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

A Test Method for Determining the Effect of Thermal Transients on Pressure-Transducer Response

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FOREWORD

The work described was performed as a task within the NBS Inter Agency Transducer Project. This is a continuing project for the development of calibration and evaluation techniques for electromechanical transducers which is currently supported by the Naval Air Systems Command, the Transducer Committee of the Telemetry Group, Range Commanders Council (TG/RCC), and the National Bureau of Standards.

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CONTENTS

A TEST METHOD FOR DETERMINING THE EFFECTS OF THERMAL TRANSIENTS ON PRESSURE-TRANSDUCER RESPONSE

A TEST METHOD FOR DETERMINING THE EFFECTS OF THERMAL TRANSIENTS ON PRESSURE-TRANSDUCER RESPONSE

A test method for evaluating the effects of short-duration, thermal radiant-energy transients on pressure-transducer response is described. The method consists of monitoring pressure-transducer output (zero shift with the transducer at atmospheric pressure) as the transducer is exposed to radiation resulting from the ignition of a photographic flashbulb or from the discharge of an electronic flash. The method is intended to serve as an initial screening test. Thermal energy pulses as great as 0.1 J/cm^2, with durations of about 6 ms, have been generated using an electronic flash; pulses of up to 2.2 J/cm^2, with durations of about 37 ms, have been generated using No. 22 flashbulbs. In tests with No. 22 bulbs, 25 commercial pressure transducers have shown zero shifts ranging from 0.4%to about 400% of the full-scale output.

Key words: calibration; dynamic; photo flashbulb; pressure; pressure measurement; pressure transducer; thermal transient; transducer; zero shift.

1. SUMMARY

In response to requests from the Naval Air Systems Command and the Transducer Committee of the Telemetry Group, Range Commanders Council, a test method has been developed to serve as an initial screening test to identify pressure transducers that tend to give erroneous readings when subjected to thermal radiant-energy transients.

The method consists of monitoring pressure-transducer output as the test transducer is exposed to a transient thermal radiant-energy stimulus resulting from the ignition of a photographic flashbulb or from the discharge of an electronic flash. The method also provides for monitoring energy and duration of the transient stimulus. The test transducer is mounted in a fixture at one end of an optical bench so that the transducer diaphragm faces toward the center of the bench. At the other end of the bench is an energy meter positioned with its sensor also facing toward the center of the bench. The flash source is located midway between the transducer diaphragm and the sensor of the energy meter. Transducer, flash source, and energy meter are all at the same distance above the bench. The NBS embodiment of this apparatus (shown in figure 1) incorporated a photodiode mounted at right angles to the bench and aimed at the flash source. The photodiode was intended to provide a check on the operation of the energy meter and information about the waveshape of the stimulus.

In a test, the pressure transducer is mounted in the fixture and provided with the manufacturer's specified excitation, if any. Quantities monitored are as follows: (1) the transducer output, displayed on an oscilloscope; (2) the digital reading of the energy meter (which displays pulse energy in joules, as intercepted by the 1-cm^2 area of the sensing element); (3) the energy-meter output, displayed on an oscilloscope (with peak amplitude proportional to the total pulse energy incident on the sensing element); and (4) the photodiode output, also displayed on an oscilloscope.

Of the various flash sources considered or evaluated during the development of the method, the commercial No. 22 photographic flashbulb and an electronic xenon flash operated at 150 J have proven most satisfactory. The No. 22 flashbulb provides a test duration of approximately 37 ms with energy-density levels of up to 2.2 J/cm^2. According to the manufacturer, the spectral distribution of energy curve for the No. 22 bulb closely approximates that predicted by the Wien Law over the wavelength range of about 350 to 650 nm. Above 650 nm, the flashbulb curve deviates upward from the Wien-Law curve; information is not available for wavelengths shorter than 350 nm or longer than about 750 nm. With the No. 22 bulb used as source, the method provides knowledge of the transducer zero shift as a function of measured energy level to within an estimated ±14% of the true value. The electronic flash at 150 J provides a test duration of approximately 6 ms with energy-density levels of 0.1 J/cm^2. The spectral distribution of energy for a flashtube depends on the operating voltage, as well as on the fill gas and the envelope material. Typical manufacturer's data show that the relative energy per wavelength step of 100 nm is approximately constant over the range of 400 to 800 nm. Specific spectral information for the flashtube used is not available. With the electronic flash used as a source, the method provides knowledge of the transducer zero shift as a function of measured energy level to within an estimated ±10% of the true value.

Twenty-five selected transducers were evaluated by the method, using No. 22 flashbulbs. These represented seven models of strain-gage types and three models of piezoelectric-crystal types. The center plane of the bulb was 7 cm from the transducer diaphragm. Zero shifts measured ranged from 0.4% to about 400% of the full-scale readings. Tests on several transducers of the same model resulted in zero shifts with maximum deviations from the average for that model within the estimated ±14% uncertainty. In general, semiconductor strain gage transducers exhibited larger zero shifts than the other types of transducers tested. Within the semiconductor transducers, the largest zero shift occurred in transducers with strain gages diffused into a silicon diaphragm. Next come those transducers which had semiconductor strain gages bonded to a metal diaphragm. Lesser zero shifts were measured for transducers with semiconductor strain gages mounted on an auxiliary beam connected to the diaphragm by means of a push rod.

Experimental work carried out in the development of the method other than that concerned with evaluating sources included investigations of energy available as a function of distance*, of transducer shift as a function of distance, of flash source duration and waveform, and of test-method repeatability. Also evaluated experimentally were various aspects of the method, including the effect of introducing apertures in front of the energy meter, the effect of supply-voltage variation on electronic-flash output, the effect of misalignment of the transducer on the measured zero shift (found not to be significant for misalignment angles of up to six degrees), the use of reflectors, and the amount of output shift resulting from exposure to the transient with the transducer at full-scale pressure.

Recommendations include that pressure transducers being considered for use in environments in which thermal transients are likely to exist be screened by the method to detect, prior to use, those vulnerable to such transients. Also recommended is that the present method be extended to provide thermal radient-energy transients with considerably greater energy content. This proposed extension of the method would contribute to the evaluation of the effectiveness of techniques for protecting a transducer from thermal transients, as well as provide a better simulation of the transients encountered in some applications.

2. INTRODUCTION

In field use, pressure transducers are often required for measurements under adverse experimental conditions. Among these conditions are those in which the transducers are exposed to thermal transients, that is, to rapidly changing temperature conditions which are found in measurements of such quantities as nuclear or high-explosive blast pressures, rocket- and jet-engine parameters, shock-tube phenomena, and nuclear reactor performance parameters. NBS was asked by the Naval Air Systems Command and the Transducer Committee TG/RCC† to:

> "Develop a test device and generate a test procedure to impinge thermal-transient inputs on pressure transducers. The requirements of the test device should include:
>
> 1. Inexpensive to build;
> 2. Simple to operate;
> 3. Easily reproducible by transducer manufacturers, test ranges, or range users;
> 4. Capable of impinging thermal transients of any duration greater than 1 millisecond;
> 5. Controlled heat flux inputs capable of being quantized."

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* In general, over the range of distances investigated, deviations from the inverse-square law of intensity as a function of distance were within the estimated uncertainty of measurement of energy-density levels, including the effects of flash repeatability.

† Transducer Committee, Telemetry Group, Range Commanders Council.

In addition, the precision of the method was required to be at least adequate for the method to serve as an initial screening test, that is, to provide information to the engineer permitting him to select a pressure transducer having minimal response to thermal radiant-energy transients for use in measurement situations where such transients are expected or are known to exist.

The method consists of monitoring pressure-transducer output as the test transducer is exposed to a transient thermal radiant-energy stimulus resulting from the ignition of a photographic flashbulb or from the discharge of an electronic flash. The method also provides for monitoring the energy and duration of the transient stimulus. The selected radiant-energy sources were chosen to satisfy the foregoing requirements, in particular the requirements concerning low cost, simplicity of operation, and ready reproducibility.

3. DEVELOPMENT OF TEST METHOD

3.1 Background

Work had been done previously in the Components and Applications Section of NBS on the effects of thermal gradients and transients on the performance of transducers. This work began with a method which generated relatively slowly changing thermal gradients in pressure transducers by partially immersing the test transducers in a hot bath [1]*. Subsequently, a laser-source method was developed for applying thermal radiant-energy transients to pressure transducers with an exposure time of about one minute [2]. Following this work, a thermal-transient testing method was developed for piezoelectric accelerometers, involving transients with durations from 1 s to 15 s [3]. The experience gained from this earlier work contributed to the development of the test method described here.

Experimental considerations, including selection of energy sources, establishment of test parameters, evaluation of method accuracy and repeatability, as well as the results of the experimental evaluation of selected transducers, are presented in detail in the following sections.

3.2 Description of Experimental Arrangement

The experimental arrangement is shown in figure 1 and is as follows: The flashbulb or flashtube is mounted in a vertical position at the center of an optical bench. Mounted on the bench, on opposite sides of the energy source, are an energy meter and the transducer mounting fixture. The diaphragm of the mounted pressure transducer and the sensing element of the energy meter are aligned with, and equidistant from, the center of the flash unit. The energy meter and transducer

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* Figures in brackets indicate literature references listed in Section 7.

may be moved along the bench to vary the respective distances between them and the flash unit, which is held fixed. Also fixed in position is a photodiode mounted at right angles 35 cm from the bench center and used as a flash output monitor to check the operation of the energy meter. All four elements are positioned to lie in the same horizontal plane.

In a test, the quantities monitored are as follows: (1) the pressure-transducer output, displayed on an oscilloscope; (2) the digital reading of the energy meter (which displays pulse energy in joules, as intercepted by the 1-cm^2 area of sensing element); (3) the energy-meter output, displayed on an oscilloscope (with peak amplitude proportional to the total pulse energy incident on the sensing element); and (4) the photodiode output, also displayed on an oscilloscope. If the transducer is at atmospheric ambient pressure at the beginning of the test, transducer output is identical to zero shift.

3.3 Description of Apparatus

3.3.1 Energy Sources - Four sources were used in the investigations: an electronic flash at an energy setting of 150 J, No. 5 flashbulbs, No. 22 flashbulbs, and flood-flash FF-33 bulbs. The original plan of experiment also included the electronic flash at 50 J; however, these runs were dropped from the schedule because, even at the 150-J setting, the zero shift in the selected test transducer output in response to thermal radiant-energy transients from the electronic flash was small compared to the zero shifts resulting from the flashbulb source.

3.3.1.1 The No. 5 and No. 22 flashbulbs are readily available from photographic supply houses; the FF-33 bulb was designed for use in automotive crash photography and can be purchased directly from the manufacturer. According to the manufacturers, the amplitude-time waveform of the radiation output from all three bulbs is roughly triangular in shape. This waveshape was confirmed by trials with the No. 5 and No. 22 flashbulbs, but not with the FF-33 (section 3.4.4.2). Characteristics of the three flashbulbs are given in table 1, which is derived from manufacturers' literature.

The manufacturers of the No. 5 and No. 22 flashbulbs provide the following information concerning (1) light-output repeatability and (2) spectral distribution of energy: (1) Assuming that the specified excitation is supplied in each case, the population mean of measurements of the light output (measured with an integrating sphere or equivalent method) should fall within 10% of the manufacturer's published light-output value, with a confidence level of 95%. Experimental measurements of repeatability tend to agree with this statement, but are themselves subject to the variability in performance of the energy meter used to make the measurements (section 3.4.4.1). (2) The spectral distribution of energy closely approximates that predicted by the Wien Law over the wavelength range of approximately 350 to 650 nm. At wavelengths longer than about 650 nm, the spectral energy distribution curve for the flashbulbs diverges upward from the Wien-Law curve; information is not available for wavelengths shorter than 350 nm or longer than about 750 nm. Note: The exact spectral energy distribution for flashbulb sources depends on the combustible material, the oxygen fill pressure (most modern flashbulbs burn aluminum in pure oxygen), and the absorption characteristics of the envelope. The flame emission lines of aluminum are available in the literature; the other information is proprietary.

Repeatability and spectral information were not sought for the FF-33 bulbs, as trials showed these bulbs to be unsatisfactory sources for this application for a variety of reasons (section 3.4.4.2).

3.3.3.2 The electronic flash system consists of a xenon-filled flash tube, a capacitor bank, a power supply, and other associated electronic components including a triggering circuit. In use, the capacitor bank is charged by the power supply to approximately 450 V dc; the bank is then discharged through the flash tube by applying a trigger pulse to the gate of a silicon-controlled rectifier by means of a mechanical switch.

The system used can operate at one of two energy levels, either 50 or 150 J. In the 150-J mode, the peak intensity of the light is only slightly increased over the 50-J mode, but the capacitor discharge time is extended. The rise time is about 0.3 ms for both the 50- and 150-J positions, but the fall time to about 10% of the peak value is about 6 ms and 10 ms, respectively.

A repeatability figure is not available for the flashtube used in the electronic flash or for the performance of the flash system as a whole. Flashtube light output depends on physical dimensions, on energy input, on the operating voltage, and on xenon fill pressure. A representative for the manufacturer of the system stated that variations in flash-to-flash output under the operating conditions specified in the instruction manual should be significantly smaller than those which would adversely affect photographic results with available general-purpose films, including low-exposure-latitude color films. This statement is interpreted to mean that the flash-to-flash variation is perhaps of the order of ten percent, or possibly less. As with the No. 5 and No. 22 flashbulbs, the experimental measurements tend to confirm this figure, but are subject to the variations in performance of the energy meter (section 3.4.4.1).

The manufacturer of the electronic flash system describes the color content of the light as very closely resembling that of daylight. The spectral distribution of energy for a flashtube depends on the operating voltage, as well as on the fill gas and envelope material. Typical manufacturer's data show that the relative energy per 100-nm step is approximately constant from 400 to 800 nm. At wavelengths greater than 800 nm, the operating voltage has a large inverse effect, with a 500-V tube producing on the order of half again as much energy as a 2000-V tube. Specific spectral-energy-distribution data for the flashtube used are not available from the manufacturer.

