RADIO SCIENCE Journal of Research NBS/USNC-URSI
Vol. 68D, No. 6, June 1964

Electrical Properties of Sea Ice at 0.1 to 30 Mc/s[1]

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(Received Dec. 16, 1963; revised Jan. 16, 1964)

This paper sets forth the details of an experimental program in which the resistivity and dielectric constant of Arctic sea ice were measured. Fourteen ice samples ranging in salinity from 0.067°/₀₀ (parts per thousand) to 23°/₀₀ by weight were studied. The values of dielectric constant and the computed values of loss tangent are given as a function of frequency (0.1 to 30 Mc/s) for temperatures from −5 °C to −40 °C. The relationship of dielectric constant and conductivity at 3 Mc/s is also given as a function of salinity for temperatures of −10 °C, −20 °C, and −30 °C.

1. Introduction

Sea ice covers a sizable portion of the Earth's surface; yet, it appears that very little data on the electrical properties of natural sea ice exist. Such data would be helpful in planning and predicting the performance of electromagnetic systems operating in the polar regions.

Considerable data are available [Auty and Cole, 1952; Cummings, 1952; Dorsey, 1940; Eder, 1947; Jackson and Saxton, 1949; Lamb, 1946; MIT, 1953, and Murphy, 1940], however, on the properties of fresh water ice. The most extensive work on the electrical properties of artificially formed fresh ice is from Eder [1947]. His data on the dielectric constant (ϵ_r) and dielectric loss tangent ($\tan\delta$) as a function of frequency and temperature are reproduced in figures 1 and 2, respectively, so that the reader can compare the properties of pure ice with the data to be presented here for natural sea ice. Data like that of figure 1 and 2 are needed for natural sea ice, but due to the additional and often uncertain variables, e.g., salinity, age, and history, the electrical properties of natural sea ice are much more complicated than that of ice artificially formed from pure water.

The d-c conductivity of natural sea ice has been measured a number of times [Brown and Howick, 1958; Dichtel and Lundquist, 1951; and Pounder and Little, 1959]. These measurements showed that the d-c conductivity of sea ice varied from 100 to 100,000 times as high as that of pure ice. Some data are available on the electrical properties of synthetic sea ice at a frequency of 100 Mc/s [Cook, 1960]. These latter data were obtained from measurements on ice made from water to which the proper salts had been added to synthesize natural sea ice of various salinities. The 100 Mc/s measurements showed that the conductivity of the synthetic sea ice varied from 2 to 50 times that of pure ice depending on the temperature and salinity. The conductivity and dielectric loss tangent of the synthetic ice were approximately proportional to the salinity within the following range of salinities: 3.5°/₀₀ to 35°/₀₀ (parts per thousand). The dielectric constant was somewhat higher than that of pure ice and increased slightly with increasing salinity. The above cited sparse data on natural and artificial sea ice further indicate that added salts have a diminishing effect on the electrical properties of ice as the frequency is increased. Some data are available on the electrical properties of natural glacier and continental shelf ice [Watt and Maxwell, 1960; and Waite and Schmidt, 1961], at frequencies from 20 c/s to 4400 Mc/s. These measurements similarly showed that the difference between the properties of artificial pure ice and natural ice decreased as the frequency was increased. The results of the work reported here verify the fact that the salinity of sea ice has a diminishing effect on the electrical properties with increasing frequency. Fortunately, the transition regions from high to low values of both dielectric constant and loss tangent were manifest within the frequency band (0.1 to 30 Mc/s) chosen for this study.

2. Acquisition of Ice Samples

During the month of October 1962, a field trip was made to Barrow, Alaska and the floating ice islands T–3 (Fletcher's Ice Island) and ARLIS II (Arctic Research Lab. Ice Station) for the purpose of collecting samples of sea ice of various ages. T–3 and ARLIS II are operated by the Arctic Research Laboratory of the University of Alaska. Transportation to the ice islands was by a U.S. Navy aircraft which is assigned to ARL for this work.

The ice samples were cut by hand with a SIPRE 3-in. coring auger. On October 24, 1962, nine cores were cut at points from a few hundred yards to 2500 yd from ARLIS II, which at the time was located at 84°00′ N, 168°34′ E. Three cores of newly formed sea ice were taken from a recently frozen lead. This ice was about one month old.

[1] The work reported here was supported by the Bureau of Ships, Dept. of the Navy under Contract No. NObsr 87667.

