Everything You've Wanted To Know About Measurement Microphones

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There are three basic types of measurement microphones, distinguished by their principle of operation, in common use. These types are the piezoelectric ceramic or "ceramic," air-condenser or "condenser," and electret-condenser or "electret." The purpose of this article is to acquaint the reader with the performance and environmental characteristics, and applications for each type. Much information about the characteristics of air-condenser and ceramic microphones has been published, but little iinformation about the electret-condenser microphone is available, simply because the electret measurement microphone has been available for only a few years. For this reason, greater emphasis is placed on the characteristics of the electret-condenser microphone which is frequently compared with the other two types.

It may seem that a microphone for measurement (or other purposes) is a simple device. It should respond to the rapid changes in air pressure associated with sound to produce an output voltage that is a replica of the air pressure variations. The principle is rather simple, but in practice many characteristics must be carefully controlled to achieve satisfactory performance. The relative importance of these characteristics for a given application must be understood before an informed choice of type and size can be made.

Ceramic Microphone — The ceramic microphone, shown schematically in Figure 1, makes use of the piezoelectric effect in certain materials. Such materials generate a voltage between electrodes in contact with material, when subjected to a mechanical force. In a microphone application, the force is produced by the sound pressure on the microphone's diaphragm. The diaphragm is constructed from very thin, light-weight material and suspended at the perimeter so that its central portion is free to move in response to the sound pressure. The force on the diaphragm is transmitted to the piezoelectric ceramic element through a connecting rod. Output voltage is sensed by electrodes bonded to the ceramic.

Air-Condenser Microphone — The operating principle of an air-condenser microphone, Figure 2, differs markedly from that of the ceramic microphone. An electrical capacitor is formed by a movable, metallic microphone diaphragm and a metallic, fixed back plate. This capacitor is charged, and the charge maintained by an external, regulated power source. Voltage on a capacitor varies inversely with its capacitance if the charge on the capacitor is held constant. The diaphragm's motion in response to the sound pressure results in a capacitance change which produces the output voltage. The diaphragm is very thin and spaced typically 0.02 mm from the fixed back plate of the capacitor.

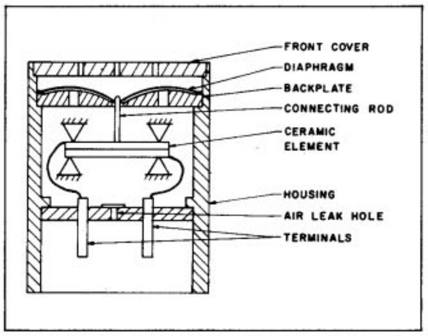

Figure 1 — Ceramic microphone.

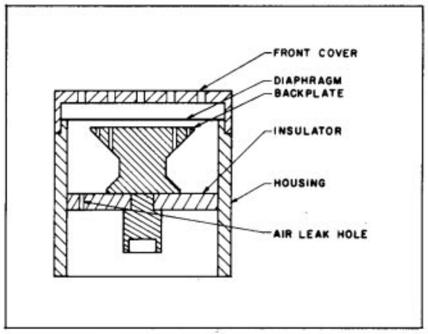

Figure 2 — Air-condenser microphone.

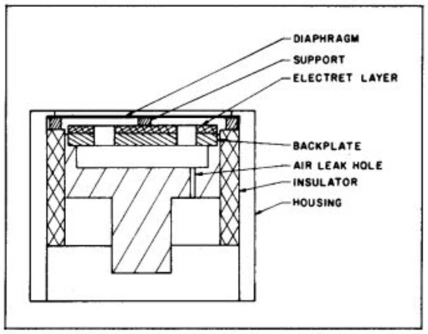

Figure 3 — Electret-condenser microphone.

Electret-Condenser Microphone — The electret-condenser microphone (Figure 3) uses a principle that is similar to that used in the air-condenser microphone. A fundamental difference is that the capacitor's charge is permanently imbedded in a layer of electret material that forms part of the dielectric of the capacitor (i.e., the electret layer is between the diaphragm and back plate). The other element of the dielectric is air. The diaphragm, which is the movable part of a capacitor, is constructed from a thin plastic material coated with a conductive layer of gold.

Sensitivity — The higher the sensitivity of a microphone (smaller negative number expressed in dB re 1 V/Pa), the greater will be its output voltage for a given input sound pressure. A high output voltage means that less amplification is needed in the measuring instrument to which the microphone is connected, and further that any noise generated within the instrument will be lower in relation to the signal produced by the microphone. At a given sound level, "signal-to-noise ratio" (the difference between the signal level and internally generated noise level) will be higher for the sensitive microphone than for one that is less sensitive, if the capacitance of the two microphones is about equal. In modern instruments, amplification is rather easy to achieve so that a high signal-to-noise ratio in the microphone system including the preamplifier, and not just the microphone sensitivity, is the important thing. If measurements are to be made at low levels (say below 40 dB re 20 μPa), then high sensitivity is quite important. On the other hand, a very sensitive microphone may, in fact, be a disadvantage for use at high levels because the larger voltages produced may overload the preamplifier or other circuits and result in distortion.

Measurement microphones range in sensitivity from about −25 dB re 1 volt/Pa to about −60 dB re 1 volt/Pa. There is a clear trade-off between the upper frequency limit (bandwidth) and sensitivity. Microphones of large size having large diameter diaphragms are more sensitive but do not work to as high a frequency limit as microphones of small diameter. Generally, a microphone should be chosen with as high a sensitivity as possible (but not so high as to overload the preamplifier) while still providing an adequate high-frequency response limit. If the upper limit in sound level to be measured will exceed 130 dB, then a microphone with less than maximum sensitivity (and consequently wider frequency range than necessary) should be chosen.

In considering microphone sensitivity, another factor that will be discussed further under the heading of *Dynamic*

Table 1 – Typical sensitivity levels and capacitance values for various measurement microphones.

	One-Inch Diameter		One-Half-Inch Diameter	
	Typical Sensitivity (dB re 1 V/Pa)	Typical Capacitance (Pf)	Typical Sensitivity (dB re 1 V/Pa)	Typical Capacitance (Pf)
Electret Condenser	−38	125	−40	25
Air Condenser	−26	55	−38	18
Ceramic	−40	400	—	—

Definition of Measurement Microphone Characteristics

The performance and environmental characteristics of a measurement microphone must be defined before any discussion and comparison of these characteristics is possible.

Sensitivity — This fundamental characteristic of a measurement microphone relates the output voltage to the input sound pressure. It is usually specified at a single frequency in the range between 200 and 1000 Hz as a level in decibels referred to a sensitivity of one volt of output for one Pascal of input sound pressure (1 volt/Pascal). (One Pascal equals one Newton per square meter.)

Frequency Response — The frequency response is the relative sensitivity level in decibels of the microphone as a function of frequency. It may be specified using a typical curve with tolerance limits. Such a specification is shown in Figure 4 for the one-half-inch diameter Type 1962 Electret-Condenser Microphone calibrated at perpendicular incidence. Another method of specification is simply a statement of upper and lower frequency limits where the relative sensitivity remains within a given tolerance band; for example, "±2 dB from 15 Hz to 15 kHz." A qualifying statement of the angle of incidence of the sound wave for which the stated frequency response applies must be given. Or, alternatively, if response is measured in a closed cavity, this must be stated.