3.3.2 Energy Meter - The following information is abstracted from the manufacturer's instruction manual: The energy meter consists of a pyroelectric detector and associated signal-processing and display electronics. The pyroelectric detector is a slice of ferroelectric material which possesses a permanent electric polarization that is highly temperature dependent. As radiant energy is absorbed by the detector coating, a current is generated that is proportional to the time-rate-of-change of the temperature of the ferroelectric material. This current is integrated by a preamplifier and produces an output that can be displayed on an oscilloscope. The peak amplitude of the preamplifier output waveform is proportional to the energy content of the radiation pulse incident on the detector. The readout circuitry measures the peak amplitude of the preamplifier output, computes a scale factor, and displays the result digitally in the proper units (joules).

The meter is provided with two modes of triggering. In the auto-trigger mode, the instrument is triggered when the energy absorbed by the detector is greater than 5% of full scale; in the external-trigger mode, a positive-going trigger pulse ranging in amplitude from 5 V to 100 V must be supplied coincident with the radiation pulse to be measured. The meter, with four-digit readout, is intended to measure the total energy content of radiation pulses with durations ranging from less than 1 ns to to a maximum of 50 ms. This range of pulse durations represents a modification of the standard meter, which covers a 1-ns to 1-ms range.

Seven ranges are provided which are switch selectable, with full-scale readings progressing in six decade steps from 2 μJ to 200 mJ, in addition to a 1-J position. In all cases, the reading represents the energy absorbed by the 1-cm^2 area of the detector.

The response of the pyroelectric detector is described as being flat to within ±2% in the wavelength range of 400 nm to 20 μm. Manufacturer's literature describes the overall system accuracy as ±4% of reading ±1% of the full-scale reading when the sensing area is fully illuminated. Least count is typically 0.05% of the full-scale reading. Maximum noise level is given as 0.3 μJ.

The meter was calibrated by C.A. Hamilton of the NBS Boulder Laboratories by comparing its measurements of laser pulse energy with those of a calibrated pyroelectric radiometer. The overall result was that the meter performed to specification. The calibration procedure requires the use of a beam with a diameter much smaller than that of the detection element of the meter; therefore, scans were made to determine the degree of uniformity of response over the detector surface. The estimated uniformity error is ±7%, and is greatest with short pulses. For the geometry used in the method, this error will not affect repeatability of the energy measurement. Uniformity error does contribute to the overall figures given by the manufacturer for the accuracy of the instrument for various ranges. A test was also made to determine if the time delay between the trigger and a short pulse (1 ms) had an effect on meter reading, with negative results over a range of delays of 0 to more than 50 ms.

3.3.3 Transducer Mounting Fixture - The transducer mounting fixture used is a rectangular brass block approximately 10-cm high, 10-cm wide, and 6-cm deep, and is purposely made massive to serve as a heat sink, with a mass of about 5 kg. A 3.8-cm bore extends through the block, centered on the front face (the face towards the flash unit). A round glass window with an aperture of 3 cm and a thickness of approximately 0.6 cm is sealed into the bore at the front face. The window glass is of a 96%-silica composition with a low coefficient of expansion. The effect on the test of this window is discussed in 3.5.5. The transducer to be tested is mounted in a brass flange; an air-tight seal to the bore is made by means of an O ring between the flange and the block. The flange is mounted to the block with six bolts. This arrangement is similar to the way in which transducers are mounted in typical applications.

A hole connecting with the bore permits pressure or vacuum to be applied to the volume between the transducer and window. Thus, the pressure the transducer sees during the test may be preselected.

3.3.4 Photodiode - The *n-p-n* planar silicon phototransistor selected may be used in either the phototransistor mode or the photodiode mode of operation; in all tests described in this report, the photodiode mode was used. The manufacturer gives the rise time and fall time as typically 350 ns and 500 ns, respectively. The output collector current is linear with irradiance from 0 to 80 $mW \cdot cm^{-2}$. The spectral response is near zero at 0.5 μm, rises to a maximum at about 0.9 μm, and returns to near zero at 1.1 μm. A supply voltage of up to 50 V dc may be used in the photodiode circuit.

3.4 Experiments to Determine Method Parameters

3.4.1 Investigation of Energy Available as a Function of Distance - The change in measured intensity (amount of energy per unit area) as a function of distance from the flash source was studied using the epxerimental arrangement described in 2.1. Four sources were used in the investigation: electronic flash at 150 J, No. 5 flashbulbs, No. 22 flashbulbs, and flood-flash FF-33 bulbs. Since the flash duration of the FF-33 bulb is much greater (by a factor between 60 and 300) than that of the other flash sources, tests with the FF-33 bulbs required modifications of the method and are described separately in 3.4.1.2.

3.4.1.1 Distance from the center plane of the flashbulb source to the energy-meter sensor (and consequently the distance from the source to the test transducer diaphragm, for the investigation described in 3.4.2) was varied in 1-cm steps over the range of 6 cm to 23 cm for runs with both No. 5 and No. 22 flashbulbs. The dimensions of the electronic-flash head and the relatively low energy levels available even at the 150-J setting determined a smaller practical range of distances for runs with this system. The minimum distance was limited to 7.5 cm; at 15 cm the test transducer zero shift (which was also measured, as described in 3.4.2) was about one-half of one percent of the full-scale output, and accordingly 15 cm was chosen as the upper limit for tests with the electronic flash. Steps of 0.5 cm were used in order to provide approximately the same number of data points as for tests with flashbulb sources.

The results from this series of tests are shown plotted as energy-meter reading ($mJ \cdot cm^{-2}$) vs separation (cm) in figure 2. Energy-meter reading is plotted on a logarithmic scale. Separation refers to the distance from the center plane of the source to the energy-meter sensor. The data-point plots A, B, and D fall along curves whose form is similar to that of an inverse-square relation; for comparison an arbitrary inverse-square plot is given (dashed curve C). The classical inverse-square relation of intensity vs distance for a point source of radiation does not strictly apply to the extended sources of these tests, particularly at the relatively short distances between the source and the sensor. Small deviations of experimental points from the smooth curves probably result from variations both in source energy and in the performance of the energy meter. These deviations do not exceed 10% of the energy-meter reading.

The maximum intensity levels were measured at the minimum source-sensor distances, which, for both flashbulb sources and for electronic flash, were limited by source and mounting-fixture dimensions. Maximum levels of about 0.1, 0.8, and 2.2 $J \cdot cm^{-2}$ were measured for the electronic flash at 150 J, No. 5 flashbulbs, and No. 22 flashbulbs, respectively.

3.4.1.2 Tests using the flood-flash FF-33 bulbs were carried out in a similar fashion to those described for the short-duration sources, with the following exceptions: (1) a power meter, calibrated in watts, was substituted for the energy meter, because the energy meter is not capable of reading energy pulses with a duration greater than 50 ms. The maximum output of the power meter was read visually on a panel meter "on the fly." That is, the operator was required to estimate the maximum upward excursion of the (relatively slowly moving) meter pointer. Output from the power meter was also displayed on an oscilloscope. (2) Tests were run in 1-cm increments from 8 cm to 15 cm; the size of the FF-33 bulbs prevented tests at source-sensor distances less than 8 cm, and the low energy level (as determined by transducer response) suggested 15 cm as a good termination point, as was the case for measurements with the electronic flash at 150 J. The data from these tests also follow an inverse-square relation.

3.4.2 Investigation of Transducer Zero Shift as a Function of Distance - In the measured intensity-vs-distance tests described in 3.4.1.1, the zero shift of a pressure transducer located on the opposite side of the radiation source from the energy meter was monitored with an oscilloscope. For tests at ambient atmospheric pressure, any transducer output is regarded as zero shift. The transducer used in these tests is a semiconductor strain-gage pressure type and is designated in this report as transducer Z*.

These measurements were made to assist the development of the method by providing information on the zero shifts exhibited by a transducer selected as being typical of a modern design in widespread use, and were not made to characterize the particular transducer so chosen.

The results from this series of tests are shown plotted as transducer zero shift (% of full scale) vs separation (cm) in figure 3. Transducer zero shift is plotted on a logarithmic scale. Separation refers to the distance from the center plane of the source to the transducer diaphragm.

The data-point plots A, B, and D fall along curves whose form is similar to that of an inverse-square relation. An arbitrary inverse-square relation is again plotted (dashed curve C) for comparison.

Table 2 shows test transducer zero shift (mV) and energy-meter reading ($mJ \cdot cm^{-2}$) for three sources (No. 5 and No. 22 flashbulbs and electronic flash at 150 J) at three selected distances: 8, 10, and 14 cm. The table also includes the computed radiation sensitivity (defined as the ratio of the transducer zero shift to the energy-meter reading, with units of $V \cdot cm^2 \cdot J^{-1}$) for the three sources at the three distances, for transducer Z.

Another measure, which permits direct comparison of zero shifts for transducers with differing full-scale outputs, is percent full-scale output radiation sensitivity ($\%FS \cdot cm^2 \cdot mJ^{-1}$). Using as a basis the value of the radiation sensitivities for 8, 10, and 14 cm (0.12, 0.14, and 0.15 $V \cdot cm^2 \cdot J^{-1}$ for electronic flash at 150 J, for No. 5 flashbulbs, and for No. 22 flashbulbs, respectively) and transducer Z full-scale output of 500 mV, percent full-scale radiation sensitivities for the three sources are 0.024, 0.028, and 0.030 $\%FS \cdot cm^2 \cdot mJ^{-1}$, for transducer Z.

As may be seen by examination of the data just presented, radiation sensitivity of transducer Z increases about 17% for the No. 5 flashbulb source as compared to the electronic flash; there is a further

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* In the progress report covering the period October 1, 1974 to December 31, 1974 (NBSIR 75-732) this transducer was identified as transducer D.

increase of about 7% for the No. 22 flashbulb source. An explanation of this situation may lie in the relative sizes of the light-emitting elements in each source. The diameter of the circular tube in which the capacitive discharge takes place in the electronic flash is about 2 cm; the diameter of the combustible filler in the flashbulbs is about 3.5 cm for the No. 5 flashbulbs and about 5 cm for the No. 22 flashbulbs. As the light-emitting element becomes large, an increasingly greater proportion of the energy radiating from the outer portions of the element will not reach the energy-meter sensor but will be intercepted by the 2.2-cm-long collimating shroud which shields it; on the other hand, the transducer test fixture does not shield the pressure-sensitive element except for very large angles of incidence. Therefore, for sources with light-emitting elements greater than a few millimeters, the transducer sees more than the sensor.

Figure 4 consists of three photographs of oscilloscope traces of transducer zero shift in response to thermal radiant-energy transients from the three sources. The source-to-transducer distance was 10 cm. In all cases, the duration of the transducer zero-shift response is much longer than that of the thermal-transient stimulus causing it. The zero-shift for electronic flash rises to approximately half the peak value in approximately 20 ms after the onset of the thermal radiant-energy transient and reaches its maximum at approximately 50 ms. For the No. 5 and No. 22 flashbulbs, the transducer zero shift peaks after about 115 ms and 130 ms, respectively. Comparison of figures 4 and 6 shows that the shape of the zero-shift response of transducer Z for the sources used is largely independent of the thermal radiant-energy transient waveshape.

Measurements of transducer Z zero shift were also made during the tests described in 3.4.1.2 with FF-33 bulbs as sources. The data are given in table 3, and follow an inverse-square relation of zero shift with source-transducer distance.

The bottom photograph of figure 5 shows an oscilloscope trace of transducer Z zero shift in response to a thermal radiant-energy transient from an FF-33 bulb at 12 cm. The upper photograph of figure 5 shows oscilloscope traces of the analog output from the power meter (thick trace) and the photodiode output (thin trace) for the same conditions. In contrast with transducer zero-shift behavior in response to short-duration transients, the duration of zero shift and thermal-transient stimulus are approximately the same, and the waveshape of power-meter output and transducer zero shift are similar, with a rise time to maximum of approximately 1 s. The photodiode response is discussed in 3.4.3.

Although the data for transducer Z zero shift as a function of the distance between the center plane of the FF-33 source and the transducer diaphragm follow an inverse-square relation, the calculated radiation sensitivities exhibit erratic behavior. An explanation has been proposed to account for the effect: Examination of figure 4 shows that the time from onset of the thermal transient until the zero shift reaches its maximum value is on the order of 100 ms, that is, transducer Z has an effective thermal time constant of approximately 100 ms. The thermal energy from transients with durations considerably shorter than 100 ms is absorbed by the transducer, and no significant conductive heat loss occurs until after the 100-ms period. This statement is in part confirmed experimentally by the results with the No. 5 and No. 22 flashbulbs and the electronic flash at 150 J, all of which produce transients with durations less than 40 ms. The duration of the thermal transient resulting from ignition of the FF-33 bulb is greater than 2 s. This very long duration compared to the transducer thermal time constant permits an appreciable amount of the absorbed energy to be lost by conduction to the massive brass block which forms the mounting fixture.

The FF-33 bulbs did not prove to be a satisfactory source for the method (section 3.4.4.2) and no experimental work was carried out relating to the behavior described.

It has been shown at the beginning of this section that zero response of transducer Z as a function of source-transducer distance follows an inverse-square relation and in 3.4.1 that energy-meter reading as a function of source-meter distance also has an inverse-square form. Therefore, transducer Z zero shift varies as a linear function of the energy impinging upon the transducer. To investigate the same function for other transducers, tests were conducted using No. 22 flashbulbs as the source at source-transducer distances of 14, 9.9, and 7 cm. These distances were chosen to produce a doubling of energy with each reduction of distance. Three transducers (B, M, and Q) of different types were evaluated, along with transducer Z as a control. Three tests were run at each distance with each transducer.

