NBSIR 76-1090
EPA 550/9-76-009

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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, *Secretary*
Dr. Betsy Ancker-Johnson, *Assistant Secretary for Science and Technology*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

# ABSTRACT

The pressure sensitivities of two "1/2-inch" electret, two "1-inch" ceramic, and two back-vented "1-inch" condenser microphones were measured for numerous combinations of temperature, percentage relative humidity, and frequency. The two condenser microphones were calibrated by the reciprocity technique at each combination of temperature, relative humidity and frequency. The condenser microphones were then used as calibrated sources to determine the pressure sensitivities of the other microphones. Insert voltage techniques were used to eliminate the environmental effects on the electronics. It was found that the back-vented condenser microphones are insensitive to changes in relative humidity. At frequencies considerably below their resonance frequencies they exhibited only a very small change in sensitivity with temperature. At frequencies closer to the resonance frequency the temperature coefficient increases approximately fourfold. The temperature and humidity coefficient for the electret and ceramic microphones could not be determined due to the instability in their sensitivities which produced changes that were larger than those induced by the temperatures and humidities.

Key Words: Calibration; ceramic; condenser; electret; humidity; microphones; reciprocity; sensitivity; temperature.

# 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 stipulated. It was felt therefore that a modestly 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,

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*By their very nature the small volumes in the electret and ceramic microphone cartirdges 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.

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.

## TEST METHOD AND PROCEDURE

The sensitivities of the microphones were measured using the procedures specified in the U.S. 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 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 both 5 kHz and the two resonance frequencies, it was possible to check that equilibrium conditions 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[8] 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.

## DISCUSSION OF RESULTS

The changes in sensitivity of the six microphones normalized to their respective pressure sensitivity 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 to 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 the vertical bars indicates that the data were only taken at a single relative humidity. The data were presented in this form because no meaningful relation could 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 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.

## CONCLUSIONS

From the data presented the following conclusions are reached:

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

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

3. Condenser microphones containing a large amount of viscous damping would be expected to 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.

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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 |

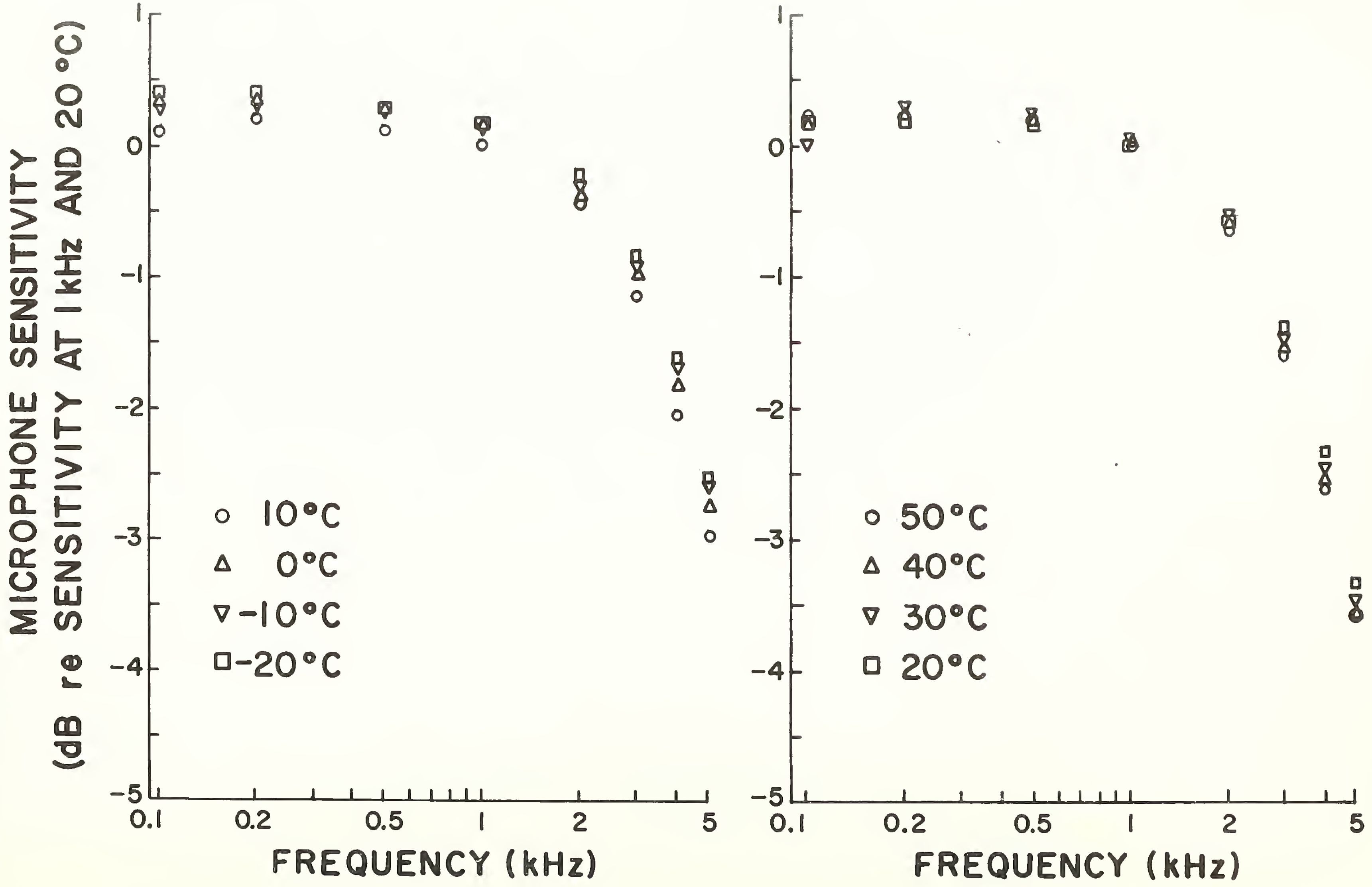


Figure 1. Change in sensitivity of "1-inch" condenser microphone No. 1 as a function of frequency and temperature. The change in relative humidity introduces an uncertainty about the data points of less than ± 0.15 dB.