Directional Response — The sensitivity of a measurement microphone would ideally be independent of the angle of incidence of the sound wave. Practical microphones are actually somewhat more sensitive to a sound wave arriving from a direction perpendicular to the plane of its diaphragm than for waves arriving from any other direction. This "directivity" is frequency dependent, becoming more pronounced at high frequencies. The directional response is usually described by a series of "polar curves," each taken at a different frequency, such as those shown in Figure 5.

Dynamic Range — Dynamic range is the range in sound-pressure level over which the microphone system will operate within stated limits of internally generated electrical noise and distortion. This characteristic is specified for a complete microphone system including a microphone and its preamplifier because both internal noise and distortion are dependent on the combination.

Temperature Characteristics — Ideally, the sensitivity of a microphone should not vary with temperature. As a practical matter, small variations are found that may need to be taken into account in critical laboratory-standard applications. These variations are specified by a temperature coefficient usually given as the change in sensitivity level in decibels to be expected for each degree Celsius change in temperature (dB/°C). Alternatively, it may be given as a curve showing sensitivity level as a function of temperature.

Humidity Characteristics — Just as a microphone's sensitivity may vary slightly with temperature, it may also vary slightly with relative humidity. Because the humidity effect is usually only significant above 90% relative humidity, information on this characteristic is not always given. The various microphone types respond in somewhat different ways to humidity, as will be described later. When a specification is given, it may be in terms of a change in sensitivity level for each percent change in relative humidity or as a limit on sensitivity change for a given range in relative humiditiy.

Sensitivity to Vibration — Often a sound field to be measured will be accompanied by vibrations of surfaces in the sound field. For example, a floor on which the microphone is to be mounted may vibrate. Vibration is coupled to the diaphragm through the microphone case and its mounting.

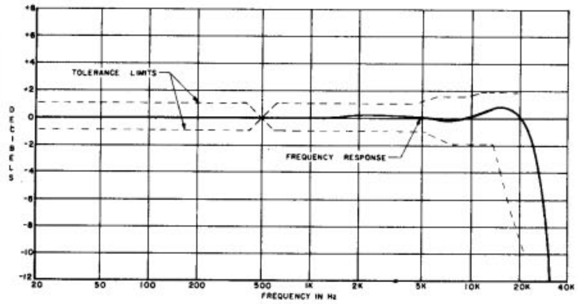

Figure 4 — Frequency response of a GR one-half-inch electret-condenser microphone (perpendicular incidence) with tolerance limits.

Range should be borne in mind. Signal-to-noise ratio is determined not only by microphone sensitivity but also by microphone capacitance. Given two microphones that have identical sensitivity but different capacitance, the one with the higher capacitance will provide better signal-to-noise ratio.

Most general laboratory and field applications are satisfied with microphones of one-inch or one-half-inch diameter having sensitivities in the range from about −30 to −40 dB re 1 volt/Pa. Typical sensitivity levels and capacitance values for various measurement electret-condenser, air-condenser, and ceramic microphones are shown in Table 1.

Frequency Response — Most general laboratory and field applications are satisfied by one-inch or one-half-inch diameter microphones that operate over a frequency range from about 5 Hz to 20 kHz. There are few applications requiring microphones of smaller or larger diameter.

The frequency response of a microphone is dependent on its type, construction, and size. Smaller microphones have wider frequency ranges than larger ones with the wider frequency range being realized at the expense of sensitivity. Because microphones are somewhat directional, the angle in a free-field at which any given frequency response is mea-

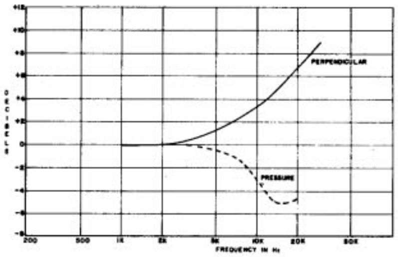

Figure 6 — Correction to perpendicular incidence and pressure response for a one-half inch microphone with uniform random-incidence response.

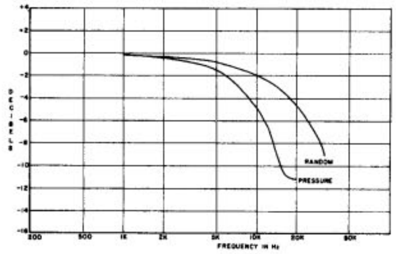

Figure 7 — Correction to random-incidence and pressure response for a one-half inch microphone with uniform perpendicular incidence response.

Output voltage caused by the vibration-induced signal will add to that produced by the sound signal and if of sufficient amplitude, will interfere with the measurement. Microphone vibration sensitivity is usually given in terms of the equivalent sound level that will be produced by a vibration acceleration of 1 g (the acceleration of gravity) applied in a direction perpendicular to the plane of the diaphragm.

Susceptibility to Corrosive Elements in the Atmosphere — Especially in a permanent outdoor installation, the possible effect of atmospheric pollutants should be considered. Corrosive elements acting on the diaphragm may, after long exposure, result in small holes and general deterioration of the diaphragm which will change the sensitivity of the microphone. It is important that any material used in the diaphragm or its mounting structure be chosen so as to be insensitive to atmospheric pollutants.

Long-Term Stability — Slight changes in the sensitivity of a microphone may take place gradually over a long time period. Consideration of such changes is particularly important in a microphone intended as a laboratory reference standard. Stability is sometimes discussed in terms of an average drift rate over a period of one year in the units of decibels/year, in accordance with ANSI Standard S1.12-1967. A standard deviation level that describes the variation about the average drift rate may also be given.

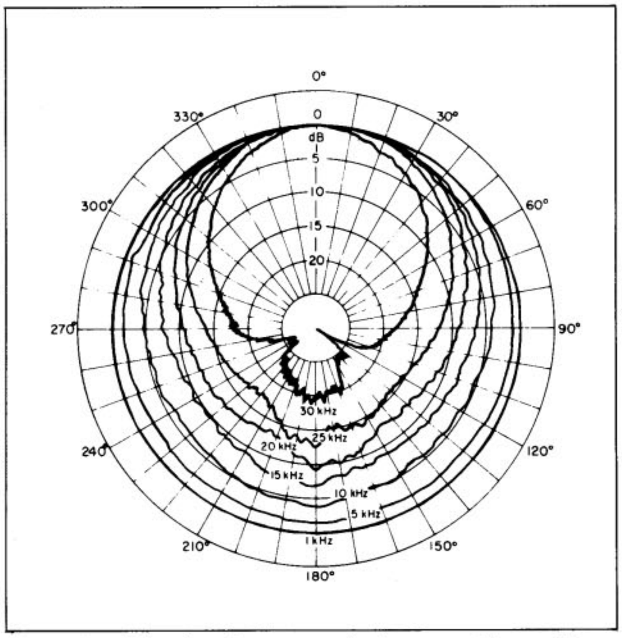

Figure 5 — Directional response (polar curves) for a GR one-half inch electret-condenser microphone.

Impedance — The electrical impedance at the terminals of all three microphone types is that of a small capacitor whose impedance is very high at low audio frequencies; on the order of 10 to 100 megohms. The relative response at low frequencies depends on how the preamplifier input resistance compares with the impedance of the microphone.