The results are given in table 4. Transducers M, Q, and Z all exhibit the anticipated doubling of zero shift as the source-transducer distance is reduced from 14 to 9.9 cm and from 9.9 to 7.0 cm, within experimental error. Transducer B, however, does not exhibit doubling, the factor being 1.6 for the first distance reduction and 1.4 for the second. The explanation probably lies in the fact that M, Q, and Z are flush-diaphragm transducers, whereas the diaphragm of transducer B is recessed 2.2 cm from the front surface. The diaphragm is thus shrouded by the transducer structure, and as the source-transducer distance is reduced, an increasingly greater proportion of the source energy is blocked from reaching the diaphragm. The geometry of the situation is akin to that discussed earlier in this section for the energy meter when the source is close to the meter sensor.

3.4.3 Investigation of Flash Source Duration and Waveform - As described in 3.3, a photodiode was used in conjunction with the energy meter to monitor the radiation emitted by the flash source. This photosensitive semiconductor component was actually a silicon phototransistor connected as a diode with a response time "better than 1 μs" over a wavelength range of 0.5 to 1.1 μm, according to the manufacturer. The output from the diode displayed on an oscilloscope screen provided the approximate shape of the radiant thermal transient as well as a measure of its amplitude.

Figure 6 consists of three photographs of oscilloscope traces of photodiode output in response to thermal radiant-energy transients from the electronic flash at 150 J, a No. 5 flashbulb, and a No. 22 flashbulb. The sweep time for each photograph was 50 ms, and the amplitude scale 2 V per division. Comparison of the photographs shows that the diode output waveform for the electronic-flash source has a sharp rise time (less than 0.2 ms measured with the oscilloscope set to a fast sweep) and a slower decay of about 6 ms to drop to 10% of its peak amplitude. The transients generated by the two flashbulb types are more nearly symmetrical in rise and fall time. Rise times, from 10% of the peak amplitude to the peak, are about 9 ms for No. 5 flashbulbs and about 13 ms for No. 22 flashbulbs. Decay times are respectively 20 ms and 24 ms. The total duration of the thermal radiant-energy transients generated by these devices as measured by the diode is therefore roughly 6 ms for the electronic flash at 150 J, 29 ms for No. 5 flashbulbs, and 37 ms for No. 22 flashbulbs.

The photodiode trace for an FF-33 bulb shown in the upper photograph of figure 5 is characterized by a number of high-amplitude spikes, as well as longer duration fluctuations of considerable amplitude (on the order of 25% of the maximum). These phenomena are presumed to result from erratic burning of the FF-33 bulb and were seen in all photodiode traces for FF-33 bulbs. Their presence makes scaling difficult.

3.4.4 Investigation of Test Method Repeatability - A series of tests was carried out to determine the repeatability of the test method with transducer Z as the test transducer. Because of the modifications of the method required for use of the FF-33 bulb as source, results of tests with long-duration flash are reported separately in 3.4.4.2.

3.4.4.1 The results of tests with No. 5 and No. 22 flashbulbs and electronic flash at 150 J are plotted in figures 7, 8, and 9, which show the deviation in percent from a ten-shot average of transducer zero shift, energy-meter response (digital reading), energy-sensor output (analog signal available from the energy meter for which peak amplitude is proportional to energy input), and photodiode output for each of the three test sources.

As described in 3.2, the outputs of the photodiode, the energy sensor, and the transducer under test were displayed on an oscilloscope and measured; the digital output displayed by the energy meter was recorded. The pressure seen by the pressure transducer at the beginning of each run was atmospheric ambient.

The distance between the center plane of the flash source and the transducer diaphragm was 7.5 cm for the electronic flash, 10 cm for the No. 5 flashbulbs, and 12 cm for the No. 22 flashbulbs. These distances were not arbitrarily selected. The minimum source-transducer distance of 7.5 cm for the electronic flash was used because this source is relatively weak. The original intent was to use the same distance of 10 cm for the two flashbulb sources. However, the intensity of the No. 22 flashbulbs at 10 cm was at or above the energy meter's upper limit of 1 J · cm^{-2}, and the slightly greater distance of 12 cm was therefore used for this source. (An attenuating screen was available for use with the energy meter. Uncertainties of calibration associated with its use suggested that a direct measurement should be employed for the repeatability study.)

Table 5 presents a summary of the data given in the figures. Sample averages, maximum upper and lower percent deviations from the average, and sample standard deviations are given for energy-meter readings, photodiode output, and transducer Z zero shift.

Examination of the data presented in figures 8 and 9 for the flashbulb sources shows that the maximum deviations for the four quantities plotted fall within ±15% of the ten-shot average values. Examination of the data presented in figure 7 for the single electronic-flash source used shows that the maximum deviations for the four quantities plotted fall within ±5% of the ten-shot average values. Coefficients of variation* of the energy-meter readings based on ten shots are 2.3% for electronic flash at 150 J, 3.6% for No. 5 flashbulbs, and 6.5% for No. 22 flashbulbs. The corresponding coefficients of variation for measured transducer zero shift are 1.1%, 6.6%, and 5.2%. The shot-to-shot repeatability with a single electronic-flash system as the source is thus seen to be greater than that for flashbulb sources. One electronic-flash system with one flashlamp was used in the tests; however, general experience with electronic flash for photography suggests that shot-to-shot repeatability for a properly designed and used (see 3.5.1) single unit can be superior to that for flashbulbs.

A detailed comparison of the plots A, B, and C in figures 8 and 9 provides the basis for some tentative conclusions; no such basis results from examining figure 7, as the fluctuations do not correlate (although the magnitude of the fluctuations is only a little greater than that of the measurement errors expected). The same remark applies to the plots of photodiode output, data points D. As expected, the plots of the digital reading of the energy meter (data points B) and the energy-meter output (data points C) are in reasonable agreement in both magnitude and direction of change.

A comparison of B or C with A of figure 8 shows agreement in the direction of change for test 2 to test 3, 3 to 4, 4 to 5, 5 to 6,

* The coefficient of variation is defined as the ratio of the sample standard deviation to the sample mean, expressed as a percentage.

6 to 7, and 9 to 10. The same comparison with the plots of figure 9 shows similar agreement for 2 to 3, 4 to 5, 5 to 6, 6 to 7, 7 to 8, 8 to 9, and 9 to 10. A possible explanation for the discrepancies lies in the fact that the energy output from the source may vary in azimuth and hence the transducer under test and the energy meter may "see" comparatively different energy levels for the same test run. The manufacturers have confirmed that a specific azimuthal variation in flashbulb output is known to exist because of the orientation of the igniter element.

Used flashbulbs were collected for safe disposal. Following the completion of experimental work, dark spots were observed on a number of No. 22 bulbs. Investigation showed that a blackened area was present on most used No. 22 bulbs, and that a somewhat lighter darkened area could be found on most used No. 5 bulbs. For both types, the darkened areas always occur in the opposite direction from that in which the ignition electrodes point. (The electrodes in the No. 22 bulb extend side-by-side vertically upward from the base of the tube except for the last half centimeter, which is bent to be at an angle of about 60° to the vertical portion; the construction of the No. 5 bulb is similar.) The construction of flood-flash FF-33 bulbs is different from that of the No. 5 and No. 22 flashbulbs; no patterns were found on used bulbs of this type.

It is recommended that No. 5 and No. 22 flashbulbs be mounted so that the area opposite to the direction in which the ignition electrodes point does not face the transducer or any sensor.

A partial explanation for the lack of correlation of photodiode output with the energy-meter outputs or with transducer zero shift may lie in the spectral response characteristics. The energy-meter sensor is described by the manufacturer as having flat response over the wavelength range 300 nm to 20 μm, whereas the photodiode range is quoted as 500 nm to 1.1 μm. [Note: The percentage deviations in photodiode output from a ten-shot average are smaller for the electronic flash than for the flashbulbs; this aspect is in general agreement with the behavior of the energy-meter outputs and the transducer zero shift with respect to the two types of source. Coefficients of variation based on ten shots for photodiode output are 0.8% for the electronic flash at 150 J, 5.3% for No. 5 flashbulbs, and 3.8% for No. 22 flashbulbs.] Azimuthal variation of source output may also contribute to the lack of correlation, as may the fact that the photodiode output as measured represents peak and not total energy.

Because there was some concern that the repeatability measurements using No. 5 and No. 22 flashbulbs were made on bulbs from a single lot for each bulb type, an extended series of measurements was made on both No. 5 and No. 22 flashbulbs taken from several lots. In these tests, only the energy meter was used, and the source-sensor distance was constant at 7 cm. The sample standard deviation for 49 No. 5 bulbs is 45 mJ · cm^{-2}, with a sample mean of 604 mJ · cm^{-2}. The coefficient of variation is therefore 7.5%, or about twice that given above. The tests with No. 22 bulbs at 7 cm required the use of a 16% screen to reduce the energy impinging on the sensor to acceptable levels. Because of their greater energy output, No. 22 bulbs are for most purposes a better source for the method than No. 5, and more No. 22 bulbs were therefore used. The sample standard deviation for 80 No. 22 bulbs is 150 mJ · cm^{-2}, with a sample mean of 1731 mJ · cm^{-2}, and a corresponding coefficient of variation of 8.7%.

3.4.4.2 Repeatability tests with the flood-flash FF-33 bulbs as the method source were carried out at a source-sensor and source-transducer distance of 12 cm and consisted of 10 consecutive shots. Transducer Z was the test transducer. The effects of the long duration (about 2 s) of the FF-33 flash, of the use of a power meter instead of an energy meter, and especially of the observed erratic burning complicate the reporting of results. Peak-power levels as determined from the analog output of the power meter, displayed and photographed on an oscilloscope, show variations of up to 12% below and 18% above the ten-shot average; the data are given in table 6. Peak-power levels determined by reading the maximum excursion of the panel meter show variations of similar magnitude. Peak transducer zero shifts, as determined from a photographed oscilloscope display, show variations of up to 24% below and up to 21% above the ten-shot average. Comparison of transducer Z zero shift with the power-meter output from one shot to another shows little or no correlation between the two quantities. An explanation may be that the energy output from the FF-33 bulbs varies greatly in azimuth, as is suggested by the erratic burning. As was the case to a much lesser extent with the short-duration sources, the transducer under test and the sensing meter would "see" different power levels for the same test run. As described in 3.4.3, the photodiode response to FF-33 bulbs was characterized by the presence of spikes and other fluctuations, and average levels could not be determined with any reasonable precision. Photodiode measurements were therefore not useful in repeatability tests with FF-33 bulbs.

Following these tests no further work was carried out with FF-33 bulbs as the method source. This type is not recommended for this application because it exhibits erratic burning and apparent large variations in output from one bulb to another, and because it has lower output and larger size relative to other sources available.

3.5 Other Experimental Investigations

3.5.1 Effect of Supply-Voltage Variation on Electronic-Flash Output - Evaluation of the electronic-flash system as a source for the method included investigation of the dependence of flash-system performance on supply voltage when the unit was operated from either the a-c line or from a battery supply.

To measure the effect of a-c line voltage variations on electronic-flash energy output, a variable transformer was inserted into the line ahead of the internal flash power supply, and the radiant-energy output was measured at selected a-c supply voltages ranging from 110 V to 120 V in 2-V steps. The a-c supply voltage was set with the variable transformer and measured on a digital multimeter. The flash energy output was measured with the energy meter and the photodiode; the corresponding zero shift of transducer Z was also measured. Table 7 shows that the radiant energy available at an a-c supply voltage of 110 V is about 20% less than that at 120 V. The percentage change in radiant energy is on the order of double the percentage change in supply voltage causing it. This observation corroborates the recommendation that some type of voltage regulation be used in the supply line to the flash system to ensure consistent flash performance.

The effect of battery voltage variations on electronic-flash energy output was measured by monitoring the voltage drop across the battery supply and the radiant-energy output of the flash system during a series of 15 consecutive shots. The voltage decreased from 419 V to 397 V during the series. The resultant energy output as measured with the energy meter decreased linearly by approximately 11%, as shown in table 7. The percentage change in radiant energy is again on the order of double the percentage change in voltage. The interval between flashes was two minutes or longer to allow the flash unit to recharge. Nevertheless, the battery voltage dropped gradually during the test, indicating that the flash system performance would be more consistent if the system were operated from a regulated a-c line. It whould be noted that the batteries used in these tests had been used for several hundred shots previously. New batteries would probably produce more repeatable flash energies.

3.5.2 Effect of Various-Sized Apertures on Energy-Meter Reading - Geometrical relationships between the energy-meter sensor, the source, and the paths followed by radiant energy from source to sensor vary considerably for the various source-sensor distances and sources used in the method. Extensions of the method have been proposed using narrow-angle, high-energy sources. For these reasons, the response of the energy meter was investigated with various-sized apertures placed at the front end of the sensor collimating tube. Apertures with diameters of 0.38, 0.53, 0.75, 1.06, 1.50, 2.12, and 3.00 cm were used. These diameters were chosen so that each aperture has twice the area of of the next smaller aperture. Three tests with each aperture were run with a No. 5 flashbulb as source 7 cm from the energy-meter sensor. The data are plotted in figure 10, which shows energy-meter reading as a function of aperture diameter, with energy-meter reading on a logarithmic scale. The solid line represents a doubling of energy for a doubling of area. The plot shows that the energy approximately doubles with doubling of the area until a diameter of 1.06 cm is reached; since the diameter of the energy-meter is 1.15 cm* (vertical dashed line), some roll off below the doubling curve at 1.50, 2.12, and 3.00 cm was to be expected.

3.5.3 Effect of Angle of Incidence on Transducer Response - The response of transducer Z to thermal radiant-energy transients impinging on the diaphragm in directions 30, 60, and 99° from the normal to the diaphragm was investigated.

It was necessary to remove the transducer mounting plug from the fixture housing to perform these tests, as the housing would otherwise shield the transducer from radiation entering the fixture at more than a few degrees from the normal. A simple mounting pedestal was fabricated on which the plug and transducer could be rotated about a vertical axis through the center of the transducer diaphragm surface.

