NBS TECHNICAL NOTE 931

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

Environmental Effects on Microphones and Type II Sound Level Meters

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Environmental Effects on Microphones and Type II Sound Level Meters

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ENVIRONMENTAL EFFECTS ON
MICROPHONES AND TYPE II SOUND LEVEL METERS

Edited by

Edward B. Magrab

For four different manufacturer's Type II sound level meters numerous experimentally-determined data concerning the effects of frequency, temperature, angle of incidence of the sound, and types of ground cover and reflecting surfaces on sound level meter readings are presented. Data are also given for the effects of ambient barometric pressure on several manufacturers' acoustic calibrators, the effect of frequency and crest factor on the sound level meters' detector circuit, the linearity of the sound level meters' range potentiometer and meter scale, and the precision of the A-weighted response in a randomly incident (diffuse) sound field. Additional data are given concerning the effects of temperature and humidity on the sensitivity of electret, condenser, and ceramic microphones. Finally, important statistical concepts and recommended data-monitoring procedures are presented to insure that the precision of repeated sound level measurements is known.

Key words: Acoustic calibrators; A-weighting; barometric pressure; crest factor; ground cover; humidity; instrumentation; microphones; sound level meters; statistical control processes; temperature; windscreens.

1. INTRODUCTION

The objective of the results presented herein is to provide the reader with a unified presentation from which an estimate of the magnitude of the variations in Type II sound level meter readings as a function of numerous environmental conditions can be obtained. Much of the data were obtained during the course of developing test methods at NBS for the evaluation of sound level meters. These data were also presented in a NBS-sponsored course entitled "Workshop on Sound Level Meters," which was held at NBS on November 20 and 21, 1975.

The information is presented in the following three chapters, with supplemental information appearing in the appendices. Each section or chapter describing a particular environmental effect consists of a brief discussion of the experimental technique used to obtain the data and a discussion of the results. Appendices A and B relate to Section 2.1 and Chapter 4, respectively, whereas Appendix C presents additional information that is not directly related to the theme of the report, but is included because it provides information regarding the magnitudes of electrical errors that are of considerable importance in certain applications.

Chapter 2 presents results illustrating the effects of temperature, wind, humidity, and static (barometric) pressure on the various components of a sound level meter. Chapter 3 presents typical variations in the meter readings as a function of the physical environment; namely, the presence or absence of reflecting surfaces. The last chapter presents a detailed outline of a method whereby one can determine both an estimate of the precision of the sound level meter readings and whether or not this precision is, at all times, within acceptable limits; that is, whether or not the measurement process is in control. It is felt that the material in this chapter will be of great importance to those enforcing noise regulations. Finally, Appendix C presents some additional data concerning certain electrical properties of sound level meters: meter scale linearity and the crest factor capability of the detector circuits.

2. ATMOSPHERIC EFFECTS

2.1. Temperature and Humidity Effects on Microphone Sensitivity*

2.1.1. Introduction

The introduction of federal regulations stipulating the permissible noise levels in the environment has made it necessary for many acoustic measurements to be performed over extended periods of time during which the temperature and humidity vary markedly. These changes in the environmental conditions could affect the sensitivity of the microphones. There exist some published data[1-5] concerning the effects of environmental conditions on microphones of various construction. However these data appear in abbreviated form, usually in terms of frequency-independent temperature coefficients. Furthermore the experimental techniques employed to obtain this information are rarely stated. It was felt therefore that a reasonably thorough investigation, which determined the changes in the pressure sensitivity of those commercially available microphone constructions most frequently found in noise-measuring and noise-monitoring systems and which used a consistent and standardized measurement procedure, would provide useful and meaningfully-comparable data.

Six commercially-available microphones were measured: two "1/2-inch" electret, two "1-inch" ceramic, and two "1-inch" condenser microphones. The condenser microphones had their pressure equalization port back-vented through a dehumidifier containing silica gel.** The sensitivity was measured (where physically possible) at the following combinations of frequency, temperature, and relative humidity: frequency: 0.1, 0.2, 0.5, 1, 2, 3, 4, and 5 kHz; temperature: every 10 °C from -20 to +50 °C; and (nominal) relative humidity: every 10% RH from 25 to 95% RH.

2.1.2. Test Method and Procedure

The sensitivities of the microphones were measured using the procedures specified in the ANSI Standard.[6] The NBS facility used to calibrate microphones was essentially duplicated, except that the 3-cm^3 coupler, the microphones and the microphone preamplifiers were placed in an environmental chamber having wet and dry bulb temperature control and spatial uniformity to within ± 0.2 °C. So that the microphone could be inserted into the coupler, several different size adapter rings, which are used to electrically isolate one of the microphones in the coupler, were required to

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*This section is identical to "Environmental Effects on Microphones of Various Constructions" by G. R. Hruska, E. B. Magrab, and W. B. Penzes, NBSIR 76-1090 (July 1976).

**By their very nature the small enclosed volumes in the electret and ceramic microphone cartridges are unaffected by humidity in the same way that condenser microphones are and therefore do not require a desiccant. However, certain electret or ceramic configurations protect their electronics from the effects of humidity with a desiccant.

compensate for thermal expansion and contraction over the temperature range. The microphone preamplifiers, having insert voltage capabilities, provided a means whereby the effects of the environmental conditions on the preamplifiers were eliminated.

The coupler, the preamplifiers and the six microphones (plus an additional "1-inch" condenser microphone required for the reciprocity calibration) were placed in the environmental chamber. The desired temperature and relative humidity were set and then two hours were allowed for the chamber to reach equilibrium. Then the "source" microphone was placed in the coupler and the "receiver" microphone connected to the preamplifier but not placed in the top of the coupler. An additional fifteen minutes were allowed for the chamber to return to equilibrium at which time the receiver microphone was rapidly placed into the coupler. After equilibrium had again been established, the measurements were started by first determining the resonance frequency of the lowest longitudinal mode of the coupler volume. Then the voltage ratio measurements were made in the following order: 5, 0.1, 0.2,...4, and 5 kHz. Then the resonance frequency measurement was repeated. By examining the first and final measurements at 5 kHz and the two resonance frequencies, it was possible to check that equilibrium conditions had existed during the course of the measurements.

The sequence of measurements was as follows: For a given temperature and humidity the three condenser microphones, labeled A, B, and C, were interchanged after each frequency run, as shown in the table below:

Frequency Run	Source	Receiver
1	A	B
2	A	C
3	B	C

Runs 1 and 2 gave the ratio of the responses of the microphones B and C. Using the results of Run 3 plus the measurement of the capacitance[7] of microphone B, the absolute pressure response levels of microphones A, B, and C were calculated. The pressure response of the remaining four microphones was determined using microphone B as the source, with the measurements on the electret microphones preceding those on the ceramic microphones. More specific details of the procedure are given in Appendix A along with a discussion of the uncertainties in the measurement. The total time, after warm-up, to perform the reciprocity and comparison measurements on all six microphones at a given temperature and humidity was approximately 6 hours. The temperatures were changed in the following order: 20, 30, 40, 10, 0, -10, -20, 50, and 20 °C. At each temperature the humidity was incrementally increased from the lowest to the highest obtainable humidity. The lowest humidity depended on the temperature, with this minimum value increasing with decreasing temperature. Below 0 °C the relative humidity could not be determined with good precision and only one set of microphone calibrations was made at these temperatures. The repeated calibration at 20 °C was only performed at 44% RH.

2.1.3. Discussion of Results

The changes in sensitivity of the six microphones normalized to their respective pressure sensitivities at 1 kHz and 20 °C are shown in Figs. 1 through 8. Figures 1 and 3 show the change in sensitivity of the "1-inch" condenser microphones as a function of frequency for the various temperatures. These figures are replotted in Figs. 2 and 4, respectively, as a function of temperature for selected frequencies. The data points shown in these four figures are the mean values of the sensitivity changes for the range of humidities tested. The spread of the data at virtually every one of the points is less than ± 0.15 dB. These figures show that the two "1-inch" condenser microphones exhibited small temperature coefficients (change in microphone sensitivity per change in temperature) of approximately -0.003 and +0.005 dB/°C, respectively, from -20 tc 50 °C and for frequencies below 1000 Hz. At frequencies above 1000 Hz the temperature coefficient increased, such that at 5000 Hz they become approximately -0.02 and -0.03 dB/°C, respectively. This variation in the temperature coefficient as a function of frequency is due to the relatively large amount of viscous damping introduced by the particular backplate design of these microphones, that is, by the distance between the diaphragm and the backplate and the location, number, and size of the holes in the backplate. Since the viscous losses greatly affect the sensitivity near resonance, smaller microphones could be expected to show less sensitivity change at high frequencies.

The changes in sensitivity for the electret microphones are shown in Figs. 5 and 6 and for the ceramic microphones in Figs. 7 and 8. In these figures the vertical bars indicate the range of the data as a function of humidity. The absence of those vertical bars indicates that those data were only taken at a single relative humidity. The data are presented in this form because no meaningful relation can be established for the change in sensitivity of these microphones as a function of either frequency, temperature or humidity. This type of behavior can be explained if the systematic changes due to temperature and humidity are much smaller than the inherent instability of the microphone itself. Consequently, it is not possible to obtain from these measurements the temperature coefficients of the electret and ceramic microphones.

If the electret and ceramic microphones are subject to these instabilities they will exhibit similar behavior at standard conditions, 20 °C and 44% RH. As can be seen from Tables 1-3 the condenser microphones are within ± 0.2 dB of their original sensitivities whereas the electret and ceramic microphones show relatively large variations. These tables give an indication of the moderately long-term stability of these types of microphone constructions.

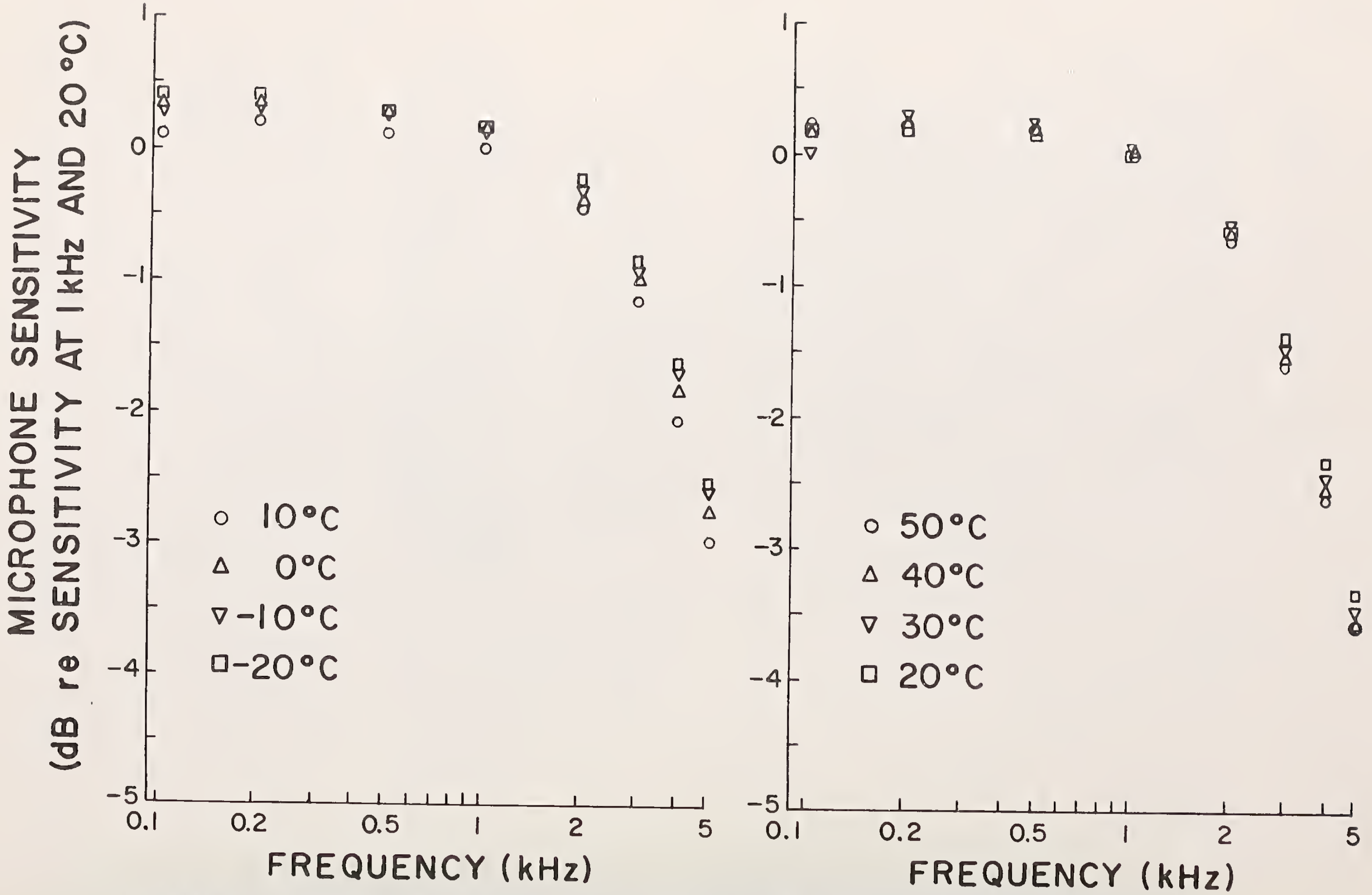

FIGURE 1. CHANGE IN SENSITIVITY OF "1-INCH" CONDENSER MICROPHONE NO. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE CHANGE IN RELATIVE HUMIDITY INTRODUCES AN UNCERTAINTY ABOUT THE DATA POINTS OF LESS THAN ± 0.15 DB.

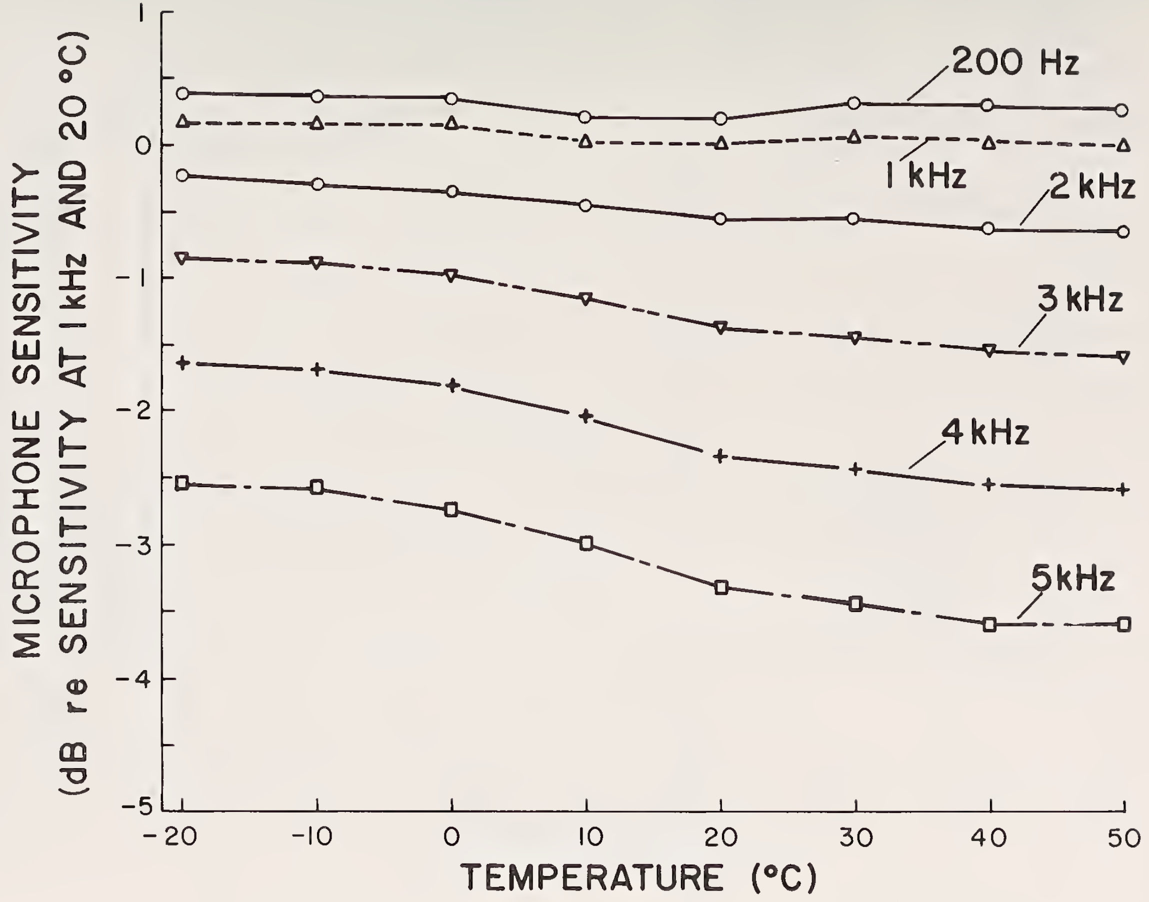

Figure 2. Change in sensitivity of "1-inch" condenser microphone No. 1 as a function of temperature for several frequencies.

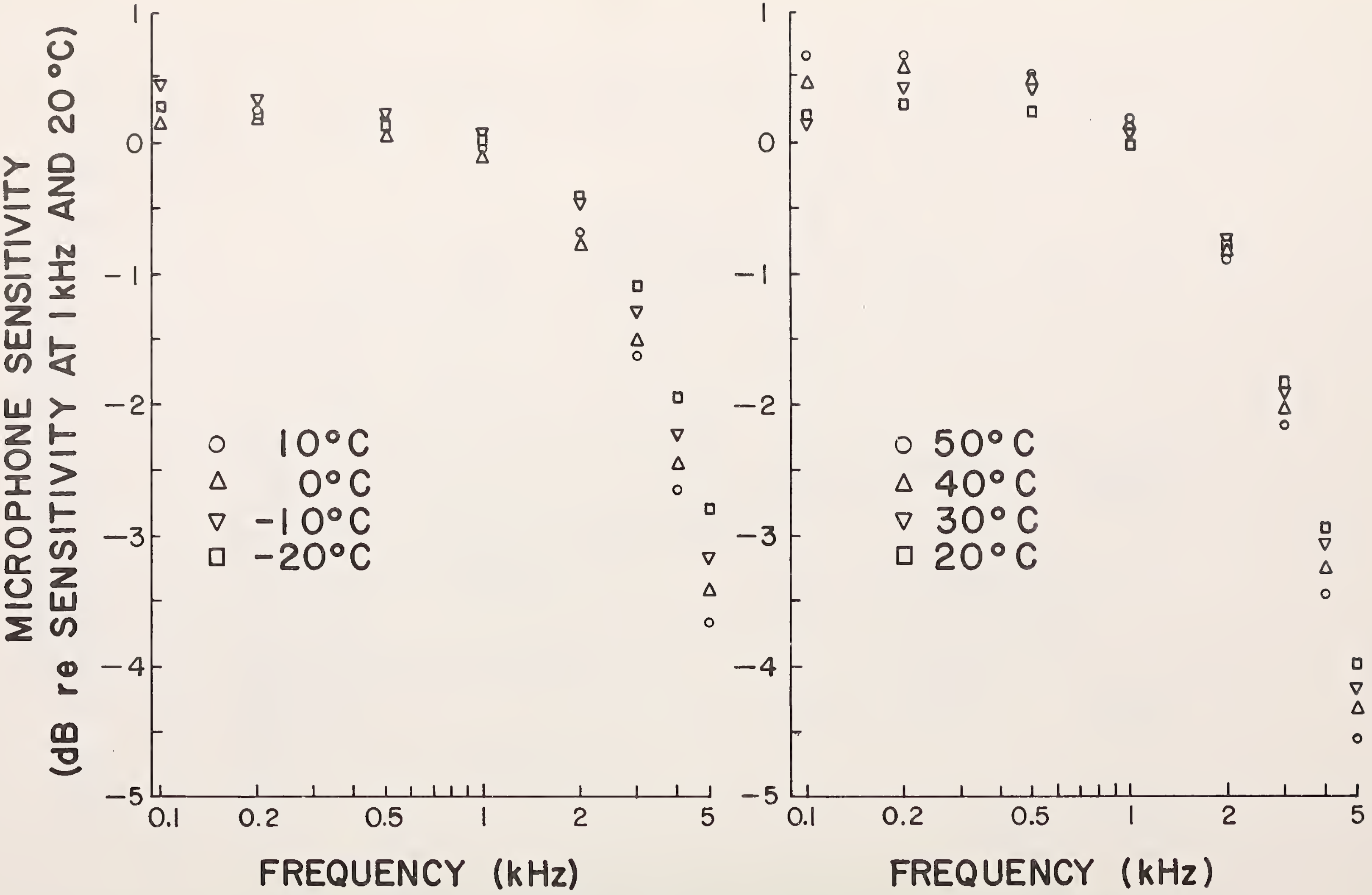

Figure 3. Change in sensitivity of "1-inch" condenser microphone No. 2 as a function of frequency and temperature. The change in relative humidity introduces an uncertainty about the data points of less than ± 0.15 dB.

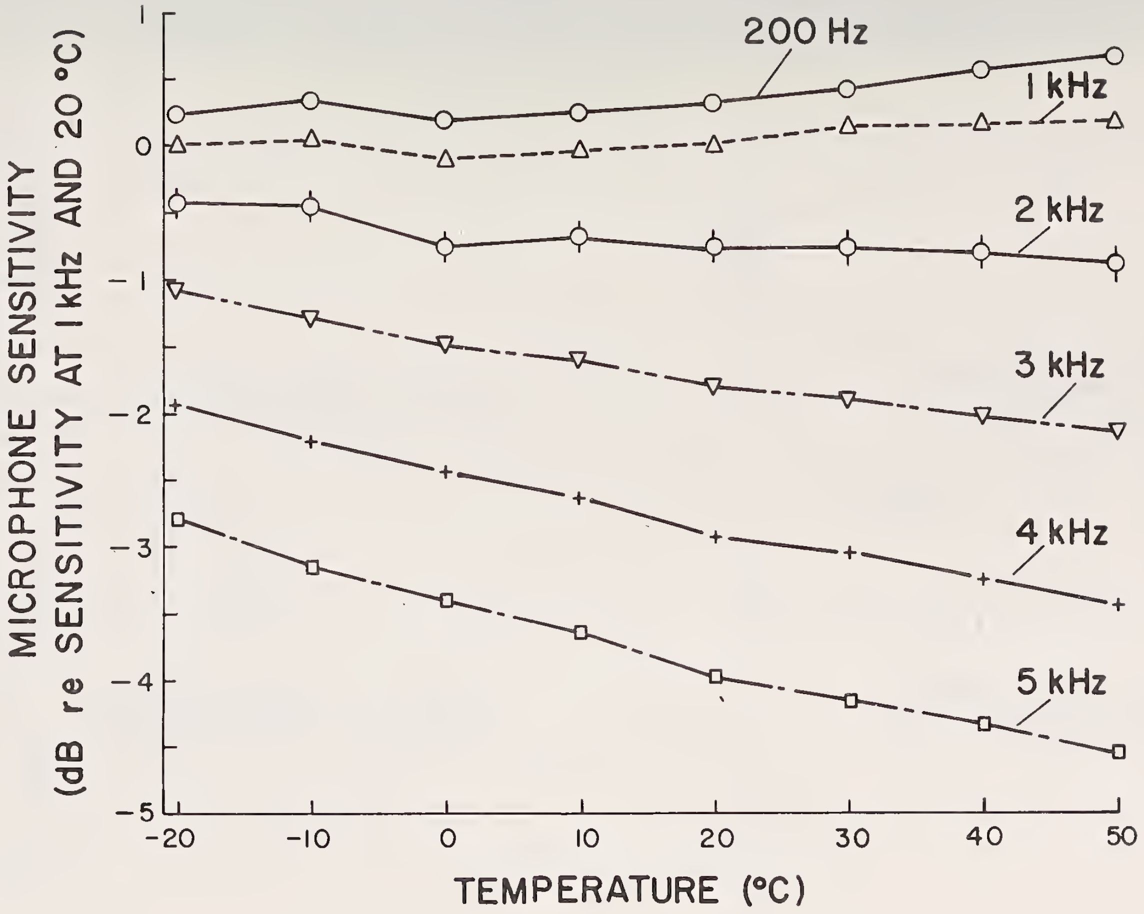

FIGURE 4. CHANGE IN SENSITIVITY OF "1-INCH" CONDENSER MICROPHONE No. 2 AS A FUNCTION OF TEMPERATURE FOR SEVERAL FREQUENCIES.

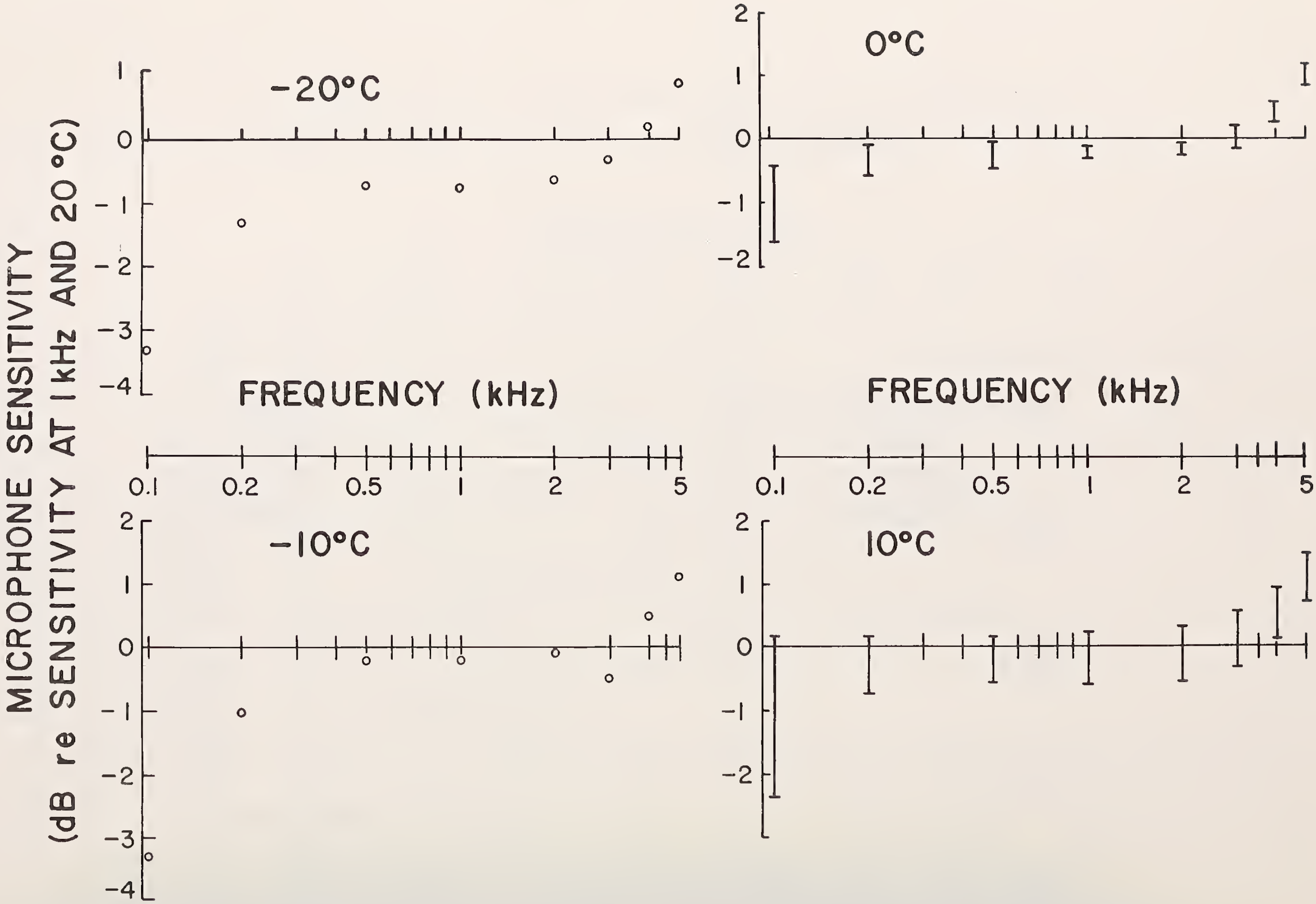

FIGURE 5A. CHANGE IN SENSITIVITY OF "1/2-INCH" ELECTRET MICROPHONE No. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

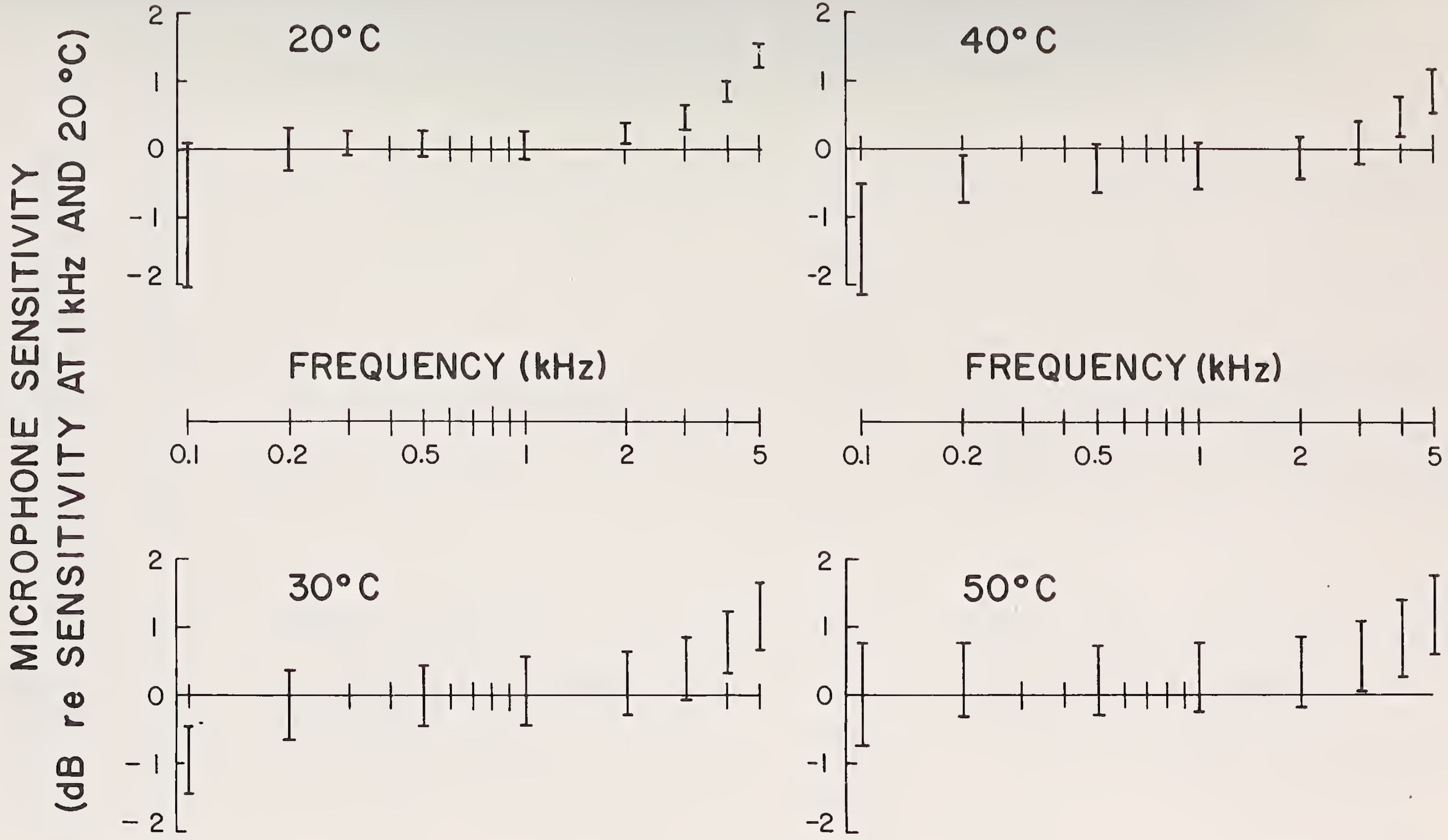

FIGURE 5B. CHANGE IN SENSITIVITY OF "1/2-INCH" ELECTRET MICROPHONE NO. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

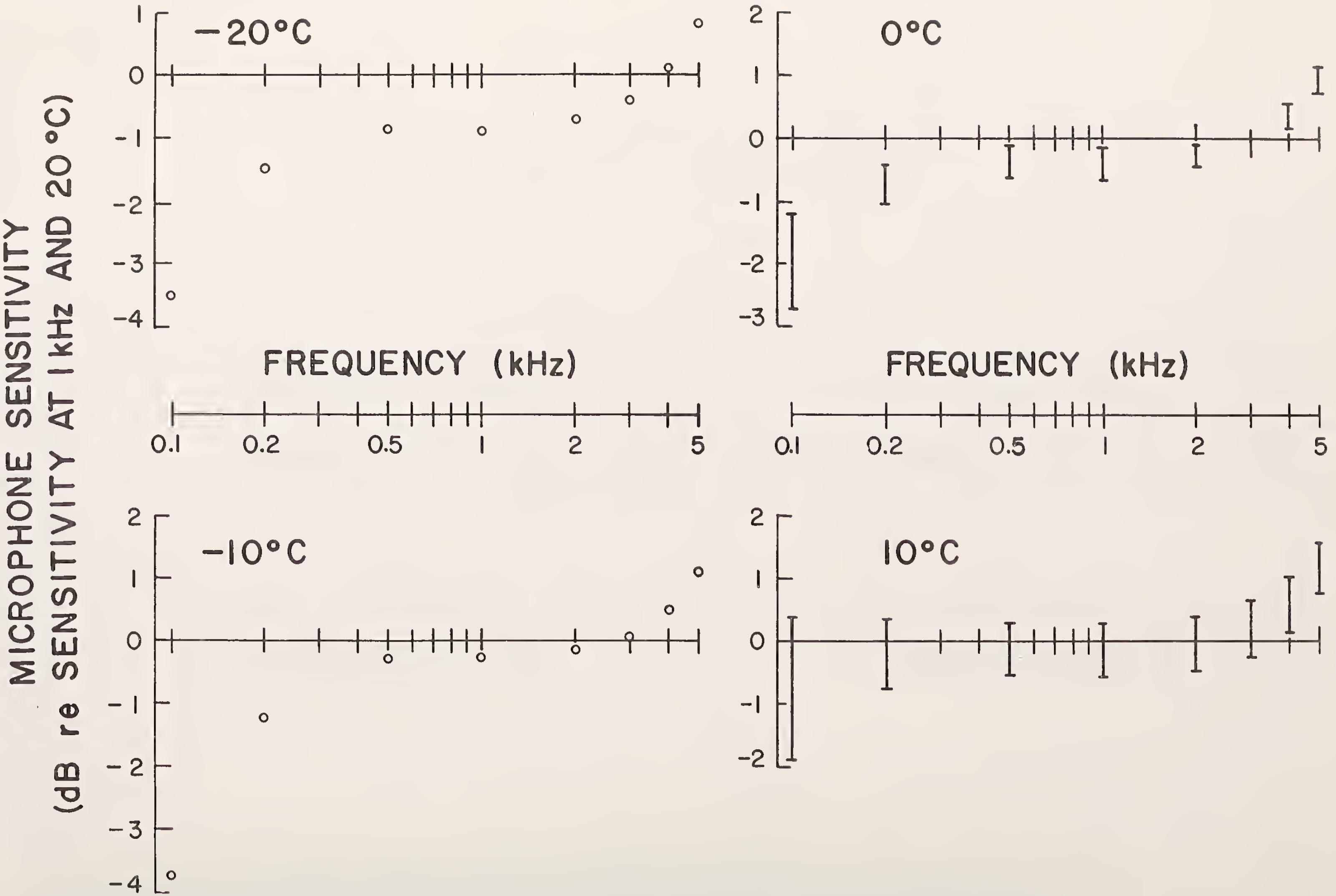

Figure 6a. Change in sensitivity of "1/2-inch" electret microphone No. 2 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