Response at Very Low Frequencies — The response of a microphone in the very low frequency range (subaudio) is dependent on two factors; a "pressure equalizing" leak and the insulation resistance between its terminals. The pressure equalizing leak consists of a small hole that leads from the space behind the diaphragm to the outside atmosphere and allows the static pressure in the enclosed space behind the diaphragm to equal that in front of the diaphragm. A low-frequency response limit specification is often given such as: ". . .microphone response typically flat ± 1 dB down to 5 Hz." (The input resistance of the preamplifier used will also affect the low-frequency response of the microphone system as described under *Impedance.*)

Mechanical Factors — Measurement microphones must have several mechanical dimensions closely controlled. Diameter is closely controlled, first to allow the microphone to fit tightly into a coupler cavity for calibration or measurement and secondly to ensure predictable directional response in a free field. The "front volume," that is the volume enclosed between the front cover and diaphragm, must be closely controlled to allow the microphone to be calibrated in an acoustic coupler. Further, the spacing between the front cover and diaphragm affects the directional response of the microphone.

All the major characteristics of a microphone have now been defined. These major characteristics of the three types of measurement microphone are discussed and compared in the paragraphs to follow. The relative importance of a given characteristic is determined by the application of the microphone to be discussed later.

sured must be stated. Measurement microphones are calibrated for most uniform frequency response in either a diffuse sound field (random incidence), a free-field with incidence perpendicular to the plane of the diaphragm, or in a closed coupler or cavity (pressure response). A microphone calibrated under one of these conditions will, of course, produce an "error" in response when used under either of the other conditions. Figures 6 and 7 show the corrections to be applied to a one-half-inch diameter electret-condenser microphone with uniform random-incidence response and uniform perpendicular-incidence response, respectively, to determine response under the other two conditions.

When microphones are being compared, it is easiest to look at, first, the frequency limits where response remains within stated tolerances and then the typical ripple or minor variations in response within the useful frequency range. Table 2 compares the upper frequency limits and ripple for various one-inch and one-half-inch microphones with perpendicular, random, and pressure calibrations. Curves showing response versus frequency are probably most useful in considering the error in an individual microphone. Such individual calibration curves are supplied with most measurement microphones.

Table 2 — Upper frequency limit and ripple for various microphones.

	Typical 1" Diameter		Typical ½" Diameter	
	Upper Frequency Limit (2 dB down)	Ripple	Upper Frequency Limit (2 dB down)	Ripple
Electret-Condenser, Random-Incidence Response	10 kHz	±1	20 kHz	±1
Electret-Condenser, Perpendicular-Incidence Response	15 kHz	±1	25 kHz	±1
Air-Condenser, Pressure Response	8 kHz	±1	20 kHz	±1
Air-Condenser, Perpendicular-Incidence Response	18 kHz	±1	40 kHz	±1
Ceramic, Random-Incidence Response	12 kHz	±2	—	—

Directional Response

A measurement microphone is, by convention and design, ideally equally responsive to sounds arriving from all directions. It is omnidirectional. In practice, this ideal can only be approximated, and measurement microphones are more sensitive to sounds arriving in a direction perpendicular to the plane of the diaphragm than to sounds arriving from any other direction. The change in sensitivity with direction of incidence is most pronounced at high frequencies as shown in Figure 8. Further, at a given upper frequency, the directional effect is more pronounced in large microphones than in small ones. Omnidirectivity is approached most closely with the smaller microphones, but these microphones are less sensitive than the larger ones are and therefore not a good choice for use at low sound levels.

If a practical microphone's sensitivity varies with the angle of incidence of the sound wave, at what angle should the microphone be calibrated? That is, at what angle should its sensitivity and frequency response be specified and controlled? The answer to this question is not simple and there are three different calibration conventions. Each has both advantages and disadvantages depending on application.

Grazing Incidence or Pressure Calibration — As shown in Figure 9, grazing incidence corresponds to the calibration angle parallel to the plane of the diaphragm. The frequency response at this angle corresponds closely to the microphone's "pressure" response, the response when the microphone is used in a small closed cavity or coupler, as for measuring the level produced by an earphone. This calibration direction is the best choice for measuring moving vehicles since, due to symmetry, grazing incidence is maintained as the vehicle passes by (see Figure 10).

A diffuse sound field is one in which sound energy flow is equally probable in all directions. The sound field in most indoor reverberant spaces approximates a diffuse sound field. Sounds reflecting from walls, ceilings, and floors reach the microphone from all directions. A microphone used in this application should be calibrated to give a uniform average result for sounds arriving (at random) from all directions. The grazing incidence or pressure microphone has the advantage that its "random" incidence response is nearly uniform and it can thus be applied in this commonly encountered situation.

A disadvantage of grazing incidence calibration is that in a given microphone size, the upper frequency limit is lower than for other calibration angles. An additional factor is that in a free-field application with sound coming mainly from one source, any interfering sound coming from a source in another direction will be amplified in relation to the sound of interest. The microphone is, in effect, more sensitive to interfering sounds than to the sound to be measured.

Perpendicular-Incidence or "Free-Field" Calibration — This calibration direction (see Figure 9) is the direction of maximum sensitivity, and one advantage is, therefore, that in a free-field any interfering sound will be attenuated in relation to the sound being measured. A second, and perhaps the most important, advantage of this angle of calibration is that its frequency range (as measured in the calibration direction) is wider than for the other two types. One further advantage is that perpendicular-incidence calibration leads to the smallest change in sensitivity as a function of angle of incidence of all three types. This means that the microphone is easier to direct toward the sound source with great accuracy. These advantages make microphones with perpendicular-incidence calibration the best choice for use in a laboratory anechoic chamber.

An important disadvantage of perpendicular-incidence calibration is that a microphone thus calibrated will not produce accurate results when used in the diffuse or random-incidence sound field encountered in enclosed spaces. It is

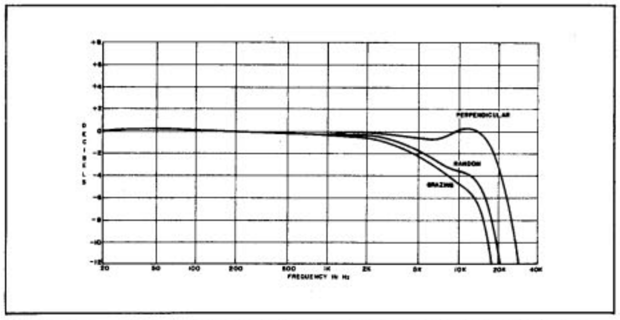

Figure 8 — GR one-half-inch diameter random-incidence calibrated electret-condenser microphone frequency response for perpendicular-incidence, random-incidence, and grazing incidence.

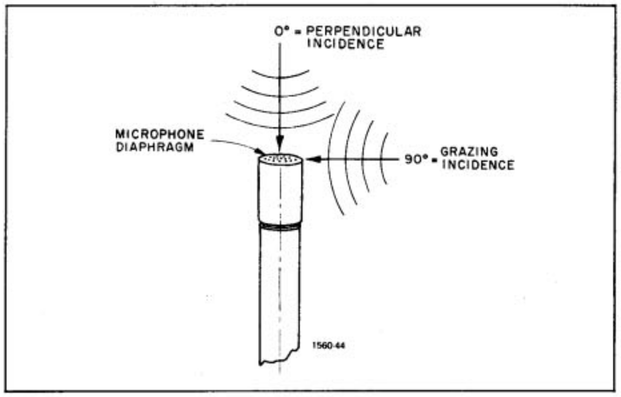

Figure 9 — Perpendicular incidence and grazing incidence calibration angles.