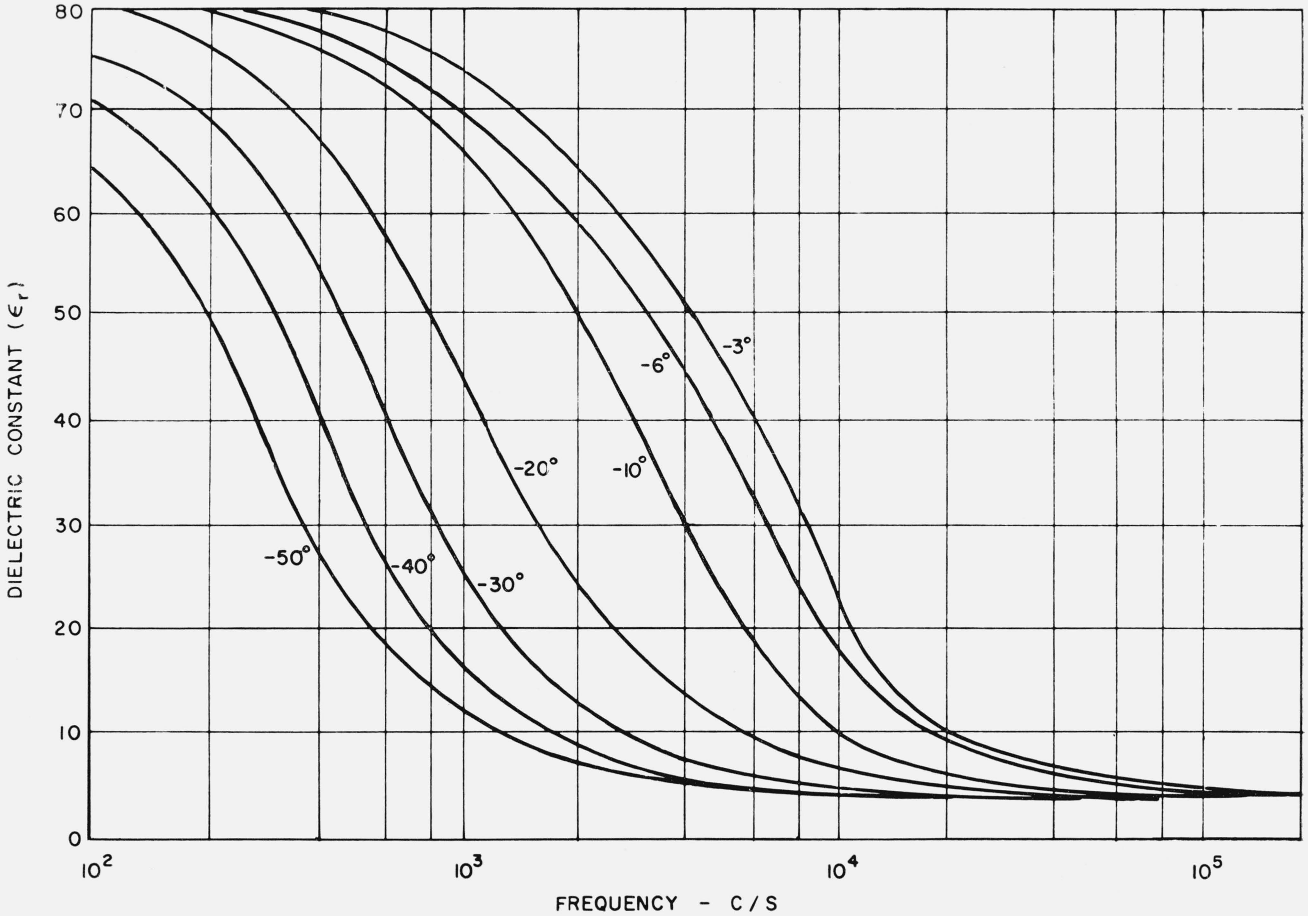


FIGURE 1. *Dielectric constant of pure ice* [*Eder, 1947*].

Three cores were cut from ice identified as being about a year old and three other cores were cut from a hummock which was at least two years old. Except for the hummock ice, all cores were cut completely through the ice to the water surface. The approximate age of the ice, from which the above cores were cut, was estimated by Arnold Hanson of the University of Washington. Mr. Hanson has spent considerable time on ARLIS II and was familiar with the conditions and history of the sea ice in its vicinity.

On November 3, 1962, five cores of one-month-old ice were cut from a point about 200 ft off shore on the lagoon at Point Barrow. In addition, two pieces of pack ice, which were piled up on the shore, and two shovelfuls of slush ice were taken. These last four samples are of questionable value since the age of the pack ice is not known and all four samples were contaminated by silt from the beach.

As the samples were collected, they were labeled with respect to estimated age, geographic location, and date acquired. It should be pointed out that there were no provisions for measuring the salinity of the samples during this time.

The ice samples were packaged in dry ice at Barrow, Alaska and shipped by air to ECI's Timonium, Md., laboratory under personal escort by one of the authors. The ice samples, individually packaged in plastic bags, have been stored in the laboratory in a domestic type upright freezer at −20 °C. After five months of storage the only visible signs of deterioration are the formation of frost on the surfaces of the sample and on the inside of the bag. The salinity of samples Nos. 17 and 18, pieces of frozen slush ice, were measured after this length of time and found to be approximately 15.5‰ and 23‰ salt. In the investigation by W. F. Weeks and O. S. Lee [1958 and 1962], the salinity of newly formed sea ice was found to be 24‰ in one measurement and 18‰ in another. They also reported that the salt content decreased rapidly during the first 10 days after initial freezing and began to approach equilibrium at approximately 8‰. It has been reported that the salinity of sea ice is inversely related to the air temperature at the time the ice was formed.[2] For example, at −17.7 °C, ice from water

[2] The progressive elimination of salt from sea ice, text in Spanish, Iberica **26,** 308 (Nov. 20, 1926).

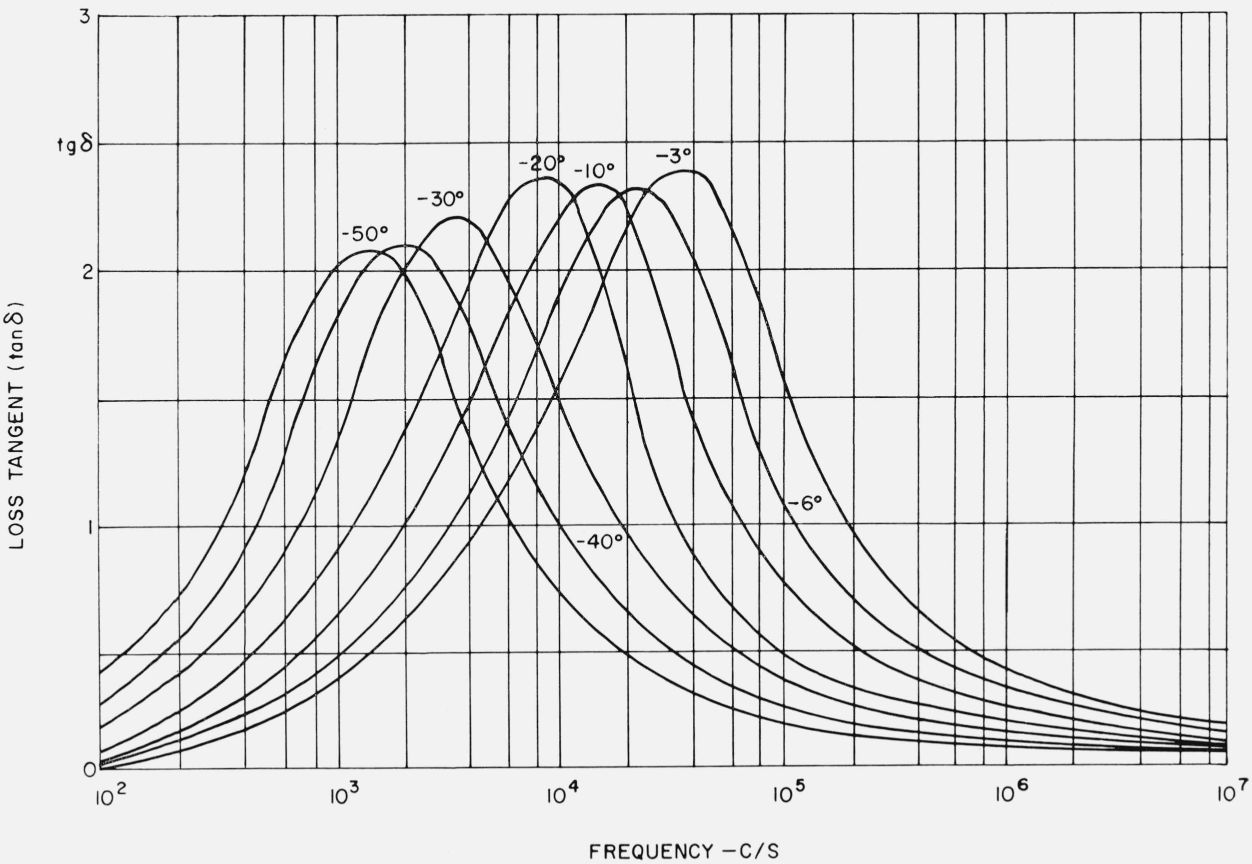


FIGURE 2. *Loss tangent of pure ice* [*Eder, 1947*].

with an initial salinity of 40‰ contained 20‰ salt. This dependence holds for temperatures down to the eutectic point (—21 °C to —23 °C) where the salt concentration reaches a maximum value of 22.5‰.

The air temperature on the day the slush ice samples (Nos. 17 and 18) were taken was about —20 °C. When a shovelful of slush was taken from the water it froze almost immediately. The rapid freezing explains the high salt content of samples 17 and 18. The fact that these samples still had salinities near the maximum value after 5 months storage indicates that the problem of salt "bleeding-out", which was reported by Weeks and Lee for natural temperature conditions, can be controlled in the laboratory with a sufficiently cold storage temperature.

