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U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Institute for Materials Science and Engineering
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

A DIELECTRIC PHANTOM MATERIAL FOR ELECTROMAGNETIC RADIATION

by

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Polymers Division
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a report for

Division of Medical Engineering
Center for Devices and Radiological Health
Food and Drug Administration

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Abstract: This report describes the design and performance of a synthetic material that has the same dielectric heating characteristics as living muscle in the 1-1000 MHz frequency range. This dielectric phantom is a combination of four components: 1) a 50/50 solution of ethylene carbonate and propylene carbonate chosen to have the same dielectric constant as water, 2) an organic salt to provide the same conductivity as biological electrolytes, 3) flakes of polyethylene terephthalate to provide the interfacial polarization that occurs at cell walls in biological tissue and 4) an inorganic and a polymeric gelling agents to provide mechanical rigidity. The resulting composite material is more stable to biological attack and drying than are existing aqueous based phantom materials, and its dielectric properties are more closely matched to those of natural tissues over most of the frequency range of interest.

Disclaimer: Certain commercial materials and equipment are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the commercial materials or equipment identified are necessarily the best available for the purpose.

INTRODUCTION

The development, testing and calibration of devices that subject human tissue to the heating effects of high frequency electromagnetic (EM) radiation [1] require a material (here called a phantom) which duplicates the dielectric and thermal properties of living tissue. Presently-used phantoms are gels made of naturally occuring biological polymers swollen with a large amount of water containing dissolved sodium chloride [2]. The dielectric constant is adjusted upward by adding aluminum particles and downward by adding polyethylene particles. The problems with the present phantoms are:

1. The gels are unstable because molds and bacteria attack the biopolymers, the salt water reacts with the aluminum and the gels dry to form hard surface layers as the water evaporates.

2. The changes in electrical properties with frequency are different from those in living tissue, so that different compositions are required for different frequencies.

3. The thermal properties of the aluminium depart significantly from those of living tissue.

It is desirable to find a new phantom material that overcomes these deficiencies. The National Bureau of Standards is helping the Food and Drug Administration's Center for Devices and Radiological Health design and test such a material.

ANALYSIS OF THE PROBLEM

We can treat a material as a frequency dependent complex admittance Y^* in which the current leads the applied field by a phase angle in the range of 0 to 90 degrees. If this phase angle

is near 0 degrees we generally consider the material an electrical conductor and characterize its impedance as a complex conductance, σ^*. If the phase angle is nearer 90 degrees we consider the material to be a dielectric and characterize its impedance with a complex dielectric constant, k^*. The dielectric constant is defined here as the ratio of the permittivity of the material to the permittivity of free space. Biological tissues tend to give phase angles that vary over much of the range of 0-90 degrees, and their electrical properties are sometimes given as a complex dielectric constant, conductivity, or as a combination involving the real parts of both the dielectric constant and the conductivity. These representations are equivalent, and a particular author usually chooses the system he is used to. In this report we will give the electrical properties in terms of the complex dielectric constant,

$$k^* = k' - ik'' = k' + \sigma'/iwe_o = \sigma^*/iwe_o = Y^*/iwC_o,$$

where w is the angular frequency, e_o the permittivity of free space, C_o is the empty specimen holder capacitance and $i = \sqrt{-1}$.

The EM heating of a material results from that part of the motion of the charges in the material that is in phase with the sinusoidally alternating electric field, E. The heat generated in the material per cycle is equal to $k''e_oE^2$. k' may be important if it affects the magnitude of E^2. If one matches k' and k'' in two homogeneous materials, one matches the electromagnetic heating behavior also.

This criterion is not a sufficient one for composite materials, because in these inhomogeneous systems, the electric field can be localized in one part of the material and produce localized heating. In two specimens with the same average complex dielectric constants, one of them might heat uniformly and the other nonuniformly. This situation is unacceptable for a phantom, and a second criterion for matching heating behavior in inhomogeneous materials must be that the distribution of electric field be similar in the two materials.

Many of the properties of living biological tissues are based on their high contents of salt water. This is true of the electrical properties of tissues at frequencies above 100 MHz, where the complex permittivity approaches that of the salt water extracted from the tissues [3]. At lower frequencies the electrical properties are extremely sensitive to the fact that the salt water is confined to small inter- and intra-cellular regions by cell membranes that partially block the ionic conduction and produce high electrical polarization. The effects of this charge blocking increase as the frequency decreases. Interfacial polarization of this type is historically referred to as Maxwell-Wagner [4] polarization and must be understood and controlled in a material for it to be a successful phantom. If the polarization mechanisms in living biological tissue can be incorporated into a phantom, then one can expect the electric field distribution and the dielectric constants to be the same. When these conditions are met, one can expect the frequency and temperature dependences of the dielectric constants to be the same also.

The thermal properties of living tissue also are dominated by the water. Few materials have as high a heat capacity as water, unless undergoing a phase change. Since this property is hard to match in non-aqueous systems, it is fortunate that heat capacity differences can be accounted for computationally and that the lower heat capacity of most common materials will actually increase the sensitivity of the temperature measurements during low-power EM exposure. For hyperthermia measurements, one would like the thermal diffusivity-a measure of the rate of relaxation of a non-equilibrium temperature distribution-to be as low as possible, to provide sufficient time to measure temperature distributions after EM exposure. Fortunately, organic materials often have lower thermal diffusivities than water. We can expect then that thermal property requirements will be met easily in a predominately organic phantom.

STATEMENT OF THE WORK TO BE DONE

In its original contract agreement with the FDA the NBS agreed to:

1. Search for materials suitable for use as dielectric phantoms over the frequency range of 10-100 MHz (of primary importance is 10-50 MHz). The desired properties are in the range $90 < k' < 120$ and $0.65 < \sigma' < 0.90$ S/m at 27 MHz (25^{o}C). The materials should be commercially available or easily prepared from commercial materials. The thermal diffusivity of the material should be no larger than that of tissue.

2. Prepare samples as appropriate to evaluate types of material.

3. Measure electrical properties of candidate materials as appropriate.

4. Provide a report to the FDA's National Center for Devices and Radiological Health on the results of the investigation which will include recommendations for the direction of future work if a phantom with satisfactory properties has not been developed or identified.

EXPERIMENTAL MEASUREMENTS

Dielectric Specimen Holder

The dielectric measurements reported here were made using a parallel plate specimen holder consisting of a cylinder cut from standard polyethylene tubing nominally 1/4" (6.35mm) ID, and 3/8" (9.52mm) OD. Polyethylene (PE) was chosen because of its low complex dielectric constants and stability in the presence of solvents. The electrodes consist of polished, gold-plated copper disks of 9.52mm diameter. The specimens used in this work were either liquids, gels or wet solids. The cell, with an electrode at each end of the tube, was able to contain the specimens via surface tension.

For some measurements the electrodes were secured to the PE cylinder with parafilm [5] tape. The area and thickness of the specimens were taken to equal the inner area and length of the PE tube. These dimensions were carefully measured with a micrometer. This gave a sample area of A = 0.317cm^2, thickness t =0.457cm, cell constant A/t = 0.694cm, and empty cell capacitance $C_o = e_o A/t$ = 0.0614pf. The sample capacitance, C_x and conductance, G_x, were taken to be the difference in measured capacitance and

conductance of the cell with ($C_m$in and $G_m$in) and without ($C_m$out and $G_m$out) the specimen in place.

$$C_x = C_m\text{in} - C_m\text{out} + C_o,$$
$$G_x = G_m\text{in} - G_m\text{out}.$$

The real and imaginary parts of the dielectric constant are given by,

$$k' = C_x/C_o,$$
$$k'' = G_x/wC_o,$$

This procedure eliminated the contributions from the fringing fields and the walls of the PE tube. Care was taken not to allow liquid from the specimen to enter the space between the parafilm and PE, as this would change the fringing fields and introduce error in the above procedure. The accuracy of the measurements was checked using distilled water as a standard specimen, and the measured k' was found to be within +/- 5% of the nominal value of 78.5 from 1 to 1000 MHz [6]. The k" was sensitive to ionic content of the water, as expected. We estimate that the accuracy of the values of k' and k" reported here is +/- 5%

Impedance Measuring Instruments

The automated instruments used to measure and analyse the impedance of the cell were the Hewlett Packard Impedance Analyser model 4191A (10^6 to 10^9Hz)[7] and an HP Network Analyser model 3570A (50Hz to $1.3\text{x}10^7$Hz)[7]. The 4191A was used with the HP

16091A[7] coaxial fixture with the cell terminating the fixture. The cell added an electrical length of 0.72cm to the fixture and this length was automatically accounted for by the instrument. The 3570A was used with the cell connected between the center leads of 35cm long coax output and input cables in one channel and a single cable of the same total length (acting as a short circuit reference impedance) in the other channel. Data were automatically recorded, processed and plotted with an HP 9845B computer[7].

MECHANISM OF DIELECTRIC HEATING IN LIVING BIOLOGICAL TISSUE

A basic assumption of this work is that we should make a dielectric material that will simulate the mechanism of EM heating in biological tissue. The first step is to thoroughly understand what this mechanism is. For convenience we chose to measure the leaves of the jade plant (Crassula portulacea) as a representative biological material. These leaves have the same dielectric behavior as muscle [3] and were much easier for us to acquire, form into dielectric specimens, and replace with fresh specimens than were muscle samples. Much of the published dielectric data on animal tissues is for 37°C [3,8], some is extrapolated to room temperature for comparisons with room temperature data [9,10] and some data is taken at room temperature [9,11]. The dielectric constant will decrease with temperature because of the 1/temperature dependence of the static k' of dipolar liquids and σ' or k" will increase with temperature because ionic transport is a thermally activated process. These differences are important only in the selection of a final data

set for duplication by the phantom. Our data are for temperatures around 25°C.

Optical micrographs of a cross section of a leaf like those used in our measurements are shown in figures 1a and 1b. Typical curves of k' and k" are shown in figure 2 for a wide range of frequencies. These data have been carefully analysed in a recent preprint [12], and details of measurement procedures and calculations will be found there. The results are summarized in this report.

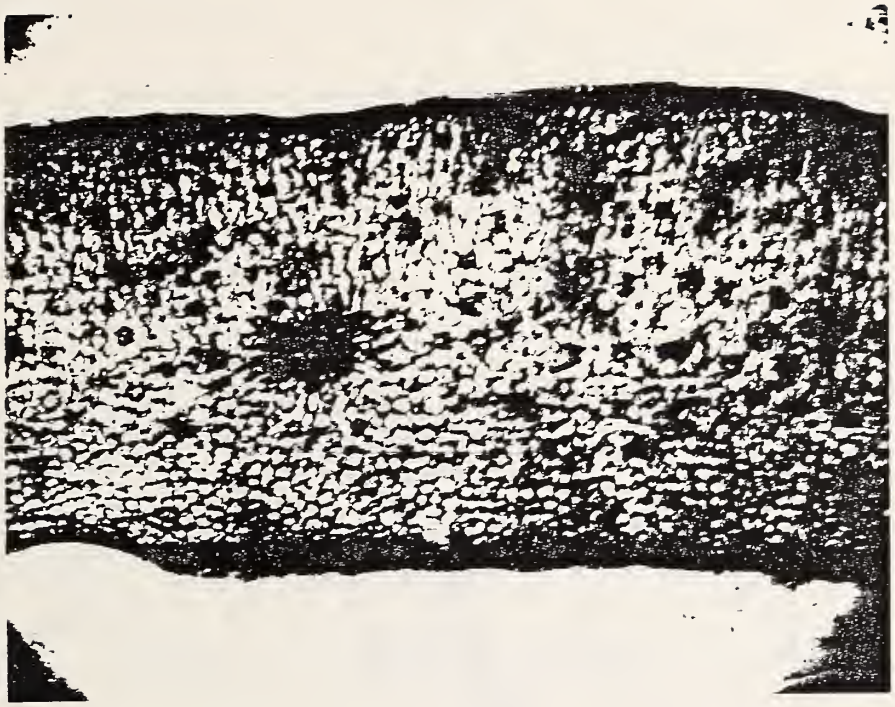
The leaf specimen can be considered for our present purpose as a series combination of three parallel resistor-capacitor pairs as shown in figure 3. These represent the bulk properties of the salt/water electrolyte (denoted with subscript 3), the resistance and capacitance of the cell walls (denoted with subscript 2) and the resistance and capacitance of the ionic double layer at the interface between the specimen and electrodes (denoted with subscript 1). The inequalities hold that $C_1 >> C_2 >> C_3$ and $R_1 >> R_2 >> R_3$. Thus the high frequency region in figure 1 is dominated by R_3 and C_3, the mid frequency region by R_2 and C_2 and the low frequency region by R_1 and C_1.

The equivalent series resistance and capacitance of the circuit in figure 3 are given by,

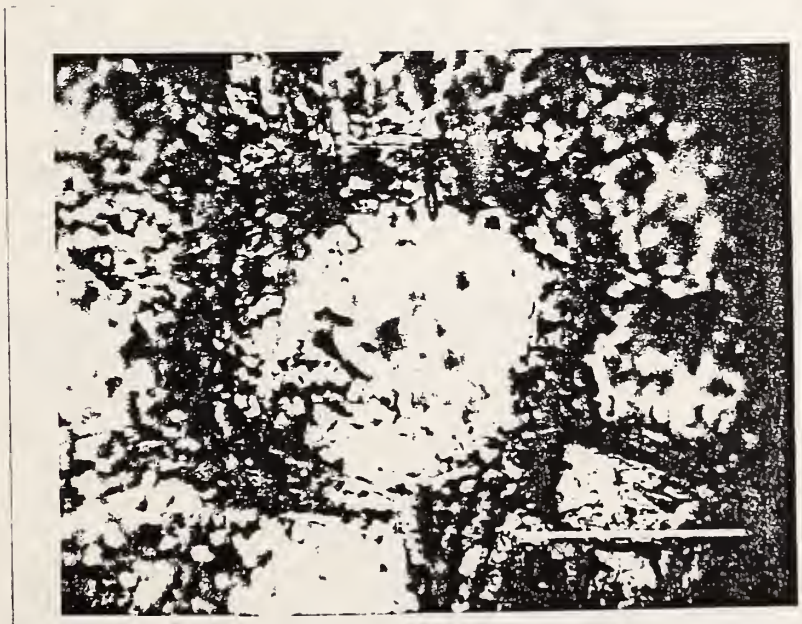
$$C_s = \{\sum_{i=1}^{3} [C_i(1+Q_i^2)/Q_i^2]^{-1}\}^{-1}$$

$$R_s = \sum_{i=1}^{3} [R_i/(1+Q_i^2)]$$

$$Q_i = wR_iC_i$$



a



b

Figure 1. Electron micrographs of a cross section of Crassula portulacea leaf showing cell structure. The leaf (figure 1a) is about 4mm thick and the scale in figure 1', showing the cell detail, is 100 um long.

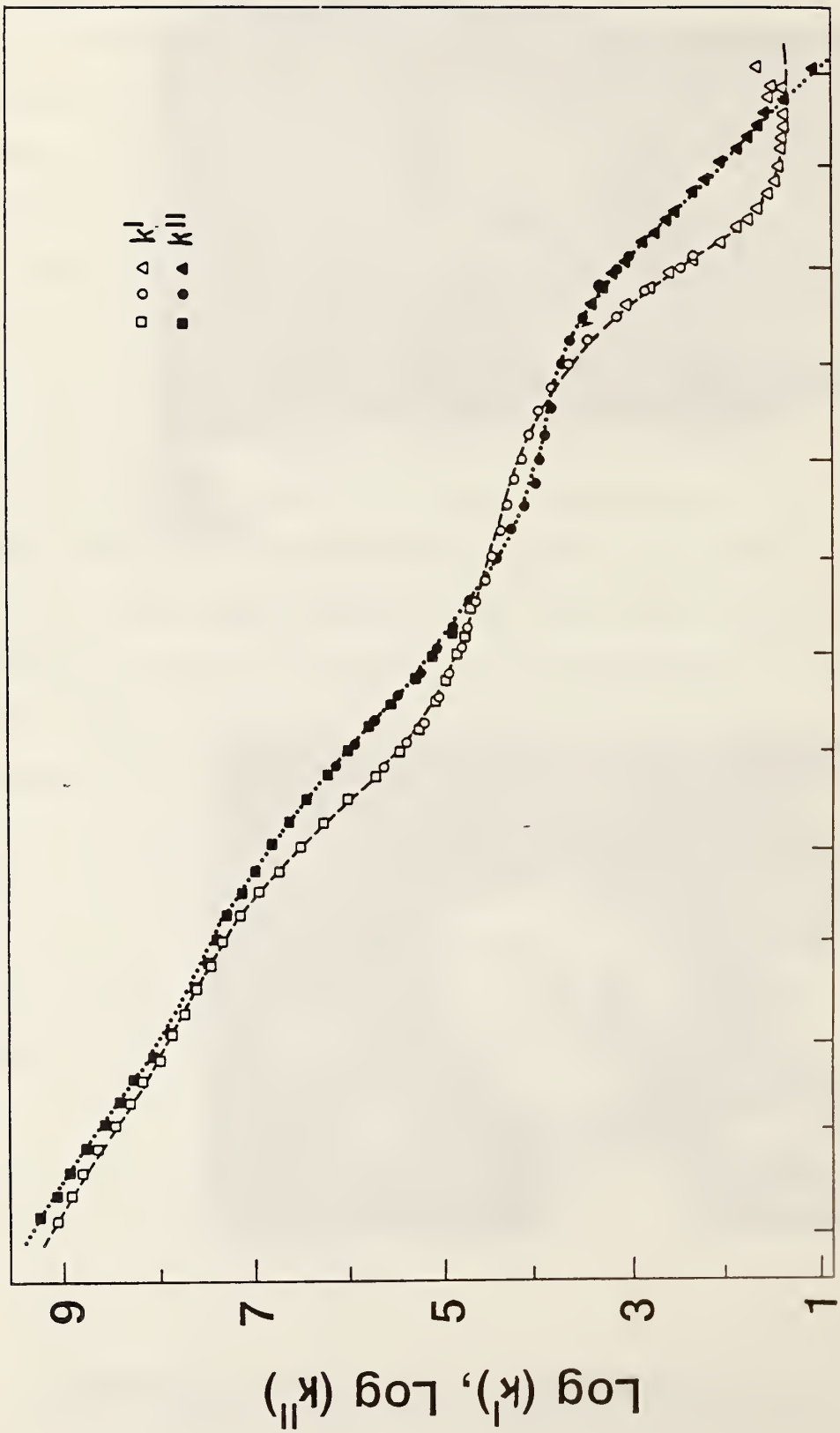


Figure 2. Real and imaginary parts of the complex dielectric constant of a Crassula portulacea leaf with the epidermus removed.