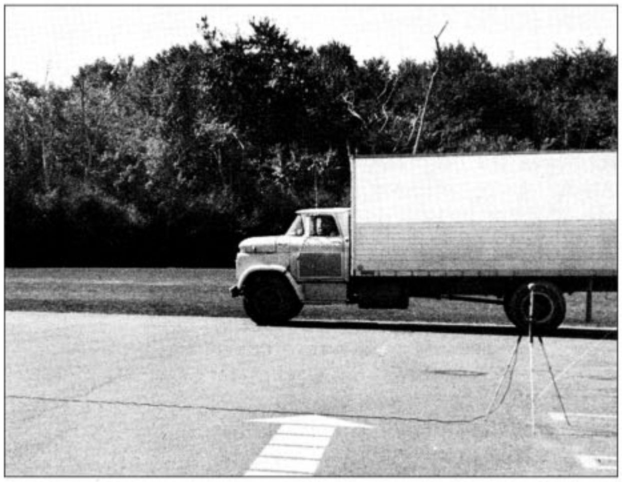

Figure 10 — Vehicle passing by microphone with grazing-incidence or random-incidence calibration.

Dynamic Range — A meaningful discussion of dynamic range must include consideration of both the microphone cartridge and the preamplifier. It is this combination that determines the upper and lower limits of sound-pressure level that can be measured. The preamplifier is the electronic amplifier that connects directly to the microphone cartridge and provides an electrical output signal capable of driving a connecting cable or other device.

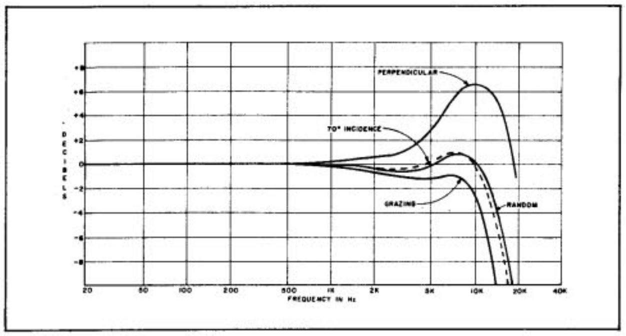

Figure 11 — Random-incidence frequency response and free-field frequency responses perpendicular to the plane of the diaphragm, grazing and at an Angle of 70° measured in reference to the perpendicular for a random-incidence calibrated microphone.

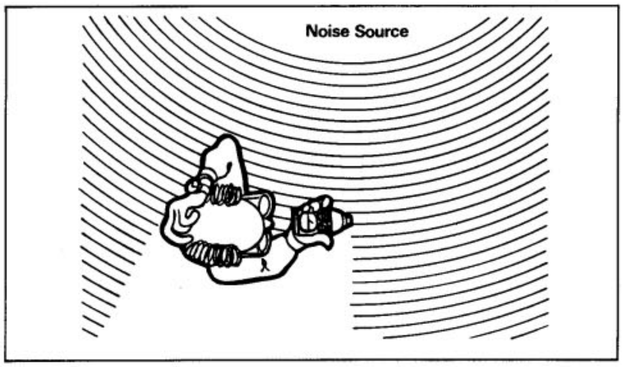

Figure 12 — Proper way to hold a sound-level meter fitted with a random-incidence calibrated microphone as required by ANSI S1.4-1971.

restricted to use out of doors or indoors in an anechoic chamber where sound relections are minimal. Neither is perpendicular incidence a good choice for outdoor use in measuring passing vehicles because the frequency response will be different for each position of the vehicle.

Random-Incidence Calibration — A random-incidence calibrated microphone is best in a diffuse or random-incidence field (i.e., in normal indoor spaces). As it turns out, random-incidence calibrated microphones can also be used for measurements in free-fields (e.g., out of doors). Figure 11 will demonstrate the reason for this. It shows the random-incidence response of a one-inch microphone which is uniform as a function of frequency by design and also the free-field responses taken perpendicular to the plane of the diaphragm, at grazing incidence, and at an angle of 70° measured in reference to the perpendicular. The point to be noted is that at 70° incidence, frequency response differs from the random-incidence by only a fraction of a decibel. It is in this direction that the microphone should be oriented for most accurate free-field measurements.

The American National Standards Institute (ANSI) specifies random-incidence calibration for all sound-level meters. It is a good choice because it provides equally accurate results in either free or diffuse sound fields, but also for other reasons. When holding and directing a sound-level meter, it has been shown* that the operator should not stand directly behind it since his body will reflect the sound and cause an error in pressure level at the microphone. A better procedure is to stand to the side or nearly so, as shown in Figure 12. This operator position is consistent with random-incidence as well as grazing-incidence calibration. Of course, it is possible, though not convenient, to stand to the side and direct a perpendicular-incidence calibrated sound-level meter at the sound source.

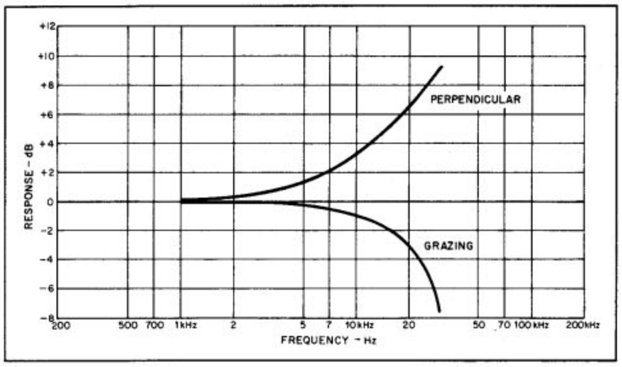

Figure 13 — Frequency response of a random-incidence calibrated microphone when measured at perpendicular incidence and at grazing incidence.

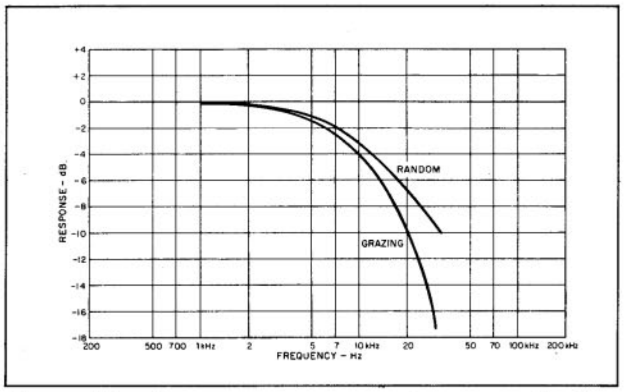

Figure 14 — Frequency response of a perpendicular-incidence calibrated microphone when measured at grazing incidence and at random incidence.

The difference between the random-incidence calibration and either perpendicular-incidence and grazing-incidence calibration is shown in Figure 13 for a one-half-inch diameter electret-condenser microphone (GR Type 1962). Corresponding differences are shown in Figure 14 for the perpendicular-incidence calibrated version of this microphone. It is possible to apply these differences as "corrections" when making critical frequency response or spectrum measurements; however, it is much more convenient to choose the proper microphone and, in a free-field, to orient it in the proper direction.

In a free-field where the angle to the source is unknown, for example, in measuring aircraft that may pass overhead flying in any direction, the smallest diameter microphone that will still provide adequate signal-to-noise level should be used. A one-half-inch diameter random-incidence microphone will produce a maximum error at 10 kHz of only 3 dB (Figure 13) when all that is known about the source direction is that it lies in the hemisphere in front of the microphone diaphragm.

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*R. W. Young (1962), "Can Accurate Measurements be Made with a Sound-Level Meter Held in Hand?" *Sound,* Vol. 1, #1, January-February, pp. 17-24.

