NBSIR 84-2862

Development of a Polymer Pressure Gage With Temperature Compensation

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National Bureau of Standards
Center for Materials Science
Polymers Division
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Interim Report
Contract No. DLYV 82-64
James R. Holder, Contract Officer

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Air Force Armament Laboratory
Vulnerability Assessment Branch
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

The development of a temperature compensated pressure transducer is described. The pressure sensing element of this transducer is a thin film of polyvinylidene fluoride which is both piezoelectrically and pyroelectrically active. In order to measure accurately a pressure pulse which is also accompanied by a temperature pulse due to adiabatic compressional heating, it is necessary to correct for the pyroelectric signal. The temperature compensation technique which we use is to measure the temperature with a fast response thermocouple, to amplify the thermocouple signal in accordance to the pyroelectric response of the transducer and to combine the transducer and amplified thermocouple signals to produce an output voltage proportional to pressure only. A compensation circuit with a frequency range of 1 Hz to 10^4 Hz was constructed and tested. The transducer was calibrated and tested using pressure pulses whose peak value was 2.1×10^7 Pa (3000 psi) and whose pulse width was approximately 5 to 10 ms. For these measurements, the transducer was placed in an oil pressure chamber at room temperature and the pressure pulse was initiated by dropping a 16 kg mass onto a plunger in the chamber. Signals from the PVDF transducer, from a reference pressure transducer and from a thermocouple were captured by a transient recorder. The pressure measured with the calibrated and compensated PVDF transducer was found to agree satisfactorially with the signal from the reference pressure gage.

SECTION I

INTRODUCTION (U)[a]

The piezoelectric material which forms the active element in this pressure gage is polyvinylidene fluoride (PVDF). It is available as thin sheets or films which are normally inactive and becomes piezoelectrically and pyroelectrically active by poling a region of the material with a large electric field. Because of its transducer behavior, PVDF has been studied and characterized in many materials experiments and transducer applications in our laboratory and elsewhere[1,2,3,4]. The designs of a variety of gages, hydrophones, pyroelectric detectors and acoustic drivers have incorporated an active PVDF element[5,6,7]. Although most of these applications involve small pressure signals, there have been some published data on the use of PVDF to measure pressure in shock tests. In laboratory shock tube experiments, Bauer has shown that PVDF can be used as a detector up to pressures of 2.5 x 10^9 newtons/m^2 (Pa) (3.6 x 10^5 psi)[8]. There appears to be no inherent materials shortcoming which would inhibit the use of PVDF at high pressures.

One of the thermodynamic consequences of pulses of high pressure imposed on a PVDF pressure gage and its surroundings is adiabatic heating which will produce a pyroelectric response along with the piezoelectric response. This effect was discussed by DeReggi et al who considered the relative time effects of pressure induced temperature changes in PVDF and temperature changes which occur in the surrounding medium[5]. Adiabatic heating of the PVDF will occur in coincidence with its pressure change, i.e. there will be no time delay of a thermal energy pulse with respect to the pressure pulse. When adiabatic heating of the

[a](U) indicates that this material is unclassified.

surrounding medium occurs, the thermal time constant for diffusion of heat into the gage will determine its pyroelectric response as a function of time. If the temperature changes in PVDF and its surroundings are identical, then there will be no heat transfer and the pyroelectric response will be due to adiabatic heating of the PVDF only. Calculations for this special case show that the pyroelectric charge signal is approximately 8% of the piezoelectric charge[5]. In general, adiabatic heating in both PVDF and its surroundings along with the time scale of each effect must be considered. For the PVDF gages used in this investigation, the time constant, τ, for heat to diffuse into the gage from the surroundings is approximately 30 milliseconds (ms). For pressure measurements at $t \ll \tau$ temperature compensation can be achieved by applying the 8% correction to the transducer signals. For longer times the conduction of heat from the surroundings must be measured in order to apply the appropriate correction to the electrical signal from the PVDF gage.

The measurement system, which we describe here, has been developed for the purpose of obtaining accurate dynamic pressure data in the presence of a changing thermal environment. Compensation is achieved by using a thermocouple with a fast response time to measure temperature changes in the PVDF gage. The dynamic range of the compensated measurement can be as broad as 0.1 Hz to 10^5 Hz. Pressure measurements at higher frequencies, 10^6 - 10^8 Hz, can also be made as long as the 8% temperature compensation is applied.

SECTION II

METHOD OF COMPENSATION (U)

The method of temperature compensation we have chosen is: (a) to measure the temperature change of the PVDF transducer using a thermocouple; (b) to amplify the thermocouple voltage to equal that generated by the pyroelectric

response of the gage; and (c) to add the transducer voltage to the amplified thermocouple voltage yielding a corrected gage voltage. This corrected output is proportional to the pressure which is applied to the active area of the transducer.

Figure 1 illustrates the compensation method. Since the PVDF transducer is a charge generating device, its signal is converted to a voltage via a feedback capacitor C_f, in a charge amplifier. When the transducer responds to both temperature and pressure simultaneously, the transducer charge, $q_t = q_p - q_{th}$, where q_p is the charge proportional to pressure and q_{th} is the charge proportional to temperature. These charges combine out of phase because a positive pressure and a positive temperature will generate charges of opposite sign. The feedback capacitor converts these charges to corresponding voltages, $e_t = q_p/C_f - q_{th}/C_f = e_p - e'_{th}$ where e'_{th} is the voltage proportional to the temperature change ΔT, e_p is a voltage proportional to the pressure change ΔP, and e_t is the output (transducer) voltage from the charge amplifier. In terms of pyroelectric and hydrostatic piezoelectric coefficients λ and d_h we have

$$q_p = d_h A_e \Delta P \tag{1}$$

$$q_{th} = \lambda A_e \Delta T, \tag{2}$$

where A_e is the area of the electrodes. Equations (1) and (2) define the coefficients λ and d_h.

The thermocouple junction, which is positioned close to the active area of the transducer, provides a voltage, $V_{th} = K\Delta T$ where K is the thermocouple constant. V_{th} is amplified to equal the quantity e_{th} by an amplification factor, A_f, so that $e_{th} = A_f V_{th}$. When e_{th} is set equal to e'_{th} by adjusting A_f and when e_t and e_{th} are added, we have

$$e_t + e_{th} = e_p - e'_{th} + e_{th} = e_p \tag{3}$$

and the compensation is achieved.

A_f can be obtained experimentally by subjecting the transducer to a temperature change with no accompanying pressure change. In this case, the gage output should be zero. In experiments to be described below, the transducer is immersed in hot or cold water and the value A_f is adjusted until the addition, $A_fV_{th} + e_t$, is zero.

