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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Experimental Investigation of Means for Reducing the Response of Pressure Transducers to Thermal Transients

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FOREWORD

The work described was performed as a task within the NBS InterAgency Transducer Project. This is a continuing project for the development of calibration and evaluation techniques for electromechanical transducers and is supported by the National Bureau of Standards and a number of other Government agencies. This task was assigned by the Transducer Committee, Telemetry Group, Range Commanders Council, with the concurrence of the Naval Air Systems Command, U. S. Navy.

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EXPERIMENTAL INVESTIGATION OF MEANS FOR REDUCING THE RESPONSE OF PRESSURE TRANSDUCERS TO THERMAL TRANSIENTS

John S. Hilten, Carol F. Vezzetti, J. Franklin Mayo-Wells, and Paul S. Lederer

Experimental efforts are described in the evaluation of protective diaphragm coatings as a means to reduce the effects produced by thermal radiant-energy transients on pressure-transducer response.

A series of tests was carried out to investigate the effects of a variety of protective coatings on the amount and rate of thermal energy transmission through thin metal disks (used to simulate transducer diaphragms) as revealed by measurements of the disk back-side temperature. The temperature histories of both bare and protected disks were measured with thermocouples during and after exposure of the disks to thermal radiant-energy transients (of approximately 20 mJ/mm^2 at the disk) generated by No. 22 photographic flashbulbs. Protective coatings investigated include various tapes, greases, and room-temperature-vulcanizing rubbers (RTVs).

Based on the results from these tests, the effectiveness of nine selected coatings in reducing thermally-induced zero shifts of four types of pressure transducers was investigated. In these tests, a pair of transducers — one protected and the other unprotected, but otherwise nominally identical — were exposed to a thermal radiant-energy transient as described above. The resulting zero shift was measured and taken as an index of coating effectiveness.

The effect of the mass of the coatings on transducer dynamic response was investigated by means of a shock tube in which a protected and unprotected pair were simultaneously exposed to a pressure step of approximately 280 kPa (40 psi). Also, the effect of selected coatings on transducer acceleration sensitivity was investigated by monitoring the outputs of pairs of transducers mounted on a vibration exciter.

Test results indicate the validity of the simulated diaphragm test as a predictor of protection effectiveness. Results from both disk and transducer tests show that some coating combinations appear to be an order of magnitude more effective than others in delaying and reducing zero shift. Coatings of multi-layer black tape, red RTV silicone rubber, and "heat sink" compound appear most effective, other materials less. Silicone grease is found least effective, while single-layer black tape appears to produce results ranging from very limited protection to actual degradation of response, based on the limited sampling carried out in this investigation.

Key words: coatings; delayed response; dynamic; dynamic response; pressure step; pressure transducer; protective coatings; shock tube; tape; thermal radiant-energy response; thermal protection; thermal transient response; transducer; zero shift.

1. INTRODUCTION

A brief background for the NBS InterAgency Transducer Project, its recent history, and current guidelines can be found in an earlier NBS publication [1]*. A previously assigned task within this Project was to develop a test method for evaluating the effects of short-duration, thermal radiant-energy transients on pressure-transducer response [2,3,4]. Following completion of this effort, the Transducer Committee** and NAVAIR as cosponsors assigned as a follow-on task the evaluation of schemes in use, or proposed, to reduce such effects. The intent was to use the test method described in [4] for evaluating methods of protection and to modify the method as required for generating other types of thermal inputs for testing protected transducers. The task assignment called for investigation of methods of protecting pressure transducers from "radiated and/or convected transients of various amplitudes and durations." The main criterion to be taken into account was the "effect of any protection scheme on transducer performance, such as increased acceleration sensitivity, degradation in dynamic performance, etc."

Following a review of various protective schemes proposed and in field use, the approach chosen for this task was to investigate the effects of various coatings applied directly to the diaphragms of pressure transducers to protect them against radiant thermal transients. Plans to investigate other means of protection, such as perforated barriers, and the effects of other types of thermal transients, such as convected-energy transients, were initially considered but dropped because of curtailed funds.

The plan of work was, first, to develop a method for evaluating coating performance; second, to test a number of coatings using this method; third, using the test method of [4], to determine the zero shifts of pairs of transducers — one with diaphragm protection and the other without; and, fourth, to compare the dynamic response of the two transducers in each pair to pressure steps generated in a shock tube. In addition, the acceleration response of the protected and unprotected transducers was to be compared.

2. DEVELOPMENT OF METHOD FOR EVALUATING COATING PERFORMANCE ON METAL DISKS

Parameters of interest for characterizing coating performance include (1) the maximum rise in temperature measured at the back surface of a transducer diaphragm following a specified thermal input to the protected front surface and (2) the time from the onset of the thermal transient to the peak back-side temperature. These parameters are of

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*Numbers in brackets indicate literature references, section 8.

**Transducer Committee, Telemetry Group, Range Commanders Council.

interest because results from earlier work together with knowledge of transducer design and construction suggest that a major source of the thermally induced zero shifts observed in a number of pressure-transducer designs is thermal energy propagated through the diaphragm to the sensing element. Especially for transducer designs in which little thermal energy is conducted via the path diaphragm-to-housing-to-sensing-element, the temperature at the back side of the diaphragm provides a convenient measure of the energy reaching the sensing element. Most modern transducer designs minimize (mechanical) contact between housing and sensing element. Thus, for purposes of evaluating coating performance, it is not necessary to accept the experimental complexity that would be involved in instrumenting a transducer diaphragm *in situ*. Instead, the thermal behavior of a thin metal disk mounted in a relatively massive housing simulates the thermal behavior of the diaphragm; an additional advantage of this approach is that nominally identical disks may be fabricated for as many tests as are required.

2.1 Preliminary Work

In order to gain familiarity with the use of thermocouples to measure the temperature of thin disks, preliminary work was carried out with a number of thermocouple systems, wire sizes, and mounting means. Thermocouples of the system copper versus copper-45% nickel were used initially because of their availability. Thermocouples of the system nickel-10% chromium versus copper-45% nickel offer greater sensitivity and were used as soon as they became available.

Thermocouples made of wire with diameters as small as 0.025 mm were tested, but were found to pose severe practical difficulties in handling; thermocouples of wire of twice this diameter proved to be acceptable. Several schemes to mount the thermocouple to the disk were tried including soldering and cementing. The small size of the measuring junction of a thermocouple made with wire as large as 0.076 mm in diameter renders it nearly impossible to determine whether or not the junction is in good contact with the disk when these mounting techniques are employed. To eliminate this difficulty, a simple mechanical mount was devised in which the thermocouple junction is pressed against the disk with a constant, but adjustable, force. The thermocouple is mounted at one end of a small ceramic rod having two axial holes for the wires. Before the thermocouple is inserted, the junction end of the rod is tapered as shown in the detail of figure 1. The thermocouple is held in place with a small quantity of white glue packed at the opening of each hole. The completed thermocouple-and-rod assembly is mounted on a swinging arm in such a manner that a counterweight acts to force the thermocouple against the surface of the disk. The position of the counterweight controls the magnitude of the force. This arrangement is shown in figure 1.

2.2 Description of Apparatus

The apparatus of the test method for evaluating coating performance is based on that for evaluating the effects of thermal radiant-energy transients on pressure-transducer response [4]. A source and the transducer mounting block are mounted on an optical rail as shown in figure 2. The mounting fixture for the thin metal disk, shown in figure 3, is designed to fit into the transducer mounting block. The vertical position of the disk, the plane of which is perpendicular to the long axis of the rail, is adjusted until the center of the exposed portion of the disk and the center of the source are in the same horizontal plane. The mechanism for supporting the thermocouple is also mounted on the rail, behind the transducer mounting block. The vertical position of the thermocouple is adjusted so that the measuring junction is in contact with the approximate center of the exposed portion of the disk.

The thermocouple cold junction is immersed in a flask of water at nominal room temperature, the water being used as a heat sink to eliminate small fluctuations in temperature which the junction would experience if exposed to air currents. The thermocouple output (thermocouple emf) is displayed on an oscilloscope whose sweep is triggered by the same switch used to initiate the flash.

The source used is a No. 22 photographic flashbulb. The performance characteristics of these flashbulbs have been characterized and are given in [4]. The source-to-disk distance selected is 70 mm, which results in a transient with an energy density of approximately 20 mJ/mm^2 at the disk.

2.3 Test Procedure Considerations

Use of the apparatus described in section 2.2 requires that certain experimental precautions be taken. First, the disk should be centered in its fixture, and the fixture tightened in a manner that does not distort the disk. Then the thermocouple assembly (which is quite fragile) should be mounted in position and adjusted so that the junction contacts the center of the disk. The force exerted by the thermocouple against the disk should be adjusted by means of the counterweight so that with the ceramic rod parallel with the optical rail, firm pressure is felt by the tip of a gloved finger (a thin polyethylene glove is used to prevent contamination of the junction by finger oils) held against the measuring junction of the thermocouple. Care should be taken to rotate the No. 22 flashbulb so that the supporting electrodes (each in the shape of an inverted "L") for the igniter element point in a direction perpendicular to the long axis of the optical rail. This orientation prevents the black spot which forms on the bulb opposite the electrodes from absorbing any of the radiant energy intended to impinge on the disk.

Note: In the interests of safety, test operators should not look at the flashbulb during ignition and should remove used bulbs with gloves.

A convenient means for recording data is to display thermocouple output as a function of time on the screen of a storage oscilloscope and to photograph the resulting traces. The amplitude of the trace may then be measured, scaled, and recorded. In the tests reported, the maximum thermocouple output was determined and recorded, as were thermocouple output values at 50, 100, 500, and 1000 ms after flash initiation. Also determined and recorded were the times required for the thermocouple output to rise to 10, 50, 90, and 100% of the maximum value and then to decay to 90 and 50%. The selected values are arbitrary; the intent was to measure enough data points for each test run to permit useful comparison of various geometrics and protective materials, as described in 2.4 and 2.6.

2.4 Experiments with Various-Sized Apertures and Disk Thicknesses

To investigate the effect of aperture size, i.e., of the exposed area of the disk, on the temperature history of the disk following exposure to a given thermal transient, disk mounting fixtures with three different apertures were fabricated. The apertures were chosen to be representative of those of commercial pressure transducers and are 6.35, 9.53, and 12.7 mm in diameter (with areas of 31.7, 71.3, and 127 mm^2, respectively).

Experiments with three disk thicknesses — 0.08, 0.13, and 0.25 mm — were also conducted. The intent of these tests was to verify the prediction that a thin, bare disk would experience a greater temperature rise following exposure to a given thermal transient than would an otherwise similar disk of greater thickness. A simple analysis suggests that this hypothesis is correct because, if the paths by which thermal energy may be removed from the disk are approximately the same in both cases, a thin disk will have to accommodate more energy per unit volume than a thicker disk.

The results of these experiments are shown in figures 4, 5, and 6. The peak temperatures reached with a particular thickness of disk are equal (within ±10%) for the three different apertures used. The peak temperatures reached with a particular aperture are inversely proportional to the disk thickness. This relation is confirmed by the result that the products of thickness and peak thermocouple output, expressed in arbitrary units, range from 0.096 to 0.12 for all tests, with a coefficient of variation of 9.2%. This degree of variation is little more than that attributable to the range of energy output from No. 22 flashbulbs, for which the coefficient of variation has previously been found to be 8.7% [4].

2.5 Experiments to Determine Method Repeatability

Twelve tests were conducted, each on a new, bare, 0.08-mm-thick stainless-steel disk, to determine the repeatability of the method. The aperture used was 9.53 mm. The average of the thermocouple outputs is plotted as the NP curve common to figures 7 and 8. The commercially available thermocouple used in these tests was fabricated from 0.051-mm-diameter wires of nickel-10% chromium and copper-45% nickel and represents the "standard" thermocouple used in the tests. This thermocouple is supplied as meeting ANSI Type E specifications. [The manufacturer cites a limit of error of ±1.7°C over the range of 0 to 315°C]. The coefficient of variation calculated from the repeatability test data is 9.4%, again only slightly greater than the degree of variation attributable to the No. 22 flashbulbs.

2.6 Experiments with Various Coatings

The protection provided by 16 different coatings was evaluated using the disk method as a preliminary screen prior to tests with transducers. The coatings are identified in the captions of figures 7 and 8. Included are 3 two-component room-temperature-vulcanizing (RTV) rubbers, 5 single-component RTV rubbers, a black plastic tape*, a white plastic tape+, high-temperature$^{\delta}$ fiberglass tape, a silicone "heat-sink" compound, and a silicone dielectric grease.

Each coating was applied to a stainless-steel disk 0.08 mm thick, the aperture selected to provide a high temperature rise for a disk with a diameter representative of that of the diaphragm of a number of commercial pressure transducers. The RTV rubbers were cast in place using as a form a metal washer which was discarded after the material had set. The thickness of the RTV layers was 0.8 mm. The tapes, in both single and triple layers, were cut to fit the aperture by means of a cork-borer. The single-layer thickness is approximately 0.15 mm for all tapes except the fiberglass thermal tape, which is 0.23 mm thick. The silicone greases required peripheral support in a vertical position. The restraint was a washer similar to that used for casting the RTV layers and was 0.8 mm thick. The hole in the washer was filled to overflowing with the grease and the excess removed by drawing a straight-edged knife blade across the face of the washer with the blade held at about 60 deg from the perpendicular to the disk. The restraint was left in place as part of the coated disk. For these two coatings, clamping plates were fabricated which were thinner than the "standard" plate by the thickness of the restraining washer. The mass of the metal in front of the disk itself was thus the same for all tests.

2.7 Test Results

The results of the coating-evaluation tests are plotted in figures 7 and 8. Each data point represents the average of 5 tests on each coating. As noted previously, the no protection (NP) curves represent the average of 12 tests. Inspection of the figures and the data shows several interesting results.

It is apparent that all but one coating provide some measure of protection in reducing the <u>amplitude</u> of the thermocouple output compared to

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*Meeting Federal Specification HH-I-595 B.

+Commercially available.

$^{\delta}$Commercially available 0.15-mm-thick glass-plastic tape with maximum continuous use temperature of 500°C and a dielectric strength of 2×10^{7} V/m.

that from the unprotected disk. These reduced amplitudes range from about 82% (silicone grease) to about 9% ("heat sink" silicone compound) of the unprotected disk output. Significantly, the single layer of black tape (figure 8) actually increases the output amplitude in these tests. It should be noted that an informal survey of installations with measurement situations calling for protection of pressure transducers from thermal transients indicates widespread use of black tape in field measurements.

It is also seen that coatings fall into three groups from the standpoint of timing: those for which the thermal transient response time of the protected disk is roughly that of the unprotected disk, those for which the response of the protected disk is delayed significantly, and those for which that response is advanced. As measured, the peak temperature of the unprotected disk occurs at about 250 ms after the peak output of the thermal-transient source. Disks protected with silicone grease and the white RTV rubber experience peak temperatures about 150 ms after source peak output; these peak temperatures are lower than that of an unprotected disk. Disks protected with white tape and with a single layer of (tan) fiberglass tape also experience an earlier and reduced peak temperature compared to unprotected disks.

In contrast, triple layers of black or fiberglass tape, black or red RTV silicone rubber, and "heat sink" silicone compound produce a delay in time of peak temperature of about 2.5 s. The remaining coatings fall between the early and delayed groups in their effect on the disk temperature.

At present, there is no explanation of why the light-colored coatings reduce the time delay between flash and measured peak temperature, compared to the temperature response of the unprotected disk. In this context, it should be noted that only for silicone grease do the temperatures of the protected disk reach higher values earlier than the temperatures of the bare disk. The performance of the other coatings is as expected: energy is absorbed at the front surface, some of the energy is consumed in heating the coating, and the remainder is transmitted through the coating material (at a slower rate than through an equivalent thickness of air) to the disk which then experiences a delayed and attenuated rise in temperature.

Silicone grease which is highly translucent appears to provide very little protection from radiant-energy transients. (However, very brief exploratory trials in which a heat gun served to generate convective thermal transients indicated that silicone grease may provide considerable protection from such transients.)

3. EXPERIMENTAL EVALUATION OF COATINGS ON PRESSURE TRANSDUCERS

On the basis of the test results described above, nine of the coatings were selected for further tests in which the coatings were applied to the diaphragms of four different types of pressure transducers. One purpose of these tests was to check the results of the disk method for evaluating coatings. A second, and more significant, purpose was to determine the effects on pressure transducer performance of the presence of a coating on the transducer diaphragm. Performance parameters of particular interest in this regard are response and acceleration sensitivity.

3.1 Selection of Coatings

The test coatings were selected from those evaluated by means of the metal disks (sections 2.6 and 2.7). The coatings chosen represent various degrees of thermal protection capability and several types of coating material. Included among the selected coatings were a two-component RTV silicone rubber, a silicone "heat-sink" compound, a silicone grease, one and three layers of black tape, one and three layers of white tape, and one and three layers of fiberglass tape.

The various tape coatings were chosen because (1) tape is commonly used as a protective coating by a number of transducer users (particularly black vinyl tape), (2) tape is easy to apply and overall thickness can be readily varied through the use of multiple layers, and (3) tapes showed considerable variation in protective ability in the tests performed earlier. One and three layers of tape represent thicknesses of 0.15 and 0.45 mm, respectively, which are typical thicknesses reported in use at several laboratories.

The silicone rubber was chosen because (1) silicone rubber is also commonly used by a number of transducer users as a thermal protective means and (2) this particular red RTV silicone rubber had performed relatively well in the earlier evaluation. Transducer users cite applications in which thicknesses varying from 0.10 to 2.0 mm are used. The 0.8-mm thickness used in these tests is considered a reasonable median value for testing. The "heat-sink" compound was chosen because it also performed relatively well in the earlier evaluation. To provide a check on the results of that evaluation, it was considered desirable to include one coating that had performed relatively poorly. Silicone grease was chosen because it is reported in use by a number of transducer users.