Preamplifiers operating at typical power supply voltages will handle peak voltages from the microphone ranging from about 5 to 10 volts. The sound-pressure level corresponding to, say, 5 volts can be determined from the specified sensitivity of −40 dB re 1 V/Pa. At a sound pressure one Pa, its output will be 40 dB below 1 volt or 10 mV.

$$\frac{5\text{ volts}}{10\text{ mV}} \times 1\text{ Pa} = 500\text{ Pa corresponds to 5 volts.}$$

The zero decibel reference for sound-pressure level is 20 μPa so the sound-pressure level corresponding to 500 Pa is:

$$\text{sound-pressure level} = 20 \log \frac{500 \text{ Pa}}{20 \times 10^6 \text{ Pa}} \text{ dB} = 148 \text{ dB}$$

This 148-dB limit is established by the preamplifier. Whether this is the upper limit on the microphone-preamplifier system is another question. The preamplifier will limit upper level abruptly, while the microphone itself will also limit the upper level by gradually increasing distortion, and one must decide how much distortion is acceptable before the upper limit on the system can be established. The upper sound-pressure limit for a microphone cartridge may be given as the minimum level at which total harmonic distortion equals 3%. A curve showing harmonic distortion as a function of sound-pressure level for the one-half-inch electret microphone under consideration is shown in Figure 15. At the 148-dB limit imposed by the preamplifier, the microphone's distortion is approximately 7%. The maximum sound-pressure level should be limited in accordance with Figure 15 if lower distortion is required.

The lower limit on dynamic range is determined by the internal electrical noise voltage generated by the preamplifier when driven by the selected microphone and by the sensitivity of the microphone. Generally, the lower the capacitance of the microphone, the higher will be the internal noise voltage generated by the preamplifier. Furthermore, noise tends to increase at low frequencies. Figure 16 illustrates these points for three microphones with different capacitance, each with a sensitivity of −40 dB re 1 V/Pa. This figure shows directly the one-third-octave band internal noise in equivalent sound-pressure level for microphones of the same sensitivity. If the sensitivity of the microphone with capacitance of 68 pF were not −40 dB but instead −35 dB, then the "68 pF" curve would be displaced lower in level by 5 dB before comparing its noise performance to the other microphones. This microphone, by virtue of its higher sensitivity and despite its lower capacitance, would offer better noise performance for frequencies above about 400 Hz than the microphone with capacitance of 390 pF and −40 dB sensitivity.

Internally generated noise is often specified as an "equivalent" input noise voltage A-, C-, or sometimes "flat"-weighted with a particular source capacitance. Noise data for the GR 1560-P42 Preamplifier when used with various microphones all having −40 dB sensitivity is given in Table 3. This preamplifier is specified to generate less than 3.5 μV of input noise, C-weighted, with a 390 pF source.

The data given in Table 3 can be corrected for microphones with sensitivities other than −40 dB re 1 V/Pa simply by adding the difference in sensitivity between the particular microphone in question and −40 dB. For example, suppose a GR 1962 one-half-inch electret microphone is supplied with a sensitivity of −42 dB; then$(-40) - (-42) = 2$ and the corrected A-weighted noise level is $29 + 2 = 31$ dB.

Given the equivalent noise levels for a particular microphone-preamplifier combination, it is necessary to consider how close an indicated sound level may be in relation to this electrical noise for a useful measurement result. In practice*, this number is often taken to be 5 dB. At this limit, the indicated level is higher than the actual level by about 1.5 dB. A signal level higher than the internally generated noise level by more than 5 dB is generally desirable.

Microphone sensitivity, capacitance, and distortion characteristics along with preamplifier, peak signal handling and noise characteristics, as discussed, determine dynamic range. Microphone characteristics are determined by microphone type (electret-condenser, air-condenser, or ceramic) construction and diameter. Generally speaking, for a given diameter, ceramic microphones have the highest capacitance and air-condenser microphones the lowest, with electret-condenser microphones falling between. Generally, the reverse is true with regard to sensitivity with the air-condenser microphone having greatest sensitivity. Ceramic microphones produce the least distortion at high levels. The largest diameter of a given type will provide greatest sensitivity and capacitance and so is the best choice for use at very low levels. The smallest diameter microphones, on the other hand, have lowest sensitivity and capacitance but lowest distortion at high levels, and they are, therefore, the best choices for use at high sound levels.

In practice it is found that for most measurements at audio frequencies (below 20 kHz), one-inch or one-half-inch diameter microphones provide the best combination of low distortion at high levels and low internally generated noise. They are, by far, the most popular choice.

Temperature Characteristics — Most applications for measurement microphones are satisfied by an operating temperature range from −20°C to +60°C (−4°F to 140°F). All three types of microphones will operate with virtually no deviation in performance over this range and with only minor deviations down to −40°C. The air-condenser microphone is capable of operation in somewhat higher temperatures.

All three types of microphones have similar temperature coefficient specifications, of the order of 0.01 dB/°C. The temperature coefficient is stated as a nominal value or sometimes as limits on temperature coefficient. The shift in sensitivity as a function of temperature is given in Figure 17 for the GR 1962 Electret-Condenser Microphone. The change in sensitivity over the temperature range from 0 to 50°C (32 to 122°F) is about ±0.25 dB. Even when measurements must be made over this wide temperature range without recalibration, this error is small in

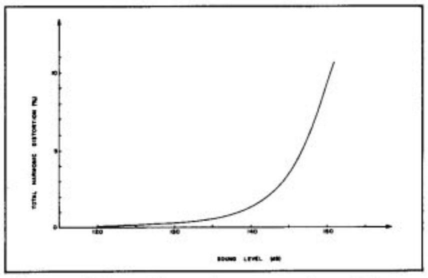

Figure 15 — Distortion produced by a one-half-inch diameter electret-condenser microphone at high sound level.

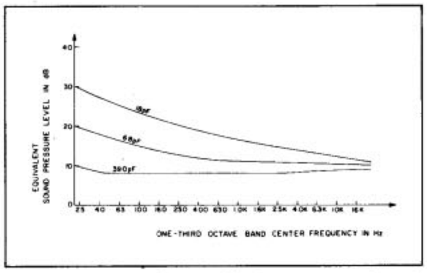

Figure 16 — One-third-octave band sound level equivalent to the internally generated electrical noise produced by the GR Type 1560-P42 Preamplifier in combination with −40 dB re 1 V/Pa microphones having various source capacitance and a sensitivity level of −40 dB re 1 V/Pa.

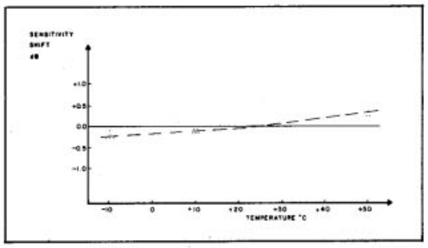

Figure 17 — Change in sensitivity versus temperature for GR 1962 electret-condenser microphones.

Table 3 — Typical equivalent input noise levels for GR 1560-P42 preamplifier when used with a microphone having a sensitivity of −40 dB re 1 V/Pa.