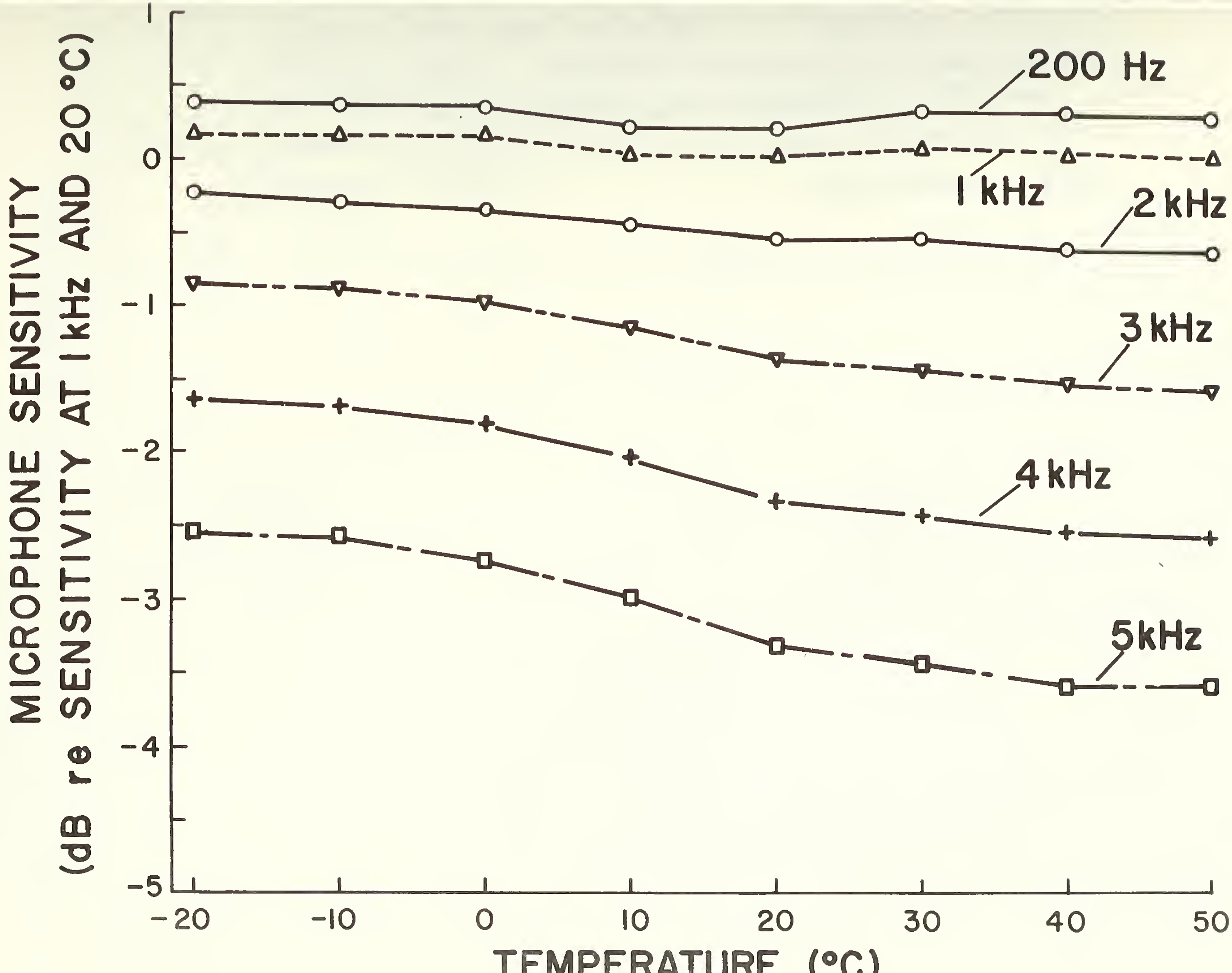


Figure 2. Change in sensitivity of "1-inch" condenser microphone no. 1 as a function of temperature for several frequencies.

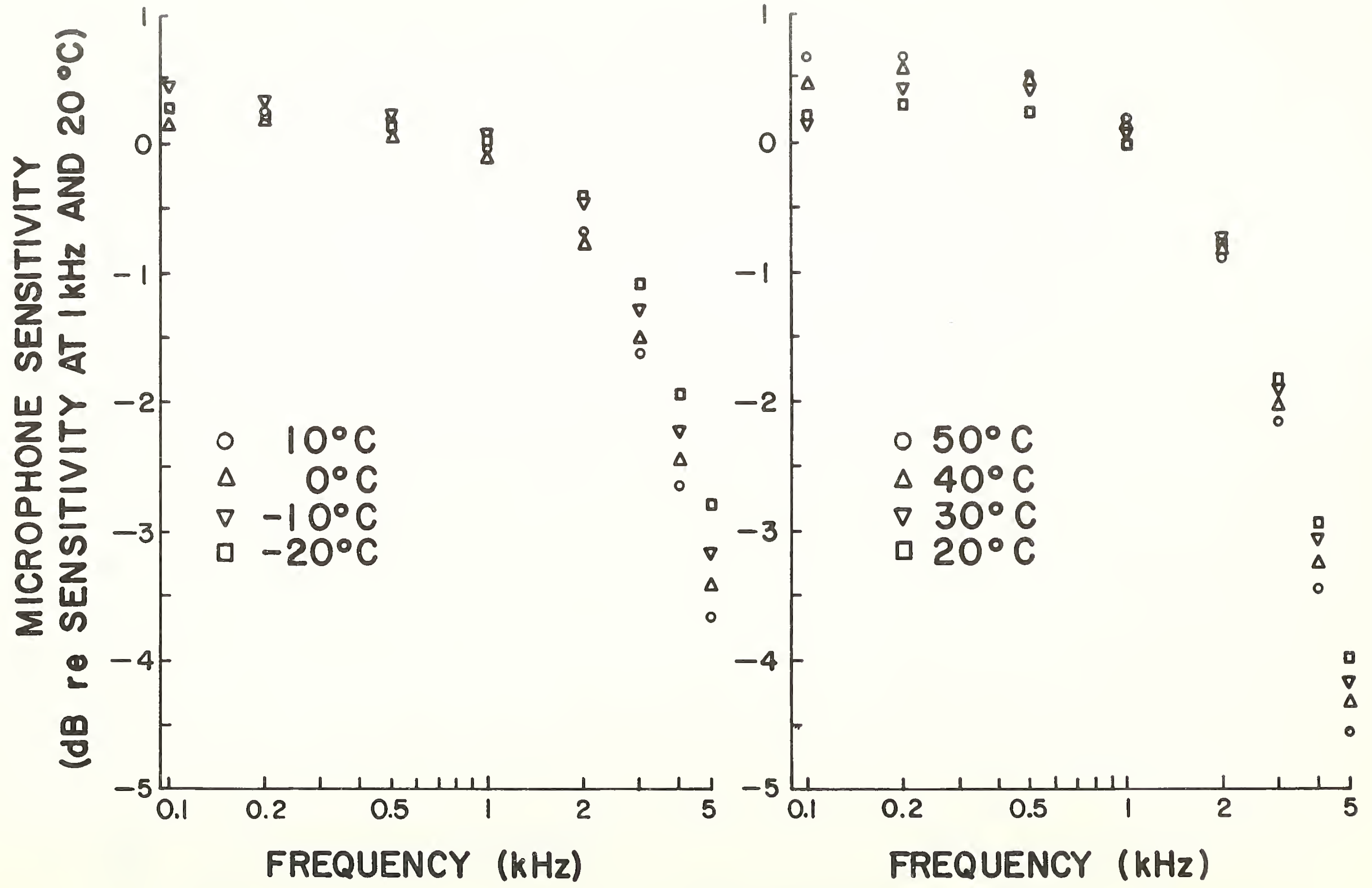


Figure 3. Change in sensitivity of "1-inch" condenser microphone no. 2 as a function of frequency and temperature. The change in relative humidity introduces an uncertainty about the data points of less than ± 0.15 dB.