The tests were conducted with the center of the transducer diaphragm 7 cm from the center plane of the No. 5 flashbulb source. Five runs were made at normal incidence and three runs each at 30, 60, and 90° from the normal. The results are given in table 8.

At 30° from the normal, the zero shift of test transducer Z was 80% of the zero shift at normal incidence. At 60° from the normal, the zero shift was 56% of that at normal incidence, and at 90°, it was 4%. These figures correspond closely with the projected area of the transducer diaphragm as seen by the beam of radiation at each angle. The areas would be 87% of the normal area of 30°, 50% at 60°, and 0 at 90°.

Comparison of the data of table 8 with data given in tables 9 or 10 shows that the zero shift of transducer Z resulting from ignition of a No. 5 flashbulb at a source-transducer distance of 7 cm is approximately 18% smaller when the transducer is mounted on the pedestal described above than when it is mounted in the fixture used in the method. A probable explanation is that internal reflections in the mounting fixture increase the total amount of energy incident on the diaphragm.

3.5.4 Effect of Reflectors on Transducer Response - A brief investigation to determine the gain in energy level that could be achieved with the use of reflectors behind the energy source showed that by using reflectors designed for photographic purposes, an increase of about 18% was achieved with the No. 5 and No. 22 flashbulbs, and about 340% with the electronic flash at 150 J, at a transducer-source distance of 7 cm, as shown by the data in table 9.

Energy levels impinging upon transducer Z with and without the reflectors behind the sources were compared by measuring the

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* The sensor diameter is also comparable to the diameter of the diaphragm of the largest transducer tested.

resultant zero shift of the transducer. In the tests with No. 5 and No. 22 flashbulbs mounted vertically as sources, a reflector from a photoflash gun was positioned behind the bulbs. This reflector has a mirror finish, a diameter of 14.2 cm, and a depth of 3.4 cm. With the reflector in place, the distance from the center of the bulb to the reflector surface is approximately 3.7 cm.

The reflector supplied with the electronic flash unit was used with the electronic flash. This reflector has a satin finish, a diameter of 13.5 cm, and a depth of 6.8 cm. In use, the flashtube base passes through the center of the reflector, and the center surface of the tube is approximately 2.6 cm from the reflector surface.

The use of a reflector, while increasing the level of energy available, renders energy monitoring difficult, since an energy sensor detector cannot be located in the normal position on the optical bench. Therefore, the use of a reflector as part of the method is not recommended unless the greater amount of energy available for a given test is an overriding consideration.

3.5.5 Effect on Method of Energy Lost in Glass Window - The transducer mounting fixture was designed to permit the transducer to be subjected to pressures above or below atmospheric pressure during exposure to thermal radiant energy entering the fixture through a glass window. The significance of the effect of this glass window on transducer response was investigated by measuring the zero shift of transducer Z with and without the window in place. No. 5 flashbulbs, 7 cm from the transducer, were used in these tests. Table 10 shows that for the ten shots without the window, the average transducer zero shift was 93.7 mV, and the average energy-meter reading 586.4 mJ $\cdot$ cm^{-2}, corresponding to a radiation sensitivity of 0.160 V $\cdot$ cm^{2} $\cdot$ J^{-1}. With the window in place in the transducer fixture, the average zero shift was 89.8 mV and the average energy-meter reading 568.3 mJ $\cdot$ cm^{-2}, corresponding to a radiation sensitivity of 0.158 V $\cdot$ cm^{2} $\cdot$ J^{-1}. Adjusting the data for the differences in energy levels shows that the zero shift with the window is only 1.1% less than that without for transducer Z. Unless a given transducer diaphragm material were especially sensitive to the effects of radiation of wavelengths absorbed by the window, this result may be taken to indicate that the presence of the window will, in general, have no significant effect on the results of the method.

3.5.6 Effect on Method of Increased Air Pressure from Heating - The possibility existed that the air in the closed volume of the mounting fixture would itself be heated by energy from the source to a significant degree. This heating would result in an instantaneous change in air pressure which in turn would be sensed by the test transducer. To investigate the significance of this effect, three tests were run with transducers M and Z with the fixture at a vacuum pressure of 3.4 Pa absolute (25 µm Hg absolute). The results were compared with results from tests under the same conditions of distance and source, but with the fixture at atmospheric ambient pressure. The data are given in table 11. No significant difference between the results of the two sets of tests is seen. The conclusion may be drawn that any "pressurizing" effect resulting from the heating of air in the mounting fixture can be ignored for the purposes of the method.

3.5.7 Effect on Transducer of Exposure to Full-Scale Pressure - A series of 9 tests was run to investigate how transducer output in response to a thermal transient was affected when the transducer was exposed to pressure above ambient atmospheric in the mounting fixture. The pressure chosen was the full-scale pressure for the two transducers used (M and Z), 345 kPa.

Transducer Z has been described (3.4.2); it is a semiconductor strain-gage type and was chosen for this investigation because its zero shift for the test conditions, other than with the fixture at 345 kPa, was well characterized and positive in direction. Transducer M is a semiconductor strain-gage type with a metal diaphragm and was also known to have a positive zero shift. Three tests were made with each transducer at atmospheric ambient and at 345 kPa, with the tests at 345 kPa first. Tests were run with the transducer diaphragm 7 cm from the center plane of the No. 5 flashbulb source. The data are given in table 11.

As might be expected, the results show that the shift in the response measured when the transducer is exposed to full-scale pressure is larger than the zero shift. The differences, however, are small. For transducer M, the shift at 345 kPa is approximately 38% of the full-scale output (38% FS), and the zero shift measured immediately following the test at full-scale pressure is approximately 34% FS. The corresponding figures for transducer Z are 19% FS and 16% FS, respectively. These results suggest that for the intended screening purposes, ambient atmospheric pressure may be specified for the method at no significant loss in discriminating power compared to tests run at pressures higher than ambient. Special circumstances, such as application of the method to transducers known to have a strongly enhanced, non-linear pressure response over some part of their rated range, may require *ad hoc* treatment.

3.6 Discussion of Uncertainties and Method

3.6.1 Method with Flashbulb Source - The experimental results show that the No. 22 flashbulb without reflector produces energy levels of about 2.2 J $\cdot$ cm^{-2} at the minimum distance of 6 cm between energy source and test transducer diaphragm and about 1.7 J $\cdot$ cm^{-2} at the recommended distance of 7 cm. The total duration of the thermal stimulus generated by this bulb is about 37 ms, roughly 30% longer than that of the No. 5 bulb. The energy level of the No. 22 bulb is almost three times that of the No. 5 bulb. Repeatability of the No. 22 bulb is somewhat poorer (coefficient of variation 8.7%) than that of the No. 5 bulb (coefficient of variation 7.5%).

The use of a glass window in front of the test transducer decreased the transducer zero shift by little more than 1%. The effects of transducer diaphragm misalignments with the normal axis of incident radiation follow the cosine law and thus produce an error of less than 1% with misalignments of up to ±6°.

The manufacturer's statement of the energy-meter accuracy allows a maximum error of ±5% of full-scale reading at full-scale (less at less than full-scale readings) plus an additional error of ±2% of reading over the wavelength range of the sensor, 0.3 to 20 µm. Over the wavelength region of interest, approximately 0.35 to 0.8 µm, this error will be proportionately less. An estimate of the overall uncertainty in the energy-meter reading for the purposes of the method may be taken to be ±5% of the reading. It is likely that variations in flashbulb energy output as a function of azimuth angle (angular orientation) are in part the source of the discrepancies found between photocell output readings and energy-meter readings. A measure of the limit of the instrumental error involved may be computed from the square root of the sum of the squares (the root-sum square, or RSS) of the maximum uncertainties observed for photodiode and energy-meter readings: ±12% and ±5%, respectively, for measurements on the No. 22 flashbulb, yielding a limit of ±13% of the reading. For the No. 5 flashbulb, the corresponding figures are ±8% and ±5%, yielding a limit of ±9.4% of the reading. Finally, it is estimated that the maximum transducer output can be determined to within ±3% using the oscilloscope.

In summary, it is estimated that with the use of the No. 22 flashbulb without reflector, 7 cm from the diaphragm of the test transducer and the sensor of the energy meter, transducer zero shift as a function of energy level for a flash duration of 37 ms can be determined within approximately ±14%.*

3.6.2 Method with Electronic-Flash Source - The experimental results show that the electronic-flash system at the 150-J setting produces energy levels of 0.1 $J \cdot cm^{-2}$ at a minimum distance of 7.5 cm. The total duration of the flash from this source is about 6 ms, about one-sixth that of the No. 22 bulb; the energy level, correspondingly, is about 5% that of the No. 22 bulb. The degree of repeatability of the electronic flash can be better (within ±5% of the average energy level) than that of the flashbulbs if appropriate precautions in use are followed.

A disadvantage of electronic-flash systems employing flashtubes such as the xenon tube is that the energy output is highly dependent on the voltage supply. Variations in line voltage or battery voltage

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* The introduction of the neutral-density screen was found to introduce no experimentally detectable error.

produce a change in energy output proportional for small voltage changes to double the percentage change in voltage. A voltage regulator is therefore highly desirable for an a-c line operated electronic-flash system and is recommended. Other test considerations are the same as those listed in 3.6.1.

In summary, use of the electronic-flash system at 150 J is recommended only if a shorter-duration transient than that provided by No. 22 flashbulbs is required, or if repeatability requirements are an overriding consideration. For the electronic flash used in this work, it is estimated that with the flash at 150 J without reflector, 7.5 cm from the diaphragm of the test transducer and the sensor of the energy meter, transducer zero shift as a function of energy level for a flash duration of 6 ms can be determined within approximately ±10%. Other electronic-flash units with significantly greater output are produced commercially, especially to order, but their usefulness for the purpose of the method is limited by considerations of size, availability, and cost.

4. RESULTS OF TESTING TRANSDUCERS USING THE METHOD

The work and results described and discussed in previous sections have been primarily concerned with the development of the method. In the course of this work, the zero shift of transducer Z as determined by the method has been well characterized. It is of interest to investigate by the method the zero shifts of other models of the same type as that of transducer Z and of other transducer types and to compare these results.

Accordingly, 25 transducers, including Z as a control, were selected and tested by the method with a distance of 7 cm* between the transducer diaphragm and the center plane of the No. 22 flashbulb source. All measurements were made with the transducer exposed to ambient atmospheric pressure. Each transducer was tested three times, and an average zero shift computed. These average zero shifts were expressed as a percentage of the transducer full-scale output and are given in table 12, along with a brief indication of transducer type, range, pressure equivalent to the zero shift, and percent full-scale radiation sensitivity. The average zero shifts ranged from about 0.4% of full-scale output for transducer S to 430% of full-scale output for transducer N. The semiconductor strain-gage transducers as a class exhibited the greatest vulnerability of any transducer type to the thermal radiant-energy transients produced in the method.

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* This distance is convenient for the No. 22 flashbulb. The energy levels available at the transducer diaphragm are considerable (approximately 1.7 $J \cdot cm^{-2}$) and there is good access to flashbulb and mounting fixture.

5. CONCLUSIONS AND RESULTS

5.1 Concerning the Test Method

The experimental work has resulted in a simple, practical method for evaluating the effect of thermal radiant-energy transients on pressure transducer performance. The method is most suitable for flush-diaphragm transducers. The use of commercial flashbulbs as the energy source provides a short-duration test (about 37 ms for the No. 22 bulb) at moderate energy-density levels (up to 2.2 J · cm^{-2}). Use of an electronic-flash source results in a test of considerably shorter duration (about 7 ms) at somewhat lower energy-density levels (up to 0.1 J · cm^{-2}). The estimated repeatability of the method, within ±14% with the flashbulb source and within ±10% with the electronic-flash source, appears to be adequate for the intended initial screening purposes and may be suitable for certain data-correction purposes as well.

The method is easy to implement, requires only a moderate amount of equipment, and produces data quickly. The energy levels generated are large enough to produce significant zero shifts in a selection of transducers, as shown in table 12. The magnitudes of the transients produced in the method are large enough to be comparable to the short-term thermal environments of some applications, as the following example shows: The time average of the energy levels generated during a run with a No. 22 bulb at a source-sensor distance of 7 cm yields a power level of approximately 1.2×10^6 W · m^{-2}, if the waveshape is assumed to be triangular over the 37-ms duration. A corresponding figure for the electronic flash is 0.3×10^6 W · m^{-2}. Heat transfer rates in common types of rocket engine are reported to range from 3×10^6 to 4×10^7 W · m^{-2}. [The laser-source method mentioned in 3.1 produced a heat transfer rate of about 1×10^6 W · m^{-2}.]

5.2 Concerning the Transducer Tests

The transducers tested were composed of strain-gage types (7 models) and piezoelectric crystal types (3 models). Each strain-gage transducer had the same full-scale range of 0 to 345 kPa (0 to 50 psig). All transducers had been calibrated prior to this program to assure that they were functioning according to specification. Of the strain-gage types, two models had metallic strain gages; the other five used semiconductor strain gages. The intent of the test program was to test several samples of each model; cost and procurement time precluded this for the transducer types represented by transducers I, M, and Z.

The main purpose of the transducer testing program was to demonstrate the thermal transient test method by applying it to a variety of types of pressure transducer. No attempt was made to sample the entire field of pressure transducers, nor was a statistically thorough sampling of each type contemplated. A secondary purpose of the transducer testing program was to obtain a rough survey of the magnitudes of zero shift likely to be encountered with commonly used transducers in measurement environments with thermal transients present. This information is reported in section 4.

Examination of the data given in table 12 shows that for some transducer models, there is good agreement between the average zero shifts. This statement particularly applies to transducers A, B, C, and D, with a maximum deviation from the average zero shift for that model (expressed as percent of the full-scale output) of 14% and to transducers E, F, G, and H, with a maximum deviation of 11.9%. These results also appear to validate the capability of the test method to produce meaningful results.