A calculation of A_f can be carried out by noting that

$$\frac{q_{th}}{C_f} = \frac{\lambda A_e \Delta T}{C_f} \quad . \tag{4}$$

Substituting $\Delta T = V_{th}/K$ into equation (4) we have

$$e'_{th} = \frac{q_{th}}{C_f} = \left(\frac{\lambda A_e}{C_f K}\right) V_{th} \quad . \tag{5}$$

Our objective is to achieve the equality, $e_{th} = e'_{th}$, where

$$e_{th} = A_f V_{th}. \tag{6}$$

Thus, a comparison between (5) and (6) yields

$$A_f = \frac{\lambda A_e}{C_f K} \; , \tag{7}$$

which is a dimensionless quantity.

A_f is proportional to λ and inversely proportional to C_f. Using $C_f = 10^4$ picofarads (pf) and considering typical values of λ = 4 nanocoulombs per square centimeter per degree Centigrade (nC/cm^2°C), A_e = 1 square centimeter (cm^2) and K = 41 microvolts per degree Centigrade (μV/°C) (for copper-constantan),

$$\frac{\lambda A_e}{C_f K} \approx 10^4 \; . \tag{8}$$

SECTION III

THE MEASUREMENT SYSTEM (U)

The temperature compensated pressure gage contains three essential elements: (a) the active PVDF transducer; (b) a thermocouple having a short rise time; and (c) compensation amplifiers which add the transducer and thermocouple signals.

1. (U) DESIGN OF THE TRANSDUCER

The PVDF transducer with thermocouple is shown in Figure 2. It is made from four sheets of PVDF which have been laminated together using epoxy. The inner two sheets (12 micrometer (µm) thickness) contain active areas on which aluminum electrodes have been deposited. The active area is 1 cm in diameter. The outer two layers (25 micrometer (µm) thickness) serve as protection for the inner two so that the gage can be used in environments requiring mechanical ruggedness. A copper-constantan thermocouple junction, made with 75 µm (3 mil) wire, is placed between the inner two sheets and within 2 millimeters (mm) of the active transducer area. The overall thickness of the transducer is approximately 0.13 mm.

Prior to lamination the electroded regions are made piezoelectrically active by poling them at room temperature with an electric field of 2 megavolts/centimeter (MV/cm). The active areas are then laminated face-to-face so that the polarization vectors in each element point in opposite directions. In this bilaminate pattern, the ground electrodes are on the exterior surface and the inner electrodes carry the signal potential. One of the advantages of this design is that signals generated in the two elements by bending are opposite in polarity and add to zero. Other details regarding gage construction can be obtained from published reports[9,10].

We have chosen the symmetric geometrical configuration of Figure 2 because this arrangement will yield nearly coincident thermal response times for both the transducer charge, q(t), and the thermocouple voltage, $V_{th}(t)$. If we consider thermal energy associated with a pressure pulse traversing across the thickness of the PVDF film from one side to the other, the conduction of heat can be described approximately by a solution to the heat flow equation in one dimension[11]. The responses q(t) and $V_{th}(t)$ will not be exactly the same, however, because $V_{th}(t)$ changes directly with T(t), the temperature change, but q(t) follows the integral of temperature over the thickness of the film[12,13]. Solutions to the heat equation are that both T(t) (or $V_{th}(t)$) and q(t) are expressed as Fourier series both of which contain the same dominant thermal time constant,

$$\tau = \frac{4\ell^2}{\pi^2\kappa} \tag{9}$$

where ℓ is the thickness of the transducer and κ is its thermal conductivity. Since the time constant varies with ℓ^2, it is important that thickness of the transducer be the same at the region of piezo-sensitivity and at the location of the thermocouple.

The differences in $V_{th}(t)$ and q(t) appear in the coefficients of the Fourier series and in the constant term, but these differences are minimized in the symmetric configuration. For a transducer thickness of 2 mil (50 micrometers) with thermocouple and piezo-sensitive region symmetrically positioned in the center, calculations show that $V_{th}(t)$ lags q(t) by 0.4 milliseconds (ms) and that the overall rise time is approximately 9 ms. (It should be emphasized that this response time corresponds to the thermal response of the gage and is not indicative of its response to pressure. Response to pressure as fast as 50 nanoseconds (ns) has been observed in shock tests by Bauer[8].)

The inherent rise time of the thermocouple, independent of its surroundings, was measured using a light flash to deposit thermal energy at the thermocouple junction. In this experiment the thermocouple signal is not determined by the thermal conductivity of the medium surrounding the junction, but rather by the geometry and electrical characteristics of the junction itself. Using a light pulse with a 20 microsecond (μs) rise time, we observed that the rise time of the thermocouple was 50 μs. Thus, the thermocouple can be used to detect adiabatic heating in the PVDF for times longer than 50 μs and can detect satisfactorially the diffusion of heat from the surroundings into the PVDF gage, for which the time constant is 30 ms. For times shorter than 50 μs, an 8% correction due to the adiabatic heating of PVDF should be used.

2. (U) DESIGN OF THE COMPENSATION CIRCUIT

In Figure 3 we show the amplifiers to which the signals from the transducer and the thermocouple are connected. The PVDF transducer is grounded on the side of negative polarization so that the output voltage of the charge amplifier is negative when a positive pressure is applied, i.e. $e_t = -\Delta Q/C_f$ where ΔQ is the charge generated by a positive pressure change ΔP. The time constants, R_fC_f and R_2C_2, determine the high and low frequency 3 db points and are set at 220 ms and 32 μs respectively; this corresponds to a frequency range from 1 Hz to 10^4 Hz. The amplifier A_2 is a voltage follower with a gain of 1 which serves as a buffer.

Amplifiers A_3 and A_4 determine the amplication factor A_f for the thermocouple signal. The exact value of A_f which is needed for a particular transducer can be obtained by adjusting the gain of A_4. The value of the input amplification, A_3, is set at 400. High and low frequency 3db points are established using time constants R_4C_4 and R_5C_5 where $R_4C_4 = R_2C_2$ and $R_5C_5 = R_fC_f$ so that the phase shifts for the transducer and thermocouple amplifiers are the same.

Since positive ΔP will contract the volume of the transducer and positive ΔT will expand the volume, these two energy excitations will produce opposite electrical charge responses in the transducer. Therefore the corrected signal e_p is obtained by adding e_t and e_{th}. This is done in the adder A_5. The output of A_5 is the reverse polarity of the input and is a positive voltage for a positive ΔP applied to the transducer.

In the compensating circuit, low noise operational amplifiers are used. This is particularly necessary at the high gain input amplifier A_3 where an OP16E operational amplifier is used. The resultant noise level permits a sensitivity of ΔT = 0.2 °C. Values of circuit elements are listed in the Appendix.

The compensation circuit also contains output connections so that the thermocouple signal and the uncorrected transducer signal can be monitored. By inspecting the uncorrected signal, it is possible to obtain information about the pressure pulse at frequencies higher than 10^4 Hz.