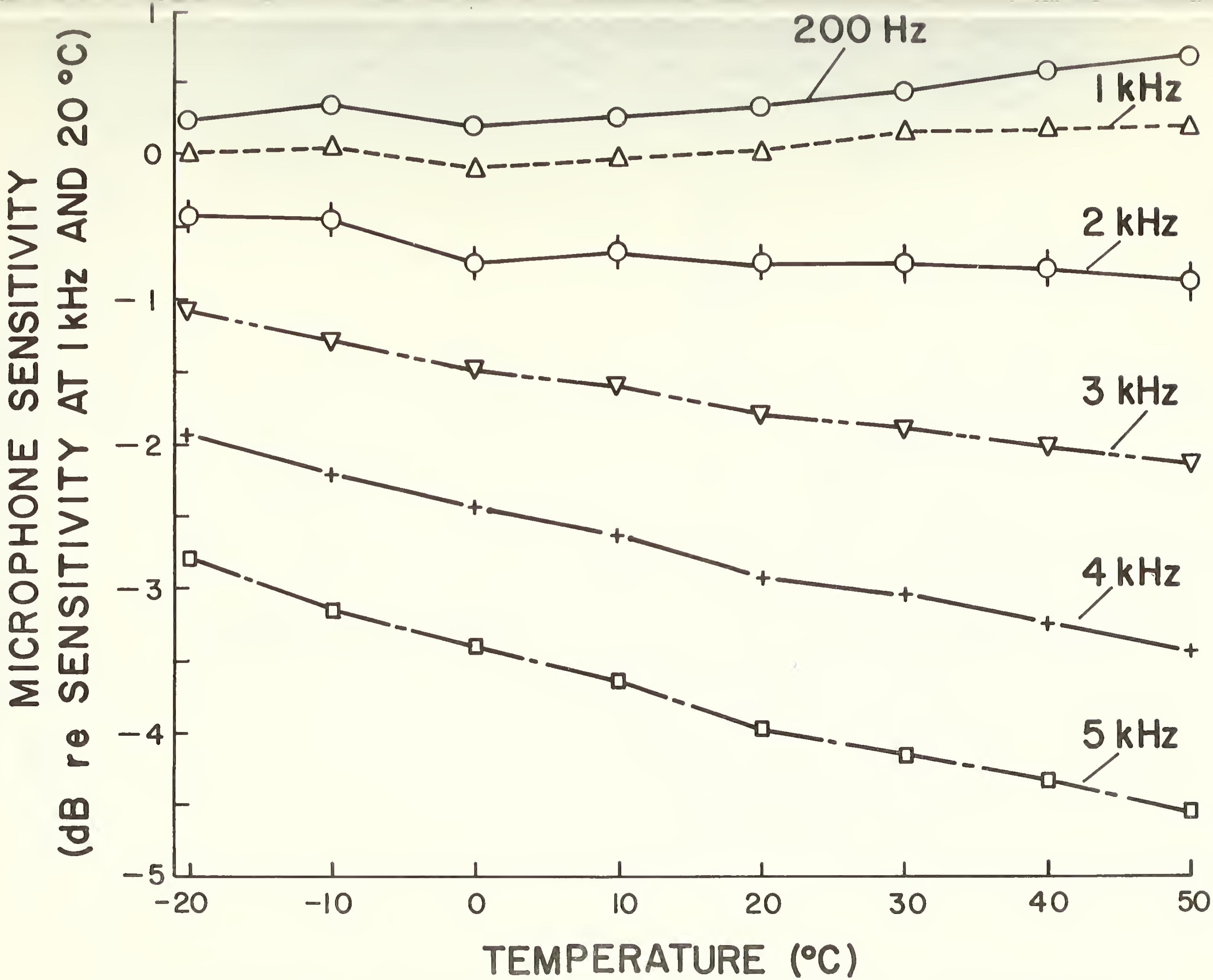


Figure 4. Change in sensitivity of "1-inch" condenser microphone no. 2 as a function of temperature for several frequencies.

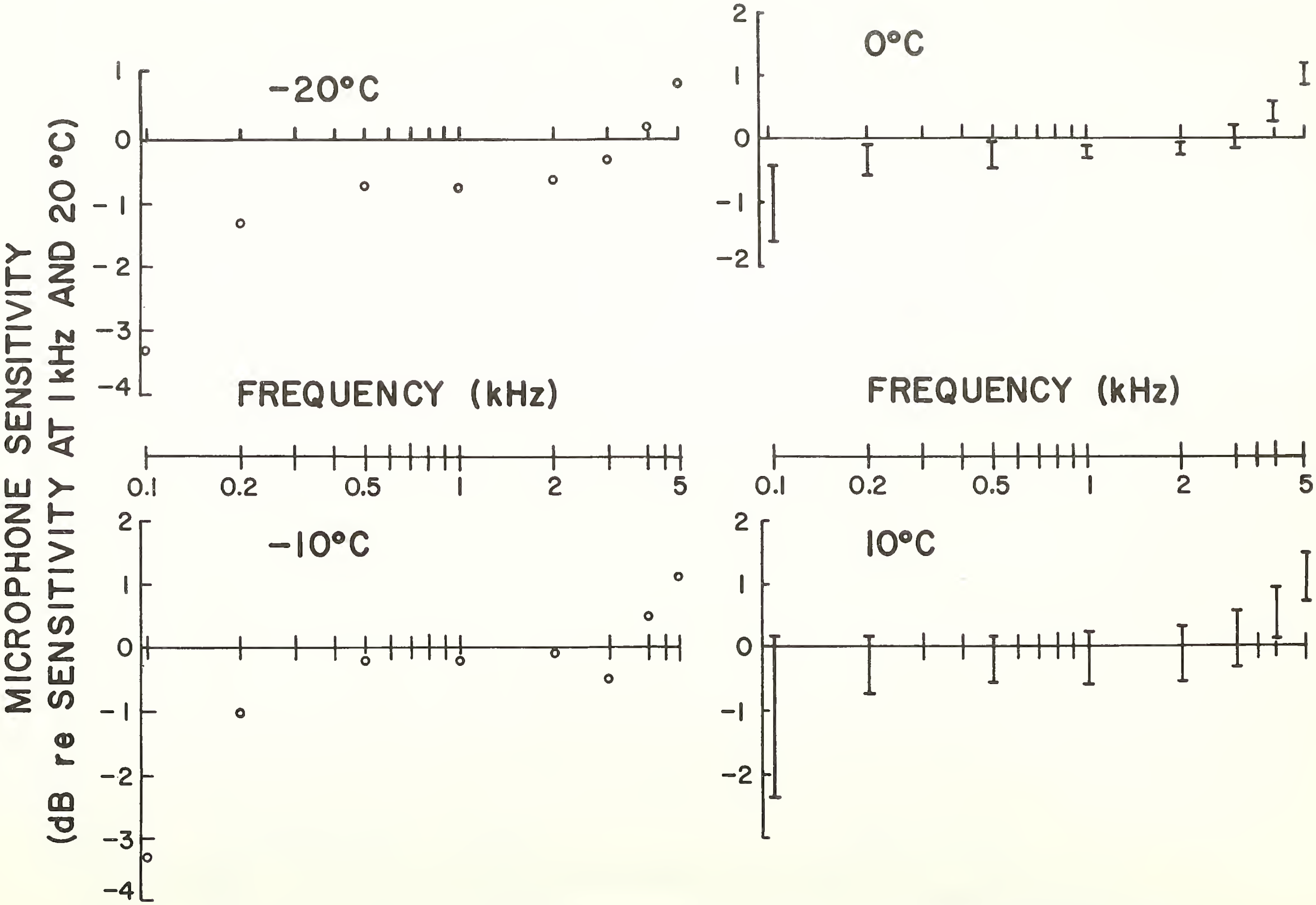


Figure 5a. Change in sensitivity of "1/2-inch" electret microphone no. 1 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