There was less consistency in the results for other types between transducers of the same model; in addition, the zero shift in some cases showed two peaks; a positive peak followed by a negative one. In the case of transducers N, O, and P, and S, T, and U, this double-peak response may result from the multiple-layer construction of the sensor. This type of construction could be expected to undergo a complex series of differential thermal expansions and other related changes in response to thermal transients.

In general, semiconductor strain-gage pressure transducers exhibited larger zero shifts than the other types of transducers tested. Within the semiconductor transducers, the largest zero shift occurred in transducers with strain gages diffused into a silicon diaphragm (such as transducers M, N, O, and P). Transducers which had semiconductor strain gages bonded to a metal diaphragm (such as transducers A, B, C, D, and Z) exhibited smaller zero shifts than did the diffused strain-gage transducers. The smallest zero shifts were measured for transducers with semiconductor strain gages mounted on an auxiliary beam connected to the diaphragm by means of a push rod (such as transducers E, F, G, and H).

In the group of 25 transducers tested, zero shifts ranged from 0.4% to about 430% of the full-scale output, a substantial spread that demonstrates the need for a screening method of this type.

6. RECOMMENDATIONS

Many transducers are currently used in thermal-transient environments with little user awareness of the resultant potentially large measurement errors. The test method developed and described here is strongly recommended for the screening of all pressure transducers that are to be used in such environments.

Tests of various schemes and techniques for mitigating the effects of thermal transients, such as protective baffles and coatings, can in principle be carried out with the aid of this test method. It is likely, however, that the evaluation of effective protection schemes will require thermal-transient inputs of greater energy than are presently available. An extension of this work with the aim of investigating potential sources of such inputs is recommended.

7. REFERENCES

[1] Horn, L., Thermal Gradient Effects on Thirteen Flush Mounted Pressure Transducers, NBS Tech. Note 490 (August 1969).

[2] Lederer, P. S., and Hilten, J. S., A Laser Technique for Investigating the Effects of Thermal Transients on Pressure Transducer Performance Characteristics, NBS Tech. Note 723 (May 1972).

[3] Vezzetti, C. F., and Lederer, P. S., An Experimental Technique for the Evaluation of Thermal Transient Effects of Piezoelectric Accelerometers, NBS Tech. Note 855 (January, 1975).

8. ACKNOWLEDGEMENTS

Kurt Muhlberg designed and constructed most of the mechanical portions of the test set-up. Clark Hamilton provided a calibration check of the energy meter.

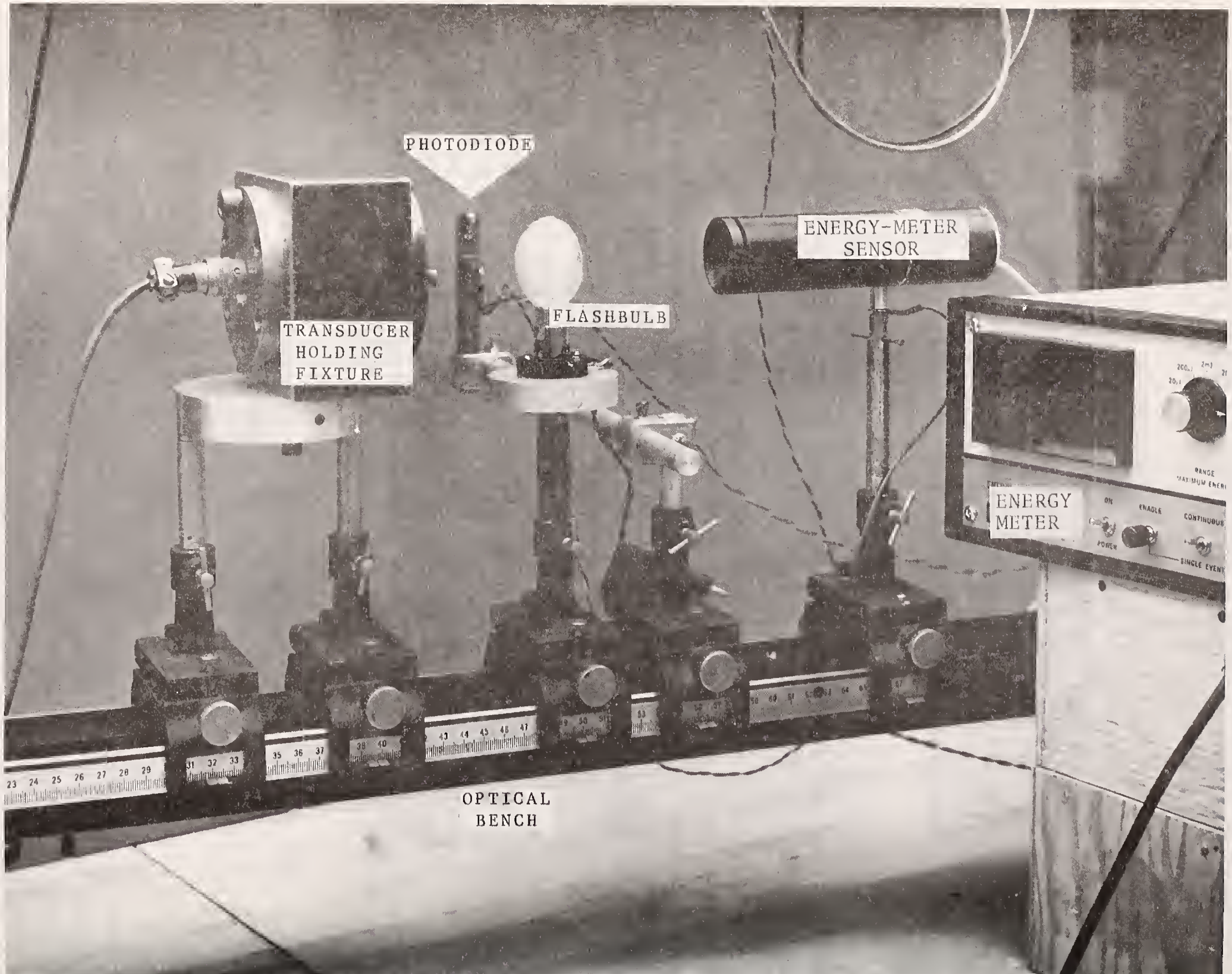

FIGURE 1. OVERALL VIEW OF EXPERIMENTAL APPARATUS WITH TRANSDUCER HOLDING FIXTURE, FLASH-BULB SOURCE, PHOTODIODE, AND ENERGY-METER SENSOR SUPPORTED BY HOLDERS MOUNTED ON AN OPTICAL BENCH. THE ENERGY METER-INSTRUMENT IS AT THE RIGHT.

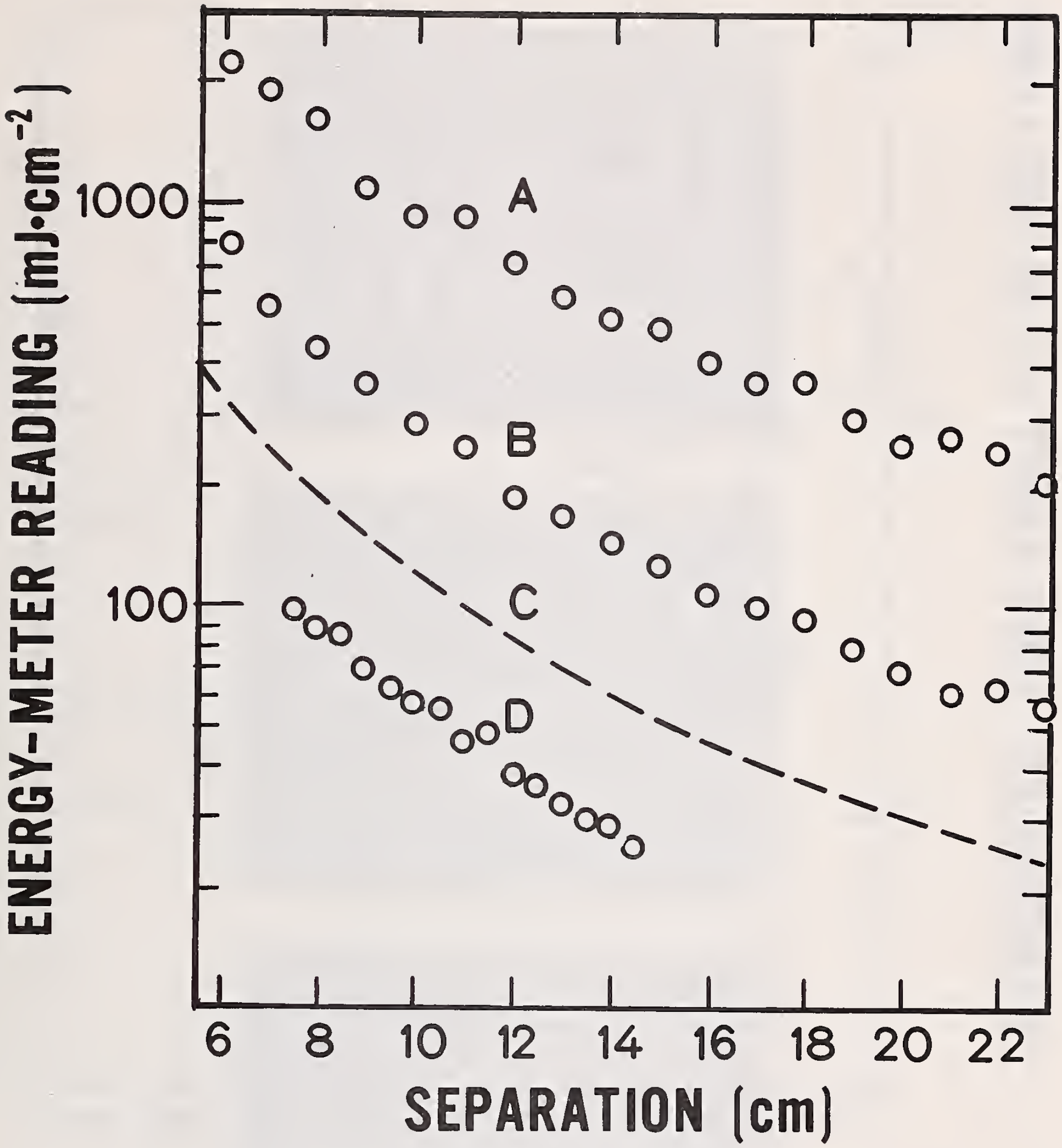

FIGURE 2. ENERGY-METER READING AS A FUNCTION OF SEPARATION, I.E., DISTANCE FROM THE CENTER PLANE OF THE SOURCE TO THE ENERGY METER SENSOR. ENERGY-METER READING IS PLOTTED ON A LOGARITHMIC SCALE. DATA POINTS A REFER TO NO. 22 FLASHBULBS, DATA POINTS B REFER TO NO. 5 FLASHBULBS, AND DATA POINTS D REFER TO THE ELECTRONIC FLASH AT 150 J. CURVE C IS A PLOT OF AN ARBITRARY INVERSE-SQUARE RELATION FOR COMPARISON.

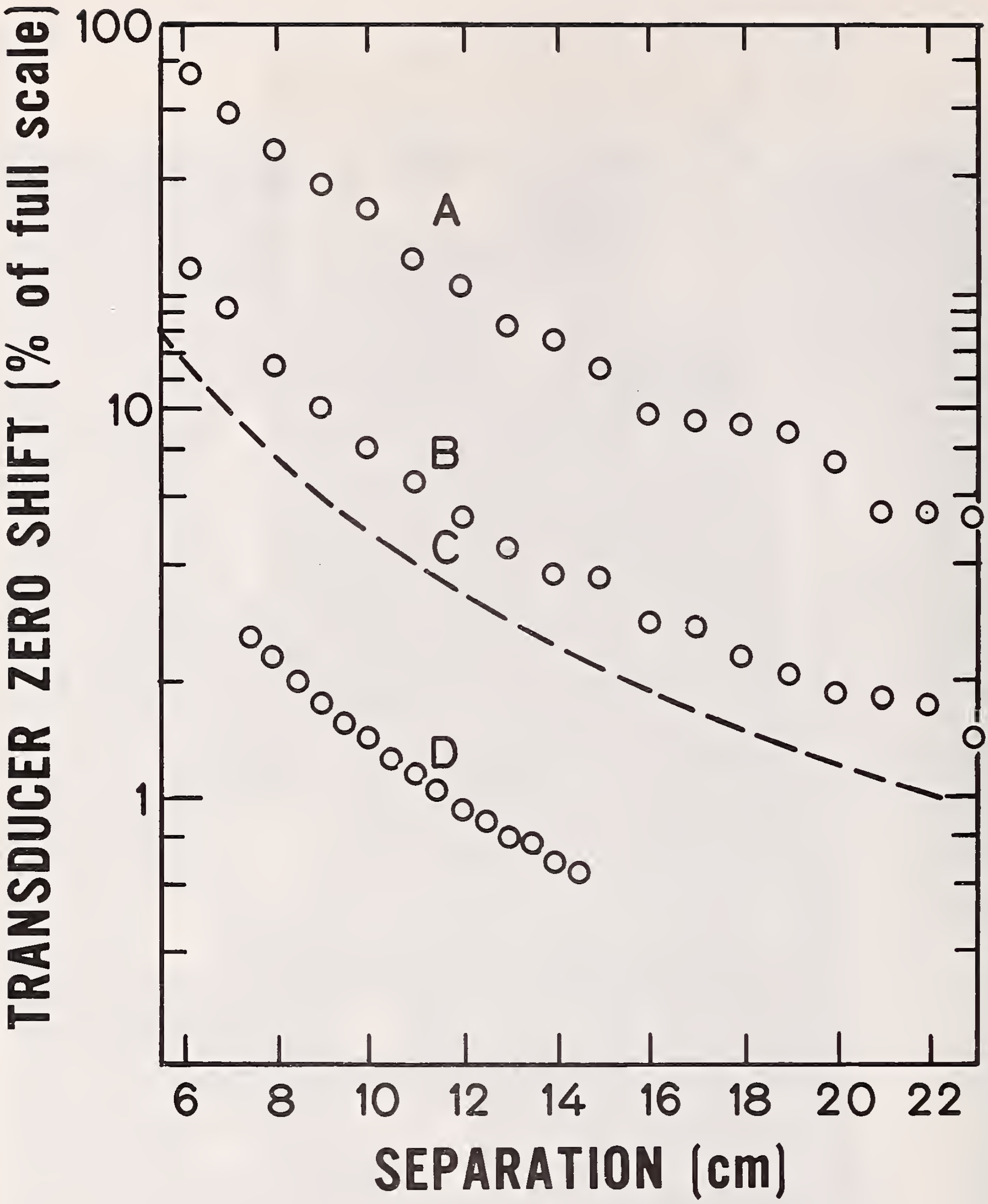

FIGURE 3: TRANSDUCER Z ZERO SHIFT EXPRESSED AS PERCENT OF THE FULL-SCALE READING AS A FUNCTION OF SEPARATION, I.E., DISTANCE FROM THE CENTER PLANE OF THE SOURCE TO THE ENERGY-METER SENSOR. TRANSDUCER ZERO SHIFT IS PLOTTED ON A LOGARITHMIC SCALE. DATA POINTS A REFER TO NO. 22 FLASHBULBS, DATA POINTS B REFER TO NO. 5 FLASHBULBS, AND DATA POINTS D REFER TO THE ELECTRONIC FLASH AT 150 J. CURVE C IS A PLOT OF AN ARBITRARY INVERSE-SQUARE RELATION FOR COMPARISON.