SECTION IV

TESTING THE COMPENSATION CIRCUIT (U)

The operating characteristics of the compensating circuit were examined by measuring the outputs, e_t and e_{th}, when a step function charge signal and a step function voltage signal were applied to the transducer and thermocouple amplifiers. The input charge signal consisted of a 5V step in series with a 3300 pf capacitor having a rise time of 5 μs. The input voltage to the thermocouple amplifier, A_3, was a 4 mv step with a rise time of 5 μs. The outputs e_t and e_{th}, display a characteristic roll-off with a 220 ms time constant which is identical in both amplifiers and therefore the resultant phase shift for each signal is the same.

In order to determine the amount of temperature compensation attainable using this circuit, two experimental tests were designed. In one test, a transducer with encapsulated thermocouple was immersed into a cold water bath by slapping the broadside surface of the transducer against the surface of the water. In the other test, the surface of the transducer was sprayed with a dull black paint which serves as a light absorber. A light pulse was then directed at the surface of the transducer and a pulse of thermal energy was absorbed. In both experiments, we attempt to simulate the onset of a thermal pulse at the site of the transducer.

The physics of the two experiments are somewhat different, however. For the water immersion experiment, the surface of the transducer in contact with the water is held at the bath temperature and heat diffuses in such a way that the transducer reaches an equilibrium temperature equal to that of the bath. For the light flash experiment, a pulse of thermal energy is imparted to the surface of the transducer and subsequently diffuses into the gage; at longer times the transducer has an average temperature which is higher than the surroundings. The water immersion test approximates the physical conditions present when the transducer is buried in soil, i.e. the transducer maintains contact with the soil which acts as a thermal reservoir. The thermal flash approximates conditions relevant to the transducer in air.

Although we have obtained valuable information from both tests, we have relied on the water immersion test to set the gain level of amplifier A_4. Since this experiment is carried out at zero pressure change, the desired output of the compensation circuit is zero. In Figure 4, we show the response curves from two immersion tests: Each experiment yields three curves: (a) the output from the transducer, e_t; (b) the signal, e_{th};

and (c) the corrected (temperature compensated) output, e_p. In Figure 4a, the gain level has been set too high. In Figure 4b the gain has been set at the optimum for maximum cancellation of the thermal or pyroelectric signal. For the data of Figure 4, the peak temperature change is approximately 3 °C and the peak value of e_t is approximately 1V.

When the initial response of the transducer and thermocouple is coincident and the rise time of each signal is the same, maximum compensation will be achieved. In Figure 4b, we note that small differences in the two signals lead to small excursions from zero in the output, e_p. Typically, 95% or more of the pyroelectric signal can be compensated by this method.

SECTION V

CALIBRATION OF GAGE IN AN OIL PRESSURE CELL (U)

The objective of the calibration is to obtain a value of d_h, the hydrostatic piezoelectric constant, for dynamic pressure pulses having a pulse width of approximately 10 ms and peak pressures between 100 and 3000 psi (7×10^5 and 2.1×10^7 Pa). For short pressure pulses, a temperature change usually accompanies the pressure change, so that

$$q_t = q_p - q_{th} = d_h A_e P - \lambda A_e T . \qquad (10)$$

When T, P and q_t are functions of time,

$$d_h = \frac{q_t(t) + \lambda A_e T(t)}{A_e P(t)} \qquad (11)$$

Since this equation will be the relationship used to determine d_h, we must make an independent measurement of λ. This is done by subjecting the transducer to a temperature change at zero pressure change. The water

immersion experiment, by which we adjust the value of A_f, can also be used to determine λ. From the data of Figure 4, λ can be determined by taking the ratio of charge to change in temperature and dividing by the area of the electrodes. Values of λ for several transducers are shown in Table I.

For the pressure experiment, the PVDF transducer is placed in an oil pressure cell at room temperature and the pressure pulse is initiated by dropping a 16 kg mass through a distance of approximately 30 cm onto a plunger in the cell as shown in Figure 5. Signals from an accelerometer (attached to the drop weight), the transducer, the reference pressure transducer and the thermocouple are captured by a transient recorder signal processor.

The pressure cell consists of a stainless steel block, 7.5 cm wide x 16 cm deep x 15.2 cm high (3 in. x $6\frac{1}{4}$ in. x 6 in.), with a 1.90 cm bore traversing the 16 cm dimension. At one end of the bore, the reference transducer, which is a resistive device with a response time of 60 μs, is placed; at the other end, feedthrough connectors carry signals from the PVDF transducer and thermocouple. The plunger fits as a piston into a 2.54 cm bore with vertical orientation which intersects with the horizontal bore. In preparation for the measurements, the cell is filled with either a vacuum pump oil or an alkyl benzene dielectric oil. Care was taken to remove all visible bubbles from the oil, but we did not degas the oil under vacuum. During the test, the cell is placed at the bottom of a vertical column which guides the drop weight as it falls onto the plunger.

Signals from the accelerometer, PVDF, thermocouple and reference pressure gage, respectively a(t), $q_t(t)$, T(t) and $P_r(t)$, are captured individually by a signal processing system. The compensation circuit is not employed here, but rather, these four signals are used to verify its operation and to independently ascertain the degree of compensation which is attainable. Examples of the signals observed during a drop test are shown in Figures 6 and

7. Here, we note that T(t) contains a significant amount of unwanted noise. It is the result of low signal-to-noise ratio at the input amplifier of the signal processing system. The total temperature change is about 0.5 °C or a thermocouple signal of 20 microvolts (μV) and the overriding noise is approximately 2.5 μV peak-to-peak. The correction to the transducer signal due to the pyroelectric effect will be about 15%.

The data of Figure 6 are captured digitally, each trace containing several hundred points. Using equation (11), we make a point-by-point calculation of d_h across the trace of the pressure pulse. The result is shown in Figure 7 where d_h for transducer AF-31 is plotted versus time along with a(t). Near zero time, oscillations occur in the result because the signals are small and contain electrical and ringing noise. When P(t) (or a(t)) is close to zero the calculation involves dividing by a small number and obtaining an abnormally large value for d_h. Over the central region of the pulse, however, d_h is seen to be constant with a value of 13.6 $\frac{pC}{N}$.[c]

SECTION VI

MEASUREMENT OF PRESSURE USING THE COMPENSATION CIRCUIT (U)

The calibrated transducer AF-31 and the compensator were employed together for the measurement of pressure pulses in the same oil cell. A comparison was made to a reference pressure pulse obtained from the accelerometer signal, a(t). Here,

$$P(t) = \frac{ma(t)}{A_p} \qquad (12)$$

[c]These numbers are called gage constants and are calculated using the area of the face of the transducer A_e. The material's d constant is only half this vlaue since the bilaminate configuration would require dividing the charge by $2A_e$ instead of A_e.

where m is the mass of the drop weight and A_p is the area of the plunger. Equation (12) was checked in turn with the resistive pressure gage in the chamber. The estimated uncertainty in the measurement of P(t) using the accelerometer signal is ± 1%.