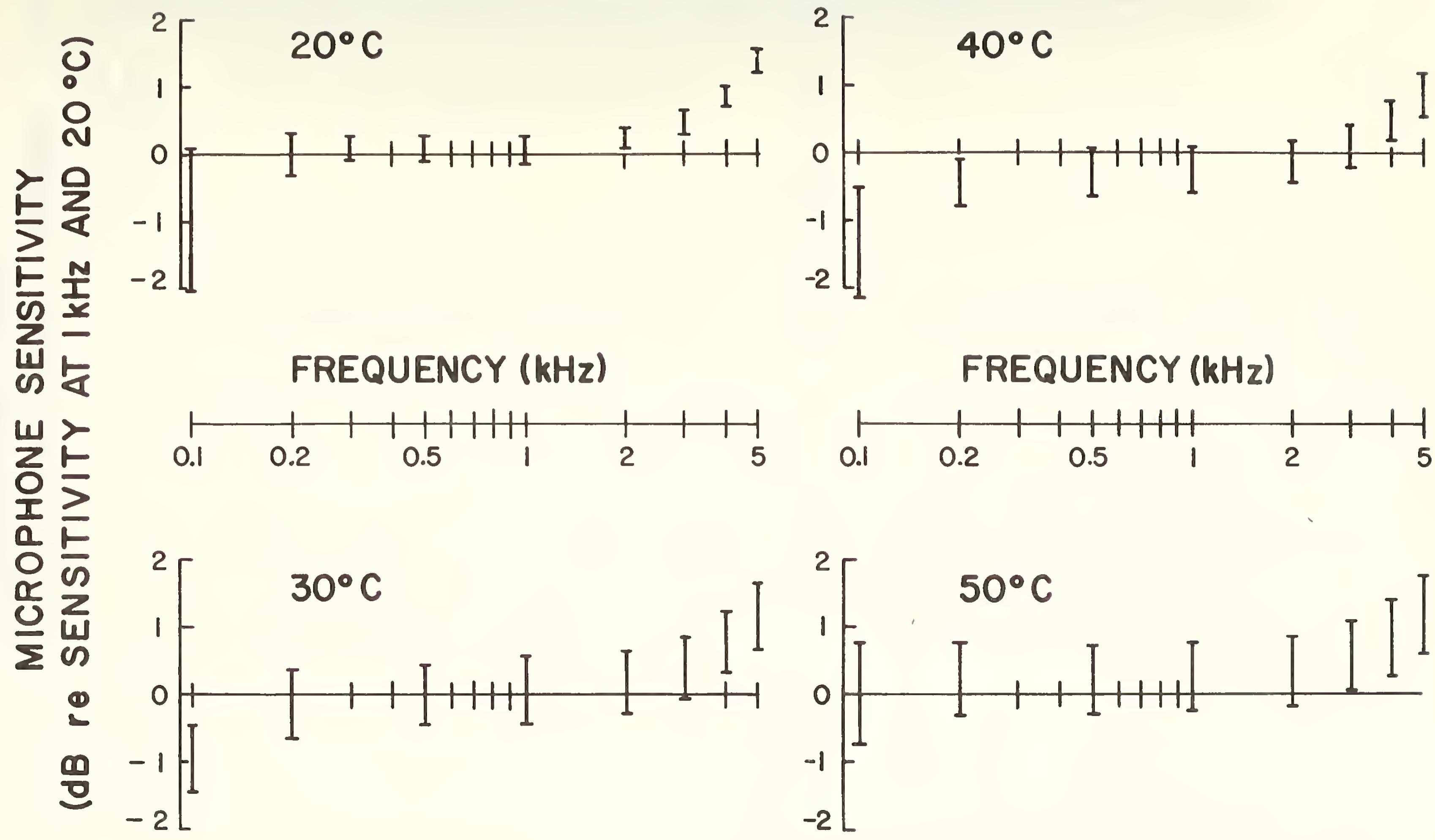


FIGURE 5B. CHANGE IN SENSITIVITY OF "1/2-INCH" ELECTRET MICROPHONE NO. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

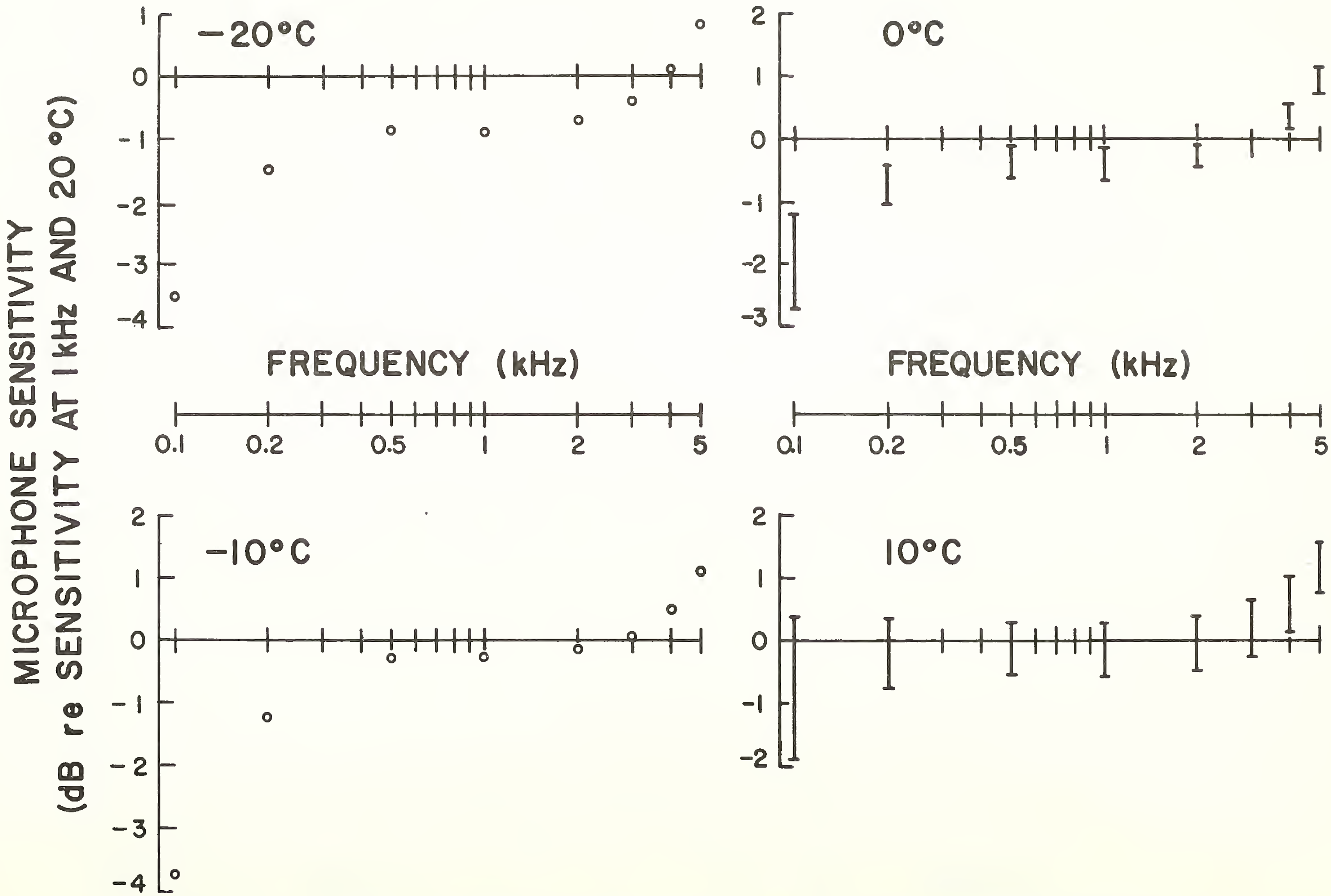


FIGURE 6A. CHANGE IN SENSITIVITY OF "1/2-INCH" ELECTRET MICROPHONE NO. 2 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

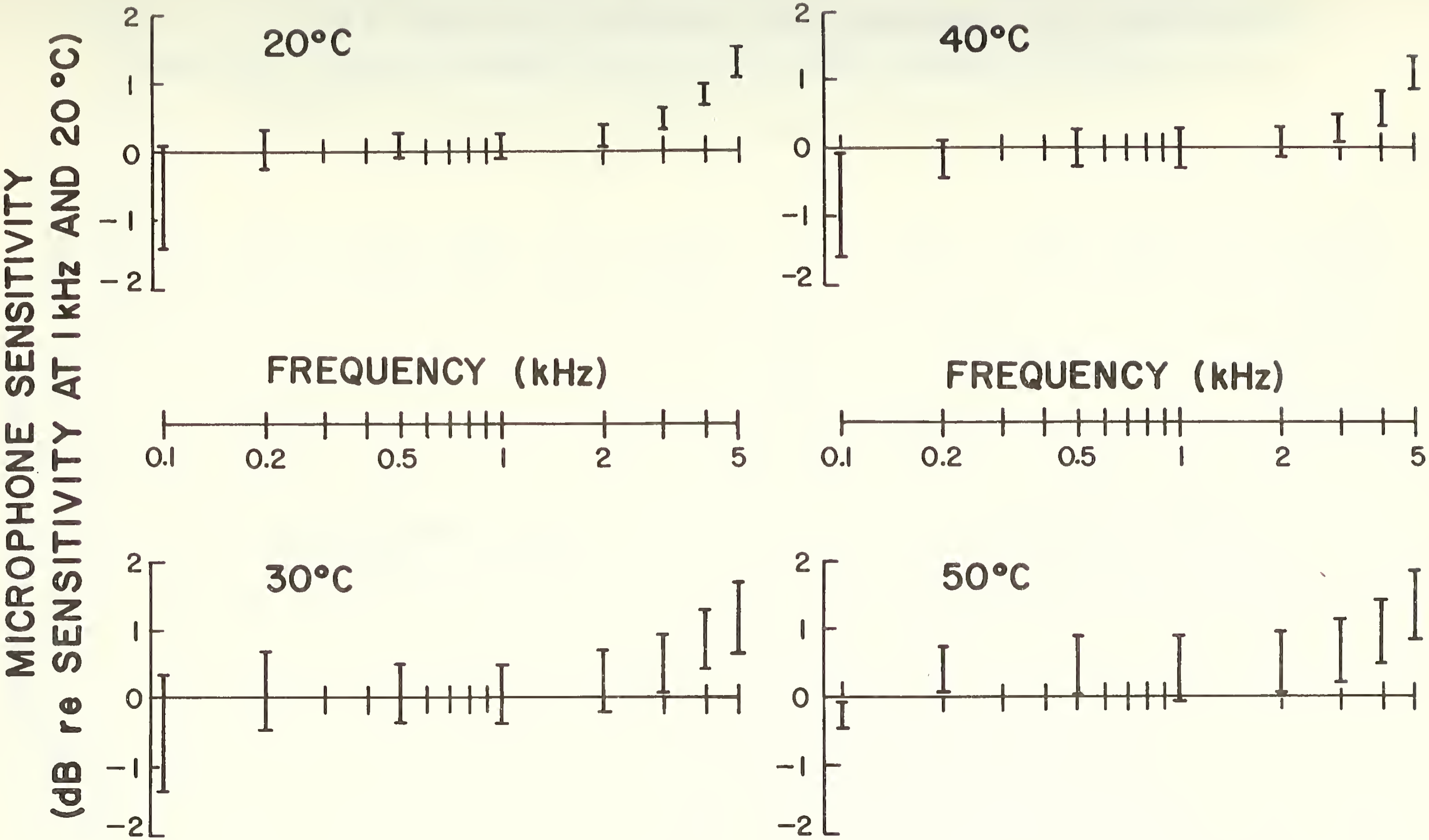


Figure 6b. Change in sensitivity of "1/2-inch" electret microphone no. 2 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

