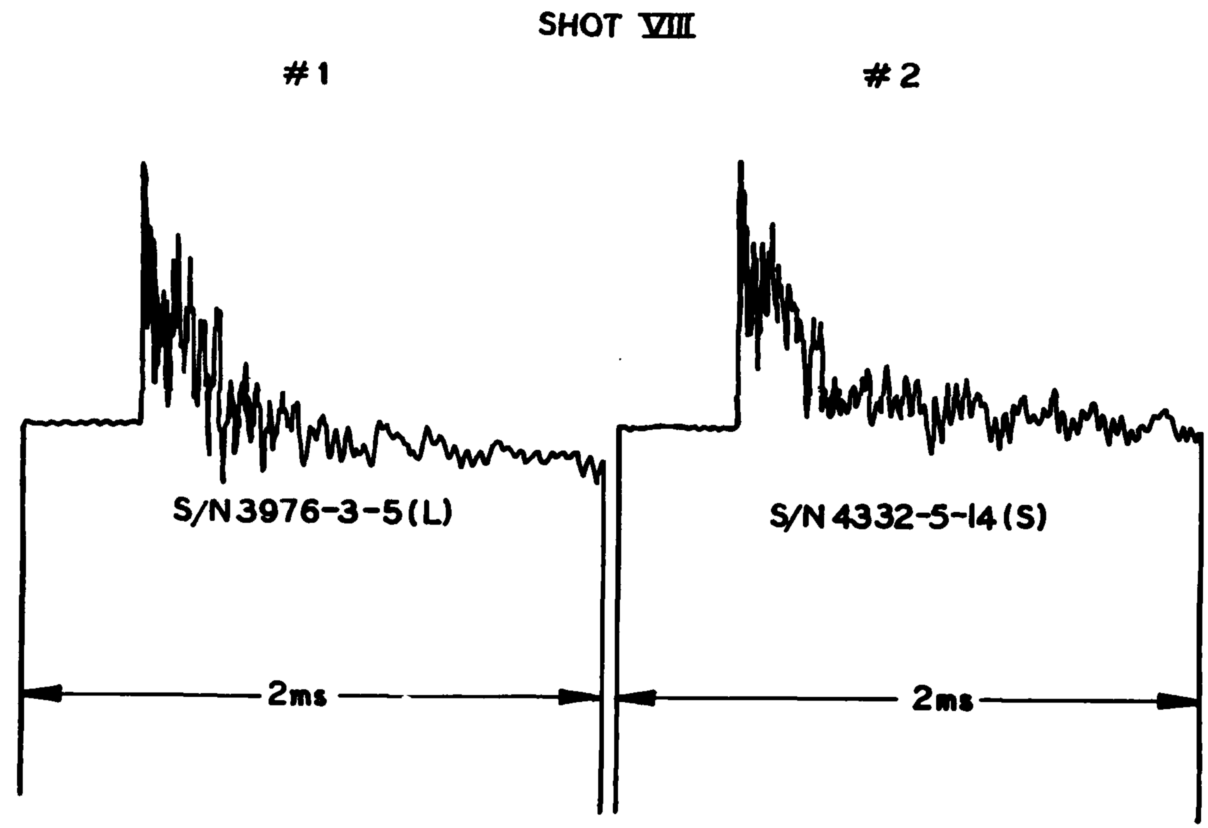

FIGURE 10. SHOCK TUBE TEST HCL-1-375-50K 2ms DURATION

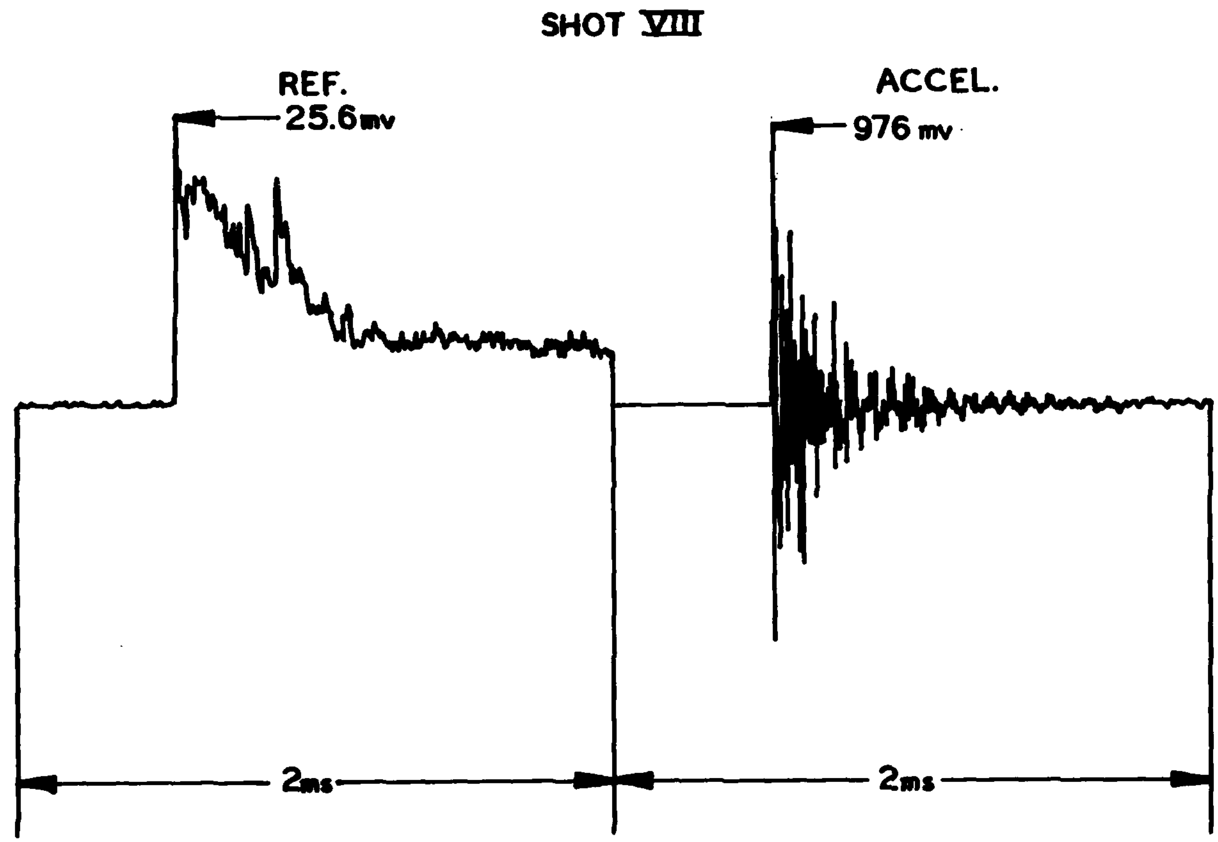

FIGURE 11. SHOCK TUBE TEST OF HKS-11-375-50K REFERENCE TRANSDUCER AND REFERENCE ACCELEROMETER, 2ms DURATION

V. CONCLUSIONS AND RECOMMENDATIONS

A novel pressure transducer was developed during this effort. The transducer, while drawing on the piezoresistive technology successful in the past, departs radically from that technology by making use of a silicon disc loaded in compression rather than the conventional flexing diaphragm normally loaded and universally employed in pressure transducers.

The initial results are quite encouraging.

a. The transducer in its final form is readily manufacturable.

b. The transducer meets the contract goals of sensitivity, resonant frequency and thermal sensitivity. Side-by-side shock tube tests at Kirtland using an HKS-11-375 as a reference indicated that the transducer performs as expected in a dynamic mode.

c. The transducer is thought to have high potential for field service in the acquisition of blast pressure data in high explosive environments.

The true test of a new transducer is its serviceability, reliability, and accuracy in simulated nuclear blast field tests. In this sense, the device remains to be proven and will be further evaluated by the Air Force.

Based on experience gained during this effort and a wealth of background design and production experience on the HKS-11-375, any problems which develop in field service can probably be addressed with minor modifications in the design. The design and its implementation appear to be sound based on the work accomplished. It is also anticipated that a design based on this principle should perform up to pressure levels of about 6.8 kbar.

In summary, a new transducer design has been implemented which extends the utility of silicon-based piezoresistive integrated sensors to the kilobar range. This design can serve as the basis for the next generation of very high-pressure blast measurements.

It is recommended that the HLC-1-375-50K be introduced into field service in sufficient quantities so that meaningful reliability and survivability data in the high explosive environment can be acquired.

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