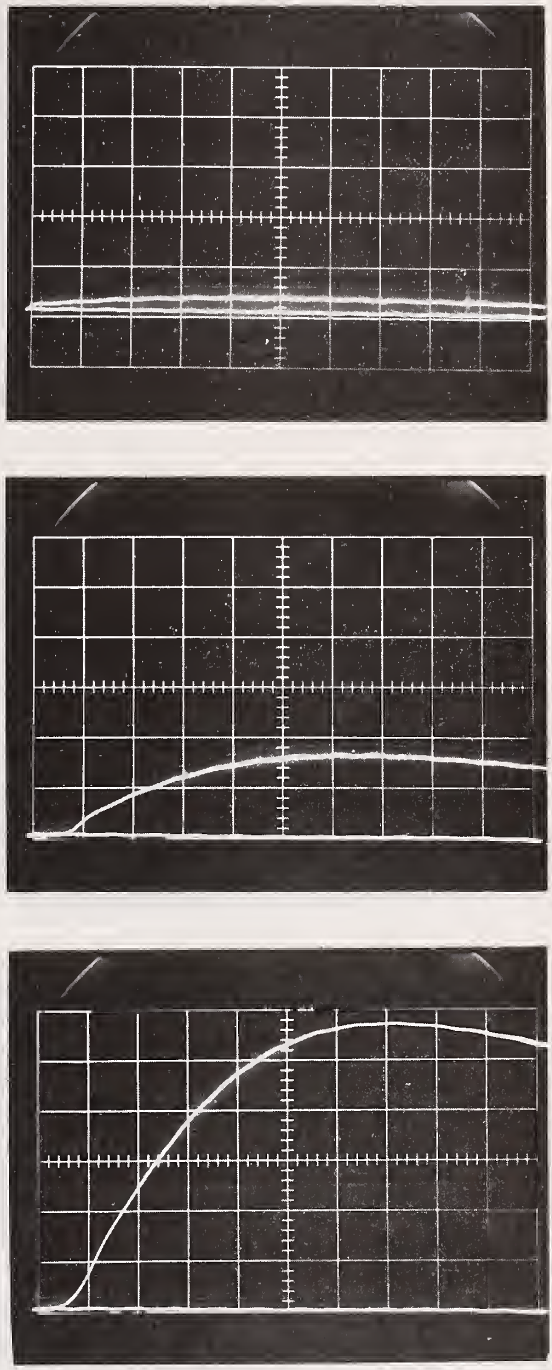

Figure 4: Oscilloscope traces showing transducer Z zero shift in response to thermal radiant-energy transients from (top) the electronic flash at 150 J, (center) a No. 5 flashbulb, and (bottom) a No. 22 flashbulb. The source-to-transducer distance was 10 cm. The sweep time for each photograph was 200 ms, and the amplitude scale, 25 mV per division (corresponding to 5% of the full-scale output per division).

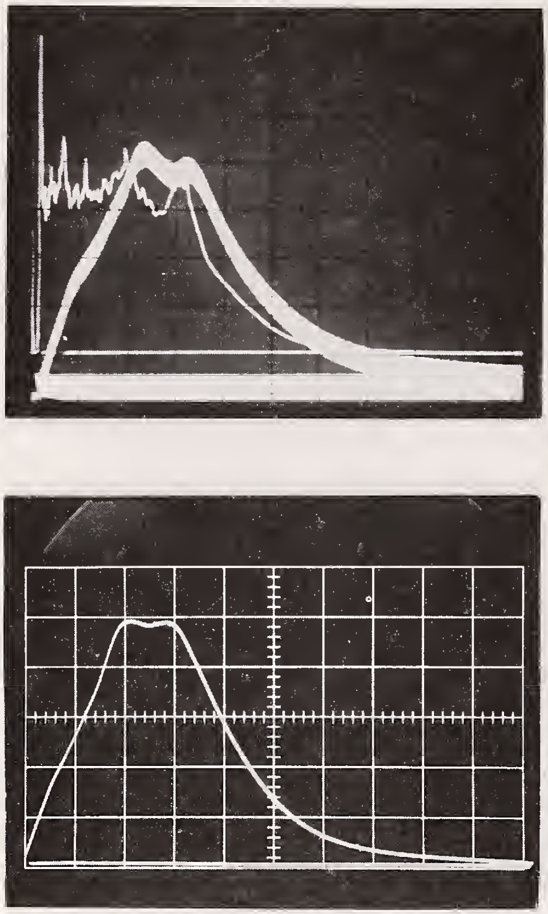

Figure 5. Response of power meter, photodiode, and transducer Z to radiation from FF-33 flashbulbs. The distance from the center plane of the flashbulb to the power-meter sensor and to the transducer diaphragm was 12 cm. In both oscilloscope-trace photographs, the time scale is 500 ms per horizontal division. The top photograph shows analog output of the power meter (thick trace) and output of the photodiode (thin trace). The bottom photograph shows transducer Z zero shift. The maximum shift shown corresponds to 9.7% of the full-scale output.

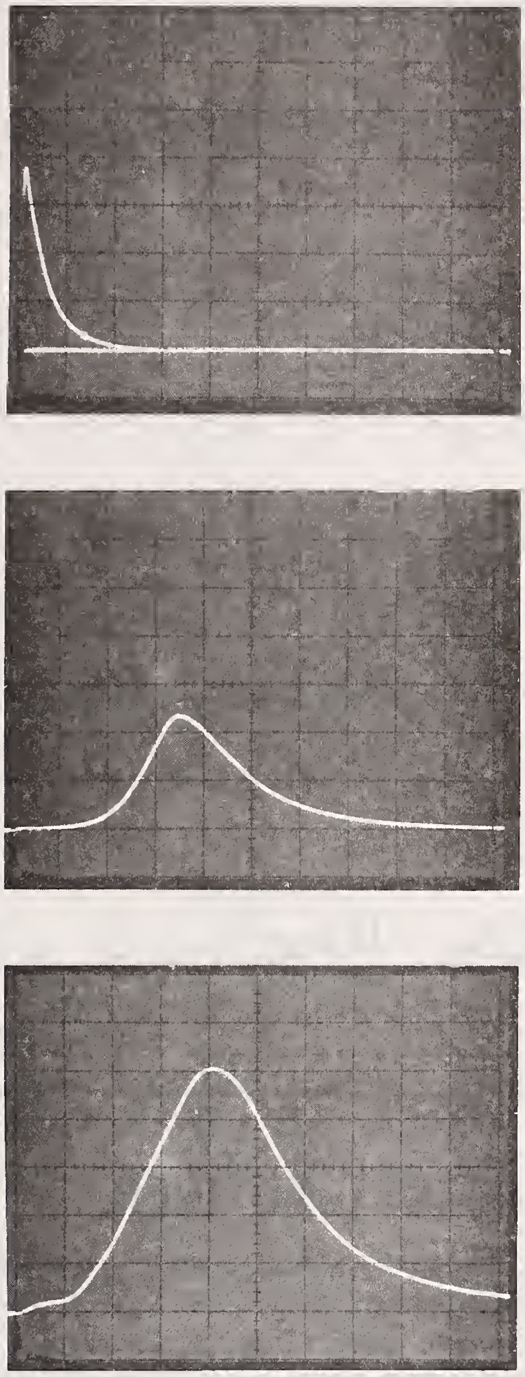

FIGURE 6: OSCILLOSCOPE TRACES SHOWING PHOTODIODE OUTPUT IN RESPONSE TO THERMAL RADIANT-ENERGY TRANSIENTS FROM (TOP) THE ELECTRONIC FLASH AT 150 J, (CENTER) A NO. 5 FLASHBULB, AND (BOTTOM) A NO. 22 FLASHBULB. THE SWEEP TIME FOR EACH PHOTOGRAPH WAS 50 MS, AND THE AMPLITUDE SCALE, 2 V PER DIVISION.

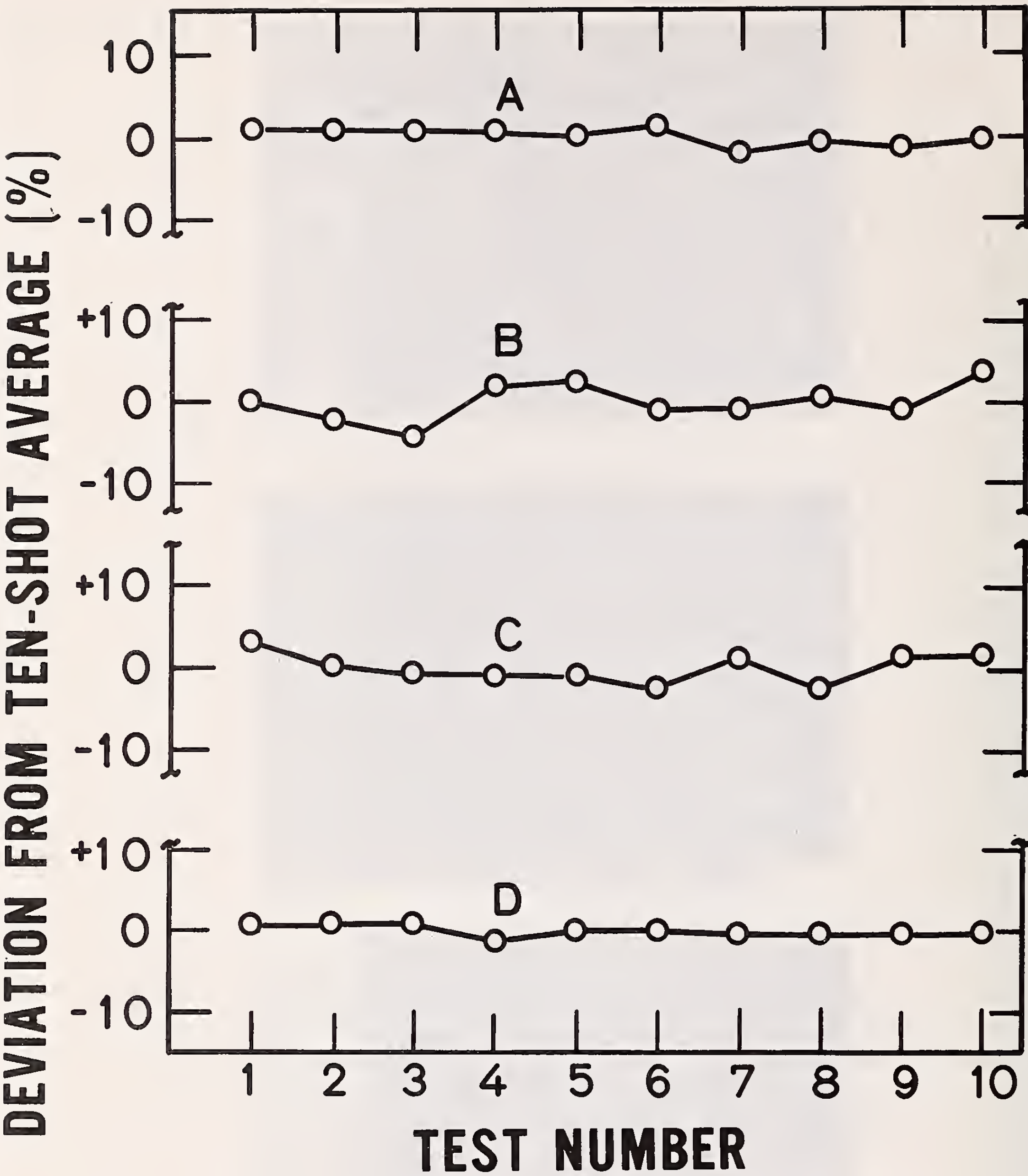

FIGURE 7: REPEATABILITY OF TEST METHOD USING ELECTRONIC FLASH AT 150 J AS SOURCE. SHOWN IS PERCENT DEVIATION FROM A TEN-SHOT AVERAGE FOR THE QUANTITIES (A) TRANSDUCER Z ZERO SHIFT, (B) ENERGY-METER RESPONSE, (C) ENERGY-SENSOR OUTPUT, AND (D) PHOTODIODE OUTPUT. THE DISTANCE BETWEEN THE CENTER PLANE OF THE FLASH SOURCE AND THE TRANSDUCER DIAPHRAGM WAS 7.5 CM.