Source Capacitance (pF)	Weighting		Typical Microphone Type (with source capacitance near value shown)
	A	C	
390	20	23	GR 1971 1″ Ceramic
125	22	28	GR 1961 1″ Electret Condenser
68	23	30	1″ Air Condenser
18	29	38	GR 1962 ½″ Electret Condenser or ½″ Air Condenser

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*IEC Publication 179-1973 (Precision Sound-Level Meters) and ANSI S1.4-1971 Specification for Sound Level Meters.

relation to many others in the measurement process. It is common practice to calibrate an acoustical measuring system, including the microphone, directly before it is used. Where calibration is performed with an acoustic calibrator before use, it is the calibrator's temperature coefficient and not that of the microphone or other elements of the system that determines system accuracy. The point is that for most purposes, the small temperature drift in a measuring microphone is insignificant. But if the temperature drift is felt to be greater than tolerable, then the temperature coefficient data supplied with the microphone can be applied reducing the uncertainty due to temperature (for the microphone only, not other equipment to which it is connected) to about 0.1 dB. It should be borne in mind that the primary source of drift in an acoustical measuring system may well be in the electronics, not the microphone. Use of an acoustic calibrator will eliminate this source of drift.

The above discussion concerns the effect on microphone sensitivity of gradual changes in temperature. But sometimes, microphones are subject to abrupt changes in temperature, such as when they are transported from a low out-door temperature to the warm indoors. Because all parts of a microphone do not change dimensions at the same rate when subject to a temperature change, transient or abrupt change may cause a short-time temporary shift in sensitivity followed by a recovery to a constant sensitivity. The effect of a thermal transient can be stated in terms of the amount of temporary change and the time required for recovery after the change. Measurements made on a group of GR one-half-inch electret-condenser microphones exposed at 0°C and lower temperatures and then suddenly brought to room temperature show a maximum sensitivity change occurring two to three minutes after temperature shock, averaging 0.7 dB. Recovery to original sensitivity was essentially completed within thirty minutes.

We have discussed the temporary (reversible) effects of a single temperature cycle. Are there any permanent effects such as might be caused by repeated exposure to temperature (and possibly humidity) extremes out of doors? Table 4 shows the effect on sensitivity of fourteen microphones continuously exposed to the New England environment for the period from November 1972 to March 1974.* The microphones were unprotected except for a foam wind-screen. Data is shown for both one-inch and one-half-inch diameter electret-condenser microphones and one-inch ceramic microphones. Two air-condenser microphones exposed in the same environment failed catastrophically (by large changes in sensitivity) repeatedly. One of these air-condenser microphones did not recover its sensitivity after continuous exposure to warm dry air for one week, and it was replaced for the remainder of the testing period. The permanent changes in sensitivity for the air-condenser microphones were larger than that for either the electret-condenser or ceramic microphones. The two microphones remaining at the end of the test showed changes of −1.4 dB and −1.0 dB.

Humidity Characteristics — Most humidity problems with measurement microphones are directly related to either the high impedance of the microphone or for air-condenser types, discharge of free electrons in the intense field between the diaphragm and backplate. Insulators in the microphone itself and in the preamplifier to which it is connected must be kept clean and free from contaminants, to minimize sensitivity changes at high humidity. The air-condenser microphone, because it has the highest impedance (lowest capacitance) of all types discussed is the most susceptible to this mode of failure. In air-condenser microphones, discharge of free electrons usually takes place at high humidity and results in high internally generated noise levels sometimes followed by large changes in sensitivity.

The electret and ceramic types do not exhibit the effects of discharge but show only small gradual changes as a function of relative humidity. The change in sensitivity as a function of relative humidity for the GR electret-condenser microphone is shown in Figure 18. The change in sensitivity is about 0.01 dB/1% R.H., nearly independent of temperature.

Sensitivity change due to relative humidity takes place gradually over a period of many hours or sometimes days. Drift results when moisture penetrates into the back space of the microphone, a process whose rate is controlled by the small air leak into this region. For the electret-condenser microphone, moisture absorbed by the diaphragm itself causes a change in sensitivity. Short exposures to high humidity cause little or no sensitivity changes while after long exposure, changes of the order of 0.5 dB can be expected for exposure above 90% relative humidity. For some microphones many hours may be required for complete recovery after long exposure at high humidity.

Sensitivity to Vibration — Of all three microphone types, the electret-condenser microphone has the lowest sensitivity to vibration. As mentioned earlier, the standard test is to subject the microphone to an acceleration of 1 g at a low frequency and to report the equivalent sound level for this acceleration. The GR one-inch and one-half-inch electret-condenser microphones when subjected to a 1 g test at frequencies of 20 Hz and 100 Hz produce

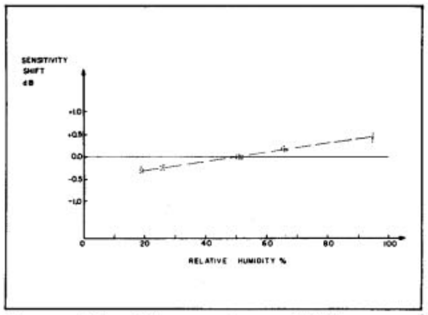

Figure 18 — Change in sensitivity versus relative humidity for a GR 1962 electret-condenser microphone.

an equivalent sound-pressure level of 83 dB. The GR one-inch ceramic microphone (Type 1971) produces a result, in the same test, of 100 dB. Air-condenser microphones lie between electret and ceramic microphones with respect to vibration sensitivity.

The direction perpendicular to the plane of the diaphragm in which the test is performed produces the greatest output. If vibration is a problem in practice, mounting the microphone so as to cause the interfering vibration to be impressed parallel to the plane of the diaphragm, when this is possible, may reduce the effect of vibration.

Susceptibility to Corrosive Elements in the Atmosphere — The outdoor measurements made during the period from November 1972 to March 1974 reported under "Temperature" above, show no effects of corrosion for either the electret or ceramic microphones. The exposed materials used in the electret-condenser microphone being Teflon, Mylar, and gold are stable and not susceptible to the contaminating elements found in air.

Long-Term Stability — Long-term sensitivity stability is a critical consideration for microphones to be used as laboratory reference standards. Such microphones are usually calibrated periodically by the

Table 4 — Effect on sensitivity of exposure to the outdoor New England environment.

Microphone Number	Sensitivity Change at 500 Hz in dB April 1973	Sept. 1973	March 1974
	One-Inch Electret		
1	0.2	0.1	0.1
2	−0.2	−0.5	−0.5
3	−0.3	−0.5	−0.3
4	−0.2	0.1	−0.2
5	0.0	0.3	0.3
	Half-Inch Electret		
1	0.2	0.6	0.0
2	0.1	0.0	0.0
3	0.2	0.5	0.6
4	0.1	0.3	0.4
5	0.4	0.2	−0.2
	Ceramic		
1	0.5	−0.3	0.2
2	0.2	−0.2	0.0
3	0.4	−0.1	0.3
4	0.4	0.2	−0.2

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*S. V. Djuric, "Comparative Outdoor Tests of Measurement Microphones," *J. Acoust. Soc. Am.*, 55: S30(A), 1974.

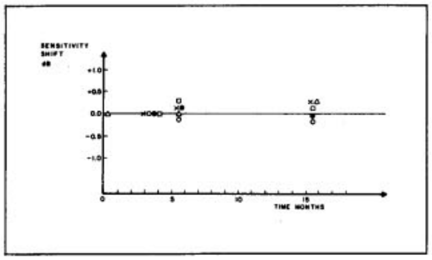

Figure 19 — Change in sensitivity versus time (long-term stability) of GR 1962 electret-condenser microphones.