The specimens for the salinity tests and the electrical tests were adjacent slices taken from the parent core at the same time. Only one salinity measurement was made for each core. The salinity measurements on the ice samples have been made by comparing the weight of a specimen of ice to the weight of the solid residue after the water has been removed by evaporation. This method was chosen in preference to a chemical analysis, which would be unnecessarily complicated for our purposes because of the many different salts found in sea water. The following is an approximate recipe for sea water [Clarke, 1924]:

Distilled H_2O	3 Liters
NaCl	82. 5 g
$MgSO_4$	10. 6 g
$MgCl_2$	6. 14 g
$CaCl_2$	3. 3 g
Kcl	0. 83 g
K_2CO_3	0. 7 g

The salinity of this recipe is approximately 33‰ by weight.

3. Measurement Technique

In the frequency region 0.1 to 30 Mc/s, the wavelength is long compared to the size of the ice specimens; consequently, the measurement scheme was based upon equipment and techniques for circuits with lumped constants rather than distributed constants. The specimen holder is a capacitor in which the specimen is the dielectric between the plates. A capacitance bridge was used to measure the values of capacity and shunt resistance of the specimen and holder. Since the physical dimensions of the holder are known, it was a simple computation to determine the dielectric constant (ϵ_r), the resistivity (ρ), and the loss tangent ($\tan \delta$) of the ice.

At the onset of the measurement program, the specifications of a number of commercial bridges were studied. It appeared that no one bridge would be able to measure the expected wide range of impedances over such a wide frequency band. The fact that the specimen had to be refrigerated further complicated the problem. The bridge could not be placed in the cold because it would soon become inoperative due to the frost which eventually forms on everything in the freezer. To resolve these difficulties, it was decided to sacrifice some of the accuracy of the commercial bridges and to build a simple form of capacitance bridge which would be an integral part of the freezer. With such a unit it would be possible to modify the operating range to suit the actual impedance values of the ice, which at this point were unknown. As it turned out, this was a good decision because of the extreme ranges of capacity and shunt resistance which were encountered. Capacity varied from 30 to 1000 pf and shunt resistance from 20 to 50,000 ohms; consequently, the bridge circuit had to be continually modified to provide the capability of a balance for all these values. Two bridges were used to cover the frequency range; one was used from 0.1 to 10 Mc/s and the other from 10 to 30 Mc/s. The schematic drawings of the two bridges are shown in figures 3 and 4.

Calibration of the bridges consists of relating the dial positions of the variable resistor and variable capacitor in the tunable leg of the bridge to known values of R and C, which were substituted in shunt for the specimen holder in the unknown leg of the bridge. These values of R and C were determined separately on standard laboratory measuring equipment.

This simple measuring technique was refined by the addition of a guard ring to the specimen holder capacitor and a third leg on the bridges for the guard ring potential. The correct guard ring potential and final bridge balance are realized when the null at the detector is undisturbed by either the open or closed position of the low capacity switch. When the guard ring potential is equal to that of the specimen holder the field through the specimen is perpendicular to the capacitor plates. This refinement prevents measurement errors through fringe field effects at the edge of the specimen holder. Figure 5 shows the specimen holder; the upper plate has been turned to show the guard ring.

An evaluation of the measurement system for determining the dielectric constants was made by placing specimens of known dielectric materials between the plates of the specimen holder. The

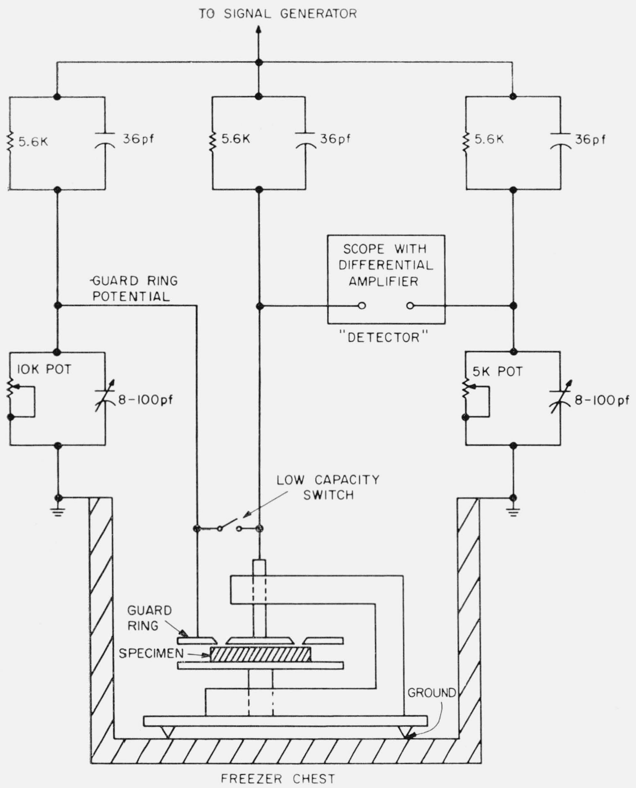


Figure 3. *Bridge schematic; 0.1–10 Mc/s.*

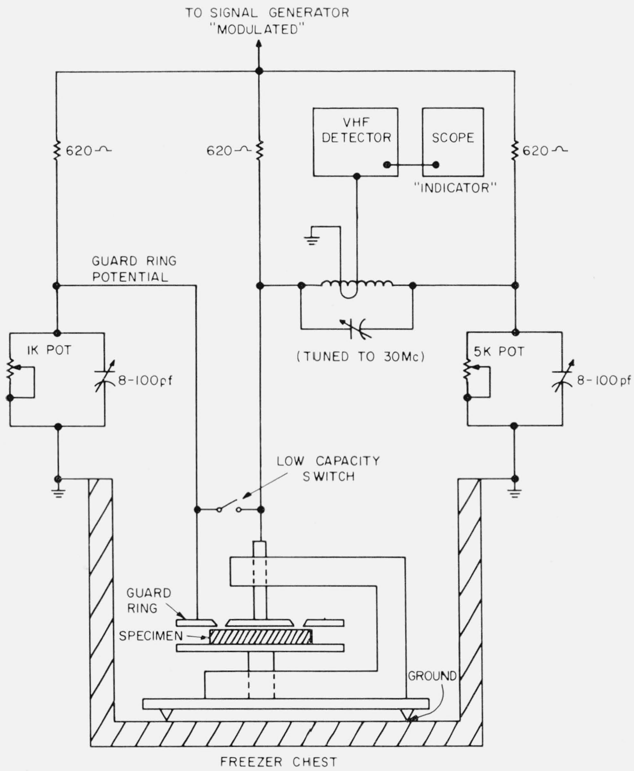


Figure 4. *Bridge schematic; 10–30 Mc/s.*

specimens were Stycast —15 (ϵ_r=15) and polystyrene (ϵ_r=2.56). Figure 6 gives the measured results of dielectric constant as a function of frequency. Two polystyrene disks were used; one was 3 in. in diameter and the other 4 in. in diameter. The two diameter sizes were used to test the selectivity of the specimen holder to measure only the amount of dielectric inside the guard ring. The diameter of the center plate of the specimen holder is 2.67 in. The data given in figure 6 show that measurement system