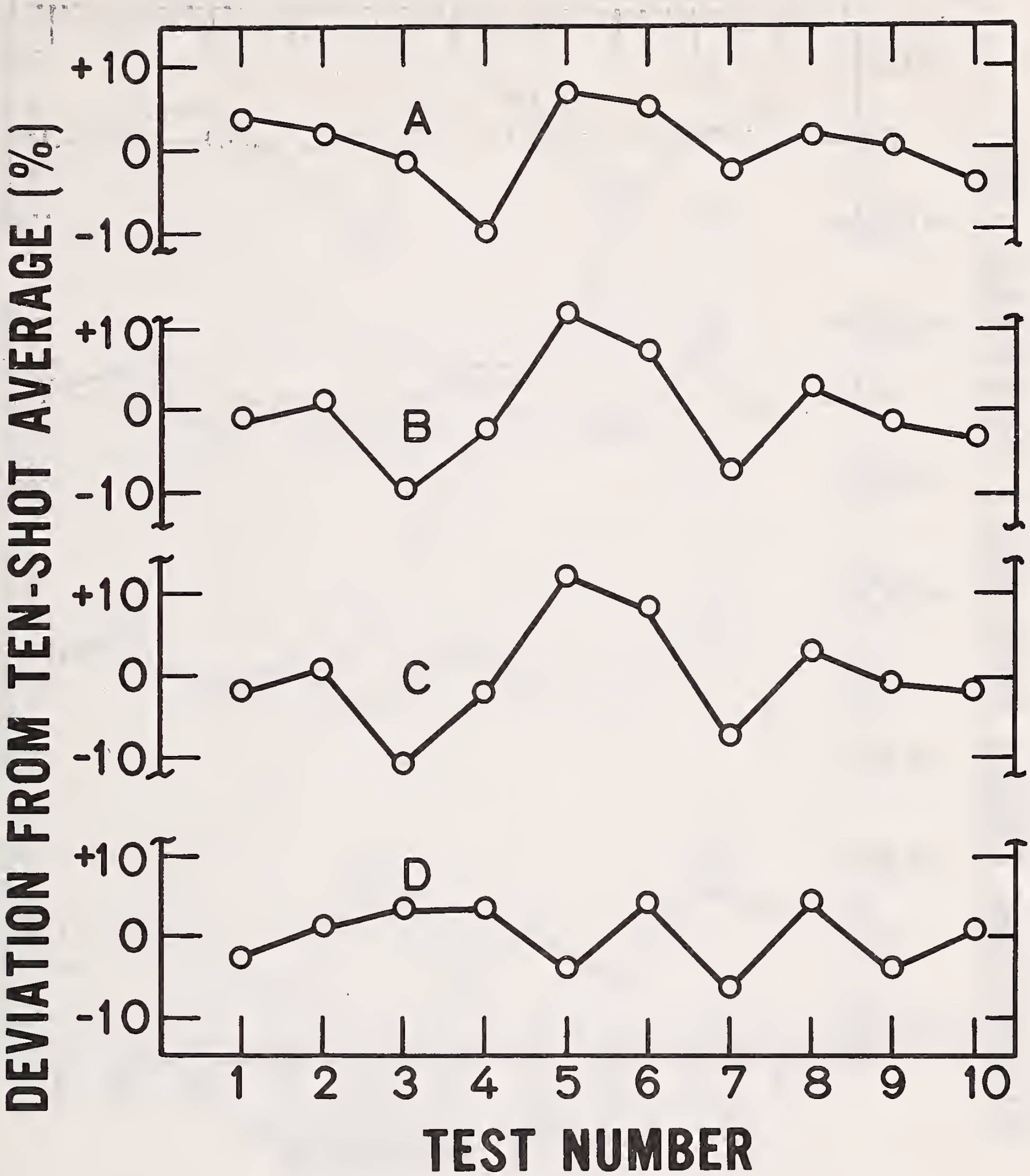

Figure 8: Repeatability of test method using No. 5 flashbulbs as source. Shown is percent deviation from a ten-shot average for the quantities (A) transducer Z zero shift, (B) energy-meter response, (C) energy-sensor output, and (D) photodiode output. The distance between the center plane of the flash source and the transducer diaphragm was 10 cm.

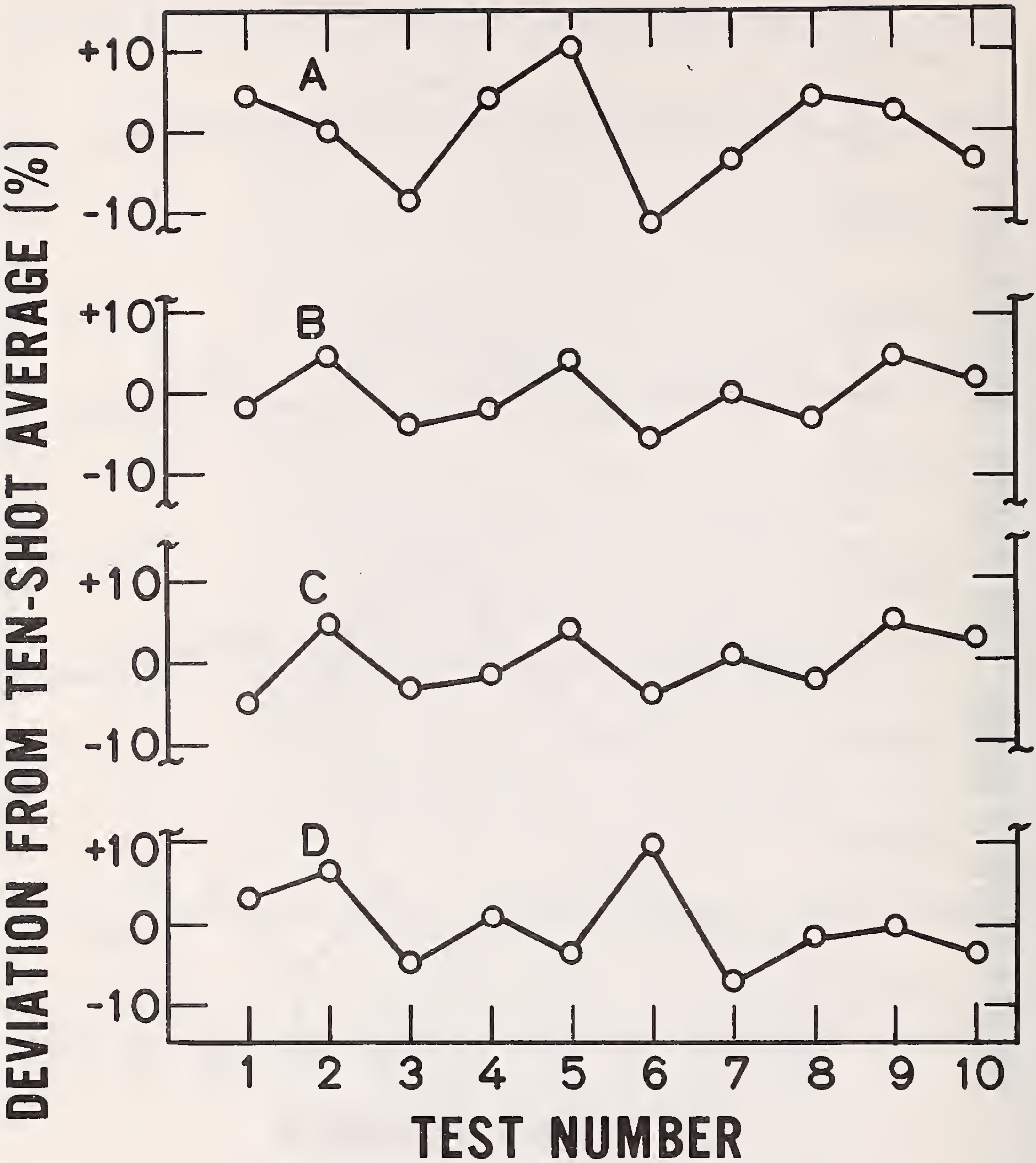

FIGURE 9: REPEATABILITY OF TEST METHOD USING NO. 22 FLASHBULBS AS SOURCE. SHOWN IS PERCENT DEVIATION FROM A TEN-SHOT AVERAGE FOR THE QUANTITIES (A) TRANSDUCER Z ZERO SHIFT, (B) ENERGY-METER RESPONSE, (C) ENERGY-SENSOR OUTPUT, AND (D) PHOTODIODE OUTPUT. THE DISTANCE BETWEEN THE CENTER PLANE OF THE FLASH SOURCE AND THE TRANSDUCER DIAPHRAGM WAS 12 CM.

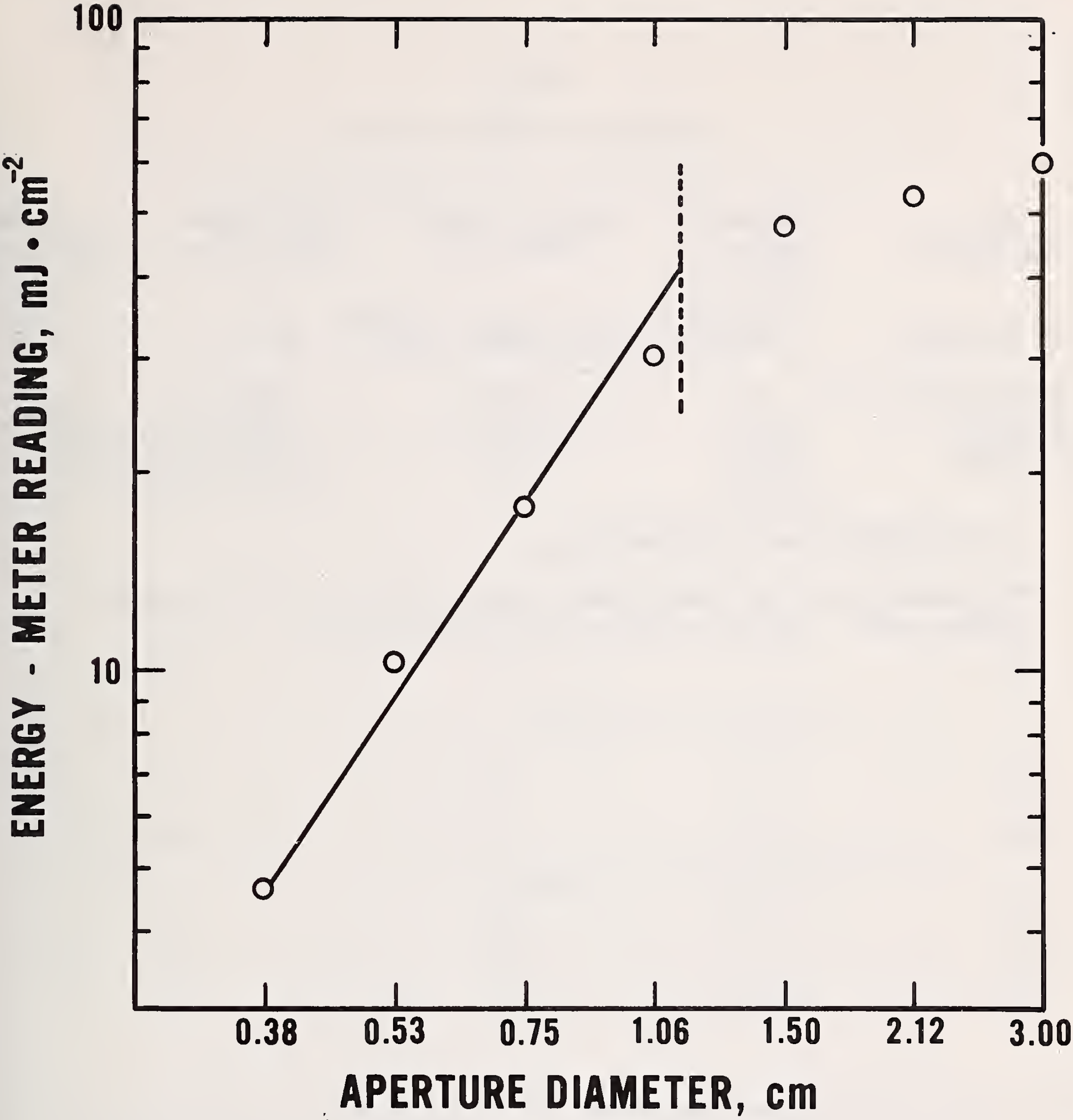

FIGURE 10: PLOT OF ENERGY-METER READINGS (mJ · cm^{-2}) CORRESPONDING TO APERTURES OF FIXED DIAMETER (cm). EACH MEASUREMENT WAS TAKEN WITH THE ENERGY-METER SENSOR 7 CM FROM THE NO. 5 FLASHBULB SOURCE, WITH THE APERTURE MOUNTED IN FRONT OF THE ENERGY METER'S COLLIMATING SHROUD. ENERGY-METER READINGS ARE PLOTTED ON A LOGARITHMIC SCALE. THE STRAIGHT LINE REPRESENTS A DOUBLING OF ENERGY FOR A DOUBLING OF AREA AND PASSES THROUGH A POINT WITH COORDINATES OF (1) THE ENERGY LEVEL MEASURED WITH THE SMALLEST APERTURE AND (2) THE DIAMETER OF THAT APERTURE. THE SENSOR DIAMETER IS INDICATED BY THE VERTICAL DASHED LINE.

TABLE 1

FLASHBULB CHARACTERISTICS*

Bulb Designation	Flashbulb Output (klm · s)	Peak Luminous Flux (klm)	Approximate Time to Peak (s)	Approximate Duration of Flash (s)**
# 5 clear	20	1450	0.020	0.033
# 22 clear	70	4200	0.020	0.030
FF-33	140	120	0.640	2.3

*From manufacturers' literature.