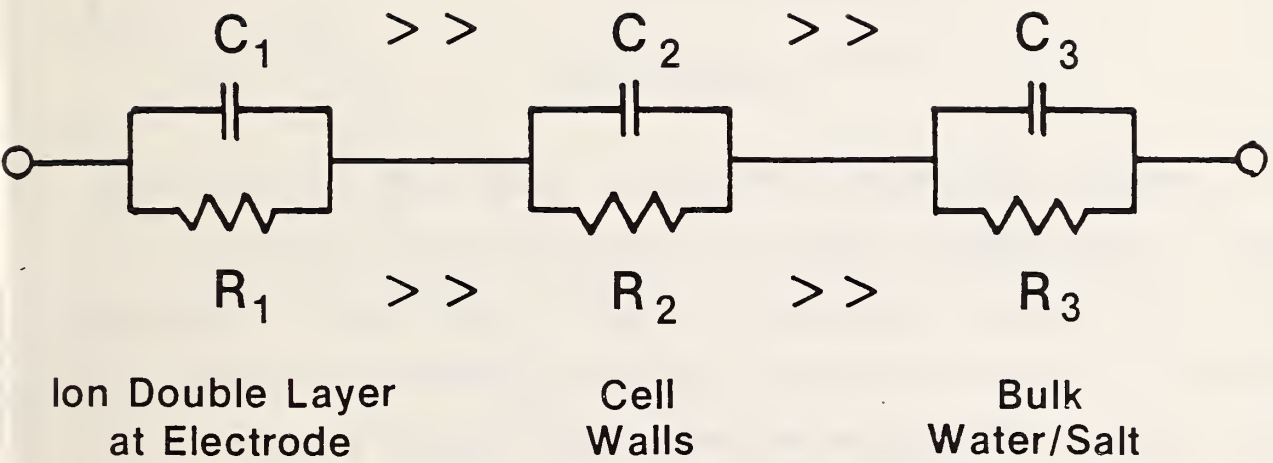


Figure 3. Model circuit for the dielectric properties of biological tissue.

To illustrate the degree of approximation involved in this model we have calculated the apparent k' and k" of the circuit in figure 3 assuming that the empty cell capacitance, C_o=0.0614 pf.

$$k' = C_s Q_s^2/[C_o(1+Q_s^2)],$$
$$k'' = 1/[wR_s C_o(1+Q_s^2)],$$
$$Q_s = 1/(wR_s C_s).$$

The results are shown in figure 4. Note that the calculated (figure 4) and measured (figure 2) data are quite similar in shape at the highest frequencies. That is, the highest frequency relaxation in the leaf acts much like the relaxation of an RC circuit. The relaxations become relatively broader in the experimental data the lower the frequency. This result is to be expected since the lowest frequency relaxation involves charging of the ionic double layer. Double layer charging is known to involve a diffusion process [13]. Such a process results in the k' and k" being equal in magnitude and with a slope of -0.5 on the log(k^*) vs log(f) plot [14]. It is reasonable to expect that ionic charging of an interface will be intermediate between diffusion and RC relaxation. The data in figure 2 show this trend from nearly ideal RC relaxation at the highest frequency to nearly ideal diffusion at the lowest frequency.

We can compare the expected values of the cell wall and double layer capacitances with the observed C_2 and C_3 in figure 3. If the cell wall thickness=0.1 μm, k'=10 and the electrode area is 0.32 cm^2 then C_w=30 nf. The series combination of

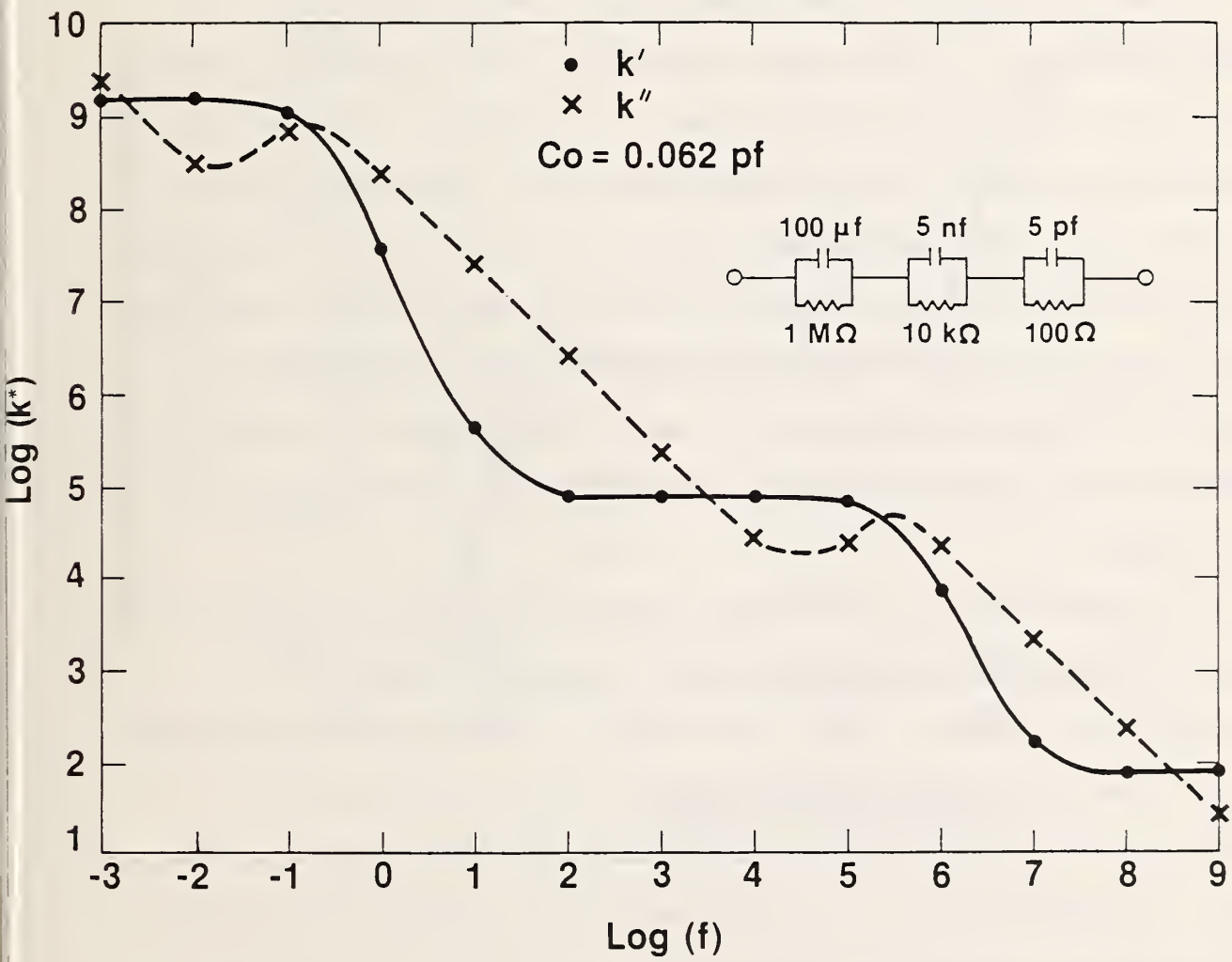


Figure 4. Real and imaginary parts of the complex dielectric constant for the model circuit of figure 3, using the resistance and capacitance values shown in the insert, and assuming an empty holder capacitance of 0.062 pf.

several cell walls would give a value near C_2=10 nf. The double layer capacitance [13], for perfectly smooth electrodes, is calculated to be about 30 μf, in reasonable accord with C_3=100 μf. These comparisons show that our model and the data are self consistent.

We can be confident then that at 100 MHz the k' is essentially that of bulk water mixed with low dielectric constant solids (see below for mixing rules) , and the k" is due to the conductivity of the ions of dissolved salt. Below 100 MHz the increase in k' and concomitant change in k" is due to interfacial polarization of the cell walls by the ions and partial blocking of the ionic transport by the cell walls. The frequency and magnitude of this increase in k' above its value at 100 MHz depends on the capacitance and concentration of the biological cell walls.

It is important to understand how the biological tissue is heated by the electromagnetic field. We can calculate the heating of the model circuit in figure 4, using the values given in the figure for the circuit elements, as an excellent approximation to the heating of biological tissue above 1 MHz. With an applied voltage, V, the rate of heat generation in each of the three circuits is given by,

$$\dot{H}_i = R_i V^2/[R_s^2(1+Q_i^2)(1+Q_s^2).$$

Figure 5 shows the total rate of heating in the circuit H_i for V = 1 volt, and figure 6 shows the fraction of this total power dissipated in each of the three RC pairs, $\dot{H}_i/\Sigma\dot{H}_i$. It is apparent

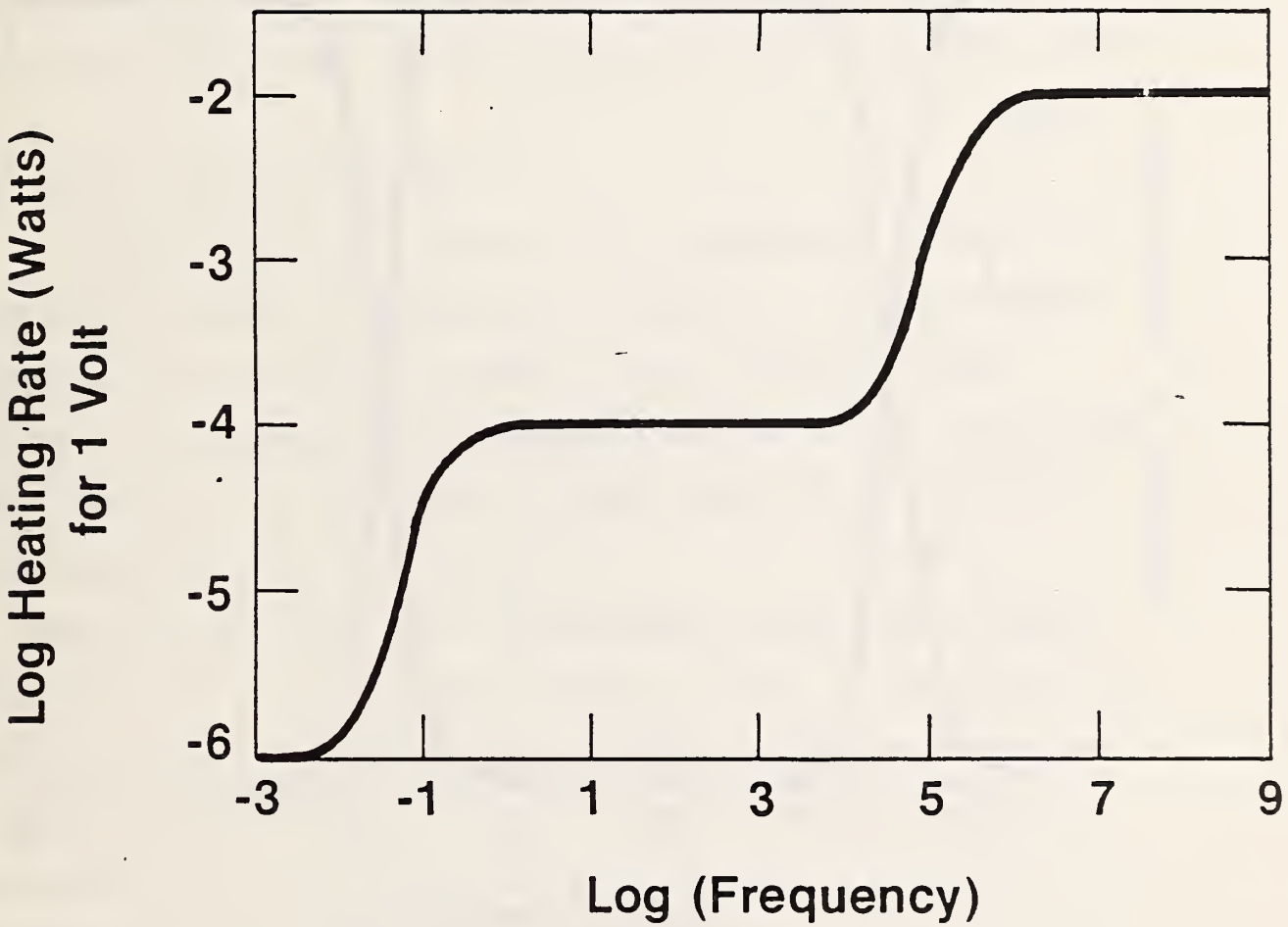


Figure 5. Rate of dielectric heating in watts of the model circuit of figure 4 as a function of frequency for an applied potential of 1 volt.

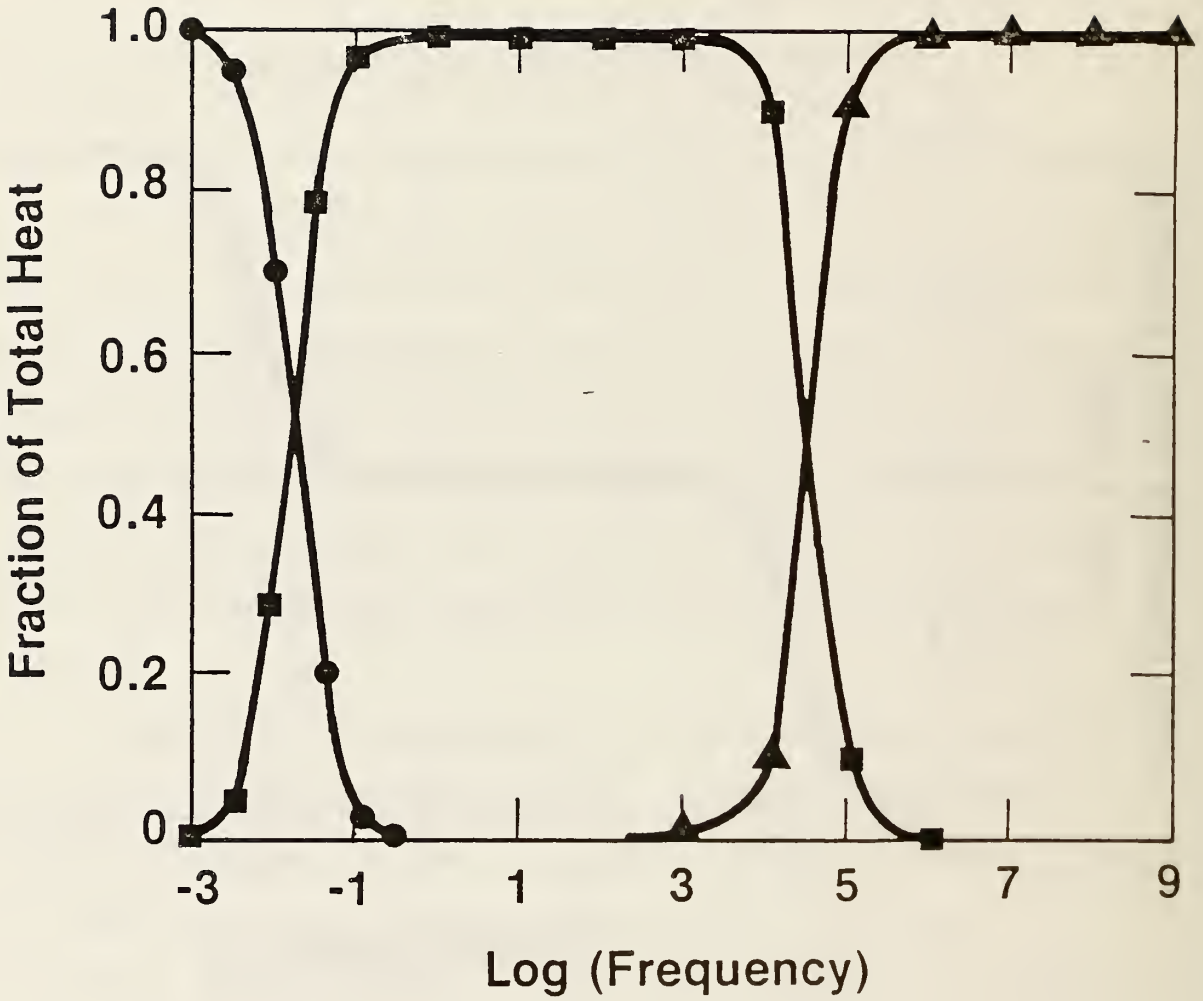


Figure 6. Fraction of total heating in each of the three parts of the circuit in figures 3 and 4. The symbols are for circuit 1, ●; circuit 2, ■; circuit 3, ▲.

from these results that the heating will be essentially independent of frequency above 1 MHz independent of changes in k' and that over 99% of the heat is dissipated in the bulk electrolyte. However the coupling of the applied electric field to the dielectric may cause the potential applied to the material to change with k'(see a later section on the use of the phantom).

DESIGN OF A PHANTOM MATERIAL

We chose to build a material using synthetic components to match the function (component for component) of the natural components in biological tissue. This approach allowed a systematic selection of components one at a time and removed the complexity of evaluating a large number of mixtures of components by trial and error.

The natural components of biological tissue and their functions are 1) water which gives a k'=79, 2) dissolved salt, mostly sodium chloride, that determines the conductivity and k", 3) cell walls that partially block the ionic transport and increase the k' by interfacial polarization, and 4) the connective solid tissue that gives mechanical stability. We discuss substitutes for each of these components below.

1) Dielectric liquid

There are very few dielectric liquids that have as high a dielectric constant as water. The one we have selected is a mixture of ethylene carbonate (EC) and propylene carbonate (PC). This mixture has low toxicity and is commonly used as a gel base in cosmetics [15]. It is also used as an electrolyte in

batteries and capacitors-an application related to the present application [15]. EC and PC have a much lower vapor pressure than water, as shown in figure 7 [15], and a convienient freezing point as shown in figure 8 [15]. The static k's of EC, PC [15] and water [6] are shown in figure 9 as a function of temperature, and of PC/EC mixtures as a function of concentration [15] in figure 10. The orientational relaxation of the dipoles of water, PC and EC are all nearly Debye in shape [6,16], so that we can calculate the high frequency k' and k" as [14],

$$k' = k_{oo}+(k_s-k_{oo})/[1+(f/f_c)^2], \text{ and}$$
$$k'' = (k_s-k_{oo})f/f_c/[1+(f/f_c)^2].$$

The k_{oo} are 5.2 for water [6] and 2.6 for the EC/PC mixture [16], and k_s= 79. The critical frequencies, f_c, for molecular relaxation of water [6] and PC and EC [16] are given as a function of temperature in figure 11. The calculated frequency dependence of the k' is shown in figure 12 for these two materials. The fact that the relaxation frequencies are lower in PC/EC than for water means that its k' and k" depart significantly from those of water above 1 GHz, as shown in figure 12.