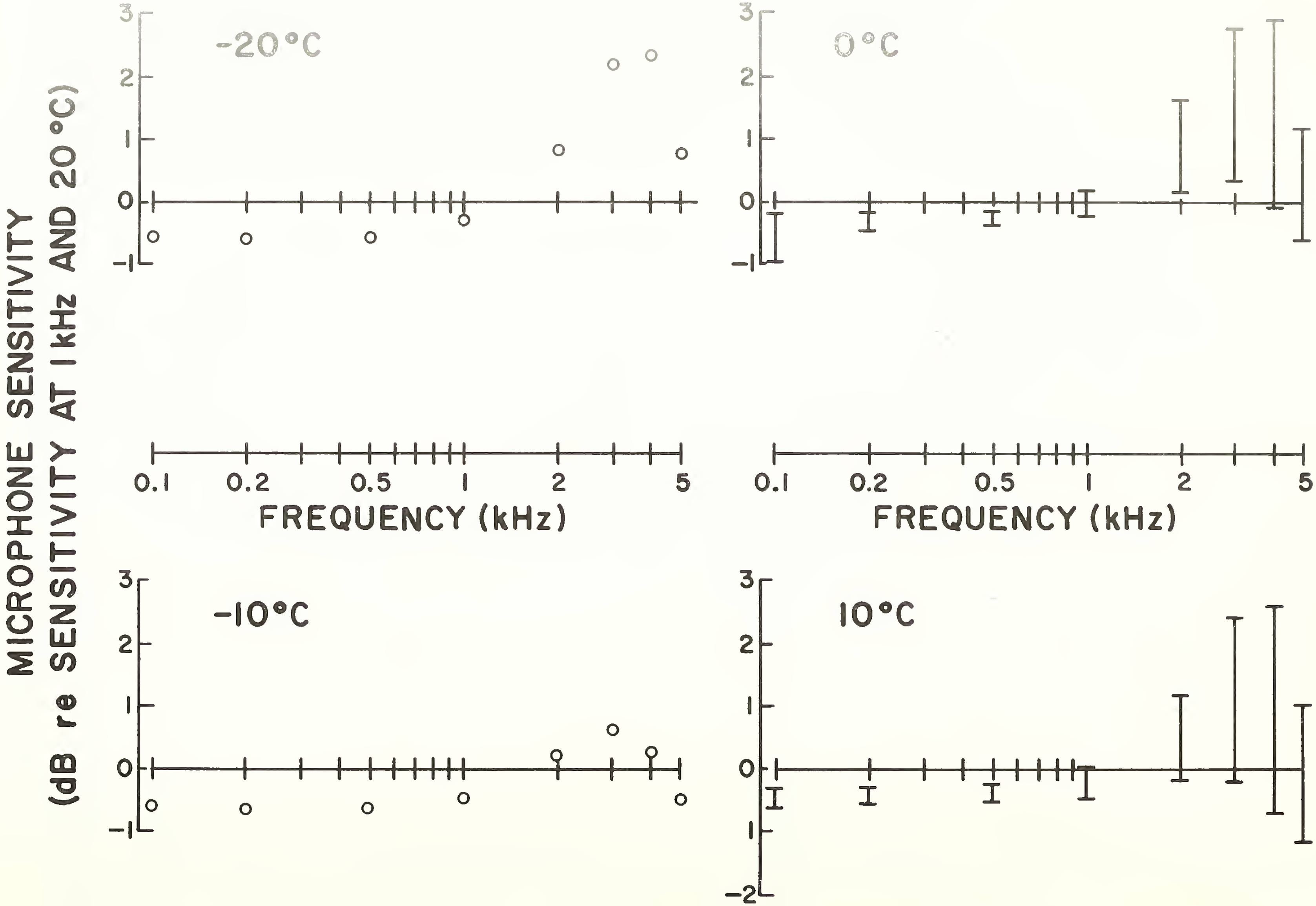


Figure 7a. Change in sensitivity of "1/2-inch" ceramic microphone No. 1 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

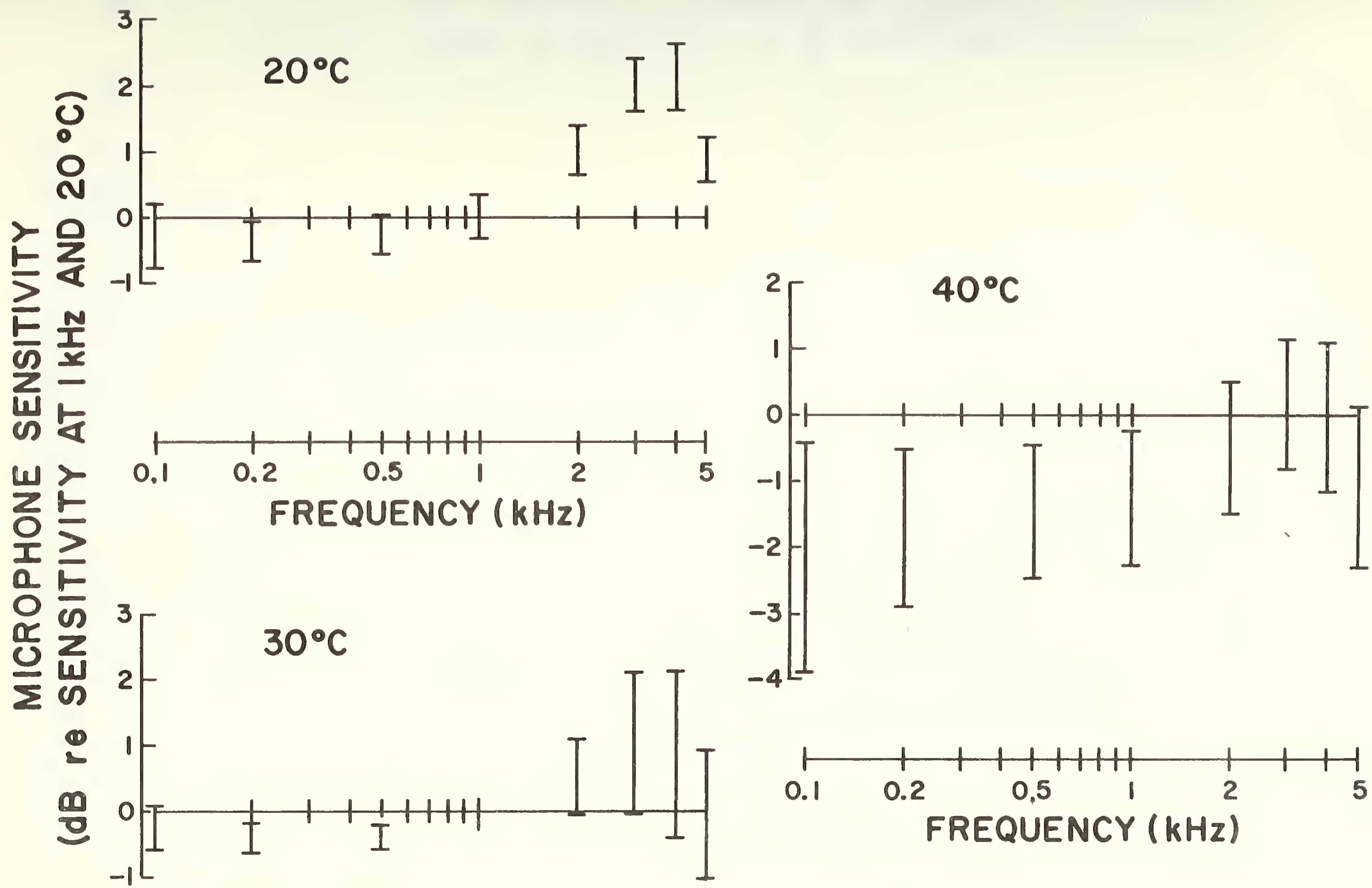


FIGURE 7B. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE NO. 1 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