**Time measured from instant when falsh reaches 10% of its maximum value until it falls to 10% of its maximum value.

TABLE 2

TRANSDUCER Z ZERO SHIFTS IN RESPONSE
TO THERMAL RADIANT-ENERGY TRANSIENTS

Distance from Center Line of Energy Source to Transducer Diaphragm (cm)	Transducer Zero Shift* (mV)	Energy Meter Reading ($mJ \cdot cm^{-2}$)	Radiation Sensitivity ($V \cdot cm^2 \cdot J^{-1}$)
	Source:	Electronic Flash at 150 J	
8	11.3	91	0.12
10	7.2	59	0.12
14	3.5	28	0.12
	Source:	No. 5 Flashbulb	
8	63	440	0.14
10	41	290	0.14
14	19	140	0.14
	Source:	No. 22 Flashbulb	
8	240	1630	0.15
10	140	930	0.15
14	76	520	0.15

*Full-scale output for transducer Z is 500 mV, corresponding to 340 kPa (50 psig). All measurements were taken with transducer at ambient atmospheric pressure and with constant electrical excitation.

TABLE 3

TRANSDUCER Z ZERO SHIFT IN RESPONSE TO THERMAL RADIANT-ENERGY TRANSIENTS FROM FF-33 FLASHBULB SOURCE AS A FUNCTION OF SOURCE-TRANSDUCER DISTANCE

Distance from-Energy Source to Transducer Diaphragm (cm)	Transducer Z Zero Shift (% of full scale)	Power Meter Reading (W)**	Power Meter Reading Corrected* to 1 cm^2 (W)
8	23.2	30.3	10.7
9	20.0	27.9	9.8
10	15.2	18.6	6.5
11	14.4	18.3	6.4
12	9.7	12.2	4.3
13	8.5	8.4	3.0
14	8.2	8.0	2.8
15	6.9	6.8	2.4

*All measurements were taken with constant electrical excitation supplied to the transducer and at ambient atmospheric pressure.

**Power meter sensor has an area of 2.84 cm^2; for comparison, calculated values are also shown for 1 cm^2, the area of the energy-meter sensor.

TABLE 4

ZERO SHIFT OF FOUR DIFFERENT TRANSDUCERS IN RESPONSE TO THERMAL RADIANT-ENERGY TRANSIENTS AS A FUNCTION OF SOURCE-TRANSDUCER DISTANCE*

Transducer	Distance- Energy Source To Transducer Diaphragm (cm)		Transducer Zero Shift (%FS)	
B	9.2	(7.0)**	18	(22)**
	12.1	(9.9)	12	(16)
	16.0	(14)	8	(10)
M	7.0		115	
	9.9		59	
	14.0		28	
Q	7.0		2.2	
	9.9		1.1	
	14.0		0.54	
Z	7.0		60	
	9.9		32	
	14.0		15	

*All measurements were taken at ambient atmospheric pressure.

**The distances 7, 9.9 and 14 cm were measured to the front edge of transducer B; its diaphragm is recessed 2.2 cm. Equivalent values for zero shift have been calculated for comparison and are given in parentheses in the third column.

TABLE 5

TEN-SHOT REPEATABILITY OF THERMAL-TRANSIENT SOURCE AND TRANSDUCER Z ZERO SHIFT*

	Electronic Flash at 150 J	No. 5 Flashbulb	No. 22 Flashbulb
	Energy-Meter Readings		
Sample Average ($mJ\cdot cm^{-2}$)	101.0	297.0	763.6
Maximum Deviation from Average (%)	-4.0, +3.4	-5.1, +4.7	-10, +12
Sample Standard Deviation ($mJ\cdot cm^{-2}$) [1S%]	2.3 [2.3]	10.8 [3.6]	49.8[6.5]
	Photodiode Output**		
Sample Average (V)	8.02	4.36	12.78
Maximum Deviation from Average (%)	-1.5, +1.0	-7, +10	-6, +4
Sample Standard Deviation (V)[1S%]	0.6 [0.8]	0.23 [5.3]	0.48[3.8]
	Transducer Z Zero Shift		
Sample Average (mV)	12.81	38.56	98.59
Maximum Deviation from Average (%)	-2.0, +1.1	-11.1, +10.5	-10.3,+6.9
Sample Standard Deviation (mV)[1S%]	0.14 [1.1]	2.54 [6.6]	5.17 [5.2]

*All measurements were taken at ambient atmospheric pressure; the transducer diaphragm was 7.5 cm, 10 cm, and 12 cm from the center plane of the electronic flashtube, the No. 5 flashbulb source, and the No. 22 flashbulb source, respectively.

**The photodiode output is given in peak volts and, unlike the energy-meter readings, does not represent a measure of the total energy available in the transient.

TABLE 6

TRANSDUCER Z ZERO SHIFT IN RESPONSE TO
THERMAL RADIANT-ENERGY TRANSIENTS FROM FF-33 FLASHBULB SOURCE

Run	Transducer Zero Shift as Percentage of 10-Run Average*	Power Meter Output as Percentage of 10-Run Average
1	96.6	87.9
2	96.6	101.1
3	92.5	102.7
4	103.8	93.7
5	107.9	105.2
6	103.8	95.3
7	102.8	93.7
8	76.1	98.6
9	121.3	103.5
10	98.7	118.3

*All measurements were taken with constant electrical excitation supplied to the transducer and at ambient atmospheric pressure.

TABLE 7

EFFECT OF SUPPLY-VOLTAGE VARIATION ON PERFORMANCE OF THE ELECTRONIC FLASH*

Tests with Line Power Supply

Supply Voltage (a-c V)	Run	Energy Meter Reading ($mJ\cdot cm^{-2}$)
110	1	81.9
	2	80.4
	3	83.9
	av	81.8
112	1	91.1
	2	84.7
	3	92.9
	av	89.6
114	1	92.6
	2	90.0
	3	95.3
	av	92.6
116	1	98.8
	2	92.7
	3	96.5
	av	96.0
118	1	97.0
	2	94.2
	3	102.4
	av	97.9
120	1	100.5
	2	104.8
	3	103.5
	av	102.9

Tests with Battery Power Supply

Supply Voltage (d-c V)	Energy Meter Reading ($mJ\cdot cm^{-2}$)
419	73.7
414	71.9
411	70.7
409	70.0
408	69.4
406	68.5
404	67.6
403	67.2
402	66.8
401	66.3
400	66.2
399	65.9
398	65.6
398	65.4
397	64.7

*The electronic flash was operated at a setting of 150 J; the energy meter was 7.5 cm from the center of the flashtube.

TABLE 8

TRANSDUCER Z ZERO SHIFT IN RESPONSE TO
THERMAL RADIANT-ENERGY TRANSIENTS
INCIDENT AT SELECTED ANGLES

Angle of Incidence (rad) [deg]	Run	Zero Shift* (mV)	Ratio of Zero Shift at Test Angle to Zero Shift at Normal Incidence
0	1	72	1.00
0	2	81	1.00
0	3	69	1.00
0	4	69	1.00
0	5	74	1.00
		av 73.0	1.00
$\frac{\pi}{6}$ [30]	1	59	0.81
$\frac{\pi}{6}$ [30]	2	68	0.93
$\frac{\pi}{6}$ [30]	3	67	0.92
		av 64.7	0.89
$\frac{\pi}{3}$ [60]	1	40	0.55
$\frac{\pi}{3}$ [60]	2	37	0.51
$\frac{\pi}{3}$ [60]	3	46	0.63
		av 41.0	0.56
$\frac{\pi}{2}$ [90]	1	2.5	0.03
$\frac{\pi}{2}$ [90]	2	2.5	0.03
$\frac{\pi}{2}$ [90]	3	4.5	0.06
		av 3.2	0.04

*All measurements were taken with constant electrical excitation supplied to the transducer and at ambient atmospheric pressure.

TABLE 9

TRANSDUCER Z ZERO SHIFT
WITH AND WITHOUT FLASH REFLECTOR

Zero Shift*(mV)

	No. 5 Flashbulb			No. 22 Flashbulb			Electronic Flash at 150 J	
Run	No Reflector	Reflector in Use	Run	No Reflector	Reflector in Use	Run	No Reflector	Reflector in Use
1		102	1		450	1		45
2	78		2	330		2		45
3		106	3		440	3		45
4	85		4	330		4		44
5		97	5		340	5		43
6	84		6	380		6	10.5	
7		107	7		450	7	10.0	
8	105		8	350		8	9.5	
9		106	9		360	9	10.5	
10	87		10	340		10	10.0	
av	87.8	103.6		346	408		10.1	44.4
sample SD	10.2	4.2		20.7	53.6		0.4	0.9

Reflector factor: ratio of av zero shift with reflector in use to av zero shift with no reflector

No. 5 Flashbulb	No. 22 Flashbulb	Electronic Flash at 150 J
1.18	1.18	4.37

*All measurements were taken with constant electrical excitation supplied to the transducer and at ambient atmospheric pressure; the transducer diaphragm was 7 cm from the center plane of the flash source.

TABLE 10

GLASS WINDOW ENERGY TRANSMISSION LOSS
AS SEEN IN TRANSDUCER Z ZERO SHIFT

Run	Transducer Zero Shift* (mV) with window	Transducer Zero Shift* (mV) without window	Energy Meter Reading ($mJ \cdot cm^{-2}$)
1		78	665
2		95	660
3		94	579
4		104	561
5		94	551
6		94	592
7		91	519
8		96	569
9		91	581
10		100	587
		av 93.7	av 586.4
		sample SD 6.8	sample SD 45.3
11	84		600
12	90		576
13	95		557
14	97		560
15	98		549
16	90		589
17	80		580
18	82		524
19	88		582
20	94		566
	av 89.8		av 568.3
	sample SD 6.3		sample SD 22.0

*All measurements were taken with constant electrical excitation supplied to the transducer and at ambient atmospheric pressure; the transducer diaphragm was 7 cm from the center plane of the No. 5 flashbulb source.

TABLE 11

SHIFT IN TRANSDUCER OUTPUT FROM INCIDENT THERMAL RADIANT-ENERGY TRANSIENTS WITH TRANSDUCER MEASURING ELEVATED, AMBIENT, AND VACUUM PRESSURE, FOR SELECTED TRANSDUCERS

Test Fixture Pressure	Output Shift*(mV)	
	Transducer Z	Transducer M
345 kPa [50 psi]	97	28
	95	30
	96	28
	av 96	av 29
Ambient Atmospheric	82	25
	78	26
	80	25
	av 80	av 25
Vacuum (3.4 Pa absolute) [25 μm Hg absolute]	78	22
	92	26
	85	25
	av 85	av 24

*All Measurements were taken with the transducer diaphragm 7 cm from the center plane of the No. 5 flashbulb source.

TABLE 12

ZERO SHIFT OF SELECTED TRANSDUCERS IN RESPONSE TO THERMAL RADIANT-ENERGY TRANSIENTS*

Transducer Code Letter	Description	Range (kPa)**	Zero Shift (% of full scale) Positive	Zero Shift (% of full scale) Negative†	Equivalent Pressure (kPa)² Positive	Equivalent Pressure (kPa)² Negative	Percent Full-Scale Output Radiation Sensitivity (% of full scale · cm · mJ⁻¹) Positive	Percent Full-Scale Output Radiation Sensitivity (% of full scale · cm · mJ⁻¹) Negative
A	Semiconductor strain gage; diaphragm recessed 2.2 cm	345	21	-	73	-	11.6	-
B		345	17	-	59	-	9.4	-
C		345	18	-	62	-	10.0	-
D		345	18	-	62	-	10.0	-
E	Semiconductor strain gage; industrial transducer	345	-	7.0	-	24	-	3.9
F		345	-	8.0	-	28	-	4.4
G		345	-	6.8	-	23	-	3.8
H		345	-	6.8	-	23	-	3.8
I	Unbonded strain gage	345	-	4.8	-	17	-	2.7
J	Thin film; strain gage vacuum deposited on beam	345	1.0	0.27	3	1	0.6	0.2
K		345	3.9	-	13	-	2.2	-
L		345	0.45	0.60	1	2	0.2	0.3
M	Semiconductor strain gage; metal diaphragm using an integrated sensor	345	113	-	390	-	62.8	-
N	Semiconductor strain gage; silicon diaphragm; RTV coating	345	430	-	1480	-	239	-
O		345	320	310	1120	1080	178	172
P		345	250	290	870	980	139	161
Q	Quartz crystal	68,900	-	2.2	-	1530	-	1.2
R		68,900	-	2.4	-	1650	-	1.3
S	Quartz crystal; built-in integrated circuit	55,200	0.34	0.44	190	240	0.2	0.2
T		55,200	0.29	0.88	160	490	0.2	0.5
U		55,200	-	0.70	-	390	-	0.4
V	Tourmaline crystal	68,900	2.20	-	1516	-	1.2	-
W		68,900	2.79	-	1922	-	1.5	-
Y		68,900	2.73	-	1881	-	1.5	-
Z	Semiconductor strain gage	345	60	-	210	-	33.3	-

*All measurements were taken at ambient atmospheric pressure; the transducer diaphragm was 7 cm from the center plane of the No. 22 flashbulb source. At this distance, approximately 1.8 J · cm^{-2} is incident upon the diaphragm.

**1 kPa - 0.145 psi

†The existence of positive and negative zero shifts is explained in 5.2.

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15. SUPPLEMENTARY NOTES

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

A test method for evaluating the effects of short-duration, thermal radiant-energy transients on pressure-transducer response is described. The method consists of monitoring pressure-transducer output (zero shift with the transducer at atmospheric pressure) as the transducer is exposed to radiation resulting from the ignition of a photographic flashbulb or from the discharge of an electronic flash. The method is intended to serve as an initial screening test. Thermal energy pulses as great as 0.1 J/cm^2, with durations of about 6 ms, have been generated using an electronic flash; pulses of up to 2.2 J/cm^2, with durations of about 37 ms, have been generated using No. 22 flashbulbs. In tests with No. 22 bulbs, 25 commercial pressure transducers have shown zero shifts ranging from 0.4% to about 400% of the full-scale output.

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)* Calibration; dynamic; electronic flash; photographic flashbulb; pressure; pressure measurement; pressure transducer; thermal transient; transducer; zero shift.

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