Some of the important physical properties of PC and EC [15] are summarized in Table 1. A heat capacity, thermal conductivity and density of about 1.4 J/gmK (one third that of

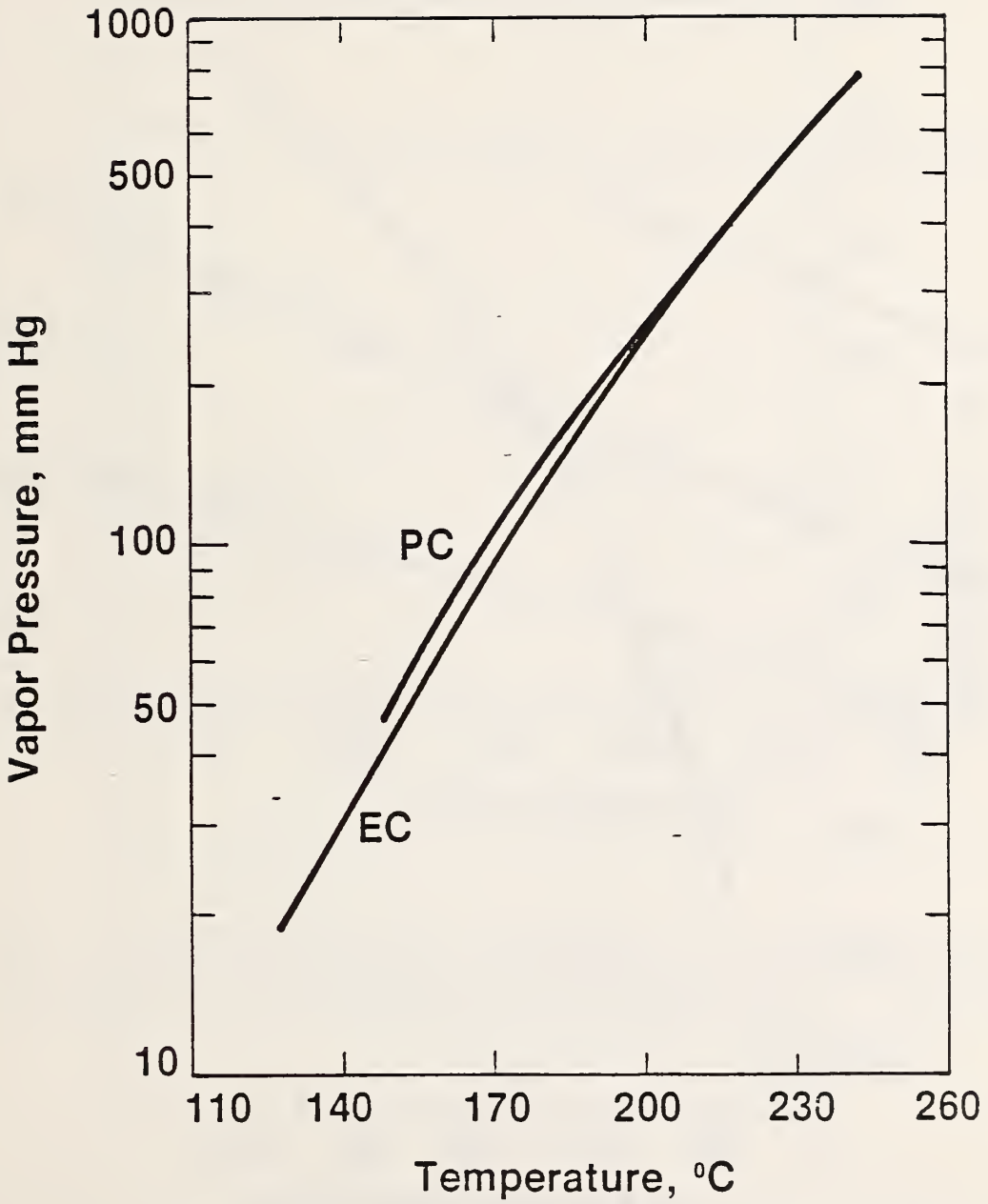


Figure 7. Vapor pressure of propylene carbonate and ethylene carbonate as a function of temperature, (from reference [15]).

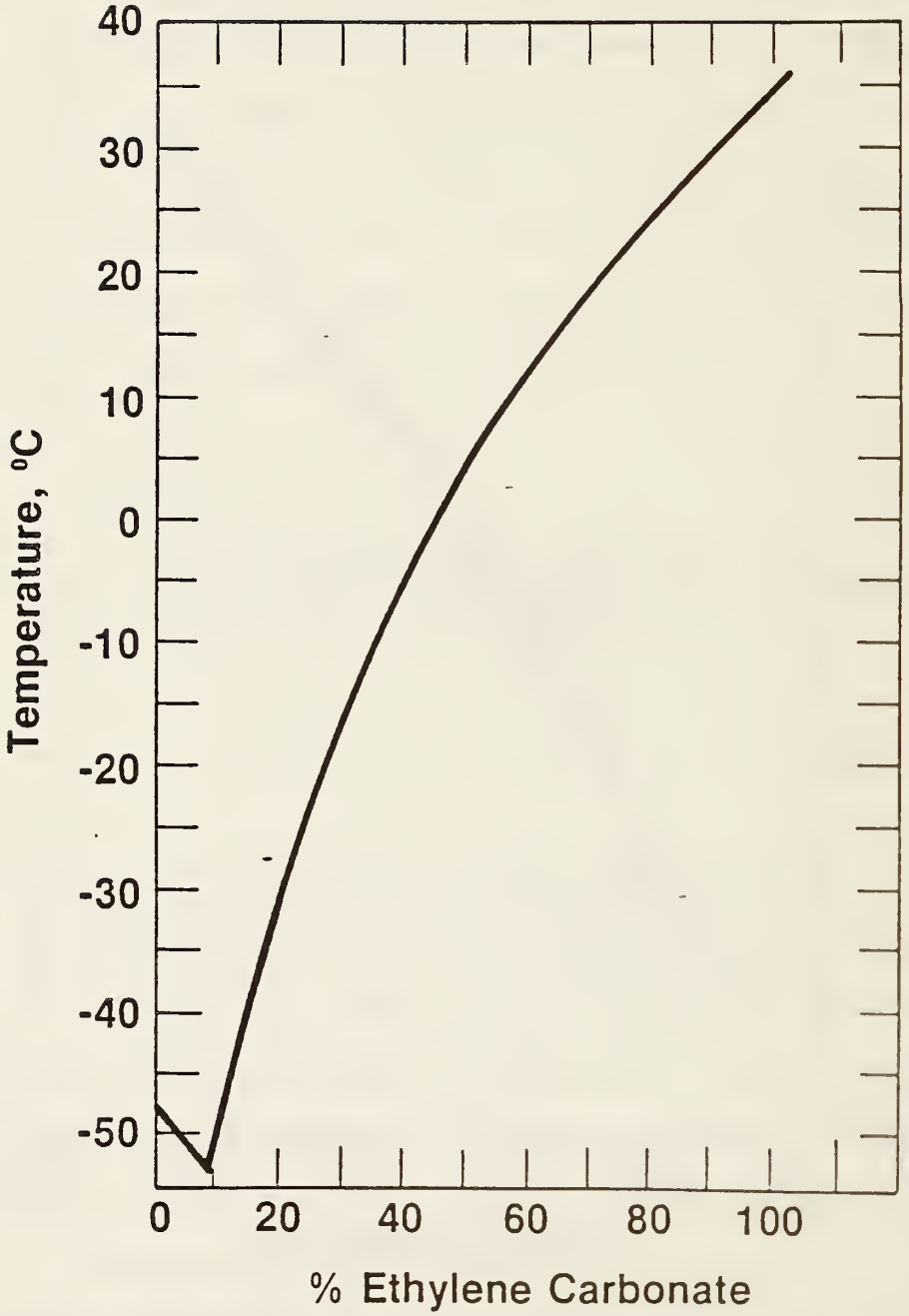


Figure 8. Freezing points of ethylene carbonate/propylene carbonate mixtures as a function of composition (from reference [15]).

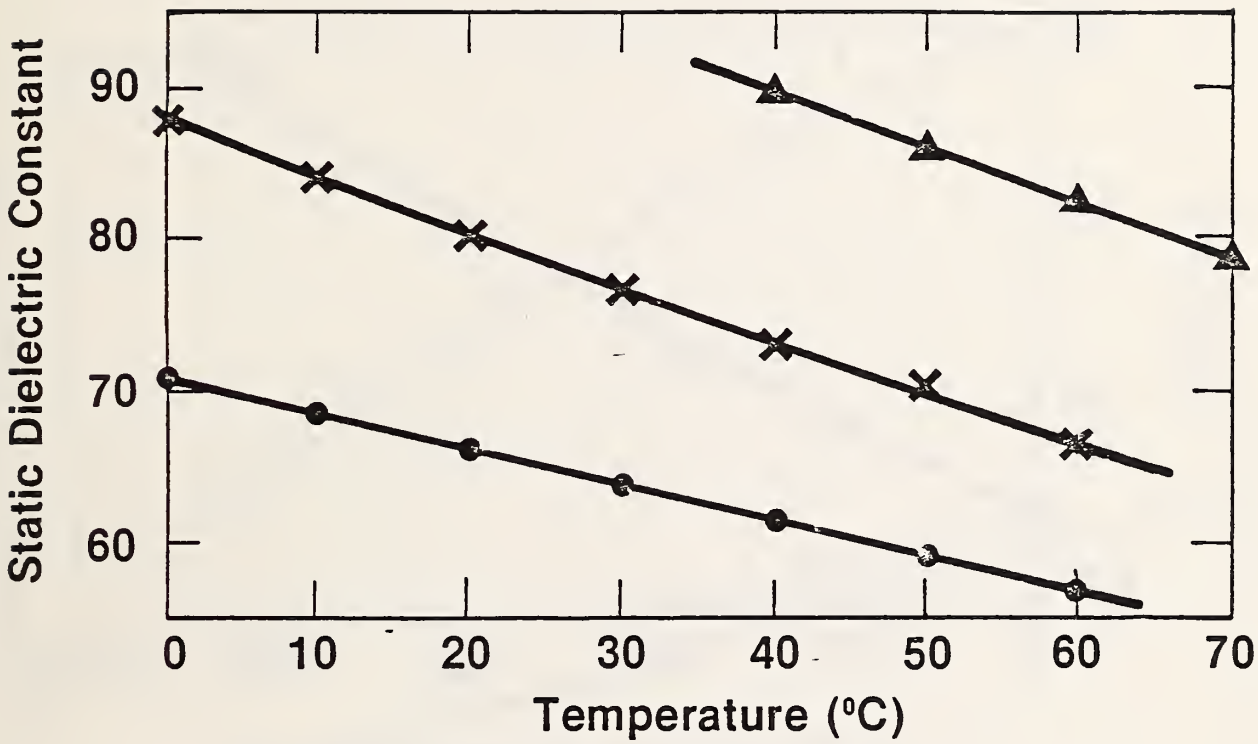


Figure 9. Static dielectric constants of ethylene carbonate, ▲ and propylene carbonate, ● ,(reference [15]) and water, ✖ , (reference [6]) as a function of temperature.

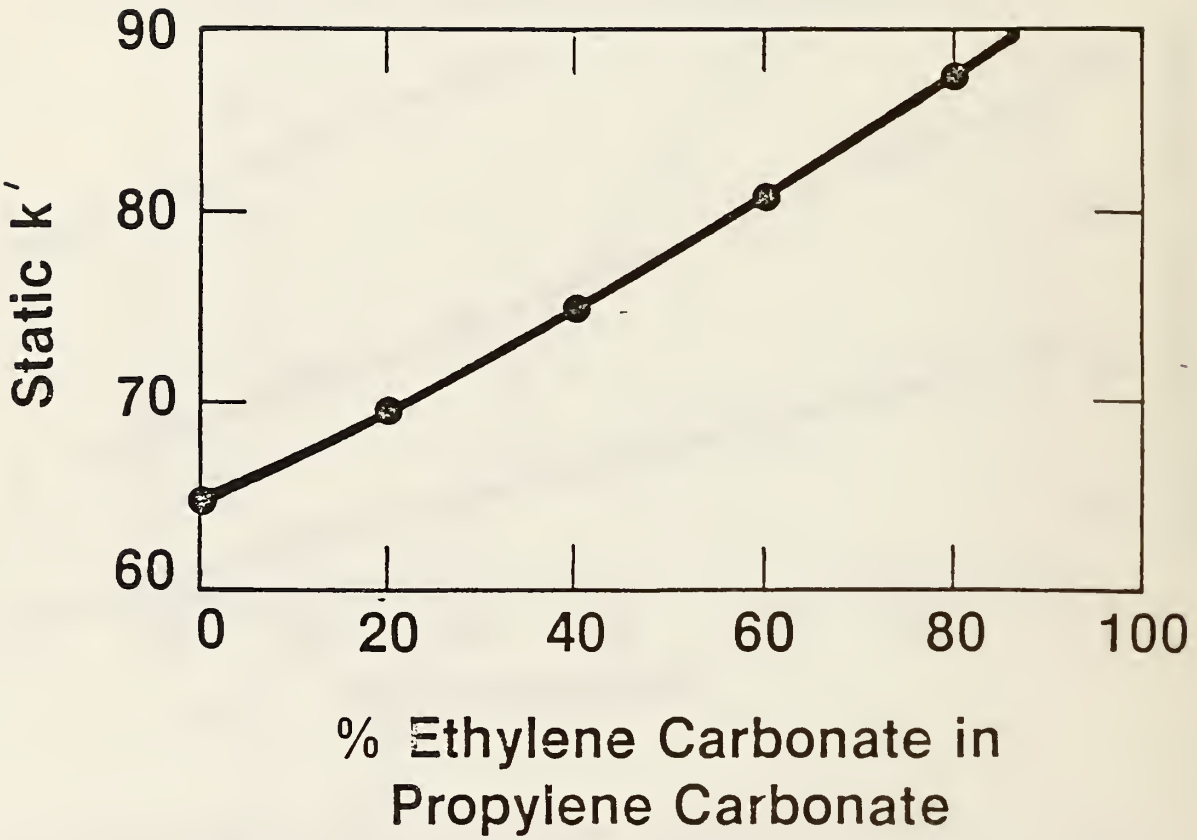


Figure 10. Static dielectric constants of mixtures of propylene carbonate and ethylene carbonate as a function of concentration at 25°C (from reference [15]).

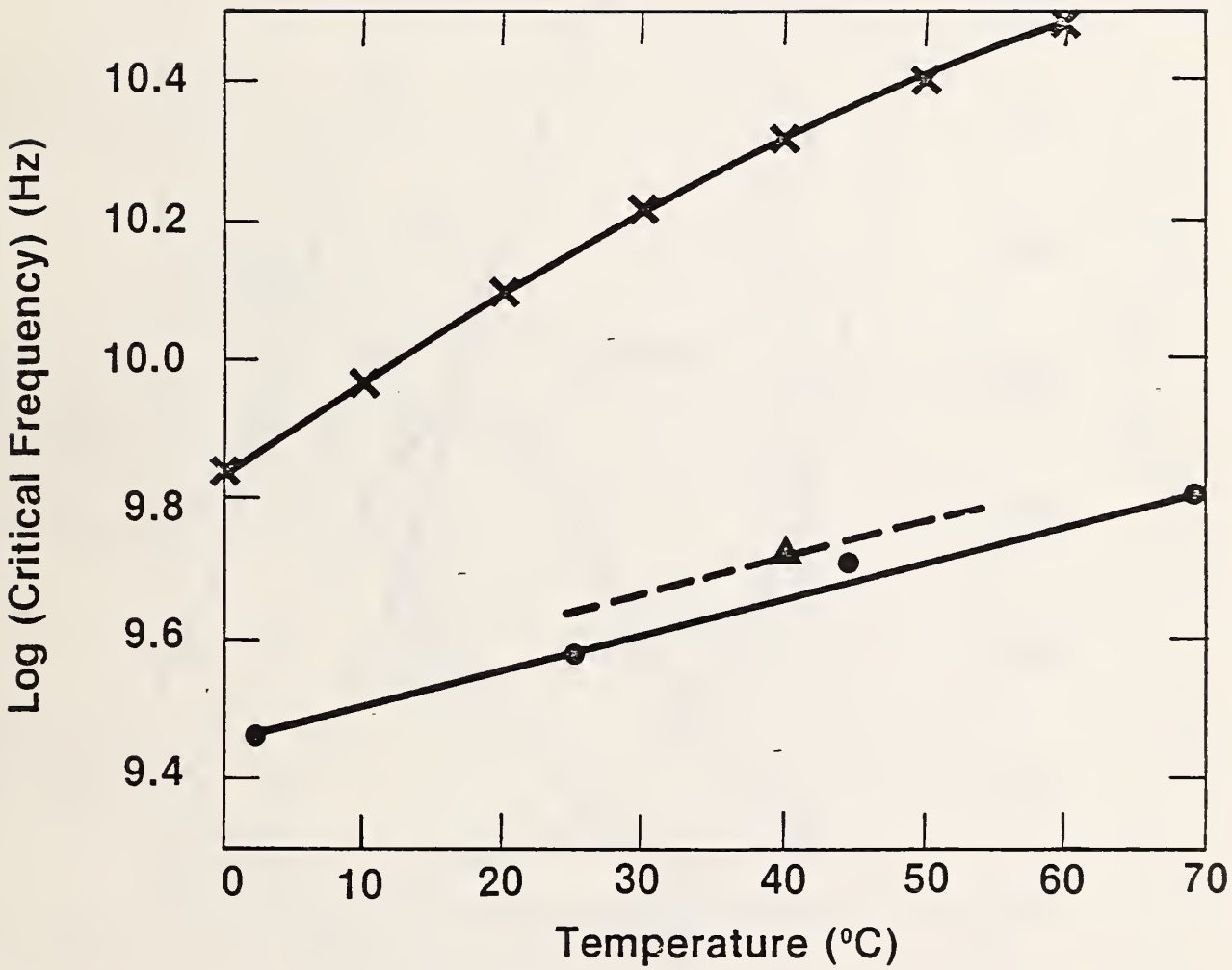


Figure 11. Critical frequencies for molecular dipole relaxation of ethylene carbonate, ▲, propylene carbonate, ●, (reference [16]) and water, ✖, (reference [6]) as a function of temperature.

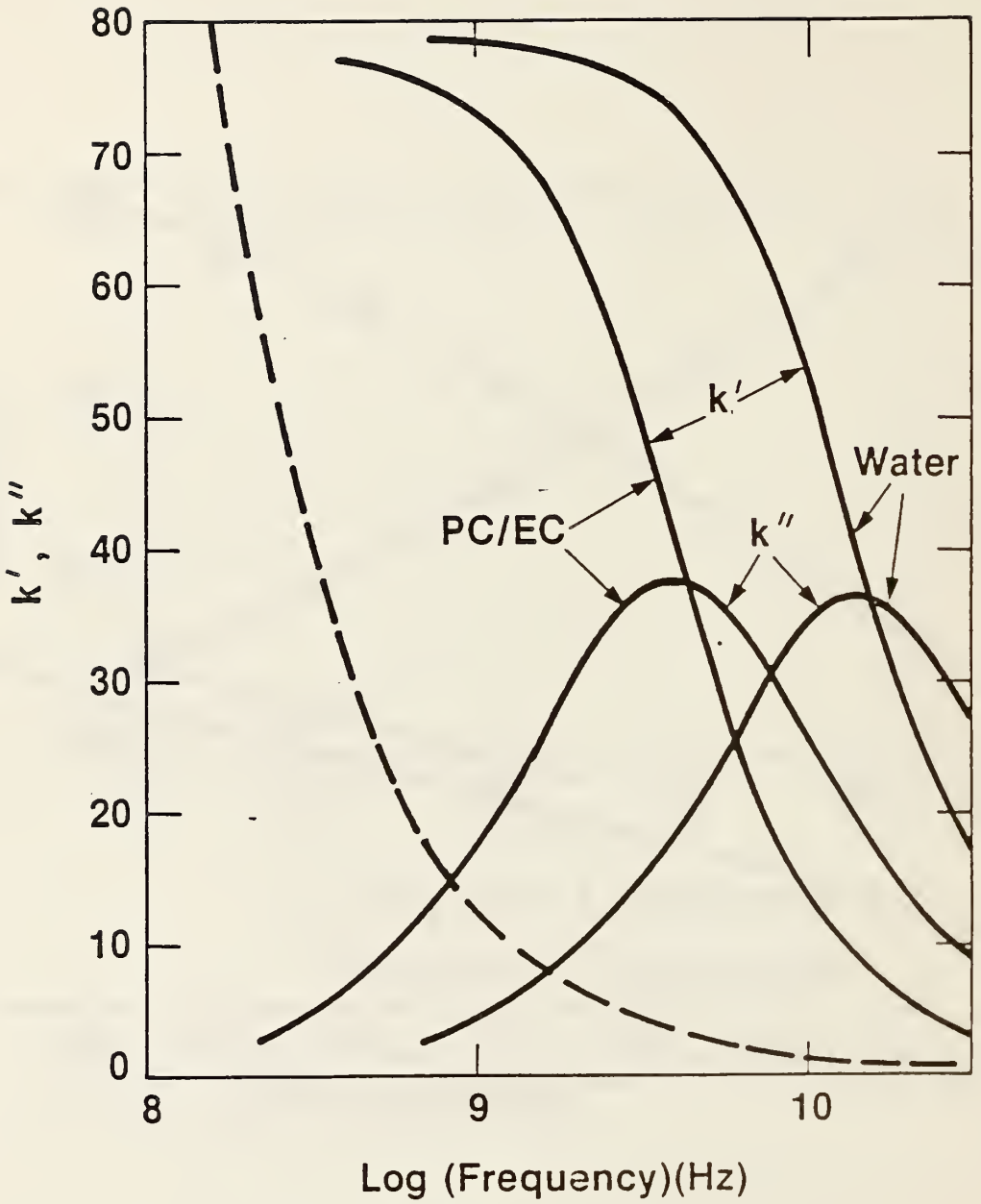


Figure 12. Calculated high frequency dielectric behavior of water and a 50/50 mixture of ethylene carbonate and propylene carbonate as a function of frequency. The dashed curve is the contribution to k" expected from a conductivity of 0.7 S/m. The relaxations are the orientational relaxations of the molecular dipoles and are essentially single relaxation time processes. These calculated curves do not take into account the effects of low dielectric constant additives.