After each set of tests with a given coating, the coatings were removed and the transducers cleaned with acetone and allowed to air dry. The silicone materials were applied to the test transducer diaphragms after the tapes and RTV silicone rubber applied last.

3.2 Selection of Transducers

Nine transducers of four different types were used in the coating evaluation. The four types, unbonded strain-gage (one transducer pair), quartz-crystal (one transducer pair), semiconductor (single transducer), and piezoelectric (two transducer pairs), are representative of those reported in use in applications in which thermal transients are encountered.

A single model of each type was selected for the tests so that each test pair is composed of two nominally identical transducers; all four piezoelectric transducers are nominally identical. Although four semiconductor transducers of the same model were initially available, only one was in operating condition at the time of these tests (the diaphragm of the selected model having proved to be more fragile than anticipated).

The strain-gage transducer model used has unbonded strain gages attached to a structure composed of four support members; this assembly is attached to a push rod that in turn is fastened to the transducer diaphragm. An analysis of this geometry suggested that performance should not be affected appreciably by thermal transients of short duration. The pressure range is 0 to 345 kPa. The diameter of the diaphragm is approximately 13 mm.

The quartz-crystal transducer model used incorporates an impedance-matching amplifier as part of the transducer. This model was also not expected to have its performance appreciably affected by thermal transients. The pressure range is 0 to 6.9 MPa. The diaphragm end of the transducer has a diameter of approximately 10 mm.

The semiconductor transducer model used has a silicon diaphragm (approximately 3.6-mm diameter) into which a Wheatstone bridge has been diffused. On the basis of experience with pressure transducer behavior, it was expected that the performance of this model would be affected considerably by thermal transients. The pressure range is 0 to 345 kPa.

The piezoelectric transducer model used has a lead metaniobate sensor. The body is stainless steel with a nylon pressure plate. The pressure range is 0.7 to 3.5 MPa. This model was also expected to be affected appreciably by thermal transients. The diameter of the sensitive surface is approximately 5.3 mm.

3.3 Application of Protective Coatings

For all tests, the protective material was applied directly to the transducer diaphragm. The exposed diaphragm surface was first cleaned with acetone and allowed to dry; then the transducer was installed in the mounting fixture with the diaphragm surface either flush or recessed as required by the coating.

The protective materials were applied in the same manner previously described for the disk method (section 2.6).

3.4 Descriptions of Tests

3.4.1 Zero-Shift Measurements - The observed change (zero shift) in transducer output in response to thermal radiant-energy transients with the transducer sensing atmospheric ambient pressure was determined and recorded according to a modification of the method of [4]*. Eleven sets of tests were carried out using the four types of transducers. With the exception of tests on the semiconductor strain-gage transducer, in each test, a pair of transducers was used, one with a protective coating applied to the sensing diaphragm and the other unprotected, but otherwise nominally identical and, where applicable, supplied with nominally identical excitation voltages. Two of the test sets were conducted for the purposes described below with both test and control transducers unprotected; each of the remaining sets were conducted with one of the nine selected coatings applied to the test transducer.

A brief series of tests, using the two pairs of piezoelectric transducers was carried out to provide a measure of the repeatability of the method. Transducer output and time to peak transducer output was measured in eighteen test runs. The transducers were uncoated for these tests.

As the dynamic performance of each pair of transducers was measured following the zero-shift measurements, it was found convenient to mount the fixture onto the hinged end plate of the shock tube used in the dynamic measurements (see 3.4.2). The flashbulb source was mounted on a bracket designed to be clamped to the end plate. This arrangement permits either dynamic or zero-shift measurements to be carried out with a minimum of effort required to shift from one test to the other.

Test procedure considerations are similar to those given in section 2.3 for the coating evaluations on metal disks. A detailed procedure for these tests appears in appendix A. This procedure results in a set of two to four photographs of the oscilloscope traces. The zero shift is determined by scale measurement of the photographed traces. The measurements are made from whichever photographs provide the greatest time resolution and incorporate peak voltage values. The reference voltage levels are those levels, nominally zero, corresponding to the output of each transducer before ignition of the flashbulb. For each transducer, the zero shift is measured as the difference between the peak output voltage and the reference voltage level. The time, following source triggering, at which the transducer output peaks is also determined. If positive- and negative-going peaks are present in a single trace, both peak values and times are to be determined.

For each trace, amplitudes and times are measured at inflection points and a sufficient number of other points to enable a reasonable facsimile of the oscilloscope trace to be reproduced.

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*In the method of [4] test transducer output is monitored and displayed on the screen of a storage oscilloscope or otherwise recorded as the transducer is exposed to a thermal radiant-energy transient resulting from the ignition of a flashbulb or flashtube. As the transducer senses atmospheric ambient pressure, that is, a gage pressure nominally of magnitude zero, any observed change in output is taken as zero shift.

3.4.2 Dynamic Response Measurements - The effects of test coatings on the transducer dynamic performance were evaluated by comparing the simultaneous outputs of a pair of transducers — one protected, the other not, but otherwise nominally identical — in response to pressure steps generated in a shock tube. Transducer outputs were recorded and analyzed to determine the effects of coatings on such parameters as ringing frequency, rise time, and amplitude response.

The shock tube employed in this work is capable of providing a calculable pressure step with rise time on the order of 10 ns and duration of approximately 4 ms. (The duration is limited by the rarefaction wave which reaches the end of the test section at approximately 4 ms.) Some variations in pressure-step amplitude as seen at the end of the test section result from the method of generating the pressure wave, which is the rupture of a cellulose-acetate diaphragm interposed between the high-pressure and low-pressure sections. This variation may be as much as 5% and may be accompanied by a variation in waveform, especially during the first 0.5 ms. This consideration led to a decision to expose test and control transducers to the same pressure step and to record the outputs simultaneously. An incidental advantage of this procedure is that any error introduced by the calibration of the recording means (estimated to be ±3% for the oscilloscope) may be ignored for the comparison measurement.

For these tests, the low-pressure section (i.e., the section downstream from the diaphragm) was operated at atmospheric ambient pressure to simplify operation. With helium at about 300 kPa used in the high-pressure section (upstream section), the amplitude of the pressure step is approximately 280 kPa when the tube is run at the laboratory ambient temperature of 21°C.

Symmetry of the shock wave was established by a brief series of tests using a pair of nominally identical uncoated transducers. The right and left positions of the transducers in the shock tube were reversed after each of six successive exposures of the transducers to a pressure step. No differences in the transducer outputs attributable to the position of the transducer were detected, and the shock wave is assumed to be symmetrical for the purposes of this study.

A detailed procedure for the thermal transient test method appears in appendix A, as the information contained in that procedure may be used as a guide for the use of whatever apparatus is available to accomplish the same purpose. This statement is not true for the operation of the shock tube, for which the procedure is specific to the particular device employed, and therefore no procedure is given. The methods used to determine rise time, average amplitude, and ringing frequency depend to some extent on the transducers used in the test.

For the unbonded strain-gage transducers, the outputs of the test and control transducers exposed to the pressure step were both displayed on the screens of two storage oscilloscopes, one operating at a sweep rate of 0.1 ms/div and the other at 1.0 ms/div (total sweep times of 1 and 10 ms, respectively). The traces were photographed. Information from the slow-sweep traces was used for monitoring the system behavior and for determining the duration of ringing to provide an estimate of the degree of damping present. Rise times were determined from the photograph of the fast-sweep traces as the difference between the times at which the initial transducer pulse in response to the pressure step reaches 10% and 90% of its peak value.

Since the output signal exhibited ringing, an averaging calculation was used to compute the amplitude as follows: A value of "average" peak output was determined from scale measurement of (1) two consecutive output minima at about 150 μs after the start of the response to the pressure step and (2) the included maximum. The reference level was taken as the transducer output for zero applied pressure. The average value of the two minima was calculated. The average of the minima average and the included maximum was calculated to give the average amplitude. The procedure was repeated at about 500 μs.

For determinations of ringing frequency, a two-channel transient recorder was used to record the two transducer outputs resulting from exposure to the pressure step. The recorded signals were then supplied sequentially to a frequency analyzer-oscilloscope combination adjusted to operate over a frequency range of 0 to 40 kHz and with a sensitivity of 4 kHz/cm of displayed trace. Each resulting trace of the frequency spectrum was photographed. Ringing frequency was then determined by inspection.

For the three other transducer types, no measurement of ringing frequency was possible as available equipment has an upper frequency limit of 100 kHz, while the manufacturers report natural frequency values of 100 kHz and greater for these transducers.

Average peak amplitudes and rise times were determined in a manner similar to that described for the strain-gage transducers, except that the sweep rates were 0.01 and 1.0 ms/div, and the amplitude measurements were carried out at 15 and 50 μs on the fast-sweep trace and at 1, 2, and 3 ms on the slow-sweep trace.

3.4.3 Acceleration Sensitivity Tests - The effect on transducer acceleration sensitivity (i.e., the output of the transducer at zero applied pressure resulting from sinusoidal acceleration perpendicular to the plane of the diaphragm) of the mass added to the transducer diaphragm by the coatings was determined using a vibration exciter. The transducer fixture (with test and control transducers installed) was mounted on a cylindrical spacer ring attached to the vibration-exciter armature. The surface plane of the transducer diaphragms was perpendicular to the plane of the armature motion. The pair of transducers was then vibrated sinusoidally at 10 g_n zero-to-peak over the frequency range 25 Hz to 3 kHz and both transducer outputs monitored on a storage oscilloscope.

Tests were performed first without and then with two of the coatings on each type of pressure transducer. "Heat-sink" compound and three layers of black tape were selected as being representative of the types of coatings used (viscous liquid and pliable solid) and because they are among the more massive coatings.

4. RESULTS FROM TESTS OF COATINGS ON PRESSURE TRANSDUCERS

Tests of the effects of selected coatings on pressure transducer performance were carried out as have been described. As an example, figure 9 shows the photographically recorded zero shift for a protected and unprotected transducer pair with three different coatings applied to the diaphragms.

Test data were obtained from photographs of the traces appearing on the screens of the storage oscilloscopes used in the tests. Maximum recorded transducer zero shifts and maximum recorded time delays in transducer response are tabulated in tables 1-4, with a summary of results in table 5. Dynamic pressure response data appear in tables 6-9. Except for the semiconductor strain-gage, for which no control was available, the responses of the control transducers are included to provide further information on the repeatability of the test procedure. Times of occurrence of maximum zero shift are measured from the initiation of the thermal transient. As noted previously, the peak occurs approximately 20 ms after initiation.

4.1 Zero Shift

The results of the repeatability trials show that for 18 tests with four nominally identical uncoated transducers the measured transducer zero-shift magnitude has a coefficient of variation of 8.4%, which is not significantly different from the variation of 8.7% ascribed to flashbulb energy. The variation in time of peak transducer output is greater, with a coefficient of variation of 10.4%. Time of peak output appears to be a parameter that varies with the individual transducer, as the coefficients of variation for the four instruments are 6.1%, 8.2%, 8.0%, and 8.9%.

Table 5 summarizes the test results for both unprotected control and protected test transducers. The coefficients of variation of transducer zero-shift magnitude range from 7.3% to 8.4%, which result again suggests that the chief source of variation is to be found in flashbulb energy.

Detailed results are discussed in the following four sections.

4.1.1 Unbonded Strain-Gage Transducers - As shown in table 1, for the 11 tests with unbonded strain-gage transducers, the control instrument had an average maximum zero shift of approximately 7.3% of the transducer output corresponding to full-scale applied pressure (denoted as 7.3% FS), with a sample coefficient of variation of 7.3% and an average time of occurrence of 60 ms (sample coefficient of variation 8.2%). For the two tests in which the test transducer was not protected, the average maximum zero shift was 7.6% FS with an average time for the peak zero shifts of 65 ms; these results show good agreement with those from the control transducers.

While an insufficient number of tests was run to draw any statistically significant conclusions, the data show that coatings of one layer of white tape, three layers of white tape, one layer of fiberglass tape, three layers of fiberglass tape, and silicone grease appear not to delay the time of occurrence of the maximum zero shift. However, all of these but the silicone grease appear to reduce the magnitude of the zero shift appreciably. The use of one layer of black tape, three layers of black tape, "heat-sink" compound, and red RTV silicone rubber tends to delay the time of occurrence of the maximum zero shift and reduces the magnitude of the zero shift as well. Comparisons of the effectiveness of a single layer of tape with the silicone materials should take into account the fact that the tape has one-fourth the thickness of these materials.

As shown in figures 10A and 10B, the zero shift of the unprotected transducers resulting from exposure to the thermal transient is relatively small (less than 8% FS) and slow to develop. This behavior is consistent with the construction of the transducer. Presumably, only a portion of the thermal energy reaches the strain gage, and it takes time for that energy to travel from the diaphragm through the push rod to the strain gage.

4.1.2 Quartz-Crystal Transducers - Zero-shift tests with quartz-crystal piezoelectric transducers resulted in all cases in the production of negative shift followed by a positive shift of comparable magnitude. For the 11 tests, the control instrument had an average negative zero shift of 5.2% FS (sample coefficient of variation 7.3%) and an average maximum positive zero shift of 2.7% (sample coefficient of variation 8.1%). The average time at which the negative peak zero shifts occurred was 36 ms (sample coefficient of variation 5.2%) and the average time at which the positive peak occurred was 113 ms (sample coefficient of variation 5.2%). The data are given in table 2.

In the tests in which the test transducer was uncoated, the average negative zero shift was 5.3% FS at 36 ms, and the positive zero shift was 5.5% FS at 110 ms. While the positive zero shift for the test transducer was significantly larger than that for the control transducer, differences of this magnitude are not uncommon in transducers of the same model, as shown in [4].

As shown in figures 11A and 11B, these transducers respond more rapidly to the thermal transient than the unbonded strain-gage transducers, and shift first in the negative direction, as the sensor is heated, and then in the positive direction, as the sensor cools.

As in the tests with the unbonded strain-gage transducers, one layer of white tape, one layer of fiberglass tape, three layers of white tape, three layers of fiberglass tape, and silicone grease do not delay appreciably the time of occurrence of the maximum zero shift; all but the silicone grease reduce the magnitude of the zero shift appreciably. The use of one layer of black tape, three layers of black tape, "heat-sink" compound, and red RTV silicone rubber delays the time of occurrence of the zero shift (both positive and negative peaks) and the magnitude of the zero shift as well.

4.1.3 Semiconductor Strain-Gage Transducer - Tests with the semiconductor strain-gage transducer showed a very rapid response to the thermal transient input in all cases. As has been explained, since only a single transducer was available, no control data are given in table 3. However, the two tests with the unprotected transducer show good agreement.

In this transducer the sensing element, bridge circuit, and diaphragm are integral, and therefore the maximum zero shift, without protective coating, is large (almost 200% FS) and rapid (occurring almost simultaneously with the flash). Also, the transducer output increases and decreases in a series of peaks and valleys, as shown by curve NP in figures 12A and 12B. Two possible explanations for this behavior are (1) the transducer response may be wavelength dependent, or (2) various stresses cancel and reinforce each other as various parts of the transducer structure heat and cool. Note in curve NP the initial negative zero shift of about 50% FS 10 ms prior to the transient peak.

The magnitude of the zero shift is reduced substantially by the use of protective coatings. As shown in figures 12A and 12B, one and three layers of black tape, red RTV silicone rubber, and "heat-sink" compound greatly reduce the zero shift compared to that recorded for the unprotected transducer. Three layers of white and three layers of fiberglass tape reduce the magnitude of the shift moderately; single layers of white and fiberglass tapes and the silicone grease appear to have little effect on zero shift. Only the red RTV silicone rubber coating is effective in delaying the time of occurrence of the zero shift, with a small maximum positive zero shift at 500 ms.

4.1.4 Lead Metaniobate-Crystal Transducers - Tests with two of the lead metaniobate-crystal piezoelectric pressure transducers resulted in all cases in negative zero shifts as a result of exposure to the thermal transient input. As given in table 4, these shifts range from about 50% FS for the unprotected transducers to about 5% FS for tests in which the silicone "heat-sink" compound coated the diaphragm. For the unprotected instruments, peak zero shift occurs about 150 ms after the transient peak.

As shown in figures 13A and 13B, substantial reductions in zero shift result from the use of "heat-sink" compound, one and three layers of white tape, three layers of fiberglass tape, and the red RTV silicone rubber. Three layers of black tape and one layer of fiberglass tape appear to be moderately effective; neither one layer of black tape nor the silicone grease appear to have any significant effect on the magnitude of the zero shift.

All coatings, except for the silicone grease, were effective in delaying the time of occurrence of the zero shift by amounts ranging from 1.8 s to 4 s.

4.2 Dynamic Response

To provide a means for comparing the dynamic performance of protected transducers, a parameter known as amplitude ratio is used to characterize the dynamic response of a test transducer relative to that of its control. Amplitude ratios are calculated by determining (by scale measurement of oscilloscope trace photographs) the amplitude of the recorded test transducer output signal at 15 μs, 50 μs, 1 ms, 2 ms, and 5 ms after the start of the pressure step, adding these five values, and dividing this sum by the sum of the five control transducer signal amplitudes measured for corresponding times. Use of this ratio as a performance parameter eliminates the effects of errors affecting both test and control transducers in a given trial, such as oscilloscope amplitude calibration errors, variations in shock-tube step pressure, and differences in transducer sensitivity. For these tests, amplitude-ratio coefficients of variation thus represent, largely, the effect of the coating materials, and the degree to which accurate measurements of transducer signal amplitudes may be made from photographs of oscilloscope traces.