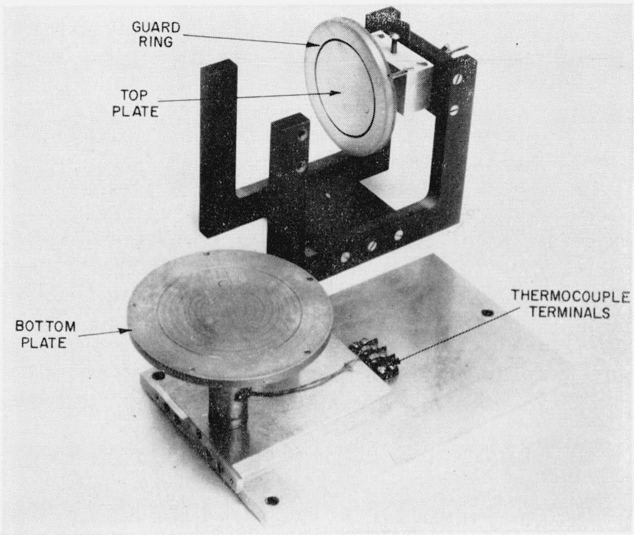


FIGURE 5. *Specimen holder.*

is flat over the frequency band 0.03 to 30 Mc/s except for a small deviation at 30 Mc/s, and that only the portion of the specimen inside the guard ring affects the measurement. The measurement accuracy for dielectric constant is better than ±½ unit of ϵ_r which is considered rather coarse by ordinary bridge standards; however, the evaluation data have been plotted on figure 6 to the same scale as used for presenting the ϵ_r of sea ice in order to place the measurement accuracy in the proper perspective to the measured data.

4. Preparation of Specimens

The specimens of sea ice were prepared for the specimen holder with the equipment shown in figure 7 in the following manner: three ¼ in. thick disks were sawed from one of the 3 in. diameter cores. The first piece is discarded since it is usually covered with frost and it could be contaminated. The second piece was sealed in a plastic bag and set aside for a salinity test. The third piece, being thick enough at this stage, was clamped at its edges in the shaving jig. The shaving of the ice was done by a hand operation in the fashion of a microtome. When the specimen was made smooth and flat on the first side, it was turned over and held fast to the shaving jig by differential air pressure between the top and bottom surfaces. The pressure differential was produced by drawing a vacuum on the bottom surface of the specimen through small holes in the shaving

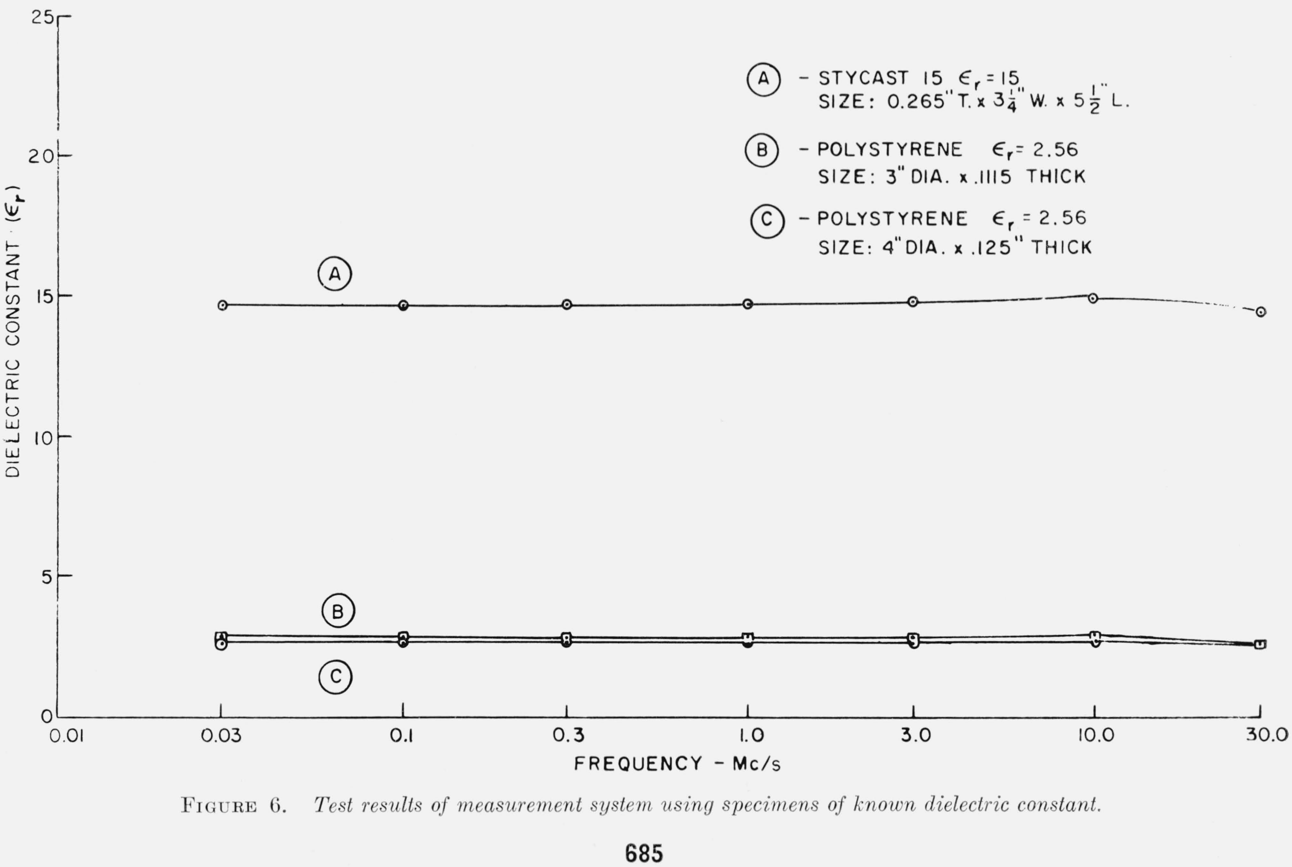


FIGURE 6. *Test results of measurement system using specimens of known dielectric constant.*