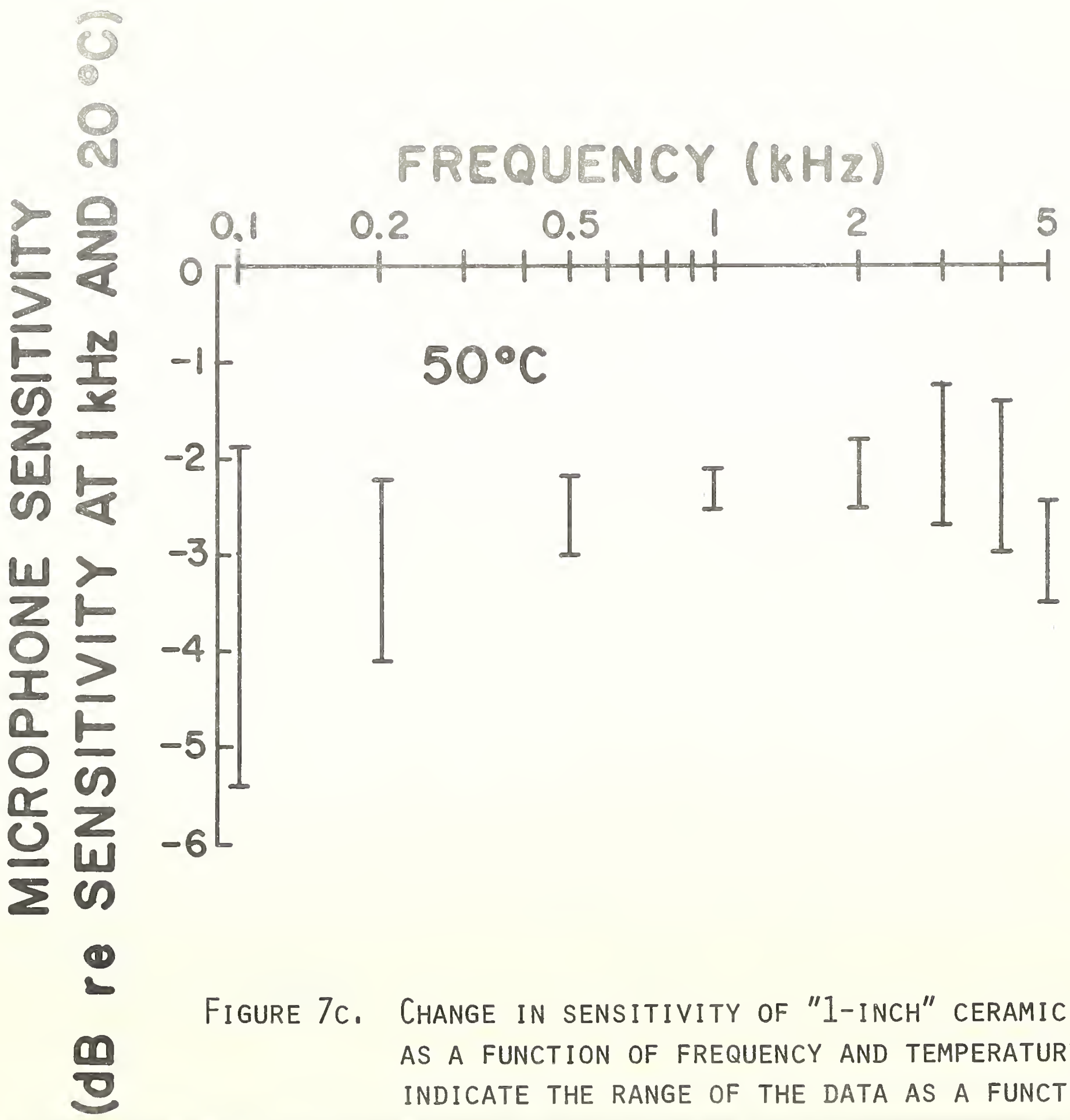


FIGURE 7C. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE NO. 2 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

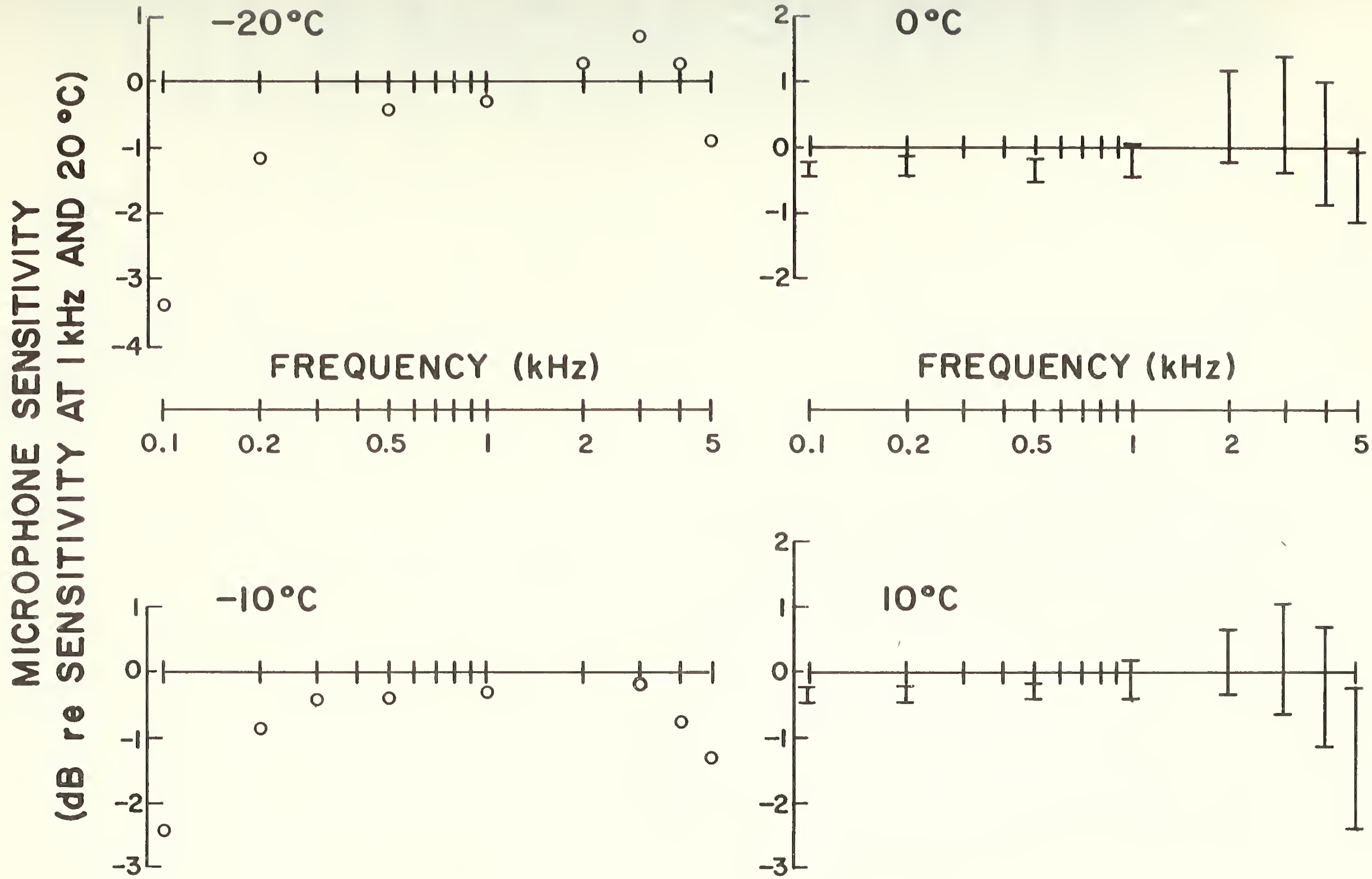


Figure 8a. Change in sensitivity of "1-inch" ceramic microphone no. 2 as a function of frequency and temperature. The vertical bars indicate the range of the data as a function of humidity.