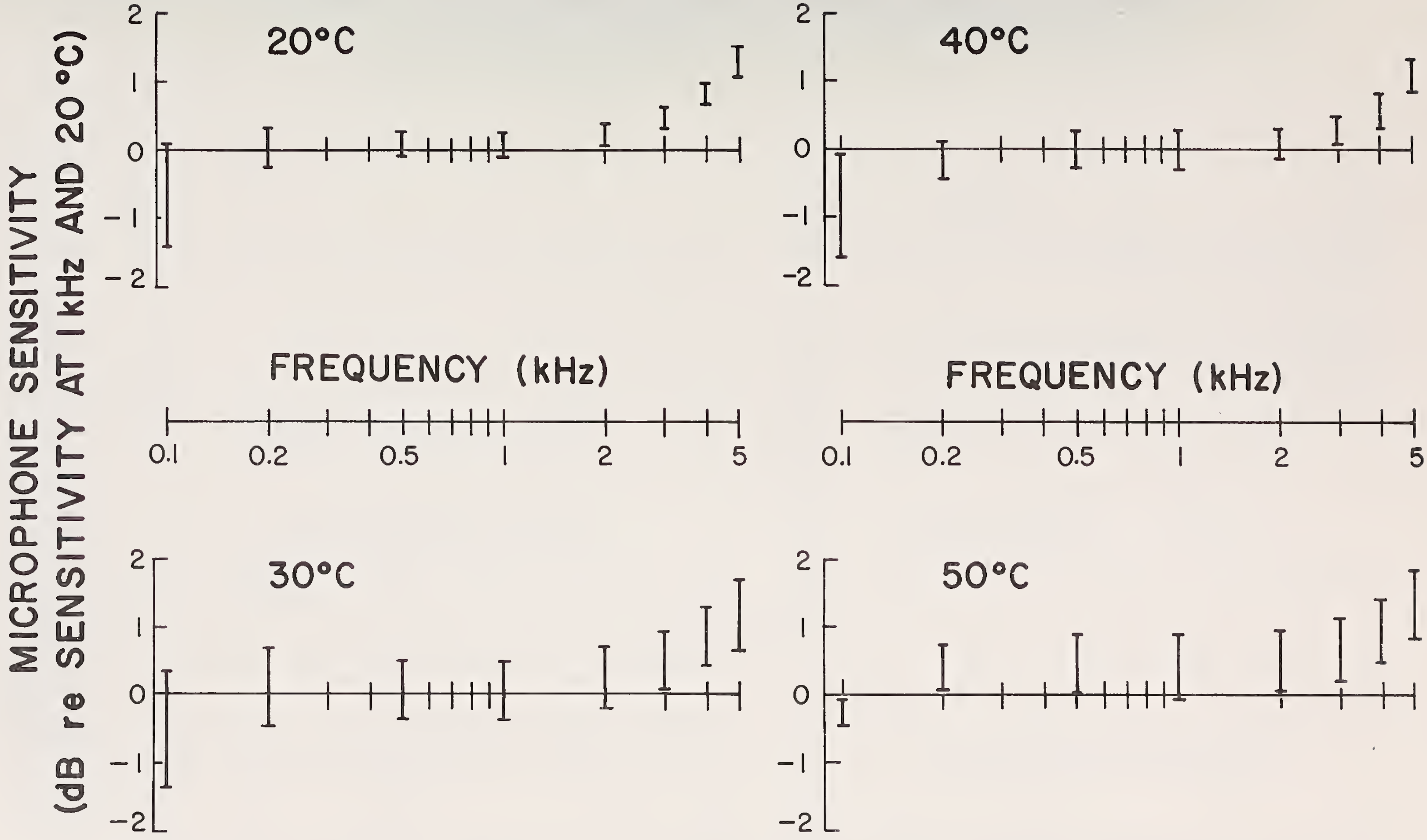

Figure 6b. Change in sensitivity of "1/2-inch" electret microphone No. 2 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

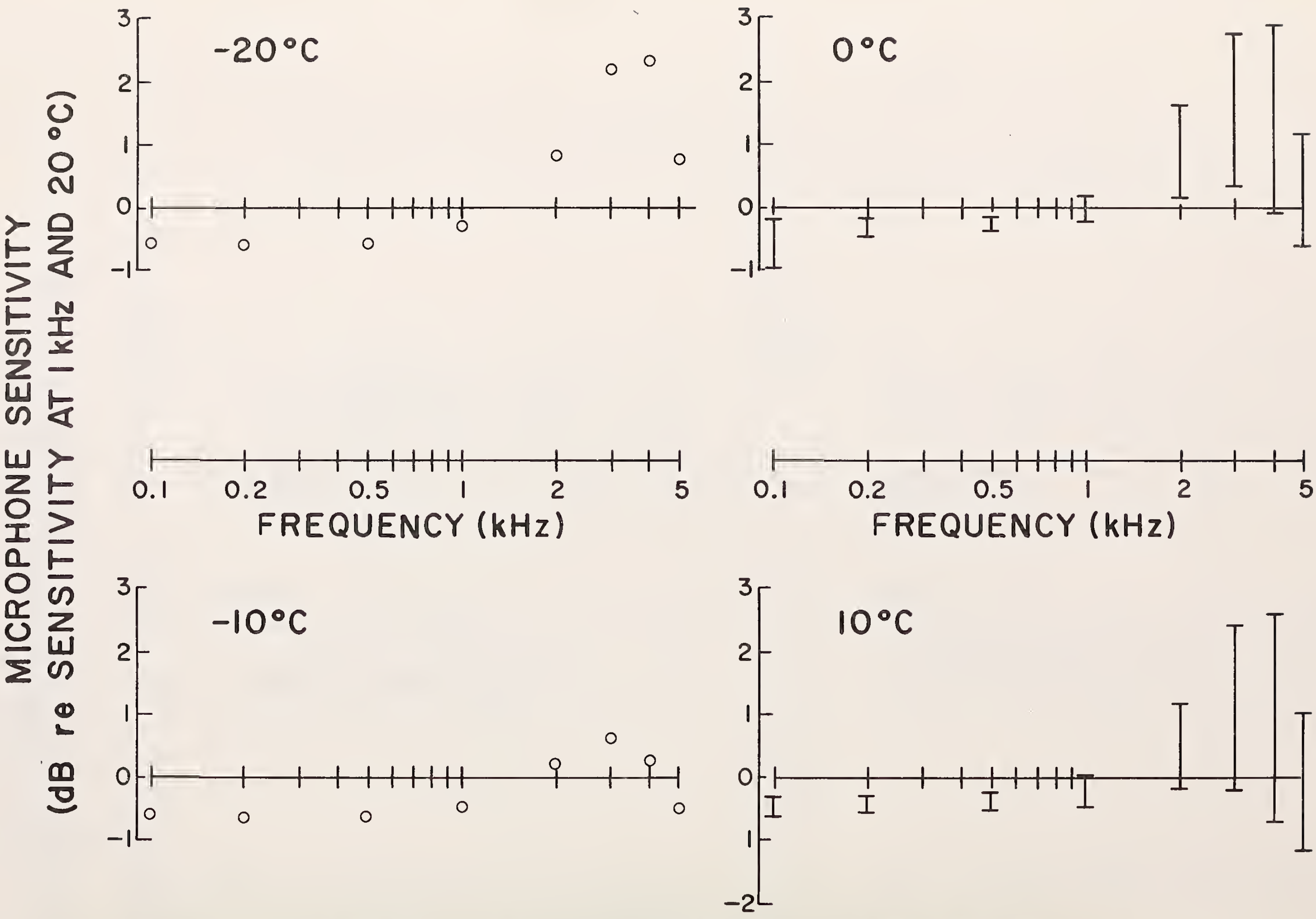

Figure 7A. Change in sensitivity of "1-inch" ceramic microphone No. 1 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

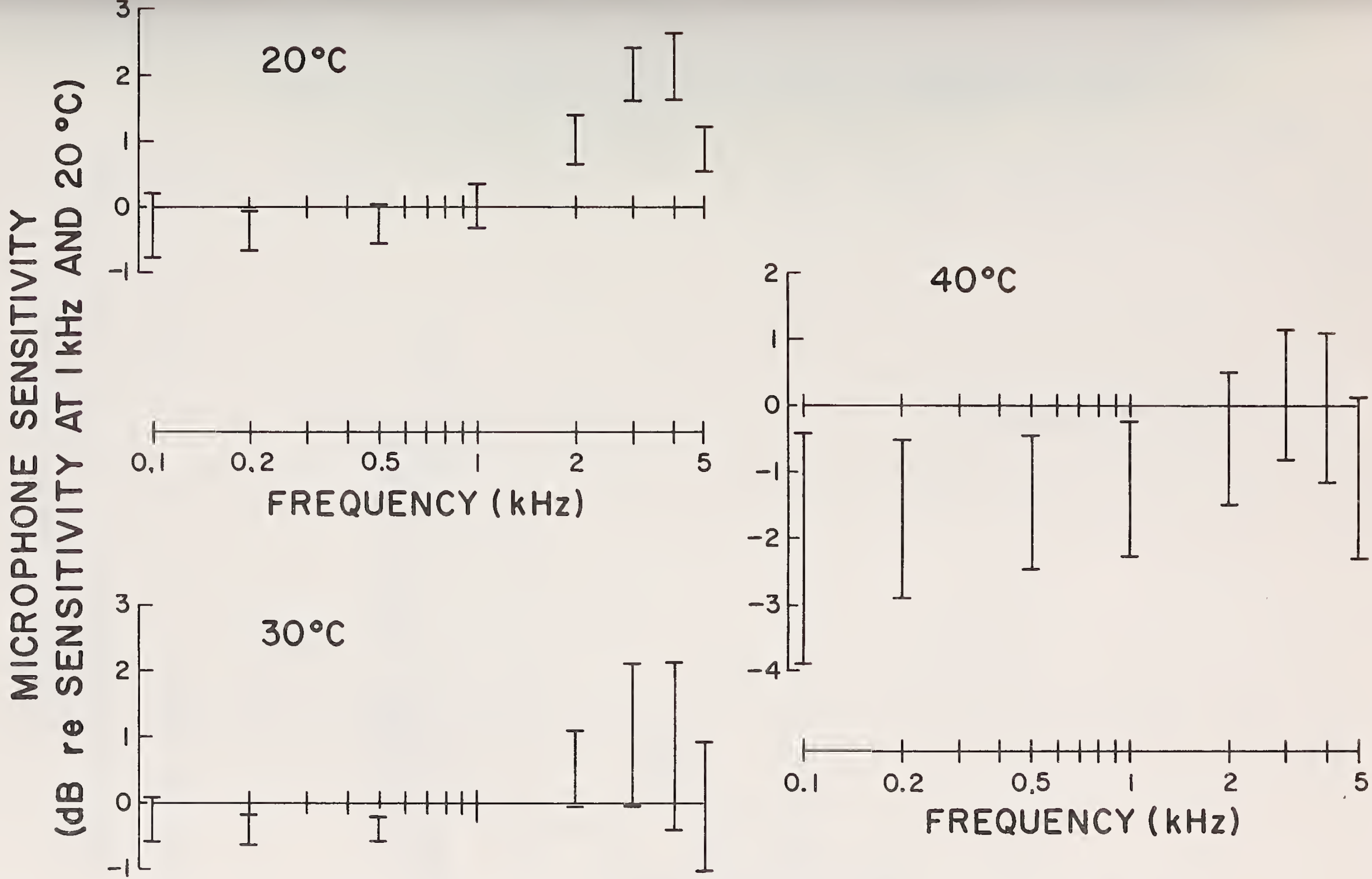

FIGURE 7B. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE NO. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

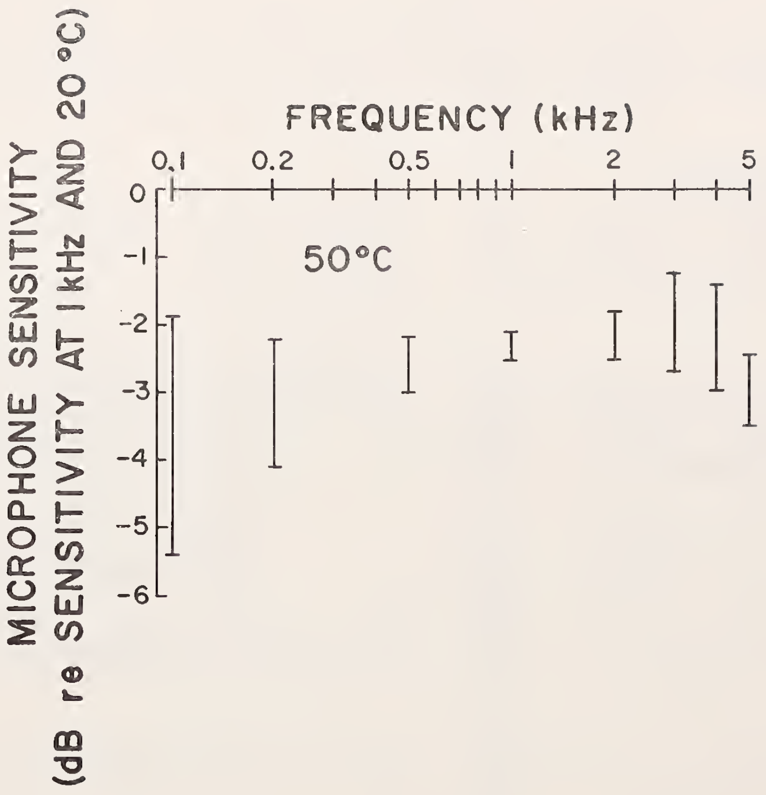

FIGURE 7C. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE No. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

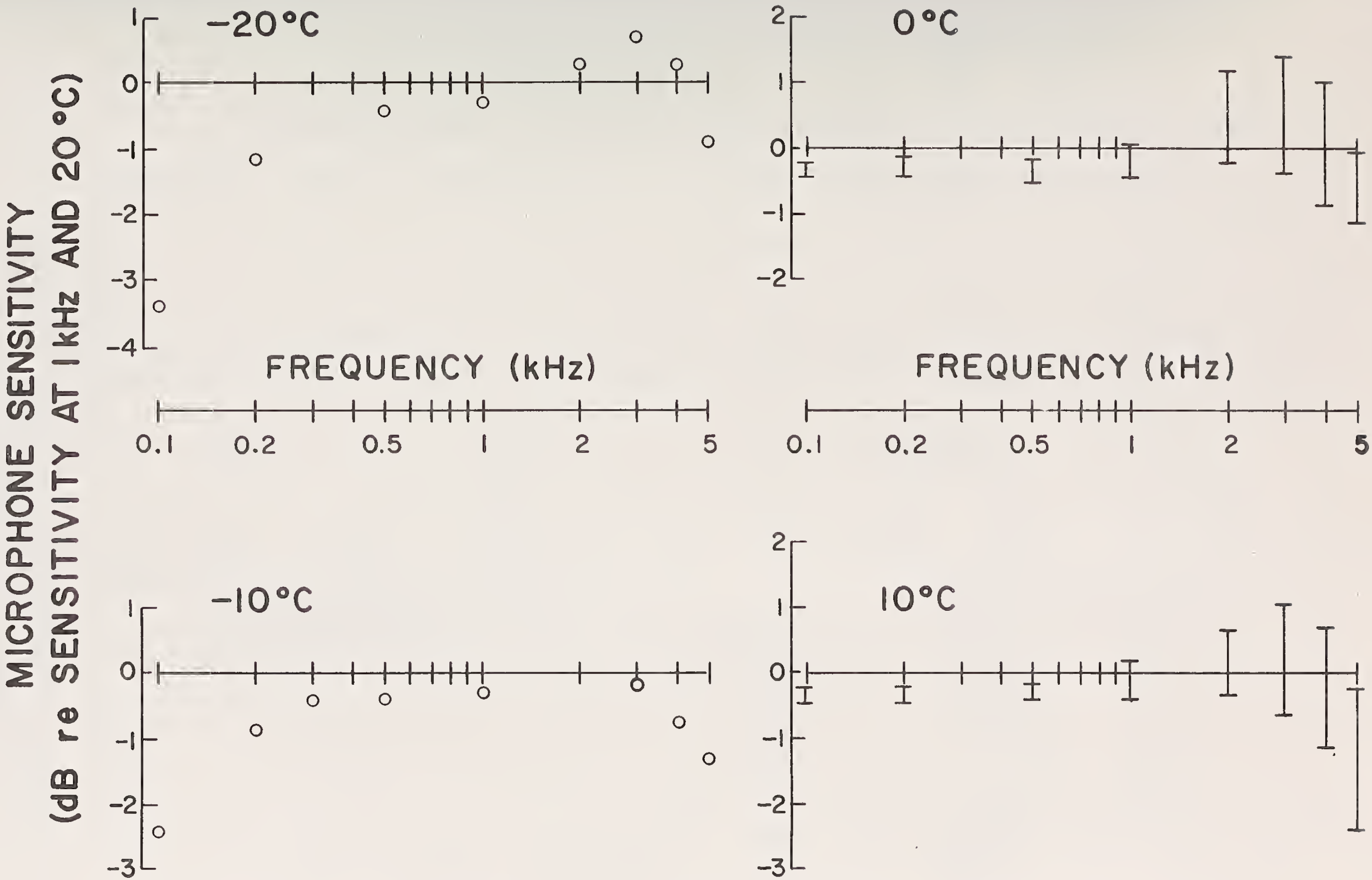

FIGURE 8A. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE NO. 2 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

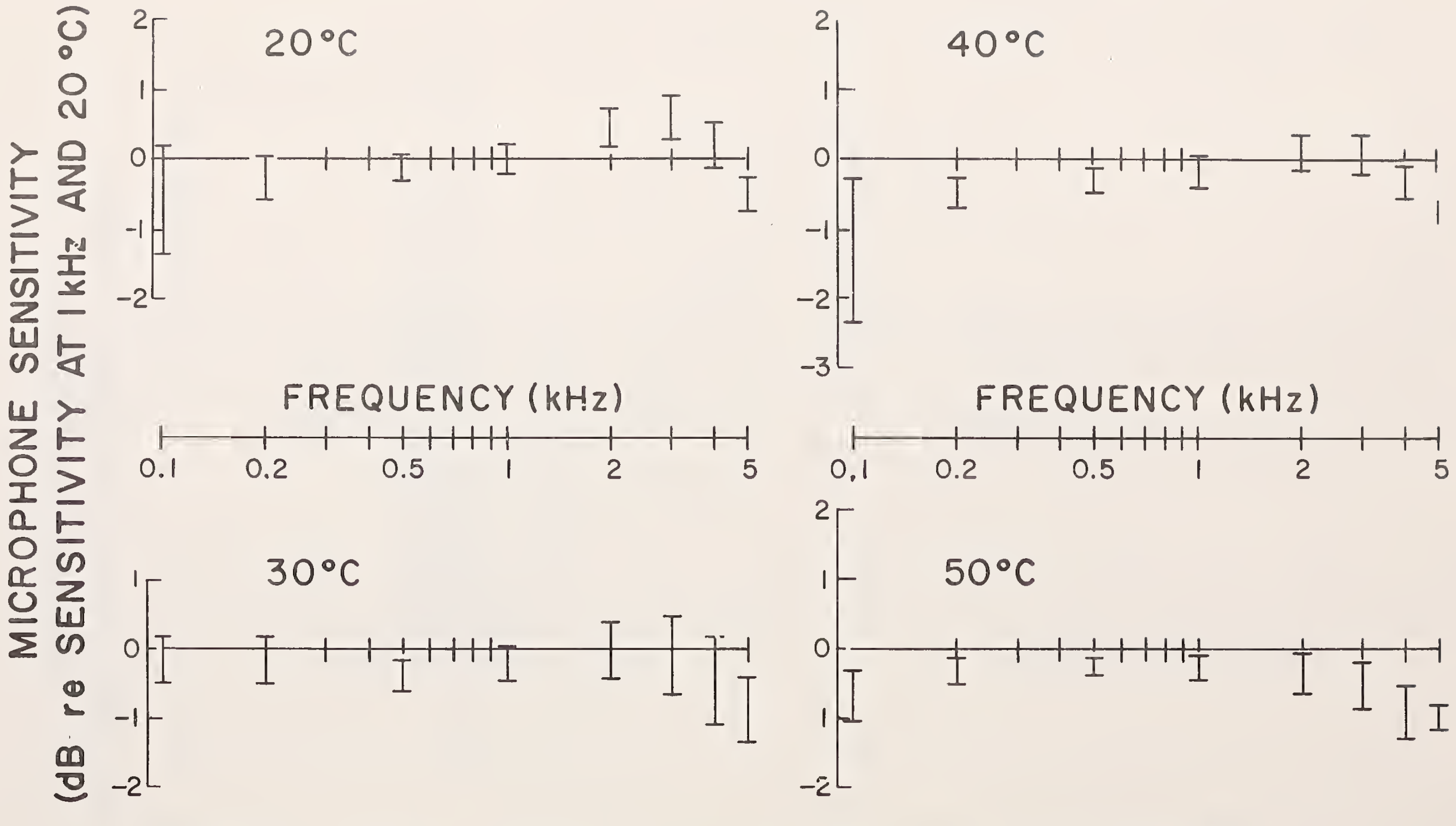

FIGURE 8B. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE NO. 2 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

TABLE 1

Long-Term Stability of "1-inch" Condenser Microphones at 20 °C and 44% RH

	Change in Sensitivity (dB re value on May 21, 1975)		
Frequency (Hz)	June 17, 1975	July 22, 1975	September 9, 1975
	Cartridge #1		
100	0.17	-0.11	-0.04
200	0.07	-0.12	-0.09
500	0.04	-0.15	-0.09
1000	0.06	-0.12	-0.05
2000	0.07	-0.03	+0.01
3000	0.08	+0.11	+0.11
4000	0.08	+0.17	+0.19
5000	0.07	+0.21	+0.22
	Cartridge #2		
100	+0.18	+0.18	-0.11
200	+0.17	+0.12	-0.16
500	+0.18	+0.06	-0.15
1000	+0.12	+0.06	-0.12
2000	+0.01	+0.03	+0.01
3000	-0.09	+0.05	+0.13
4000	-0.15	+0.02	+0.18
5000	-0.17	+0.03	+0.26

TABLE 2

Long-term Stability of "1/2-inch" Electret Microphones at 20 °C and 44% RH

Frequency (Hz)	Change in Sensitivity (dB re value on May 21, 1975)	
	July 23, 1975	September 9, 1975
	Cartridge #1	
100	-1.22	+1.53
200	-0.51	+1.33
500	-0.30	+1.25
1000	-0.34	+1.24
2000	-0.34	+1.17
3000	-0.38	+1.05
4000	-0.40	+0.97
5000	-0.32	+0.93
	Cartridge #2	
100	+0.26	+2.47
200	-0.02	+1.26
500	-0.11	+0.88
1000	-0.12	+0.88
2000	-0.12	+0.88
3000	-0.14	+0.84
4000	-0.16	+0.70
5000	-0.17	+0.59

TABLE 3

Long-Term Stability of "1-inch" Ceramic Microphones at 20 °C and 44% RH

Frequency (Hz)	Change in Sensitivity (dB re value on May 21, 1975) July 23, 1975	 September 9, 1975
	Cartridge #1	
100	-1.51	0.19
200	-1.47	0.04
500	-1.44	0.04
1000	-1.45	0.04
2000	-1.40	0.31
3000	-1.40	0.81
4000	-1.56	1.16
5000	-3.90	0.70
	Cartridge #2	
100	0.23	0.73
200	0.24	0.12
500	0.26	0.00
1000	0.30	0.05
2000	0.49	0.57
3000	0.78	1.08
4000	0.52	1.25
5000	0.07	0.36

2.1.4. Conclusions

From the data presented the following conclusions are reached:

1. The back-vented condenser microphones with a dehumidifier were largely insensitive to relative humidity.

2. At frequencies far below the condenser microphone's resonance frequency the temperature coefficient was extremely small (∿ ± 0.005 dB/°C).

3. Condenser microphones having a large amount of viscous damping could have a greatly increased (by a factor of 4) temperature coefficient in the vicinity of the microphone's resonance frequency.

4. The electret microphones which were tested exhibited short-term sensitivity instabilities of the order of ± 0.5 dB. The ceramic microphones examined showed short-term instabilities of the order of ± 1 dB or larger, at some frequencies. The magnitudes of these instabilities made it impossible to determine the changes in sensitivity as functions of temperature or relative humidity.

5. The condenser microphones exhibited long-term instabilities (i.e., over a period of about sixteen weeks) of the order of ± 0.2 dB. The electret and ceramic microphones showed long-term instabilities of up to ± 1.5 dB, with larger values at a few frequencies.

From the data which were taken, it is not possible to predict with assurance what uncertainties would occur if the ceramic and electret microphones were used for outdoor noise measurements. It seems reasonable, however, to assume that if significant changes in temperature and relative humidity occur between system calibrations, then the uncertainties in the measured sound levels could be at least of the magnitude of the short-term instabilities already mentioned. Furthermore, in actual sound measuring systems, changes in temperature and relative humidity could affect the electronics thus introducing additional changes in overall system sensitivity.

2.1.5. References

1. G. M. Sessler and J. E. West, "Electret Transducers: A Review," J. Acoust. Soc. Amer. 53, 1589-1600 (1973).

2. L. L. Beranek, Ed., Noise and Vibration Control (McGraw-Hill Book Co., New York, 1971), pp. 48-49.

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5. A.P.G. Peterson and E. E. Gross, Jr., Handbook of Noise Measurement, 7th Edition (General Radio Co., Concord, Mass., 1972), pp. 172-173.

6. "Method for the Calibration of Microphones," S1.10-1966, American National Standards Institute, New York, N. Y.

7. R. K. Cook, "Measurement of Electromotive Force of a Microphone," J. Acoust. Soc. Amer. 19, 503 (1947).

2.2. Static Pressure Effects on the Output Sound Level of Microphone Calibrators

A microphone calibrator consists of a transducer that drives a piston or a diaphragm inside a small cavity to generate a known sound pressure level at a fixed frequency. The microphone is inserted into this cavity. The calibrator's transducer may be electrodynamic, mechanical, piezoelectric, magnetostrictive, or some other type. From the known pressure generated by the calibrator and the measured output voltage of the microphone, the microphone sensitivity, defined as the ratio of the microphone output voltage to the input sound pressure, is determined.

The output sound pressure level of the calibrators changes with changes in the static (barometric) pressure. This effect on the sound pressure level output of a calibrator as a function of static pressure is most easily demonstrated if one considers a constant (volume) displacement of a piston in a cavity. For an ideal gas under adiabatic conditions it can be shown that

$$\frac{\Delta P}{P_o} = -\gamma \frac{\Delta V}{V_o} \qquad (1)$$

where P_o is the static pressure, V_o is the undisturbed volume, ΔP is the acoustic pressure resulting, in this instance, from the change in volume ΔV, the volume displacement of the piston. The quantity γ is the ratio of specific heats of air at constant pressure and constant volume. The acoustic pressure is, therefore

$$\Delta P = P_{acoustic} = -\gamma P_o \frac{\Delta V}{V_o} \qquad (2)$$

It is apparent that a calibrator with a constant displacement transducer generates an acoustic pressure proportional to the static pressure of the environment.

Microphone calibrators that do not use transducers of the constant displacement type are not easily described analytically and their output sound pressure level versus static pressure must be determined experimentally. (Each manufacturer of microphone calibrators provides a calibration graph of the calibrator's sound pressure level versus static pressure.)

Calibrators from several manufacturers were checked for their sound pressure level output as a function of static pressure. The experimental setup for measuring the effect of static pressure on the sound pressure level of the calibrator and on the microphone is shown in Fig. 9. First, the change in the (condenser) microphone sensitivity as a function of static pressure is measured with an electrostatic actuator by placing the microphone and the calibrator inside a bell jar. The microphone output voltage is then recorded as a function of the static pressure. The change in the calibrator's sound pressure level, Δ_{SPL}, is determined from

$$\Delta_{SPL} = 20 \log_{10}[(R/R_o)/(S/S_o)] \quad \text{dB} \qquad (3)$$

where R/R_o and S/S_o are the ratios of the microphone output voltages and sensitivities, respectively, at any given static pressure to the output voltage and sensitivity at a reference static pressure.

Figure 10-14 show both the measured Δ_{SPL} and the Δ_{SPL} specified by the manufacturer as a function of pressure. Figure 15 compares the measured Δ_{SPL} to that predicted by Eq. (1), since this particular calibrator uses a constant displacement transducer. The vertical bars on the experimentally determined curve shows the spread in the measurement when repeated several times.

It is apparent from these results that certain calibrators deviated considerably from the manufacturer's specification, whereas others followed the predictions or specifications very closely.

2.3. Temperature Effects on the Electrical Sensitivity of Type II Sound Level Meters

Tests were conducted on several sound level meters in an environmental chamber to determine the change in the electrical sensitivity of the sound level meters as a function of temperature. The sound level meter was placed in an environmental chamber wherein a constant relative humidity of 70% was maintained. The sound level meter's microphone was removed and an electrical signal at 1000 Hz was inserted at the same location that the microphone's output voltage normally would be found. The sound level meter was left at the desired temperature for one hour, during which time thermal equilibrium was reached. The amplitude of the input signal was kept constant for each temperature considered. The output voltage of the sound

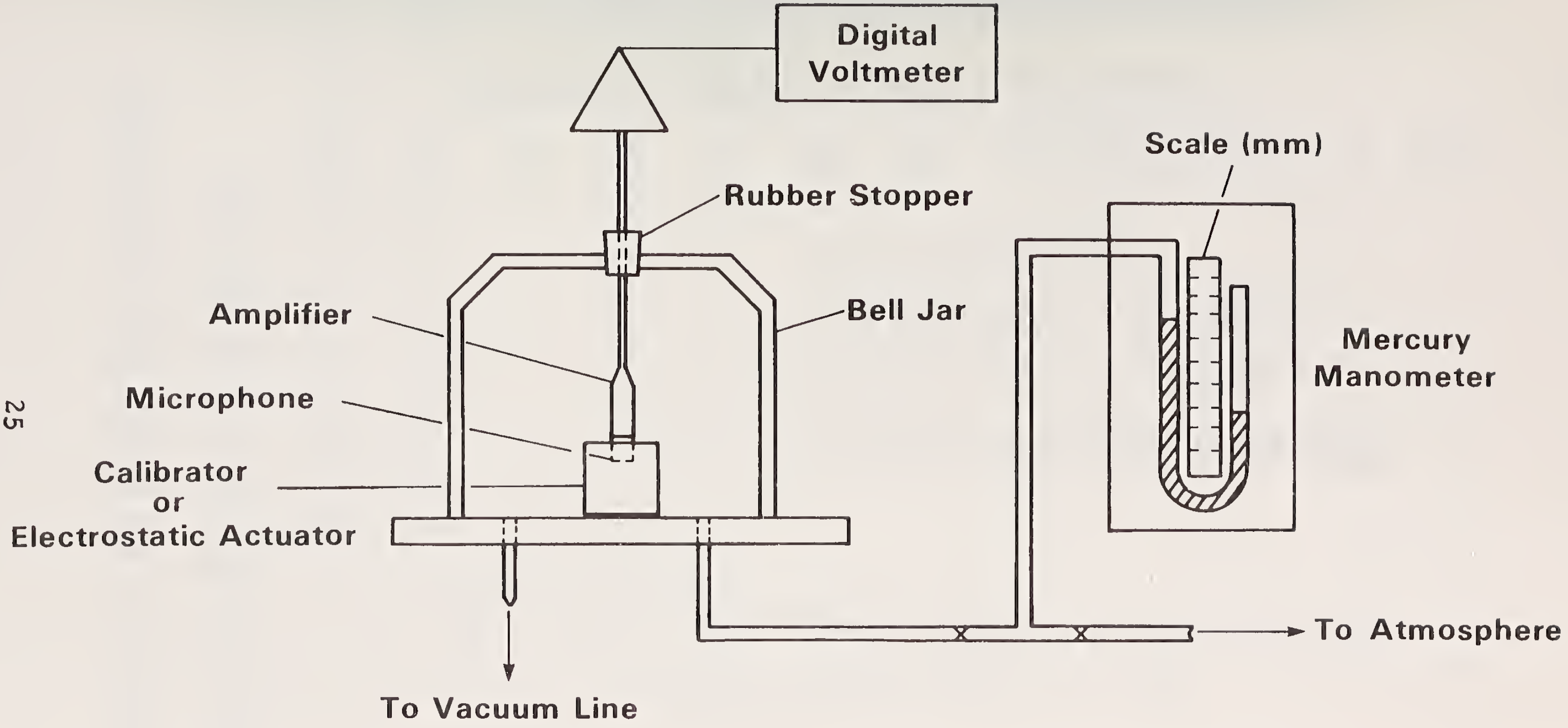

FIGURE 9. EXPERIMENTAL SETUP TO DETERMINE THE CHANGE IN CALIBRATOR LEVEL AS A FUNCTION OF STATIC PRESSURE.

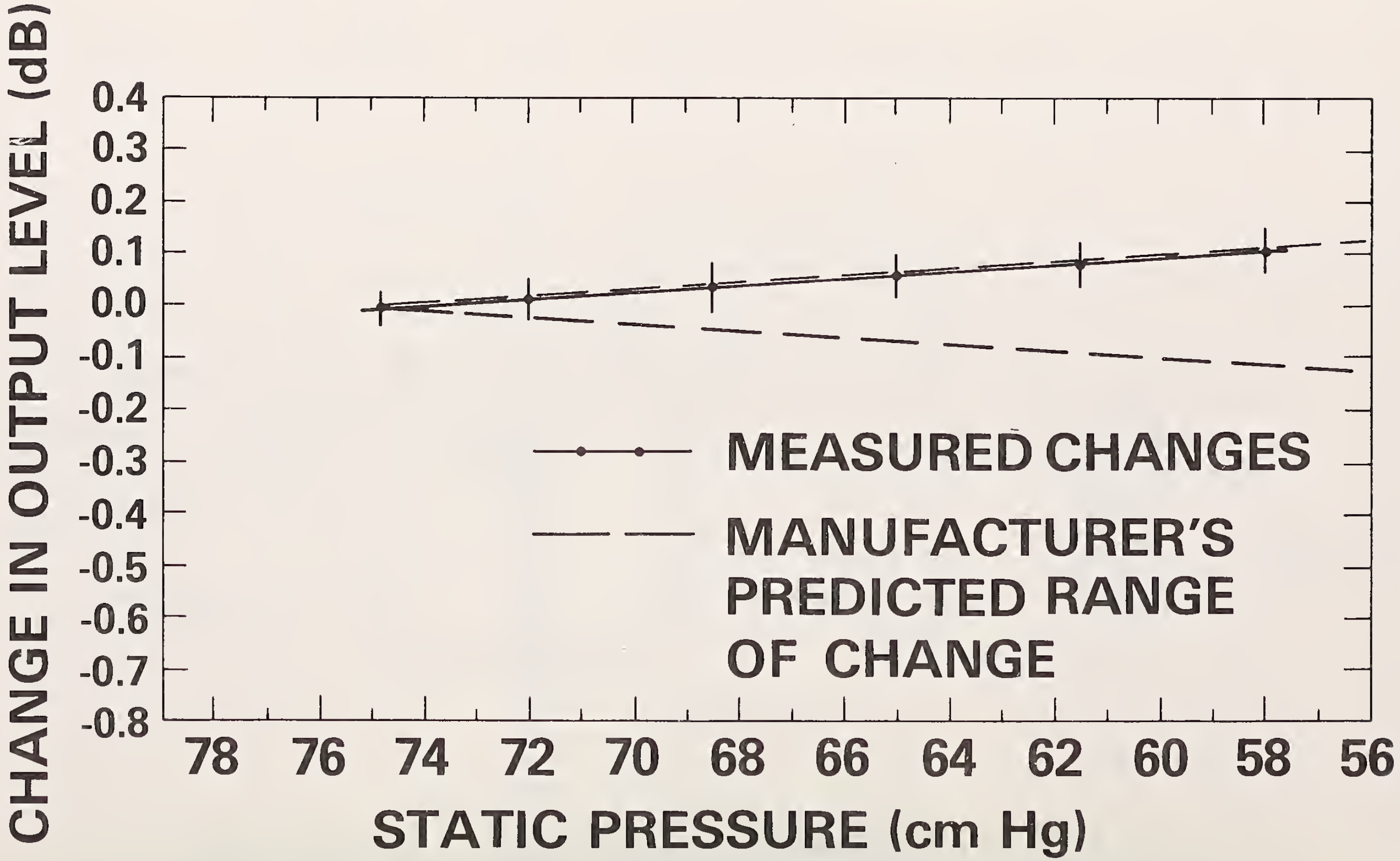

Figure 10. Change in the sound pressure level of calibrator A as a function of static pressure.