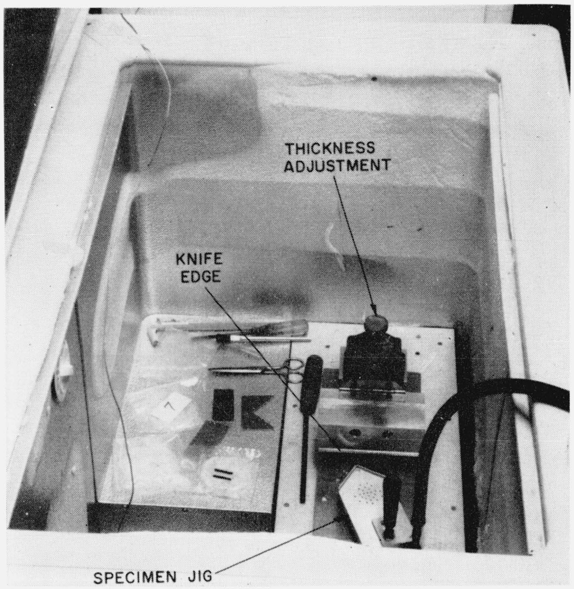


FIGURE 7. *Ice shaving tools.*

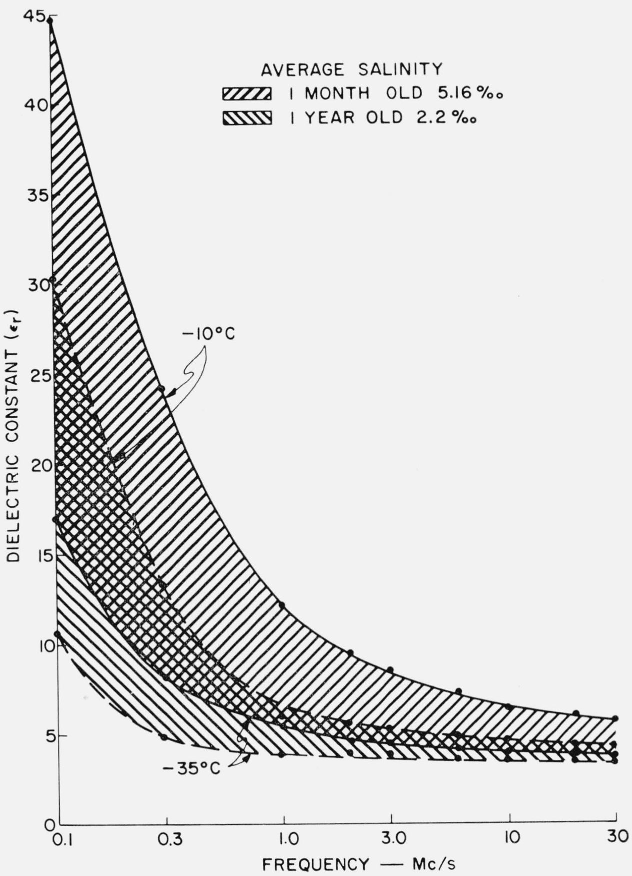


FIGURE 8. *Average maximum and minimum dielectric constant for sea ice.*

jig. With this method of holding the ice, very thin specimens can be made; however, it was found that ⅛ in. thick specimens are electrically satisfactory and are less likely to break.

Sea ice forms in long thin crystals which are orientated normal to the surface of the water, as might be expected, since this is the direction of growth. The crystal structure in the cores is, therefore, longitudinal. The major portions of the measurements have been made on specimens which have been sliced from the cores in a plane normal to the core axis. The electric field in the ice for the measurement is, thus, parallel to the crystal structure. In two cases, specimens were also cut so that the normal to the specimen faces was perpendicular to the core axis for the purpose of comparing the effect of different ice crystal orientations.

In the measurement setup, three freezer chests were used. The first was used for storage of the large ice samples, the second for the cutting and shaving operation, and the third for the bridge and the measurement operation. It was found that the prepared disks could not be stored for longer than a day or two. Storage for longer periods resulted in deterioration due to recrystallization of vapor from the specimen back onto itself.

5. Electrical Characteristics of Sea Ice

The philosophy behind the measurements was that of determining only the gross electrical properties of sea ice because the salinity measurements of various samples had given such a wide range of values, even between samples from the same core. These variations within a core were, of course, expected since the salinity of sea ice varies with depth and only vertical cores were acquired. The result of the evaluation of dielectric constant (ϵ_r) and loss tangent ($\tan \delta$) has shown that these properties vary widely as a function of frequency, temperature, and salinity. In view of this, the electrical properties of sea ice are presented at the extreme temperatures as a function of frequency in figures 8 and 9. Both ϵ_r and $\tan \delta$ are maximum for warm ice and minimum for cold ice. In order to also show the lesser effect of salinity, which is inversely related to the age of the ice, the extreme values are given for both one-month- and one-year-old sea ice. The values which are given are the average values at the extreme temperatures of three samples of both one-month-old and one-year-old ice, respectively. The ice samples chosen were all taken at ARLIS II.

Of the 18 samples which were collected, specimens were sliced from 14 of them. Two samples of the hummock ice could not be cut into specimens because they were too fragile. The two specimens of pack ice from just off the beach of Barrow, Alaska, appeared too dirty to be representative of pack ice, and they too were not used.

In figures 10 and 11 values of ϵ_r and conductivity at 3 Mc/s for temperatures of -10 °C, -20 °C, and -30 °C are given as a function of salinity. In both figure 10 and figure 11, for salinities up to about