The two pressure signals are shown in Figure 8. It is seen that the PVDF pressure pulse faithfully follows the reference signal. There is, however, noise on the PVDF signal which is attributed entirely to the thermocouple input amplifier. If translated into pressure, the uncertainty in the PVDF pressure measurement due this noise is ± 3.50×10^5 Pa (± 50 psi).

SECTION VII

DISCUSSION AND CONCLUSIONS (U)

The adiabatic heating under pressure of the PVDF and oil was just large enough that compensation was appropriate. In soil, which usually contains a small fraction of gas, or in air, we expect that adiabatic heating will be larger and the need for compensation greater. It should be emphasized that compensation is achieved for times greater than 50 μs which is the rise time of the thermocouple. At shorter times the adiabatic heating of the PVDF will produce a pyroelectric signal which decreases the transducer output by approximately 8%. Both long and short time data can be acquired using the compensating circuit because the uncorrected signal, e_u, from the charge amplifier A_1 will contain short-time information. If e_u is sent thru a high pass RC filter, whose time constant is 32 μs, and if this signal is then increased by 8% and added to e_p (the compensated signal), a full spectrum of pressure data for long and short times will be obtained.

A constant value of d_h, which we observe up to a pressure of 2.1×10^6 Pa (3000 psi), indicates that we are operating the transducer in the linear range. At much higher pressures (5×10^4 psi), non-linear effects can be expected since

the compressibility of the PVDF decreases with pressure[8]. This would be reflected as a decrease in output charge per unit applied pressure or, in other words, an effective decrease in d_h. A close inspection of the data of Figure 7 shows a slight dip in the center of the curve corresponding to a minimum in d_h at peak pressure. We observed this effect routinely in the calibration experiment when the peak pressure surpassed 7×10^6 Pa (1000 psi). The effect is small at these relatively low pressures, only 3 or 4%, i. e. several times less than the overall accuracy of our measurement of pressure which we estimate to be ± 10% with a sensitivity of 3.5×10^4 Pa (50 psi).

A needed improvement in the compensation circuit is to lower the electrical noise in amplifier A_3, the input amplifier for the thermocouple signal. At present, A_3 is an OP16E, an operational amplifier with 5 μV peak-to-peak noise and wide bandwidth capacity. At the time of construction of this compensating amplifier, the OP16E represented the optimum for low cost, wide bandwidth amplifiers. As the market and the state-of-the-art improve in this area, other units will be available to replace the OP16E.

SECTION VII

APPENDIX (U)

The following is a list of the components used in the temperature compensation circuit shown in Figure 3.

- Amplifiers A_1, A_2, A_3[d], A_4 and A_5:

  operational amplifier OP16E

- Resistors and capacitors:

  R_{in} - 5 ohms

  R_f - 22×10^6 ohms

  R_2 - 4.7×10^3 ohms

  R_3 - 560 ohms

  R_4 - 2.2×10^5 ohms

  R_5 - 22×10^3 ohms

  R_6 - 1×10^6 ohm variable

  R_7 - 5×10^3 ohm

  R_8 - 5×10^3 ohm

  R_9 - 5×10^3 ohms variable

  C_f - 10^4 pF

  C_2 - 6800 pF

  C_4 - 150 pF

  C_5 - 10 μF

- Thermocouple:

  Copper-Constantan

d Operational amplifier, OP27, has lower noise characteristics than the OP16E and could be used for amplifier A_3.

References

1.) "Piezoelectricity and Pyroelectricity in Polyvinylidene Fluoride - A Model" by M. G. Broadhurst, G. T. Davis, J. E. McKinney and R. E. Collins, J. Appl. Phys. 49, 4992 (1978).

2.) "Piezoelectricity and Pyroelectricity in Polyvinylidene Fluoride" by R. G. Kepler and R. A. Anderson, J. Appl. Phys. 49, 4490 (1978).

3.) "Characterization and Piezoelectric Activity of Stretched and Poled Polyvinylidene Fluoride. Part I: Effect of Draw Ratio and Poling Conditions" by R. J. Shuford, A. F. Wilde, J. J. Ricca, and G. R. Thomas, Polym. Eng. Sci. 16, 25 (1976).

4.) "Ferroelectric Reorientation of Crystallites in Polyvinylidene Fluoride" by N. Takahashi and A. Odajima, Ferroelectrics 32, 49 (1981).

5.) "Piezoelectric Polymer Transducers for Dynamic Pressure Measurements" by A. S. DeReggi, S. Edelman, S. C. Roth, National Bureau of Standards Internal Report, NBSIR 76-1078, June 1976.

6.) "Ferroelectric Polymers and Their Applications" by Michael Marcus, Ferroelectrics 40, 29 (1982).

7.) "Piezoelectricity in Polyvinylidene Fluoride" by G. M. Sessler, J. Acoust. Soc. Am. 70, 1596 (1981).

8.) "Piezoelectric and Pyroelectric Polymers" by F. Bauer, Polymers as Synthetic Metals Conf., London, May, 1983.

9.) "Room Temperature Poling of Polyvinylidene Fluoride with Deposited Metal Electrodes" by J. M. Kenney and S. C. Roth, J. Res. Nat'l. Bur. Stds. 84, 447 (1979).

10.) "Piezoelectricity and Pyroelectricity in Polymer Electrets" by M. G. Broadburst, W. P. Harris, F. I. Mopsik, and C. G. Malmberg, in Electrets, Charge Storage and Transport in Dielectrics, M. M. Perlman, Ed., Electrochemical Soc., Princeton, NJ, p. 492 (1973).

11.) Conduction of Heat in Solids, by H. S. Carslaw and J. C. Jaeger, Oxford University Press, Amen House, London, 1948, p. 84.

12.) "Determination of Charge or Polarization Distribution Across Polymer Electrets by the Thermal Pulse Method and Fourier Analysis" by A. S. DeReggi, C. M. Guttman, F. I. Mopsik, G. T. Davis and M. G. Broadhurst, Phys. Rev. Letters 40, 413 (1978).

13.) "Numerical Evaluation of the Dielectric Polarization Distribution From Thermal Pulse Data" by F. I. Mopsik and A. S. DeReggi, J. Appl. Phys. 53, 4333 (1982).

FIGURE CAPTIONS

Figure 1.. The technique of temperature compensation is described.

Figure 2. A diagram of the PVDF transducer with thermocouple is shown.

Figure 3. A schematic diagram of the temperature compensation circuit is shown.