The coefficient of variation is one common statistical measure of the variation in a series of "identical" tests. Since the addition of coating materials does not appear to alter the amplitude of the transducer dynamic response to a pressure step, coefficients of variation are presented for each transducer type as if all tests for that type were "identical." (Quartz-crystal tape tests are not included because of air-entrapment problems, and semiconductor strain-gage tests are not included because of the absence of control transducer results with which to normalize any pressure-step variation.) The coefficients of variation calculated are 1.7%, 0.9%, and 1.7%, representing 11, 5, and 11 paired trials for unbonded strain-gage, quartz-crystal, and lead metaniobate-crystal transducers, respectively, as shown in tables 6, 7, and 9. These results may be interpreted as indicating that, for the limited number of tests conducted, the coatings produce no significant degradation of the dynamic performance of the test transducers. Detailed results are discussed in the following four sections.

4.2.1 Unbonded Strain-Gage Transducers - Figure 14 shows the transducer output response behavior of two unbonded strain-gage transducers to a pressure step of 280 kPa with both test and control instruments unprotected. Comparison of the traces representing one instrument with the traces for the other shows slight variations in degree of damping, ringing frequency, and sensitivity. (For example, the control transducer exhibits a ringing frequency approximately 7% higher than that of the test transducer; on the other hand, the sensitivity of the control instrument is some 2% lower.) This degree of variation may be expected with instruments of this type.

Figure 15 shows the same two transducers in a similar pressure-step test in which the diaphragm of the test transducer is protected by three layers of black tape; there is slight reduction in the ringing frequency of the test transducers and a noticeable increase in damping, but rise time and amplitude changes are too small to be significant. None of the nine different coating materials was observed to produce a significant change in the dynamic characteristics of the protected transducer. Table 6 summarizes the data in detail.

4.2.2 Quartz-Crystal Transducers - The results of a series of pressure-step tests with the various tapes applied as protective coatings to quartz-crystal piezoelectric transducers show that the dynamic responses vary widely in rise time and amplitude. The recorded output amplitudes range from 20% above to about 90% below that of the unprotected transducer outputs. Figure 16 shows two examples of the variety of response recorded for the tape coatings. An explanation of these results may lie in the design of this model of transducer and in the fact that test tapes were applied to the entire sensing face of the transducers, as at the time of the tests the face was thought to constitute the diaphragm. More recent information reveals that the instrument has a ridge around the periphery of the diaphragm, as shown in figure 17. If the tape layer is applied across the entire face of the transducer covering the ridge, there may be a tendency for air to be trapped along the inner edge of the ridge. Such trapped air would be expected to "cushion" the pressure step in an uncontrolled manner, causing variation in the pressure seen by the transducer diaphragm (and hence by the transducer) compared to the pressure amplitude of the step.

In pressure-step tests with quartz-crystal transducers protected by silicone materials, there was no significant variation between the outputs of protected and unprotected instruments. The data are given in table 7.

The test results discussed in the previous two paragraphs are for shock-tube tests with a pressure step of 280 kPa, as has been described. This pressure level amounts to only 4% FS for the quartz-crystal transducers. Since considerable variations in transducer output were observed in the tests with tape coatings, as noted above now thought the result of air entrapment, it was of interest to determine if tests with pressure steps of greater amplitude would show similar variation. Accordingly, a series of tests was run with the diaphragm of the test transducer protected with three layers of black tape and the step-pressure amplitude alternately at 280 kPa and 2070 kPa. The ratios of test-transducer-to-control-transducer output signal amplitudes for individual times of 0.5 ms, 1 ms, 2 ms, and 3 ms are 0.13, 0.15, 0.32, and 0.41, respectively, at 280 kPa and 0.73, 0.77, and 0.83 at 2070 kPa. (At 2070 kPa, data are no longer available 3 ms after the shock wave reaches the transducers.)

When these ratios are corrected for the slight differences in sensitivity between the test and control instruments, the results indicate that, as expected, changes in transducer output attributable to the tape coatings tend to decrease as the measured pressure increases.

4.2.3 Semiconductor Strain-Gage Transducer - The results of a series of pressure-step tests with the various tapes applied as protective coatings to a semiconductor strain-gage transducer show that the dynamic responses vary widely in rise time, amplitude, and ringing frequency. These transducers, like the quartz-crystal instruments, have a ridge around the periphy of the diaphragm providing a site at which air may be trapped when tape is applied to the entire sensing face, with the same results described in 4.2.2.

The silicone materials (silicone grease, "heat-sink" compound, and red RTV silicone rubber) do not appear to alter the rise time and amplitude response of the transducer significantly, but the ringing frequency was reduced significantly by the addition of the coatings, as shown in table 8. Because there is no control transducer to provide a basis for normalizing variations in the measurement results, and because considerable difficulty was encountered in getting the various tapes to stick to the small diaphragm (size of a 10-32 screw, 3.8 mm in diameter), the data presented in table 8 should be interpreted with caution.

4.2.4 Lead Metaniobate-Crystal Transducers - The results of a series of pressure-step tests with protective coatings applied to lead metaniobate-crystal piezoelectric transducers indicate that the dynamic characteristics are not significantly altered by any of the coatings. It is not possible to analyze the variations of transducer ringing frequency with various coatings because the amplitude of the ringing is too small to permit frequency measurements from the recorded oscilloscope traces and the frequency range of the available transient recorder-spectrum analyzer combination is too limited. Table 9 summarizes the data.

4.3 Acceleration Sensitivity

Results of the acceleration sensitivity tests are not conclusive, since for three of the transducer pairs the recorded changes in transducer output signal resulting from acceleration of the transducer are less than the electrical noise in the system. The semiconductor strain-gage transducer did experience an approximately 40% signal increase (from 0.0016% FS/g_n without coating to 0.0023% FS/g_n with coating) with three layers of tape and a fourfold increase (from 0.0016% FS/g_n to 0.066% FS/g_n) with the "heat-sink" compound at a driving frequency of 3 kHz and a level of 10 g_n, zero to peak. However, even these increased acceleration sensitivities are smaller than many found in the specifications for models of currently marketed pressure transducers, and the changes are probably not significant.

4.4 Coating Evaluations

To permit ready comparison of the relative effectiveness of the various coatings, the data obtained in the tests are summarized in table 10. Test data from the metal-disk (simulated transducer diaphragm) experiments and from tests using the four transducer types are tabulated to show the effects of protection on zero-shift amplitude and zero-shift delay. The data are presented in terms of normalized ratios: the maximum observed "protected" zero shift divided by the corresponding maximum "unprotected" zero shift. A similar normalizing procedure is used for the zero-shift delays. The protective coatings are ranked in the order of decreasing protection (increasing zero-shift amplitude), as obtained from the disk tests; transducer data are listed according to the protective coating applied during the respective tests.

It should be noted that, while the data from the disk tests represent averages of five tests for each type of protective coating, transducer results are for single tests.

The table shows generally good correspondence between disk and transducer data on zero shift, with a few anomalies. The results of the strain-gage transducer tests indicate three layers of black tape to be about twice as effective as suggested by the disk tests, and indicate one layer of black tape to be slightly more effective than determined in the disk tests.

For the quartz-crystal transducers and semiconductor strain-gage transducers, black tape appears to perform much better than suggested by the disk tests. However, these are the transducers with rimmed diaphragms or very small diaphragms for which the dynamic response test data contain anomalies. As explained in 4.2.2, these anomalies are thought to be the result of trapped air. Air trapped between tape coating and diaphragm would tend to reduce and delay the zero shift resulting from the thermal transient.

Zero-shift time delays do not correspond with zero-shift amplitude changes, however, and show considerable variations for the various types of protective coatings, with a range of about 15 to 1 for the disk experiments, and of as much as 27 to 1 for the semiconductor strain-gage transducers.

5. CONCLUSIONS

The following conclusions can be drawn from the work, although the limited number of specimens and trials suggests caution.

1. The metal-disk (simulated transducer diaphragm) test method for evaluating coating materials appears to be a valid, simple, and relatively inexpensive method for initial screening.

2. Data obtained from dynamic pressure tests of protected transducers indicate that the materials sampled in these tests, in the thicknesses used, do not degrade significantly the dynamic performance of the pressure transducers tested.

3. Anomalies observed in the results, such as the effects attributed to possible air entrapment, demonstrate that a prospective coating should be evaluated in tests in which the coating is applied to the transducer model it is intended to protect. Evaluation should consist of both thermal transient and dynamic pressure tests covering the range in which the transducer is to be used.

4. The most desirable protection is that which eliminates completely the thermal transient response of the transducers. For most applications, next is that which reduces the amplitude of that response. For applications in which pressure is measured only over a short interval of time, protection which simply delays the thermal transient response well beyond that interval should be acceptable.

In regard to the coatings tested, certain conclusions can be drawn. In general, it appears that the "heat-sink" silicone compound and the two-component red RTV silicone rubber offer the best all-around protection. Multi-layer white and fiberglass tapes offer reasonable protection; single layers of these tapes offer poor protection. Silicone grease appears of little use with thermal transients similar to those used in the tests. Although used commonly in the field, black tape appears not only to be of dubious value as a protective coating, but may degrade dynamic performance unpredictably, varying with transducer type and application.

6. RECOMMENDATIONS

Recommendations for future work include the following:

1. Statistically significant tests to determine the effects of varying the thickness of protective coatings, to provide information to permit an optimum choice of thickness for a given coating;

2. Tests using a convective heat source;

3. Evaluation of the durability of the protective coatings; and

4. Investigation of the use of path-geometry protective schemes (such as mechanical screens).

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TABLE 1

Zero Shift Resulting from Thermal Radiant-Energy Transient
Applied to Protected and Unprotected Unbonded Strain-Gage Pressure Transducers

		Test Transducer		Control Transducer	
Test No.	Protective Coating on Diaphragm of Test Transducer	Maximum Negative Zero Shift % FS*	Time to Maximum Negative Zero Shift, ms	Maximum Negative Zero Shift % FS*	Time to Maximum Negative Zero Shift, ms
1	None	7.4	65	6.4	65
2	One Layer Black Tape	6.5	260	7.3	60
3	Three Layers Black Tape	2.2	860	7.1	55
4	One Layer White Tape	3.7	70	6.5	65
5	Three Layers White Tape	2.0	50	7.4	50
6	One Layer Fiberglass Tape	4.1	55	7.7	55
7	Three Layers Fiberglass Tape	1.5	60	7.3	60
8	None	7.7	65	7.1	65
9	Silicone Grease	6.4	55	7.1	60
10	Silicone "Heat-Sink" Compound	0.4	500	8.3	60
11	Two-Component Red RTV Silicone Rubber	1.2	750	7.6	64
			Average	7.3	60
			Coefficient of Variation, %	7.3	8.2

*FS = full-scale reading of the transducer

TABLE 2

Zero Shift Resulting from Thermal Radiant-Energy Transient
Applied to Protected and Unprotected Quartz-Crystal Pressure Transducers

Test Transducer					
Test No.	Protective Coating on Diaphragm	Maximum Negative Zero Shift % FS	Maximum Positive Zero Shift % FS	Time to Maximum Negative Zero Shift, ms	Time to Maximum Positive Zero Shift, ms
12	None	5.3	5.5	36	110
13	One Layer Black Tape	0.4	3.6	74	370
14	Three Layers Black Tape	0.0	0.9	—	1100
15	One Layer White Tape	1.8	2.4	34	120
16	Three Layers White Tape	0.9	0.9	37	120
17	One Layer Fiberglass Tape	2.5	2.9	36	120
18	Three Layers Fiberglass Tape	0.7	0.7	35	110
19	Silicone Grease	4.9	4.9	33	120
20	Silicone "Heat-Sink" Compound	0.2	0.2	36	1000
21	Two-Component Red RTV Silicone Rubber	0.0	0.4	—	1500
22	None	4.6	4.3	34	120

Control Transducer					
Test No.	Protective Coating on Diaphragm	Maximum Negative Zero Shift % FS	Maximum Positive Zero Shift % FS	Time to Maximum Negative Zero Shift, ms	Time to Maximum Positive Zero Shift, ms
12	None	4.7	2.7	38	105
13	None	5.8	3.1	39	120
14	None	5.5	2.9	38	120
15	None	4.5	2.4	35	105
16	None	5.1	2.5	36	110
17	None	5.1	2.7	38	120
18	None	5.3	2.9	35	110
19	None	5.1	2.5	34	110
20	None	5.3	2.9	34	110
21	None	5.5	2.9	35	110
22	None	4.9	2.6	36	120
	Average	5.2	2.7	36	113
	Coefficient of Variation, %	7.3	8.1	4.9	5.4

TABLE 3

Zero Shift Resulting from Thermal Radiant-Energy Transient Applied to Protected and Unprotected Semiconductor Strain-Gage Pressure Transducer

Test No.	Protective Coating on Diaphragm of Test Transducer	Maximum Positive Zero Shift % FS	Time to Maximum Positive Zero Shift, ms
23	None	180	39
24	One Layer Black Tape	9	25
25	Three Layers Black Tape	3	20
26	One Layer White Tape	160	28
27	Three Layers White Tape	90	25
28	One Layer Fiberglass Tape	130	27
29	Three Layers Fiberglass Tape	70	21
30	None	200	34
31	Silicone Grease	190	33
32	Silicone "Heat-Sink" Compound	6	19
33	Two Component Red RTV Silicone Rubber	1	500

*FS = full-scale reading of transducer

TABLE 4

Zero Shift Resulting from Thermal Radiant-Energy Transient Applied to Protected and Unprotected Piezoelectric Lead Metaniobate-Crystal Pressure Transducers

		Test Transducer			Control Transducer	
Test No.	Protective Coating on Diaphragm of Test Transducer (Control Transducer Uncoated)	Maximum Negative Zero Shift % FS*	Time to Maximum Negative Zero Shift, ms		Maximum Negative Zero Shift % FS*	Time to Maximum Negative Zero Shift, ms
34	None	56	130		54	140
35	One Layer Black Tape	48	2600		50	150
36	Three Layers Black Tape	30	3000		50	140
37	One Layer White Tape	18	1800		49	150
38	Three Layers White Tape	10	3000		46	160
39	One Layer Thermal Fiberglass Tape	24	1800		49	140
40	Three Layers Thermal Fiberglass Tape	10	3500		44	140
41	None	56	160		56	140
42	Silicone Grease	56	200		58	200
43	Silicone "Heat-Sink" Compound	5	3500		48	160
44	Two Component Red RTV Silicone Rubber	17	3600		48	140
				Average	50.2	151
				Coefficient of Variation, %	8.4	12.0

*FS = full-scale reading of the transducer

TABLE 5

Zero Shift Resulting from Thermal Radiant-Energy Transient
Applied to Unprotected Pressure Transducers
Summary of Responses of Four Pairs of Transducers

	Control Transducers (11 tests)				Test Transducers (2 tests)	
Type of Transducer	Maximum Zero Shift, % FS	Coefficient of Variation, %	Time to Maximum Zero Shift, ms	Coefficient of Variation, %	Maximum Zero Shift, % FS	Time to Maximum Zero Shift, ms
Unbonded Strain Gage Transducer	-7.3	7.3	60	8.2	-7.6	65
Quartz Piezoelectric Transducer	-5.2*	7.3	36	4.9	-5.0	35
	2.7	8.1	113	5.4	4.9	115
Semiconductor Strain Gage Transducer	--------N O C O N T R O L T R A N S D U C E R---------------				189**	37
Piezoelectric Transducer	-50	8.4	151	12.0	-56	145

*Negative shift followed by a positive shift.

**Some negative shift, but only positive shift tabulated because of complex waveform.

TABLE 6

Response of Two Unbonded Strain-Gage Pressure Transducers, One Protected and One Unprotected, to a Pressure Step of 280 kPa

Test Transducer

Test No.	Protective Coating on Diaphragm	Amplitude Ratio*	Rise Time 10-90% μs	Lowest Major Resonant Frequency kHz
1	None	1.000	14	9.8
2	One Layer Black Tape	1.026	14	10.0
3	Three Layers Black Tape	.972	16	10.0
4	One Layer White Tape	.998	16	9.8
5	Three Layers White Tape	1.008	16	9.8
6	One Layer Thermal Fiberglass Tape	1.007	16	9.6
7	Three Layers Thermal Fiberglass Tape	.998	14	9.2
8	None	1.001	16	9.6
9	Silicone Grease	.974	16	9.9
10	Silicone "Heat-Sink" Compound	1.024	14	8.8
11	Two-Component Red RTV Silicone Rubber	.990	14	9.2

Control Transducer

Test No.	Protective Coating on Diaphragm	Amplitude Ratio*	Rise Time 10-90% μs	Lowest Major Resonant Frequency kHz
1	None	1.000	9	10.6
2	None	1.026	14	10.6
3	None	.972	11	10.6
4	None	.998	14	10.4
5	None	1.008	11	10.6
6	None	1.007	14	10.6
7	None	.998	11	10.6
8	None	1.001	14	10.0
9	None	.974	11	10.6
10	None	1.024	16	10.6
11	None	.990	11	10.6
	Average	1.000	12	10.6
	Coefficient of Variation, %	1.7	17	1.8

*Average of 5 test transducer amplitudes (at 150 μs, 500 μs, 1 ms, 2 ms, and 3 ms) divided by 5 control transducer amplitudes at same times. Since the sensitivity of two instruments may not be the same, the amplitude ratio may not be 1.000.