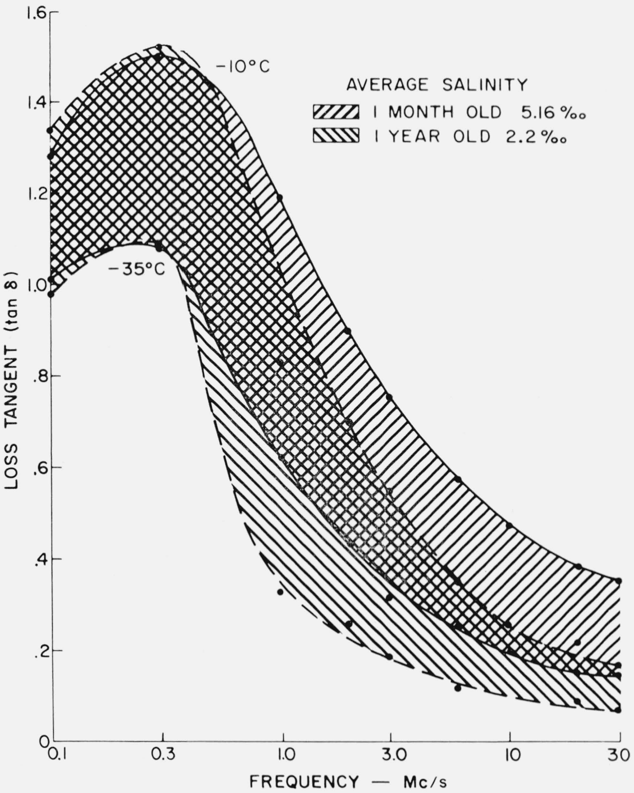


FIGURE 9. *Average maximum and minimum loss tangent for sea ice.*

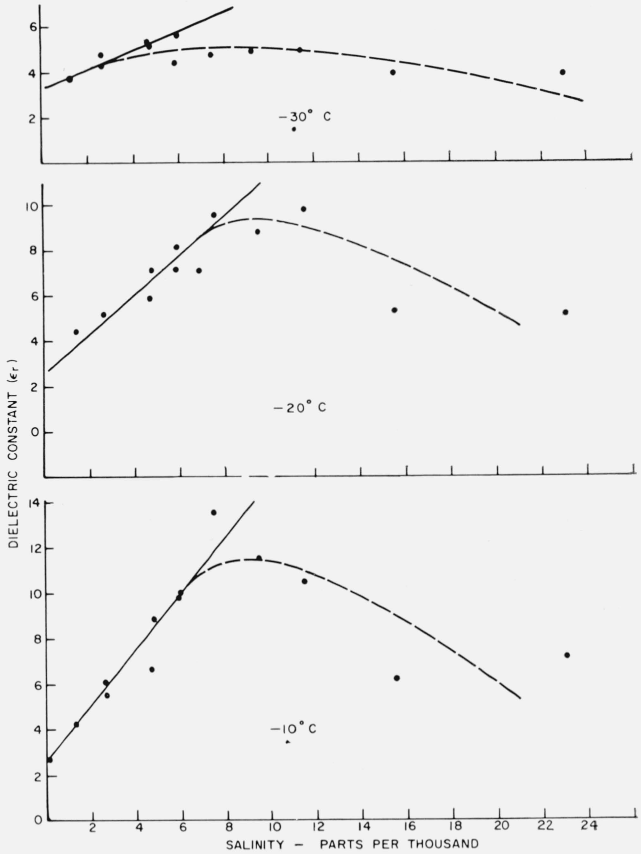


FIGURE 10. *Effect of salinity on dielectric constant of sea ice at 3 Mc/s.*

10 ‰, these parameters increase with increasing salinity as might be expected. For salinities greater than 10 ‰, the results indicate a reverse trend. There is, however, some reason to suspect the values for 15.5 ‰ and 23 ‰ because the ice samples on which these were taken are the pieces of slush ice which are quite unlike naturally grown sea ice.

In general, the data were taken for temperatures from −35 °C to −10 °C in steps of 5 °C, however, some data were taken at −40 °C and −5 °C. Temperatures below −20 °C were obtained by adding dry ice to the freezer; it was not always possible to achieve −40 °C. At −5 °C some samples became wet on the surface, and the shunt resistance of the specimens was too small to measure.

The effect of polarization with respect to crystal structure direction is demonstrated in figures 12 and 13, which are typical families of curves of ϵ_r versus frequency at various temperatures. Both specimens were cut from the same sample of one-month-old ice. The data in figure 12 are for the electric field parallel to the ice crystal growth and the data of figure 13 are for a field transverse to the crystal growth. The curves of tan δ versus frequency for the same two specimens are shown in figures 14 and 15, respectively. These are typical families of curves of tan δ versus frequency at various temperatures.

The similarity in shape of figures 12 and 13 to figure 1 and of figures 14 and 15 to figure 2 should be noted. This comparison shows that a principal effect of the salt inclusion is to shift the region in which the dielectric constant decreases and the loss tangent peaks to higher frequencies. Similar characteristics were observed with most of the specimens tested. The electrical properties of lower salinity specimens had their greatest variation at lower frequencies than those shown in figures 12 through 15.

For several samples, the data of tan δ versus frequency yielded a family of curves similar to those shown in figure 16. In an attempt to improve the presentation of the data, ϵ_r and ρ were plotted as a function of temperature for various frequencies. The results are shown in figures 17 and 18. In this new presentation, the data give a more satisfying picture in that, within the family of curves, there are no crossovers except possibly where some error in the measurement has occurred. The data of each frequency curve show a definite relationship to all the others. For example, the resistivity versus temperature curves (fig. 17) show peaks at a temperature of −20 °C which grow in magnitude with decreasing frequency. This explains why the presentation in figure 16 was so confusing. A similar peak can be observed on a number of other samples, but not on all of them. It is a temptation to relate the occur-

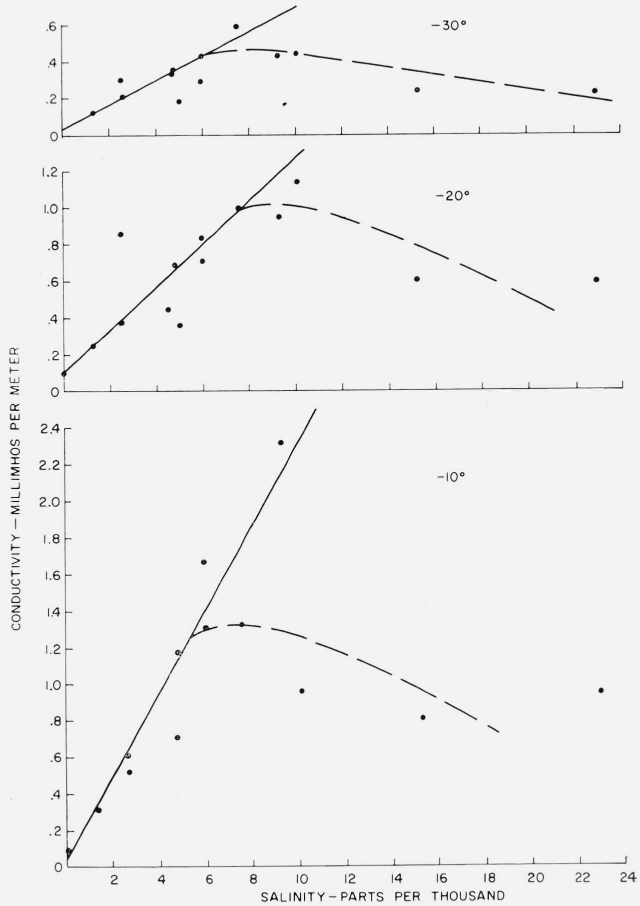


FIGURE 11. *Effect of salinity on conductivity of sea ice at 3 Mc/s.*

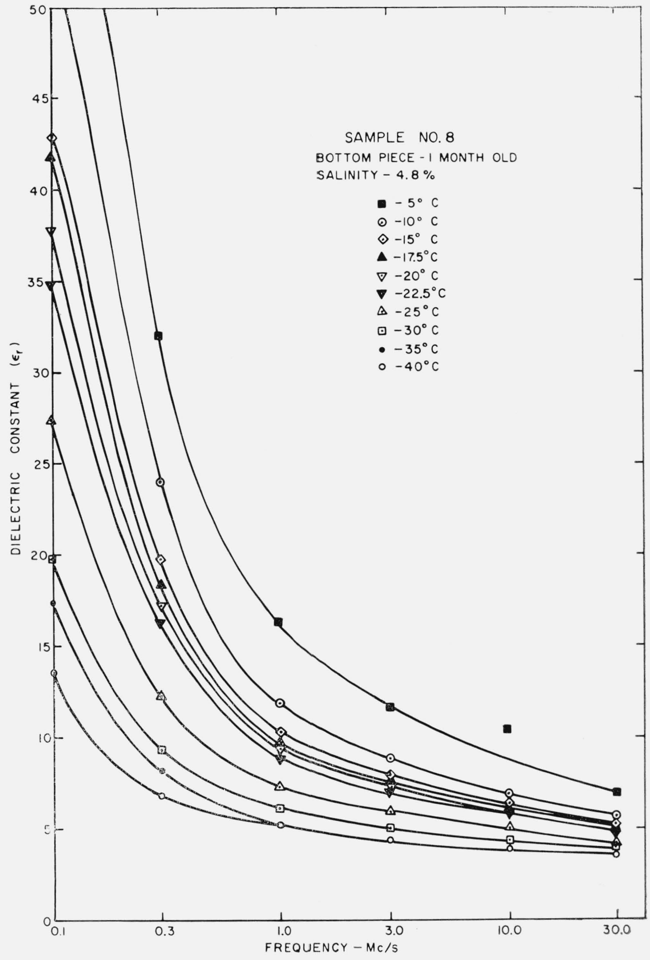


FIGURE 12. *Experimental values—dielectric constant versus frequency—for various temperatures.*

rence of these peaks to the eutectic temperature where the brine cells freeze; however, in a few samples, the peaks have developed at −30 °C and at −12 °C. It should also be observed that, where there is a peak in the resistivity curve, there is depression in the dielectric constant curve.