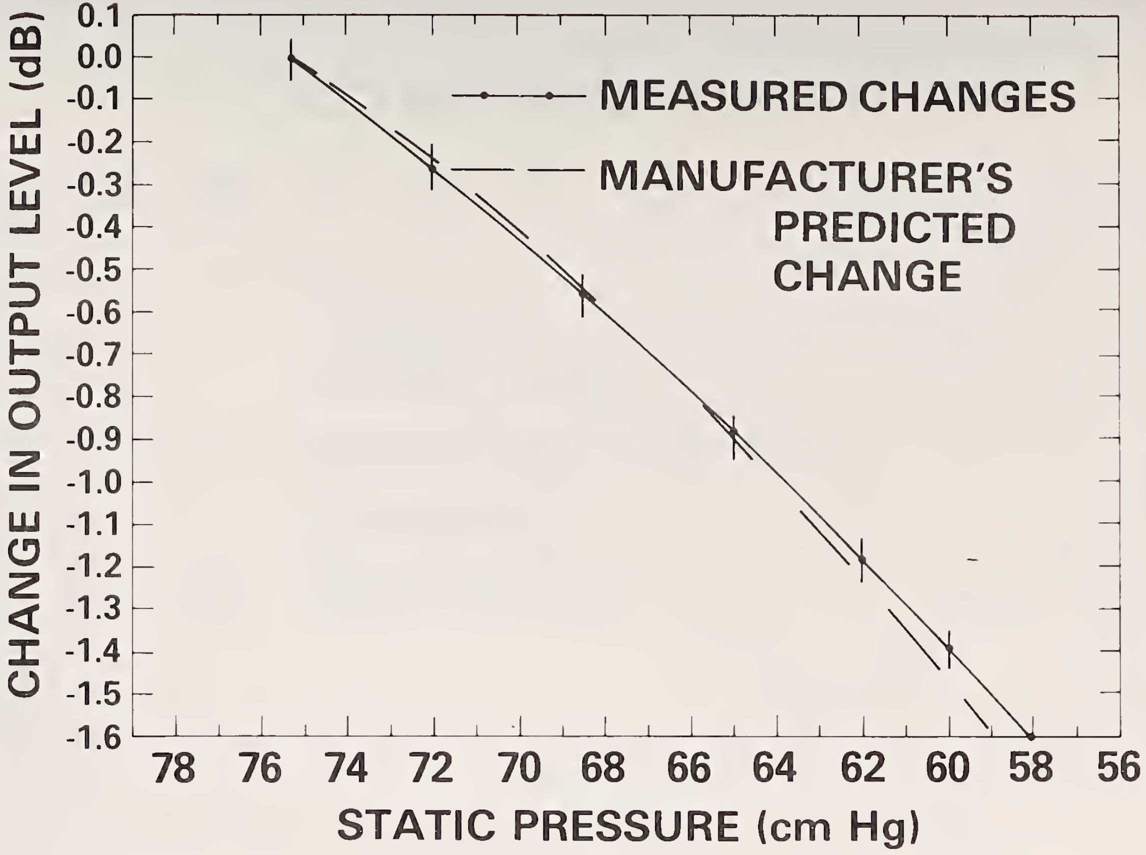

Figure 11. Change in the sound pressure level of calibrator B as a function of static pressure.

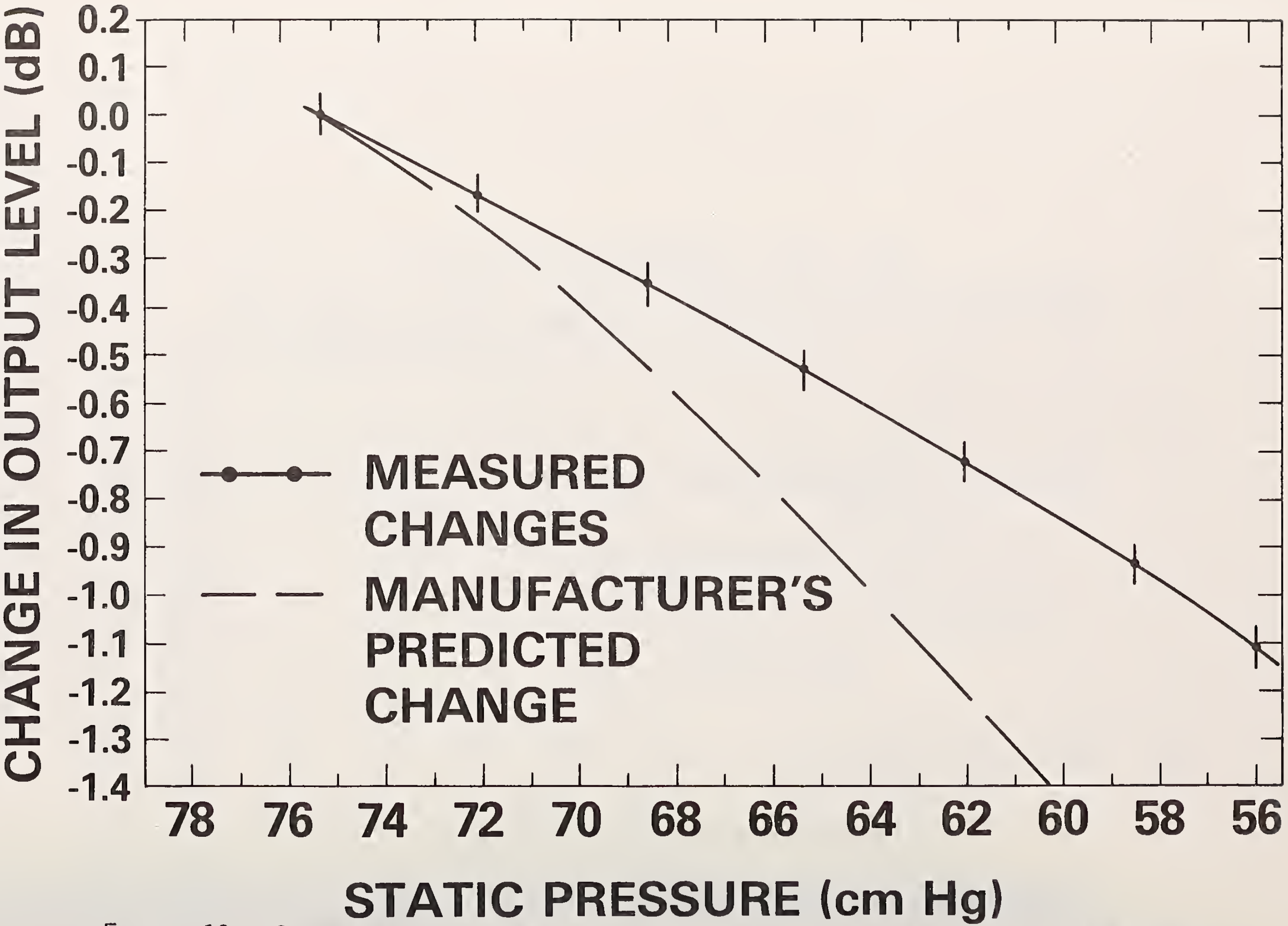

Figure 12. Change in the sound pressure level of calibrator C as a function of static pressure.

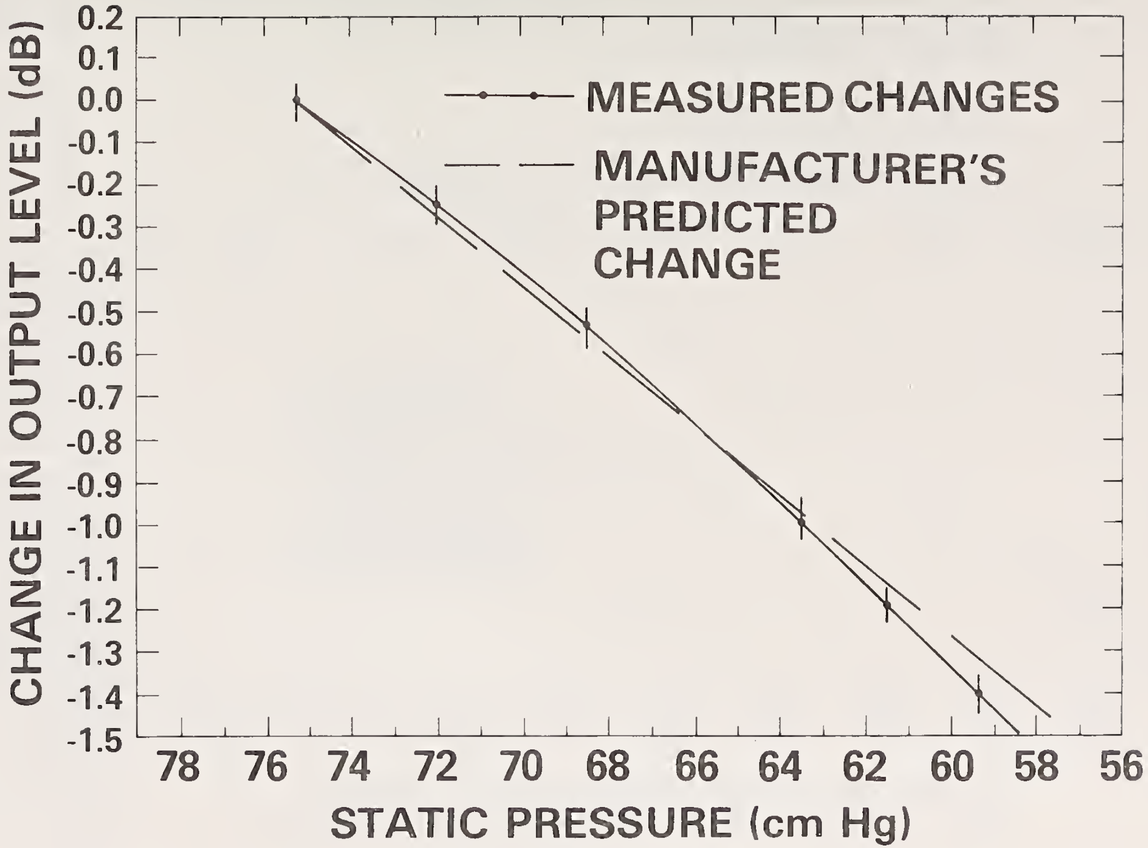

Figure 13. Change in the sound pressure level of Calibrator D as a function of static pressure.

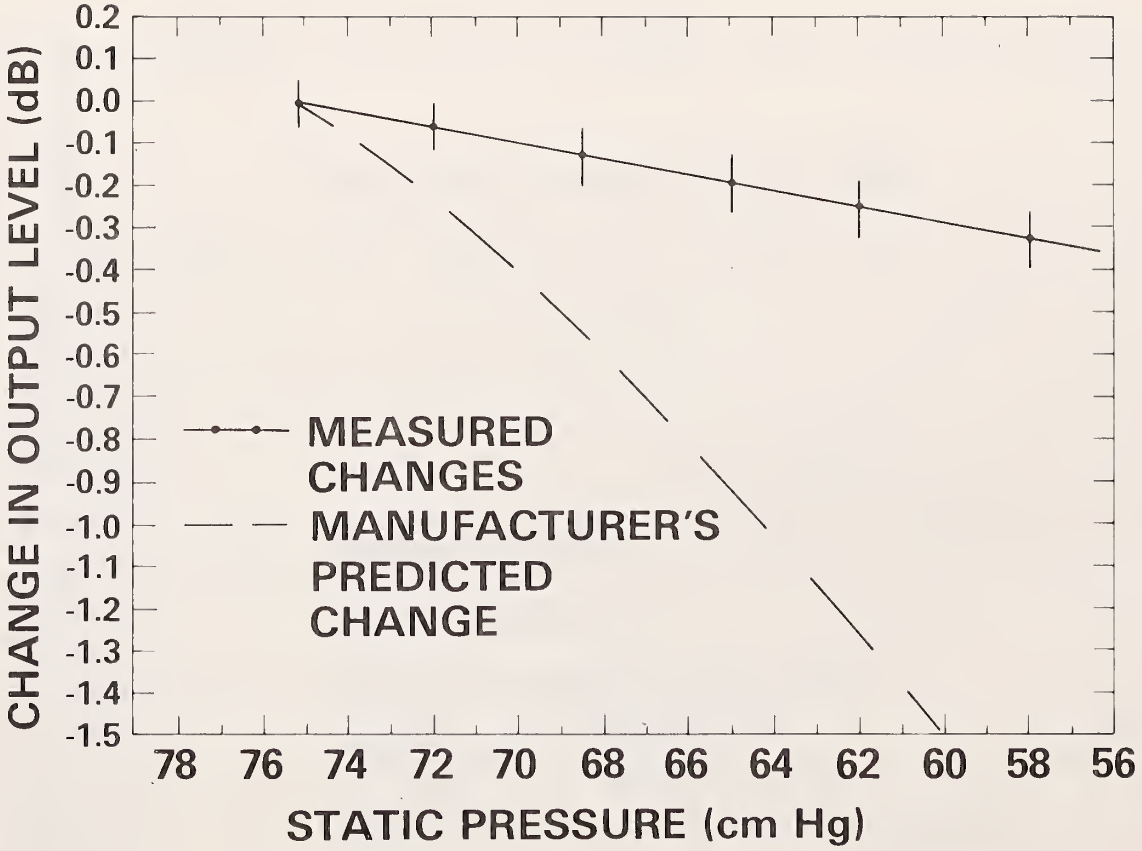

Figure 14. Change in the sound pressure level of calibrator E as a function of static pressure.

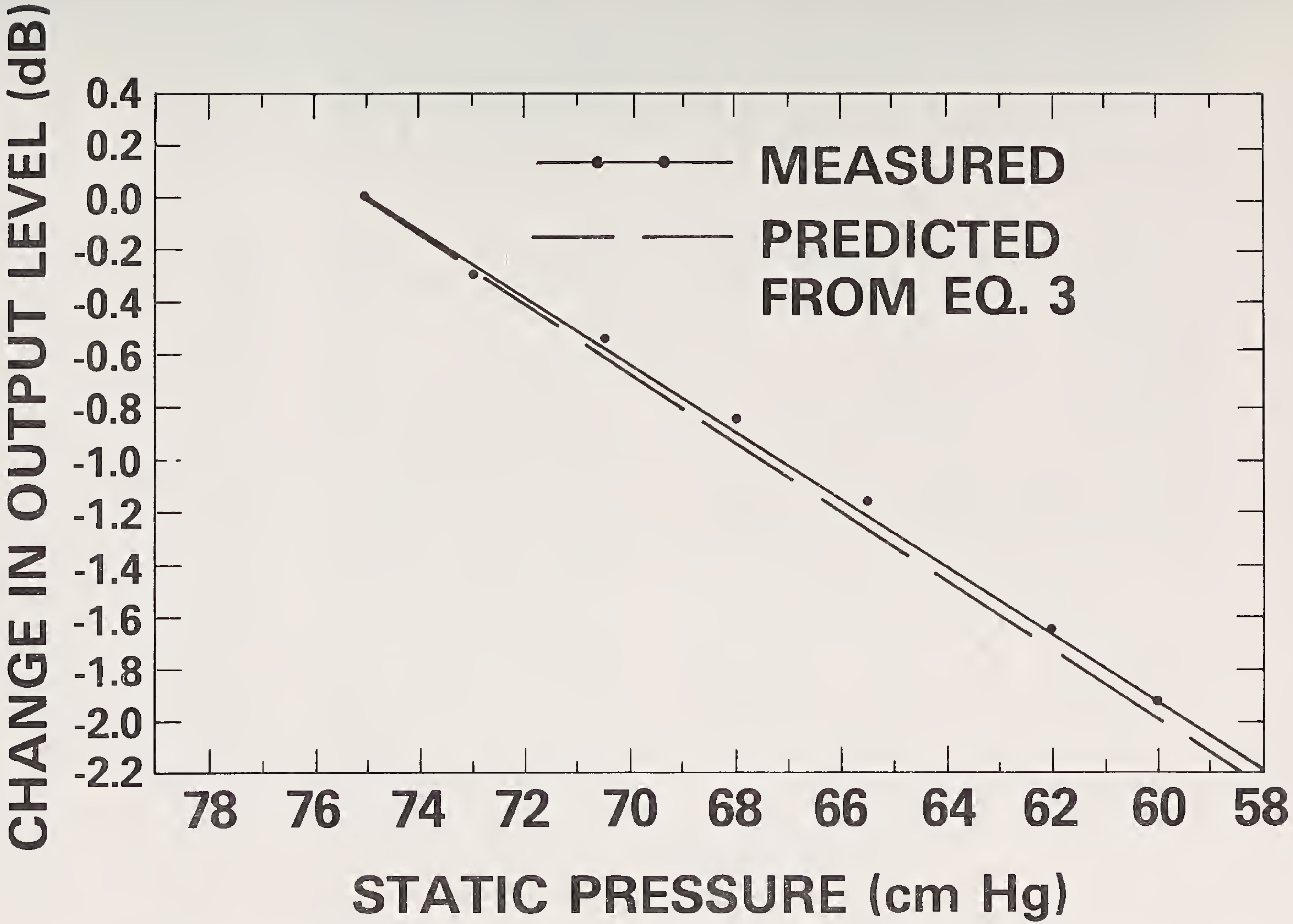

Figure 15. Change in the sound pressure level of calibrator F as a function of static pressure.

level meter at each temperature was compared to the sound level meter's output voltage at 20 °C. The results* are shown in Fig. 16. In addition, the entire A-weighting curve was checked from 100 to 10 000 Hz at each temperature. However, since the shape of this curve remained virtually constant over the range of temperatures considered only the change in level at 1000 Hz is shown.

It is seen that when the sound level meter is used in a changing temperature environment one can often expect relatively rapid changes in the sound level meter's sensitivity. However, when the sound level meter is used in a uniform temperature environment these electrical sensitivity changes due to temperature can be accounted for with the use of a sound level calibrator just before a measurement.

2.4. Attenuation of Aerodynamically Generated Noise by Foam Windscreens**

Various configurations of microphone windscreens are used to reduce wind-generated noise, which allow the acoustic signal to be measured without excessive attenuation while keeping the turbulent eddies away from the microphone sensing element. Since the direction of the wind usually is not known *a priori* and it is often desired that the directional characteristics of the microphone not be changed, a spherical-shaped windscreen is most commonly used. Previous investigators[1-3] frequently have used a light wire framework covered with cloth. A reduction of wind-generated noise by 20 dB has been reported using a cloth screen 12 cm in diameter.

Recently spheres of open-cell polyurethane foam have been used as windscreens. The spheres are solid except for a cylindrical hole in which the microphone is placed. These windscreens have the advantage of not degrading the directional characteristics of the microphone over most of the frequency range and are inexpensive compared to cloth windscreens. However, no specific information regarding the effects of sphere size and pore size of these open-celled materials appears to be available in the literature. Consequently, an investigation was conducted to determine, as a function of frequency for four different pore sizes and various diameters of spheres, the amount of reduction in wind-generated noise and the amount of acoustic attenuation of the signal.

Since available wind tunnels are too noisy for windscreen testing, the measurements of wind-generated noise were made by mounting the microphone and windscreen combination at the end of a rotating arm in a large (452 m^3) anechoic room. An aerodynamically-smooth radial arm of 1.57 m radius was mounted on a variable-speed turntable. The table had slip rings to

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*The four different manufacturers' sound level meters are denoted SLM-U, SLM-V, SLM-W, and SLM-Y. This denotation, where appropriate, is employed throughout the report.

**Based on material previously reported in a paper entitled "An Experimental Investigation of Foam Windscreens" presented at INTER-NOISE 73, Copenhagen, Denmark (August, 1973).

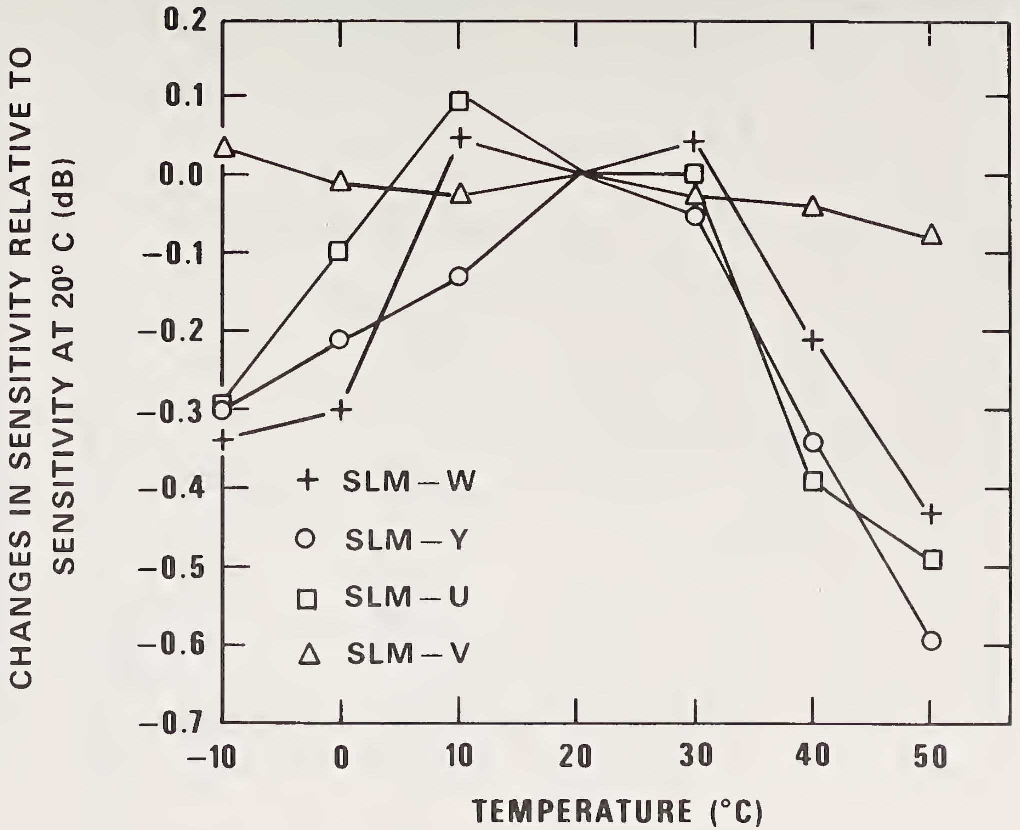

FIGURE 16. CHANGE IN THE ELECTRICAL SENSITIVITY OF FOUR DIFFERENT SOUND LEVEL METERS AT 1000 Hz AS A FUNCTION OF TEMPERATURE.

bring the microphone signal out to the measuring instrumentation. The microphone was mounted at the top of a 0.75 m vertical support (also aerodynamically smooth) at the end of the rotating arm so that the air flow passed across the microphone diaphragm at grazing incidence. The turntable was rotated at angular speeds corresponding to microphone speeds of 24, 32, and 40 km/hr. For the measurements reported here a "1-inch" condenser microphone was used. The output of the microphone was analyzed in 1/3-octave bands.

The results of the measurements of wind-generated noise are shown in Figs. 17 and 18. Figure 17 shows the 1/3-octave band sound pressure levels for 10-cm, 17.8-cm, and 25.4-cm diameter windscreens, fabricated from foam having a nominal linear pore density of 800 pores/m, subjected to a wind speed of 40 km/hr. A-weighted sound pressure levels are shown in Fig. 18 where these levels, corresponding to a speed of 40 km/hr, are plotted as a function of windscreen diameter for four different linear pore densities.

In order to measure the sound attenuation due to the windscreens, the insertion losses under random incidence conditions were measured in a large (425 m^3) reverberation room. With the room excited with broad-band pink noise, the signal from the condenser microphone was measured in 1/3-octave bands with and without the various windscreens in place. Figure 19 shows the attenuation (insertion losses) as a function of frequency for the different linear densities and sphere diameters tested.

As a result of this investigation it is recommended that (1) for maximum reduction of wind noise, where the main frequency of interest is less than 1 kHz, an 18-cm diameter windscreen with 1600 pores/m should be used, and (2) for other uses an 18-cm diameter windscreen with 800 pores/m should be used.

References

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2. J. C. Bleazey, "Experimental Determination of the Effectiveness of Microphone Wind Screens," J. of the Audio Eng. Soc. <u>9</u>, No. 1, 48-54 (1961).

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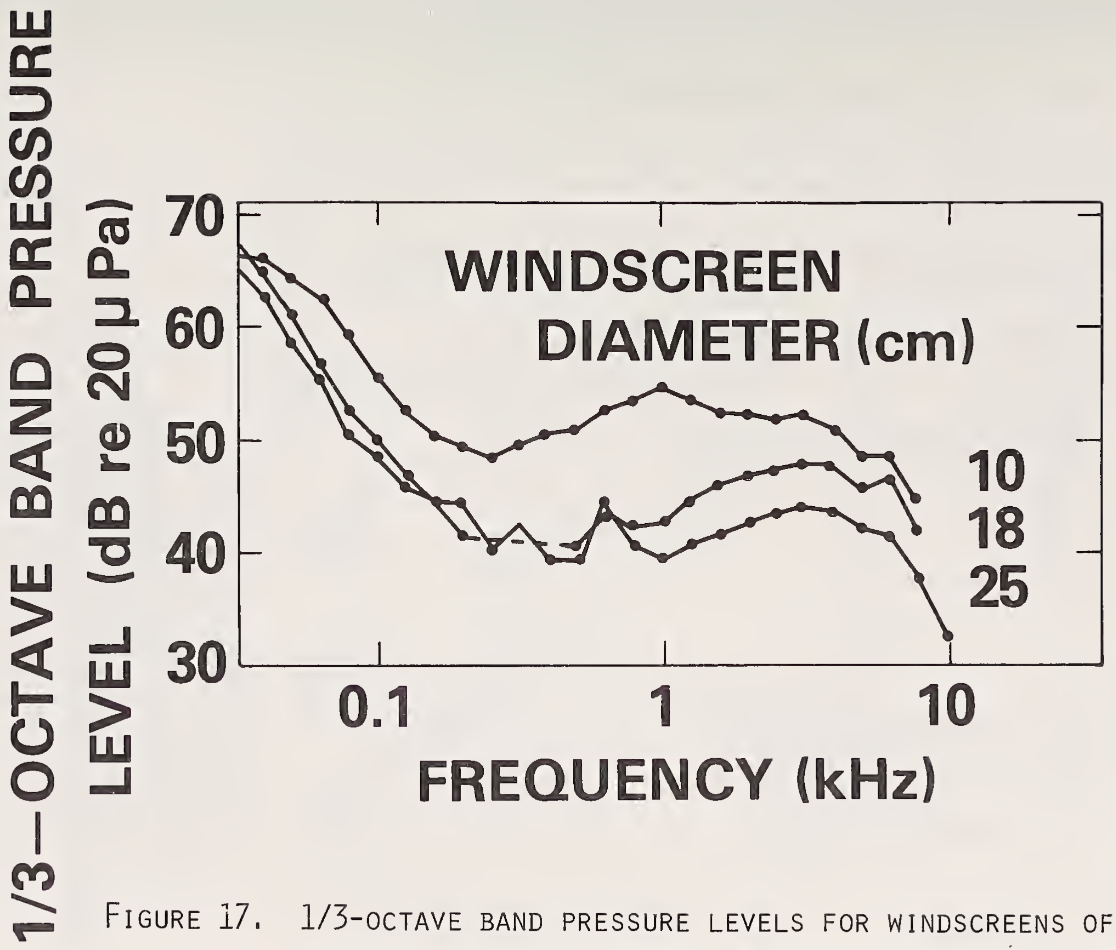


FIGURE 17. 1/3-OCTAVE BAND PRESSURE LEVELS FOR WINDSCREENS OF VARIOUS DIAMETERS HAVING A NOMINAL LINEAR PORE DENSITY OF 800 PORES/M AND SUBJECTED TO A WIND SPEED OF 40 KM/HR BLOWING ACROSS THE MICROPHONE GRID AT GRAZING INCIDENCE.

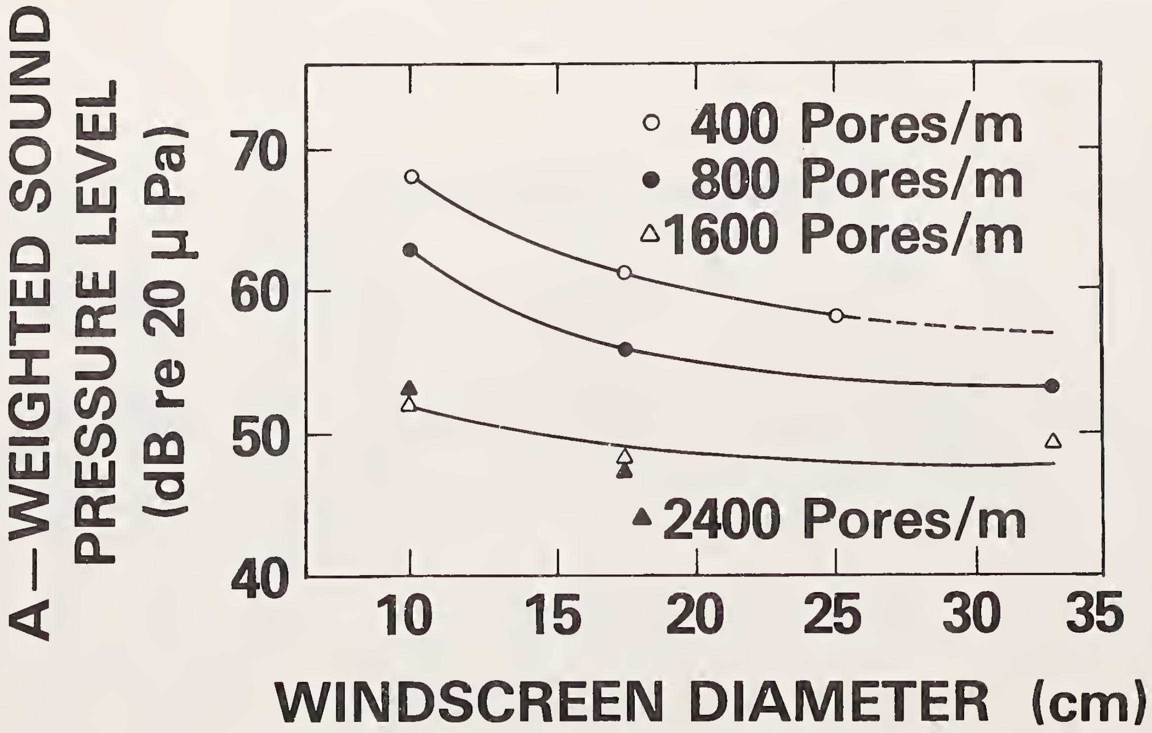
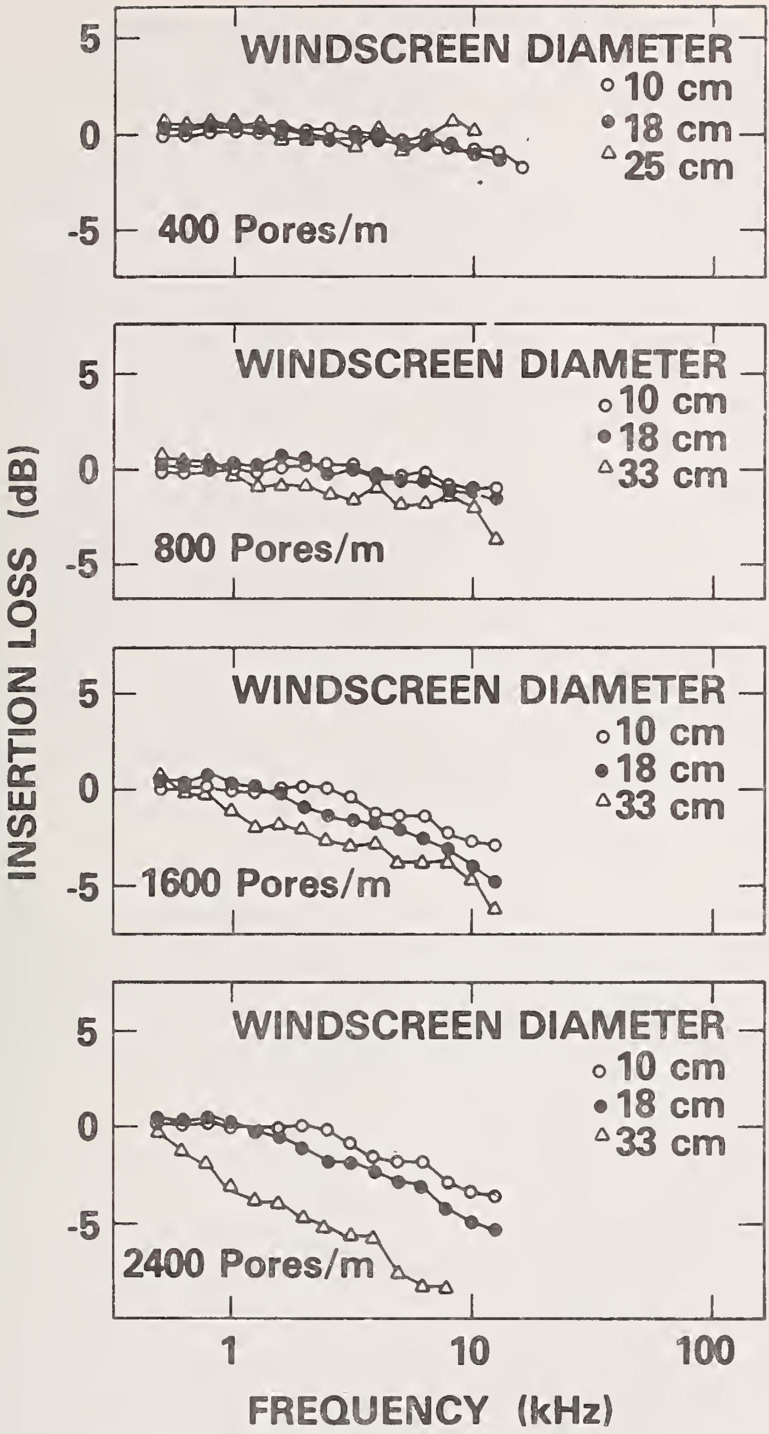


FIGURE 18. A-WEIGHTED SOUND LEVELS AS A FUNCTION OF WINDSCREEN DIAMETER WHEN WINDSCREEN HAS A 40 KM/HR WIND BLOWING ACROSS THE MICROPHONE GRID AT GRAZING INCIDENCE.