TABLE 7

Response of Two Quartz Crystal Pressure Transducers, One Protected and One Unprotected, to a Pressure Step of 280 kPa

Test No.	Protective Coating on Diaphragm	Amplitude Ratio*	Rise Time 10-90% µs	Lowest Major Resonant Frequency
Test Transducer				
12	None	.992	1	-
19	None	.985	2	NO
20	Silicone Grease	1.008	1	
21	Silicone "Heat-Sink" Compound	.996	1	DATA
22	Two-Component Red RTV Silicone Rubber	.992	4	-
Control Transducer				
12	None	.992	1	-
19	None	.985	2	NO
20	None	1.008	1	
21	None	.996	1	DATA
22	None	.992	1	-
	Average	.995	1.2	
	Coefficient of Variation, %	0.9	37	

*Average of 5 test transducer amplitudes (at 15 µs, 50 µs, 1 ms, 2 ms, and 3 ms) divided by the average of 5 control transducer amplitudes at the same times.

TABLE 8

Response of One Semiconductor Strain-Gage
Pressure Transducer, Protected, to Pressure Step of 280 kPa

Test Transducer				
Test No.	Protective Coating on Diaphragm	Amplitude Ratio*	Rise Time 10-90% μs	Lowest Major Resonant Frequency kHz
23	None	1.031	2.4	128
30	None	.969	2.8	125
31	Silicone Grease	1.003	6.4	37
32	Silicone "Heat-Sink" Compound	1.014	5.0	49
33	Two-Component Red RTV Silicone Rubber	.921	5.4	46
	Average	.988		
	Coefficient of Variation, %	4.4		

*Since no control transducer was used, the data from the two uncoated tests was averaged and used as the denominator in the equation; this then does not correct for shock tube pressure step variations.

TABLE 9

Response of Two Lead Metaniobate Crystal Pressure Transducers, One Protected and One Unprotected, to Pressure Step of 280 kPa

Test No.	Protective Coating on Diaphragm		Amplitude Ratio*	Rise Time 10-90%, μs	
	Control Transducer	Test Transducer		Control Transducer	Test Transducer
34	None	None	1.028	1.8	1.4
35	None	One Layer Black Tape	1.026	1.4	1.4
36	None	Three Layers Black Tape	1.043	1.1	1.1
37	None	One Layer White Tape	1.057	0.9	1.1
38	None	Three Layers White Tape	1.021	0.9	0.9
39	None	One Layer Fiberglass Tape	1.019	0.7	0.7
40	None	Three Layers Fiberglass Tape	1.024	0.5	1.4
41	None	None	1.051	0.5	0.9
42	None	Silicone Grease	1.035	0.5	0.9
43	None	Silicone "Heat-Sink" Compound	1.050	0.5	1.4
44	None	Two-Component Red RTV Silicone Rubber	1.073	0.5	0.7
		Average	1.039	0.8	
		Coefficient Variation, %	1.7	52	

*Average of 5 test transducer amplitudes (at 15 μs, 150 μs, 1 ms, 2 ms, and 3 ms) divided by 5 control transducer amplitudes.

Since the sensitivity of two instruments may not be the same, the amplitude ratio may not be 1.000.

TABLE 10

Comparison of Coating Effectiveness

Protective Coating	Metal Disk Tests		Strain Gage Transducer Tests		Quartz-Crystal Transducer Tests				Semiconductor Strain-Gage Transducer Tests		Lead Metaniobate-Crystal Transducer Tests	
	Maximum Amplitude Response, Ratio*	Delay of Maximum Response, Ratio**	Maximum Amplitude Response, Ratio	Delay of Maximum Response, Ratio	Maximum Amplitude Response, Ratio Negative	Maximum Amplitude Response, Ratio Positive	Delay of Maximum Response, Ratio Negative	Delay of Maximum Response, Ratio Positive	Maximum Amplitude Response, Ratio	Delay of Maximum Response, Ratio	Maximum Amplitude Response, Ratio	Delay of Maximum Response, Ratio
None	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
"Heat-Sink" Silicone Compound	0.10	2.7	0.05	7.7	0.04	0.04	1.0	8.7	0.03	0.52	0.09	24
Two-Component White RTV	0.15	0.56	—	—	—	—	—	—	—	—	—	—
Two-Component Red RTV - (A)	0.18	6.5	0.16	11.5	0	0.08	—	13.	0.01	14.	0.30	25
Two-Component Red RTV - (B)	0.24	4.3	—	—	—	—	—	—	—	—	—	—
Three Layers Fiberglass Tape	0.24	4.1	0.20	0.92	0.14	0.14	1.0	0.96	0.37	0.58	0.18	24
Three Layers White Tape	0.25	1.3	0.26	0.77	0.18	0.18	1.1	1.0	0.49	0.68	0.18	21
Single-Component Aluminum RTV	0.41	3.2	—	—	—	—	—	—	—	—	—	—
Single-Component White RTV - (E)	0.48	0.50	—	—	—	—	—	—	—	—	—	—
Single-Component White RTV - (F)	0.48	0.42	—	—	—	—	—	—	—	—	—	—
Single-Component White RTV - (G)	0.49	0.47	—	—	—	—	—	—	—	—	—	—
Single-Component Black RTV	0.52	6.9	—	—	—	—	—	—	—	—	—	—
One Layer Fiberglass Tape	0.59	1.3	0.54	0.85	0.51	0.59	1.0	1.0	0.71	0.74	0.43	12
One Layer White Tape	0.61	0.89	0.49	1.1	0.36	0.49	0.97	1.0	0.86	0.77	0.32	12
Three Layers Black Tape	0.65	4.7	0.29	13	0	0.18	—	9.6	0.02	0.55	0.54	28
Silicone Grease	0.84	0.44	0.85	0.85	0.99	1.0	0.94	1.0	0.98	0.90	1.0	1.4
One Layer Black Tape	1.4	2.1	0.86	4.0	0.08	0.73	2.1	3.2	0.05	0.68	0.86	18

*Ratio of zero shift with protection to that without protection.
**Ratio of time of maximum zero shift with protection to time of maximum zero shift without protection

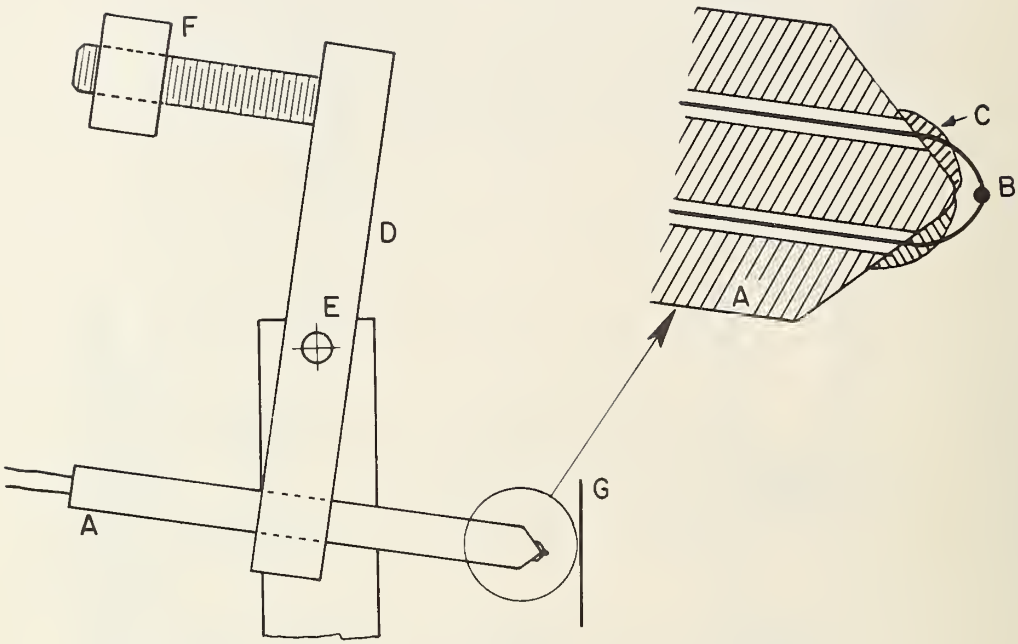


Figure 1: Sketch of thermocouple fixture with cross-section detail of thermocouple mounted in ceramic rod (A). The thermocouple measuring junction is identified by (B). The thermocouple wires project back through two axial bores in the rod. White glue (C) holds the thermocouple in place. The thermocouple-and-rod assembly is clamped in arm (D) pivotally mounted at (E). The position of the counterweight (F) may be adjusted to control the force exerted by the junction against the disk (G).

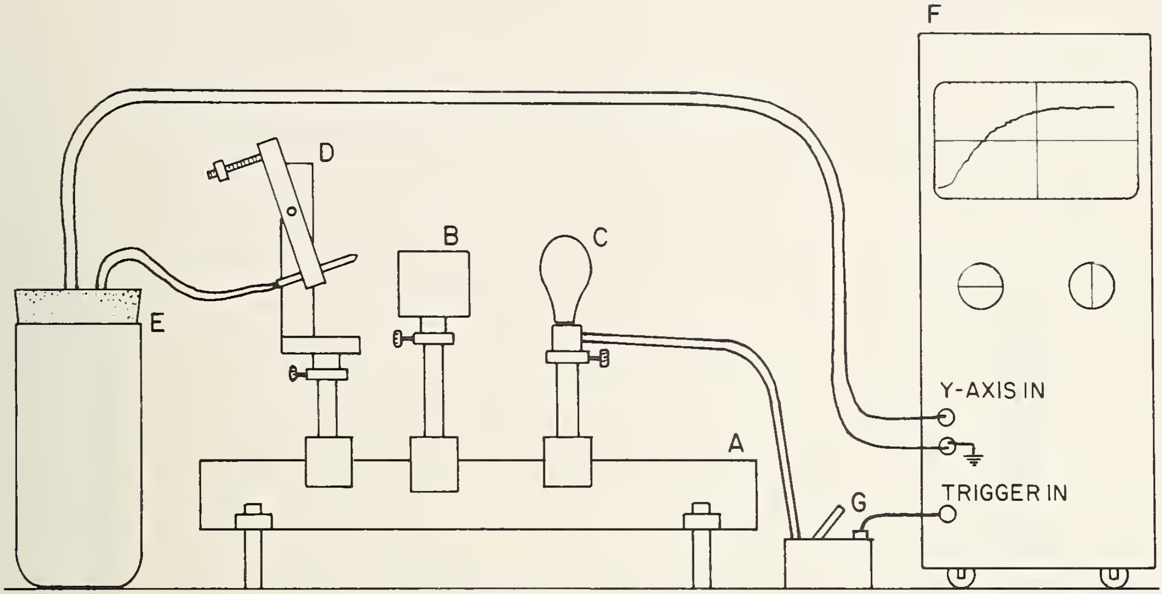


Figure 2: Arrangement of the test-method apparatus. Mounted on optical rail (A), are the transducer mounting block (B), the thermal radiant-energy source (C), and the thermocouple bracket assembly (D). The thermocouple cold junction is immersed in water contained in flask (E), and the thermocouple output signal is displayed on storage oscilloscope (F). The ignition system (G) for the source also supplies a trigger signal to the oscilloscope. The disk and its fixture are hidden within the transducer mounting block, as described in the text.

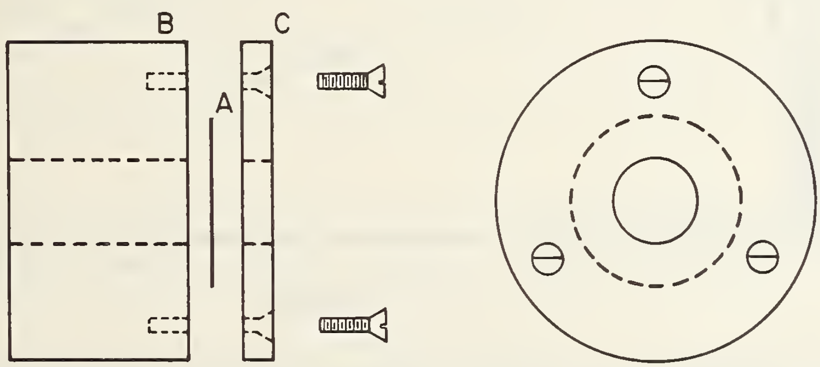


Figure 3: Sketch of disk mounting fixture. The side view at the left shows the fixture disassembled with the disk (A) in position ready to be clamped to the body (B) by clamping plate (C). As explained in the text, the diameter of the bore determines the aperture, that is, the area of disk exposed to thermal radiant energy. The outer diameter of the fixture is set by the requirements of the transducer mounting block.

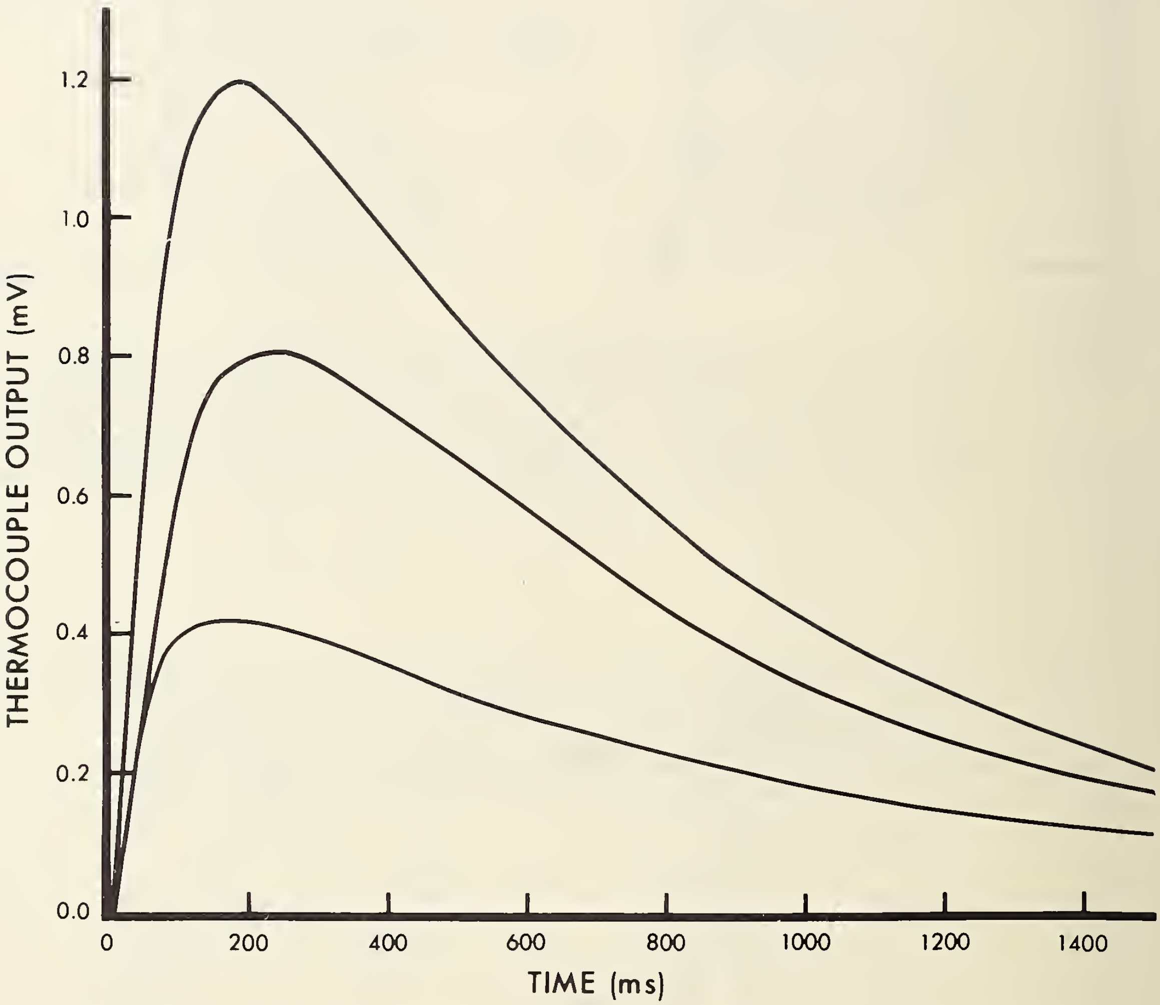


Figure 4: Thermocouple output (mV) as a function of time (ms) for three disk thicknesses, as measured by the method described in the text. The aperture used is 6.35 mm in diameter. The top curve represents a disk thickness of 0.08 mm; the middle curve, 0.13 mm; and the bottom curve, 0.25 mm.