Table 1. Physical data on ethylene carbonate and propylene carbonate ††

	Ethylene Carbonate	Propylene Carbonate
Boiling point, °C(760 mm)	238	241.7
Coefficient of expansion, cc/cc/°C	-	0.096
Dielectric constant, 25°C esu	95.3*	64.9†
36°C	90.8	62.4†
40°C	89.1	61.4†
50°C	85.1	59.2†
60°C	81.0	56.9†
Dipole moment, 25°C, Debye units	4.60	4.94†
Fire point, °F	-	280
Flash point (PMCC),°F	305	275
Freezing point, °C	36.4 (melting point)	-49.2
Heat of fusion, cal/g	34	18
Heat of combustion, cal/g	2,662	3,396
Kcal/mol	234	347
Heat of vaporization, cal/mol, 150°C	13,500	13,200
175°C	-	12,600
200°C	13,000	12,200
230°C	12,400	-
240°C	-	11,900
248°C	12,200*	-
Pour point, °F	-	-100**
Refractive index	1.4158 (n_D^{50})	1.4210 (n_D^{20})
Specific gravity	1.3218 (39/4°C)	1,2057 (20/4°C)
Specific heat, cal/g, 15°C	0.321	-
50°C	0.363	0.375 (25°C)
100°C	0.461	0.438
150°C	0.479	0.480
Thermal conductivity at 41°C, BTU/(hr) (ft^2) (°F/ft)	0.12	0.12
cal/(sec) (cm^2) (°C/cm)	49.3×10^{-5}	49.6×10^{-5}
Viscosity, cs., -65°F	Solid	57.6*
-40°F	Solid	19.4
0°F	Solid	6.64
100°F	0.90	1.67
210°F	0.42	0.78

* Extrapolated.

** Propylene Carbonate supercools easily and has remained liquid at temperatures as low as -80°C for a period of several months.

†† Ref. 15
† Ref. 16

water), 2 mJ/sec/cm/K and 1.2 gm/cm^3 respectively [15], give a thermal diffusivity of 0.0012 cm^2/sec. This value is less than the corresponding value for water (0.0014 cm^2/sec) [17]. This means that non-equilibrium temperature distributions will be slower to relax in the PC/EC mixture than in water and thus easier to measure. The lower heat capacity of the PC/EC mixture will also increase the temperature rise for a given input of power and aid the measurement of temperature changes.

Propylene carbonate and ethylene carbonate are available in drum quantities for around $0.90/lb. or a little less than $500/drum [15]. While toxicity of these materials is low, we understand that new information about trace impurities is being incorporated into a new product brochure.

2) Organic salts

A large variety of organic and inorganic salts were mixed with a 50/50 mixture of PC/EC and the conductivities were measured at 1, 10, 100, and 1000 MHz, using equipment described earlier in this report. Generally the conductivities reported in table II were the ones measured at 10 MHz since they were reasonably free of interfacial polarization present at lower frequencies and dipolar relaxation effects at higher frequencies.

The initial screening was done by adding an excess of salt to the solvent and mixing to obtain a roughly saturated solution at room temperature. The salts were not specially dried for these measurements and probably contained some water. The salts tested in this way and the maximum resulting conductivities obtained are listed in table 2. In general, the inorganic salts provided

conductivities at or below the required levels of 0.7 S/m. In some cases the conductivities were limited by low solubility as with NaCl while in other cases the salts seemed quite soluble but had limited dissociation, as with mercuric chloride and the lithium salts in general.

The organic salts were generally easier to dissolve and provided conductivities above 0.7 S/m. Tetraethyl ammonium tetra fluoroborate (TEATFB) is a conveniently available [18] organic salt that we chose for use in the phantom because it provides a reasonably linear conductivity with concentrations up to about 2 S/m, or 3 times the conductivities needed. The conductivity vs concentration of TEATFB in a 50/50 mixture of PC/EC is shown in figure 13. These data show that the conductivity of PC/EC with this salt can be adjusted well beyond the 0.65 to 0.9 S/m range of current interest. A 0.28 mol/litre solution of TEATFB gives a conductivity of about 0.7 S/m in PC/EC while only 0.06 mol/litre of NaCl in water gives the same conductivity, as shown in figure 13. This difference is presumably due to the lower mobility of the organic ions in PC/EC relative to NaCl in water, possibly because of their larger size and the greater viscosity of the solvent. Also, we do not know the degree of association of the organic salt.

In subsequent sections of this report we will refer to PC/EC/salt meaning a mixture of 50% propylene and 50% ethylene carbonate with about 0.28 mol/litre of TEATFB. It should be clear that the k' and the k" of this mixture will vary with the concentrations of the three components in a controllable way as shown in figures 10 and 13, and can be easily

Table 2. Conductivities of satuarated solutions of various salts in a mixture of equal parts of ethylene carbonate and propylene carbonate.

Salt	Conductivity at Saturation (S/
KI	0.52
$LiCF_3SO_3$	0.22
$SrCl_2 \cdot 6H_2O$	0.12
KCl	0.13
Na_2SO_4	0.01
$Zn(OOCCH_3)_2$	<0.01
$FeSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$	<0.01
LiBr	0.36
KNO_3	0.35
CsCl	0.03
CsSCN	1.07
KSCN	1.08
$CoCl_2 \cdot 6H_2O$	0.15
$Co(NO_3)_2$	0.70
Tetrabutylammoniumbromide	0.74
Tetrabutylammoniumnitrate	0.97
Tetraethylammoniumtetrafluoroborate (TEATFB)	>1.7

The following organic salts gave conductivities similar to TEATFB but w less conductivity per unit molarity.

Tetra(n-butyl)ammoniumtetraphenylborate
Tetraethylammoniumtoluenesulfonate
Tetraethylammoniumhexafluorophosphate
Dodecyltrimethylammoniumchloride

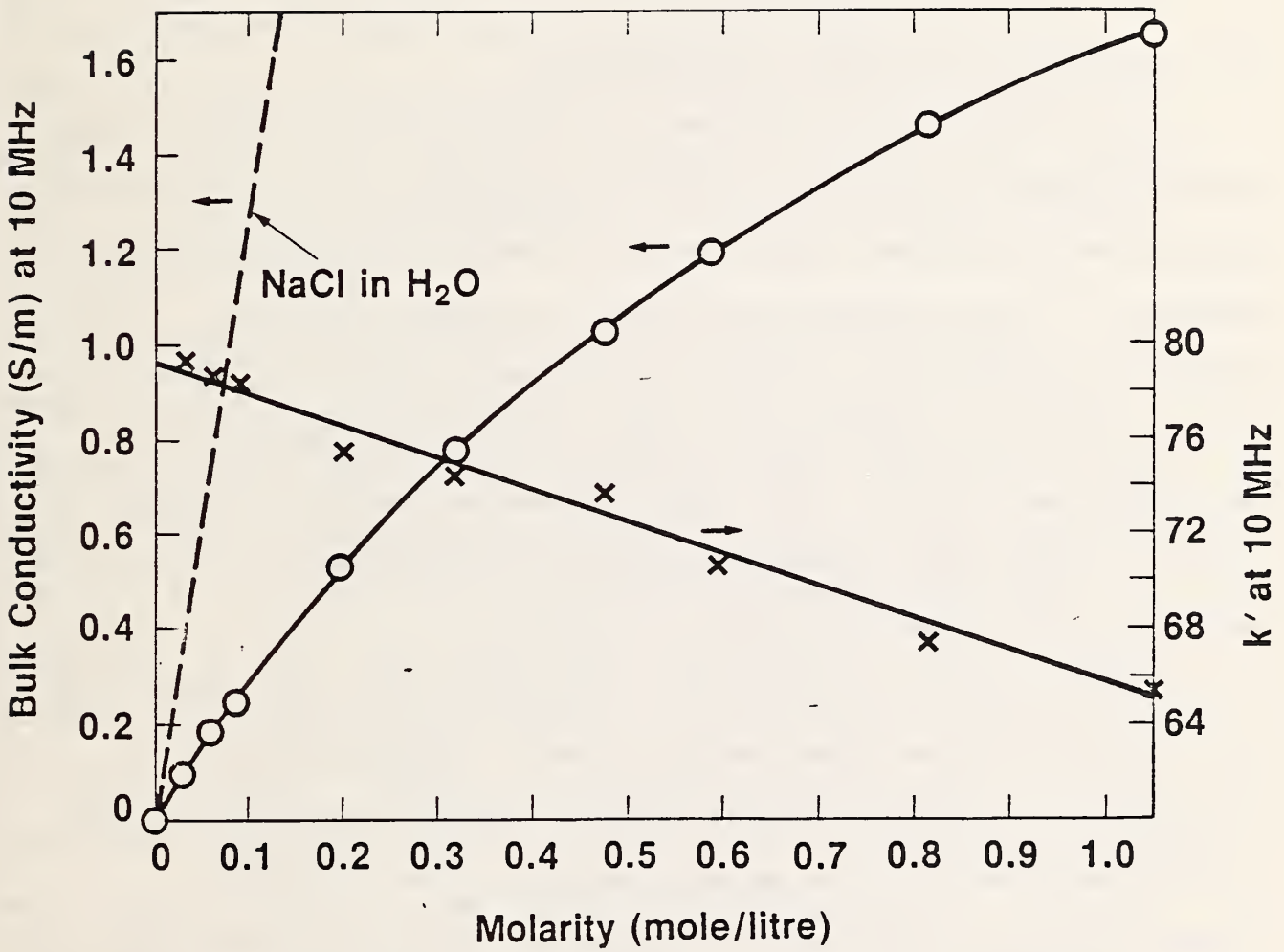


Figure 13. Conductivities and static dielectric constants of solutions of tetraethylammonium tetrafluoroborate in a 50/50 mixture of ethyene carbonate and propylene carbonate. The dashed line gives the conductivities of sodium chloride in water for comparison. Biological electrolytes have about 0.14 molar NaCl.

adjusted over the range of values of interest. We have observed no changes in the conductivity of the initial mixture of PC/EC/salt during several months of use. TEATFB is commonly available from chemical supply companies [18].

3) Films for interfacial polarization

The most difficult component to simulate was the cell walls which encapsulate the salt water in biological tissues. Presently used aqueous phantoms either do not attempt to incorporate this feature, or use aluminum particles to achieve the effect. It is known to be difficult to obtain interfacial polarization with low k' particles in a material of high k' and k" as, for instance, oil droplets in water [19]. This is because the ion transport is not effectively blocked by spherical particles, as it is by an encapsulating structure like a cell wall.

Ideally we want the liquid to be in the form of droplets and the films to encapsulate these droplets. Encapsulation techniques are commonly developed for aqueous solutions but the techniques developed for aqueous media are not directly transferrable to other solvent systems. Liposome technology [20] provides a means of making phospholipid bilayers that encapsulate droplets of water in oil or oil in water. We attempted to incorporate liposomes produced in water into the PC/EC/salt solution, but were unable to obtain structures that provided interfacial polarization.

We contacted one company [21] with experience in encapsulation of ink. One of their researchers tried unsuccessfully to encapsulate PC using simple techniques. An

expert in the use of microencapsulation [22] said he could apply other standard technologies to PC/EC/salt if requested. Another technology that might be useable [23] involves atomizing the solvent, freezing it into fine solid particles and then coating these frozen particles with sub micrometer thick films of poly-p-xylylene. While this process should lead to an easily handled powder, and it might be possible to develop the process [24], it could be quite expensive for the production of large quantities of material.

The simplest adequate solution is to use thin flakes of a barrier material in the solvent. We tried several different sources of ready-made flakes with the general guidance that we needed them to be as thin as possible to have a high capacitance and with a large area so as to more effectively block the transport of ions. We tried paper and found it was too thick. However, the ashes of burnt paper were thinner and showed some of the desired effect. Flakes of glass from bubbles that had been blown thin enough to show interference colors (about 3 μm thick) were found to support some interfacial polarization. We then tried single crystals of polyethylene grown from solution that were nominally 10 nm thick. These showed very little indication of interfacial polarization. Mica was obtained in several sizes [25] having thicknesses as low as 0.5 μm and aspect ratios of 25 to 1. These mixtures gave less interfacial polarization than desired probably because the aspect ratios were too small. In all of the above trials we thickened the PC/EC/salt with about 5 weight percent of cabosil [26] in order to make the solution thick enough that the suspended flakes did not separate from the

solvent.

By far the most successful interfaces were polymer films. For example, polyethylene from grocery produce or dry cleaning bags of 12 μm thickness can be drawn by hand to about 4 μm so that it shows interference colors in white light. Both PE and 4 μm polyvinylidene fluoride (PVDF) were added to the PC/EC/salt. Even though they increased k' by about 4 times at 1 MHz, they also reduced the higher frequency values, indicating that the film capacitances were lower than desired. In addition, PVDF is soluble in PC at elevated temperatures.

The thinnest commercial film that we found was polyester (PET) in 1.5 μm thickness [27]. When cut into flakes a few mm in diameter this film gave an acceptable interfacial polarization down to 4 MHz. At 1 MHz these flakes could increase k' by 10 times which approaches the increases found for biological tissue (40 times). For high electrical capacitance one would prefer a thinner film and for sufficient stiffness to ensure that the film will remain extended when mixed into the PC/EC/salt one would prefer a thicker film. As a compromise the 1.5 μm film is adequate for our purposes.

The optimum concentration of 1.5 μm thick PET films in the PC/EC/salt can be calculated for an ideal case. Assume that the films lie parallel to the electrodes (perpendicular to the electric field) with an $k_f'=3.2$ [28] and thickness $t_f=1.5$ μm. The desired apparent k_c' for the combination of fully polarized film and bulk material between films is about 8×10^4. To provide such an k_c', the films will have to be spaced $k_c' t_f / k_f' = 4$ cm apart. This gives a relaxation time, $R_1 C_2 = 10^{-6}$ sec as desired.

If the films are stirred into the PC/EC/salt only 1/3 of them on average will have the proper orientation (perpendicular to the electric field). Thus for each $(4cm)^3$ of phantom we need $3x(4cm)^2$ of film. This calculation is completely valid only when the film completely blocks all liquid paths for ion transport from one electrode to the other. Film pieces mixed into the conductive electrolyte will be subject to a low resistance path around the flakes of film which will reduce their charge storage ability and lower the maximum interfacial polarization they can support.

A comparison of the effect of the film geometry on its charging characteristics is shown in figures 14-17. Our measurements show that a 1.5 μm film mixed in the bulk gives good results down to 4 MHz but gives less polarization than biological cell walls at 1 MHz. Heterogeneities on the scale of 4 cm in the phantom should not cause heterogenieties in the heating. As shown in figure 6 for frequencies above 1 MHz the heating is entirely in the bulk and not affected by the presence of the films.

The specimen holder we used for these measurements was too small (thickness = 0.457 cm and area = 0.317 cm^2) to measure the formulation suggested above. With PC/EC/salt and a single film of area 0.32 cm^2 in the holder we obtained the results shown in figure 14. These data are compared to the results using the same PC/EC/salt mixture without a film present in the holder. The data are in reasonable agreement with expectations. The mean frequency for charging the film is 8 MHz rather than the desired 1 MHz because the holder is 1/8 as thick as desired. And the value of log (k') is about 0.5 decades too low because the conduction

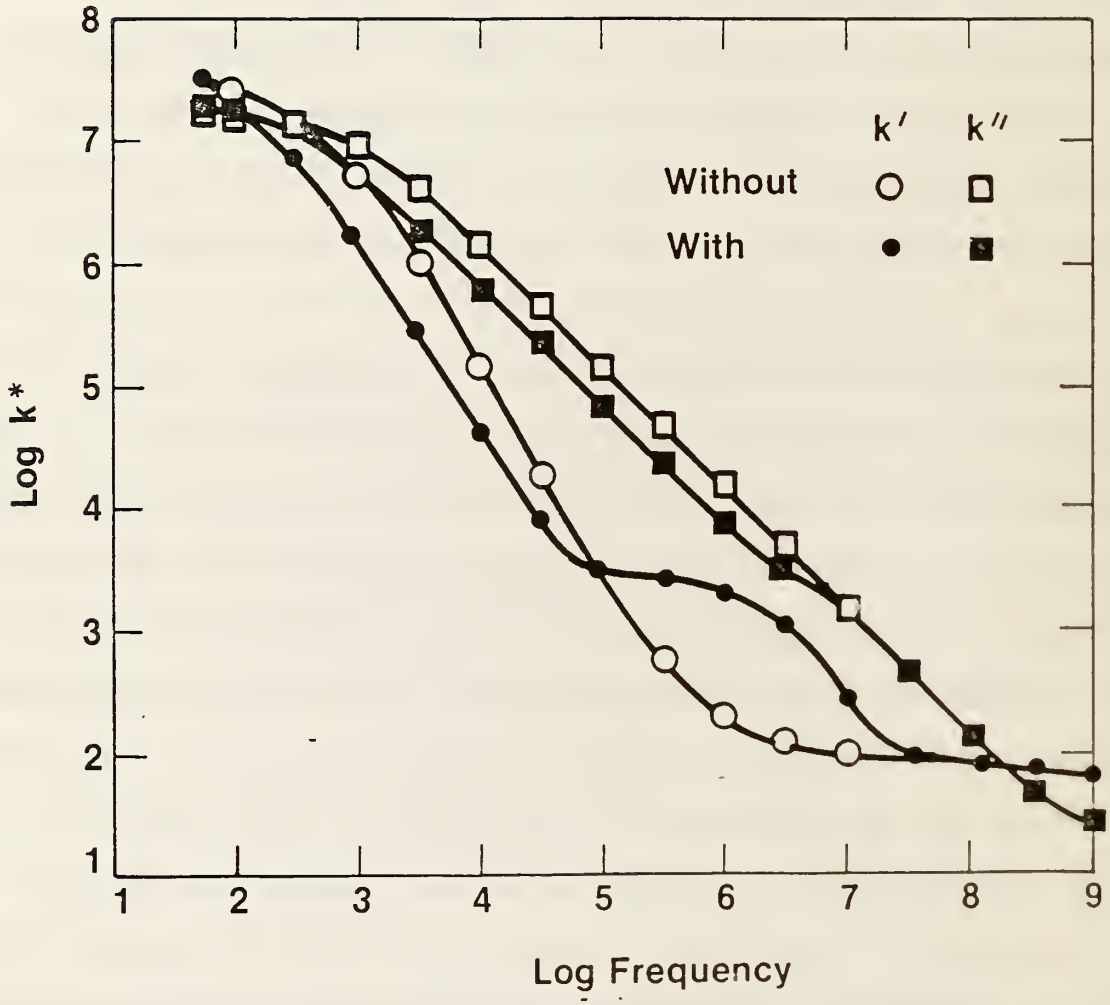


Figure 14. Dielectric properties of a 50/50 mixture of ethylene carbonate and propylene carbonate with 0.28 molar tetraethylammonium tetrafluoroborate. A single film of 1.5 μm thick PET the same diameter as the specimen holder is used for the "with" data.