IGURE 19. RANDOM INCIDENCE INSERTION LOSS AS A FUNCTION OF FREQUENCY FOR WINDSCREENS OF VARIOUS DIAMETERS AND LINEAR PORE DENSITY.

3. EFFECTS OF THE PHYSICAL ENVIRONMENT

3.1. Free-Field Response of Type II Sound Level Meters

Sound level meters are often used in nonreverberant environments wherein their A-weighted frequency response as a function of the angle of incidence of sound can deviate markedly from the ideal response. The amount of deviation permitted is stipulated in the appropriate standards document.* To obtain an estimate of the actual deviation from the ideal A-weighted frequency response that one could encounter, the free-field frequency response for five angles of incidence of sound was measured on one Type II sound level meter from each of four manufacturers from 400 to 10 000 Hz in a large (452 m^3) anechoic room.

The deviations from the ideal A-weighted response were obtained in the following manner. A "1/2-inch" condenser microphone, which had a uniform frequency response at normal sound incidence over the frequency range of interest, was placed 68 cm from the loudspeaker while the second sound level meter was placed 233 cm away. Both the microphone and the sound level meter were oriented, with respect to each other, such that the axes perpendicular to the center of each microphone diaphragm were coincident. The sound level meter was suspended from the ceiling of the room by thin wires. The "1/2-inch" microphone was used in a feedback loop so that the output sound level of the loudspeaker was uniform within ± 1 dB over the frequency range. The interconnection of the instrumentation used to perfrom the experiment is shown in Fig. 20.

The results, retraced and slightly smoothed, are shown in Figs. 21-24. From these figures it is seen that the deviation from the ideal A-weighted response at frequencies below 1000 Hz is relatively small for most of the meters compared to the deviation above 1000 Hz where the diffraction of sound by the microphone and the sound level meter cause the deviations to be larger and, except for SLM-Y, to vary irregularly as a function of both angle of incidence and frequency.

3.2. Random Incidence Response of Type II Sound Level Meters

The A-weighted frequency response of sound level meters is specified only for a very specific acoustic environment; namely, a spatially homogeneous sound field.** This environment is very closely approximated in properly configured reverberations rooms, provided that sufficient spatial and temporal sampling is employed. All other specified acoustic and electrical characteristics of sound level meters are referred to the A-weighted response. Consequently, the actual deviation of the A-weighted response from its idealized response is an important indicator of a sound level meter's precision. Therefore, the actual deviations from the ideal

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*See, for example, American National Standard S1.4-1971, "Specification for Sound Level Meters," American National Standards Institute, New York.

**More commonly referred to as a diffuse or random incidence sound field.

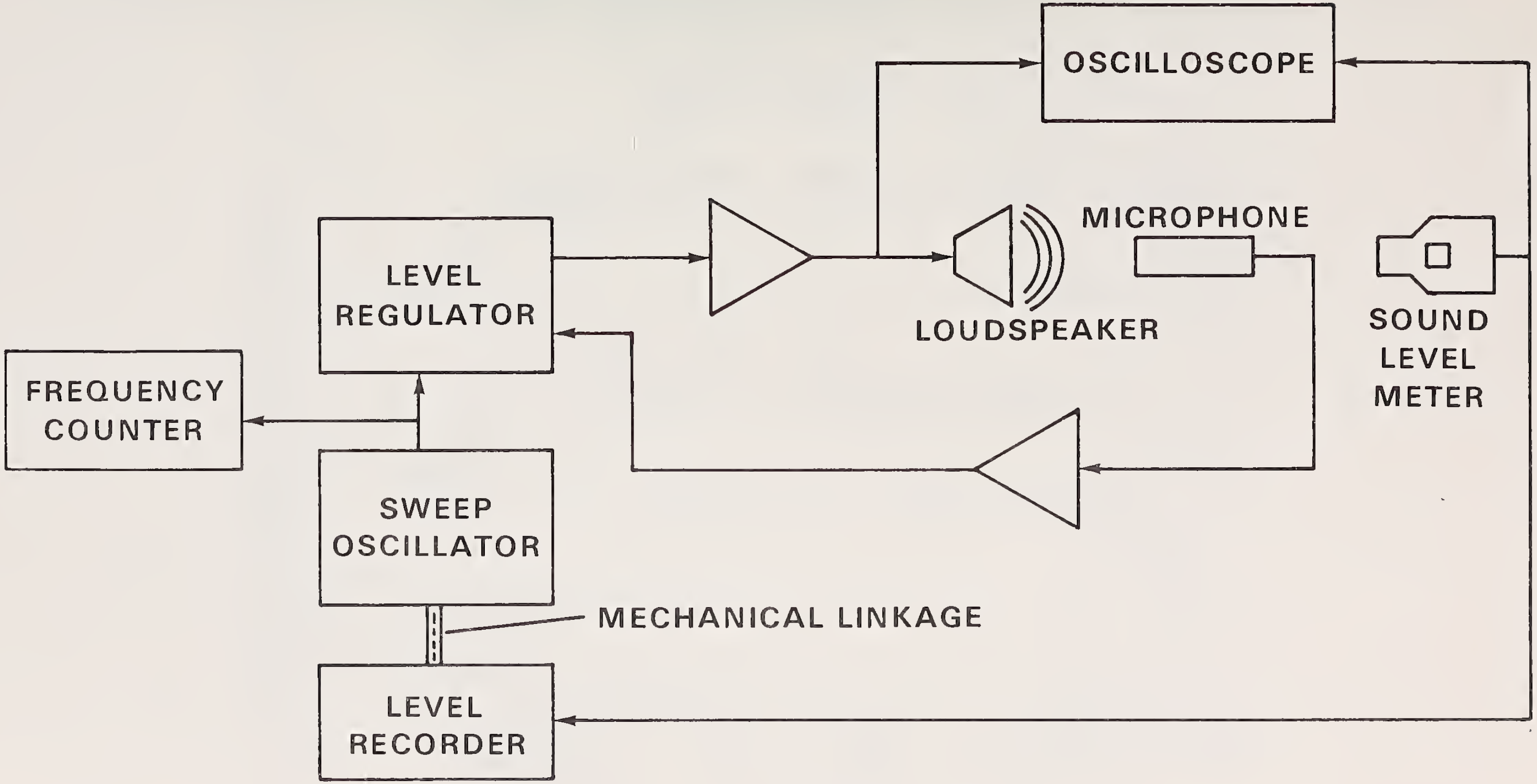

Figure 20. Schematic of the instrumentation used to determine the free-field response of sound level meters.

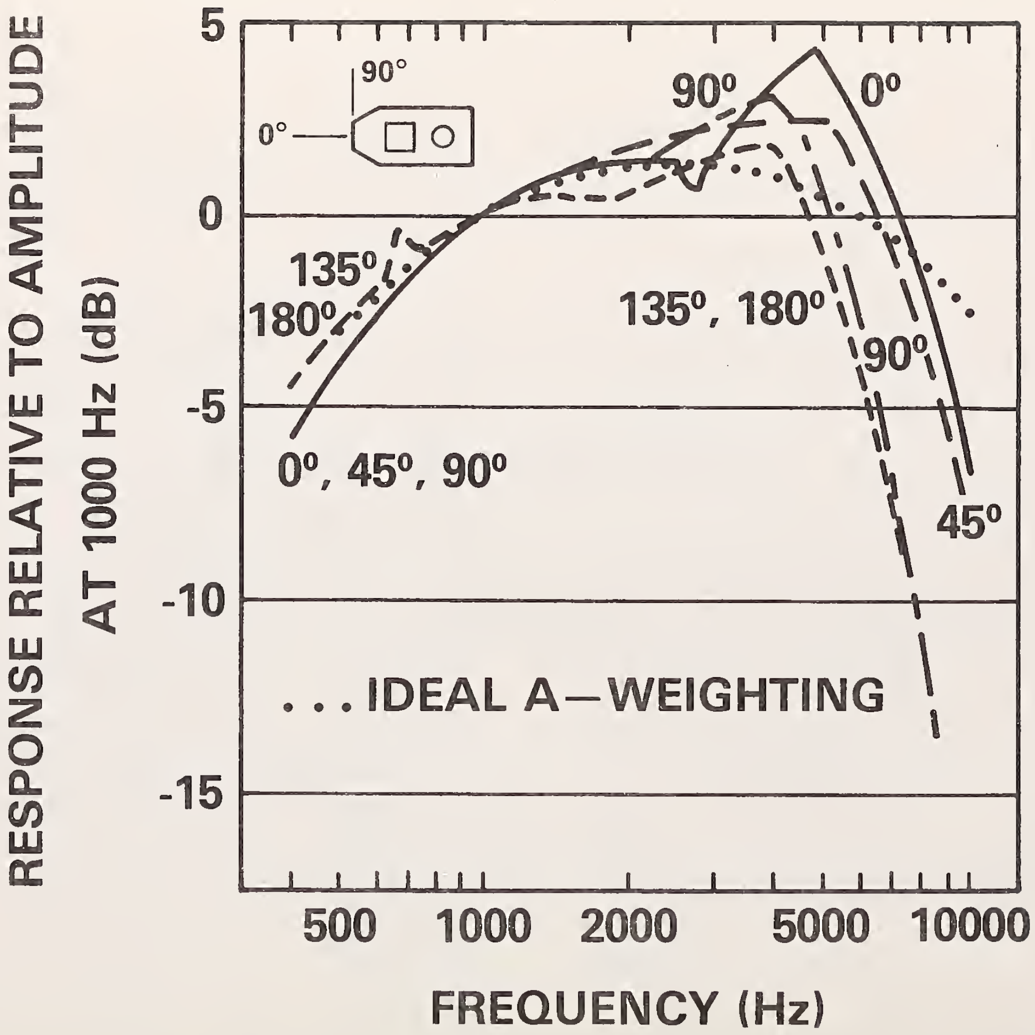

Figure 21. Free-field A-weighted response of SLM-U as a function of several angles of incidence.

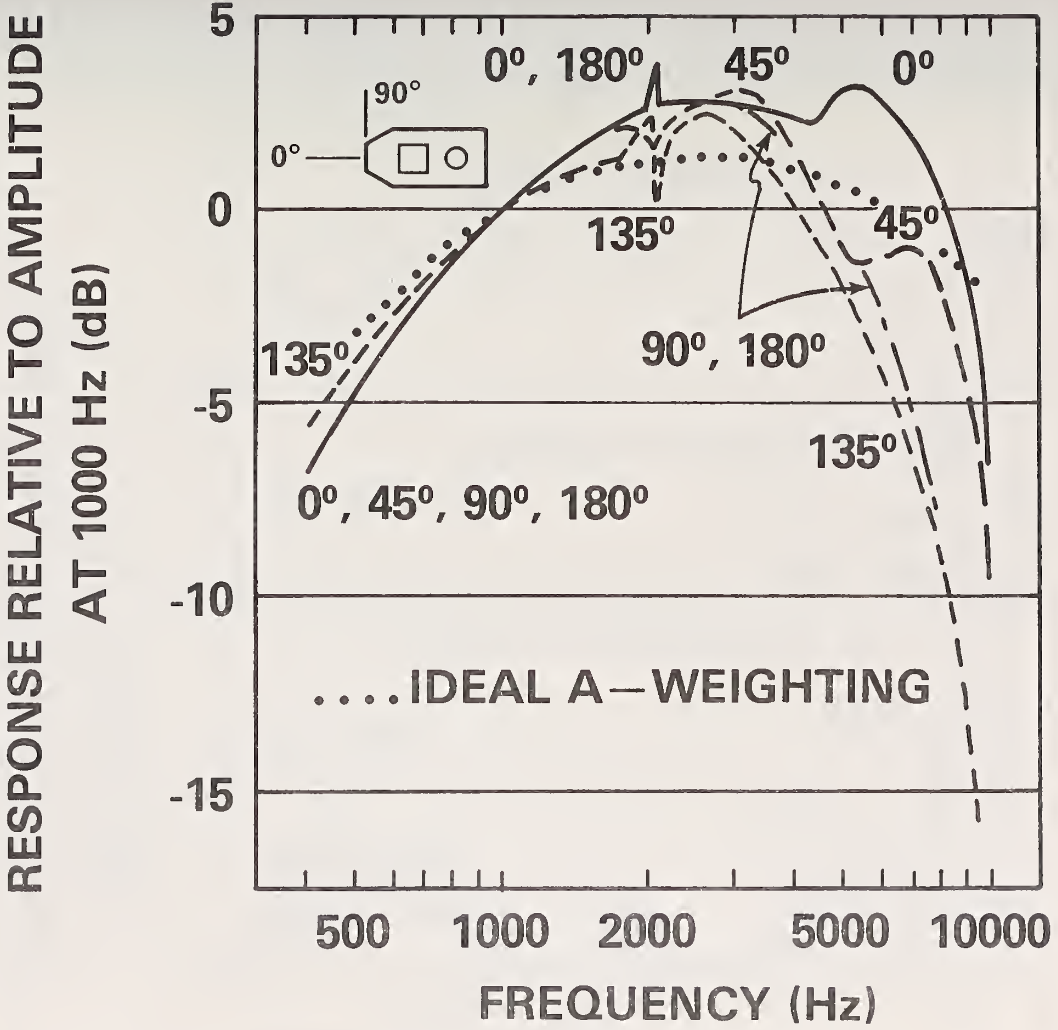

FIGURE 22. FREE-FIELD A-WEIGHTED RESPONSE OF SLM-V AS A FUNCTION OF SEVERAL ANGLES OF INCIDENCE.

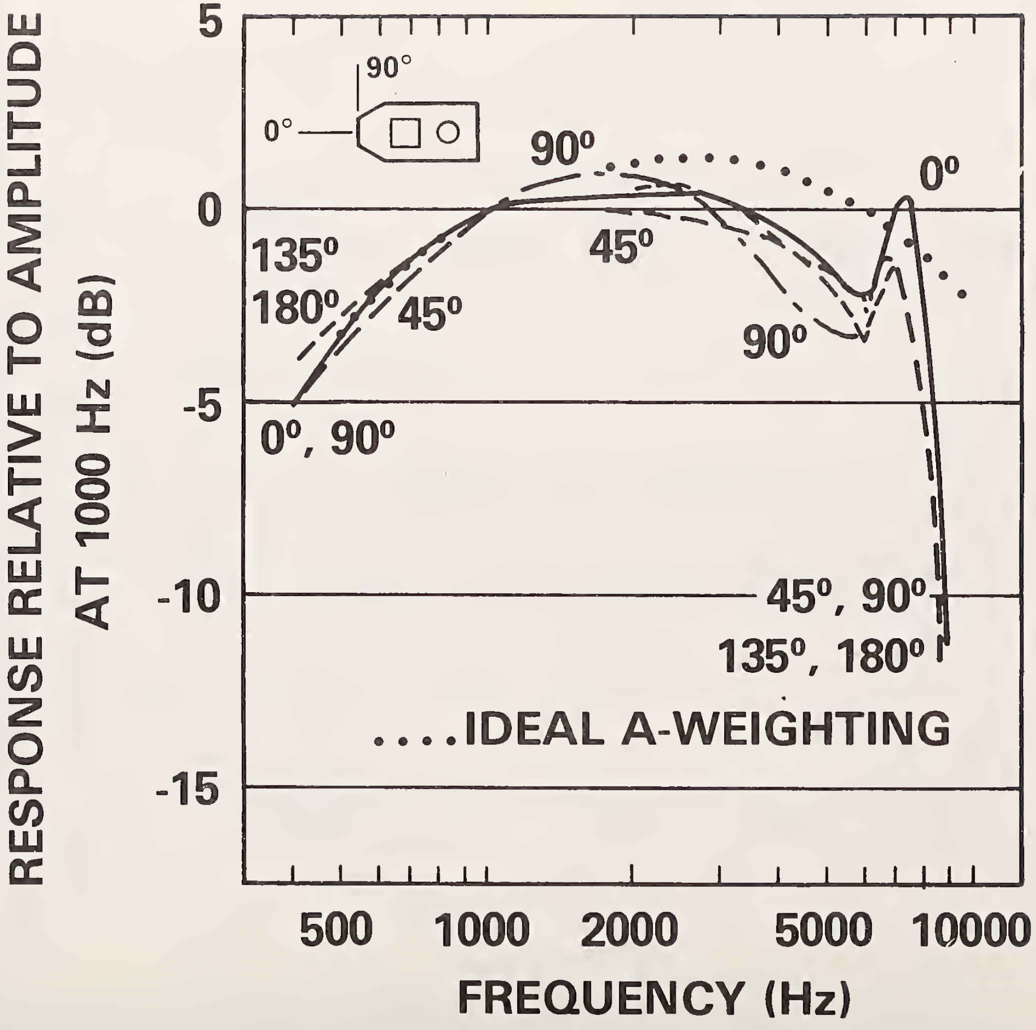

Figure 23. Free-field A-weighted response of SLM-W as a function of several angles of incidence.

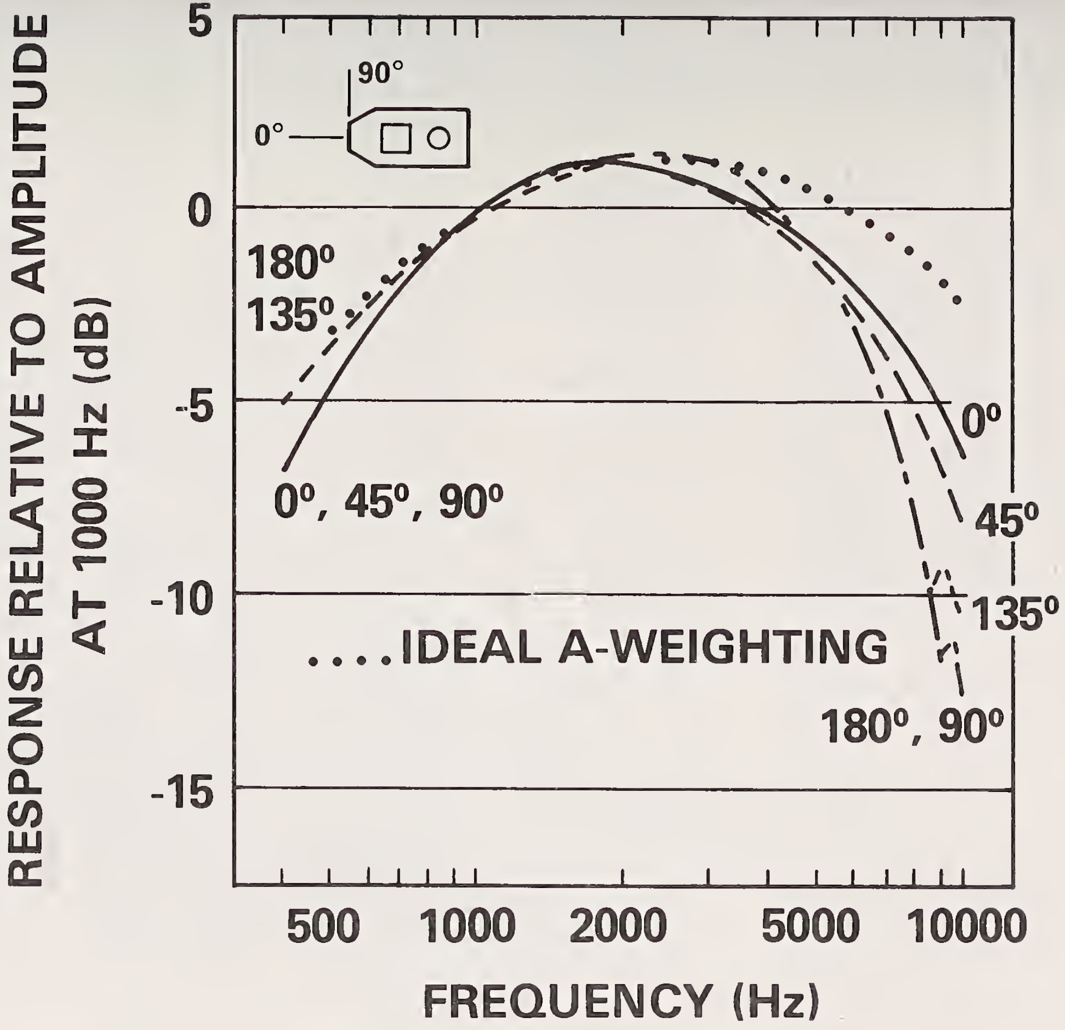

Figure 24. Free-field A-weighted response of SLM-Y as a function of several angles of incidence.

A-weighting, as specified in the American National Standard S1.4-1971,* of three Type II sound level meters from each of four manufacturers was determined in a 425-m^3 reverberation room.

A close approximation to the random incidence A-weighted sound pressure level existing in the room was obtained by measuring the space-time averaged sound level in each 1/3-octave band with a "1/2-inch" condenser microphone having a uniform random incidence frequency response from 100-10 000 Hz and adding to its electrical output the appropriate A-weighting as defined in the standard. The sound field in the reverberation room was generated by a loudspeaker excited by broadband white noise at a constant rms voltage. The "1/2-inch" microphone was placed on a cart at a height of 2.06 m from the floor of the room and pulled across the room a distance of 6.4 m along a line connecting two diagonally opposed trihedral corners. The microphone was never closer than 1 m to any room surface during this traverse. The time to traverse this distance was 1920 s (32 min). During this traverse the microphone's electrical signal was analyzed in 1/3-octave bands from 100-10 000 Hz using 1920 s of rms averaging in each of the 21 bands.

The cart was returned to its original position and the microphone was replaced by one of the sound level meters. The A-weighted electrical output of the sound level meter was analyzed in the same manner as the output of the "1/2-inch" microphone, except that no conversion to A-weighting was required. The resulting 1/3-octave levels from the two traverses were subtracted from each other and normalized (referenced) to 1000 Hz. The results are shown in Figs. 25-28.

Examination of these figures indicates that each set of three sound level meters yields fairly consistent deviations of their A-weighted response as a function of frequency. However, the actual magnitudes of the deviations from manufacturer to manufacturer vary widely depending on the frequency. It should be noted that units designated SLM-U have a deviation that is within ± 1 dB over almost the entire frequency range whereas units designated SLM-V have deviations that vary widely as a function of frequency. However all units tested meet the S1.4-1971 specification for Type II sound level meters.

3.3. Effects of Ground Reflections on Sound Level Meter Measurements

Measurements made with sound level meters are usually performed in the presence of a large (nominally) flat reflecting surface, namely the ground. The acoustical reflecting properties of such a surface can alter the sound pressure level recorded by the sound level meter. The degree to which such a surface affects the measurement depends on the reflection coefficient of the ground cover as a function of frequency, the location of the sound source relative to the ground, the frequency spectrum of the sound source and its directivity, the location of the sound level meter relative

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*Loc. cit.

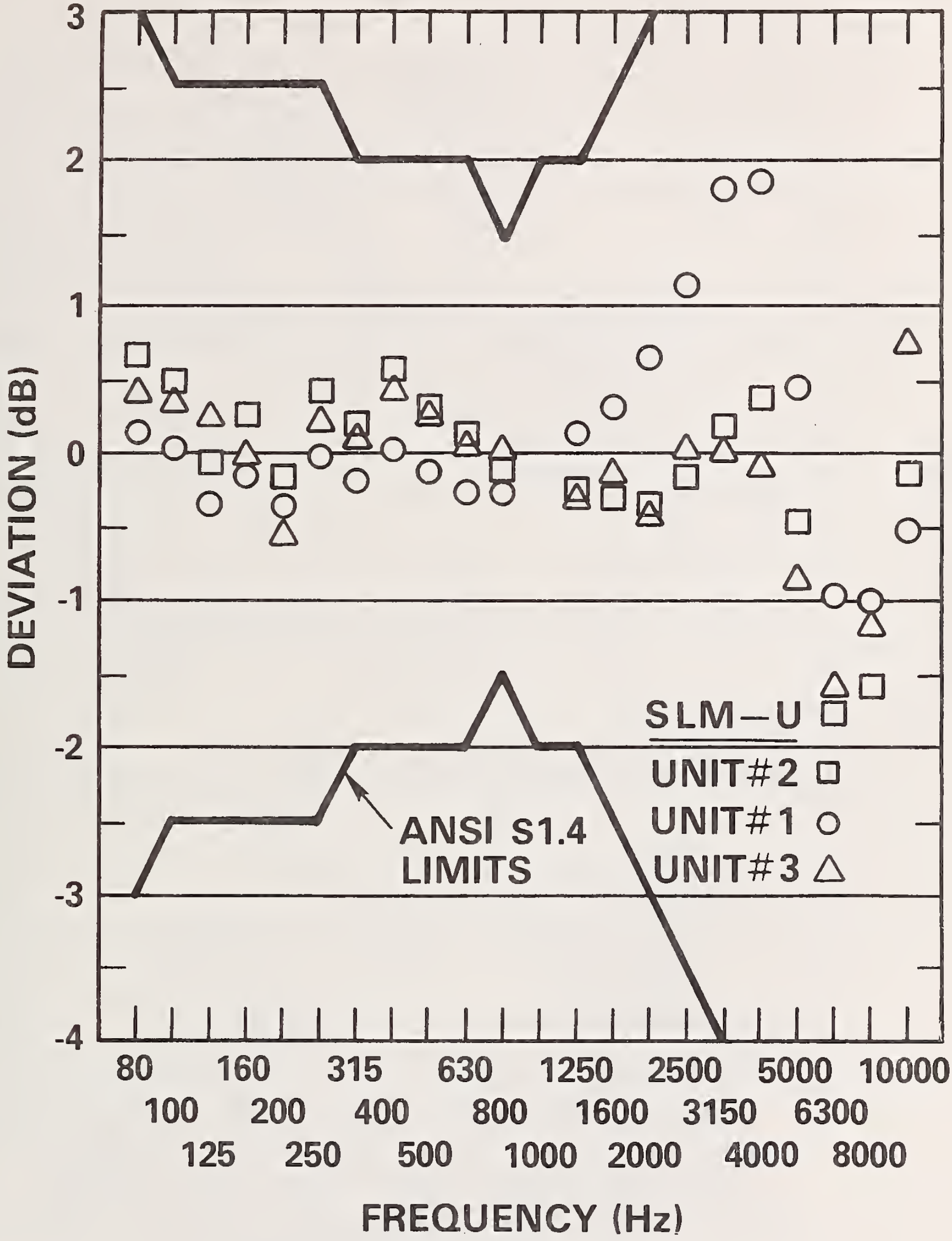

Figure 25. Deviation of SLM-U from the ideal random incidence A-weighting.

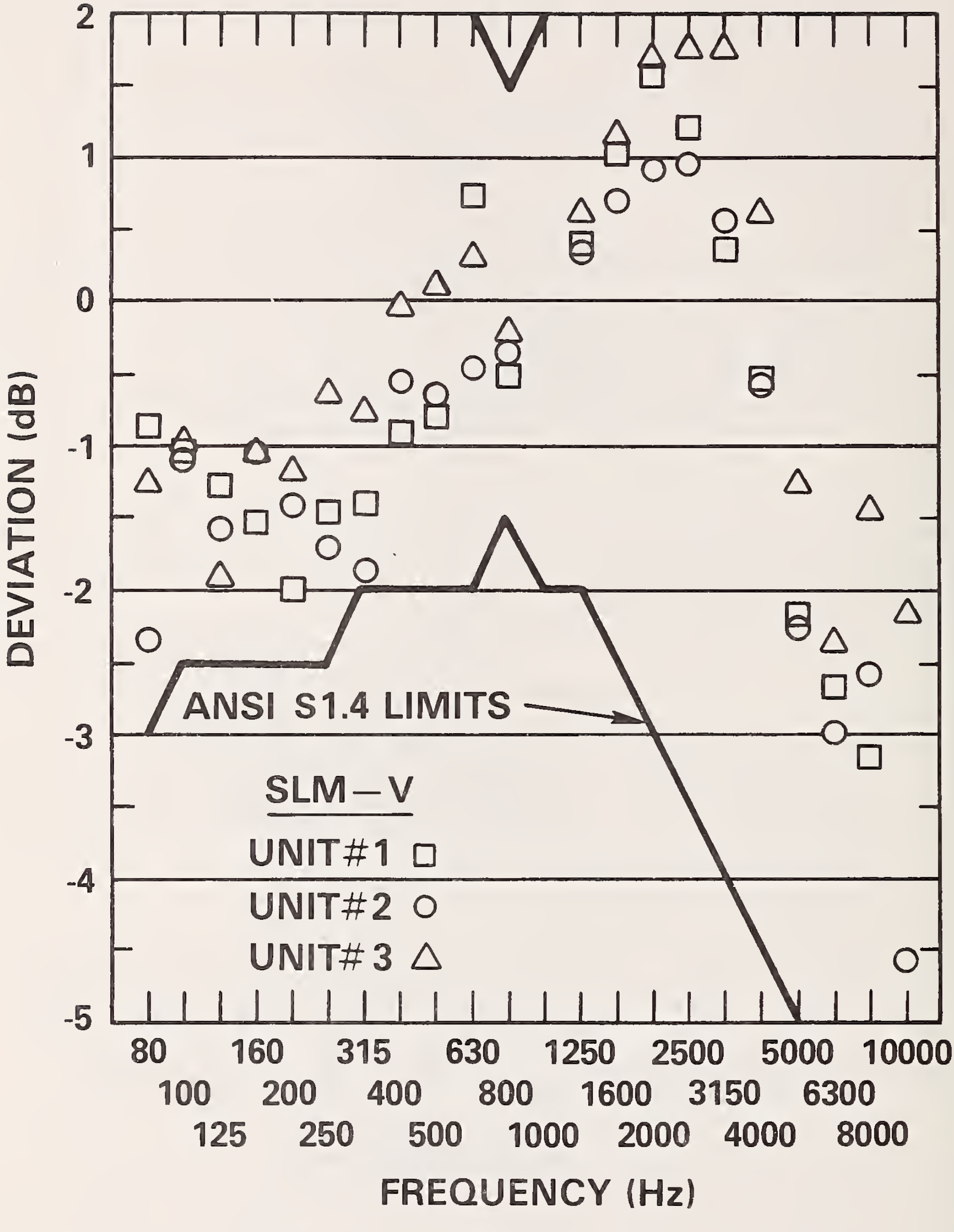

Figure 26. Deviation of SLM-V from the ideal random incidence A-weighting.

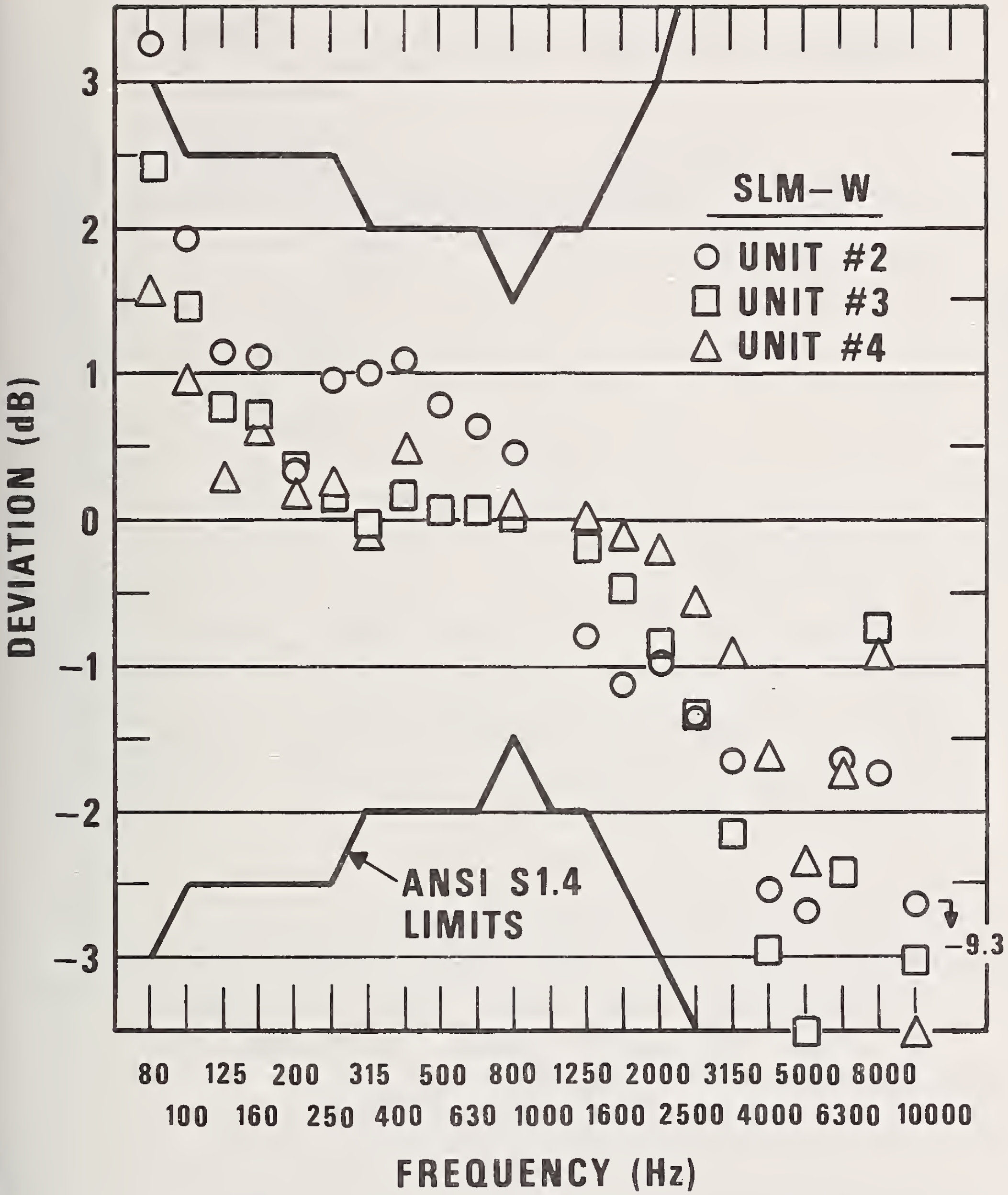

FIGURE 27. DEVIATION OF SLM-W FROM THE IDEAL RANDOM INCIDENCE A-WEIGHTING.