Figure 4. The response curves, e_t, e_{th} and e_p, are shown for two water immersion experiments. Temperature change was approximately 3 °C. (a) Amplification factor, A_4, set too high; (b) A_4 set for optimum compensation.

Figure 5. A diagram of the drop test and pressure cell is shown.

Figure 6. Signals, T(t), q(t) and $P_r(t)$, from a drop test experiment are shown. Peak pressure is approximately 7×10^6 Pa (1000 psi). Maximum temperature change is approximately 0.5 °C. The peak charge is approximately 7.4×10^{-9} C.

Figure 7. d_h and a(t) are plotted versus time for PVDF transducer AF-31.

Figure 8. P(t) is plotted versus time for the reference pressure gage (the accelerometer) and for the calibrated PVDF transducer AF-31. The signal with the larger noise component is from the PVDF transducer.

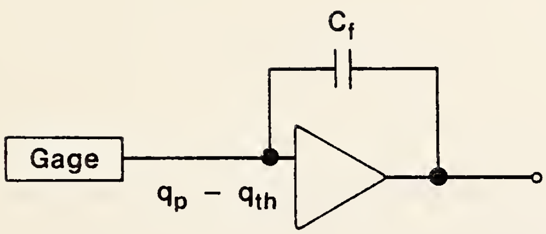
TABLE I

Pyroelectric Coefficient, λ

Transducer	λ[b]
AF-16	4.4 $\frac{nC}{cm^2\,°C}$
AF-18	4.0
AF-19	3.0
AF-31	3.4

[b] These numbers are called gage constants and are calculated using the area of the face of the transducer, A_e. The material's λ constant is only half this value since the bilaminate configuration would require dividing the charge by $2A_e$ instead of A_e.