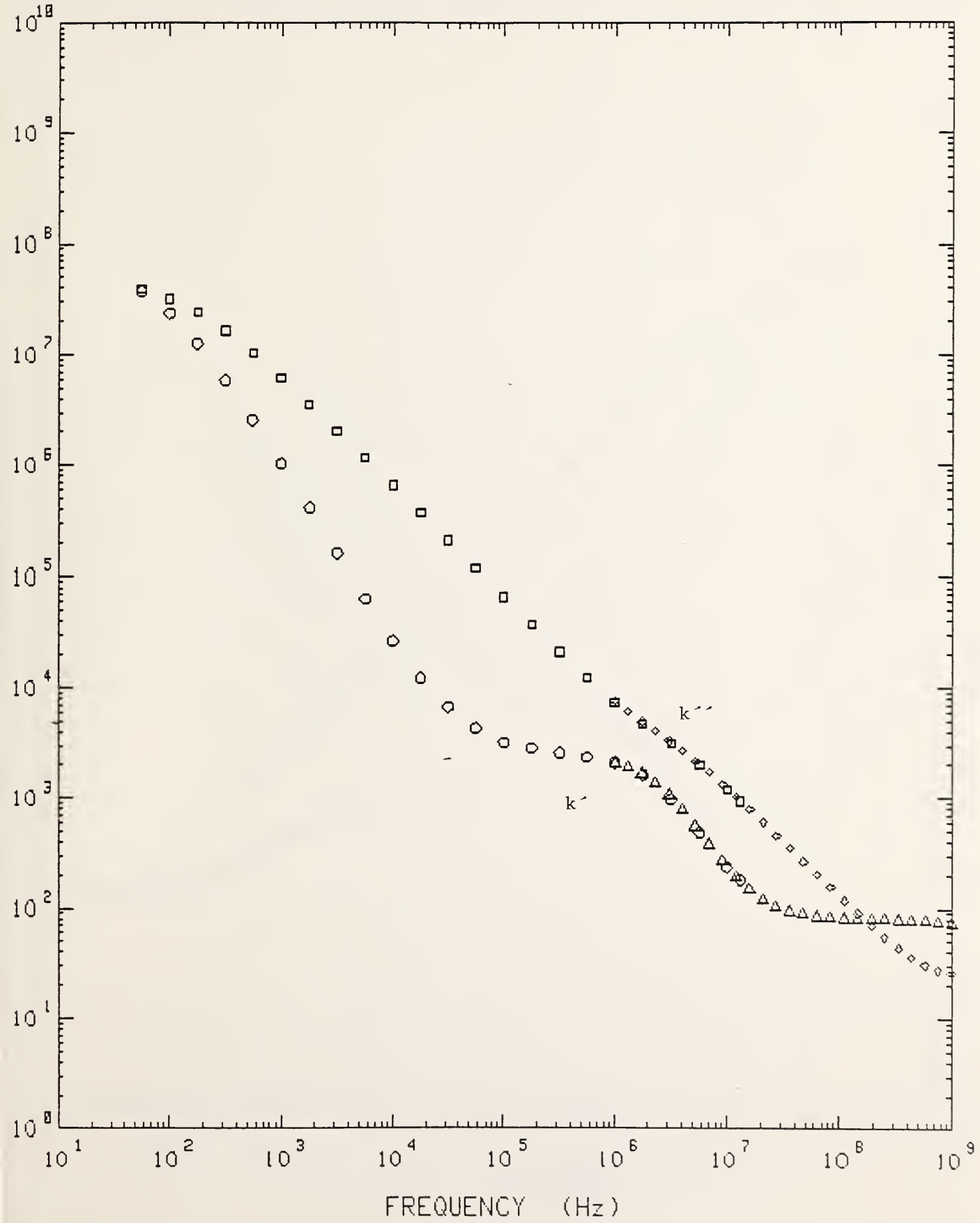


Figure 15. Dielectric properties of the synthetic phantom material with 4.5 weight% of silica thickener and a single film of PET.

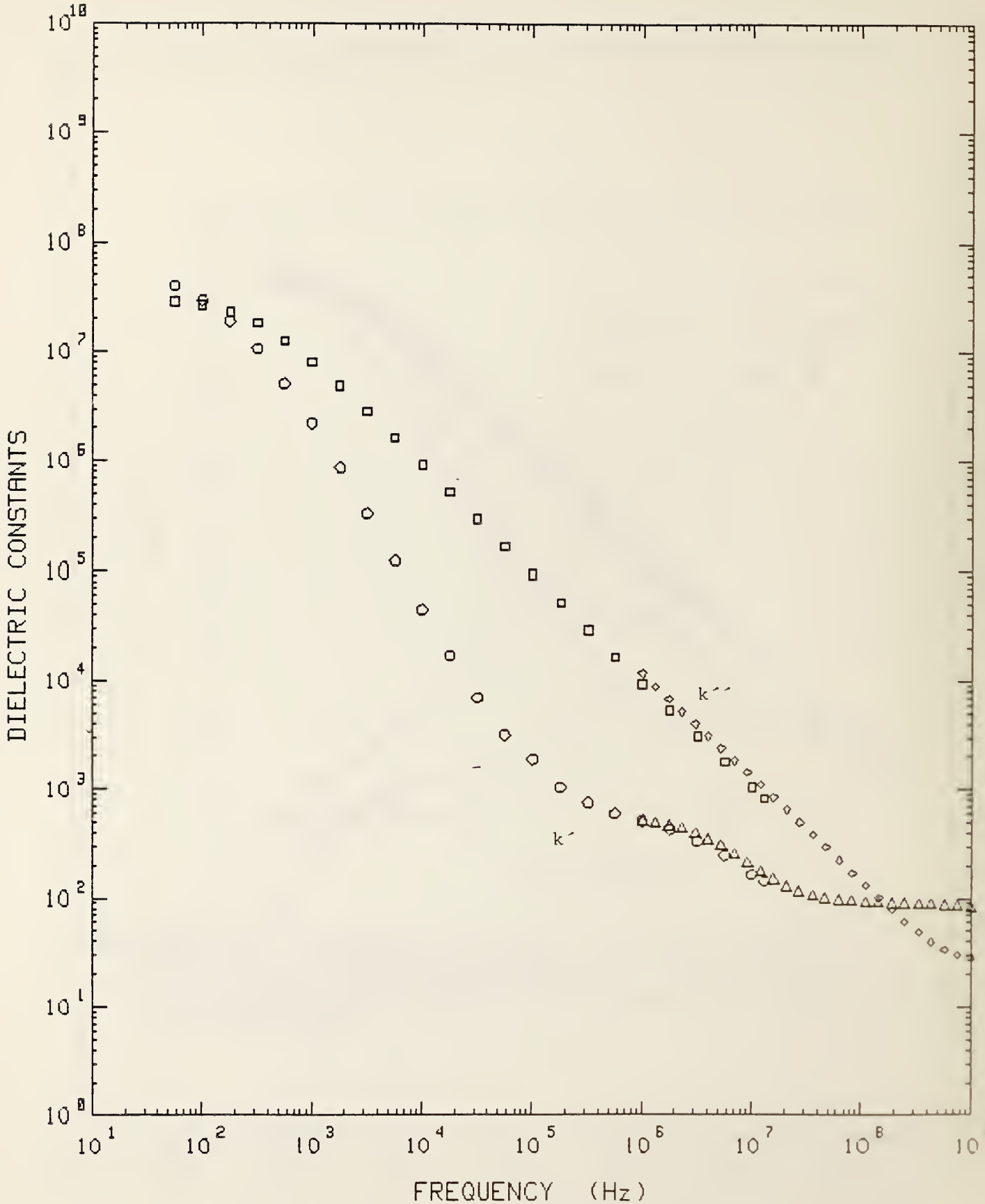


Figure 16. Dielectric properties of the synthetic phantom material containing 3mm x 3mm flakes of PET film.

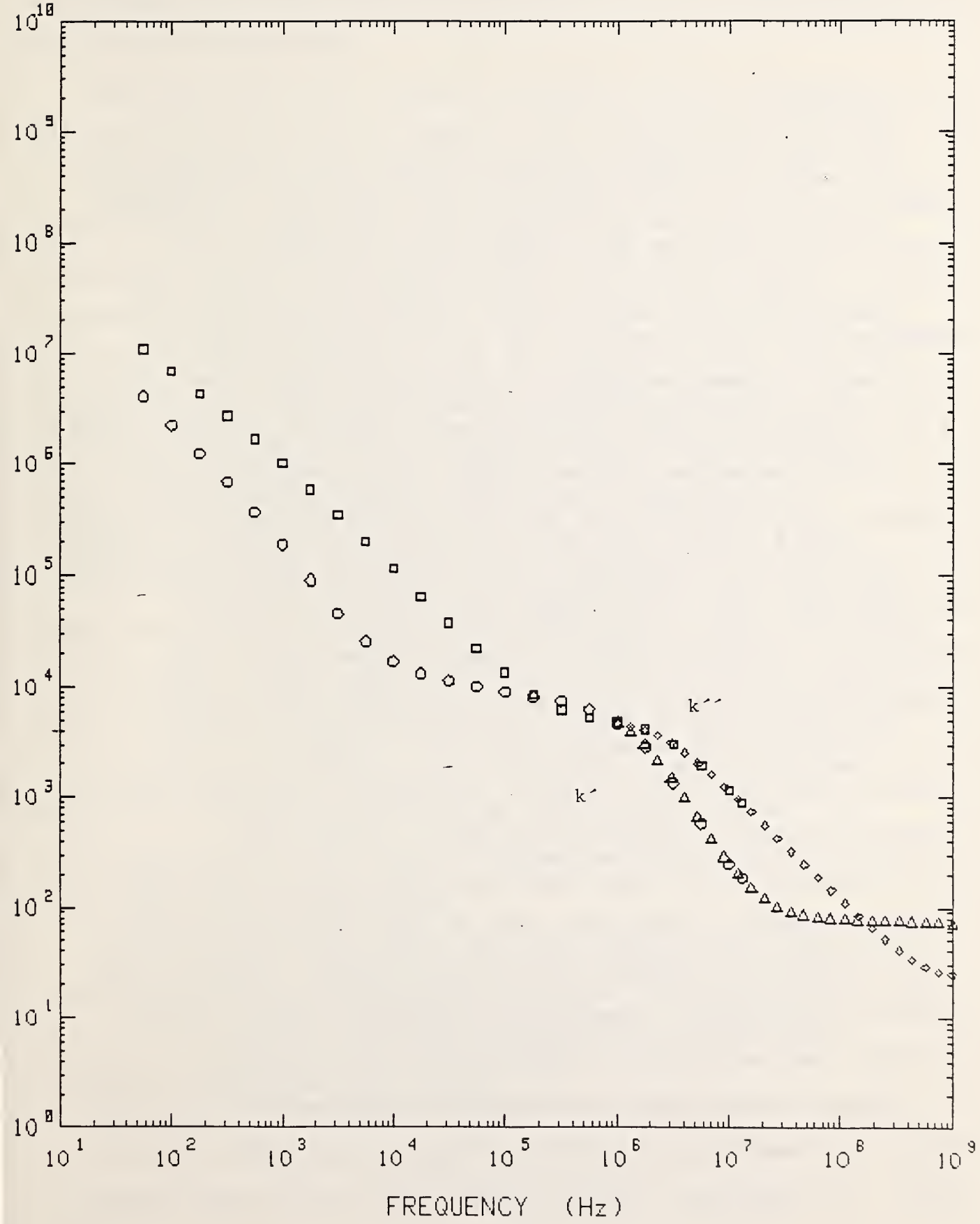


Figure 17. Dielectric properties of the synthetic phantom material with a single film of PET completely covering one electrode.

around the edge of the film limits the charge that can be placed on the film.

4) Thickeners

Two types of thickener are of potential use in the phantom. Fumed silica [26] can be stirred in the PC/EC/salt to increase its viscosity and keep the polymer flakes suspended, or a soluble polymer can be cross-linked chemically to give a more permanent gel. Both types provide a network which gives the PC/EC/salt increased mechanical stability. We found that about 4.5% by weight of fumed silica yielded a gel that is thick enough to suspend the polymer flakes without being so thick that air bubbles are suspended in the mixture. Air bubbles must be avoided if the dielectric properties of the unthickened PC/EC/salt are to be preserved. Gels can be formed also by mixing into the PC/EC/salt a soluble polymer like polyethylene glycol 600 dimethacrylate (PEG)[29], and cross linking it with a photo initiator like benzoin methyl ether [30]. We used 7% of the polymer and 0.5% of the initiator to produce a clear gel which showed no signs of exuding the solvent. The PEG 400 dimethacrylate on the other hand partially separated from the liquid phase when crosslinked. PEG of higher molecular weight (1000 or 2000 for example) can be used at higher concentrations than the 400 without increasing the crosslink density and the tendency for the solvent to separate from the network.

Figure 15 shows data for PC/EC/salt thickened with 4.5 % by weight of fumed silica, and with a single 1.5 μm thick film of PET. For comparison, figure 16 shows data for the same material

but with 0.96 cm^2 of film cut into about 3 mm x 3 mm squares and mixed into the specimen.

The system that gave the most interfacial polarization was the one giving the data of figure 17 with one thickness of film covering one electrode so that a conduction path around the film was eliminated. These data were quite close to a recent set of Jade plant leaf data as shown in figure 18 over the whole frequency range from 100 Hz to 1 GHz. We expect the differences between the data in figures 2 and 18, are due to how tightly the specimen fits in the polyethylene tube of the specimen holder, but these differences are not significant for present purposes. Even the phantom with flakes (figure 16) follows well the increase in dielectric properties of the leaf down to 4 MHz.

For a more careful analysis of the dielectric data than the graphs allow we have included tabulated data in tables 3-9. Table 3 is the data for the empty holder to be used to correct the data given in tables 4-9. This correction is made by subtracting the k' and k" given in table 3 from the values given in the other tables at corresponding frequencies. This correction is significant only at the highest frequencies. The tables 4-9 are for figures 15-20 respectively.

These results confirm that the basic concepts described above are correct and that commercially available 1.5 μm thick PET film can provide adequate interfacial polarization to mimic that provided by biological cell walls.

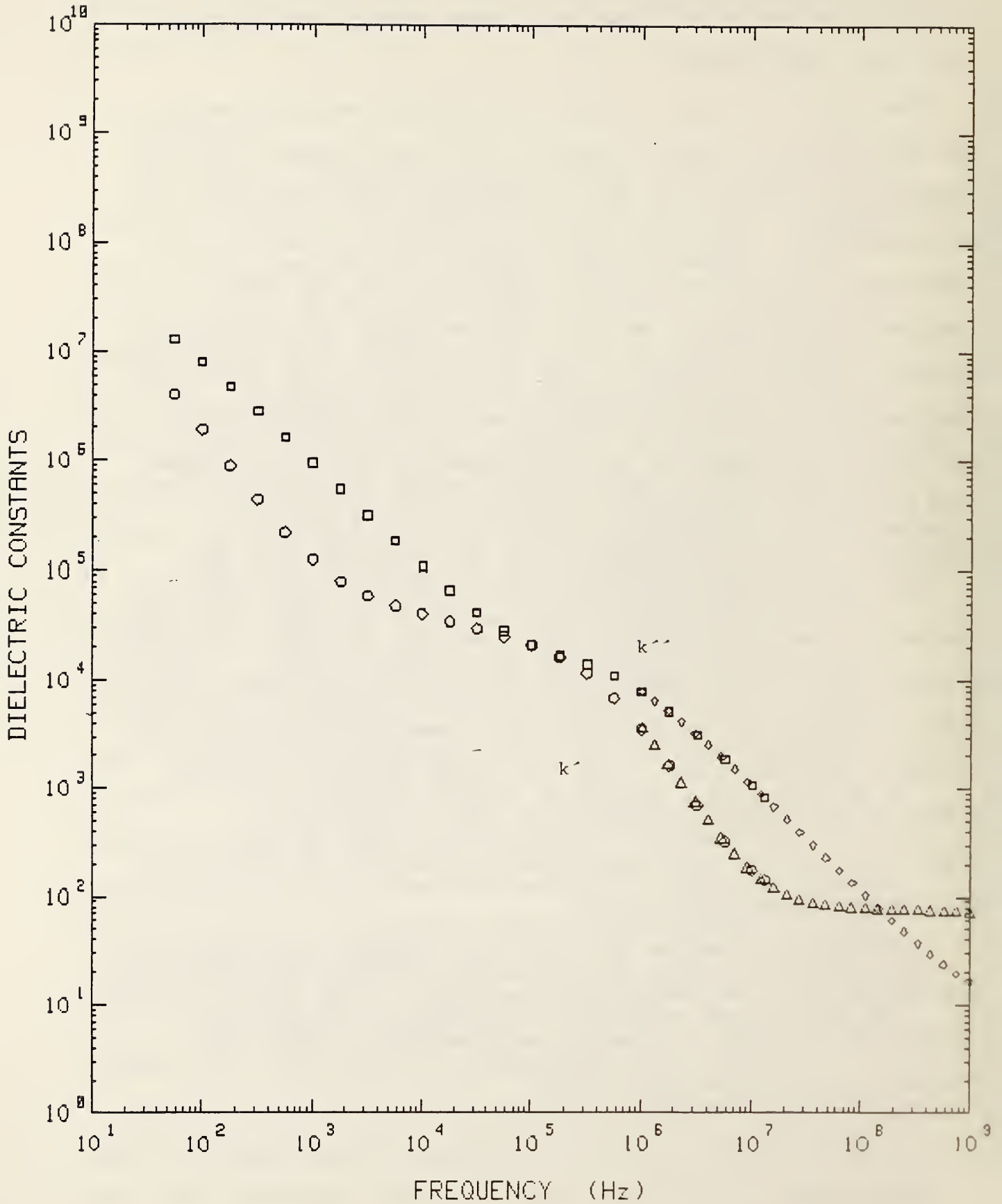


Figure 18. Dielectric properties of a jade plant leaf measured under the same conditions as was the synthetic phantom.

DIELECTRIC CONSTANTS OF MIXTURES

It is important to be able to calculate the decrease in k' of the PC/EC/salt when we add thickeners and other materials. A useful additivity rule for dilute mixtures is that the cube roots of the components are additive [30]. The k' of a mixture is given by;

$$k' = (\sum_i \phi_i k_i'^{1/3})^3,$$

where ϕ_i and k_i' are the volume fraction and k' of component i.