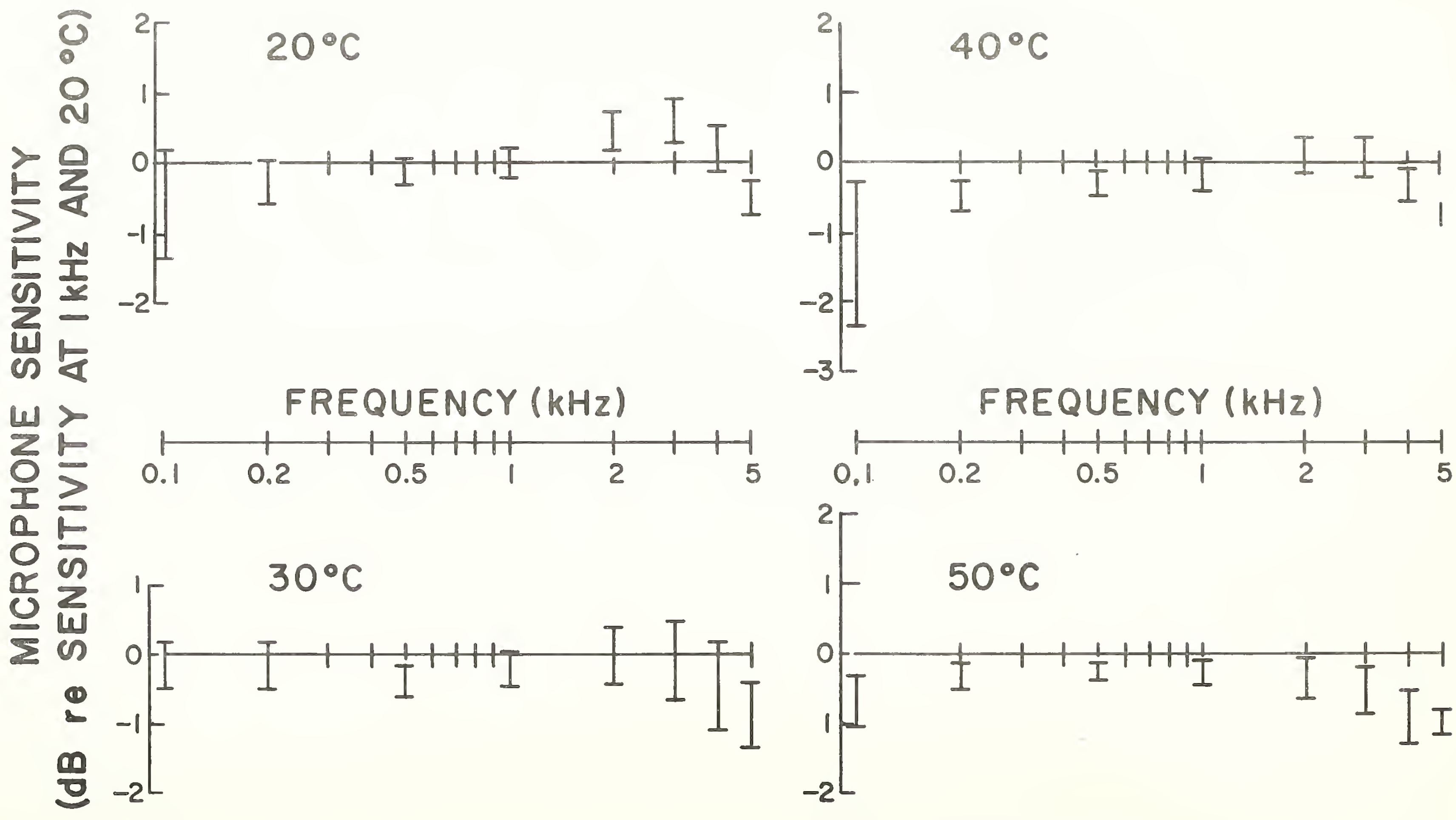


FIGURE 8B. CHANGE IN SENSITIVITY OF "1-INCH" CERAMIC MICROPHONE NO. 2 AS A FUNCTION OF FREQUENCY AND TEMPERATURE. THE VERTICAL BARS INDICATE THE RANGE OF THE DATA AS A FUNCTION OF HUMIDITY.

## APPENDIX A

## MICROPHONE CALIBRATION METHOD

### 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 microphone. 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. 6. The purpose of this appendix is to describe how NBS performed these measurements.

### 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 developed by Koidan[8] 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 a voltage is placed across the source microphone, which is in series with a resistance R. The reading of the meter, denoted $M_1$, 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

$$C = \frac{1}{2\pi f R V_3} \qquad \text{(A-1)}$$

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 ration $V_2$ is obtained. Lastly, with microphone #1 used as a source and microphone #2 as the receiver a voltage ratio $V_3$ is obtained. Using Eq. (A-1) this yields the capacitance of the microphone. 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. 6 the expressions for the pressure response of microphones #1 and #2, denoted $r_1$ and $r_2$, respectively, are

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

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

where

$$G(f) = \frac{1}{P_s C}\,\Delta^2(f,f_o) \qquad \text{(A-4)}$$

and

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

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.

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

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

where $f_\alpha$ is the first longitudinal natural frequency of the coupler with the microphone $\alpha$ as the receiver, $V_\alpha$ is the voltage ratio, $K_\alpha$ is assumed constant,

$$\beta = \frac{K}{r_1 C} \qquad \text{(A-7)}$$

and $r_1$ is given by Eq. (A-2) and C by Eq. (A-1). The constant $K_\alpha$ 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.

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)<br>0.05 (comparison) |
| 8. Barometric pressure | 0.01 |