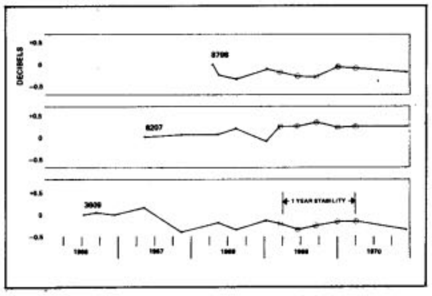

Figure 20 — Change in sensitivity versus time for GR 1971 ceramic microphones.

National Bureau of Standards in the U.S. or by other national laboratories. They may also be calibrated using a "primary" method known as reciprocity calibration. This method compares the sensitivity of a microphone to an electrical impedance standard. A laboratory standard microphone is used as a reference for calibration of working microphones. The standard microphone itself is kept under closely controlled environmental conditions.

For laboratory standard applications, stability of 0.40 decibels/year or better is prescribed by the ANSI standard Specification for Laboratory Standard Microphones S1.12-1967. Many measurement microphones, manufactured under close control, meet this requirement. The air-condenser microphone, after many years of experience, has been shown to have stability even greater than required by this standard.

The measurement electret-condenser microphone has not been available for a sufficient number of years to compile the long-term stability data that is available for air-condenser microphones. Yet what data is available demonstrates great promise for this type. Figure 19 shows the sensitivity shift for a group of five GR electret-condenser microphones taken over a period of one year or more. All microphones qualify for laboratory standard use under the ANSI standard.

Table 5 — Drift limits imposed by ANSI S1.12-1967 and measured drift of GR Type 1971 microphone.

	Short-Term Stability, 5-Day Period		Long-Term Stability, 1-Year Period	
	|m| dB/day	S dB	|m| dB/Yr.	S dB
Standard Drift Limit	0.04	0.1	0.4	0.15
Type 1971	0.0075	0.032	0.085	0.07

Where: |m| = Magnitude of the slope of curve of sensitivity versus time

S = Standard deviation of residuals.

Stability data are shown in Figure 20 for three GR Type 1971 one-inch ceramic microphones over a time period up to four and one-half years. Several Type 1971 microphones were tested by the method prescribed in the ANSI standard. The standard requires specification of two factors describing sensitivity as a function of time. These factors are given for both short-term and long-term stability. Short-term stability is described by the average drift and the standard deviation of drifts (referred to the average) over a five-day period. Long-term stability is described by these factors but measured over a period of one year. The standard deviation gives a measure of the probability of any particular sensitivity measurement conforming to the sensitivity predicted from the given average drift rate. A standard deviation of 0.0 dB would imply that sensitivity at any time in the future is perfectly predictable from the given short-term or long-term average drift rates. Limits on both short-term and long-term drift and corresponding standard deviations are specified in ANSI S1.12-1967 and given in Table 5 along with measured data on the Type 1971 microphone.

It is common practice that working microphones are frequently checked using an acoustic calibrator and not by comparison with a laboratory standard microphone. It is then the stability of the calibrator and not that of either a standard microphone or the working microphone that is being relied upon.

Impedance — The high impedance of measurement microphones at low frequencies demands that a preamplifier with high input resistance be used and that care be taken to keep insulation free from contamination that could reduce resistance. The input resistance of GR 1560-P42 and 1972 Preamplifiers is over 2 GΩ (2×10^9 Ω) which is sufficiently high to allow operation with even the lowest capacitance (highest impedance) measurement microphones at low frequencies. Generally speaking, the lower the impedance of the microphone (i.e., the higher the capacitance), the lower will be the probability of noise or low-frequency response error due to contamination of the insulation of either the microphone or preamplifier.

In addition to determining the low-frequency response limit, the impedance (capacitance) of the microphone in combination with the preamplifier affects the level of internally generated electrical noise and thus the lower limit on dynamic range. This effect has already been discussed under the heading of *Dynamic Range*.

Response at Very Low Frequencies — The "pressure equalizing" leak which is one factor that determines response at very low frequencies consists of a small hole that leads from the space behind the diaphragm to the outside atmosphere and allows the static pressure in the enclosed space behind the diaphragm to equal atmospheric pressure at the front. Without this leak, a microphoine would respond to the difference between atmospheric pressure at any given time and the pressure that existed in the inside of the microphone at the time it was sealed. The microphone would tend to function as a barometer and as its diaphragm position changed relative to its back plate, its characteristics as a microphone would be affected. Without a leak, the dynamic range of the microphone would be impaired, and if the pressure outside a sealed microphone were made sufficiently low, as at high altitudes, the diaphragm would rupture.

The pressure equalizing leak is essential, yet its design directly affects the lower frequency limit of the microphone. The size of the leak, which determines the rate at which the static pressure in the back space can change, must be large enough to allow the microphone to be used in circumstances where static pressure may change rapidly yet small enough not to limit low-frequency response. In practice, a typical leak is designed to limit low frequency response at about 5 Hz.

The second factor limiting low-frequency response is the electrical impedance between the terminals of the microphone which has already been discussed under the heading of *Impedance*.

Mechanical Factors — Figure 21 shows a measurement microphone mounted in a coupler and being used to measure the sensitivity and frequency response of an earphone. The microphone must fit tightly into the coupler in order that the coupler's voume and shape will be accurately maintained. Calibration of a microphone in a coupler also requires close control on the enclosed volume.

ANSI standard S1.12-1967 requires that the size of a nominal one-inch diameter microphone be 0.936 ±0.002 inches. The diameter of the GR "one-inch" 1961 Electret-Condenser and 1971 Ceramic Microphones are controlled within this limit. The "one-half inch" microphone has similar control on diameter with a tolerance of ±0.001 inches. A further consideration for coupler use is control of the front volume of the microphone. This volume adds directly to the coupler volume and so directly affects the sound-pressure level in the coupler. The mechanical dimensions of individual parts of the microphone control front volume.

Aside from considerations of coupler applications, microphone dimensions must be controlled to ensure uniform directional characteristics for the microphone when used in a free-field. The upper frequency limit where the micro-

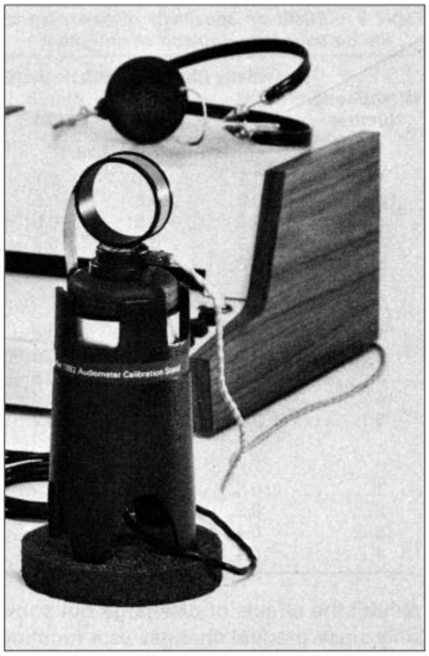

Figure 21 — Microphone used in coupler measurements.

phone when used in a free-field. The upper frequency limit where the microphone exhibits a certain directivity error varies inversely with the diameter of the microphone. Therefore, one microphone is, say, 10% larger in diameter than another but otherwise identical will have an upper frequency limit as determined by directivity that is 10% lower. S/V

Microphone Applications

Measurement microphone applications may be grouped by consideration of: 1. the degree of performance required, 2. the environment in which the microphone must function, and 3. cost constraints. All specific applications will fall into one of the following general application areas.

Severe Field use — where the microphone must operate unattended and unprotected out of doors or where it will be worn or by other means constantly transported while in use. Cost may be an important consideration in this application.