6. Conclusions

These preliminary measurements on the electrical properties of sea ice in the 0.1 to 30 Mc/s frequency range have shown that it is an extremely complex dielectric material. It is recognized that the data presented in this paper are limited by the fact that measurements were made on only fourteen ice samples. Correlation of the measured electrical properties of sea ice with the history and crystal structure of the ice samples would be desirable. Confidence in the validity of the measured data would be increased if the measurements could be made on undisturbed ice on site. Such measurements, unfortunately, are extremely expensive and difficult to perform.

The measured data presented in this paper are believed to be a sufficiently accurate approximation of the actual electrical properties of sea ice to be useful in predicting the performance of electromagnetic systems operating in the polar regions. Confidence in this data is enhanced by the fact that, even after months of storage, the total salt content of the ice samples was in the range expected for the age of the ice at the time the cores were cut.

Families of curves of the dielectric constant and loss tangent as a function of frequency and temperature were plotted for all of the ice samples. Almost all of these curves are similar in shape to those shown in figures 12 through 15. It is thus believed that the average curves shown in figures 8 and 9 are representative of the dependence of the dielectric constant and loss tangent on frequency and temperature. It should be noted that these curves are similar in shape to the corresponding curves for pure ice (fig. 1 and 2). The principal difference is that the region of greatest dispersion and loss is shifted to higher frequencies for the sea ice.

The authors would like to express their appreciation to Arnold Hanson of the University of Washing-

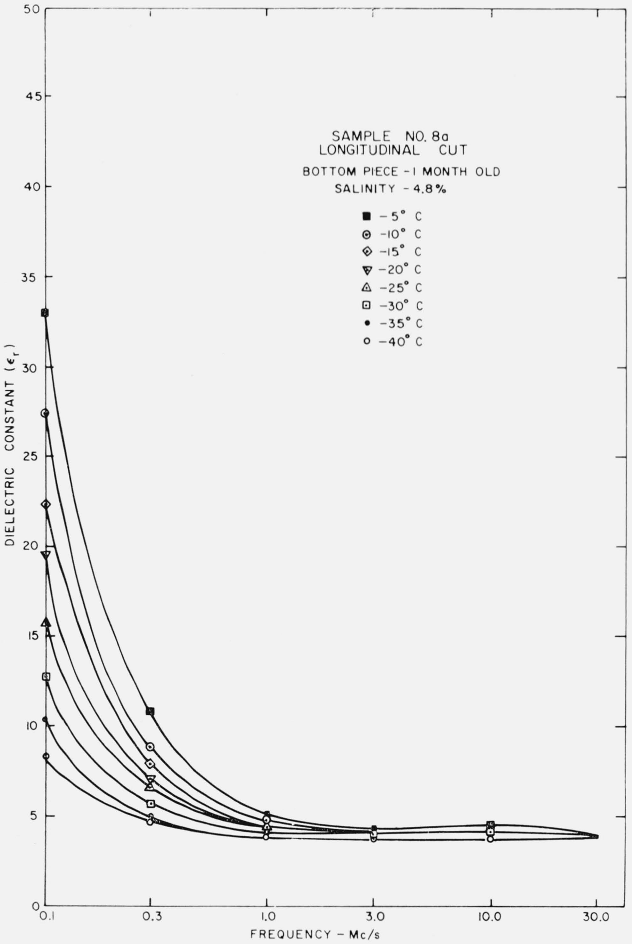


FIGURE 13. *Experimental values—dielectric constant versus frequency—for various temperatures.*

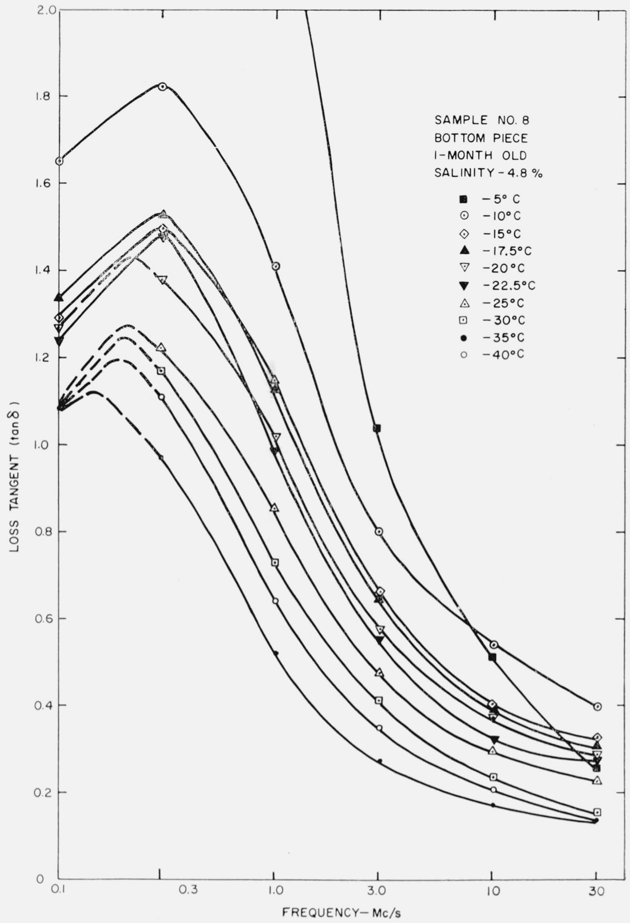


FIGURE 14. *Experimental values—loss tangent versus frequency—for various temperatures.*