A more accurate mixing rule is the one given by Bruggeman [32] for concentrated mixtures of spherical particles of dielectric constant, k_p' and volume fraction, ϕ, in a medium of dielectric constant, k_m. The dielectric constant of the mixture is given by,

$$[(k'-k_p')/(k_m'-k_p')](k_m'/k')^{1/3} = 1-\phi.$$

A useful approximation [19] to this rule for our present case of $k_m' >> k_p'$ is,

$$k' = k_m'(1-\phi)^{3/2}, \text{ or}$$
$$k' = k_m'(1-3\phi/2), \quad \text{for } \phi << 1.$$

The fumed silica has a k' = 3.8 [28] and a density of 2.2 [26]. Five percent by weight of SiO_2 is equivalent to 3 percent by volume in the PC/EC/salt. This should decrease the dielectric constant from 79 to 75. This is about the same decrease as we

measured directly for different concentrations of fumed silica in PC/EC/salt. The addition of 7% by weight of polyethylene glycol with a density of 1.1 and an k'=8 [28] reduces the k' of the mixture from 79 to 70, and 5% by volume of air reduces the k' from 79 to 73. Note that the last equation above does not require knowledge of the k' of the particles as long as it is small. For muscle, 25% organic material of k'=3 in water should lower the k' from 79 to 49 according to the last equation given above. The unsimplified Bruggeman equation gives 53. This prediction agrees with k'= 50-60 reported for muscle around 1 GHz [3]. We use these mixing rules only at higher frequencies where interfacial polarization is not important. It has been suggested that the Bruggeman equation can be used also to calculate k" of a mixture [19]. That is, we can substitute σ' or k" for k' in the previous three equations as long as there is no interfacial polarization. Thus a water-salt solution of biological concentration and σ'=1.4 S/m, when mixed with 25 volume % of solids of low conductivity gives σ'=0.9 S/m, in fair agreement with muscle data at about 100 MHz [3]. Mixing material of a low k' such as a thickening agent is a useful way (in addition to changing the relative concentrations of the PC and EC) of adjusting the high frequency k' of PC/EC/salt.

There is a detectable decrease in k' due to the addition of 0.28 mol/litre of TEA TFB. Assuming a density of 1.1 gm/cm^3 for the salt (217 is the formula weight), we have 5 volume % of salt in the phantom. The mixing equations give an expected decrease in the k' of 6 which is close to the change found in figure 13.

STABILITY

We did not study stability of the phantom but observed no changes in our PC/EC/salt solution during the six months we have been using it. The product brochure [15] warns that "If an acid, base or salt is present in the aqueous solutions of these products, decomposition will occur." Water is soluble to the extent of 8.3gm/100gm of PC and highly soluble in EC [15]. We have taken no precautions to avoid water in our samples. While evaporation of PC is much slower than evaporation of water, drying will still occur. The long term stability and useful lifetime of this synthetic electrolyte should be determined before compositions are standardized.

THE USE OF THE TISSUE PHANTOM

The phantom is usually placed in a mold. In a common version, the mold material is made with the same electrical properties as fat. A plastic film may cover the ends of the mold. In these cases the covering acts as a relatively small capacitance in series with the phantom. This is equivalent to placing an additional capacitance in series with the circuit of figure 3. The impedance of this capacitor can easily dominate the circuit impedance and reduce the electric field in the phantom and reduce the bulk heating. The effect increases as the frequency is lowered. A 25 μm (1 mil) thick coating on the surface of a 1 meter long specimen of phantom will have the same effect on the interfacial polarization as 1.5 μm thick films spaced 6 cm apart within the bulk of the phantom. A much thicker surface coating can greatly modify the electrical response.

We caution that if a parallel plate specimen holder is not used for measuring the phantom, care must be taken to assure that a sufficiently large volume of material is sampled. For example, the fringing field from a small open-terminated coaxial probe is sometimes used to measure the impedance of a material. Used with this phantom it can give a wide variation in properties depending on the proximity and orientation of pieces of film in the phantom with respect to the end of the probe. The electrical properties of the phantom containing dispersed films will be isotropic but only when sampled over distances of several centimeters.

For comparison with our results, we include data from aqueous muscle and brain phantoms currently in use at the FDA (figures 19 and 20). The brain phantom values are probably too low because we had trouble removing all air from the holder. Note that these data have the same form as our data for the synthetic phantom without film added (figure 14). This means that this new phantom can be used in place of the aqueous phantom without the film component, for use over small frequency ranges.

The formulation given in this report is not intended as the optimum for a particular use. It is proposed as a close approximation to the required material to illustrate the important design factors involved and the way in which the electric properties can be easily manipulated to give desired magnitudes and shapes to the k' and k" curves.

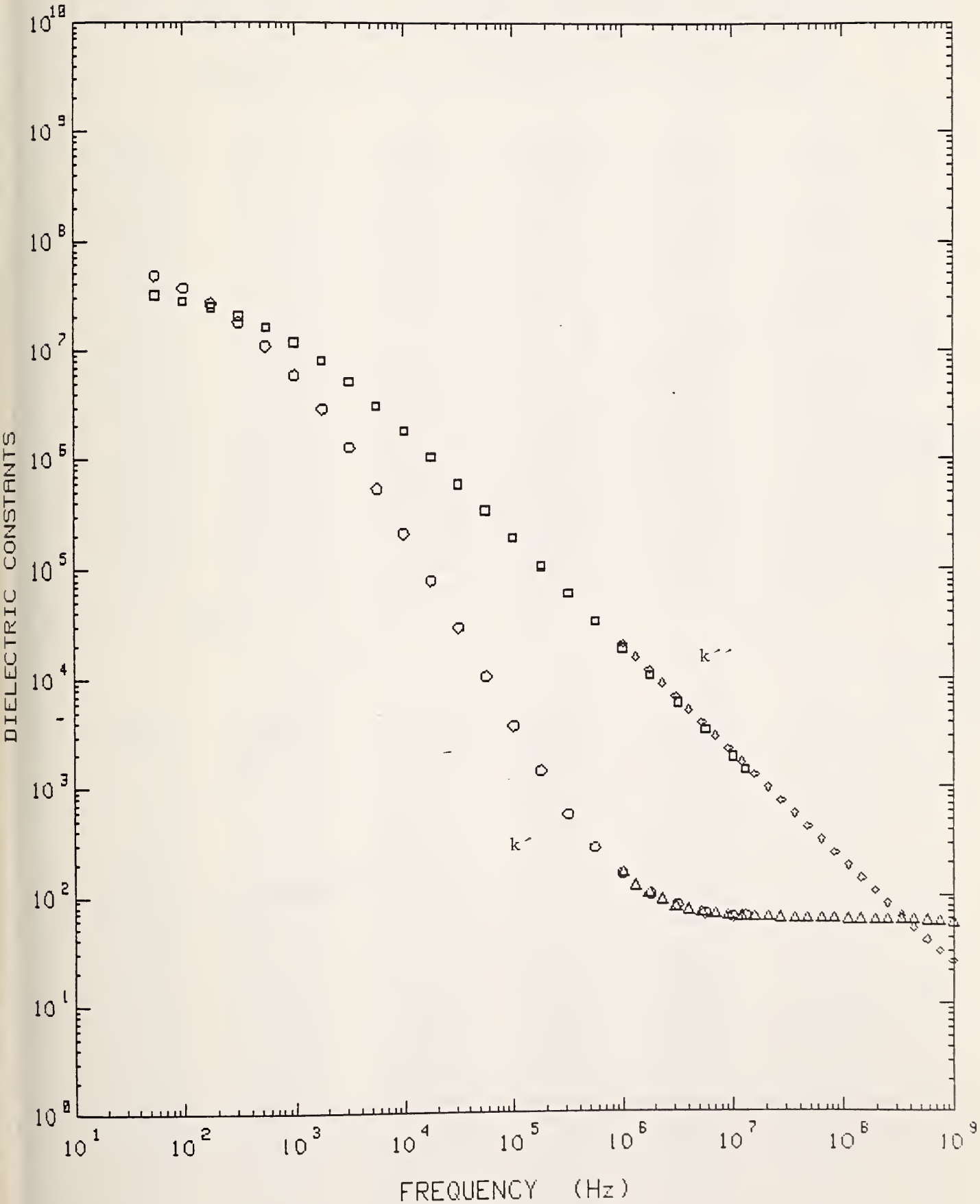


Figure 19. Dielectric properties of an aqueous brain phantom in current use at the Center for Devices and Radiological Health.

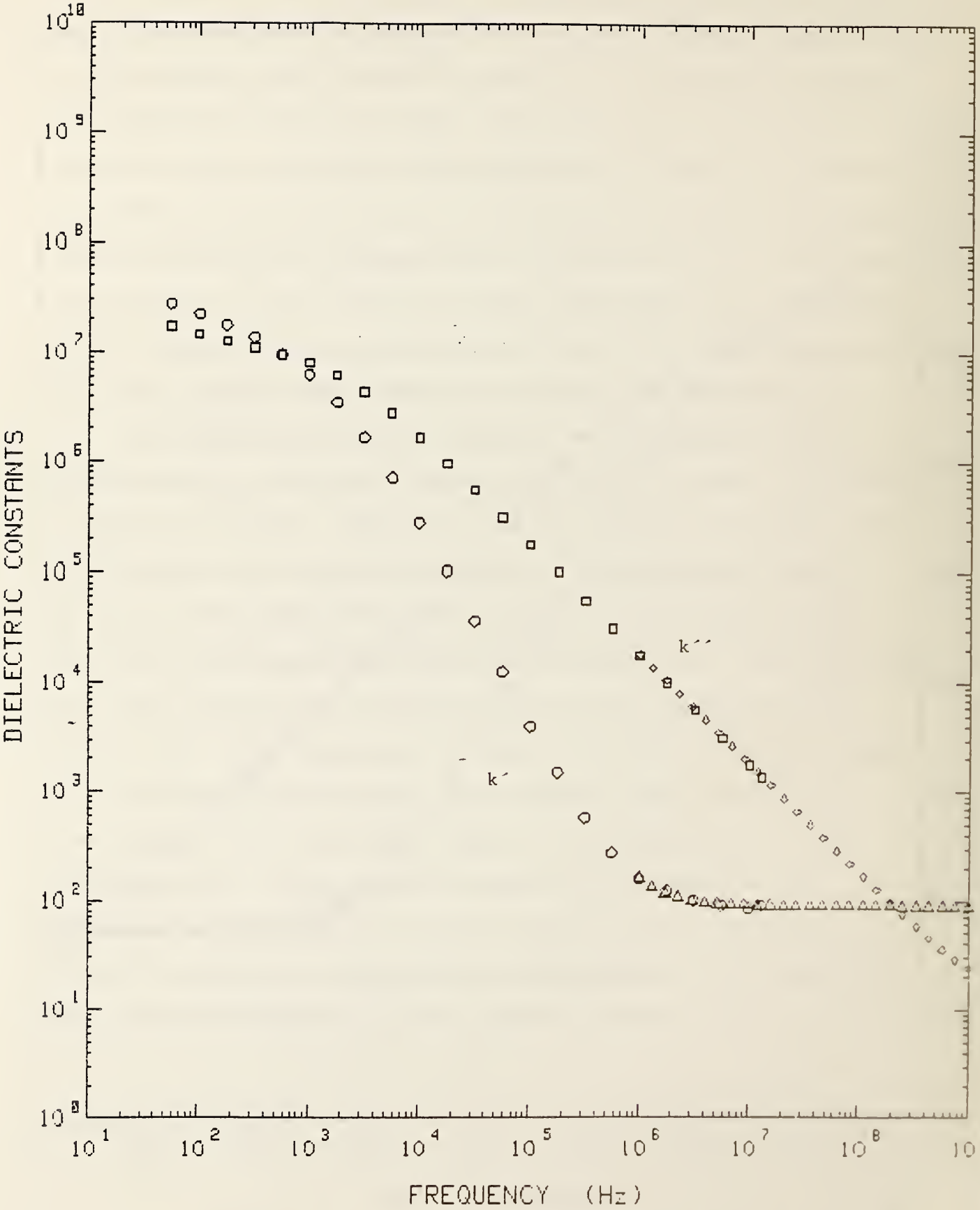


Figure 20. Dielectric properties of an aqueous muscle phantom in current use at the Center for Devices and Radiological Health.

Table 3. Calibration data for k' and k" obtained with an empty specimen holder. To correct the measured values reported in the other data tables subtract these values of k' and k" and σ' from the values reported in the other tables at the corresponding frequencies. The differences will be important only for the higher frequency data.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	5.600E+01	8.404E-07	-9.000E+02	1.212E-06	-1.465E+04	3.891E+04	1
2	1.000E+02	3.966E-07	7.415E+02	5.718E-07	1.207E+04	1.028E+04	2
3	1.780E+02	1.471E-07	1.896E+02	2.121E-07	3.088E+03	2.143E+03	3
4	3.160E+02	1.352E-07	4.937E+01	1.949E-07	8.039E+02	1.109E+03	4
5	5.620E+02	1.219E-07	1.900E+01	1.758E-07	3.093E+02	5.625E+02	5
6	1.000E+03	1.340E-07	7.970E+00	1.931E-07	1.298E+02	3.473E+02	6
7	1.780E+03	1.507E-07	6.149E+00	2.172E-07	1.001E+02	2.195E+02	7
8	3.160E+03	1.571E-07	4.108E+00	2.264E-07	6.689E+01	1.289E+02	8
9	5.620E+03	1.733E-07	3.657E+00	2.499E-07	5.954E+01	7.995E+01	9
10	1.000E+04	1.966E-07	3.247E+00	2.834E-07	5.287E+01	5.096E+01	10
11	1.780E+04	2.348E-07	2.678E+00	3.384E-07	4.360E+01	3.419E+01	11
12	3.160E+04	2.785E-07	2.256E+00	4.015E-07	3.674E+01	2.285E+01	12
13	5.620E+04	3.484E-07	1.941E+00	5.022E-07	3.160E+01	1.607E+01	13
14	1.000E+05	4.393E-07	1.661E+00	6.333E-07	2.704E+01	1.139E+01	14
15	1.780E+05	5.525E-07	1.535E+00	7.965E-07	2.499E+01	8.047E+00	15
16	3.160E+05	7.001E-07	1.416E+00	1.009E-06	2.305E+01	5.744E+00	16
17	5.620E+05	8.899E-07	1.339E+00	1.283E-06	2.180E+01	4.105E+00	17
18	1.000E+06	1.118E-06	1.257E+00	1.612E-06	2.047E+01	2.899E+00	18
19	1.780E+06	1.404E-06	1.214E+00	2.024E-06	1.977E+01	2.045E+00	19
20	3.160E+06	1.762E-06	1.168E+00	2.540E-06	1.901E+01	1.445E+00	20
21	5.620E+06	2.306E-06	1.147E+00	3.324E-06	1.868E+01	1.064E+00	21
22	1.000E+07	3.394E-06	1.116E+00	4.893E-06	1.817E+01	8.800E-01	22
23	1.299E+07	4.004E-06	1.101E+00	5.772E-06	1.793E+01	7.991E-01	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	1.000E+06	5.000E-06	1.751E+00	7.208E-06	2.851E+01	1.296E+01	1
2	1.318E+06	6.000E-06	1.690E+00	8.650E-06	2.752E+01	1.179E+01	2
3	1.738E+06	7.000E-06	1.649E+00	1.009E-05	2.684E+01	1.044E+01	3
4	2.291E+06	7.000E-06	1.667E+00	1.009E-05	2.715E+01	7.918E+00	4
5	3.020E+06	9.000E-06	1.634E+00	1.297E-05	2.660E+01	7.723E+00	5
6	3.981E+06	1.100E-05	1.599E+00	1.586E-05	2.604E+01	7.160E+00	6
7	5.248E+06	1.300E-05	1.547E+00	1.874E-05	2.518E+01	6.419E+00	7
8	6.918E+06	1.700E-05	1.518E+00	2.451E-05	2.472E+01	6.368E+00	8
9	9.120E+06	2.100E-05	1.466E+00	3.027E-05	2.387E+01	5.967E+00	9
10	1.202E+07	2.600E-05	1.416E+00	3.748E-05	2.306E+01	5.604E+00	10
11	1.585E+07	3.100E-05	1.366E+00	4.469E-05	2.224E+01	5.069E+00	11
12	2.089E+07	3.900E-05	1.318E+00	5.622E-05	2.146E+01	4.837E+00	12
13	2.754E+07	4.700E-05	1.277E+00	6.776E-05	2.079E+01	4.422E+00	13
14	3.631E+07	5.800E-05	1.227E+00	8.362E-05	1.998E+01	4.140E+00	14
15	4.786E+07	7.000E-05	1.184E+00	1.009E-04	1.927E+01	3.790E+00	15
16	6.310E+07	8.300E-05	1.143E+00	1.197E-04	1.861E+01	3.409E+00	16
17	8.318E+07	9.700E-05	1.112E+00	1.398E-04	1.810E+01	3.022E+00	17
18	1.096E+08	1.100E-04	1.081E+00	1.586E-04	1.761E+01	2.600E+00	18
19	1.445E+08	1.240E-04	1.058E+00	1.788E-04	1.723E+01	2.223E+00	19
20	1.905E+08	1.350E-04	1.042E+00	1.946E-04	1.696E+01	1.836E+00	20
21	2.512E+08	1.550E-04	1.028E+00	2.235E-04	1.674E+01	1.599E+00	21
22	3.311E+08	1.740E-04	1.017E+00	2.508E-04	1.655E+01	1.362E+00	22
23	4.365E+08	2.150E-04	1.006E+00	3.100E-04	1.637E+01	1.276E+00	23
24	5.754E+08	2.570E-04	9.893E-01	3.705E-04	1.611E+01	1.157E+00	24
25	7.586E+08	3.360E-04	9.653E-01	4.844E-04	1.572E+01	1.148E+00	25
26	1.000E+09	4.210E-04	9.360E-01	6.069E-04	1.524E+01	1.091E+00	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