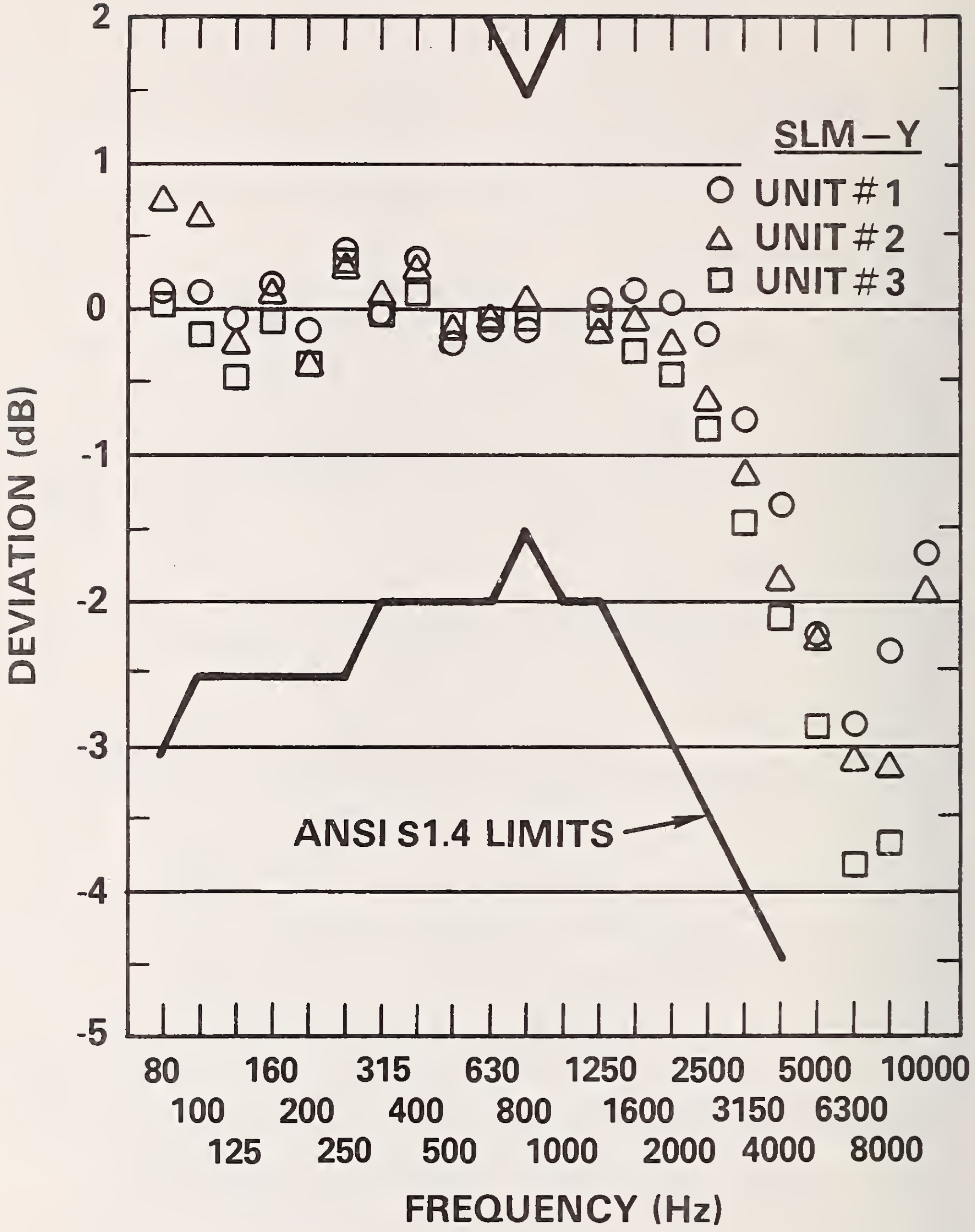

Figure 28. Deviation of SLM-Y from the ideal random incidence A-weighting.

to both the surface and the source, and the directional characteristics of the sound level meter. To obtain some idea of the possible variations one can expect from the numerous combinations of the above-mentioned variables the following parametric tests were conducted at NBS. A loudspeaker was excited by broadband noise. A sound level meter was placed a distance varying from 1 to 12 m from the loudspeaker. Both the loudspeaker and the sound level meter were held at various heights relative to the ground and to each other. Each of these combinations was investigated over an asphalt surface and over a grass-on-earth surface.

The two sites chosen for these investigations were a flat asphalt parking lot 33 m by 21 m and a large, fairly smooth grass area. The nearest vertical obstruction from the measurement area was more than 20 m away. The subsoil of the grass was hard-packed clay. The grass height varied during the tests from 6 cm (freshly cut) to approximately 10 cm. The background noise during the daytime was an A-weighted level of 55 dB requiring certain runs to be made in the late evening/early morning hours. No measurements were made when the wind velocity exceeded 15 km/hr.

The instrumentation used in the experiment is shown in Fig. 29. The loudspeaker's directivity patterns were measured in a large (452 m^3) anechoic room and are shown in Fig. 30. The electrical broadband noise signal to the loudspeaker was kept at a constant value throughout the experiment and was monitored by an AC ammeter. Since the signal-to-noise ratio at frequencies below 200 Hz was relatively poor, the output signal from the sound level meter was analyzed in 1/3-octave bands from 80 to 10 000 Hz for both the background noise and for the loudspeaker's output. The background noise levels were subtracted in the appropriate manner from those levels obtained from the loudspeaker's output in each 1/3-octave band and then recombined to obtain the A-weighted levels. The signal in each 1/3-octave band was averaged over a period of 320 s (5-1/3 min). This long averaging time was sufficient to reduce the influence of the fluctuations in the sound levels due to any transient acoustic disturbances.

To determine the effects of the ground on the sound level meter measurements, the difference between the A-weighted level measured over asphalt and that over grass is presented in Figs. 31 and 32 for various combinations of orientations and distances of the sound level meter relative to the loudspeaker and to the ground. From Fig. 31 it is seen that for the particular sound level meter used (SLM-Y) the orientation of the meter with respect to the source caused differences in the A-weighted readings of more than 1 dB at separations from 4 to 9 m. If the response of the sound level meter were truly omnidirectional these differences for the two orientations would have had virtually the same values. This figure clearly shows that for precision measurements in the presence of a reflecting surface sound level meter orientation is important.

Figure 32 shows the effects that the ground reflections can cause for two placements of the sound level meter and the loudspeaker relative to each other and relative to the ground. At relatively large distances from the source for the case where the loudspeaker is placed on the ground, the

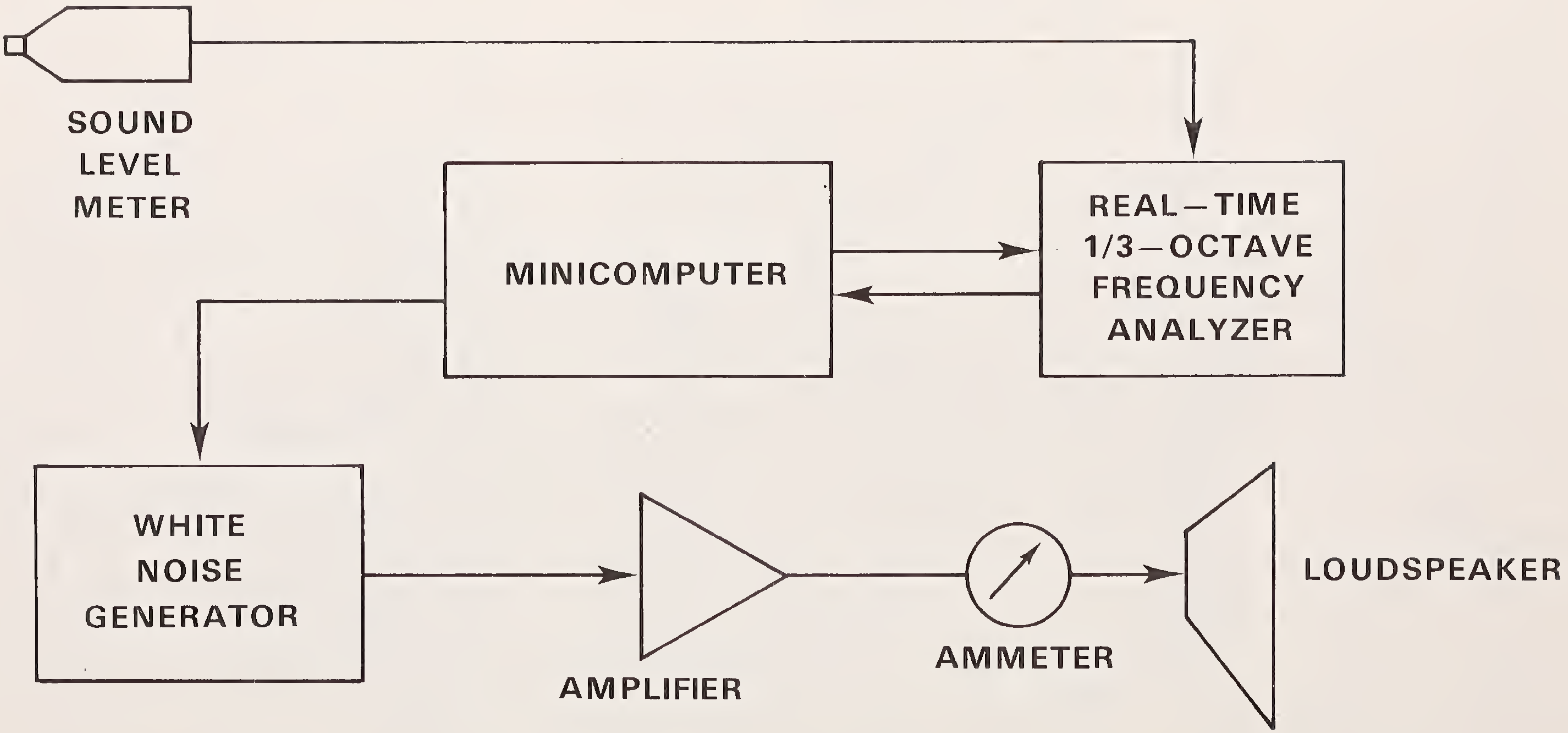

Figure 29. Schematic of instrumentation used to measure sound propagation over reflecting surfaces.

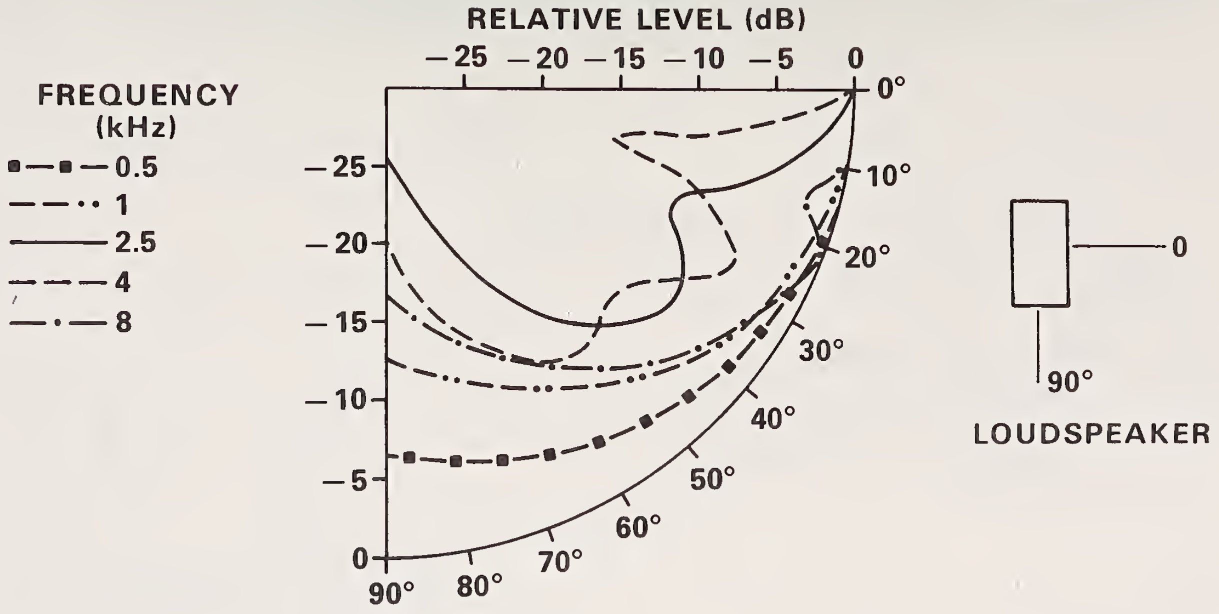

FIGURE 30. DIRECTIVITY PATTERNS AT SEVERAL FREQUENCIES OF LOUDSPEAKER USED IN PROPAGATION STUDIES.

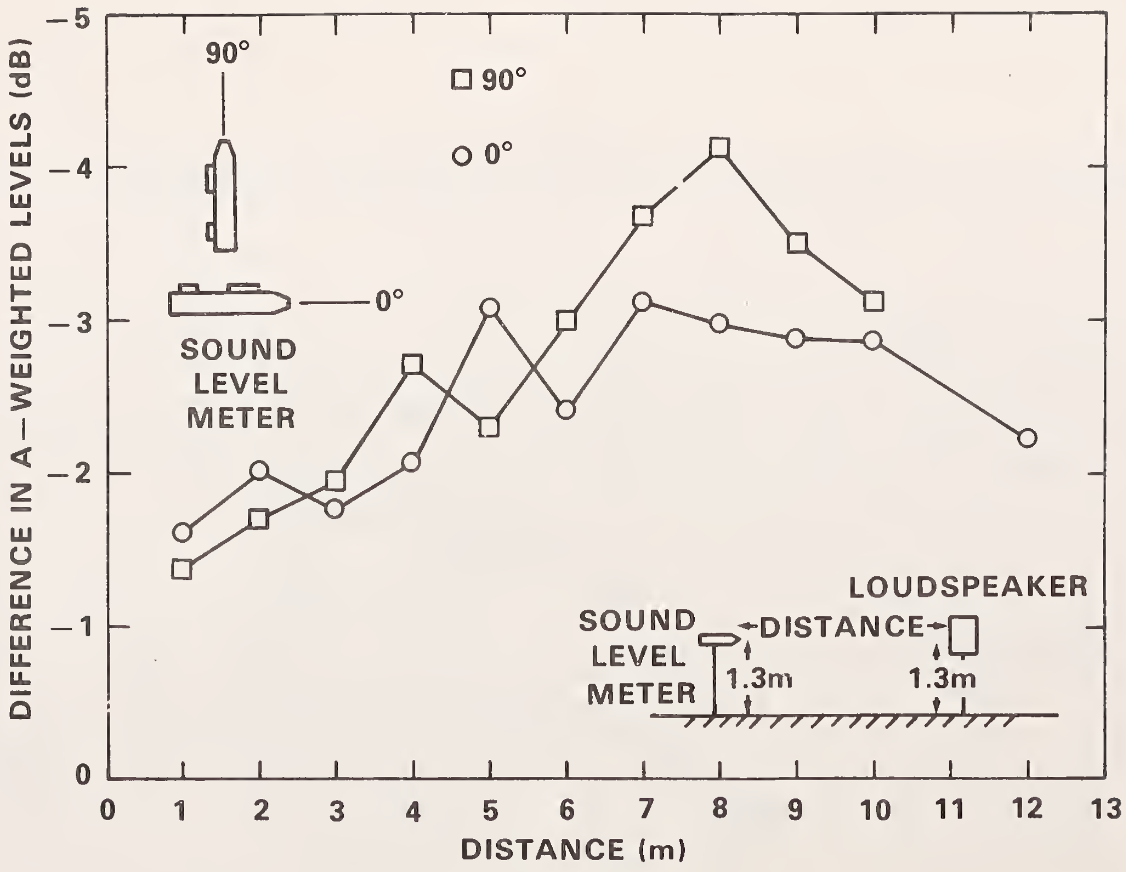

FIGURE 31. DIFFERENCE BETWEEN A-WEIGHTED LEVELS OF SOUND PROPAGATING OVER GRASS AND THOSE OVER ASPHALT AS A FUNCTION OF SOUND LEVEL METER ORIENTATION AND ITS DISTANCE FROM THE LOUDSPEAKER.

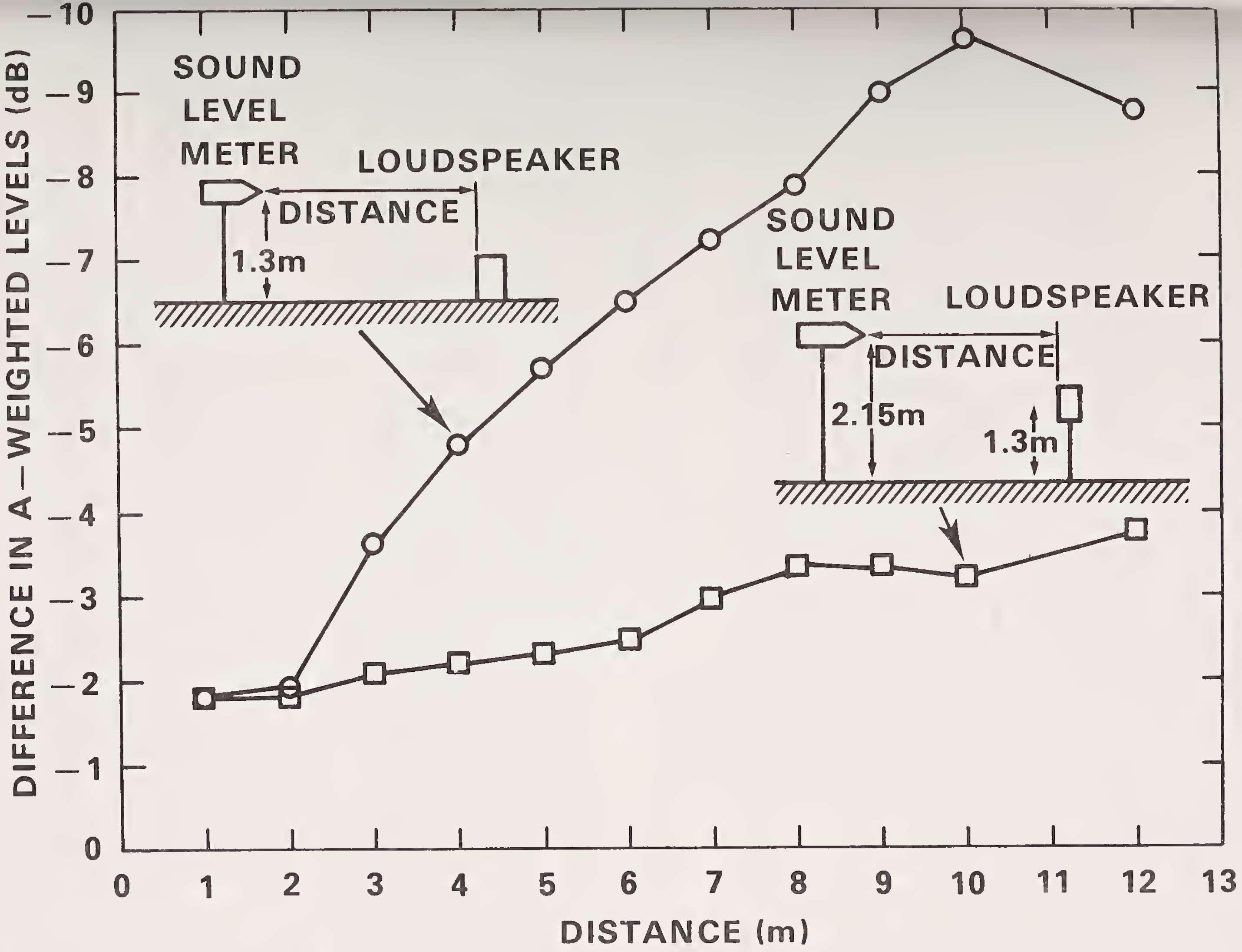

FIGURE 32. DIFFERENCE BETWEEN A-WEIGHTED LEVELS OF SOUND PROPAGATING OVER GRASS AND THOSE OVER ASPHALT AS A FUNCTION OF DISTANCE OF THE SOUND LEVEL METER FROM THE LOUDSPEAKER.

differences in the A-weighted levels due to differences in ground reflection properties can be as large as 9.5 dB. For the loudspeaker off the ground a distance of 1.3 m the differences do not exceed 4 dB. This figure indicates the complex nature by which the ground affects the sound level meter readings. Also, it is seen that at microphone distances less than 2 m these results are independent of the relative locations of the sound level meter and the loudspeaker.

Figures 33 to 36 give the actual 1/3-octave band pressure levels, for several selected bands, as a function of the type of ground cover and the separation distance between the sound level meter and the loudspeaker when they are both 1.3 m from the ground. In addition, Figs. 33 to 35 give the results for a point source over a perfectly reflecting plane when the source is oscillating at the center frequency of the respective 1/3-octave band. From Fig. 33 it is seen that the idealized model and the test results agree fairly well for sound propagating over asphalt. This agreement is, in part, due to the omnidirectional characteristics of the loudspeaker at this particular frequency. Further comparisons with other theoretical models are difficult because the source is not omnidirectional at the higher frequencies and the impedances of the ground covers are not known. These figures indicate that at distances large compared to the wavelength of sound from the source the interference caused by reflections from the surface can cause large variations in the band pressure levels, especially for propagation over asphalt.

3.4. Effects of Walls, Persons, and Tripods on Sound Level Meter Measurements

To obtain an estimate of the magnitude of the effects that certain frequently-encountered obstacles have on sound level meter measurements two separate experiments were conducted. The first set of experiments were conducted in an anechoic room. A "1-inch" microphone with a uniform frequency response over the frequency range was placed in a metal stand 3 m from the source. The output of the "1-inch" microphone was analyzed in 1/3-octave bands. The "1-inch" microphone was then replaced by a sound level meter and its output analyzed in 1/3-octave bands for the following four configurations:

Case A: The sound level meter is placed on a metal stand with the microphone diaphragm facing the sound source.

Case B. Same as Case A except a person is standing 20 cm behind the sound level meter. (The sound level meter is 1.49 m above the wire grid.)

Case C: Same as Case B except the sound level meter is resting against the person and the metal stand has been removed.

Case D: Same as Case C except the sound level meter is 55 cm (arm's length) from the person.

These results are shown in Fig. 37.

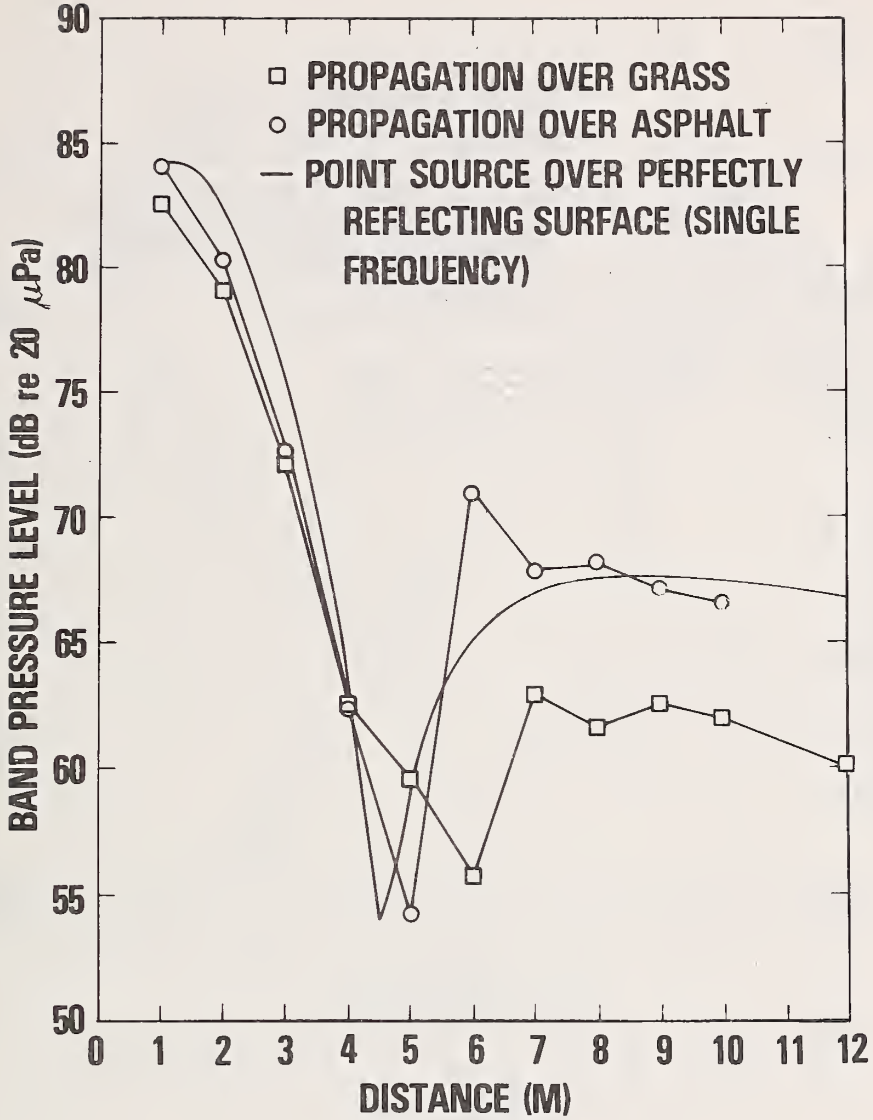

FIGURE 33. BAND PRESSURE LEVEL OF A 250-Hz 1/3-OCTAVE BAND OF NOISE PROPAGATING OVER GRASS AND ASPHALT AS A FUNCTION OF THE DISTANCE BETWEEN THE SOUND LEVEL METER AND LOUDSPEAKER FOR THE CONFIGURATION SHOWN IN THE BOTTOM OF FIG. 31. POINT SOURCE FREQUENCY IS 250 Hz.

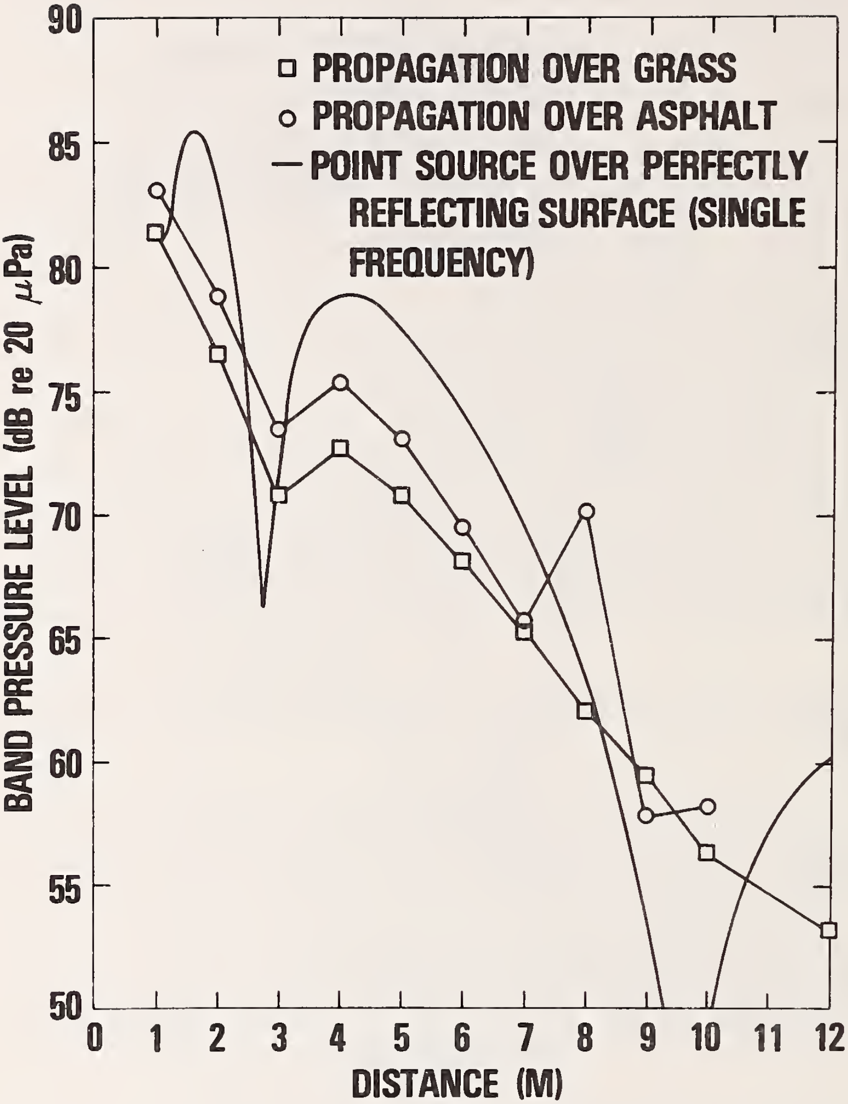

FIGURE 34. BAND PRESSURE LEVEL OF A 500-Hz 1/3-OCTAVE BAND OF NOISE PROPAGATING OVER GRASS AND ASPHALT AS A FUNCTION OF THE DISTANCE BETWEEN THE SOUND LEVEL METER AND LOUDSPEAKER FOR THE CONFIGURATION SHOWN IN THE BOTTOM OF FIG. 31. POINT SOURCE FREQUENCY IS 500 Hz.

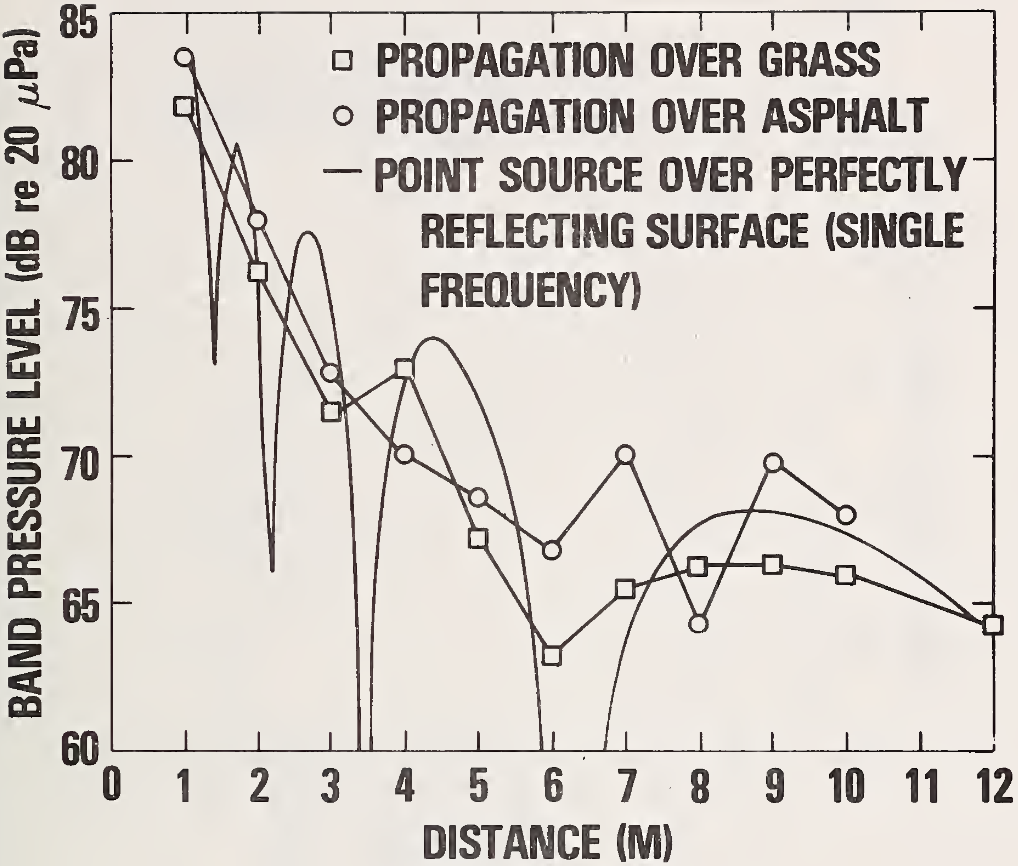

FIGURE 35. BAND PRESSURE LEVEL OF A 1000-Hz 1/3-OCTAVE BAND OF NOISE PROPAGATING OVER GRASS AND ASPHALT AS A FUNCTION OF THE DISTANCE BETWEEN THE SOUND LEVEL METER AND LOUDSPEAKER FOR THE CONFIGURATION SHOWN IN THE BOTTOM OF FIG. 31. POINT SOURCE FREQUENCY IS 1000 Hz.

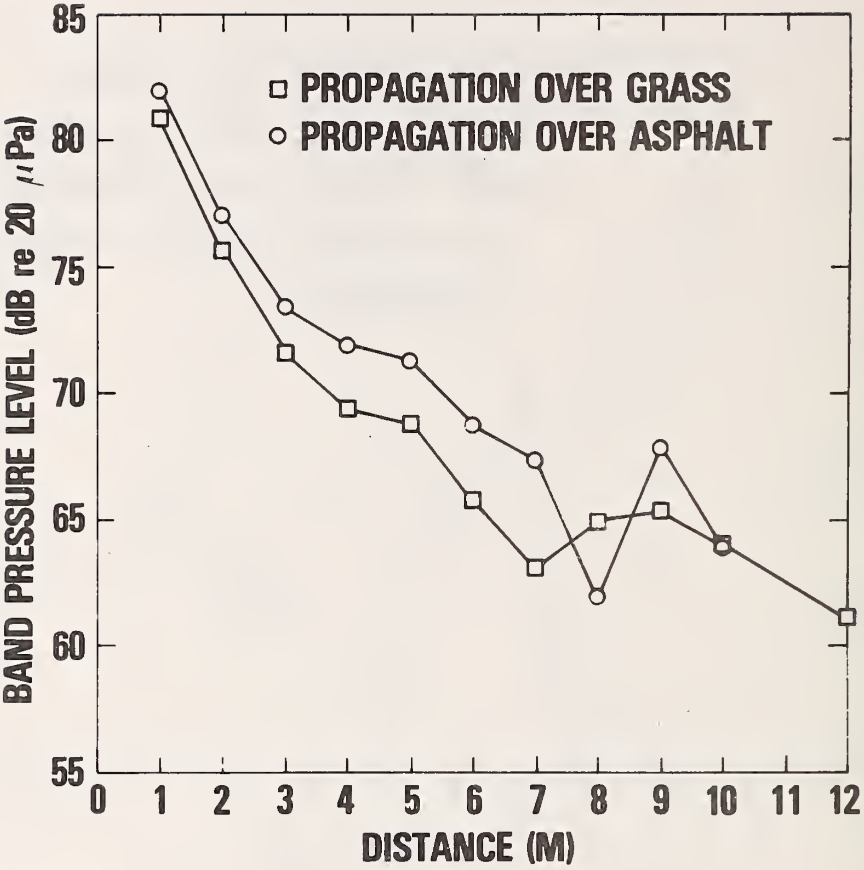

Figure 36. Band pressure level of a 2000-Hz 1/3-octave band of noise propagating over grass and asphalt as a function of the distance between the sound level meter and loudspeaker for the configuration shown in the bottom of Fig. 31.