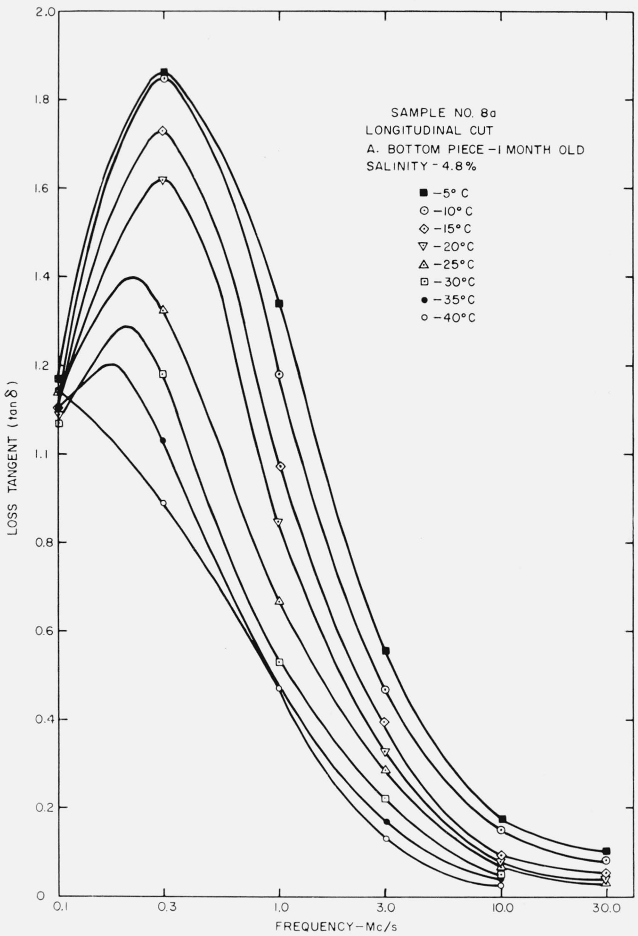
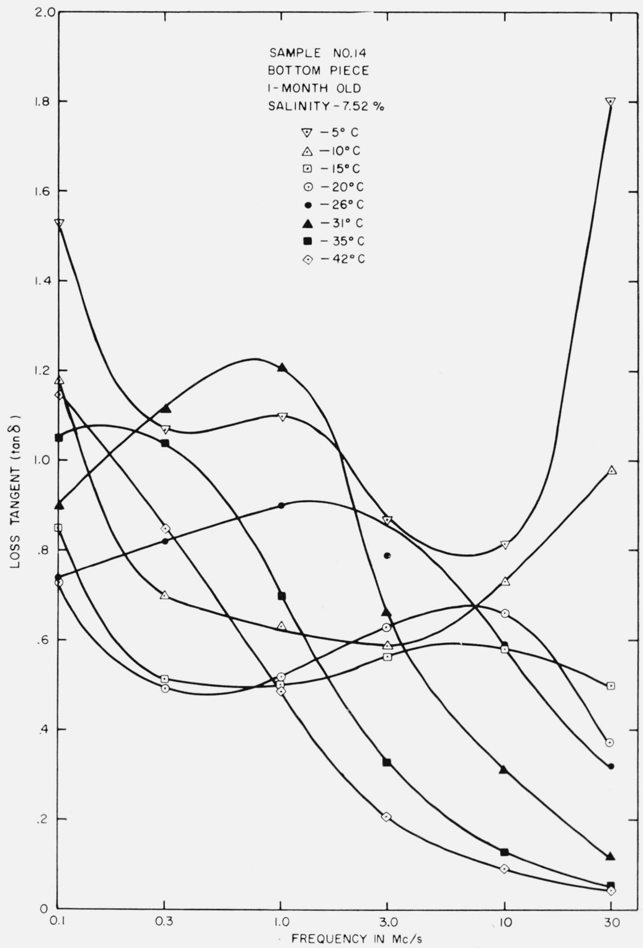


FIGURE 15. *Experimental values—loss tangent versus frequency—for various temperatures.*



FIGURES 16. *Experimental values—loss tangent versus frequency—for various temperatures.*

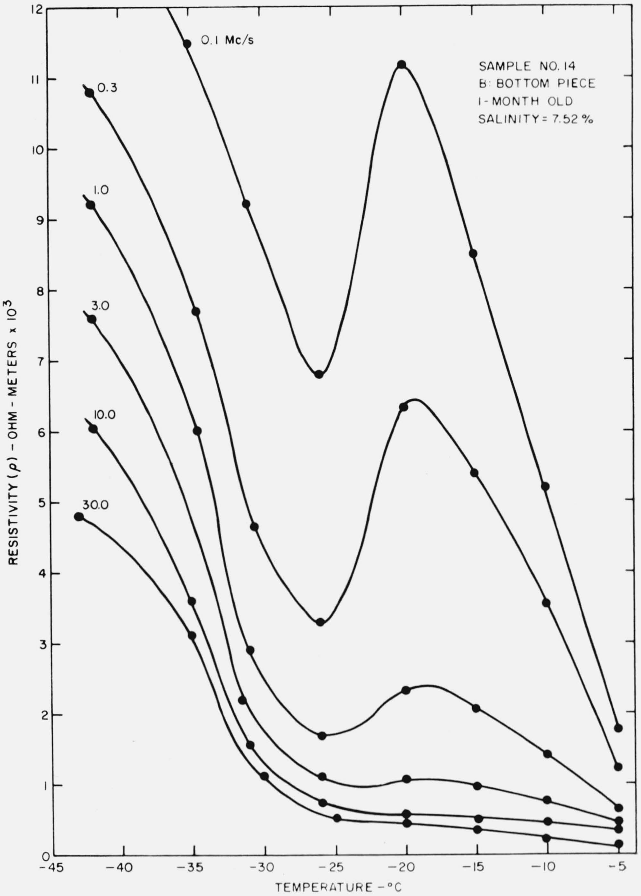


FIGURE 17. *Experimental values—resistivity versus temperature—for various frequencies.*

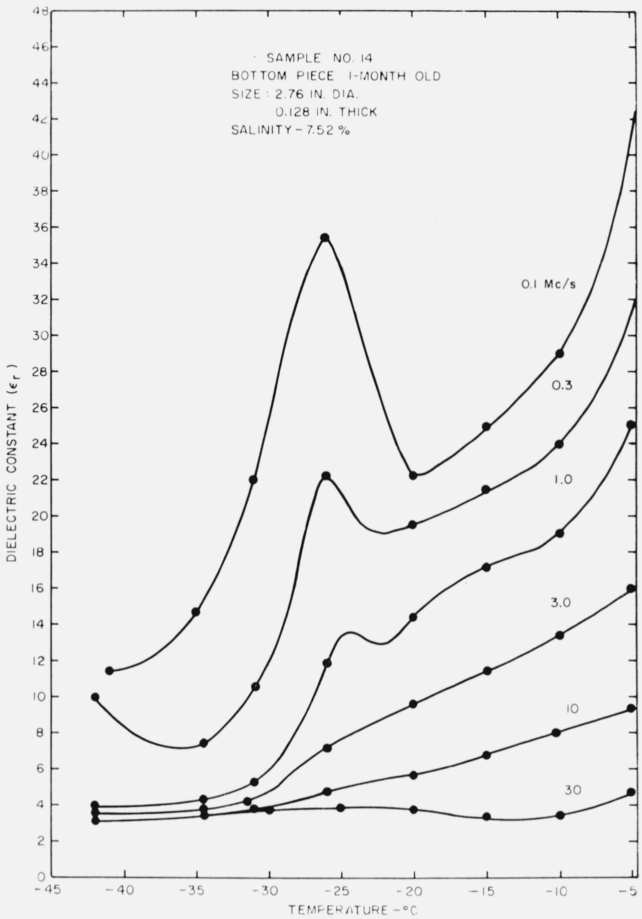


FIGURE 18. *Experimental values—dielectric constant versus temperature—for various frequencies.*

ton for his advice and assistance in acquiring the ice samples at ARLIS II. Similarly, thanks are due to Charles Cooke of ARL for assistance given at Barrow. Acknowledgment is also due to others on the staff of ARL for their assistance in the successful completion of the field trip.

Acknowledgment is especially due to D. A. Youngberg and J. L. Molz for their work in performing the major portion of the measurements and in plotting the data.

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