Table 4. Data for figure 15, phantom with a single film of PET.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	5.600E+01	8.370E-04	2.303E+06	1.207E-03	3.750E+07	3.875E+07	1
2	1.000E+02	1.235E-03	1.440E+06	1.781E-03	2.344E+07	3.202E+07	2
3	1.780E+02	1.649E-03	7.724E+05	2.378E-03	1.258E+07	2.402E+07	3
4	3.160E+02	1.989E-03	3.643E+05	2.867E-03	5.932E+06	1.632E+07	4
5	5.620E+02	2.220E-03	1.566E+05	3.200E-03	2.550E+06	1.024E+07	5
6	1.000E+03	2.366E-03	6.388E+04	3.411E-03	1.040E+06	6.134E+06	6
7	1.780E+03	2.455E-03	2.527E+04	3.539E-03	4.115E+05	3.576E+06	7
8	3.160E+03	2.506E-03	9.931E+03	3.613E-03	1.617E+05	2.056E+06	8
9	5.620E+03	2.534E-03	3.949E+03	3.654E-03	6.430E+04	1.169E+06	9
10	1.000E+04	2.548E-03	1.652E+03	3.674E-03	2.690E+04	6.606E+05	10
11	1.780E+04	2.558E-03	7.623E+02	3.688E-03	1.241E+04	3.726E+05	11
12	3.160E+04	2.564E-03	4.136E+02	3.696E-03	6.735E+03	2.104E+05	12
13	5.620E+04	2.567E-03	2.692E+02	3.701E-03	4.383E+03	1.184E+05	13
14	1.000E+05	2.569E-03	1.991E+02	3.704E-03	3.241E+03	6.661E+04	14
15	1.780E+05	2.582E-03	1.777E+02	3.722E-03	2.894E+03	3.761E+04	15
16	3.160E+05	2.606E-03	1.615E+02	3.757E-03	2.629E+03	2.138E+04	16
17	5.620E+05	2.675E-03	1.479E+02	3.856E-03	2.407E+03	1.234E+04	17
18	1.000E+06	2.867E-03	1.301E+02	4.133E-03	2.118E+03	7.433E+03	18
19	1.780E+06	3.286E-03	1.004E+02	4.737E-03	1.634E+03	4.786E+03	19
20	3.160E+06	3.893E-03	6.171E+01	5.612E-03	1.005E+03	3.194E+03	20
21	5.620E+06	4.410E-03	3.074E+01	6.358E-03	5.005E+02	2.035E+03	21
22	1.000E+07	4.691E-03	1.483E+01	6.763E-03	2.415E+02	1.216E+03	22
23	1.299E+07	4.749E-03	1.135E+01	6.846E-03	1.849E+02	9.478E+02	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	1.000E+06	2.960E-03	1.261E+02	4.267E-03	2.052E+03	7.671E+03	1
2	1.318E+06	3.129E-03	1.149E+02	4.511E-03	1.871E+03	6.151E+03	2
3	1.738E+06	3.359E-03	1.007E+02	4.842E-03	1.639E+03	5.009E+03	3
4	2.291E+06	3.642E-03	8.323E+01	5.250E-03	1.355E+03	4.120E+03	4
5	3.020E+06	3.949E-03	6.466E+01	5.693E-03	1.053E+03	3.389E+03	5
6	3.981E+06	4.239E-03	4.749E+01	6.111E-03	7.733E+02	2.759E+03	6
7	5.248E+06	4.480E-03	3.348E+01	6.459E-03	5.451E+02	2.212E+03	7
8	6.918E+06	4.662E-03	2.321E+01	6.721E-03	3.779E+02	1.746E+03	8
9	9.120E+06	4.789E-03	1.623E+01	6.904E-03	2.643E+02	1.361E+03	9
10	1.202E+07	4.873E-03	1.176E+01	7.025E-03	1.914E+02	1.050E+03	10
11	1.585E+07	4.928E-03	8.978E+00	7.104E-03	1.462E+02	8.058E+02	11
12	2.089E+07	4.964E-03	7.290E+00	7.156E-03	1.187E+02	6.157E+02	12
13	2.754E+07	4.990E-03	6.281E+00	7.194E-03	1.023E+02	4.695E+02	13
14	3.631E+07	5.010E-03	5.690E+00	7.223E-03	9.264E+01	3.576E+02	14
15	4.786E+07	5.029E-03	5.334E+00	7.250E-03	8.684E+01	2.723E+02	15
16	6.310E+07	5.051E-03	5.113E+00	7.282E-03	8.325E+01	2.075E+02	16
17	8.318E+07	5.079E-03	4.981E+00	7.322E-03	8.110E+01	1.582E+02	17
18	1.096E+08	5.119E-03	4.893E+00	7.380E-03	7.967E+01	1.210E+02	18
19	1.445E+08	5.180E-03	4.833E+00	7.468E-03	7.869E+01	9.287E+01	19
20	1.905E+08	5.271E-03	4.789E+00	7.599E-03	7.798E+01	7.169E+01	20
21	2.512E+08	5.436E-03	4.755E+00	7.837E-03	7.743E+01	5.608E+01	21
22	3.311E+08	5.702E-03	4.719E+00	8.220E-03	7.684E+01	4.462E+01	22
23	4.365E+08	6.157E-03	4.675E+00	8.876E-03	7.611E+01	3.655E+01	23
24	5.754E+08	6.901E-03	4.613E+00	9.949E-03	7.511E+01	3.108E+01	24
25	7.586E+08	8.111E-03	4.519E+00	1.169E-02	7.358E+01	2.771E+01	25
26	1.000E+09	1.014E-02	4.396E+00	1.462E-02	7.158E+01	2.629E+01	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

Table 5. Data for figure 16, flakes of film of PET mixed into the phantom.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k´	k´´	No.
1	5.600E+01	6.173E-04	2.447E+06	8.899E-04	3.984E+07	2.858E+07	1
2	1.000E+02	1.016E-03	1.786E+06	1.465E-03	2.909E+07	2.635E+07	2
3	1.780E+02	1.566E-03	1.158E+06	2.258E-03	1.886E+07	2.282E+07	3
4	3.160E+02	2.177E-03	6.481E+05	3.138E-03	1.055E+07	1.786E+07	4
5	5.620E+02	2.716E-03	3.138E+05	3.916E-03	5.109E+06	1.253E+07	5
6	1.000E+03	3.101E-03	1.351E+05	4.471E-03	2.200E+06	8.040E+06	6
7	1.780E+03	3.336E-03	5.350E+04	4.809E-03	8.711E+05	4.859E+06	7
8	3.160E+03	3.467E-03	2.023E+04	4.998E-03	3.294E+05	2.845E+06	8
9	5.620E+03	3.533E-03	7.458E+03	5.094E-03	1.214E+05	1.630E+06	9
10	1.000E+04	3.568E-03	2.752E+03	5.143E-03	4.482E+04	9.249E+05	10
11	1.780E+04	3.582E-03	1.048E+03	5.164E-03	1.707E+04	5.218E+05	11
12	3.160E+04	3.591E-03	4.295E+02	5.176E-03	6.993E+03	2.946E+05	12
13	5.620E+04	3.596E-03	1.968E+02	5.184E-03	3.204E+03	1.659E+05	13
14	1.000E+05	3.596E-03	1.168E+02	5.183E-03	1.902E+03	9.322E+04	14
15	1.780E+05	3.601E-03	6.567E+01	5.192E-03	1.069E+03	5.245E+04	15
16	3.160E+05	3.604E-03	4.756E+01	5.196E-03	7.744E+02	2.957E+04	16
17	5.620E+05	3.617E-03	3.794E+01	5.214E-03	6.178E+02	1.668E+04	17
18	1.000E+06	3.639E-03	3.196E+01	5.247E-03	5.205E+02	9.436E+03	18
19	1.780E+06	3.691E-03	2.679E+01	5.321E-03	4.361E+02	5.375E+03	19
20	3.160E+06	3.796E-03	2.116E+01	5.472E-03	3.445E+02	3.114E+03	20
21	5.620E+06	3.950E-03	1.528E+01	5.695E-03	2.489E+02	1.822E+03	21
22	1.000E+07	4.120E-03	1.038E+01	5.940E-03	1.690E+02	1.068E+03	22
23	1.299E+07	4.183E-03	8.908E+00	6.030E-03	1.450E+02	8.348E+02	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k´	k´´	No.
1	1.000E+06	4.010E-03	2.722E+01	5.781E-03	4.431E+02	1.039E+04	1
2	1.318E+06	4.030E-03	2.584E+01	5.810E-03	4.207E+02	7.922E+03	2
3	1.738E+06	4.059E-03	2.454E+01	5.852E-03	3.996E+02	6.053E+03	3
4	2.291E+06	4.100E-03	2.286E+01	5.911E-03	3.722E+02	4.638E+03	4
5	3.020E+06	4.156E-03	2.071E+01	5.991E-03	3.372E+02	3.566E+03	5
6	3.981E+06	4.229E-03	1.827E+01	6.097E-03	2.975E+02	2.753E+03	6
7	5.248E+06	4.313E-03	1.580E+01	6.218E-03	2.573E+02	2.130E+03	7
8	6.918E+06	4.403E-03	1.327E+01	6.348E-03	2.161E+02	1.649E+03	8
9	9.120E+06	4.494E-03	1.108E+01	6.479E-03	1.804E+02	1.277E+03	9
10	1.202E+07	4.577E-03	9.214E+00	6.598E-03	1.500E+02	9.866E+02	10
11	1.585E+07	4.647E-03	7.773E+00	6.699E-03	1.266E+02	7.598E+02	11
12	2.089E+07	4.706E-03	6.711E+00	6.784E-03	1.093E+02	5.837E+02	12
13	2.754E+07	4.752E-03	5.987E+00	6.851E-03	9.748E+01	4.471E+02	13
14	3.631E+07	4.788E-03	5.497E+00	6.903E-03	8.950E+01	3.417E+02	14
15	4.786E+07	4.819E-03	5.184E+00	6.947E-03	8.441E+01	2.609E+02	15
16	6.310E+07	4.848E-03	4.982E+00	6.989E-03	8.112E+01	1.991E+02	16
17	8.318E+07	4.882E-03	4.853E+00	7.038E-03	7.901E+01	1.521E+02	17
18	1.096E+08	4.924E-03	4.764E+00	7.099E-03	7.757E+01	1.164E+02	18
19	1.445E+08	4.983E-03	4.705E+00	7.184E-03	7.661E+01	8.934E+01	19
20	1.905E+08	5.071E-03	4.661E+00	7.311E-03	7.589E+01	6.897E+01	20
21	2.512E+08	5.228E-03	4.628E+00	7.537E-03	7.536E+01	5.394E+01	21
22	3.311E+08	5.480E-03	4.593E+00	7.900E-03	7.478E+01	4.289E+01	22
23	4.365E+08	5.913E-03	4.551E+00	8.524E-03	7.409E+01	3.510E+01	23
24	5.754E+08	6.621E-03	4.493E+00	9.545E-03	7.315E+01	2.982E+01	24
25	7.586E+08	7.787E-03	4.404E+00	1.123E-02	7.171E+01	2.660E+01	25
26	1.000E+09	9.736E-03	4.288E+00	1.404E-02	6.981E+01	2.523E+01	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

Table 6. Data for figure 17, phantom with a single film of PET covering one electrode.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k′	k′′	No.
1	5.600E+01	2.359E-04	2.497E+05	3.401E-04	4.066E+06	1.092E+07	1
2	1.000E+02	2.648E-04	1.354E+05	3.817E-04	2.204E+06	6.865E+06	2
3	1.780E+02	2.951E-04	7.609E+04	4.255E-04	1.239E+06	4.298E+06	3
4	3.160E+02	3.265E-04	4.224E+04	4.708E-04	6.878E+05	2.679E+06	4
5	5.620E+02	3.583E-04	2.254E+04	5.166E-04	3.670E+05	1.653E+06	5
6	1.000E+03	3.866E-04	1.140E+04	5.573E-04	1.856E+05	1.002E+06	6
7	1.780E+03	4.091E-04	5.606E+03	5.897E-04	9.128E+04	5.958E+05	7
8	3.160E+03	4.250E-04	2.830E+03	6.127E-04	4.609E+04	3.487E+05	8
9	5.620E+03	4.356E-04	1.586E+03	6.280E-04	2.583E+04	2.010E+05	9
10	1.000E+04	4.436E-04	1.050E+03	6.395E-04	1.709E+04	1.150E+05	10
11	1.780E+04	4.515E-04	8.194E+02	6.509E-04	1.334E+04	6.576E+04	11
12	3.160E+04	4.640E-04	7.044E+02	6.690E-04	1.147E+04	3.807E+04	12
13	5.620E+04	4.862E-04	6.250E+02	7.010E-04	1.018E+04	2.243E+04	13
14	1.000E+05	5.240E-04	5.581E+02	7.554E-04	9.086E+03	1.358E+04	14
15	1.780E+05	5.945E-04	5.057E+02	8.570E-04	8.234E+03	8.659E+03	15
16	3.160E+05	7.608E-04	4.578E+02	1.097E-03	7.454E+03	6.242E+03	16
17	5.620E+05	1.142E-03	3.925E+02	1.647E-03	6.390E+03	5.270E+03	17
18	1.000E+06	1.867E-03	2.919E+02	2.691E-03	4.752E+03	4.839E+03	18
19	1.780E+06	2.870E-03	1.755E+02	4.138E-03	2.857E+03	4.180E+03	19
20	3.160E+06	3.757E-03	8.427E+01	5.416E-03	1.372E+03	3.082E+03	20
21	5.620E+06	4.286E-03	3.574E+01	6.179E-03	5.820E+02	1.977E+03	21
22	1.000E+07	4.520E-03	1.575E+01	6.517E-03	2.565E+02	1.172E+03	22
23	1.299E+07	4.568E-03	1.174E+01	6.586E-03	1.911E+02	9.118E+02	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k′	k′′	No.
1	1.000E+06	1.901E-03	2.971E+02	2.741E-03	4.838E+03	4.926E+03	1
2	1.318E+06	2.385E-03	2.429E+02	3.438E-03	3.955E+03	4.688E+03	2
3	1.738E+06	2.908E-03	1.876E+02	4.192E-03	3.054E+03	4.336E+03	3
4	2.291E+06	3.412E-03	1.363E+02	4.919E-03	2.219E+03	3.860E+03	4
5	3.020E+06	3.844E-03	9.423E+01	5.542E-03	1.534E+03	3.299E+03	5
6	3.981E+06	4.180E-03	6.277E+01	6.026E-03	1.022E+03	2.721E+03	6
7	5.248E+06	4.421E-03	4.106E+01	6.373E-03	6.686E+02	2.183E+03	7
8	6.918E+06	4.585E-03	2.692E+01	6.610E-03	4.383E+02	1.717E+03	8
9	9.120E+06	4.693E-03	1.808E+01	6.766E-03	2.944E+02	1.333E+03	9
10	1.202E+07	4.762E-03	1.267E+01	6.865E-03	2.063E+02	1.026E+03	10
11	1.585E+07	4.807E-03	9.429E+00	6.930E-03	1.535E+02	7.860E+02	11
12	2.089E+07	4.836E-03	7.511E+00	6.972E-03	1.223E+02	5.998E+02	12
13	2.754E+07	4.857E-03	6.380E+00	7.002E-03	1.039E+02	4.570E+02	13
14	3.631E+07	4.874E-03	5.716E+00	7.027E-03	9.307E+01	3.479E+02	14
15	4.786E+07	4.891E-03	5.320E+00	7.051E-03	8.663E+01	2.648E+02	15
16	6.310E+07	4.912E-03	5.085E+00	7.081E-03	8.280E+01	2.017E+02	16
17	8.318E+07	4.939E-03	4.941E+00	7.120E-03	8.044E+01	1.539E+02	17
18	1.096E+08	4.980E-03	4.848E+00	7.179E-03	7.894E+01	1.177E+02	18
19	1.445E+08	5.040E-03	4.785E+00	7.266E-03	7.792E+01	9.036E+01	19
20	1.905E+08	5.131E-03	4.741E+00	7.397E-03	7.719E+01	6.978E+01	20
21	2.512E+08	5.295E-03	4.709E+00	7.633E-03	7.667E+01	5.463E+01	21
22	3.311E+08	5.562E-03	4.674E+00	8.018E-03	7.611E+01	4.353E+01	22
23	4.365E+08	6.020E-03	4.633E+00	8.679E-03	7.543E+01	3.574E+01	23
24	5.754E+08	6.770E-03	4.577E+00	9.760E-03	7.452E+01	3.049E+01	24
25	7.586E+08	8.008E-03	4.492E+00	1.154E-02	7.314E+01	2.736E+01	25
26	1.000E+09	1.009E-02	4.380E+00	1.454E-02	7.132E+01	2.614E+01	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

Table 7. Data for figure 18, jade plant leaf.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	5.600E+01	2.774E-04	2.470E+05	3.999E-04	4.022E+06	1.284E+07	1
2	1.000E+02	3.053E-04	1.171E+05	4.401E-04	1.906E+06	7.915E+06	2
3	1.780E+02	3.271E-04	5.540E+04	4.716E-04	9.021E+05	4.765E+06	3
4	3.160E+02	3.442E-04	2.667E+04	4.962E-04	4.342E+05	2.824E+06	4
5	5.620E+02	3.571E-04	1.354E+04	5.147E-04	2.204E+05	1.647E+06	5
6	1.000E+03	3.672E-04	7.619E+03	5.294E-04	1.241E+05	9.520E+05	6
7	1.780E+03	3.761E-04	4.946E+03	5.423E-04	8.052E+04	5.478E+05	7
8	3.160E+03	3.862E-04	3.660E+03	5.568E-04	5.960E+04	3.169E+05	8
9	5.620E+03	3.996E-04	2.952E+03	5.761E-04	4.806E+04	1.844E+05	9
10	1.000E+04	4.208E-04	2.494E+03	6.066E-04	4.061E+04	1.091E+05	10
11	1.780E+04	4.554E-04	2.146E+03	6.566E-04	3.494E+04	6.634E+04	11
12	3.160E+04	5.151E-04	1.846E+03	7.425E-04	3.006E+04	4.226E+04	12
13	5.620E+04	6.192E-04	1.559E+03	8.927E-04	2.538E+04	2.857E+04	13
14	1.000E+05	8.140E-04	1.292E+03	1.174E-03	2.103E+04	2.110E+04	14
15	1.780E+05	1.167E-03	1.011E+03	1.682E-03	1.647E+04	1.699E+04	15
16	3.160E+05	1.714E-03	7.118E+02	2.472E-03	1.159E+04	1.407E+04	16
17	5.620E+05	2.414E-03	4.284E+02	3.481E-03	6.976E+03	1.114E+04	17
18	1.000E+06	3.092E-03	2.201E+02	4.457E-03	3.584E+03	8.016E+03	18
19	1.780E+06	3.591E-03	1.005E+02	5.177E-03	1.636E+03	5.231E+03	19
20	3.160E+06	3.904E-03	4.422E+01	5.628E-03	7.201E+02	3.203E+03	20
21	5.620E+06	4.086E-03	2.045E+01	5.891E-03	3.329E+02	1.885E+03	21
22	1.000E+07	4.197E-03	1.097E+01	6.050E-03	1.787E+02	1.088E+03	22
23	1.299E+07	4.228E-03	9.027E+00	6.095E-03	1.470E+02	8.438E+02	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	1.000E+06	3.263E-03	2.258E+02	4.704E-03	3.677E+03	8.456E+03	1
2	1.318E+06	3.541E-03	1.562E+02	5.105E-03	2.544E+03	6.961E+03	2
3	1.738E+06	3.771E-03	1.059E+02	5.436E-03	1.724E+03	5.623E+03	3
4	2.291E+06	3.952E-03	7.100E+01	5.697E-03	1.156E+03	4.470E+03	4
5	3.020E+06	4.094E-03	4.743E+01	5.902E-03	7.723E+02	3.513E+03	5
6	3.981E+06	4.205E-03	3.202E+01	6.062E-03	5.214E+02	2.737E+03	6
7	5.248E+06	4.289E-03	2.205E+01	6.183E-03	3.590E+02	2.118E+03	7
8	6.918E+06	4.354E-03	1.569E+01	6.277E-03	2.555E+02	1.631E+03	8
9	9.120E+06	4.405E-03	1.163E+01	6.350E-03	1.904E+02	1.252E+03	9
10	1.202E+07	4.446E-03	9.161E+00	6.410E-03	1.492E+02	9.583E+02	10
11	1.585E+07	4.479E-03	7.572E+00	6.457E-03	1.233E+02	7.324E+02	11
12	2.089E+07	4.507E-03	6.582E+00	6.497E-03	1.072E+02	5.590E+02	12
13	2.754E+07	4.533E-03	5.952E+00	6.535E-03	9.691E+01	4.265E+02	13
14	3.631E+07	4.557E-03	5.550E+00	6.570E-03	9.036E+01	3.253E+02	14
15	4.786E+07	4.583E-03	5.294E+00	6.607E-03	8.619E+01	2.481E+02	15
16	6.310E+07	4.611E-03	5.118E+00	6.647E-03	8.333E+01	1.894E+02	16
17	8.318E+07	4.645E-03	4.998E+00	6.696E-03	8.138E+01	1.447E+02	17
18	1.096E+08	4.688E-03	4.906E+00	6.758E-03	7.988E+01	1.108E+02	18
19	1.445E+08	4.739E-03	4.837E+00	6.832E-03	7.876E+01	8.496E+01	19
20	1.905E+08	4.804E-03	4.780E+00	6.926E-03	7.783E+01	6.533E+01	20
21	2.512E+08	4.907E-03	4.736E+00	7.074E-03	7.712E+01	5.062E+01	21
22	3.311E+08	5.049E-03	4.692E+00	7.279E-03	7.640E+01	3.951E+01	22
23	4.365E+08	5.273E-03	4.648E+00	7.602E-03	7.568E+01	3.130E+01	23
24	5.754E+08	5.591E-03	4.599E+00	8.060E-03	7.489E+01	2.518E+01	24
25	7.586E+08	6.060E-03	4.538E+00	8.736E-03	7.389E+01	2.070E+01	25
26	1.000E+09	6.778E-03	4.480E+00	9.771E-03	7.295E+01	1.756E+01	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