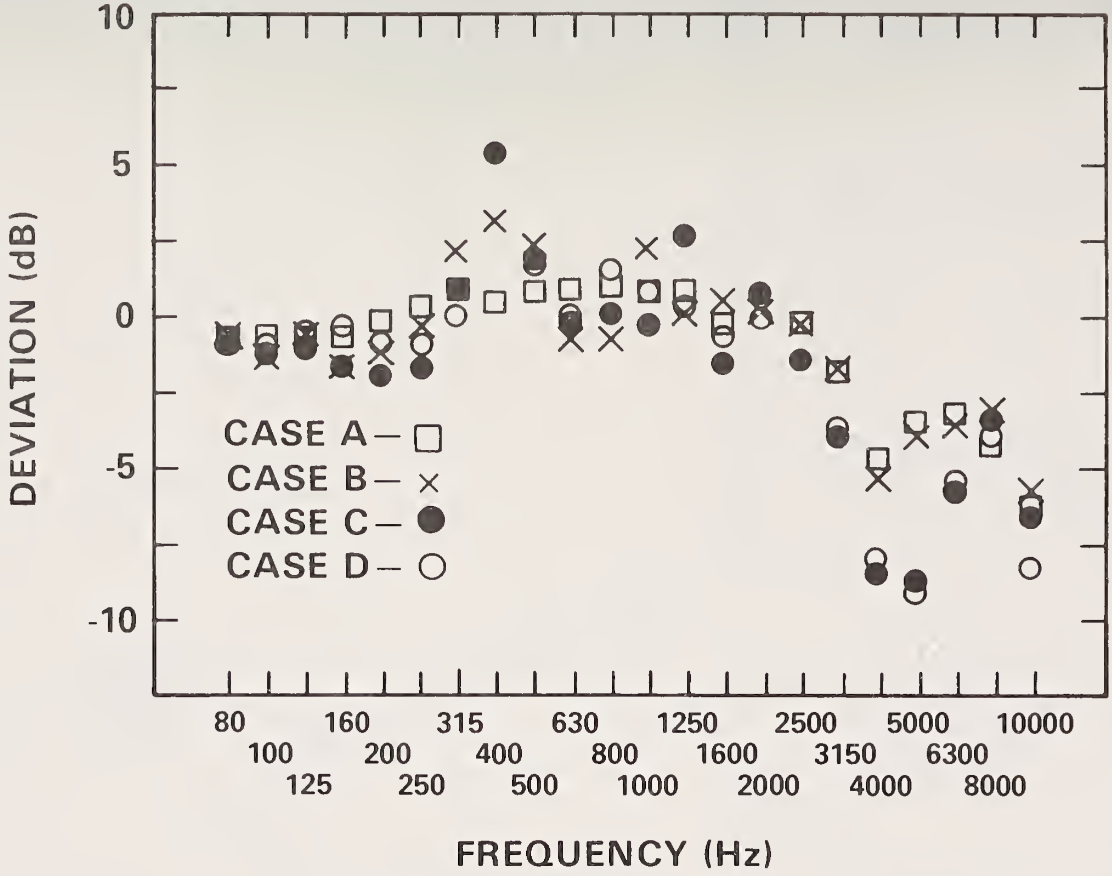

Figure 37. 1/3-octave band analysis of the effects of people and tripods on sound level meter measurements of broadband noise. See text for description of the cases A through D.

As can be seen from Fig. 37 the differences in the 1/3-octave band levels are usually within ± 2 dB except in two frequency regions, 315 to 500 Hz and above 3150 Hz, where the deviations increase markedly. At 400 Hz it appears that the presence of a person within 0.5 m of the sound level meter greatly increases the sound pressure recorded by the meter. At frequencies above 3150 Hz both the presence of a person and the metal stand greatly affect the sound field.

The second set of experiments, using the previously described source, signal, and data reduction techniques, determined the effects of two adjacent and perpendicular reflective surfaces on sound level meter measurements. The experimental set-up is shown in Fig. 38. The differences between the A-weighted levels as both a function of distance from the source, and the distance of the source and sound level meter from the vertical wall, to those levels obtained at 1 m are shown in Fig. 39. As seen from this figure, as the distance from the source increases the attenuation that would normally be obtained from the spherical spreading of sound decreases, the magnitude of the decrease being greater when the meter and source are closer to the vertical wall. For a simple broad-band source near the corner of the two surfaces, the increase in sound pressure level is expected to be about 6 dB at locations near and along the corner. This 6-dB increase is evident when the source and meter are 1.3 m from the wall.

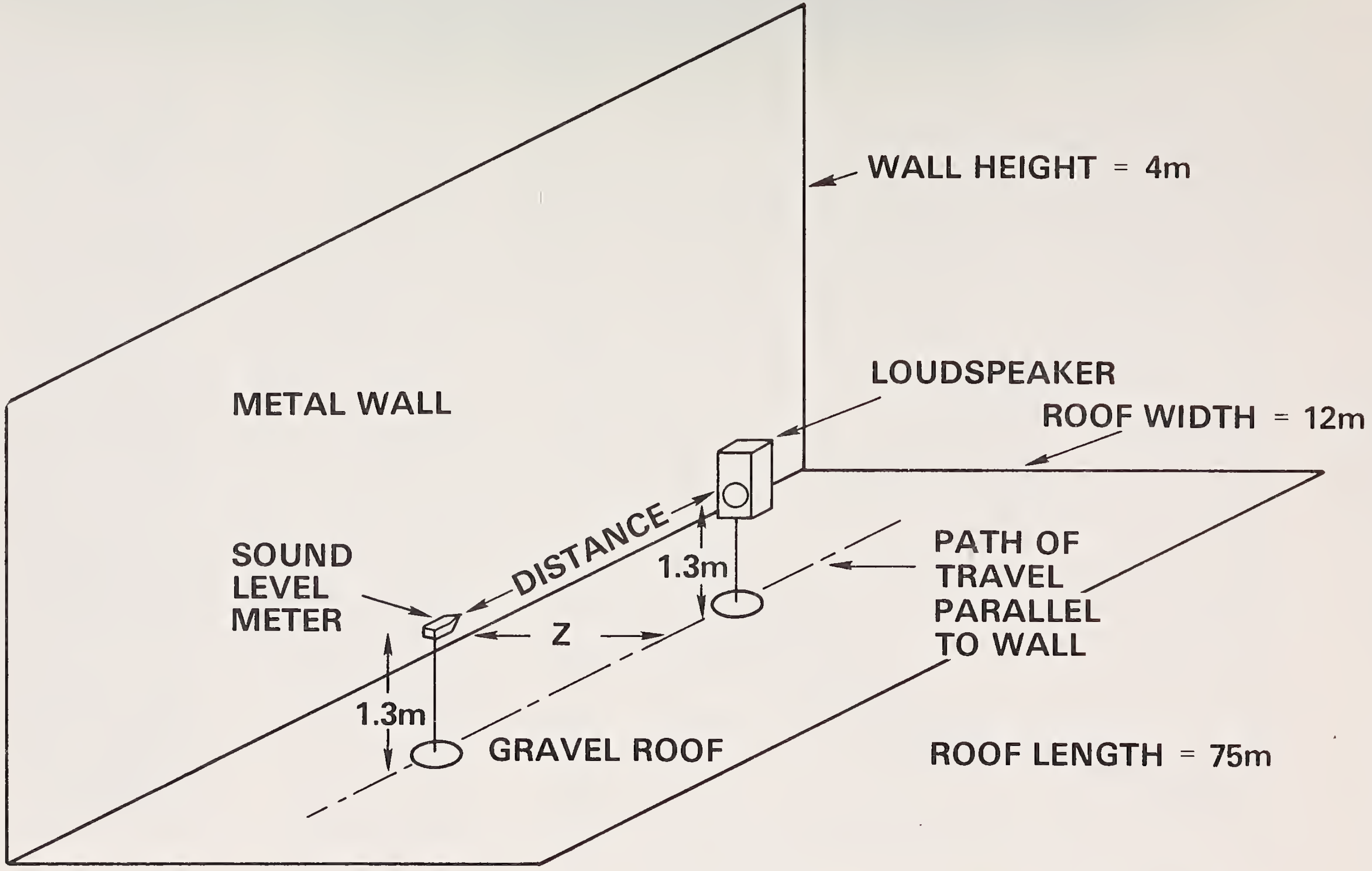

Figure 38. Experimental configuration used to determine the effects of mutually perpendicular and adjacent reflecting surfaces on sound level meter measurements.

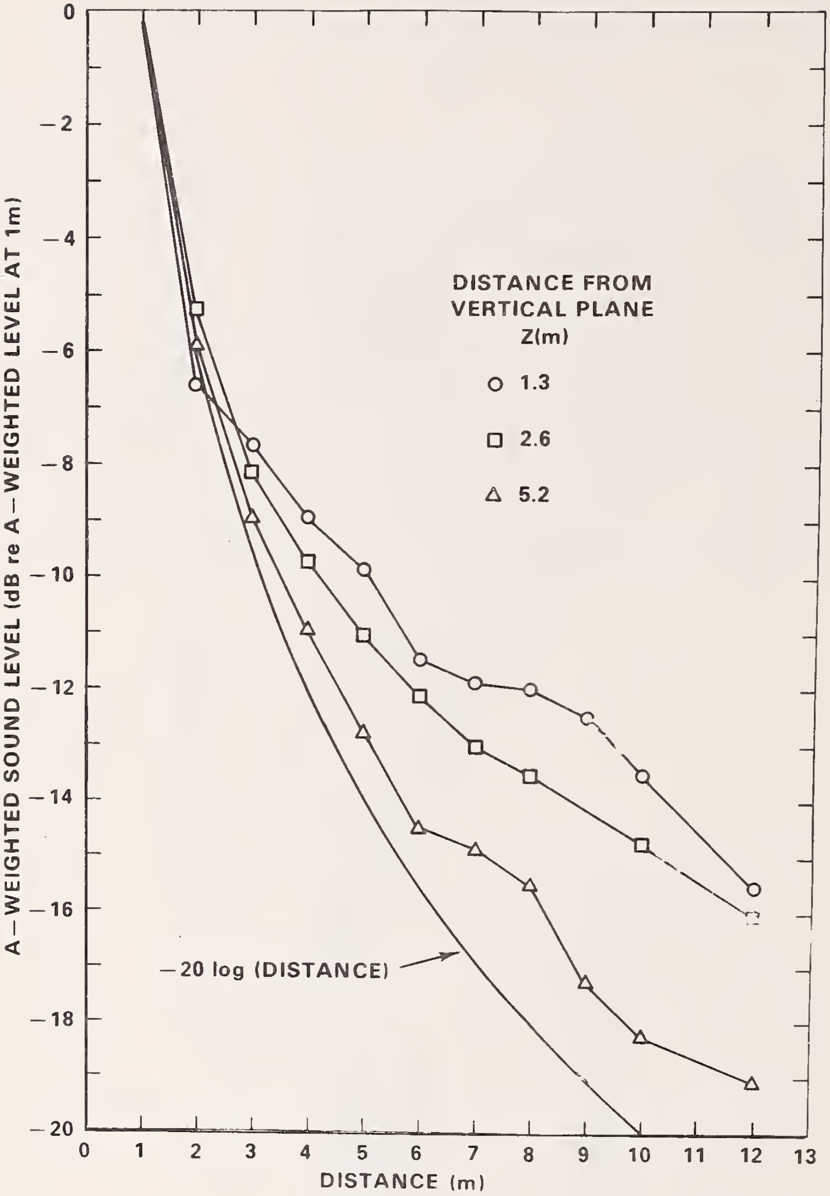

FIGURE 39. A-WEIGHTED SOUND LEVELS AS A FUNCTION OF THE DISTANCE OF BOTH THE LOUDSPEAKER AND SOUND LEVEL METER FROM A VERTICAL SURFACE FOR THE CONFIGURATION SHOWN IN FIG. 38.

4. PROCEDURES FOR THE ASSURANCE OF THE ADEQUACY OF SOUND LEVEL MEASUREMENTS

4.1. Introduction

There is an obvious need that measurements in the fields of health, safety, environmental control, or governmental regulatory actions be adequate for their intended purpose - that their uncertainty be small enough to only negligibly affect the decisions and performances of the processes of which they are a part. But this is no less true for all other measurements in science and industry and even though legal action may not be involved, the validity of scientific inference, the effectiveness of process control, or the quality of production may depend on adequate measurements.

Attention must therefore be focussed on the question of what constitutes adequate measurement from the point of view of the intended use of the measurement. For this reason, procedures will be needed by which one arrives at the uncertainty of an individual measurement and maintains assurance on a continuing basis that the quality of one's measurements stays "in control." This emphasis on the uncertainty to be attached to the measured value comes naturally in legal proceedings - the cross-examination seeks to develop the width of the shadow of doubt around the value. The same type of scientific evaluation has to be carried out to determine whether the uncertainty of one's measurement is less than some allowable amount. The error allowance is determined by program needs such as, for example, the physiological tolerances on noise pollution, radioactivity dosage, and similar quantities in matters of health and safety.

In cases where the measurement relates to only a component of the system, there may be an arbitrariness about what is "good enough," but in any case the requirement on measurement will be in the form of a limit on the allowable uncertainty.

This section gives procedures for describing the measurement process in such a manner that valid statements about the uncertainty of individual measurements can be made. To do this, the term "uncertainty" needs to be given an operational meaning. One then can discuss method of monitoring the measurement effort to assure that it remains in a state of statistical control, so that the uncertainty statement can be applied to each measurement.

4.2. The Cross-Examining of Measurement Data

One of the central problems of measurement is that of demonstrating that the number one assigns to a phenomenon measures uniquely that phenomenon and does not depend on the instrument used, the environmental conditions, or the procedures involved. In a single isolated experiment one is prepared to go to some lengths to develop the necessary evidence that one has, in fact, a valid measurement. The amount of work one does to obtain the supporting evidence will depend on factors related to time, cost, accuracy needs, etc.

It is instructive to consider this question in terms of the cross-examination of measurement data that might be expected in a scientific review as part of a legal contest.

The question to be addressed is: What region of doubt would surround, for example, a single value of noise level when used in a regulatory action?

For the regulatory agency, the objective is to be able to defend a single measurement. It must be able to withstand cross-examination. Particularly when repeated measurements of the same quantity disagree by an amount of practical significance, one needs some assurance that his measurements are correct enough for his purpose.

The key word in this discussion is "repetition." There are many levels of repetition as illustrated by the following questions.

> Within what limits would an additional measurement by the same instrument agree when measuring some stable quantity?
>
> Would the agreement be poorer if the time interval between repetitions were increased?
>
> What if different instruments from the same manufacturer were used?
>
> If two or more types (or manufacturers) were used, how much disagreement would be expected?

To these can be added questions related to the conduct of the measurement.

> What effect does geometry (orientation, etc.) have on the measurement?
>
> What about environmental conditions - temperature, moisture, etc.?
>
> Is the result dependent on the procedure used?
>
> Do different operators show persistent differences in values?
>
> Are there instrumental biases or differences due to reference standards or calibrations?

It should be obvious that one needs additional evidence beyond that of the measurement itself to demonstrate that one's measurements are "in control." To do this one needs a perspective from which to view measurement so that one can arrive at an uncertainty to be attached to a measurement - an uncertainty that will "stand up in court."

4.3. The Measurement Method

One begins with the objective of the measurement - for example, the protection of the individual from noise pollution. One of the important components of this problem is sound level and one can use the accepted physical theory and measurement methods to set regulatory limits and to monitor various noise sources. In general, however, there are several measurement approaches possible.

One thus begins with the specification of a measurement method - the detailed description of apparatus, procedures and conditions by which one will measure some quantity.

The current understanding of this process or any other scientific or industrial process is embodied in a physical model which explains the interactions of various factors, corrections for environmental or other effects, and the probability models necessary to account for the fact that repetitions of the same event give rise to nonidentical answers. For example, in noise level measurement one is involved with assumptions regarding frequency response, weighting networks, influence of procedures and geometry, and an accepted theory for making corrections for temperature and other environmental factors.

In this conceptual framework one speaks of the "true value," τ, of the measurements x_1 x_2 . . . having "errors" of $\varepsilon_1 = x_1 - \tau$, $\varepsilon_2 = x - \tau$, . . . , but one must keep in mind that τ (and also the ε's) are unknowable so that one must replace these theoretical constructs by operationally defined quantities. (It will turn out that one need not refer to "true value" in practice.) Once the apparatus is assembled and checked out, one has a measurement process whose output can be studied to see if it conforms to the requirement for which it was created.

4.4. Measurement as a Production Process

Measurement, like history, can be looked at from a number of perspectives. A number in isolation is like a single event in history - its meaning depends on the context in which it occurred. To arrive at a meaningful perspective, several properties of measurement can be noted: First, that repeated measurements of the same quantity disagree but after sufficient work to remove the larger sources of systematic error and correlation among the measurements have the properties and predictability of random variables from a probability distribution. Second, that the parameters of the distribution still depend on the apparatus, procedures, or environment and only by careful experimentation can the effect of changes on the parameters of the process be evaluated.

This idea of measurements as the output of a process, analogous to an industrial production process, is the unifying concept that enables one to discuss the adequacy of measurement. The output of measurement processes are the numerical values for industrial, medical, scientific or other use. These values pass on to the user but the measurement process remains and one must build in some redundancy in order to determine the properties of the process.

As an example, a sequence of measurements was made using two sound level meters to measure a sound of nominally 90 dB re 20 μPa. The sound was generated by a loudspeaker fed broadband noise. On 16 different days measurements were made outdoors and over grass with the loudspeaker in the same orientation and location relative to a building 2 m behind the loudspeaker. The sound level meter was always the same distance (10 m) from the loudspeaker and on a line perpendicular to the face of the loudspeaker. Other than the grass, the person holding the sound level meter, and the building to the rear of the loudspeaker, there were no other reflecting surfaces or obstacles within 50 m. No measurements were made in the rain or in winds exceeding a few km/hr. The results from these 16 repetitions are shown in Fig. 40. Typically, had duplicate measurements been made on the same day they would have given results as shown in Fig. 41.

One now faces the question of how to describe the variation that exists. Obviously there will be a different level of agreement expected between pairs on the same day, but this variation in no way predicts that encountered from day-to-day. The issue is not so much the statistical procedures to be used - these will follow after one defines the set of repetitions over which his conclusions must apply. For measuring the short term change in noise level, the difference between duplicates would apply; for any regulatory action, the day-to-day variation would have to be considered.

The crucial step in assessing the effects of random error is that of defining the set of repetitions over which the measurement is to apply. In the context of legal proceedings, one arrives at the degree of credibility of evidence by questions designed to find out how far the statement could be in error. In measurement, the uncertainty is arrived at by determining the amount of disagreement expected in the set of repetitions that would be appropriate in the context of the intended use of the measurement.

4.5. The Concept of a "Repetition" of a Measurement

Every measurement has a set of conditions in which it is presumed to be valid. At a very minimum, it is the set of repeated measurements with the same instrument-operator procedure-configuration. (This is the type of repetition one would envision in some process control operations.) If the measurement is to be interchangeable with one made at another location, the repetition would involve different instrument-operator-procedure-environment configurations. (This type of repetition is involved in producing items to satisfy a specification and of manufacturing generally.) When the measurement is to be used for conformance to a health, safety, or environmental regulation even different methods may be involved in a "repetition."

In Fig. 40 the difference between meters is small relative to the day-to-day variation. When the difference between the meters on the same condition on the same day is examined (see Fig. 42), one finds that the variation is somewhat reduced. However, with differences one would expect an increase in variation (by a factor of $\sqrt{2}$) leading one to suspect that the signal was not constant. (This was confirmed by determinations with a much more accurate meter, a condition not usually available in routine measurements.)

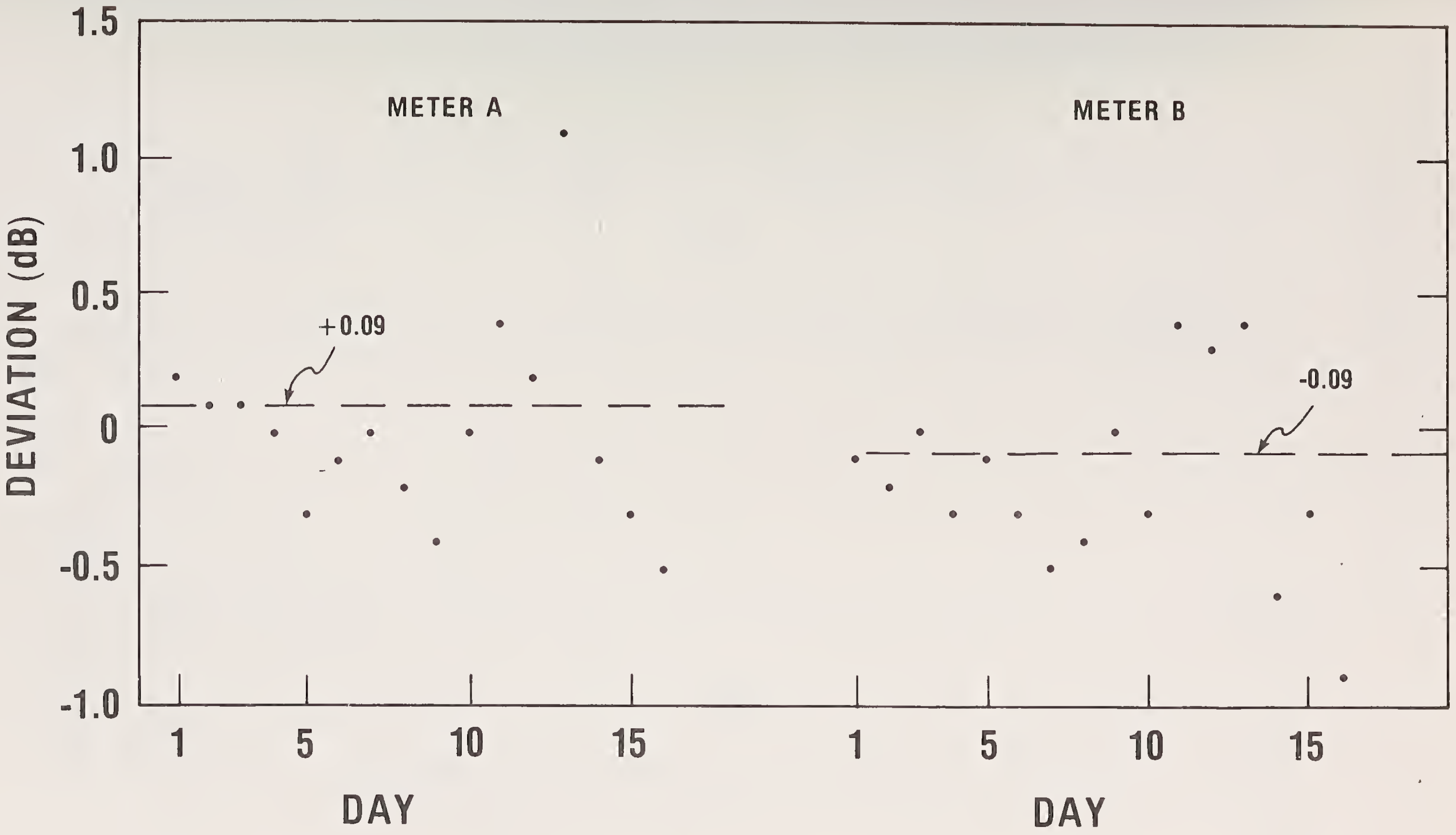

FIGURE 40. DAY-TO-DAY VARIATION IN METER READINGS.

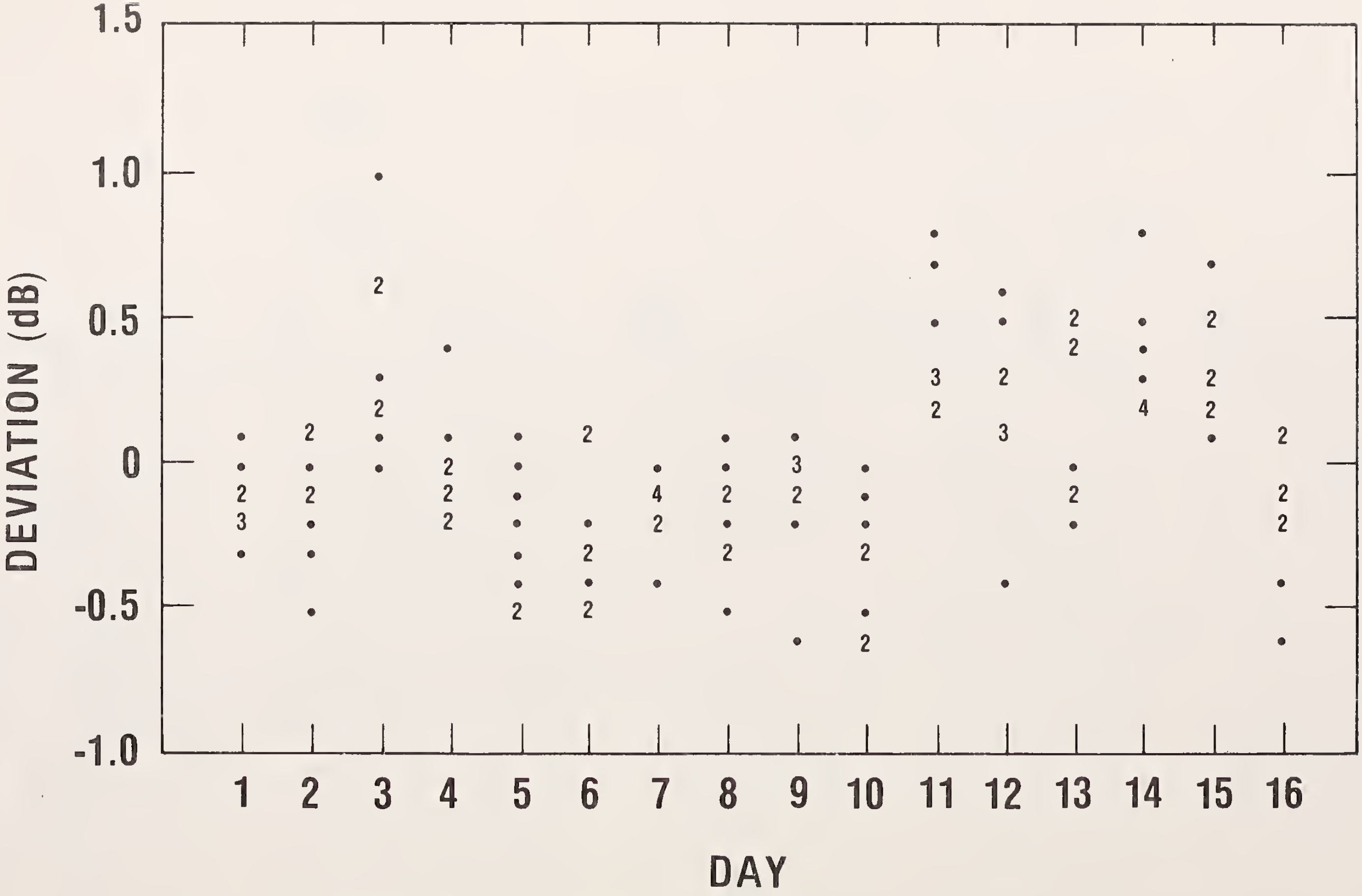

FIGURE 41. DAY-TO-DAY VARIATION IN METER READINGS WITH MULTIPLE VALUES PER DAY. (COINCIDENT POINTS INDICATED BY NUMBERS.)

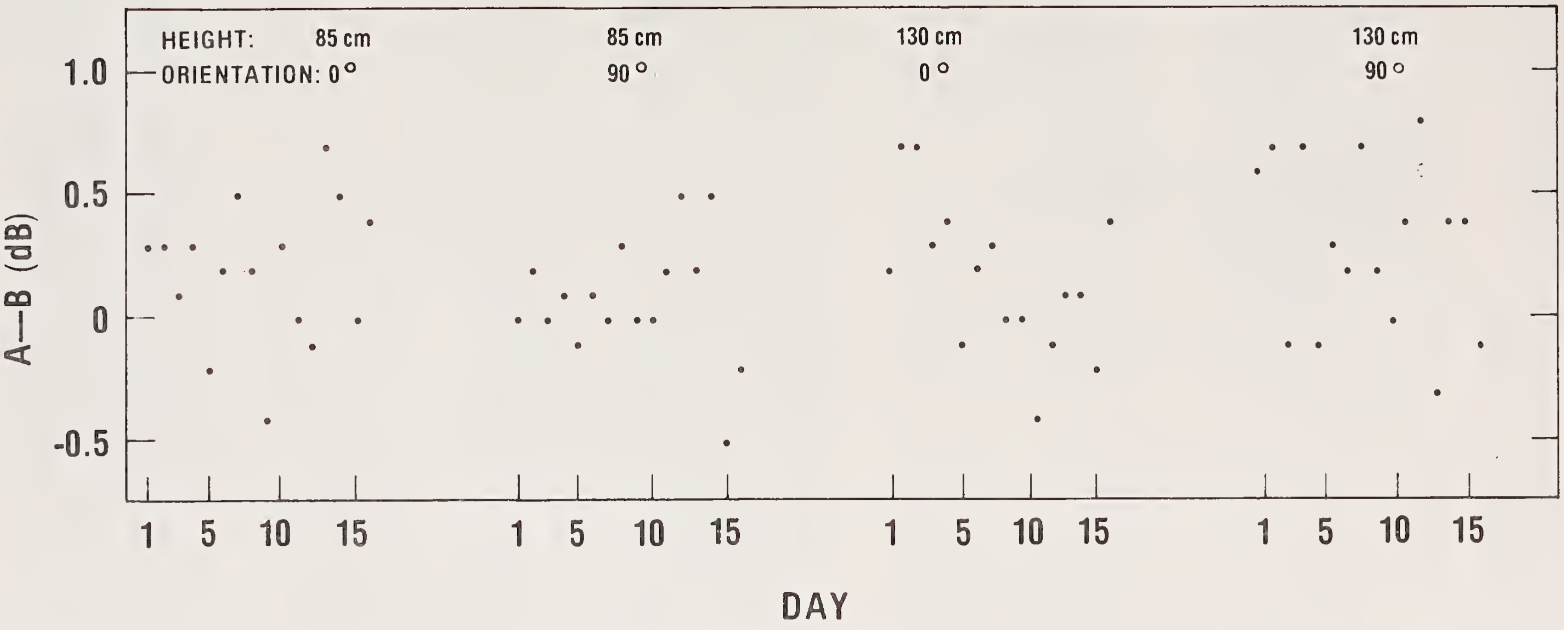

FIGURE 42. DIFFERENCE BETWEEN READINGS BY METERS A AND B UNDER A VARIETY OF CONDITIONS.

This example brings out two important points: First, that some redundancy must be introduced into the system to determine the process parameters; and second, that the values used to evaluate or monitor the process should be representative (or a sample in some sense) of the set of repetitions with respect to which the uncertainty is to apply.

In NBS's measurements of mass, a check standard is measured in parallel with the unknowns submitted for calibration. One thus generates a sequence of measurements of the same object covering an extended time period. From these results one can answer questions relating to the agreement expected in a recalibration and the operating characteristics of the measurement process. In this simple case the check standard is treated exactly the same way as the unknowns so that the properties of the process related to it are transferrable to the unknown.

The essential characteristic in establishing the validity of measurement is predictability that the variability remains at the same level and that the process has not drifted or shifted abruptly from its established values. One must build in redundancy in the form of a control - the measurement of a reference quantity of known value - or by remeasuring some values by a reference method (or by an instrument with considerably smaller uncertainty). In cases where the phenomenon can be repeated, one can learn about random errors by remeasuring at a later time sufficiently far removed to guarantee independence.

In measuring an "unknown" one gets a single value, but one still is faced with the need to make a statement that allows for the scatter of the results. If we had a sufficiently long record of measurements, we could set limits within which we were fairly certain that the next measurement would lie. Such a statement should be based on a collection of independent determinations, each one similar in character to the new observation, that is to say, so that each observation of the collection and also the new observation can be considered as random drawings from the same probability distribution. These conditions will be satisfied if the collection of points is from a sufficiently broad set of environmental and operating conditions to allow all the random effects to which the process is subject to have a chance to exert their influence on the variability. Suitable collections of data can be obtained by incorporating an appropriate reference measurement into routine measurement procedures, provided they are representative of the same variability to which the "unknown" is subject. The statistical procedures for expressing the results will depend on the structure of the data but they cannot overcome deficiencies in the representativeness of the values being used.

The results from the reference item provide the basis for determining the parameters of the measurement process and the properties are transferable. One is saying, in effect, if we could have measured the "unknown" again and again, a sequence of values such as those for the reference item would have been obtained. Whether our single value is above or below the mean we cannot say, but we are fairly certain it would not differ by more than the bounds to the scatter of the values on the reference item.

The bound, ±R, to be used for the possible effect of random errors may be as simple as ±3(standard deviation) or may involve the combination of many components of variance. Once the set of repetitions over which one's conclusions must apply is defined, the structure of the random error bound can be determined.

4.6. Possible Offset of the Process

Once one has established that his measurement process is "in control" from the point of view of random variation, there remains the question of the possible offset of the process relative to other processes. It is not helpful to speak of the offset from a "true value" which exists only in the mathematical or physical model of the process. The usefulness of considering measurement in the context of legal proceedings helps clear away some of the classical confusion about errors of measurement. In a legal or regulatory setting, one is forced to state what would be accepted as correct such as comparison (by a prescribed process) with national standards or with the results from a designated laboratory or concensus of many laboratories.

The idea of defining uncertainty as the extent to which a measurement is in doubt relative to a standard or process defined as correct finds expression in the recent Nuclear Regulatory Commission statement:[1]

> 70.57(a) (4) "Traceability" means the ability to relate *individual measurement results* to national standards or nationally accepted measurement systems ... (italics added)

The logic of this approach seems unassailable - if one cannot state what measurement system would be accepted as "correct," then one would have no defensible way of developing specifications or regulations involving such measurements.

One could measure the offset of his process relative to the accepted process, and make suitable corrections to eliminate the offset. However, for most processes, one is content with setting bounds to the possible offset due to factors such as:

> errors in the starting standards
>
> departures from sought-after instrumentation (e.g., geometrical discrepancies)
>
> errors in procedures, environment, etc.

and other effects which are persistent. From properly designed experiments, one can arrive at a limit to the possible extent of errors from these sources in answer to the question, "If the process were set up *ab initio*, how large a difference in their limiting means would be reasonable?"

A bound to a number of factors can be determined as part of regular measurement. For example, the effect of elevation could be evaluated by occasionally duplicating a measurement at a different height and taking an appropriate fraction of the observed difference as the limit to the possible offset due to any error in setting elevation. Figure 43 shows some results from sound level meters at two heights with the source at a constant height.

Even if one has a functional relation, $y = f(h)$, expressing the dependence of the result, y, on height, h, one still has to carry out these measurements. The usual propagation of error approach involving partial derivatives, etc., implies that all instruments are equally dependent on the parameter under study, that there are no effects related to the factor except that contained in the formula. This can be verified for a particular instrument by actually measuring its response.

A similar comparison was made for a different orientation of the instrument with respect to this signal source and is shown in Fig. 44. The effect of orientation is negligible and one would not be justified in adding an allowance for possible systematic error from this source based on a theoretical calculation.

From these measurements, one will have a set of bounds E_1, E_2, E_3, ... to the possible offset or systematic error from the various factors. The question as to how to combine these to a single bound to the possible offset depends on knowledge of the joint effects of two or more factors and on the physical model assumed for the process. For example, if the bounds E_i and E_j arise from independent random error bounds, then it would be appropriate to combine them in quadrature, i.e., $\sqrt{E_i^2 + E_j^2}$. An error in the model e.g., assumed linearity even when nonlinearity exists) would act as an additive error. The properties of any combination rule can be evaluated and a selection made of the most appropriate. The result will be an overall value, E, for the possible offset for the limiting mean of the process from that of the nationally accepted process.

4.7. Uncertainty

What can one say about the uncertainty of a measurement made by a process that may be offset from the nationally accepted process by some amount ±E, and is subject to random errors bounded by ±R. How should these values be combined? To begin with, one could raise the question, "If the random error could be made negligible, what uncertainty would one attach to a value from the process?" Clearly the answer is ±E. The next question, "If, in addition, a random error of size R is possible, what do we now say about the uncertainty?" The answer seems obvious - E and R are added to give an uncertainty of $\pm[E + R]$.

But what if E were itself the result of only random errors? The answer depends on what one calls a repetition. By the way E is defined, it is the bound for the systematic offset of the process and although it may be arrived at from consideration of random errors, the factor involved keeps the same (unknown) value throughout. Our ignorance does not make it a random variable.