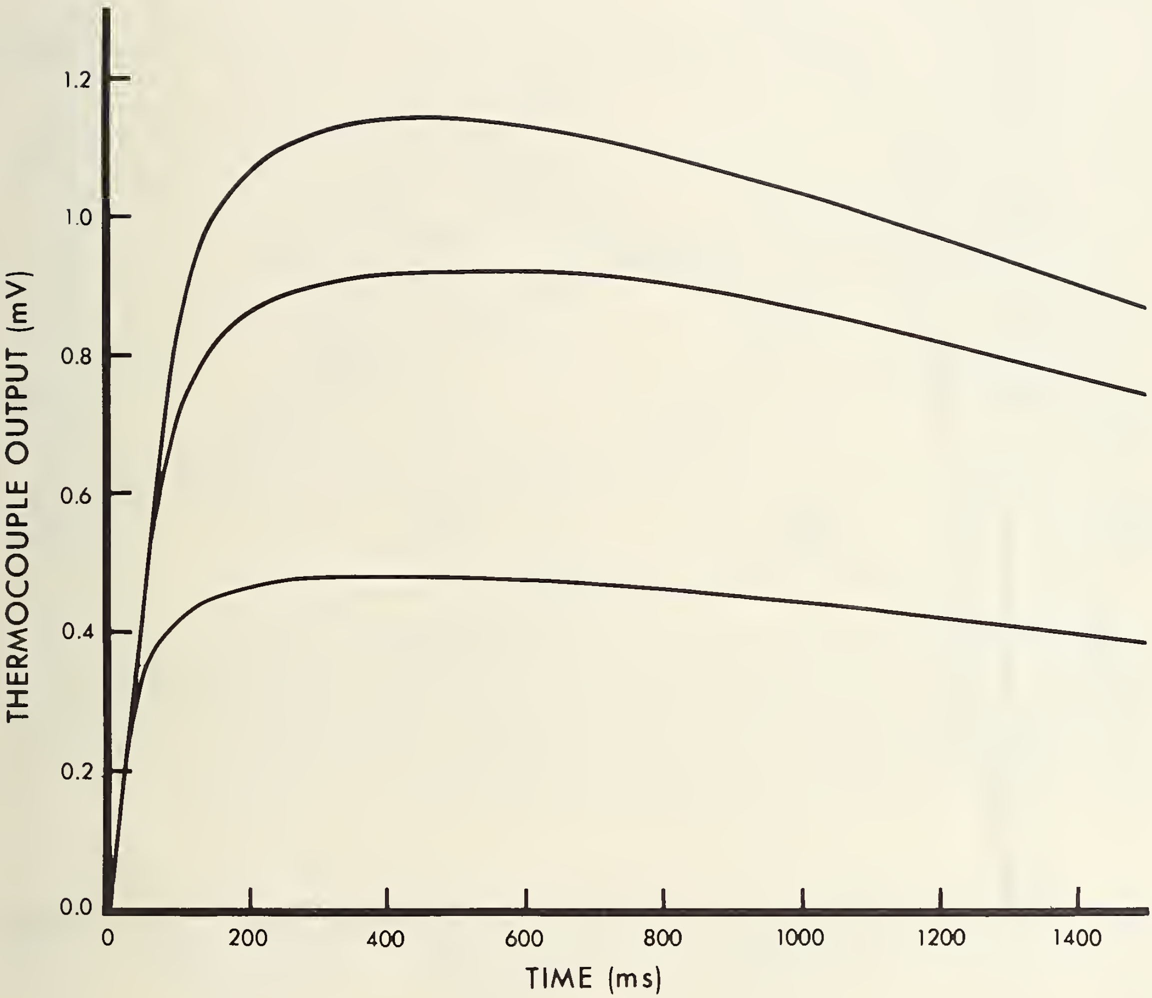


Figure 5: Thermocouple output (mV) as a function of time (ms) for three disk thicknesses, as measured by the method described in the text. The aperture used is 9.53 mm in diameter. The top curve represents a disk thickness of 0.08 mm; the middle curve, 0.13 mm; and the bottom curve, 0.25 mm.

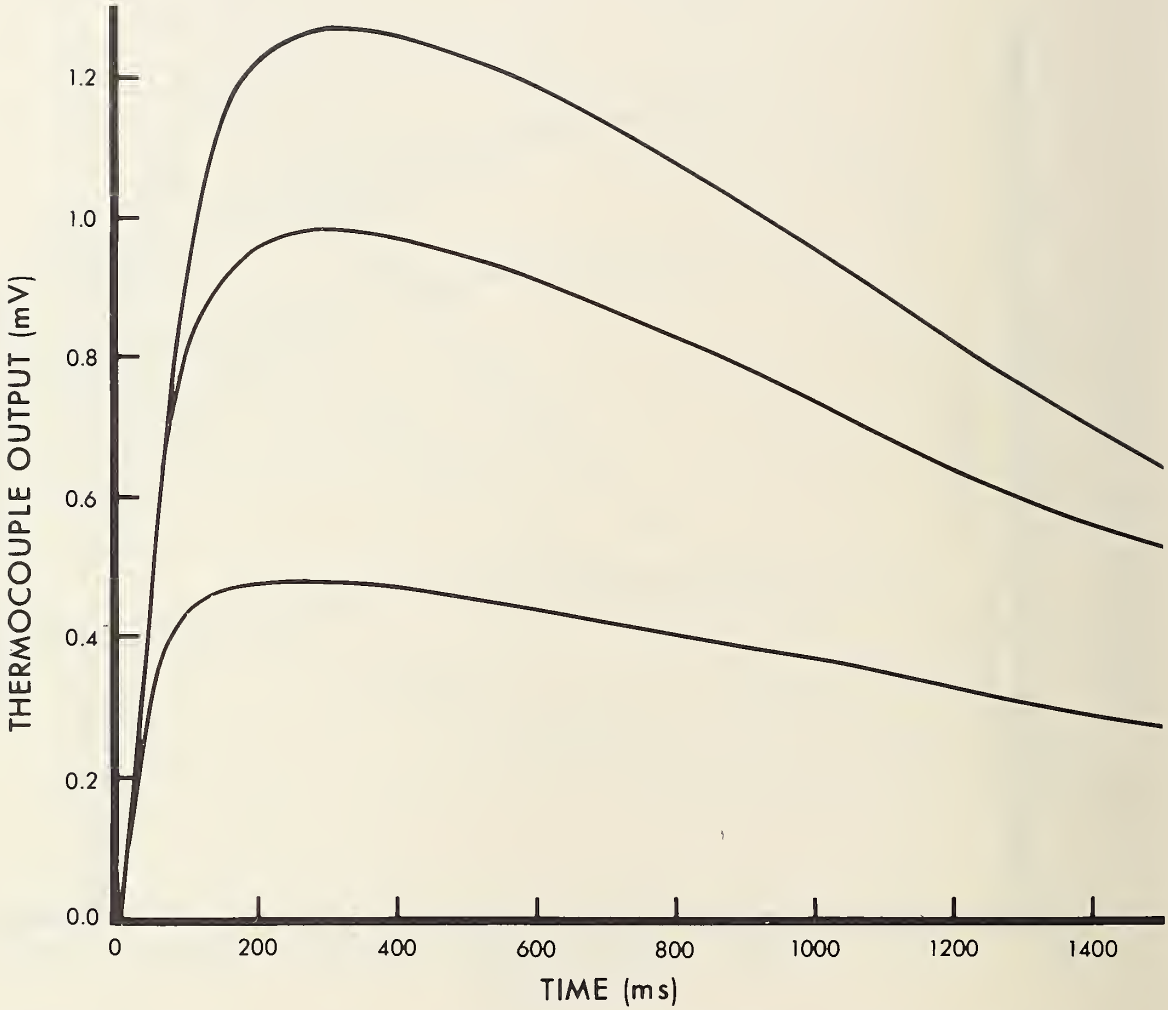


Figure 6: Thermocouple output (mV) as a function of time (ms) for three disk thicknesses, as measured by the method described in the text. The aperture used is 12.7 mm in diameter. The top curve represents a disk thickness of 0.08 mm; the middle curve, 0.13; and the bottom curve, 0.25 mm.

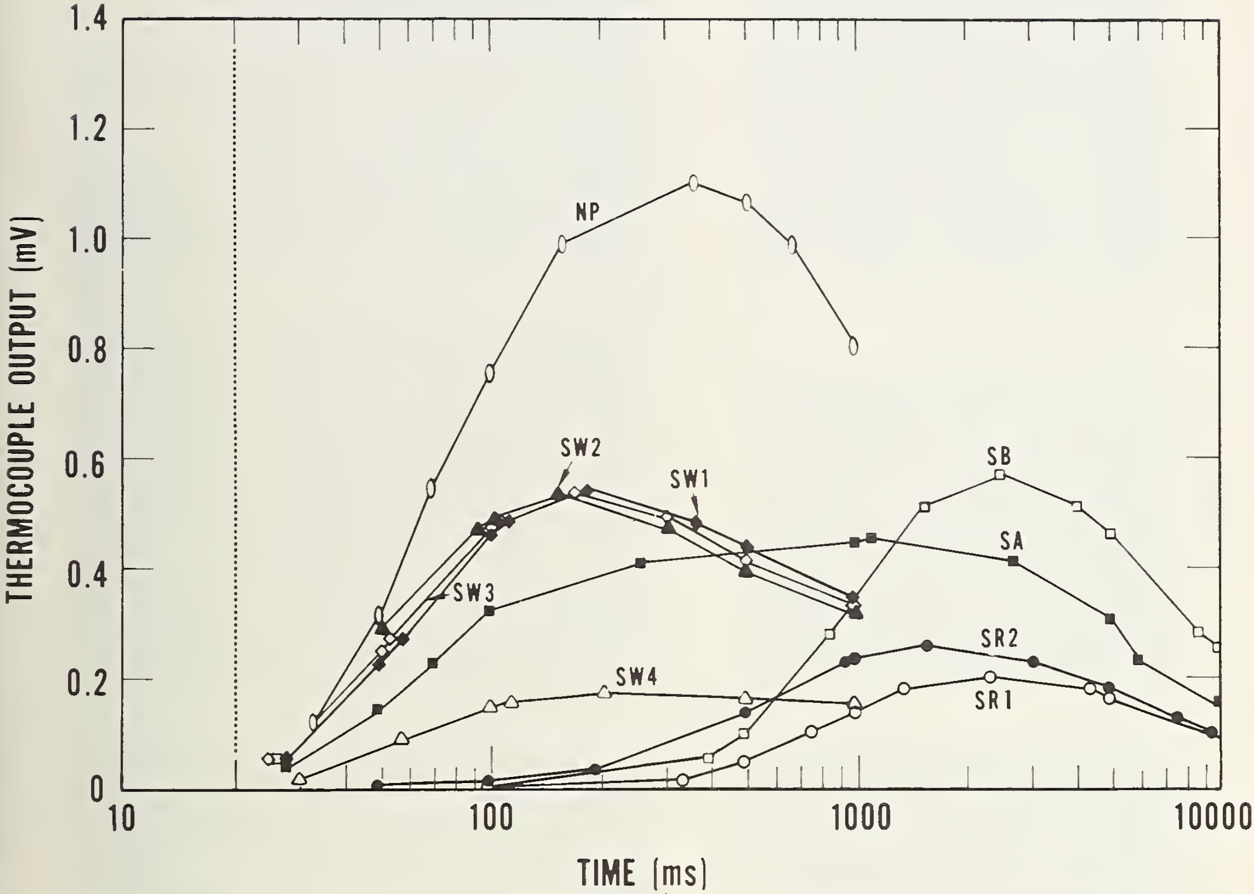


Figure 7: Results of tests using coatings on stainless steel disks. The plots show thermocouple output (mV) as a function of time (ms), with time plotted on a three-cycle logarithmic scale. As a rough guide, 1 mV corresponds to a rise of 16.6 Celsius degrees. The peak of the source output occurs at approximately 20 ms, as indicated by the dotted line. The curve NP represents an unprotected disk for comparison. As described in the text, each data point for the coating curves is an average from five tests. Curve NP is the average of twelve tests.

Coating identification:

SR1 = red RTV silicone rubber, two-component
SR2 = red RTV silicone rubber, two-component
SB = black RTV silicone rubber, single-component
SA = aluminum RTV silicone rubber, single-component

SW1 = white RTV silicone rubber, single-component
SW2 = white RTV silicone rubber, single-component
SW3 = white RTV silicone rubber, single-component
SW4 = white RTV silicone rubber, two-component

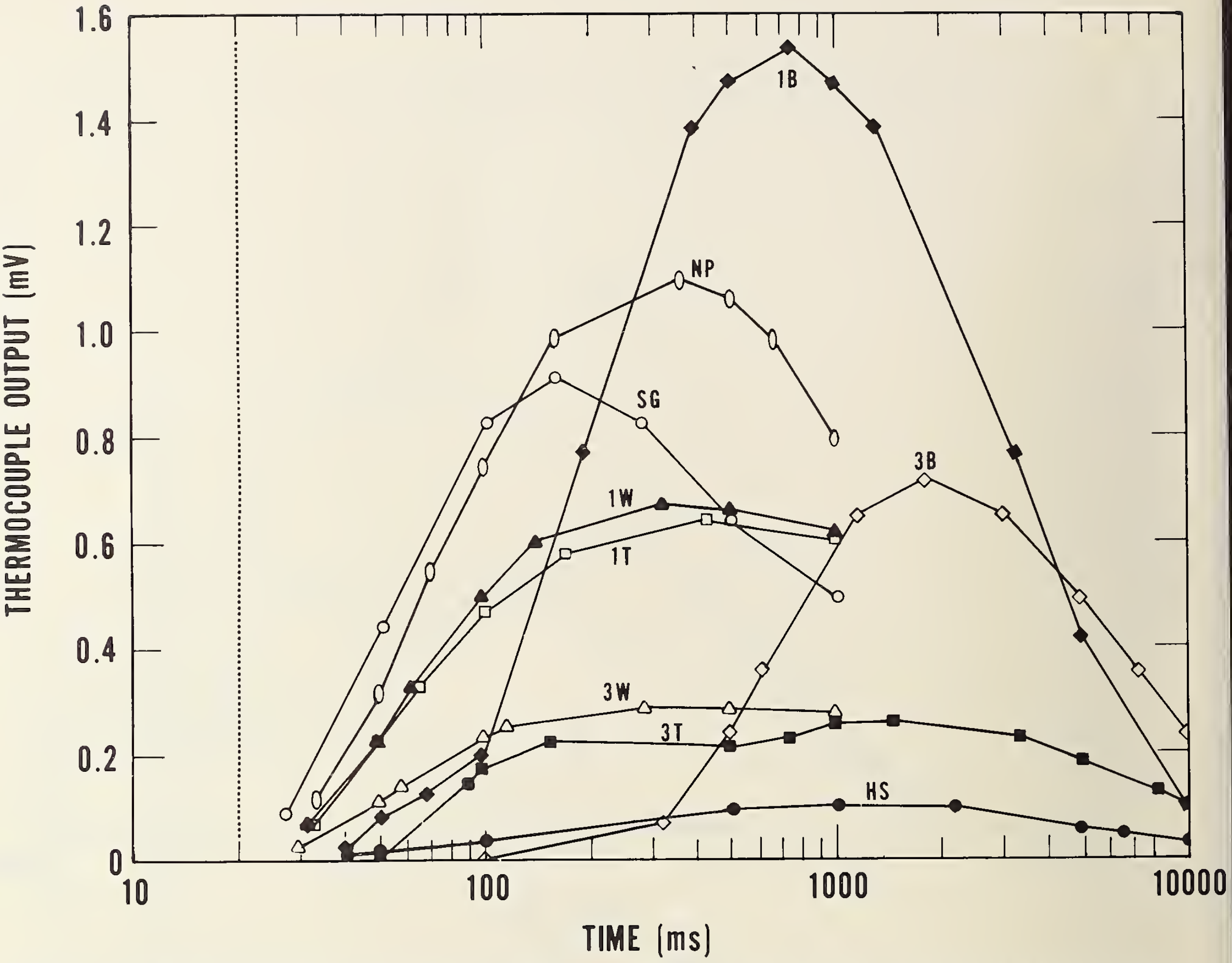


Figure 8: Results of tests using coatings on stainless steel disks. The plots show thermocouple output (mV) as a function of time (ms), with time plotted on a three-cycle logarithmic scale. As a rough guide, 1 mV corresponds to a rise of 16.6 Celsius degrees. The peak of the source output occurs at approximately 20 ms, as indicated by the dotted line. The curve NP represents an unprotected disk for comparison. As described in the text, each data point for the coating curves is an average from five tests. Curve NP is the average of twelve tests.