Table 8. Data for figure 19, aqueous brain phantom material from the FDA.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	5.600E+01	6.919E-04	2.912E+06	9.974E-04	4.741E+07	3.203E+07	1
2	1.000E+02	1.084E-03	2.262E+06	1.562E-03	3.682E+07	2.809E+07	2
3	1.780E+02	1.681E-03	1.639E+06	2.423E-03	2.669E+07	2.448E+07	3
4	3.160E+02	2.506E-03	1.094E+06	3.613E-03	1.781E+07	2.056E+07	4
5	5.620E+02	3.514E-03	6.623E+05	5.066E-03	1.078E+07	1.621E+07	5
6	1.000E+03	4.569E-03	3.605E+05	6.586E-03	5.869E+06	1.184E+07	6
7	1.780E+03	5.496E-03	1.762E+05	7.923E-03	2.870E+06	8.004E+06	7
8	3.160E+03	6.199E-03	7.874E+04	8.936E-03	1.282E+06	5.086E+06	8
9	5.620E+03	6.678E-03	3.265E+04	9.628E-03	5.316E+05	3.081E+06	9
10	1.000E+04	6.972E-03	1.281E+04	1.005E-02	2.086E+05	1.807E+06	10
11	1.780E+04	7.155E-03	4.850E+03	1.032E-02	7.896E+04	1.042E+06	11
12	3.160E+04	7.261E-03	1.799E+03	1.047E-02	2.929E+04	5.957E+05	12
13	5.620E+04	7.317E-03	6.561E+02	1.055E-02	1.068E+04	3.376E+05	13
14	1.000E+05	7.345E-03	2.266E+02	1.059E-02	3.689E+03	1.904E+05	14
15	1.780E+05	7.366E-03	8.943E+01	1.062E-02	1.456E+03	1.073E+05	15
16	3.160E+05	7.378E-03	3.494E+01	1.064E-02	5.689E+02	6.053E+04	16
17	5.620E+05	7.378E-03	1.730E+01	1.064E-02	2.817E+02	3.404E+04	17
18	1.000E+06	7.378E-03	1.004E+01	1.064E-02	1.635E+02	1.913E+04	18
19	1.780E+06	7.376E-03	6.521E+00	1.063E-02	1.062E+02	1.074E+04	19
20	3.160E+06	7.377E-03	5.049E+00	1.064E-02	8.221E+01	6.053E+03	20
21	5.620E+06	7.379E-03	4.197E+00	1.064E-02	6.834E+01	3.404E+03	21
22	1.000E+07	7.378E-03	3.899E+00	1.064E-02	6.348E+01	1.913E+03	22
23	1.299E+07	7.374E-03	4.007E+00	1.063E-02	6.524E+01	1.472E+03	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k'	k''	No.
1	1.000E+06	7.911E-03	9.549E+00	1.140E-02	1.555E+02	2.050E+04	1
2	1.318E+06	7.904E-03	7.244E+00	1.139E-02	1.179E+02	1.554E+04	2
3	1.738E+06	7.895E-03	6.045E+00	1.138E-02	9.842E+01	1.177E+04	3
4	2.291E+06	7.890E-03	5.349E+00	1.137E-02	8.710E+01	8.925E+03	4
5	3.020E+06	7.886E-03	4.638E+00	1.137E-02	7.551E+01	6.767E+03	5
6	3.981E+06	7.881E-03	4.318E+00	1.136E-02	7.030E+01	5.130E+03	6
7	5.248E+06	7.876E-03	4.064E+00	1.135E-02	6.617E+01	3.889E+03	7
8	6.918E+06	7.872E-03	3.934E+00	1.135E-02	6.405E+01	2.949E+03	8
9	9.120E+06	7.870E-03	3.804E+00	1.135E-02	6.194E+01	2.236E+03	9
10	1.202E+07	7.868E-03	3.720E+00	1.134E-02	6.057E+01	1.696E+03	10
11	1.585E+07	7.867E-03	3.655E+00	1.134E-02	5.952E+01	1.286E+03	11
12	2.089E+07	7.865E-03	3.611E+00	1.134E-02	5.879E+01	9.755E+02	12
13	2.754E+07	7.866E-03	3.565E+00	1.134E-02	5.805E+01	7.401E+02	13
14	3.631E+07	7.868E-03	3.537E+00	1.134E-02	5.760E+01	5.616E+02	14
15	4.786E+07	7.872E-03	3.515E+00	1.135E-02	5.723E+01	4.262E+02	15
16	6.310E+07	7.878E-03	3.494E+00	1.136E-02	5.688E+01	3.236E+02	16
17	8.318E+07	7.887E-03	3.473E+00	1.137E-02	5.655E+01	2.457E+02	17
18	1.096E+08	7.901E-03	3.455E+00	1.139E-02	5.625E+01	1.867E+02	18
19	1.445E+08	7.919E-03	3.436E+00	1.142E-02	5.595E+01	1.420E+02	19
20	1.905E+08	7.947E-03	3.420E+00	1.146E-02	5.568E+01	1.081E+02	20
21	2.512E+08	7.999E-03	3.404E+00	1.153E-02	5.542E+01	8.252E+01	21
22	3.311E+08	8.077E-03	3.382E+00	1.164E-02	5.507E+01	6.321E+01	22
23	4.365E+08	8.203E-03	3.355E+00	1.183E-02	5.463E+01	4.870E+01	23
24	5.754E+08	8.391E-03	3.320E+00	1.210E-02	5.406E+01	3.779E+01	24
25	7.586E+08	8.681E-03	3.269E+00	1.251E-02	5.323E+01	2.966E+01	25
26	1.000E+09	9.143E-03	3.209E+00	1.318E-02	5.224E+01	2.369E+01	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

Table 9. Data for figure 20, aqueous muscle phantom material from the FDA.

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k´	k´´	No.
1	5.600E+01	3.656E-04	1.676E+06	5.270E-04	2.729E+07	1.692E+07	1
2	1.000E+02	5.522E-04	1.356E+06	7.961E-04	2.207E+07	1.432E+07	2
3	1.780E+02	8.543E-04	1.080E+06	1.232E-03	1.759E+07	1.244E+07	3
4	3.160E+02	1.330E-03	8.259E+05	1.918E-03	1.345E+07	1.091E+07	4
5	5.620E+02	2.056E-03	5.881E+05	2.964E-03	9.576E+06	9.484E+06	5
6	1.000E+03	3.066E-03	3.794E+05	4.421E-03	6.177E+06	7.950E+06	6
7	1.780E+03	4.236E-03	2.134E+05	6.107E-03	3.474E+06	6.170E+06	7
8	3.160E+03	5.272E-03	1.034E+05	7.600E-03	1.684E+06	4.325E+06	8
9	5.620E+03	6.009E-03	4.409E+04	8.663E-03	7.178E+05	2.772E+06	9
10	1.000E+04	6.449E-03	1.722E+04	9.297E-03	2.804E+05	1.672E+06	10
11	1.780E+04	6.693E-03	6.316E+03	9.649E-03	1.028E+05	9.748E+05	11
12	3.160E+04	6.823E-03	2.261E+03	9.836E-03	3.682E+04	5.598E+05	12
13	5.620E+04	6.892E-03	7.821E+02	9.936E-03	1.273E+04	3.179E+05	13
14	1.000E+05	6.938E-03	2.445E+02	1.000E-02	3.982E+03	1.799E+05	14
15	1.780E+05	6.936E-03	9.351E+01	1.000E-02	1.523E+03	1.010E+05	15
16	3.160E+05	6.950E-03	3.615E+01	1.002E-02	5.885E+02	5.702E+04	16
17	5.620E+05	6.949E-03	1.747E+01	1.002E-02	2.844E+02	3.206E+04	17
18	1.000E+06	6.949E-03	1.014E+01	1.002E-02	1.652E+02	1.802E+04	18
19	1.780E+06	6.948E-03	7.736E+00	1.002E-02	1.260E+02	1.012E+04	19
20	3.160E+06	6.949E-03	6.369E+00	1.002E-02	1.037E+02	5.702E+03	20
21	5.620E+06	6.947E-03	5.664E+00	1.001E-02	9.223E+01	3.205E+03	21
22	1.000E+07	6.950E-03	5.370E+00	1.002E-02	8.744E+01	1.802E+03	22
23	1.299E+07	6.950E-03	5.630E+00	1.002E-02	9.168E+01	1.387E+03	23

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP3570A

No.	f(Hz)	G (S)	C (pF)	σ (S/cm)	k´	k´´	No.
1	1.000E+06	6.944E-03	9.549E+00	1.001E-02	1.555E+02	1.799E+04	1
2	1.318E+06	6.943E-03	7.848E+00	1.001E-02	1.278E+02	1.365E+04	2
3	1.738E+06	6.942E-03	6.869E+00	1.001E-02	1.118E+02	1.035E+04	3
4	2.291E+06	6.941E-03	6.392E+00	1.001E-02	1.041E+02	7.852E+03	4
5	3.020E+06	6.941E-03	5.903E+00	1.001E-02	9.611E+01	5.956E+03	5
6	3.981E+06	6.940E-03	5.637E+00	1.000E-02	9.178E+01	4.517E+03	6
7	5.248E+06	6.939E-03	5.519E+00	1.000E-02	8.987E+01	3.426E+03	7
8	6.918E+06	6.938E-03	5.429E+00	1.000E-02	8.840E+01	2.599E+03	8
9	9.120E+06	6.938E-03	5.375E+00	1.000E-02	8.752E+01	1.971E+03	9
10	1.202E+07	6.938E-03	5.335E+00	1.000E-02	8.686E+01	1.495E+03	10
11	1.585E+07	6.937E-03	5.292E+00	1.000E-02	8.617E+01	1.134E+03	11
12	2.089E+07	6.937E-03	5.264E+00	1.000E-02	8.571E+01	8.604E+02	12
13	2.754E+07	6.938E-03	5.247E+00	1.000E-02	8.543E+01	6.528E+02	13
14	3.631E+07	6.939E-03	5.234E+00	1.000E-02	8.522E+01	4.953E+02	14
15	4.786E+07	6.945E-03	5.224E+00	1.001E-02	8.506E+01	3.760E+02	15
16	6.310E+07	6.951E-03	5.209E+00	1.002E-02	8.481E+01	2.855E+02	16
17	8.318E+07	6.962E-03	5.199E+00	1.004E-02	8.465E+01	2.169E+02	17
18	1.096E+08	6.978E-03	5.186E+00	1.006E-02	8.444E+01	1.649E+02	18
19	1.445E+08	7.003E-03	5.173E+00	1.010E-02	8.423E+01	1.256E+02	19
20	1.905E+08	7.038E-03	5.161E+00	1.015E-02	8.403E+01	9.572E+01	20
21	2.512E+08	7.110E-03	5.152E+00	1.025E-02	8.388E+01	7.335E+01	21
22	3.311E+08	7.224E-03	5.139E+00	1.041E-02	8.368E+01	5.653E+01	22
23	4.365E+08	7.419E-03	5.124E+00	1.070E-02	8.343E+01	4.404E+01	23
24	5.754E+08	7.725E-03	5.105E+00	1.114E-02	8.312E+01	3.479E+01	24
25	7.586E+08	8.218E-03	5.077E+00	1.185E-02	8.267E+01	2.807E+01	25
26	1.000E+09	9.070E-03	5.066E+00	1.308E-02	8.248E+01	2.350E+01	26

Sample Area= 3.170E-01 cm^2 Thickness= 4.570E-01 cm A/d= 6.937E-01 cm
Measured with HP4191A

REFERENCES

[1]. A recent popular article on the use of heat for cancer treatment is in the Wall Street Journal, November 29, page 15, (1985).

[2]. A.Y.Cheung and D.W.Koopman, IEEE Transactions on Microwave Theory and Technique, 24, 669, (1976).
A.W.Guy, "Analysis of Electromagnetic Fields Induced in Biological Tissues by Thermographic Studies on Equivalent Phantom Models." IEEE Microwave Theory and Techniques, vol MTT-19, no. 2, (1971).

[3] R.Pethig, "Dielectric Properties of Biological Materials: Biophysical and Medical Applications", IEEE Transactions on Electrical Insulation, Vol EI-19, No. 5, Oct. (1984) pp.453-474.

[4] J.C.Maxwell, "Electricity and Magnetism" Vol.I, p 452, London (1892).
A.R.Von Hipple, "Dielectrics and Waves", John Wiley & Sons, New York, (1954) p.228.

[5] Parafilm is a self sealing tape manufactured by the American Can Company, Greenwich, CT 06830.

[6] F. Buckley and A.A.Maryott, "Tables of Dielectric Dispersion Data for Pure Liquids and Dilute Solutions" National Bureau of Standards Circular 589, Nov. 1, (1958).

[7] Hewlett-Packard Company, Eastern Headquaters, 4 Choke Cherry Road, Rockville, MD 20850, (301) 258-2000.

[8] J.L.Schepps and K.R.Foster, "The UHF and Microwave Dielectric Properties of Normal and Tumour Tissues: Variations in the Dielectric Properties with Tissue Water Content", Phys. Med. Biol., 25, 1149 (1980).

[9] A.Surowiec, S.S.Stuchly and A. Swarup, "Radiofrenquency Dielectric Properties of Animal Tissues as a Function of Time Following Death" Phys. Med. Biol., 30, 1131 (1985).

[10] H.P.Schwan and K.R.Foster, Proc. IEEE 68, 104 (1980)

[11] M.C.Steel and R.J.Sheppard, "Dielectric Properties of Mammalian Brain Tissue Between 1 and 18 GHz", Phys. Med. Biol., 30, 621 1985.

[12] M.G.Broadhurst, C.K.Chaing, K.J.Wahlstrand, R.M.Hill, L.A.Dissado and J.Pugh, "The Electrical Response of Jade Leaves", submitted to the Journal of Colloid and Interface Sciences.

[13] J.D.Ferry, J. Chem. Phys. 16, 737, (1948).

[14] A.K.Jonscher, "Dielectric Relaxation in Solids", Chelsea Dielectrics Press, London (1983)

[15] Texaco Chemical Company, 4800 Fournace Place, Bellaire, TX 77401, (713) 432-3071, Robert E. Watson, Jr., Product Supervisor. Mr. Watson said during a phone conversation that a new product brochure was in preparation and gave me permission to use data from the old brochure in the interim.

[16] R. Payne and I.E.Theodorou, "Dielectric Properties and Relaxation in Ethylene and Propylene Carbonate". J. Phys. Chem., 76 no.2, 2892-2900, (1972).

[17] H.S.Carslaw and J.C.Jaeger, "Conduction of Heat in Solids", Clarendon Press, Oxford, (1947), Appendix VI.

[18] For example, Aldrich Chemical Company, Inc. Catalog no.24,214-4.

[19] T.Hanai, N.Koizumi, T.Sugano and R.Gotoh, "Dielectric Properties of Emulsions", Kolloid-Zeitschrift, 171, 20 (1960).

[20] Liposome Technology volumes I, II and III, Edited by Gregory Gregoriodis, CRC Press, Boca Raton, Florida 33431.

E.D.Eanes of the National Institute of Dental Research provided Liposomes for our Exploratory Measurements.

[21] Hung Chao, Moore Business Machines, Inc., Research Division, 300 Long Blvd., Grand Island, NY 14072.

[22] Curt Thies, Professor of Chemical Engineering, Washington University, Saint Louis, MO, (314) 889-6066.

[23] W.M.Jayne, Jr., "Microencapsulation by Vapor Deposition", in "Microencapsulation, Processes and Applications", Jan E.Vandergaer, Ed., Plenum Press, N.Y., (1973).

[24] Dr. Jayne (reference 23) suggested that Dr. W.Beach of Bound Brook R&D, (201) 563-5000, had used this technology and might be able to apply it to encapsulation of propylene carbonate.

[25] Samples were supplied by The Mearl Corporation, Franklin Mineral Products Div., 41 East 42nd Street, New York, NY 10017, (Attn. Roger Hayden), and the English Mica Co., Highway 2165, P.O.Box709, Kings Mountain, N.C. 28086, (704) 739-1321.

[26] Fumed Silica, "cab-o-sil" was obtained from Cabot Corporation, 125 High Street, Boston, Mass. 02110, (617) 423-6000. Density data were taken from their product brochure.

[27] Polyethylene terephthalate film in 6 guage was supplied by the DuPont Company, Polymer Products Dept., Chestnut Run Bldg. 712, Wilmington, DE 19898, (800) 441-9494.

[28] F.M.Clark, "Insulating Materials for Design and Engineering Practice", John Wiley & Sons, New York, (1962).

[29] Polyethylene glycol dimethacrylate was obtained from Ware Chemical Corp., who no longer supply the material. It can be purchased from Sartomer Company, subsidiary of Atlantic Richfield Co., Marshall Bldg., West Chester Plaza, West Chester, PA 19380, (215) 692-8400, Nancy Dunn, Market Area Manager, Mid Atlantic Reagion, (800)345-8247

[30] Benzoin methyl ether was obtained from Polysciences, Inc., 400 Vally Road, Warrington, PA 18976, (215) 343-6484.

[31] L.D.Landau and E.M.Lifshitz, "Electrodynamics of Continuous Media", Pergamon Press, Oxford, (1960) p.45.

[32] D.A.G.Bruggeman, Annalen der Physik, 24, 636 (1935).

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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

This report describes the design and testing of a synthetic electromagnetic tissue phantom (a material that has the same response to electromagnetic fields as human tissue). The phantom overcomes some of the disadvantages of aqueous biopolymer based phantoms. These disadvantages include instabilities from water evaporation, biological attack, and metal-salt-water reactions, and the need to use different formulations for different frequencies. The synthetic phantom uses a mixture of ethylene and propylene carbonate with dissolved organic salt to provide permittivities and conductivities that are adjustable over the range of values found for biological electrolytes from 100 to 1000 MHz. Interfacial polarization that enhances the permittivity and lowers the conductivity below 100 MHz is produced by the inclusion of flakes of micrometer thick polymer film like Mylar or polyethylene. Flake size and concentration regulate the dielectric properties and their frequency dependence below 100 MHz. The phantom was thickened to a gel without change in electrical properties by addition of fumed silica or by polymerizing dissolved polyethylene glycol dimethacrylate into a swollen polymer network within the liquid. The permittivity and conductivity of a sample formulation is shown to match those of biological tissue from 1 to 1000 MHz.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

dielectric, phantom, electromagnetic, microwave heating, propylene carbonate, ethylene carbonate, interfacial polarization, conductivity, jel, biological tissue, electrolyte

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