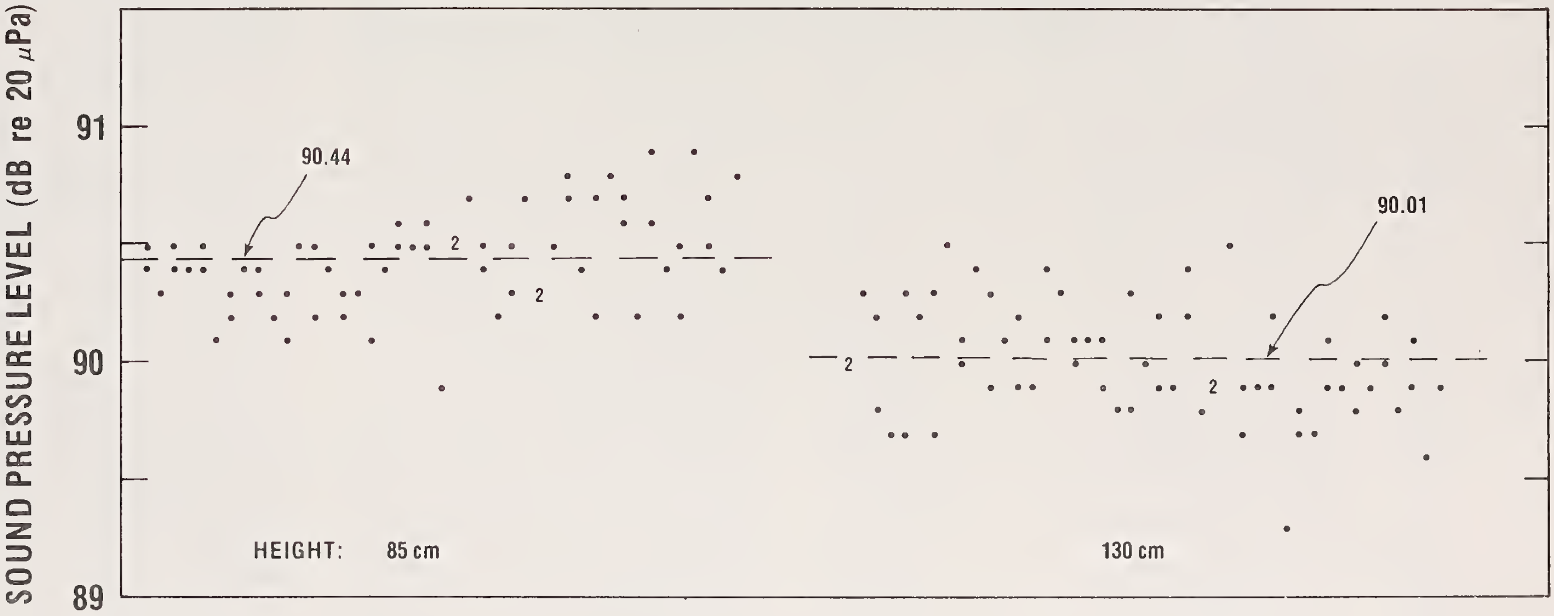

FIGURE 43. DIFFERENCE BETWEEN METER VALUES WITH CHANGE IN HEIGHT.

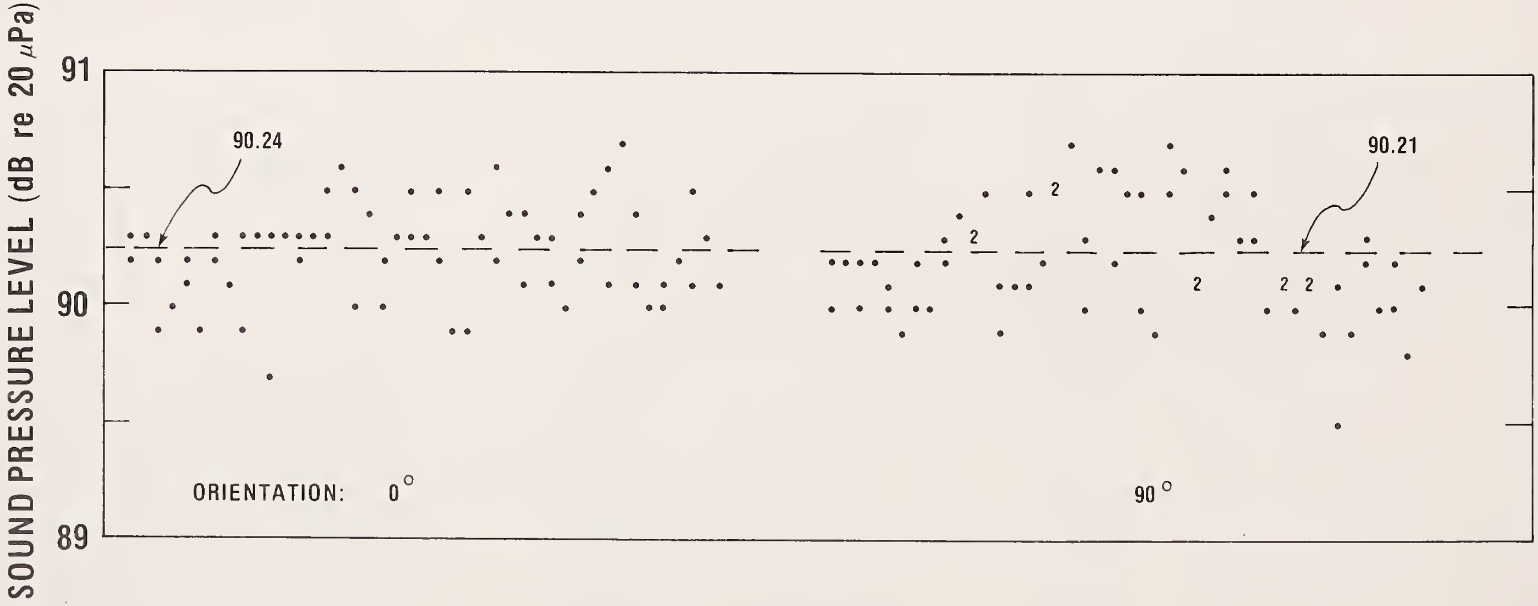

FIGURE 44. DIFFERENCE BETWEEN METER VALUES WITH A CHANGE IN ORIENTATION.

Consider the case of a mass standard. NBS's certificate states that the uncertainty is based entirely on random variation, the effects from systematic errors being negligible. But unless one recalibrates, the error due to calibration remains fixed.

The uncertainty of a measurement - the width of its "shadow of doubt" in a legal proceeding - must therefore be the sum of the random error and systematic error limits.

There are some who suggest that the uncertainty should be $\sqrt{E^2 + R^2}$. Let us consider the case where both are the same size (i.e., $E = R$), then the uncertainty becomes $\sqrt{E^2 + E^2} = E\sqrt{2}$ by this rule. One is thus able to reduce that part of the uncertainty due to the systematic offset to 40 percent of its actual value on the grounds that it is unlikely in repetitions involving setting up the process *ab initio* that the random and systematic effects will always add up to this extreme. This is fallacious because we are not talking about repetitions, otherwise all of the systematic error would already be in the random error.

4.8. Measurement Process Control

The essential feature for the validity of the uncertainty statement is that the process remain in a state of statistical control. Once an out-of-control condition occurs, one has lost predictability and the previous uncertainty statements are no longer valid.

To monitor the process some redundancy has to be built into the system. A variety of techniques can be used to give assurance of continued control. For example, one could periodically measure the same reference item or artifact or one could make duplicate measurements on some production items with enough delay to guarantee independence. The American National Standards Institute Standard N15.18 for mass measurement[2] is an example where this approach is worked out in detail. But one has to verify more than just those parameters related to random variations. One needs to build in tests of the adequacy of the physical model by a variety of tests on the process (e.g., by repeating measurements under different conditions to verify the adequacy of the corrections for such changes) as well as periodic redetermination of the bounds for systematic error. One thus tests that the assumed model is still acceptable and that the parameters assigned to that model have not changed.

An excellent example of the efficacy of this approach is given by the recent announcement[3] of discrepancies of 1 mg in the assignment of mass to aluminum kilogram standards. The mass measurement system has long been shown to be nearly perfect for the usual standards. To check up on the performance of the system at densities nearer to that of most objects involved in practical measurement, an aluminum kilogram was sent to laboratories including several at high elevations. It turns out that the difference between the mass of a stainless steel and an aluminum kilogram is significantly different at different elevations. This unsuspected property of the real measurement system is now the subject of considerable study.

4.9. Measurement Assurance

All measurements have some form of measurement assurance program associated with them although, as with quality control, we usually reserve the term for a formal program. In a formal measurement assurance program one treats the whole process - beginning with a study of the need, the development of a measuring process and a procedure for determining and monitoring its performance, and an evaluation of the effectiveness of the whole effort.

One needs a criterion of success to be able to determine whether more of one's current activity or perhaps some alternative would contribute most to the overall program, and this is not necessarily provided by the smallness of the uncertainty for a measurement.

When the measurement requirements are stated in terms of the needs of the system (protection of the individual, process control, etc.), one can measure success of the measurement effort in terms of closeness to meeting those goals. Measurement efficiency is thus judged in terms of the output of the organization rather than by the count of the number of significant digits. Also, one needs this measure of performance of the measurement effort to be able to identify those areas which need improvement.

The emphasis in measurement assurance is on the properties of the measurements relative to their use. (This is in contrast to the traditional approach which concentrated on the properties of instruments. Accuracy statements were regarded as descriptive of the equipment and by restricting the conditions more severely at each step an echelon system of instrument calibration became the accepted practice.) One builds into the measurement process redundancy sufficient to enable each measurement to withstand the kind of "cross-examination" which it will encounter whether it be a scientific evaluation or in a formal legal proceeding.

4.10. An Example

A detailed example is now presented to illustrate the concepts given in this section. The numerical values appearing in this example are based on actual measurements. The details of the formulas used below are given in Appendix B.

4.10.1. Introduction

Two Type II sound level meters, one from each of two manufacturers, are to be used to measure vehicular passby noise. The laboratory has a Type I reference sound level meter which has been calibrated by NBS and has uncertainties relative to NBS standard microphones of ± 0.75 dB. It is regularly compared against a second reference which is a "1/2-inch" microphone. The largest difference ever recorded between these two standards has been 0.08 dB.

4.10.2. Initial Determination of Process Parameters

A. Errors in Meter Calibration

Meter: SLM-A
Factors: Broad band noise signal generated by a company Q loudspeaker. Sound level meter oriented 90° with respect to the loudspeaker at a height of 1.3 m from the ground.

TABLE 4.

Determination of Sound Level Meter x Calibration Errors

		Low Level	Middle Level			High Level
Meas. No.	Date (1975)		Reading from Type 1 Reference Standard y (dB)	Reading from Type 2 Meter x (dB)	Difference b=x-y (dB)	
1	8/12		90.3	89.6	- 0.7	
2	13		90.4	89.5	- 0.9	
3	14		90.5	90.8	0.3	
4	15		90.5	89.8	- 0.7	
5	18		90.3	89.8	- 0.5	
6	19		90.3	89.9	- 0.4	
7	20	Data Not Given	90.4	89.8	- 0.6	Data Not Given
8	21		90.6	89.5	- 1.1	
9	25		90.3	89.7	- 0.6	
10	26		90.3	89.5	- 0.8	
11	27		90.6	90.0	- 0.6	
12	28		90.6	89.4	- 1.2	
13	29		89.8	90.2	0.4	
14	9/2		91.1	90.0	- 1.1	
15	3		91.1	90.0	- 1.1	
16	4		91.1	89.6	- 1.5	

average; $\bar{b} = -\ 0.69375$ dB

standard deviation; $\hat{\sigma}_b =$ 0.5026 dB

uncertainty in reference standard; $U_s =$ 0.75 dB

meter calibration error limit; $U_s + |\bar{b}| + 3\hat{\sigma}_b/\sqrt{m} =$ 1.8027 dB

Meter: SLM-B

Factors: Broad band noise signal generated by a company Q loudspeaker. Sound level meter oriented 90° with respect to the loudspeaker at a height of 1.3 m from the ground.

TABLE 5.

Determination of Sound Level Meter z Calibration Errors

		Low Level	Middle Level			High Level
Meas. No.	Date (1975)		Reading from Type 1 Reference Standard y (dB)	Reading from Type 2 Meter z (dB)	Difference $b=x-z$ (dB)	
1	8/12		90.3	90.2	- 0.1	
2	13		90.4	90.2	- 0.2	
3	14		90.5	90.7	0.2	
4	15		90.5	90.5	0.0	
5	18		90.3	89.7	- 0.6	
6	19		90.3	90.2	- 0.1	
7	20	Data Not Given	90.4	90.0	- 0.4	Data Not Given
8	21		90.6	90.2	- 0.4	
9	25		90.3	89.9	- 0.4	
10	26		90.3	89.5	- 0.8	
11	27		90.6	90.4	- 0.2	
12	28		90.6	90.2	- 0.4	
13	29		89.8	89.9	0.1	
14	9/2		91.1	90.4	- 0.7	
15	3		91.1	90.4	- 0.7	
16	4		91.1	89.5	- 1.6	

average; $\bar{b}$ = - 0.39375 dB

standard deviation; $\hat{\sigma}_b$ = 0.4358 dB

uncertainty in reference standard; U_s = 0.75 dB

meter calibration error limit; $U_s + |\bar{b}| + 3\hat{\sigma}_b/\sqrt{m}$ = 1.4706 dB

B. Meter Random Errors

Meter #1: SLM-A
Meter #2: SLM-B
Factors: Broad band noise signal generated by a company Q loudspeaker. Sound level meter is oriented normal (pointing) to the loudspeaker and 85 cm from the ground.

TABLE 6

Determination of the Random Errors of Two Sound Level Meters

Meas. No.	Date (1975)	Reading from Meter #1 x (dB)	Reading from Meter #2 z (dB)	Difference x-z=d (dB)
1	8/12	90.2	90.3	- 0.1
2	13	90.2	90.5	- 0.3
3	14	90.7	90.8	- 0.1
4	15	90.2	90.4	- 0.2
5	18	90.1	90.1	0.0
6	19	89.1	89.3	- 0.2
7	20	90.3	90.4	- 0.1
8	21	90.2	90.6	- 0.4
9	25	90.5	90.6	- 0.1
10	26	89.9	90.0	- 0.1
11	27	90.6	90.9	- 0.3
12	28	90.5	91.1	- 0.6
13	29	90.8	91.1	- 0.3
14	9/2	90.8	91.4	- 0.6
15	3	90.6	90.7	- 0.1
16	4	90.3	90.4	- 0.1

standard deviation of differences; $\hat{\sigma}_d = 0.1807$

standard deviation of single measurement; $\hat{\sigma} = \hat{\sigma}_d/\sqrt{2} = 0.1278$

average; $\bar{d} = -0.225$

standard deviation of $\bar{d}$; $\hat{\sigma}_d/\sqrt{16} = 0.0452$

The measured value for the difference between the two meters is, from Tables 4 and 5, $d' = -0.69375 - (-0.39375) = -0.3$. The difference, $|\bar{d} - d'|$ is equal to $|(-0.225) - (-0.3)| = 0.075$ which is less than three times the standard deviation of the difference, i.e., $0.075/0.0452 < 3$, so that one would regard the meters as having the same relative bias as that found in the meter calibration experiment.

The standard deviation, $\hat{\sigma}$, of a single measurement should be in agreement with that found in subsection A. The combined value for the standard deviation $\hat{\sigma}_b$ is

$$\hat{\sigma}_b = \sqrt{[0.4358)^2 + (0.5026)^2]/2} = 0.4704$$

whereas the value for $\hat{\sigma}$ is only 0.1278. The ratio of the squares of these standard deviations (placing the larger in the numerator) is

$$F = (0.4704/0.1278)^2 = 13.6$$

which exceeds the critical value corresponding to the 0.01 probability value for the F distribution. The proper value for the standard deviation to account for the process random errors will therefore be $\hat{\sigma}_b$ and the value used for $\hat{\sigma}_R$ will be $\hat{\sigma}_R = 0.4704$.

If paired measurements by two meters are used to maintain process control, then $\hat{\sigma}_d = 0.1807$ (or $\hat{\sigma} = 0.1278$) would be used as the initial value for this process parameter.

C. Meter Systematic Errors

Meter: SLM-A
Factors: Broad band noise signal generated by a company Q loudspeaker.
Sound level meter oriented normal (pointing) to the loudspeaker.

TABLE 7
Determination of the Random Error of a Sound Level Meter

Test No.	Date (1975)	Height = 85 cm Reading x_1 (dB)	Height = 130 cm Reading x_2 (dB)
1	8/12	90.2	89.8
2	13	90.2	89.5
3	14	90.5	90.0
4	15	90.2	89.8
5	18	90.2	89.8
6	19	89.9	89.9
7	20	89.9	89.8
8	21	90.2	89.5
9	25	90.3	90.0
10	26	89.9	89.5
11	27	91.0	90.8
12	28	90.5	89.4
13	29	90.3	89.9
14	9/2	90.8	90.0
15	3	90.5	89.6
	Average;	$\bar{x}_1 = 90.3375$ dB	$\bar{x}_2 = 89.8625$ dB

In the absence of an assumed physical model (i.e., functional) the difference will be taken as the limit E to the possible systematic error for this factor, i.e., $E = \bar{x}_{max} - \bar{x}_{min} = 0.475$ dB.

D. Uncertainty

The uncertainty, U, of a single determination is given by

$$U = U_s + |\bar{b}| + 3\hat{\sigma}_b/\sqrt{m} + \Sigma\ E_i + 3\hat{\sigma}_R$$

where the numerical values for $\bar{b}$ are obtained from Tables 4 and 5 $\hat{\sigma}_b$ is obtained as shown after Table 6.

	SLM-A	SLM-B
$U_s + \|\bar{b}\| + 3\hat{\sigma}_b/\sqrt{m}$	1.8201	1.4706
E	0.475	0.475
$3\hat{\sigma}_R$	1.4112	1.4112
Uncertainty, U	3.71	3.36

If the height of the sound level meter were specified the allowance of 0.475 could be dropped to give

	SLM-A	SLM-B
Uncertainty (with fixed height)	3.23 dB	2.88 dB

If the calibration factor, $\bar{b}$, were applied to each determination, the uncertainty would be reduced by $|\bar{b}|$ to give

	SLM-A	SLM-B
Uncertainty (fixed height, meter calibration used)	2.54 dB	2.49 dB

4.10.3. Maintenance of Process

The process parameters were found in subsection B to be: $\bar{d} = 0.30$, $\hat{\sigma}_d = 0.1807$ with 9 degrees of freedom, and $\hat{\sigma}_R = 0.4708$ with 18 degrees of freedom.

A. Duplicate Measurements

Duplicate determination by two meters gave values as shown Table 8. They are spread far enough apart in time so that successive results should be statistically independent. The results in Table 8 show that for the two groups shown both t and F are less than their critical values, and therefore the process is accepted as being "in control."

B. Revised Process Parameter Values

The following are the updated values for the process after the first two groups:

$$\bar{d} = \frac{10(-0.30) + 5(-0.14) + 5(-0.24)}{20} = -\ 0.245 \text{ dB}$$

$$\hat{\sigma}_d = \frac{9(.1807) + 4(.2702) + 4(.3362)}{9 + 4 + 4} = 0.2471 \text{ dB; degrees of freedom} = 17$$

$$\hat{\sigma}_R = 0.4704 \text{ dB; degrees of freedom} = 18$$

These parameters are to be used to determine the uncertainty limits for measurements by the process as long as the process is "in control" relative to its parameters. Once an out-of-control condition occurs it is necessary to determine a new set of process parameters. Without this predictability the validity of its uncertainty statement is in doubt.

TABLE 8

Determination of the Revised Process Parameters for Sound Level Meters x and y

Number	Date (1975)	Meter Reading x (dB)	Meter Reading y (dB)	Difference d=x-y (dB)
		Group I		
1	9/8	90.2	90.5	- 0.3
2	9	90.0	90.5	- 0.5
3	10	90.5	90.6	- 0.1
4	11	90.5	90.5	0.0
5	12	90.2	90.0	0.2

average; $\bar{d}_5 = -0.14$ dB

standard deviation; $s_5 = 0.2702$ dB

test of average; $$t = \frac{|\bar{d}_5 - \bar{d}|}{\hat{\sigma}_d/\sqrt{5}} = \frac{.16}{0.1807/\sqrt{5}} = 0.19 < 3$$

test of variability; $$F = \frac{s^2}{\hat{\sigma}_d^{\,2}} = \frac{0.2702^2}{0.1807^2} = 2.23 < \text{Critical } F$$

Number	Date (1975)	Meter Reading x (dB)	Meter Reading y (dB)	Difference d=x-y (dB)
		Group II		
6	15	90.0	90.2	- 0.2
7	16	90.5	90.4	0.1
8	17	90.2	90.4	- 0.2
9	18	89.8	89.9	- 0.1
10	19	89.5	90.3	- 0.8

average; $\bar{d}_5 = -0.24$ dB

standard deviation; $s_5 = 0.3362$ dB

test of average; $t = 1.42 < 3$

test of variability; $F = 3.46 <$ Critical F

Group III

.

.

.

4.11. References

1. "Measurement Control Program for Special Nuclear Materials Control and Accounting (10 CFR 70.57)," Federal Register, Vol. 40, No. 155 August 11, 1975, pp. 33651-33653.

2. "Mass Calibration Techniques for Nuclear Material Control," N15.18-1975, American National Standards Institute, New York, N. Y.

3. P. E. Pontius, "Mass Measurement: A Study of Anomalies," Science 190, 379-380 (Oct. 24, 1975).

APPENDIX A

MICROPHONE CALIBRATION METHOD

A.1. Introduction

The microphone calibration procedure is performed in two stages. The first stage employs a reciprocity calibration of the two condenser microphones. The second stage uses one of these microphones as a source from which the response of the electret and ceramic microphones are obtained. The reciprocity method is used to calibrate the reference (source) microphone at a particular temperature, humidity, and frequency. The reciprocity technique requires three microphones. One of these microphones must be reversible, that is, it must perform according to certain relationships between the acoustic pressure and velocity on the surface of the microphone diaphragm and the current and voltage produced by the micorphone. A third microphone is used as a source. After the reference microphone has been calibrated it is used as a source to generate a known sound pressure from which the other microphone responses are determined. The details and theory of how one performs these calibrations are presented in Ref. 1. The purpose of this appendix is to describe how NBS performed these measurements.

A.2. Reciprocity Method

Two different types of measurements are made in the NBS reciprocity method of calibration: voltage ratio and capacitance. The voltage ratio measurement is performed as shown in Fig. A-1. With the switch in position 1 the oscillator excites the source microphone. The receiving microphone, acoustically coupled to the source through a 3-cm^3 plane-wave coupler, converts the acoustic signal into a voltage, which is filtered and amplified. The magnitude of the signal is read on the meter and is denoted A. The switch is then placed in position 2 disconnecting the oscillator from the source microphone and connecting it to an attenuator calibrated in hundredths of a decibel. The output of the attenuator is connected across the resistor R_o, which is in series with the receiving microphone. The attenuator is varied until the meter indicates a value equal to A. The resulting attenuation reading, denoted A_a (dB), gives the logarithm of the ratio between the open circuit voltage of the oscillator driving the source microphone to the open circuit voltage of the receiving microphone. Consequently the voltage ratio V_R is given by

$$V_R = 10^{(-A_a/20)}.$$

Measurements of the capacitance of a microphone are made according to the method as applied by Koidan[2] and is shown in Fig. A-2. The source and receiving microphone are placed in the coupler in the same manner as in the voltage ratio measurement in order that the source microphone be subjected to the same acoustic impedance. When the two switches are in position 1

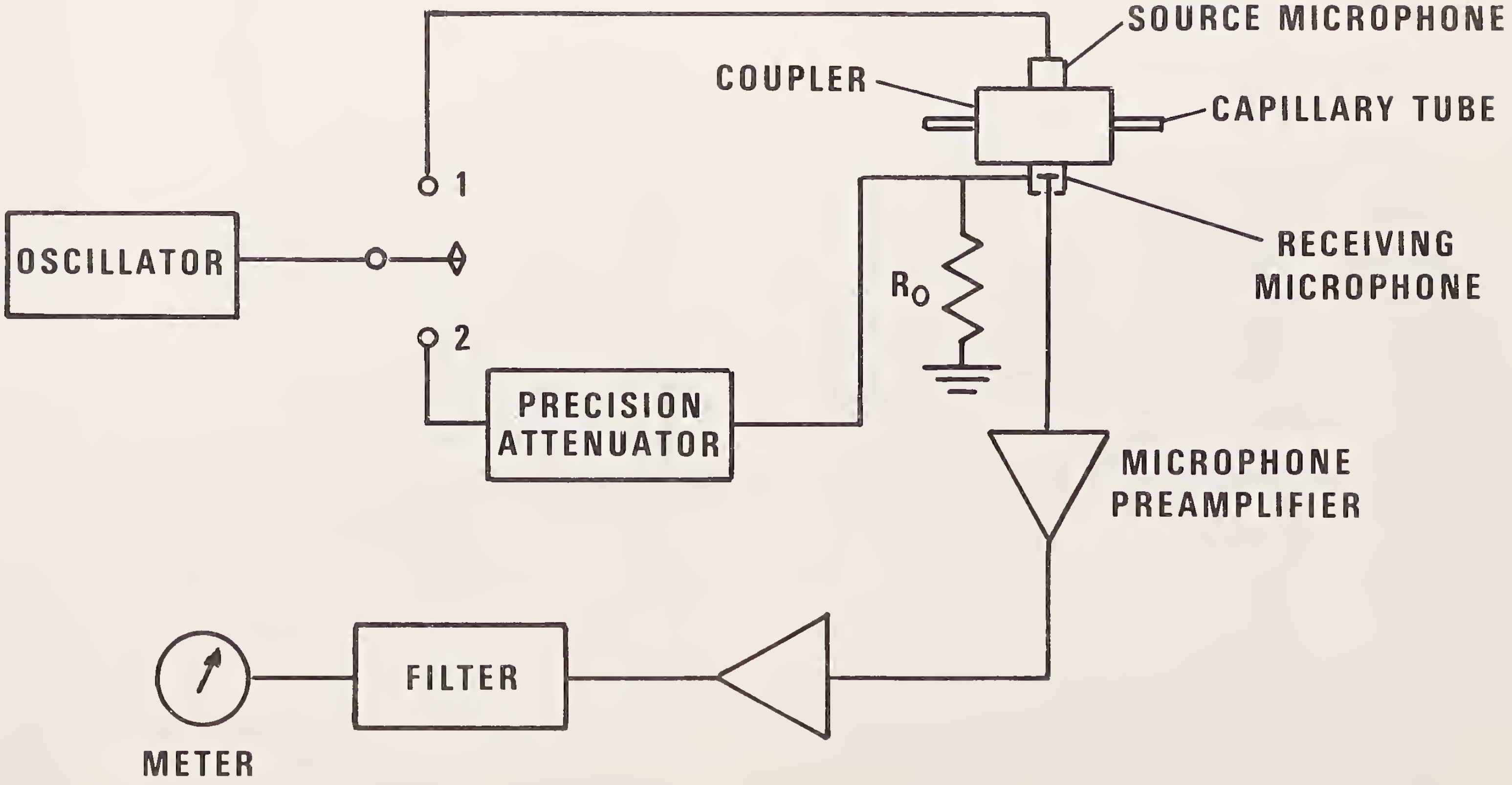

FIGURE A-1. SCHEMATIC OF EQUIPMENT REQUIRED FOR THE VOLTAGE RATIO MEASUREMENTS.

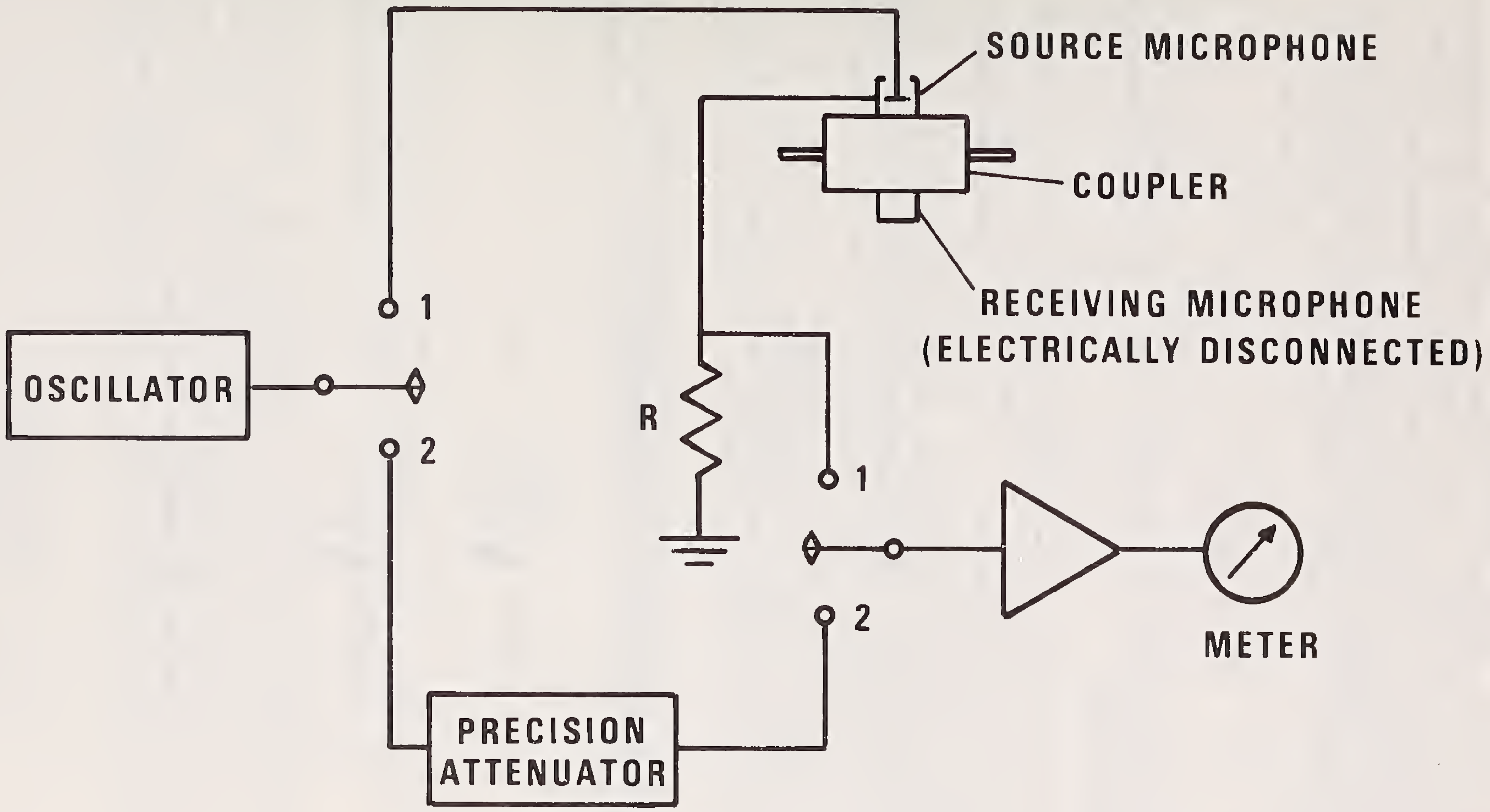

FIGURE A-2. SCHEMATIC OF EQUIPMENT REQUIRED FOR THE MEASUREMENT OF THE CAPACITANCE OF THE SOURCE MICROPHONE.

a voltage is placed across the source microphone, which is in series with a resistance R. The reading, denoted M_1, of the meter that is connected across the resistance R is recorded. The two switches are now placed in position 2 and the attenuator, which is calibrated in hundredths of a decibel, is adjusted so that the meter again reads M_1. If the microphone is assumed to be purely capacitive with an impedance at the given frequency that is much larger than R, the capacitance of the microphone, C, is given by

$$C = \frac{1}{2\pi fRV_3} \tag{A-1}$$

where f is the frequency of the oscillator (Hz), $V_3 = 10^{(-A_c/20)}$ and A_c is the attenuator reading in dB.

The reciprocity calibration method used three microphones denoted #0, #1, and #2, and the two types of measurements discussed above to determine the pressure response of two of them (#1 and #2). Microphone #0, which will not be calibrated, is used as a source. With microphone #0 as the source and microphone #1 as the receiver the voltage ratio V_1 is obtained. With microphone #0 as the source and microphone #2 as the receiver a voltage ratio V_2 is obtained. Lastly, with microphone #1 used as a source and microphone #2 as the receiver a quantity V_{21}, defined as the ratio of the output voltage of microphone #2 to the input voltage to microphone #1, is obtained. These three sets of measurements and some correction factors described below, will yield the pressure response of microphones #1 and #2.

From Section 4 of Ref. 1 the expressions for the pressure response of microphones #1 and #2, denoted r_1 and r_2, respectively, are

$$r_1 = K\sqrt{G(f)}\sqrt{\frac{V_2}{V_1}V_{21}} \quad \text{V/Pa} \tag{A-2}$$

$$r_2 = K\sqrt{G(f)}\sqrt{\frac{V_1}{V_2}V_{21}} \quad \text{V/Pa} \tag{A-3}$$

where

$$G(f) = \frac{1}{P_s C}\Delta(f,f_o) \tag{A-4}$$

and

$$\Delta(f,f_o) = \frac{\sin(\pi f/f_o)}{(\pi f/f_o)} \tag{A-5}$$

In Eqs. (A-2) to (A-4) f and R are defined as in Eq. (A-1), P_s is the ambient barometric pressure, f_o is the first longitudinal natural frequency of the coupler, and K is a constant. For the setup used in this experiment the value of f_o was the frequency at which the first maximum value of the output of the receiving microphone was obtained when the frequency was varied with a constant voltage applied to the source microphone. The quantity K is a function of the volume of the coupler and the equivalent volumes of the microphones, adjustments for the heat conduction effects at the walls of the cavity and the presence of the capillary tubes in the coupler, and the ratio of the specific heats of air. The latter is virtually independent of temperature over the range considered, and while the volumes and capillary correction change very slightly with temperature, they have been assumed to remain constant. The constant K has been eliminated from the final results by referencing the r_j to their respective values at a given frequency and temperature.

A.3. Comparison Method

Comparison calibrations used microphone #1 as the source and the electret and ceramic microphones as the receiving ones. The pressure response of these microphones is then determined from the expression

$$P_\alpha = \frac{K_\alpha \beta \Delta(f, f_\alpha)}{P_s V_\alpha} \quad \text{V/Pa} \tag{A-6}$$

where f_α is the first longitudinal natural frequency of the coupler with the microphone α as the receiver, V_α is the voltage ratio, K_α is assumed constant,

$$\beta = \frac{K}{r_1 C} \tag{A-7}$$

and r_1 is given by Eq. (A-2) and C by Eq. (A-1). The constant K_α is eliminated by referring the pressure response to its response at a given frequency and temperature.

In arriving at Eqs. (A-1) through (A-7) several assumptions were made regarding the effects of temperature on some of the constants in Eqs. (A-2), (A-3) and (A-6). Furthermore, there may be inaccuracies in the measurements themselves. The estimated maximum value of the errors introduced by these two factors is tabulated in Table A-1 which indicates that the total maximum absolute error that exists in the results presented is probably less than 0.2 dB.