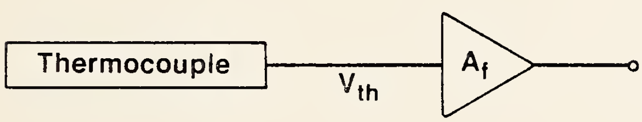
Compensation



$$e_t = \frac{q_p}{C_f} - \frac{q_{th}}{C_f}$$

$$\text{where } q_{th} = \lambda A_e \Delta T$$

$$q_p = d_h A_e \Delta P$$



$$e_{th} = A_f V_{th}$$

$$\text{if } A_f V_{th} = \frac{q_{th}}{C_f},$$

$$\text{then } e_t + e_{th} = \frac{q_p}{C_f}$$

Figure 1

PVDF Transducer

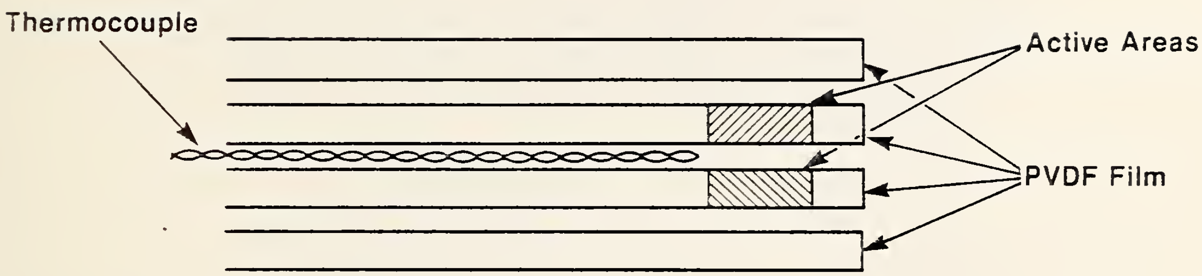
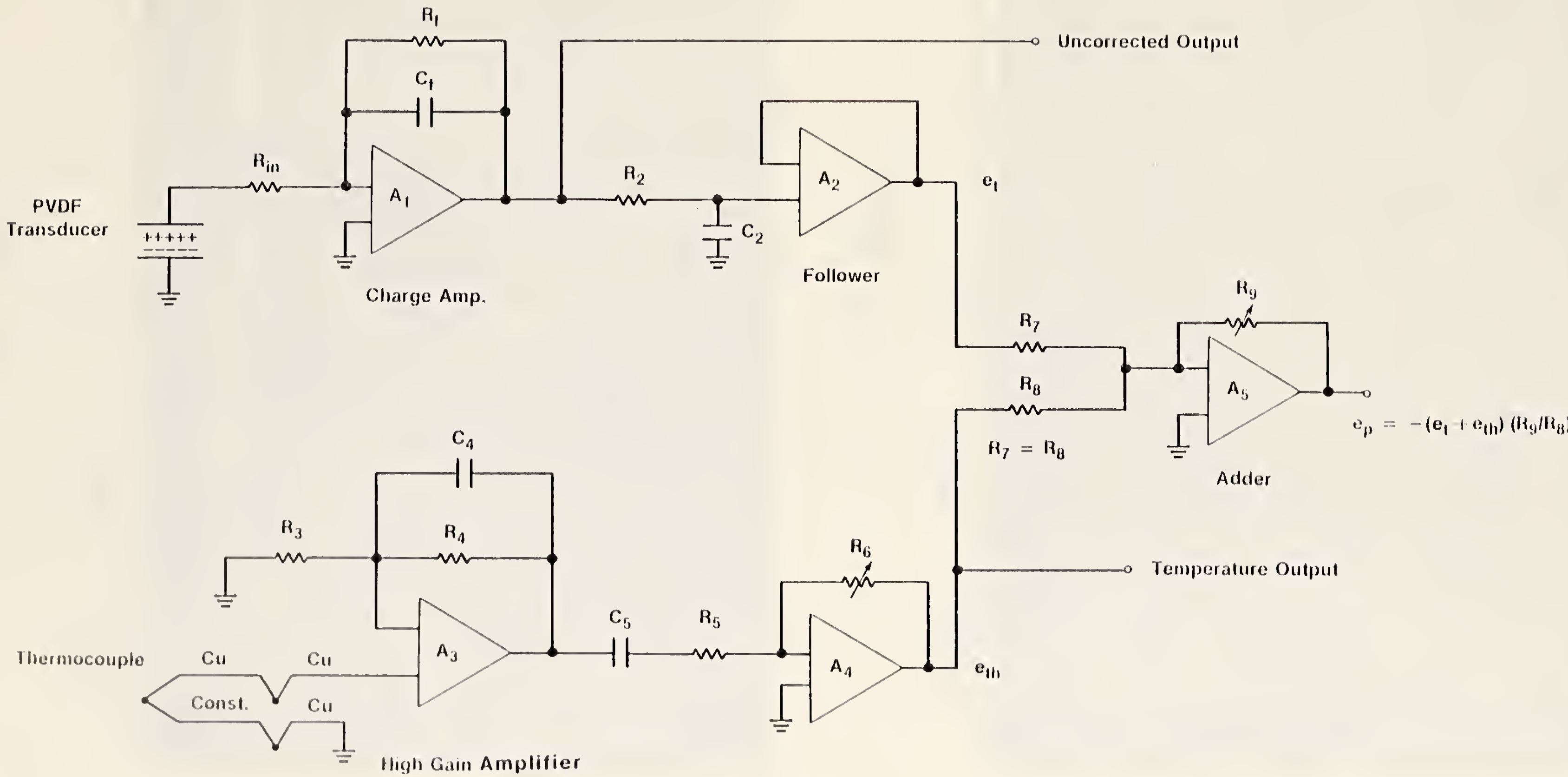
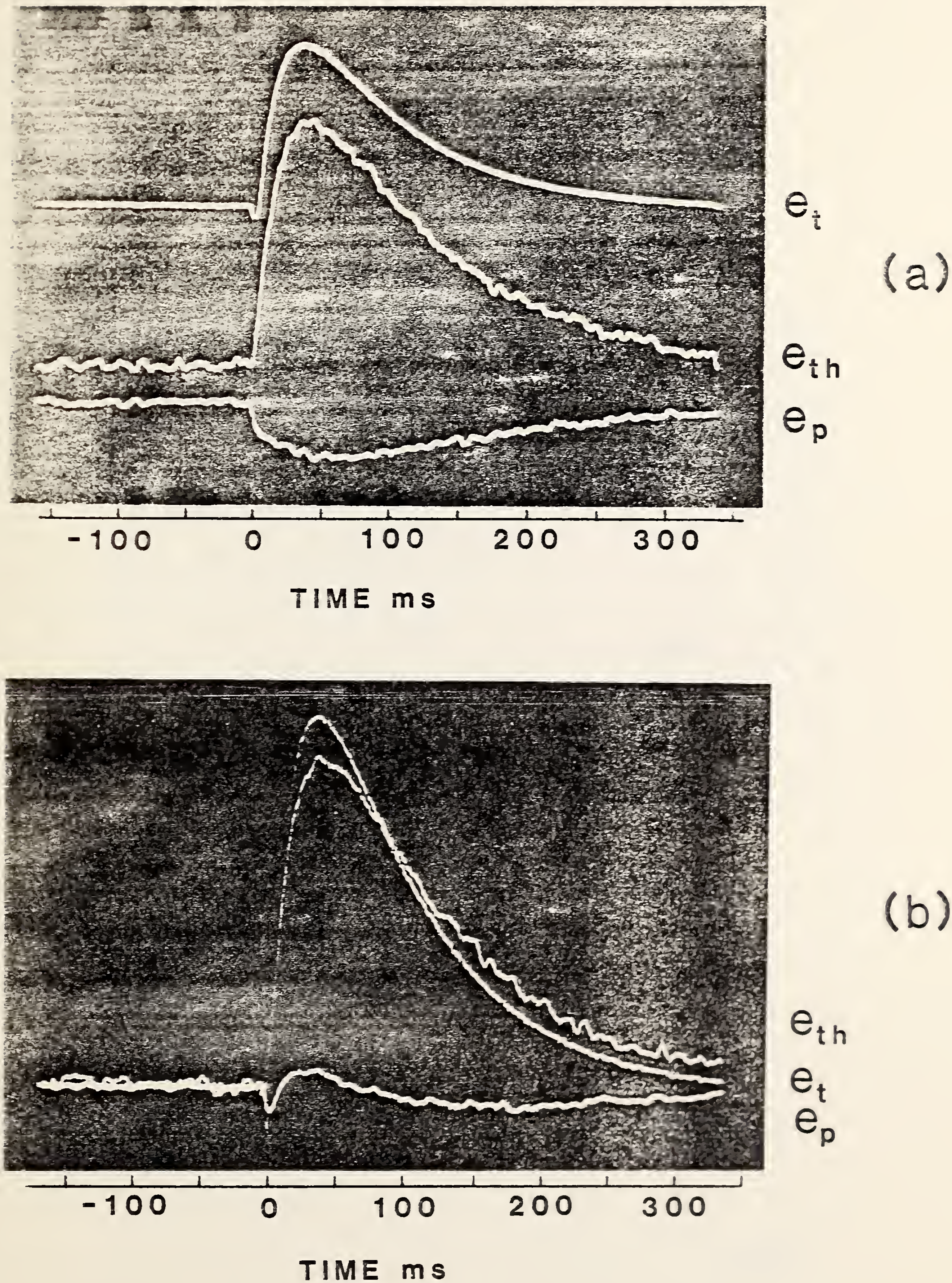


Figure 2



R_f
C_f
R_in
PVDF Transducer
A_1
Charge Amp.
Uncorrected Output
R_2
C_2
A_2
Follower
e_t
R_7
R_8
R_7 = R_8
R_9
A_5
Adder
e_p = −(e_t + e_th) (R_9/R_8)
C_4
R_3
R_4
A_3
Thermocouple
Cu
Cu
Const.
Cu
High Gain Amplifier
C_5
R_5
R_6
A_4
e_th
Temperature Output

FIGURE 3



e_t
(a)
e_{th}
e_p
-100
0
100
200
300
TIME ms
(b)
e_{th}
e_t
e_p
-100
0
100
200
300
TIME ms