Coating identification:

1W = one layer white tape
1T = one layer fiberglass tape
1B = one layer black tape
3W = three layers white tape
3T = three layers of fiberglass tape
3B = three layers of black tape
HS = "heat sink" silicone compound
SG = silicone grease

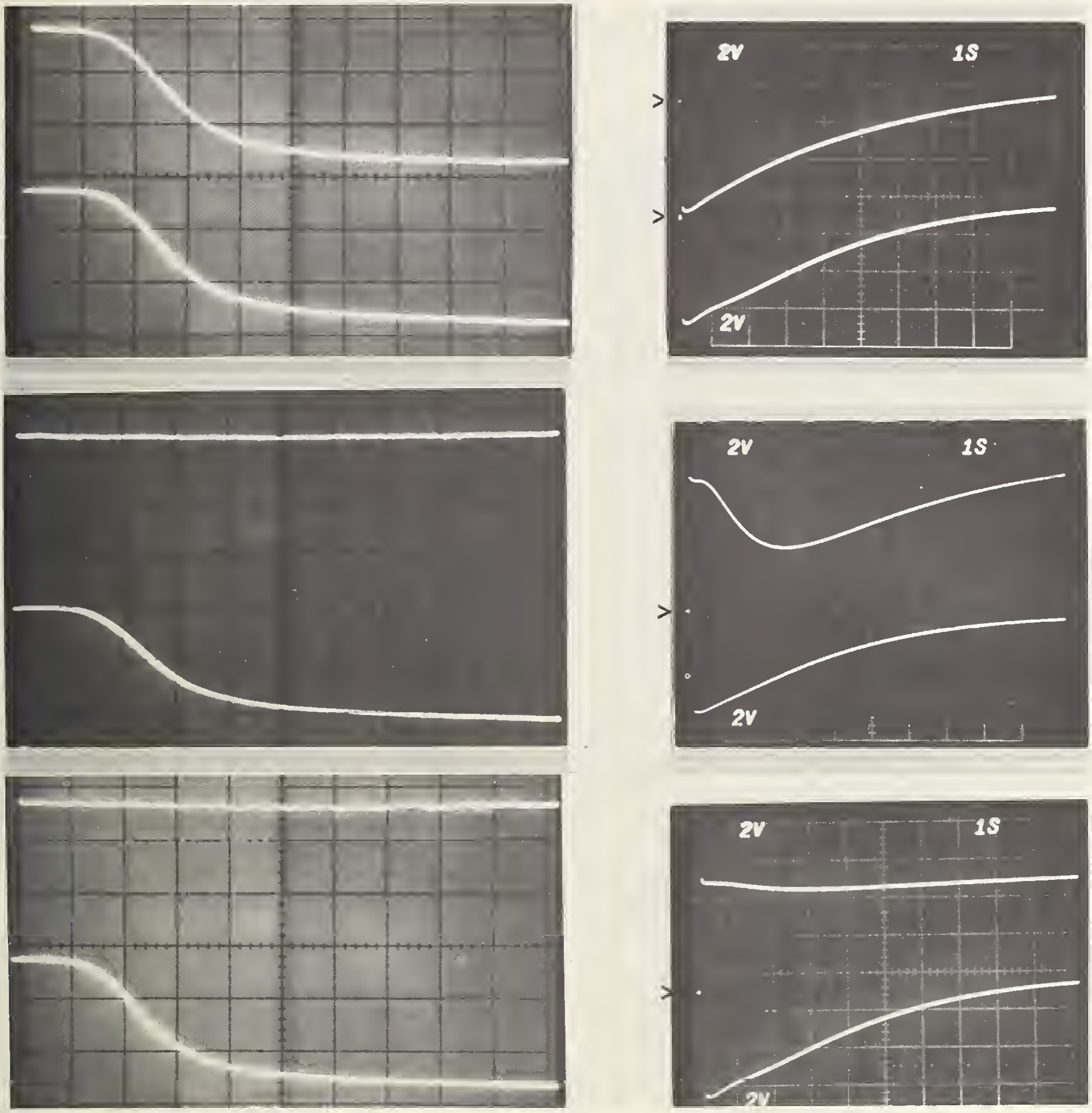


Figure 9: Responses of a pair of lead metaniobate-crystal pressure transducers exposed to a thermal radiant-energy transient of approximately 20 mJ/mm^2. Photographs of oscilloscope traces are shown. The purpose of the figure is to contrast the effect of three coatings; top photographs, silicone grease; middle, one layer of black tape; and bottom, red RTV silicone rubber. The upper trace in each photograph represents the test (coated) transducer response, and the lower trace represents the control (uncoated) response. The left-hand photographs show traces recorded at 10 ms/division, that is, over the first 0.1s after flash initiation. The right-hand traces were recorded at a rate 100 times slower, with a total sweep time of 10 s. For all traces, each vertical division represents about 20% of the transducer full-scale output. Note that for silicone grease, very little delay in, or reduction of, zero shift is recorded; for black tape, there is a considerable delay, but little reduction; and for red RTV silicone rubber, there is both delay and reduction. Because of limitations imposed by conflicting requirements of trace brightness versus focus, the initial negative trace deflection is only faintly visible in the original photographs of the 10-s sweep. Initial levels for these traces are indicated by arrows.

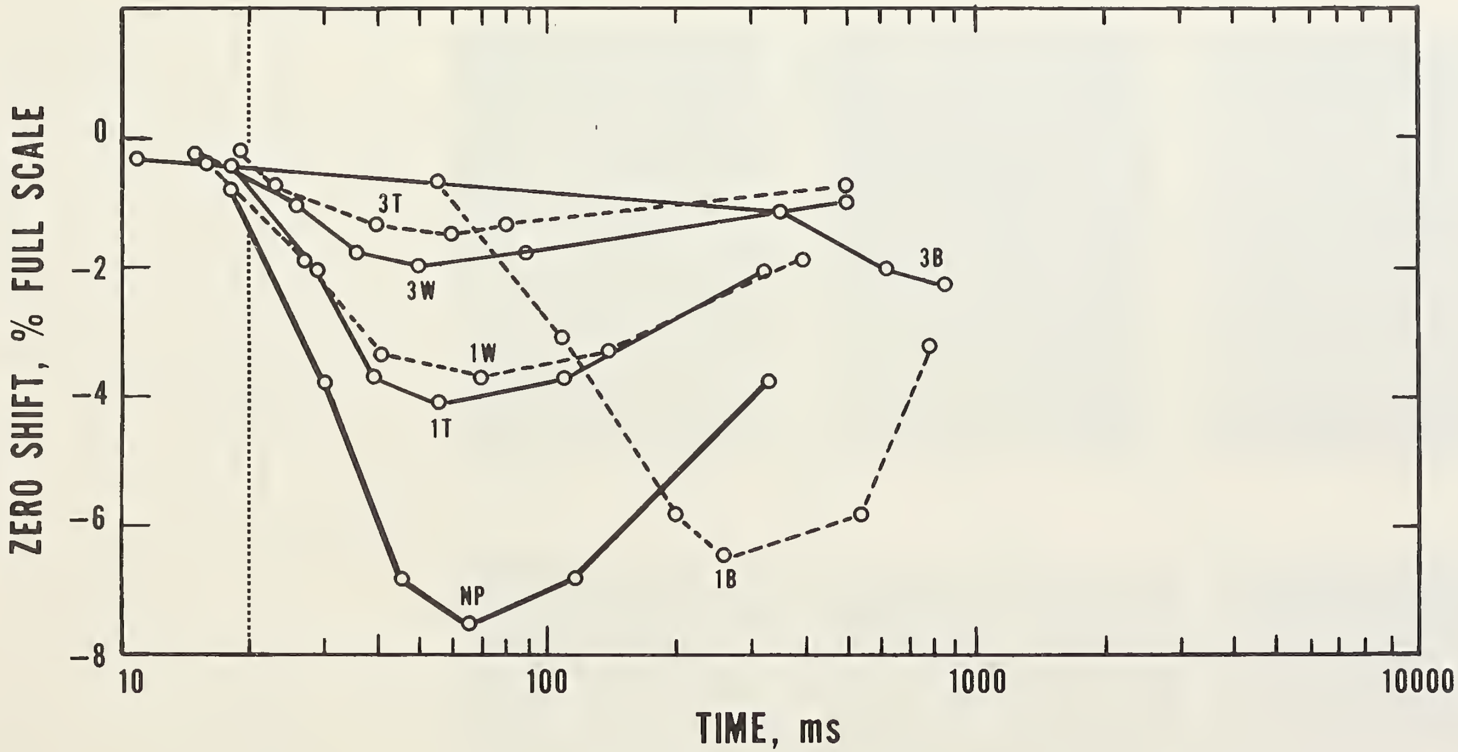


Figure 10A: Response of an unbonded strain-gage pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the dotted line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

1B - one layer of black tape	3B - three layers of black tape
1W - one layer of white tape	3W - three layers of white tape
1T - one layer of fiberglass tape	3T - three layers of fiberglass tape

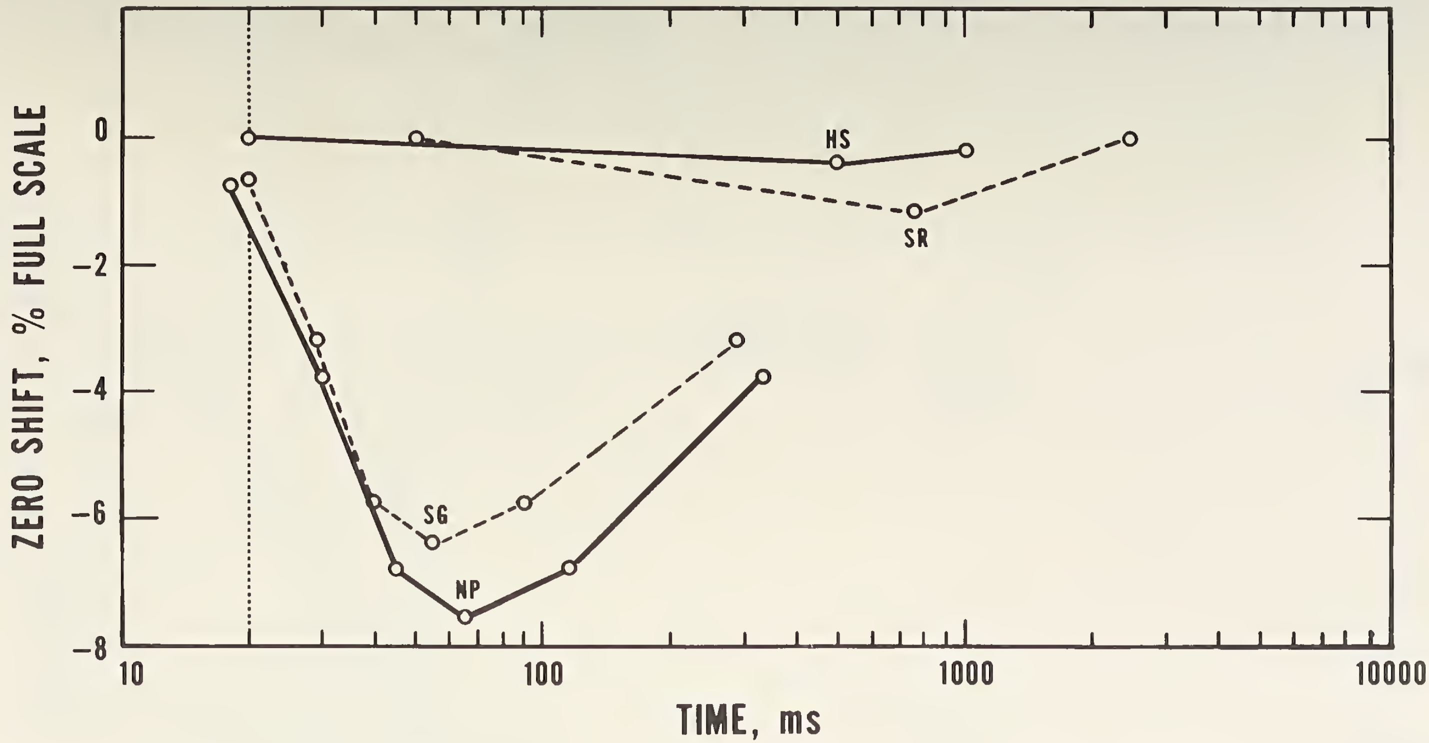


Figure 10B: Response of an unbonded strain-gage transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the dotted line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

HS - "heat-sink" silicone compound
SG - silicone grease
SR - red RTV silicone rubber

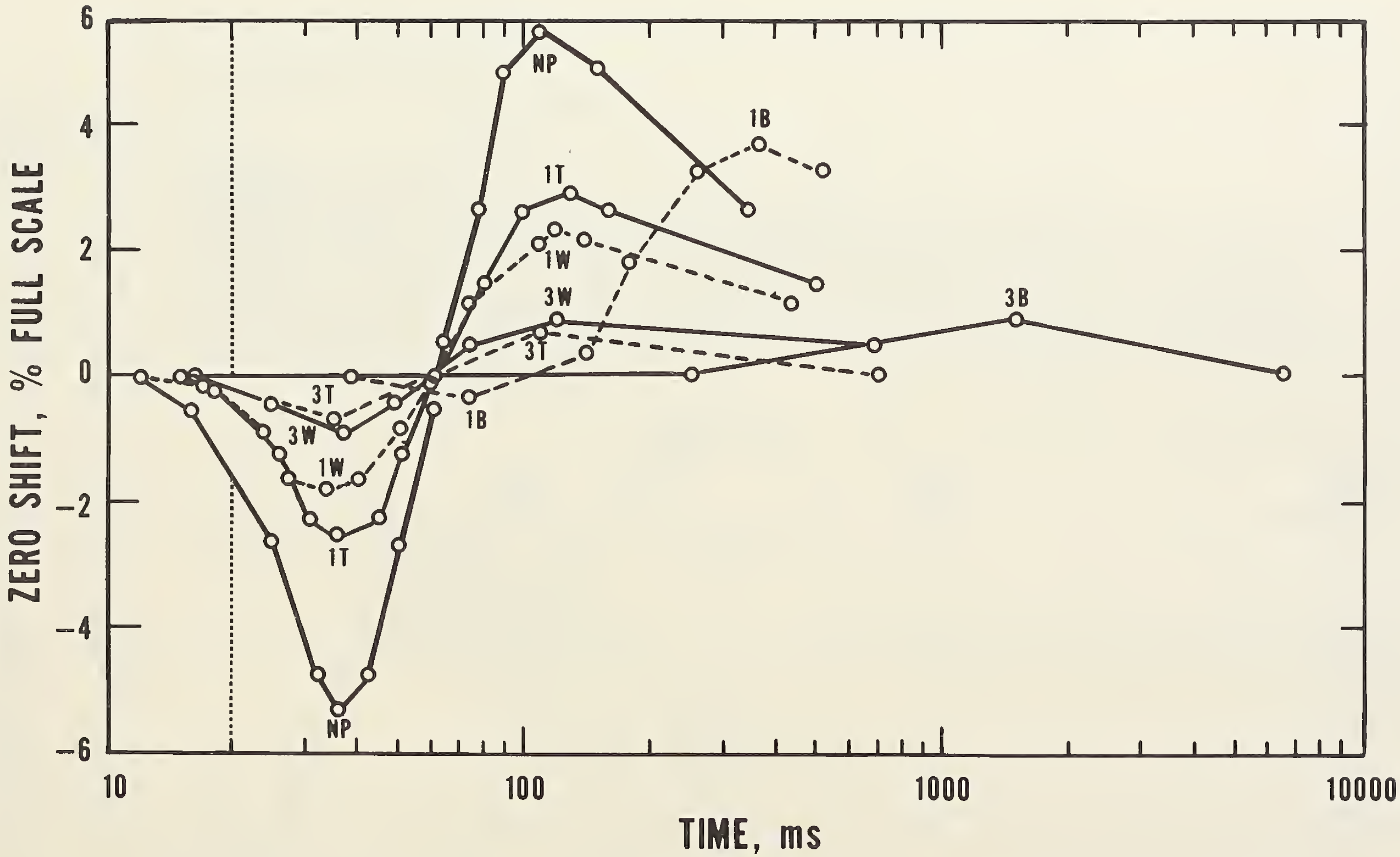


Figure 11A: Response of a quartz-crystal pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the dotted line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

1B - one layer of black tape
1W - one layer of white tape
1T - one layer of fiberglass tape

3B - three layers of black tape
3W - three layers of white tape
3T - three layers of fiberglass tape

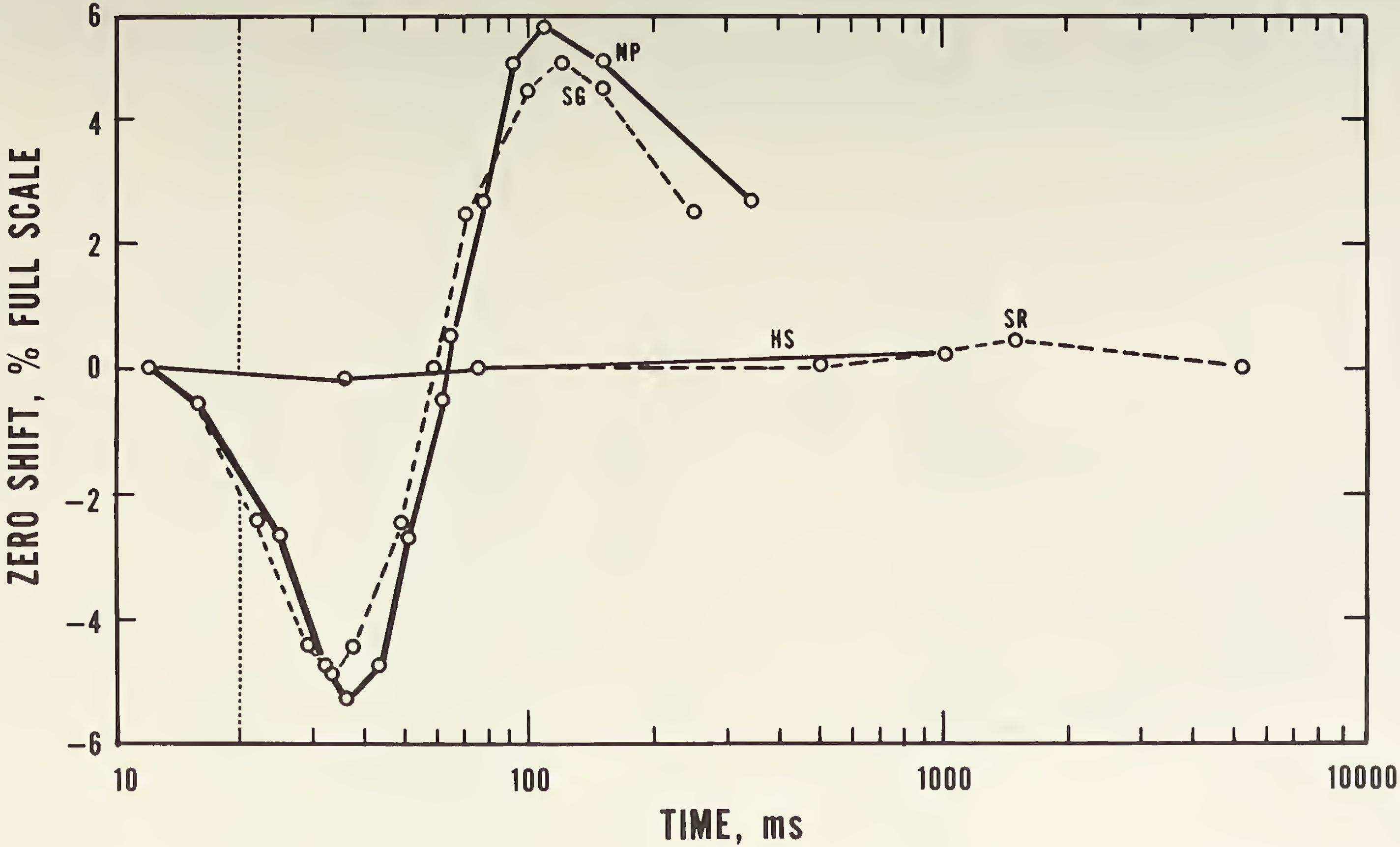


Figure 11B: Response of a quartz-crystal pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the dotted line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