A.4. References

1. "Method for the Calibration of Microphones," S1.10-1966, American National Standards Institute, New York, N. Y.
2. W. Koidan, "Method for Measurement of $|E'/I'|$ in the Reciprocity Calibration of Microphones," J. Acoust. Soc. Amer. 32, 611 (1960).

TABLE A-1

Estimated Magnitudes and Sources of Errors in the Microphone Calibration Data

Source of Error	Estimated Maximum Error (dB)
Assumptions that the following are independent of temperature:	
1. Volume of coupler	0.02
2. Coupler capillary corrections	0.02
3. Heat conduction correction	0.06 dB @ 100 Hz (less at higher freq.)
4. Equivalent volumes of microphones	Unknown
Accuracy of measurement	
6. Resonance frequency	0.02
7. Attenuator readings (combined)	0.04 (reciprocity) 0.05 (comparison)
8. Barometric pressure	0.01

APPENDIX B

MEASUREMENT ASSURANCE PROGRAM

B.1. Introduction

This appendix presents a detailed outline of a method whereby one can determine both an estimate of the precision of the sound level meter readings and whether or not this precision is, at all times, within acceptable limits; that is, whether or not the measurement process is in control.

B.2. Initial Determination of Process Parameters (to be done for each meter)

B.2.1. Errors in Meter Calibration

For: (Description of sound level meter)
Use: (Truck tire noise, factory noise, ...)

Meter: __________
Factors: (orientation, height from ground, sound source, etc.)

TABLE B-1

Determination of Sound Level Meter Calibration Errors

Method of Signal Generation[a]			Low Level			Middle Level	High Level
Date	Time	Meas. No.	Reading from Reference Standard[b] y (dB)	Reading from Meter x (dB)	Difference b=x-y (dB)	. . . y (dB)	. . . x (dB)
*	*	1	*	*	*		
*	*	2	*	*	*		
*	*	3	*	*	*		
*	*	m-1	*	*	*		
*	*	m	*	*	*		

average; $\bar{b}$ = ________ ________ ________

standard deviation; $\hat{\sigma}_b$ = ________ ________ ________

uncertainty in reference standard U_s: ________ ________ ________

meter calibration[c] error limit: $U_s + |\bar{b}| + 3\hat{\sigma}_b/\sqrt{m}$ = ________ ________ ________

---

[a] The signal should have characteristics nearly like the quantity to be measured.

[b] Reference standard should itself have a history of stability, relative immunity to environmental changes or signal characteristics, etc.

[c] If $|\bar{b}|$ is large, it should be applied as a correction to the meter and $|\bar{b}|$ should be omitted from this error limit.

B.2.2. Meter Random Errors

Meter #1 __________
Meter #2 __________
Factors: (orientation, height from ground, sound source, etc.)

TABLE B-2

Determination of Sound Level Meter Random Errors

Event	Meas. No.	Reading from Meter #1 x (dB)	Reading from Meter #2 z (dB)	Difference d=x-z (dB)
(A series of measurements which "sample" the type, level and external conditions of practical measurements. If more than one measurement per day is taken, the full set of procedures used to start a new day should be done between measurements.)	1			
	2			
	3			
	.			
	.			
	n-1			
	n			

average; $\bar{d}$ = ________

standard deviation; $\hat{\sigma}_d$ = ________

$\hat{\sigma} = \hat{\sigma}_d/\sqrt{2}$ = ________

If $\frac{\bar{d}\sqrt{n}}{\hat{\sigma}_d} > 2.59$, an explanation should be sought in the bias in the meter calibration (values of $\bar{b}$ as determined in Table B-1). If this is not sufficient, presumably some procedural difficulty exists. The process should not be implemented for practical measurements until changes have been made to eliminate this bias between instruments.

A plot of d versus x should be made to see if the variability is a function of noise level. If a dependence exists, the data should be collected for each of a number of groups within each of which the variation can be regarded as homogeneous.

The standard deviation $\hat{\sigma}_b$, obtained from Table B-1, and $\hat{\sigma}$, obtained from Table B-2, should be the same except for the effects of random error. If $\hat{\sigma}_b/\hat{\sigma} > F$ (.01, m-1, n-1) where F is the critical value of the F distribution for (m-1) and (n-1) degrees of freedom exceeded with probability .01, then the two meters show a correlated response and $\hat{\sigma}_b$ should be used as the process parameter for random error, $\hat{\sigma}_R$. Otherwise $\hat{\sigma}_R = \hat{\sigma}$. In the expression for F, m is given in Table B-1.

B.2.3. Meter Systematic Errors

Meter: __________
Factors: (orientation, reflecting surface, obstructions, etc.)

TABLE B-3

Determination of Sound Level Meter Systematic Errors

Source of Signal (equivalent to type of sound to be measured)[a]		Level 1	Level 2		Level k
Test No.	Day/Time	Reading Value x_1 (dB)	Reading Value x_2 (dB)	...	Reading Value x_k (dB)
1		*	*		*
2		*	*		*
3		*	*		*
.		.	.		.
.		.	.	...	.
.		.	.		.
n-1		*	*		*
n		*	*		*
	Averages	$\bar{x}_1$	$\bar{x}_2$		$\bar{x}_k$

---

[a] If a reproducible signal source is not available, differences from the value given by a reference standard may be used.

Unless some physical model exists (i.e., functional form) the difference between the maximum and minimum will be taken as the limit to the possible systematic error, E; from this factor, that is,

$$E = \bar{x}_{max} - \bar{x}_{min}$$

For each factor involved, the systematic error for each will be determined by this method, provided the effects of joint variation of two factors are additive and independent.

A list of those factors known to have some effect, but which were not investigated, should be maintained.

B.2.4. Uncertainty

The uncertainty of a single determination is given by

$$U_s + |\bar{b}| + \frac{3\sigma_b}{\sqrt{m}} + \Sigma E_i + 3\hat{\sigma}_R \qquad \text{(B-1)}$$

where m is given in Table B-1.

B.3. Maintenance of Process

B.3.1. Duplicate Measurements

A schedule for making duplicate determinations by a second meter will be incorporated into the regular work load to give values as shown in Table B-4. These should be spread far enough apart in time so that successive results are statistically independent.

TABLE B-4

Determination of Process Control Parameters

Number	Event/Date	Reading from Meter #1 x (dB)	Reading from Meter #2 y (dB)	Difference d (dB)
1		*	*	*
2		*	*	*
3		*	*	*
4		*	*	*
5		*	*	*
Summary after each group of 5 events			average; $\bar{d}_5$ =	________
			standard deviation; s_5 =	________
6		*	*	*
7		*	*	*
8		*	*	*
.				
.				

If $|\bar{d}_5 - \bar{d}|/(\hat{\sigma}_d/\sqrt{5}) > 3$ the process is out of control in that one or both of the meters give erroneous results. Recalibration may be necessary.

If $s_5/\hat{\sigma}_d > \sqrt{F(0.01,5,n)}$ where F is the critical value of the F probability distribution (with 5 and n degrees of freedom, where n is given in Table B-2) exceeded with probability .01, then the process is out of control on variability. Table B-2 should therefore be repeated to establish a new value for $\hat{\sigma}_d$.

The values for $\bar{d}$ and $\hat{\sigma}_d$ should be periodically updated by incorporating this sequence of differences with those of Table B-2.

B.3.2. Check on Systematic Errors

Differences between Meter #1 and Meter #2 arising in the subsection on duplicate measurements will be plotted as a function of time, and also as a function of average meter readings, of values for ambient conditions (e.g., temperature) and any other variables known to affect noise measurements. A significant dependence of the result on these variables will be studied with a view to adjusting the uncertainty statement appropriately.

A schedule of measurement designed to confirm the values of the meter's systematic errors should be implemented.

B.4. Statement of Uncertainty

If the process may be regarded as being in a state of statistical control then the uncertainty value given by Eq. (B-1) will be used.

APPENDIX C

SOME ELECTRICAL CHARACTERISTICS OF SOUND LEVEL METERS

C.1. Detector Circuit

In order that one record the correct sound level as measured by a sound level meter it is necessary to ascertain how accurately its detector circuit can convert a wide variety of signals into a rms value. As far as the detector circuit is concerned it is sufficient to consider only a class of well-characterized signals in which the ratio of the peak value of the signal to its rms value varies. Such a ratio is called the crest factor and is presented mathematically in Section C.3. The signal chosen to investigate the detector circuits was a tone burst, which is also defined explicitly in Section C.3. The experimental technique, which is discussed subsequently, determined not only the accuracy of the detector circuit but also that of the A-weighting network.

The accuracy of the detector and the A-weighting network is determined as follows. The microphone is removed and the sound level meter is switched to A-weighting and to "slow" meter response. A continuous signal at one of the center frequencies of the octave bands from 125 to 4000 Hz is passed through a precision attenuator calibrated in 0.01-dB increments. The attenuator is set such that the output of the continuous signal corresponds to 80 dB full scale. The signal is now converted to a tone burst having the number of "on" and "off" cycles described in Section C.3. The attenuator is adjusted until the meter again reads 80 dB. The difference in the attenuator readings for the continuous signal and for the tone burst is denoted Δ_m (dB). The theoretical value of this attenuation, which is also computed in Section C.3., is denoted Δ_t (dB). The differences between these two values, $\Delta_t - \Delta_m$, gives a measure of the accuracy of the sound level meter's detector and A-weighting network as a function of frequency and crest factor. Typical results for one sound level meter from each of four manufacturers are given in Tables C-1 to C-4. As can be seen from these results there is considerable variation in the error as a function of frequency for three of the four sound level meters. Thus one should expect large errors in the sound level meter readings when noises that are impulsive in character, such as in factories using punch presses, dropforges, or any type of machinery that has an intermittent cycle, are being measured with sound level meters having large errors at high crest factors.

C.2. Meter Linearity

In addition to the possible errors caused by the sound level meter's detector circuit as a function of the crest factor of the signal there is also the linearity of the meter scale itself and the linearity of the range potentiometer to be considered. Both these errors can relatively easily be experimentally determined and corrected for in all subsequent readings taken with that particular meter. Typical values obtained for

TABLE C-1

Difference Between $\Delta_t - \Delta_m$ for SLM-U as a Function of Frequency and Crest Factor*

$\Delta_t - \Delta_m$ (dB)

N/M	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
			Full Scale			
8	- .3	- .32	- .33	- .37	- .50	- .70
4	- .64	- .64	- .65	- .67	- .77	- .97
2	-1.03	-1.11	- 1.02	- 1.03	- 1.10	- 1.30
1	-1.25	-1.2	- .86	- 1.20	- 1.30	- 1.47
1/2	- .95	- .89	- .78	- .90	- .96	- 1.10
1/4	- .11	- .07	- .02	- .06	- .07	- .20
1/8			+ .69	+ .65	+ .55	+ .59
1/16			- 4.09	- 4.30	- 4.23	-10.03
1/32			-23.28	-26.33	-30.97	-33.87
1/64				-30.10		
			Full Scale - 10 dB			
8	- .37	- .4	- .32	- .47	- .56	- .80
4	- .82	- .84	- .80	- .91	- .90	- 1.25
2	-1.58	-1.61	- 1.59	- 1.61	- 1.68	- 1.95
1	-2.82	-2.8	- 2.21	- 2.87	- 2.86	- 3.10
1/2	-4.46	-4.54	- 4.15	- 4.51	- 4.50	- 4.67
1/4	-5.9	-6.01	- 5.97	- 6.05	- 6.04	- 6.15
1/8	-6.01	-6.15	- 6.16	- 6.20	- 6.13	- 6.19
1/16	-4.91	-5.11	- 5.18	- 5.14	- 5.02	- 5.05
1/32		-4.62	- 4.17	- 4.01	- 3.84	- 3.80
1/64			-11.94	-11.30	-10.21	-18.73
1/128			-24.23	-25.54	-26.13	-24.31

---

*See Section C.3. for the definitions of N and M and Table C-5 for the corresponding crest factors.

TABLE C-2

Difference Between $\Delta_t - \Delta_m$ for SLM-V as a Function of Frequency and Crest Factor*

$\Delta_t - \Delta_m$ (dB)

N/M	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
			Full Scale			
8	+ .07	+ .08	+ .04	+ .03	- .06	- .25
4	+ .03	+ .06	+ .05	+ .10	.00	- .22
2	- .16	- .17	+ .02	+ .11	+ .05	- .18
1	- .68	- .76	- .84	- .91	- .51	- .40
1/2	-1.02	-1.19	- 1.74	- 1.34	- .80	- .65
1/4	-1.4	-1.71	- 2.71	- 2.08	- 1.42	- 1.37
1/8	-2.11	-2.89	- 4.54	- 3.25	- 2.65	- 2.71
1/16			-37.54	-36.60	-26.71	-18.03
1/32						-35.12
			Full Scale - 10 dB			
8	+ .13	+ .05	+ .09	+ .13	.00	- .25
4	+ .08	+ .11	+ .15	+ .09	+ .05	- .19
2	- .01	- .04	+ .15	+ .19	+ .10	- .10
1	- .44	- .5	- .51	- .57	- .26	- .25
1/2	- .68	- .8	- 1.24	- .91	- .40	- .34
1/4	- .95	-1.21	- 1.91	- 1.38	- .82	- .83
1/8	-1.45	-1.95	- 2.84	- 2.20	- 1.80	- 1.81
1/16	-2.16	-3.36	- 3.94	- 3.50	- 3.31	- 3.43
1/32		-5.02	- 5.37	- 5.28	- 5.17	- 5.32
1/64			-11.34	-10.15	-10.21	-10.93
1/128			-29.68	-21.14	-14.93	-16.96

---

*See Section C.3. for the definitions of N and M and Table C-5 for the corresponding crest factors.

TABLE C-3

Difference Between $\Delta_t - \Delta_m$ for SLM-W as a Function of Frequency and Crest Factor*

$\Delta_t - \Delta_m$ (dB)

N/M	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Full Scale						
8	+ .03	0.00	+ .09	- .07	- .06	- .35
4	- .02	+ .01	- .39	- .01	- .10	- .39
2	0.00	+ .06	- .30	- .01	- .10	- .30
1	+ .07	+ .10	+ .05	+ .03	- .06	- .25
1/2	+ .08	+ .10	+ .01	+ .09	0.00	- .19
1/4	+ .10	+ .19	- .07	+ .02	+ .03	- .17
1/8	+ .25	+ .20	+ .19	+ .10	+ .20	- .01
1/16	+ .46	- .06	- .03	+ .30	+ .29	+ .07
1/32		- .02	- .12	+ .07	- .07	- .32
1/64			-1.43	-1.50	-1.71	-2.03
1/128			-6.08	-5.14	-5.83	-9.11
Full Scale - 10 dB						
8	- .07	+ .04	- .01	+ .03	- .06	- .35
4	- .07	+ .06	+ .05	+ .09	0.00	- .39
2	- .03	+ .06	+ .06	+ .09	0.00	- .40
1	- .03	+ .03	+ .29	+ .13	- .06	- .35
1/2	+ .02	+ .06	+ .26	+ .19	0.00	- .34
1/4	+ .03	+ .09	+ .19	+ .12	+ .03	- .32
1/8	+ .11	+ .05	+ .16	+ .20	+ .10	- .26
1/16	+ .23	+ .01	+ .16	+ .20	+ .09	- .23
1/32		- .05	+ .23	+ .27	+ .13	- .22
1/64			+ .26	+ .28	+ .19	- .13
1/128			+ .32	+ .36	+ .22	- .01

---

*See Section C.3. for the definitions of N and M and Table C-5 for the corresponding crest factors.

TABLE C-4

Difference Between $\Delta_t - \Delta_m$ for SLM-Y as a Function of Frequency and Crest Factor*

$\Delta_t - \Delta_m$ (dB)

N/M	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
			Full Scale			
8	+ .03	+ .07	+ .09	+ .08	+ .04	- .30
4	- .02	+ .04	+ .05	+ .12	+ .10	- .24
2	- .23	- .17	+ .11	+ .19	+ .17	- .13
1	- .82	- .80	- .81	- .82	- .30	- .25
1/2	-1.08	-1.13	- 1.79	- 1.11	- .34	- .29
1/4	-1.50	-1.71	- 2.86	- 1.42	- .61	- .62
1/8			-36.34	- 7.60	- 3.84	- 3.21
1/16			-54.14	-40.40	-37.11	-37.23
1/32			-53.37	-48.13	-36.57	-36.17
1/64			-48.18		-33.61	-33.03
1/128					-30.53	-30.16
			Full Scale - 10 dB			
8	- .02	0.00	- .01	- .07	- .26	- .40
4	- .08	- .04	+ .05	- .01	- .30	- .39
2	- .43	- .34	- .14	- .11	- .30	- .40
1	-1.22	-1.15	- 1.11	- 1.22	- .86	- .65
1/2	-1.57	-1.54	- 2.34	- 1.71	- 1.10	- .89
1/4	-1.95	-1.96	- 3.31	- 2.18	- 1.57	- 1.37
1/8	-2.51	-2.7	- 4.04	- 2.85	- 2.40	- 2.41
1/16	-3.29	-4.01	- 4.94	- 4.10	- 3.81	- 3.88
1/32		-9.62	-10.37	- 7.73	- 7.07	- 6.82
1/64			-33.54	-27.50	-20.01	-18.23
1/128			-33.38	-32.38	-22.63	-21.41

---

*See Section C.3. for the definitions of N and M and Table C-5 for the corresponding crest factors.

one Type II sound level meter from each of four manufacturers are shown in Figs. C-1 and C-2. Figure C-1 shows the linearity of the meter scale referenced to 10 dB down from full scale. Figure C-2 shows the linearity of the range potentiometers or the meter scales.

C.3. Crest Factor of a Tone Burst through an Ideal A-weighting Network

Consider a sinusoidal signal of frequency f_o that has a peak magnitude A_o. If this signal is altered such that it is "on" for an integer number of cycles N, "off" for an integer number of cycles M, and passed through an ideal A-weighting network, then it is not too difficult to show that the square of the rms value of this altered signal, V_D^2, can be expressed as

$$V_D^2 = \sum_{n=1}^{\infty} |C_n|^2 H(nf_o') \qquad \text{(C-1)}$$

where $f_o' = f_o/(N+M)$,

$$|C_n|^2 = \frac{A_o^2}{2\pi^2(N+M)^2}\left[1 - \left(\frac{n}{N+M}\right)^2\right]^{-2}\left[1 - \cos\left(\frac{2\pi n}{1+M/N}\right)\right] \qquad n \neq M+N$$

$$|C_n|^2 = \frac{A_o^2}{4}\left(\frac{N}{N+M}\right)^2 \qquad n = M+N$$

and

$$H(nf_o') = \prod_{j=1}^{4} H_j(nf_o')$$

is the ideal A-weighting given by

$$H_1(f) = \frac{1.0042\ (f/20.6)^2}{1 + (f/20.6)^2}$$

$$H_2(f) = \frac{1.0067}{1 + (f/12200)^2}$$

$$H_3(f) = \frac{1.0116\ (f/107.7)^2}{1 + (f/107.7)^2}$$

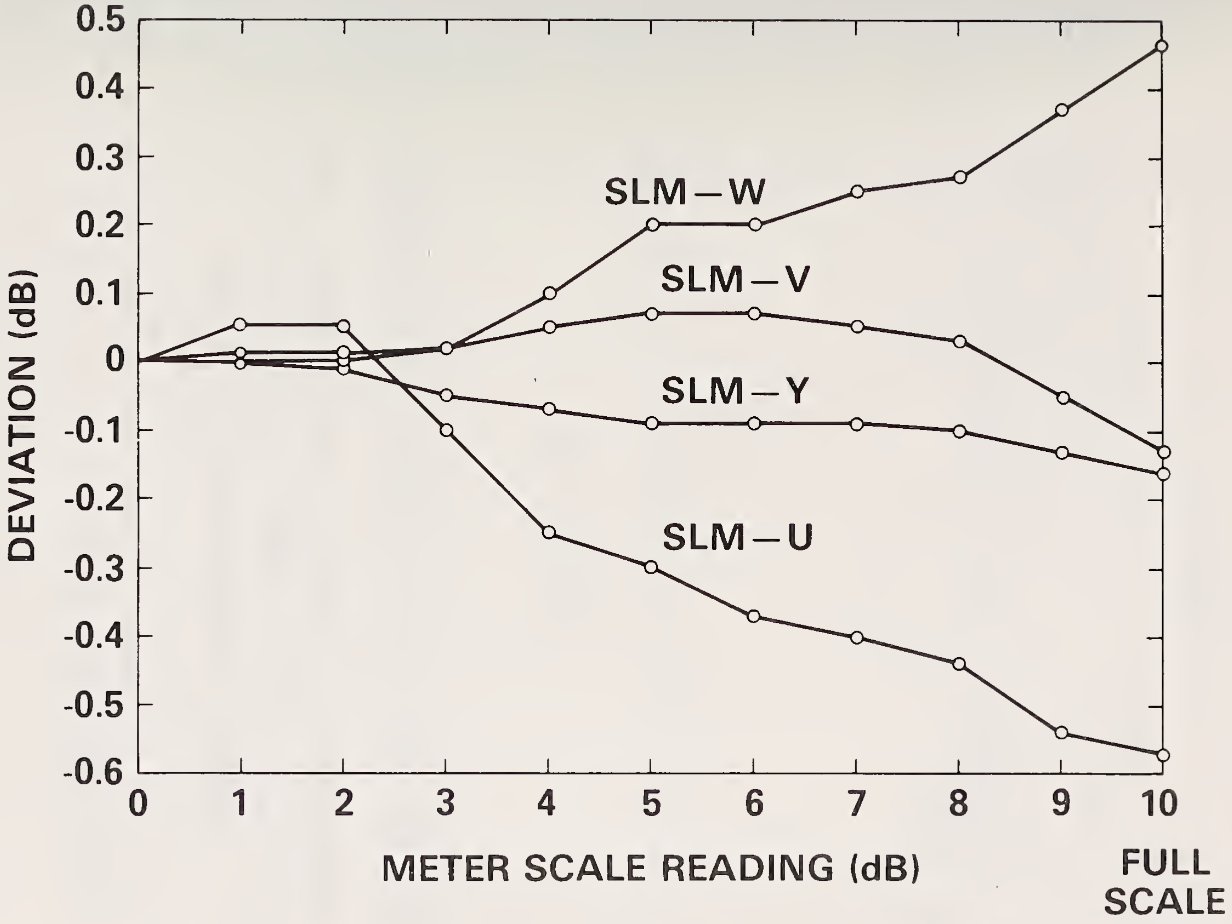

Figure C-1. Linearity of the meter scale of four different sound level meters.

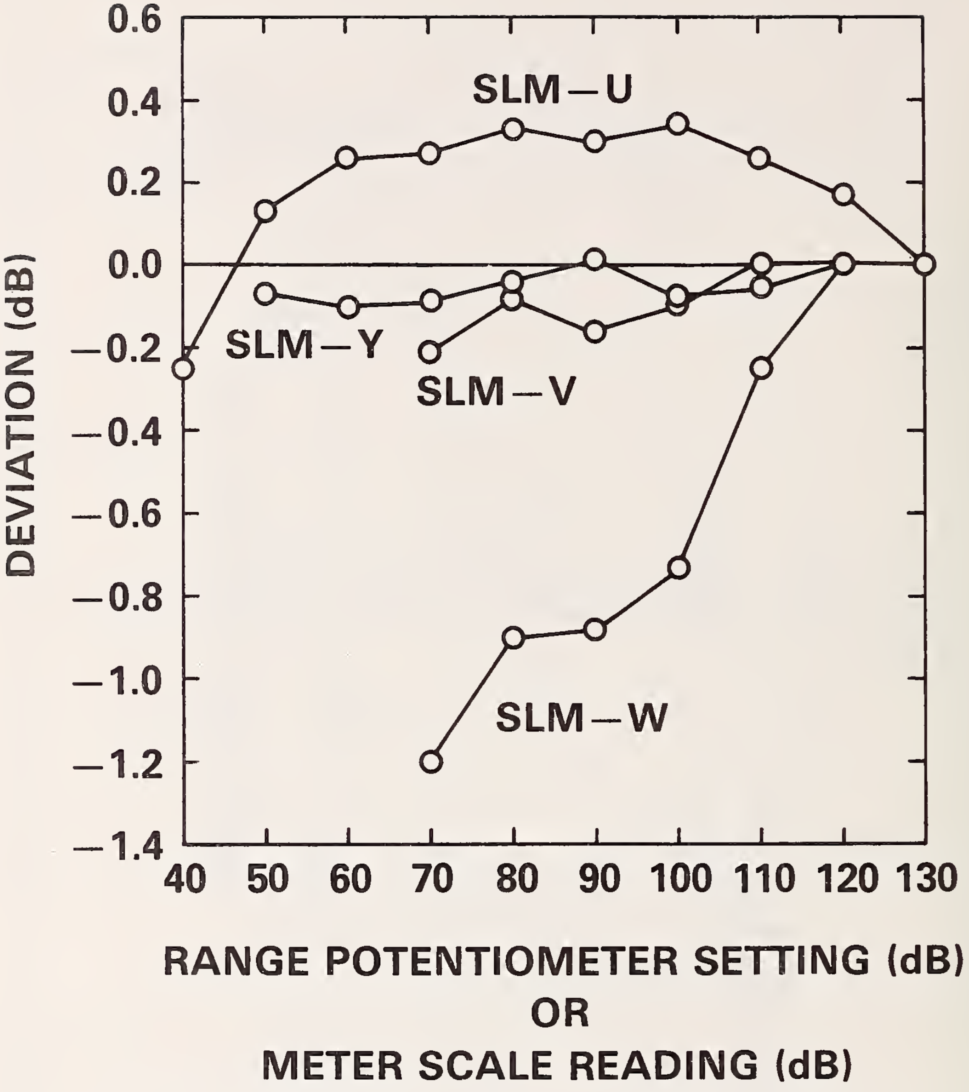

FIGURE C-2. LINEARITY OF THE RANGE POTENTIOMETER OR METER SCALE OF FOUR DIFFERENT SOUND LEVEL METERS.

$$H_4(f) = \frac{1.5445\ (f/737.9)^2}{1 + (f/737.9)^2}$$

The crest factor, CF, is given by

$$CF = 20 \log_{10} (A_o/V_D) \quad dB. \tag{C-2}$$

Using Eq. (C-1), the crest factor given by Eq. (C-2) is evaluated for various combinations of frequency and N/M and presented in Table C-5.

For a continuous signal N=1 and M=0, yielding $|C_n| = 0$, $n \neq 1$, and $|C_1| = A_o/2$. Consequently $V_D \rightarrow V_C$, the rms voltage for a continuous sinusoidal signal, where

$$V_C = \frac{A_o}{2} \sqrt{H(f_o)}$$

Since the tone burst contains less energy than the continuous signal $V_C > V_D$. Therefore, the decrease in amplitude compared to the continuous signal, denoted Δ_t, is

$$\Delta_t = 20 \log (V_C/V_D) \quad dB.$$

The quantity denoted Δ_m in Section C.1 is the measured value of this decrease. Therefore, the difference $\Delta_t - \Delta_m$ indicates the deviation from the true value.

It should be noted that the preceding analysis does not include the effects of the period and the damping of the meter movement. These effects (if any), however, are included in the Δ_m obtained by the method described in Section C.1.

TABLE C-5

Theoretical Crest Factor for a Tone Burst of Various Frequencies when Passed through an Ideal A-Weighting Network*

	Crest Factor (dB)						
N/M	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	Linear
8	3.53	3.60	3.59	3.53	3.44	3.15	3.52
4	3.98	4.06	4.05	3.99	3.90	3.61	3.98
2	4.77	4.86	4.86	4.79	4.70	4.40	4.77
1	6.02	6.10	6.09	6.03	5.94	5.65	6.02
1/2	7.78	7.86	7.86	7.79	7.70	7.81	7.78
1/4	10.00	10.09	10.09	10.02	9.93	9.63	10.00
1/8	12.55	12.65	12.66	12.60	12.50	12.19	12.55
1/16	15.31	15.44	15.46	15.40	15.29	14.97	15.31
1/32	18.18	18.38	18.43	18.37	18.23	17.88	18.20
1/64	21.11	21.43	21.56	21.50	21.29	20.87	21.14
1/128	24.06	24.65	24.92	24.86	24.47	23.89	24.12

---

*N is the number of "on" cycles of the tone burst of frequency f_o and M is the number of "off" cycles. The period of the signal is $(N+M)/f_o$.

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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.)*

For four different manufacturer's Type II sound level meters numerous experimentally determined data concerning the effects of frequency, temperature, angle of incidence of the sound, and types of ground cover and reflecting surfaces on sound level meter readings are presented. Data are also given for the effects of ambient barometric pressure on several manufacturers' acoustic calibrators, the effect of frequency and crest factor on the sound level meters' detector circuit, the linearity of the sound level meters' range potentiometer and meter scale, and the precision of the A-weighted response in a randomly incident (diffuse) sound field. Additional data are given concerning the effects of temperature and humidity on the sensitivity of electret, condenser, and ceramic microphones. Finally, important statistical concepts and recommended data monitoring procedures are presented to insure that the precision of repeated sound level measurements is known.

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)*

Acoustic calibrators; A-weighting; barometric pressure; crest factor; ground cover; humidity; instrumentation; microphones; sound level meters; statistical control processes; temperature.

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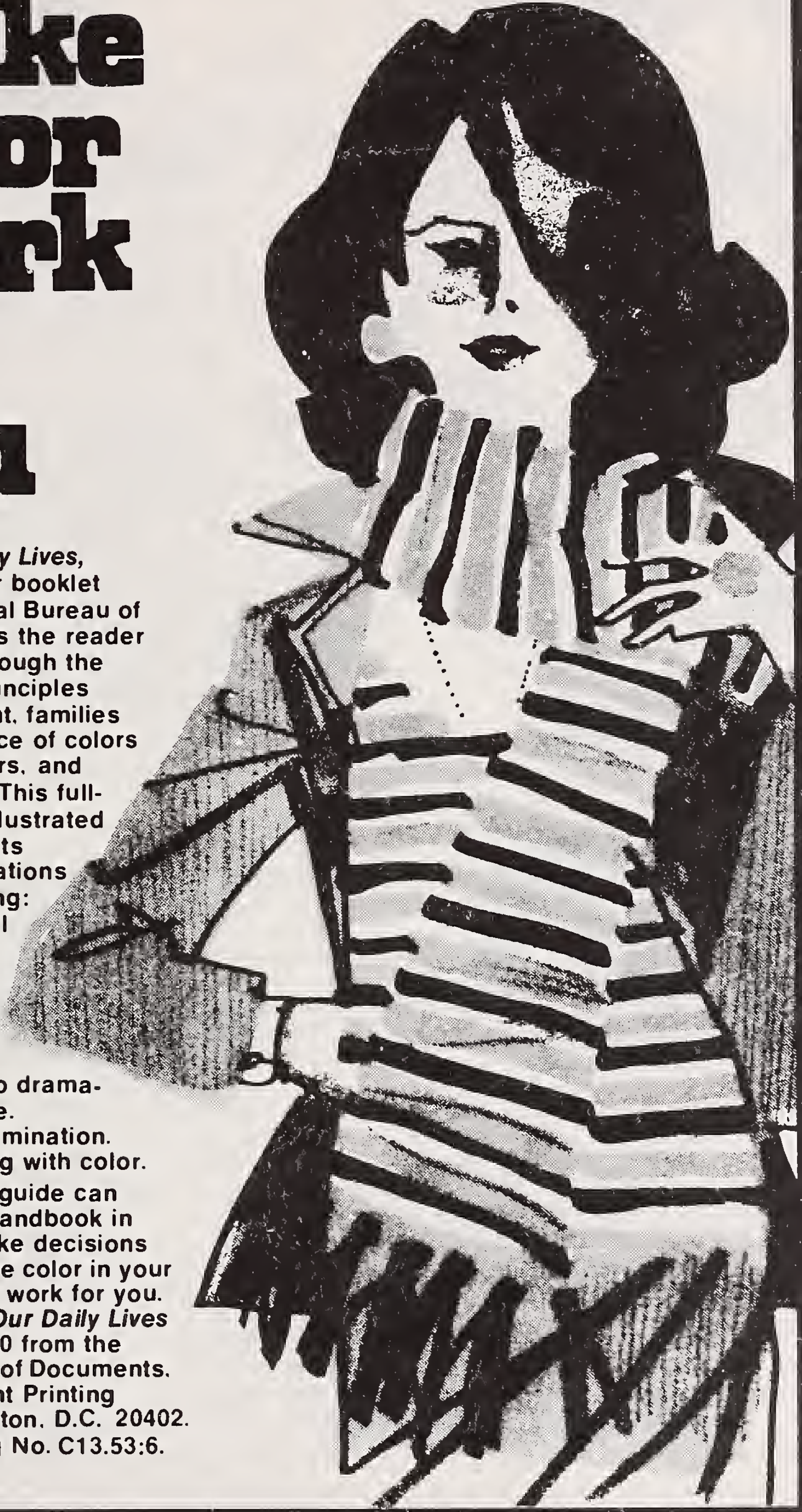

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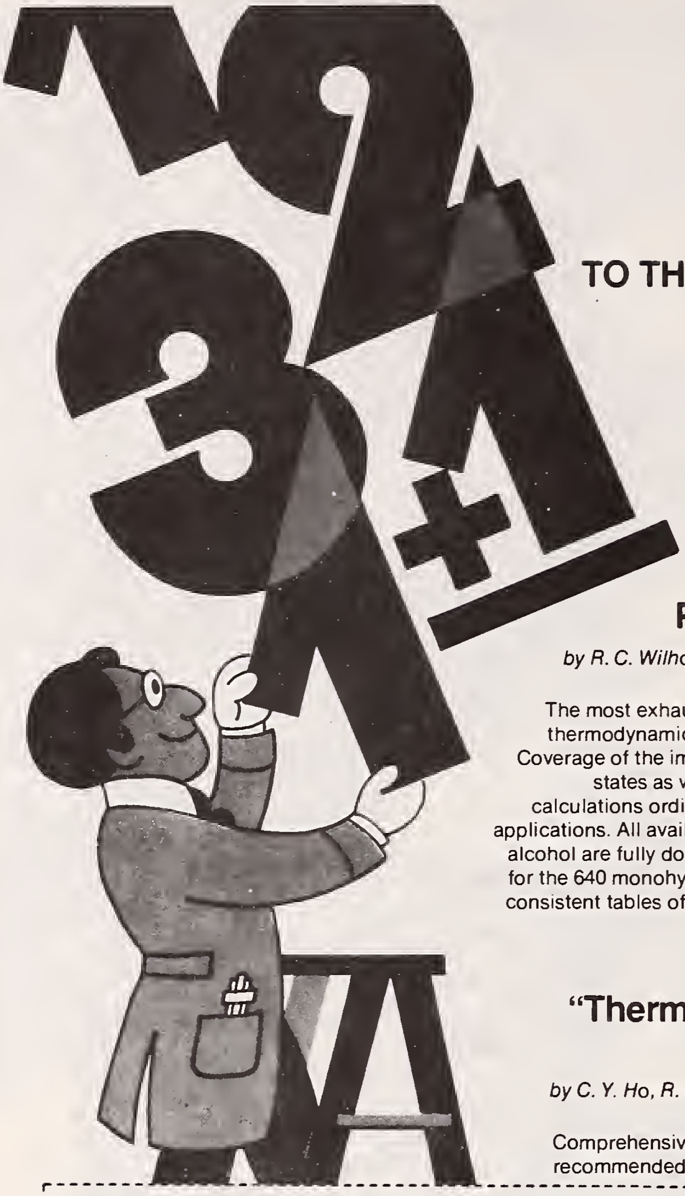

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