FIGURE 4

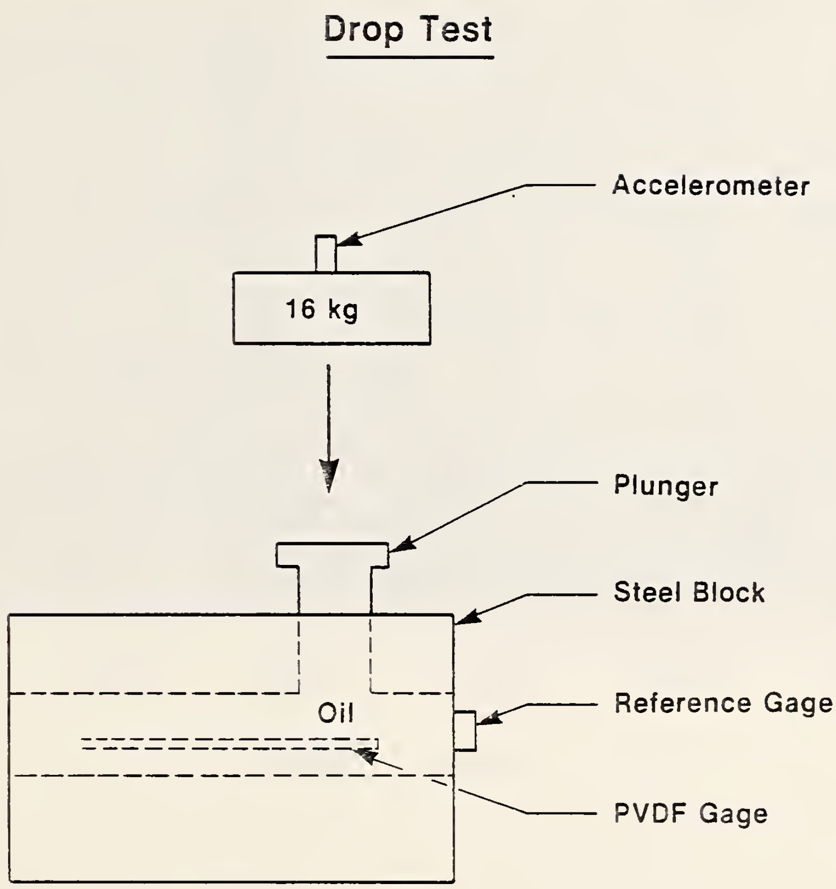

Drop Test
Accelerometer
16 kg
Plunger
Steel Block
Oil
Reference Gage
PVDF Gage

FIGURE 5

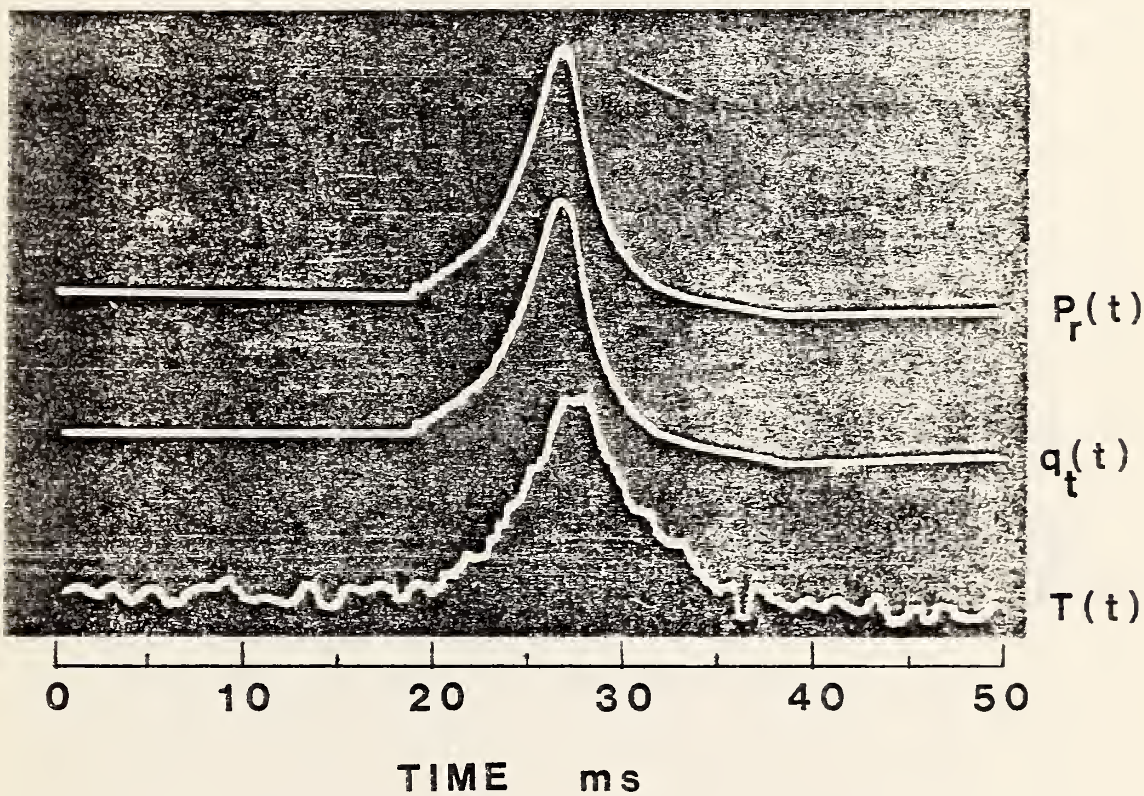


FIGURE 6

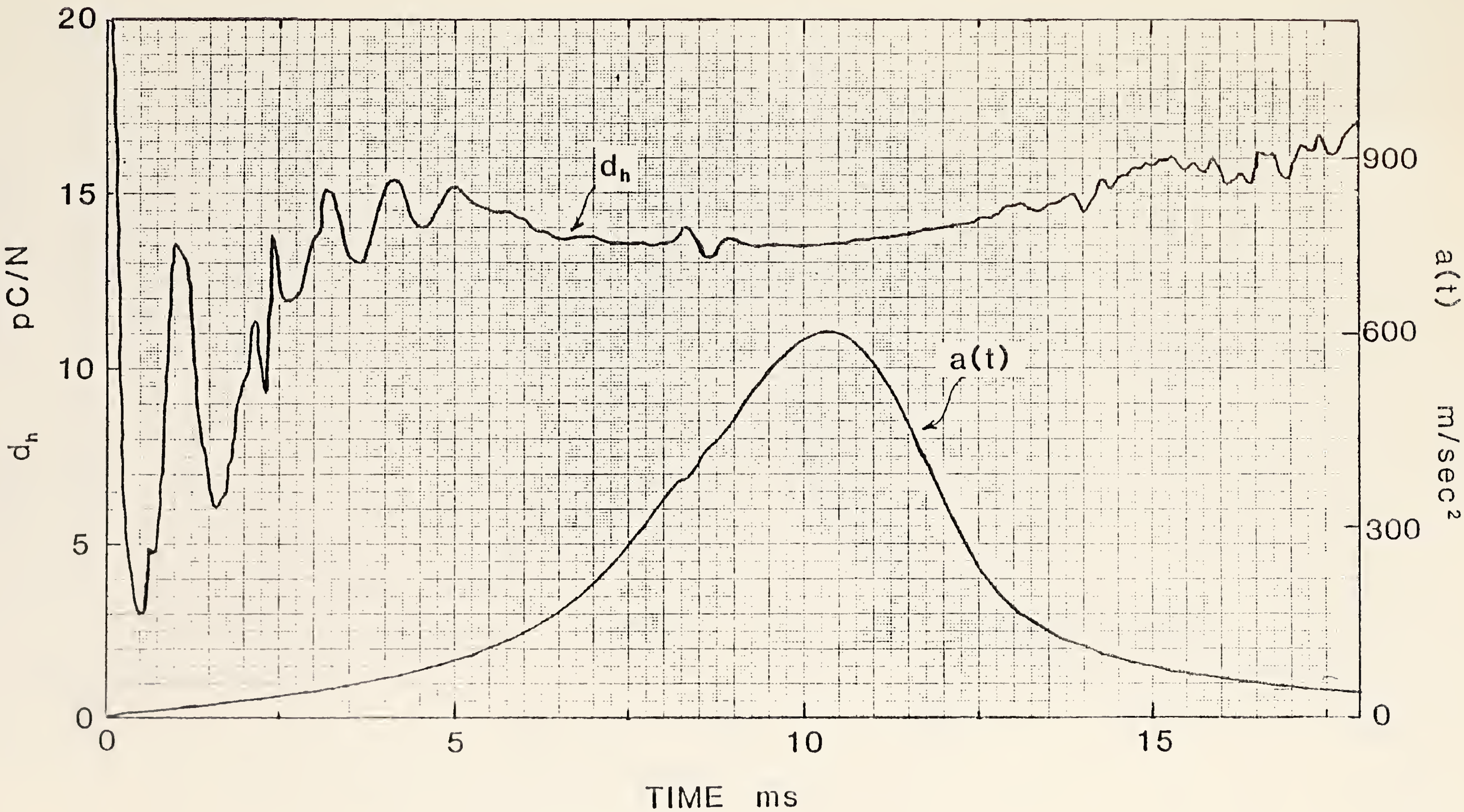


Figure 7

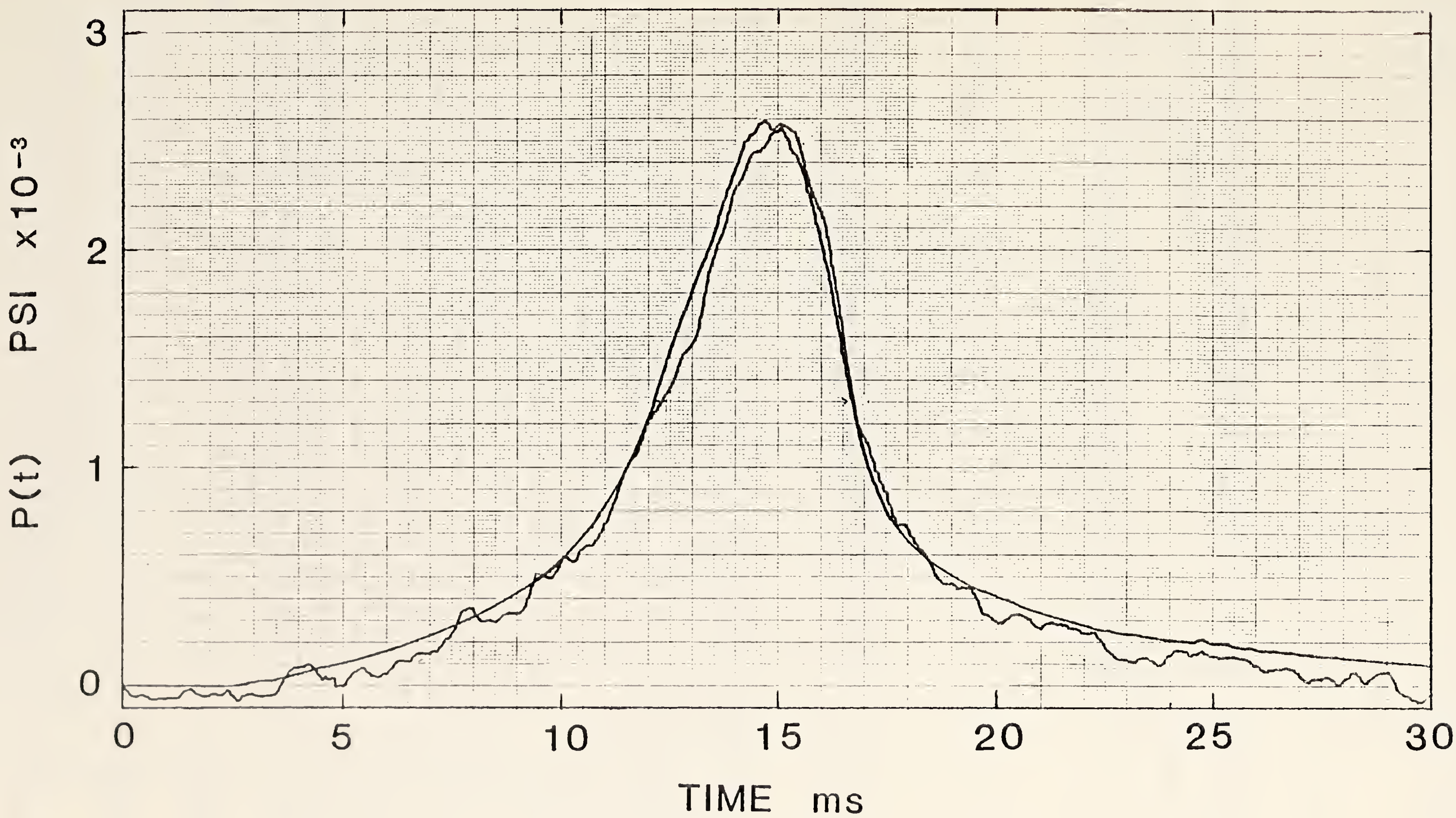


Figure 8

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 84-2862	2. Performing Organ. Report No.	3. Publication Date April 1984

4. TITLE AND SUBTITLE

Development of a Polymer Pressure Gage With Temperature Compensation

5. AUTHOR(S)

A. J. Bur, S. C. Roth

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The development of a temperature compensated pressure transducer is described. The pressure sensing element of this transducer is a thin film of polyvinylidene fluoride which is both piezoelectrically and pyroelectrically active. In order to measure a pressure pulse which is also accompanied by a temperature pulse due to adiabatic heating, it is necessary to correct for the pyroelectric signal. The temperature compensation technique which we use is to measure the temperature with a fast response thermocouple, to amplify the thermocouple signal in accordance to the pyroelectric response of the transducer and to combine the transducer and amplified thermocouple signals to produce an output voltage proportional to pressure only. A compensation circuit with a frequency range of 1 Hz to 10^4 Hz was constructed and tested. The transducer was calibrated and tested using pressure pulses whose peak value was 2.1 x 10^7 Pa (3000 psi) and whose pulse width was approximately 5 to 10 ms. For these measurements, the transducer was placed in an oil pressure chamber at room temperature and the pressure pulse was initiated by dropping a 16 kg mass onto a plunger in the chamber. Signals from the PVDF transducer, from a reference pressure transducer and from a thermocouple were captured by a transient recorder. The pressure measured with the calibrated and compensated PVDF transducer was found to agree satisfactorily with the signal from the reference pressure gage.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Adiabatic heating; piezoelectricity; polyvinylidene fluoride; pressure pulse; pyroelectricity; temperature compensation, transducer

13. AVAILABILITY

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14. NO. OF PRINTED PAGES

31

15. Price

$8.50

USCOMM-DC