HS - "heat-sink" silicone compound
SG - silicone grease
SR - red RTV silicone rubber

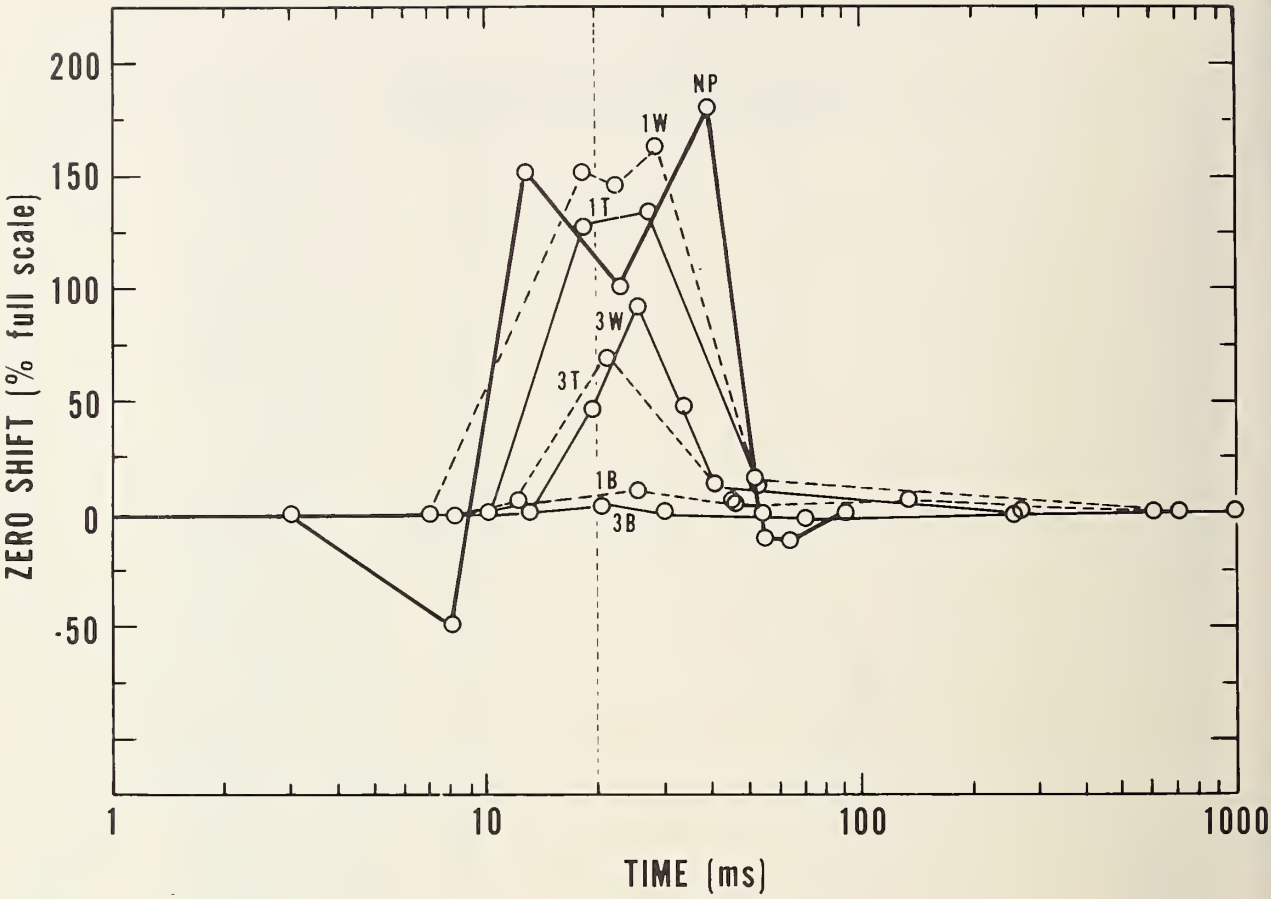


Figure 12A: Response of a semiconductor strain-gage pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the vertical line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

1B = one layer of black tape	3B = three layers of black tape
1W = one layer of white tape	3W = three layers of white tape
1T = one layer of fiberglass tape	3T = three layers of fiberglass tape

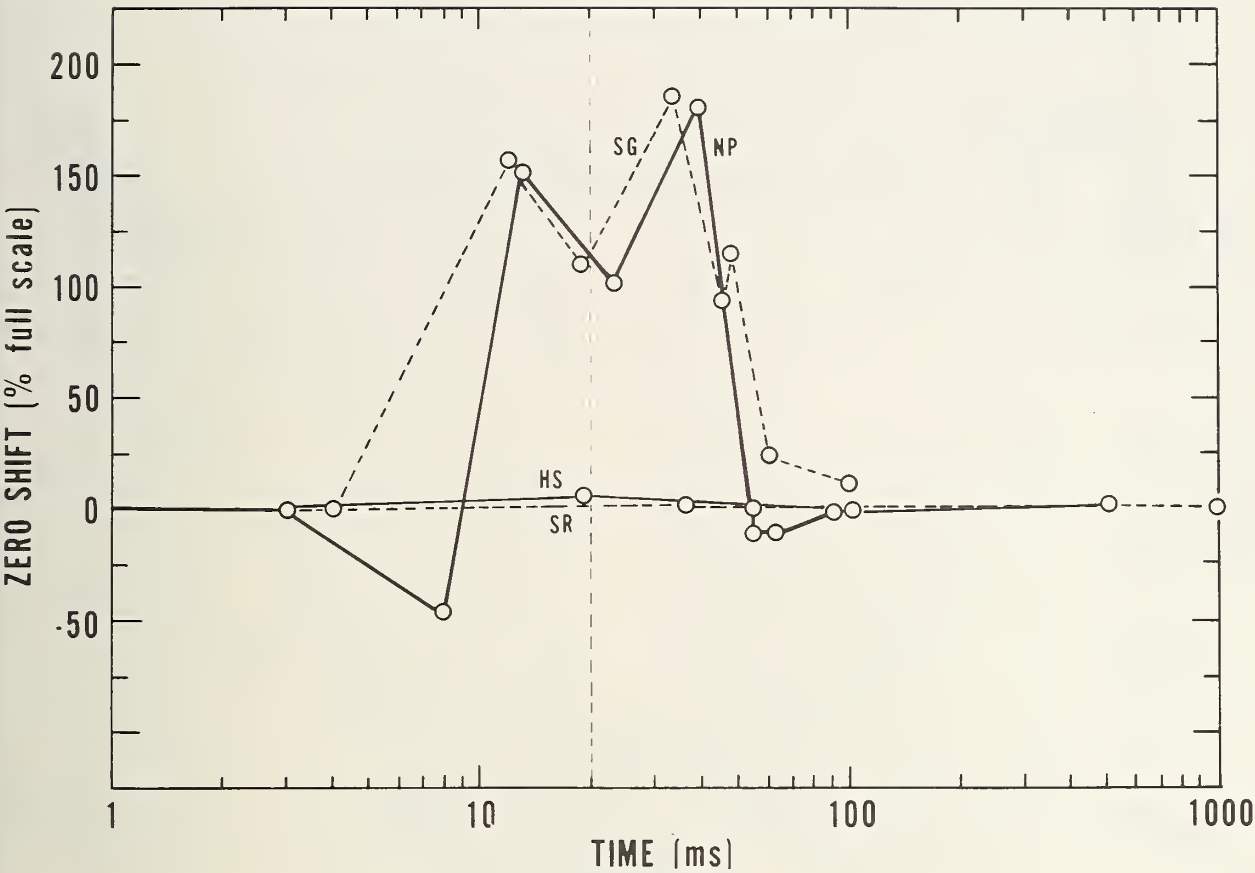


Figure 12B: Response of a semiconductor strain-gage pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the vertical line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

HS = "heat-sink" silicone compound
SG = silicone grease
SR = red RTV silicone grease

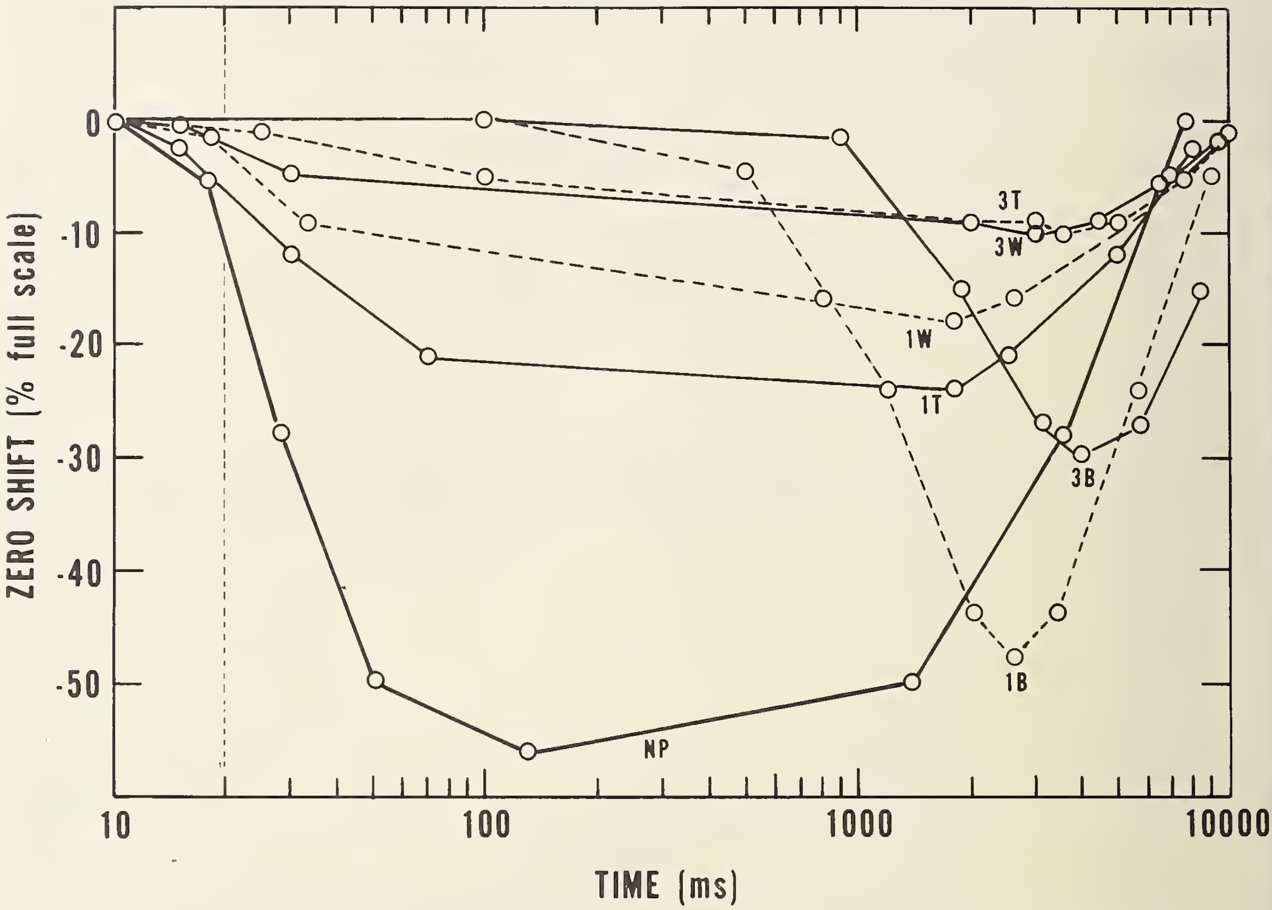


Figure 13A: Response of a lead metaniobate-crystal pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the vertical line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

1B = one layer of black tape
1W = one layer of white tape
1T = one layer of fiberglass tape

3B = three layers of black tape
3W = three layers of white tape
3T = three layers of fiberglass tape

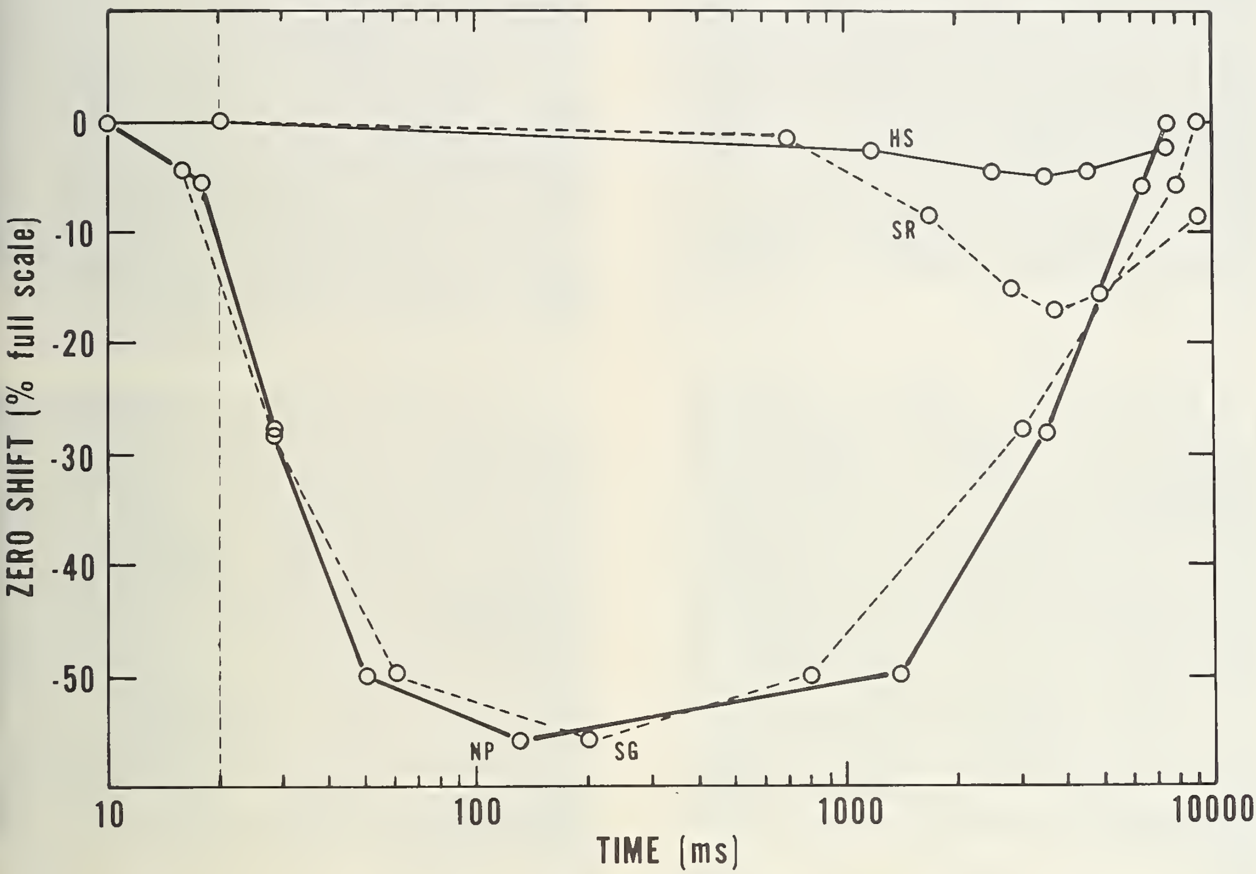
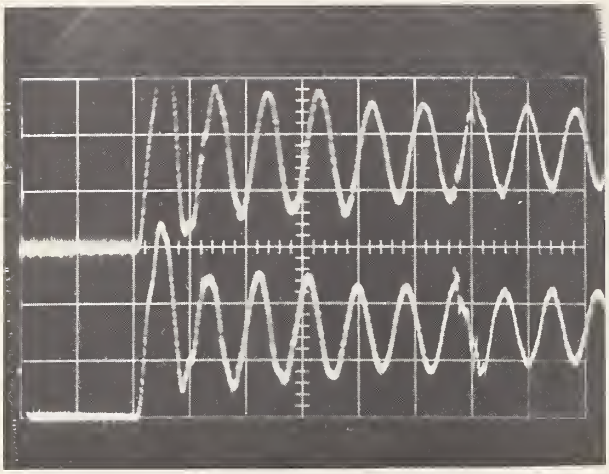


Figure 13B: Response of a lead metaniobate-crystal pressure transducer, with selected protective coatings applied to the diaphragm outer surface, to a thermal radiant-energy transient of approximately 20 mJ/mm^2. The plots are of transducer zero shift (percent of full-scale reading) as a function of time (ms), with time on a three-cycle logarithmic scale. The peak of the transient occurs at approximately 20 ms, as indicated by the vertical line. The heavy-line plot (NP) represents the transducer zero shift with no protective coating.