General Field use — where the microphone is usually mounted on a portable instrument, often transported, and attended by unskilled operators. The general purpose (Type 2) sound-level meter fits into this category. Low cost is also important here.

Precision field use — where greater accuracy is required than for general field use and where the microphone is used by a skilled operator and is not as likely to be abused.

Laboratory use — in a clean laboratory, typically environmentally controlled, handled by trained scientific personnel and where best performance is required. Cost is less important.

Laboratory standard use — where the microphone will be kept under ideal environmental conditions and handled only to make calibrations on working microphones. Best attainable performance is essential and cost is unimportant.

Figure 22 — Severe field use of microphones.

In the following paragraphs, observations are made regarding the most important and less important performance and environmental characteristics in each application. Table 6 is a summary with microphone type recommendations for each application.

Severe Field Use — In a severe environment (Figure 22) the sensitivity of the microphone to the various environmental factors previously discussed is a critical concern. There is little point in selecting a microphone with the best "performance" characteristics if it cannot stand up to its envi-

Table 6 — Importance of various performance and environmental factors for various applications.

		Microphone Application				
	Microphone Characteristics	Severe Field Use	General Field Use	Precision Field Use	Laboratory Use	Laboratory Standard Use
Performance Characteristics	Sensitivity	—	—	•	•	•
	Frequency Response	•	•	■	■	■
	Directional Response	•	•	■	■	■
	Dynamic Range	•	•	■	•	•
	Long-Term Stability	—	—	•	•	■
	Impedance	■	•	•	—	—
	Low-Frequency Response	—	—	•	•	•
	Mechanical Factors	—	—	•	■	■
Environmental Factors	Temperature Characteristics	•	•	•	•	•
	Humidity Characteristics	■	•	•	•	•
	Sensitivity to Vibration	•	•	•	—	—
	Corrosive Elements	■	•	•	—	—
	Cost	■	■	•	•	—
	Best Microphone Choice	Ceramic or Electret Condenser	Ceramic or Electret Condenser	Electret Condenser or Air Condenser	Electret Condenser or Air Condenser	Air Condenser

KEY:
- ■ Most Important Characteristics
- • Important Characteristics
- — Less Important Characteristics

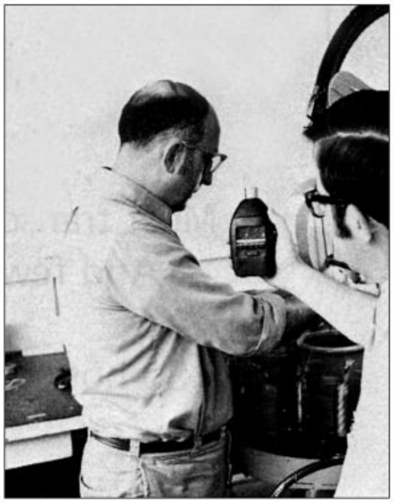

Figure 23 — General field use of microphones.

ronment. If it fails, it produces no measurement results at all. Severe field use implies either application in a wearable noise dosimeter or unattended operation in a stationary industrial or community noise monitor. In the wearable dosimeter application, the most important factors are probably impedance, humidity characteristics, and cost. Less important characteristics are sensitivity, long-term stability, low-frequency response, and mechanical factors. Considering the most important characteristic, the best choice for the wearable application is the ceramic or electret-condenser microphone.

The stationary application differs only slightly in its requirements from the wearable application. Because the microphone may be left unattended out of doors, the effects of corrosive atmospheres should be taken into account along with the other important factors. The electret-condenser or ceramic microphones will do best in this application.

General Field Use — A larger number of measurement microphone applications fall in this category than all others combined. The best example of general field use is the ordinary or Type 2 sound-level meter (Figure 23). This application is neither as demanding of environmental characteristics as the severe field application nor as demanding of performance characteristics as the "precision" and laboratory applications. A most important factor is cost. Less important characteristics are sensitivity, long-term stability, low-frequency response, and mechanical factors. A ceramic or electret-condenser microphone is the best choice here.

Figure 24 — Precision field use of microphone.

Precision Field Use — In some field applications, acoustical measurement conditions are closely specified or controlled so as to approach laboratory conditions. Instrumentation with better performance characteristics than would ordinarily be used may then offer an advantage. Measurements made on an air compressor or vehicle at a manufacturing plant (Figure 24) are examples. The Precision or Type 1 sound-level meter used either alone or in combination with other insturments is typical of instrumentation. Demands on performance are somewhat greater than for the first two categories and environmental considerations are less important. Frequency response, dynamic range, and directivity are most important characteristics. All other characteristics are important. The electret-condenser or air-condenser microphone will do best in this application.

Laboratory Use — In a laboratory (Figure 25) the acoustical measurement environment and environmental factors are closely controlled. Greater precision is demanded than for any of the field applications and so performance characteristics are very important. It might seem that environmental factors could be disregarded though because of demands on accuracy; this is not so. The most important characteristics are frequency response, directional response, and mechanical factors. Impedance and sensitivity to vibration and corrosive elements are less important.

Measurements made in anechoic chambers and reverberation rooms on products, modeling studies, and research on materials and acoustical phenomena are typical of laboratory applications. Both the electret-condenser and the air-condenser microphones are good choices here.

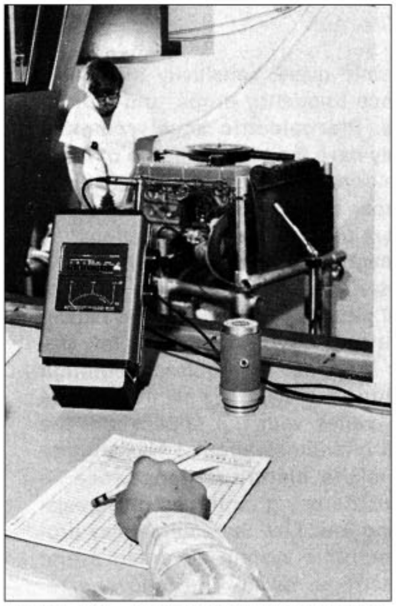

Figure 25 — Laboratory use of microphones.

Laboratory Standard Use — A microphone used for the calibration of other microphones and measuring systems must, of course, have excellent performance characteristics. Shown in Figure 26 is a comparison calibration system in use. The system operates by first applying a test acoustical signal to the laboratory standard reference microphone and measuring its output voltage. The same test signal is then applied to the microphone being calibrated and its output voltage determines the difference in sensitivities for the two microphones.

In a laboratory standard application, the most important performance factors are frequency response, directional response (comparisons are also made in a free-field), long-term stability, and mechanical factors. Impedance, sensitivity to vibration and corrosive elements, and especially cost are less important.

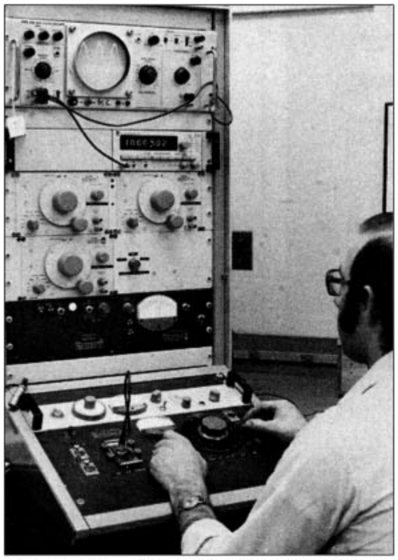

Figure 26 — Laboratory standard use of microphones.