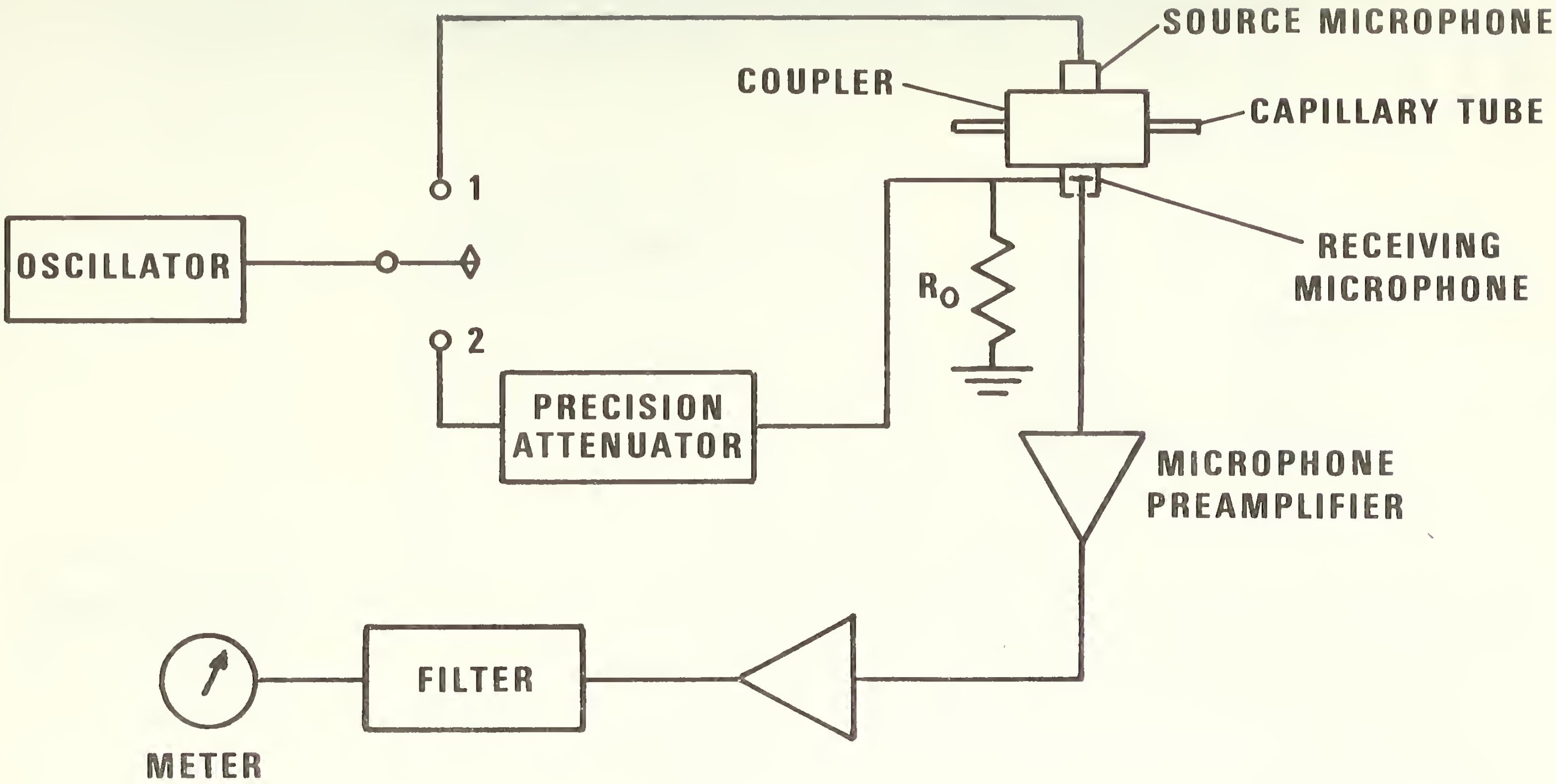


Figure A-1. Schematic of equipment required for the voltage ratio measurements.

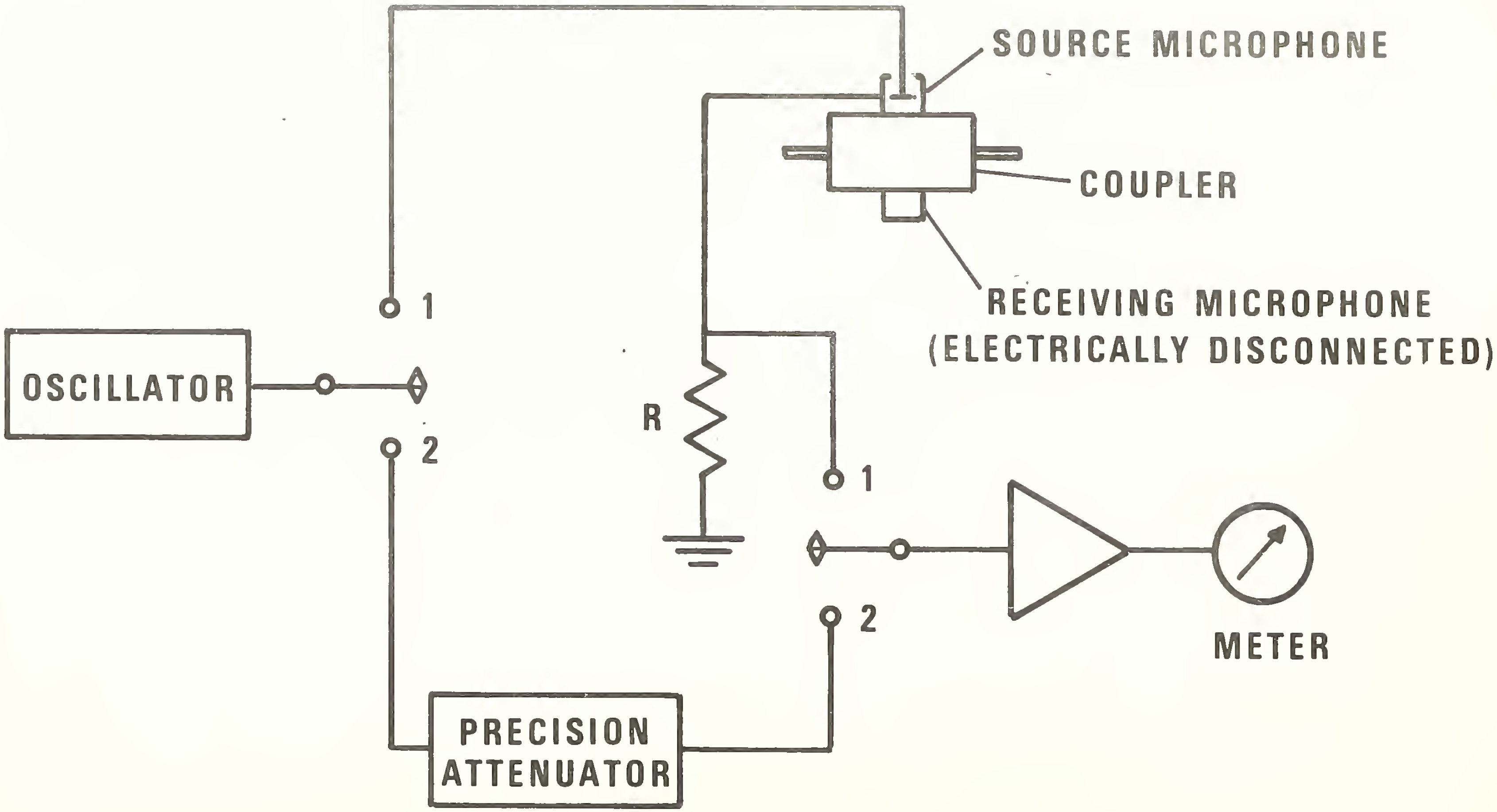


Figure A-2. Schematic of equipment required for the measurement of the capacitance of the source microphone.

NBS-114A (REV. 7-73)

| U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** | 1. PUBLICATION OR REPORT NO. NBSIR 76-1090 | 2. Gov't Accession No. | 3. Recipient's Accession No. |
|---|---|---|---|
| 4. TITLE AND SUBTITLE EPA 550/9-76-009<br>Environmental Effects on Microphones of Various Constructions | | | 5. Publication Date<br>July 1975 |
| | | | 6. Performing Organization Code<br>200.03 |
| 7. AUTHOR(S)<br>Gale R. Hruska, Edward B. Magrab, William B. Penzes | | | 8. Performing Organ. Report No. |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>**NATIONAL BUREAU OF STANDARDS**<br>**DEPARTMENT OF COMMERCE**<br>**WASHINGTON, D.C. 20234** | | | 10. Project/Task/Work Unit No.<br>2003110 |
| | | | 11. Contract/Grant No. |
| 12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*<br>Co-sponsored by NBS and Office of Noise Abatement and Control<br>U.S. Environmental Protection Agency<br>Washington, D.C. 20460 | | | 13. Type of Report & Period Covered<br>final, March-June, 1975 |
| | | | 14. Sponsoring Agency Code |

15. SUPPLEMENTARY NOTES

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

The pressure sensitivities of two "1/2-inch" electret, two "1-inch" ceramic, and two back-vented "1-inch" condenser microphones were measured for numerous combinations of temperature, percentage relative humidity, and frequency. The two condenser microphones were calibrated by the reciprocity technique at each combination of temperature, relative humidity and frequency. The condenser microphones were then used as calibrated sources to determine the pressure sensitivities of the other microphones. Insert voltage techniques were used to eliminate the environmental effects on the electronics. It was found that the back-vented condenser microphones are insensitive to changes in relative humidity. At frequencies considerably below their resonance frequencies they exhibited only a very small change in sensitivity with temperature. At frequencies closer to the resonance frequency the temperature coefficient increases approximately fourfold. The temperature and humidity coefficient for the electret and ceramic microphones could not be determined due to the instability in their sensitivities which produced changes that were larger than those induced by the temperatures and humidities.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Calibration; ceramic; condenser; electret; humidity; microphones; reciprocity; sensitivity; temperature.

| 18. AVAILABILITY | 19. SECURITY CLASS (THIS REPORT) | 21. NO. OF PAGES |
|---|---|---|
| [X] Unlimited<br>[ ] For Official Distribution. Do Not Release to NTIS | UNCLASSIFIED | 35 |
| [ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13<br>[X] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151 | 20. SECURITY CLASS (THIS PAGE)<br>UNCLASSIFIED | 22. Price<br>$4.00 |

USCOMM-DC 29042-P74