Coating identification code:

HS = "heat-sink" silicone compound
SG = silicone grease
SR = red RTV silicone rubber



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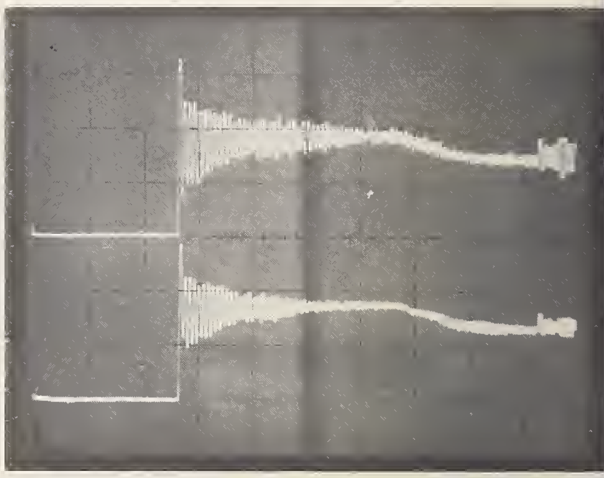

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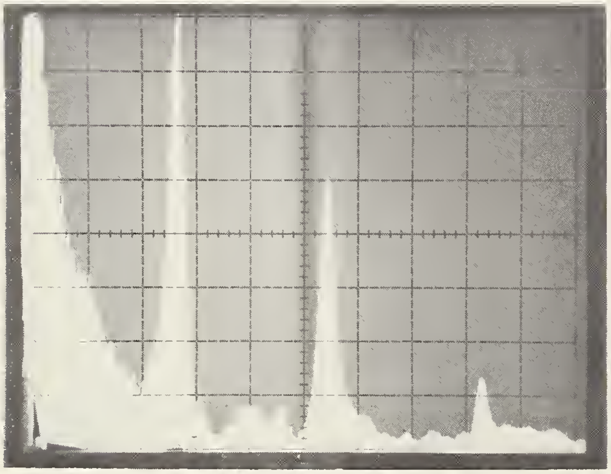

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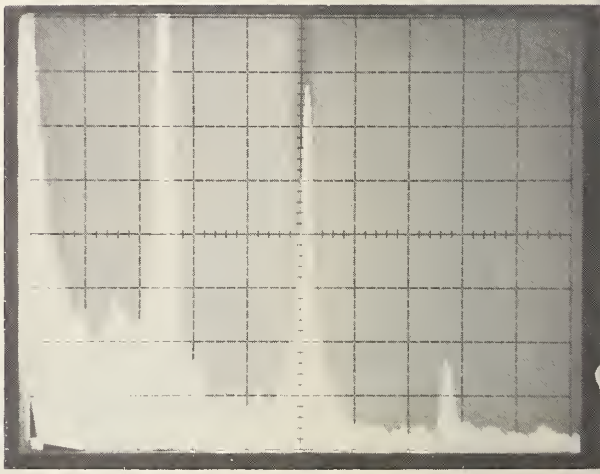
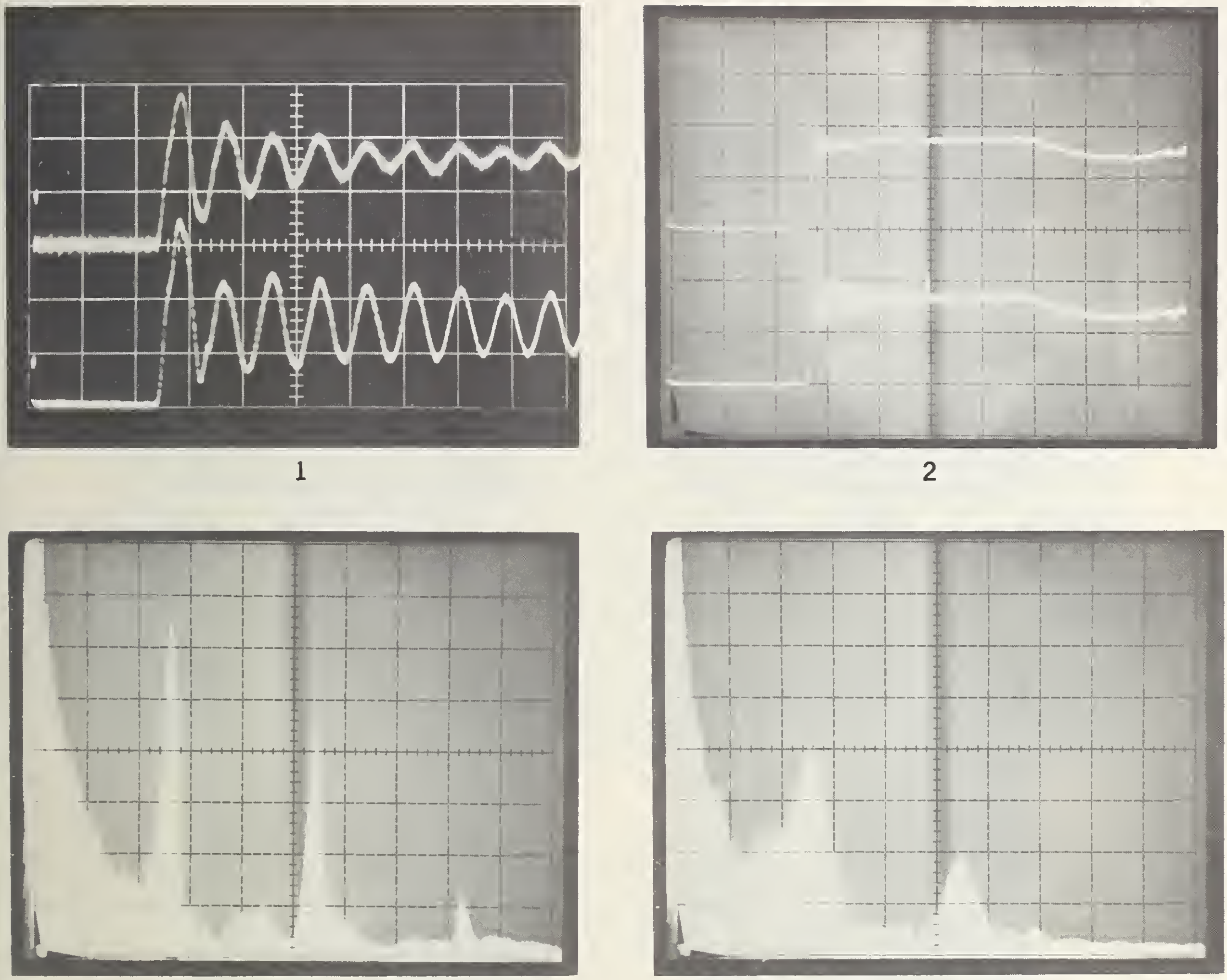


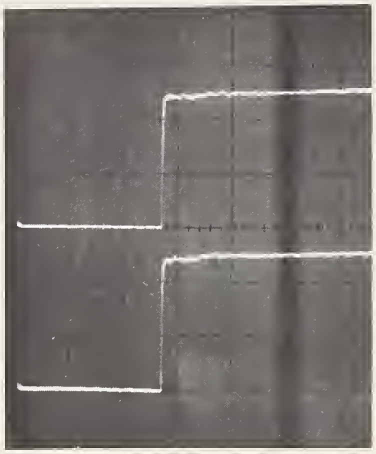
4

Figure 14: Response to a pressure step of 280 kPa of two unbonded strain-gage pressure transducers. In these tests neither test nor control transducer had a protective coating applied to the diaphragm. Photographs 1 and 2 are of oscilloscope traces displaying the outputs of the test (upper trace) and control (lower trace) transducers. The time scale of the traces in photograph 1 is 0.1 ms/division, and in 2, is 1.0 ms/division; for the traces in both photographs a deflection of one division in the vertical direction corresponds to 10 mV. Any variation between the upper and lower traces in either photograph would be expected to be attributable to the differences in performance that are commonly observed between two individual transducers of the same model. Photographs 3 and 4 are of traces displaying the frequency spectrum of the traces in 2, that is, relative intensity at a given frequency as a function of frequency. The frequency range (horizontal axis) is linear and extends from 0 to 40 kHz (4 kHz/division).



1 2 3 4

Figure 15: Response to a pressure step of 280 kPa of two unbonded strain-gage pressure transducers. In these tests the test transducer had a protective coating of three layers of black tape applied to the diaphragm; the control had no protection. Photographs 1 and 2 are of oscilloscope traces displaying the outputs of the test (upper trace) and control (lower trace) transducers. The time scale of the traces in photograph 1 is 0.1 ms/division, and in 2, is 1.0 ms/division; for the traces in both photographs a deflection of one division in the vertical direction corresponds to 10 mV. Photographs 3 and 4 are of traces displaying the frequency spectrum of the traces in 2. The frequency range (horizontal axis) is linear and extends from 0 to 40 kHz (4 kHz/division).



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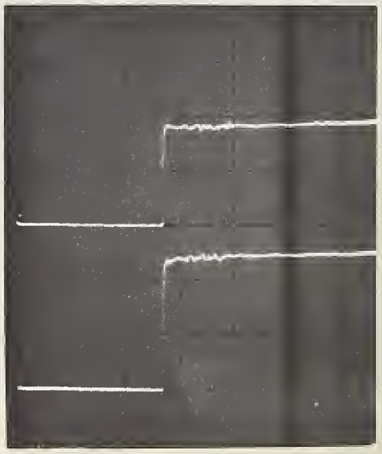
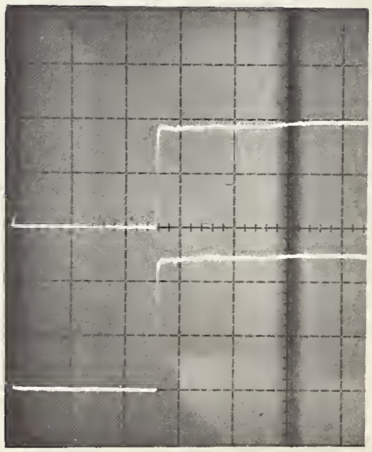


2



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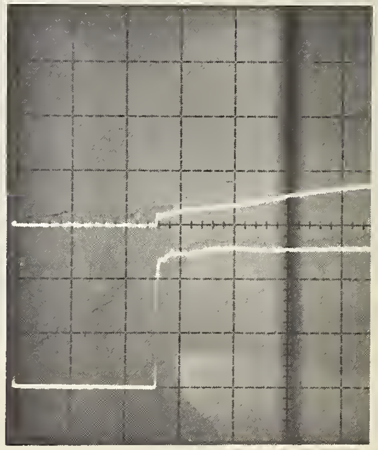

4

Figure 16: Response to a pressure step of 280 kPa of two quartz-crystal pressure transducers. In the tests represented by the photographs above, the test transducer had a protective coating of three layers of tape applied to the diaphragm; the control transducer received no protective coating. The photographs are of oscilloscope traces displaying the outputs of the test- (upper trace) and control- (lower trace) transducers. The time scale for all traces is 1 ms/division; a vertical deflection of one division corresponds to 100 mV. The test transducer traces in the four photographs above illustrate the wide variations in the pressure amplitude transmitted through the tape layers to the diaphragm; note that at the same time the four control transducer traces show little variation. A possible explanation for the variations shown here is advanced in 4.4.2.

Figure 17: Photographs of the faces forming part of the sensing assembly of a quartz-crystal (left) and an unbonded strain-gage (right) pressure transducer. Part or all of these faces are the outer surfaces of the respective instrument diaphragms. Note the presence of the annular ridge (arrow) on the face of the quartz-crystal instrument. This ridge marks the periphery of the diaphragm; the significance of the presence of the ridge is discussed in 4.4.2.

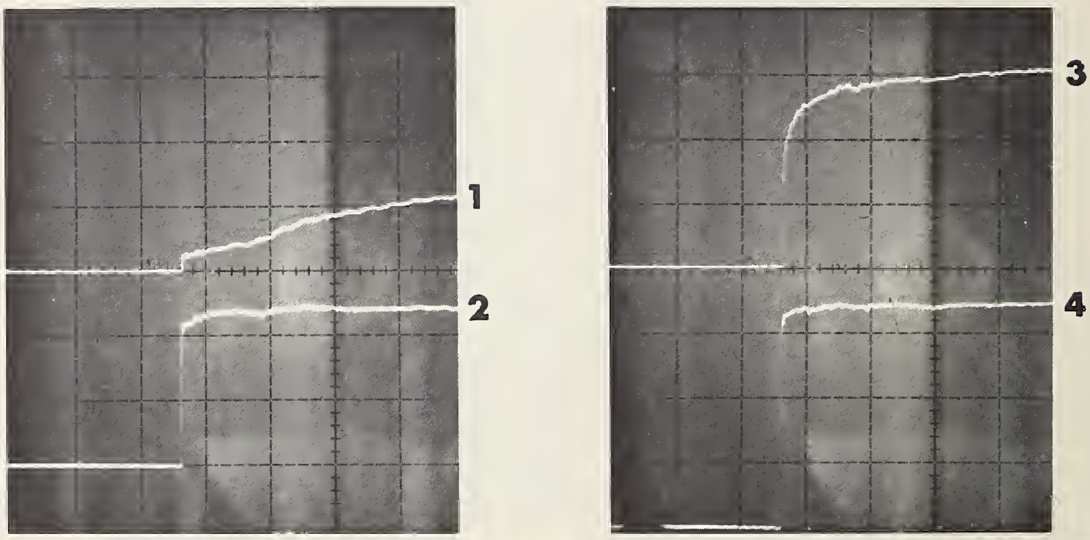

Figure 18: Response to a pressure step of 280 kPa of two quartz-crystal pressure transducers is shown in traces 1 and 2; the response to 2070 kPa of the same transducers is shown in traces 3 and 4. The diaphragm of the test transducer (response shown by traces 1 and 3) had a protective coating of three layers of black tape. The control transducer (response shown by traces 2 and 4) had no protective coating in either set of traces. The time scale for all traces is 1 ms/division; a vertical deflection of one division corresponds to 100 mV for the oscilloscope photograph on the left and 500 mV for the photograph on the right.

APPENDIX A

The test procedure used in the evaluation of protective coatings on transducer diaphragms is given in detail below. In this procedure, the transducer zero-shift is measured with a known thermal transient input.

1. Mount the transducer fixture (with test and control transducers installed) onto the end plate of the shock tube.

2. Attach the mounting bracket for the flashbulb socket to the end plate.

3. Adjust the distance from the center plane of the flashbulb to the plane of the diaphragms to be 70 mm. Tighten clamps.

4. Install a No. 22 flashbulb in the socket position.

5. Rotate the socket so that the direction in which the supporting (each in the shape of an inverted "L") electrodes point is approximately perpendicular to a line between the center of the flashbulb and a point on the face of the fixture midway between the centers of the two diaphragms and on the line joining these centers.

Note - On ignition, a black spot commonly appears on the bulb in the area opposite to that at which the electrodes point. Step 5 prevents the spot from reducing the energy reaching the transducers.

6. Make or check the required electrical connections, including the flashbulb ignition-voltage source to the socket and to the trigger of the storage oscilloscope, transducer outputs to the storage oscilloscope, and, if required, transducer excitation-voltage source to the transducers. Turn on equipment.

7. Set the oscilloscope sweep rate to 10 ms/div and adjust triggering controls as required so that ignition of the flashbulb triggers the sweep. Adjust beam intensity to a level that experience has shown will result in a well-exposed photograph of the trace for a given film, shutter speed, and aperture.

8. Load the camera with film and adjust the camera speed and aperture.

9. Fire the flashbulb. *Note - The No. 22 flashbulb constitutes a very bright source; it is recommended that the test operator not look at the bulb during ignition. The fired bulb remains hot for some time; it is also recommended that the operator wear gloves to remove it.*

10. Observe the resulting traces on the oscilloscope screen. If they are satisfactory, proceed to step 11. If they are not satisfactory, determine the cause. Make whatever adjustments may be necessary and remore the spent flashbulb. Repeat steps 4 through 8 and fire the flash-

bulb. Repeat until satisfactory traces are obtained.

11. Photograph the traces.

12. Remove the spent flashbulb and repeat steps 4, 5, and 6. Set the oscilloscope sweep rate to 100 ms/div in step 7. Repeat steps 9, 10, 11, and 12.

13. Examine the photograph taken in step 12. If the traces show that both transducer outputs have started to decay, consider the set to be complete with two photographs. If either transducer output has not started to decay, remove the spent flashbulb and repeat the procedure, setting the oscilloscope sweep rate to 1 s/div or 5 s/div in step 7.

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Experimental efforts are described in the evaluation of protective diaphragm coatings as a means to reduce the effects produced by thermal radiant-energy transients on pressure-transducer response.

A series of tests was carried out to investigate the effects of a variety of protective coatings on the amount and rate of thermal energy transmission through thin metal disks (used to simulate transducer diaphragms) as revealed by measurements of the disk back-side temperature. The temperature histories of both bare and protected disks were measured with thermocouples during and after exposure of the disks to thermal radiant-energy transients (of approximately 20mJ/mm^2 at the disk) generated by No. 22 photographic flashbulbs. Protective coatings investigated include various tapes, greases, and room-temperature-vulcanizing rubbers(RTVs).

Based on the results from these tests, the effectiveness of nine selected coatings in reducing thermally-induced zero shifts of four types of pressure transducers was investigated. In these tests, a pair of transducers - one protected and the other unprotected, but otherwise nominally identical - were exposed to a thermal radiant-energy transient as described above. The resulting zero shift was measured and taken as an index of coating effectiveness.

The effect of the mass of the coatings on transducer dynamic response was investigated by means of a shock tube, in which a protected and unprotected pair were simul-

(over)

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Key Words: coatings; delayed response; dynamic; dynamic response; pressure step; pressure transducer; protective coatings; shock tube; tape; thermal radiant-energy response; thermal protection; thermal transient response; transducer; zero shift.

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taneously exposed to a pressure step of approximately 280kPa (40psi). Also, the effect of selected coatings on transducer acceleration sensitivity was investigated by monitoring the outputs of pairs of transducers mounted on a vibration exciter.

Test results indicate the validity of the simulated diaphragm test as a predictor of protection effectiveness. Results from both disk and transducer tests show that some coating combinations appear to be an order of magnitude more effective than others in delaying and reducing zero shift. Coatings of multi-layer black tape, red RTV silicone rubber, and "heat sink" compound appear most effective, other materials less. Silicone grease is found least effective while single-layer black tape appears to produce results ranging from very limited protection to actual degradation of response, based on the limited sampling carried out in this investigation.

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