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Dielectric Measurements on High-Temperature Materials

W. B. Westphal and J. Iglesias
Laboratory for Insulation Research
Massachusetts Institute of Technology
Cambridge, Massachusetts

Technical Report AFML-TR-70-138

July 1970

AIR FORCE SYSTEMS COMMAND
AIR FORCE MATERIALS LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

NOTICES

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FOREWORD

This report was prepared by the Massachusetts Institute of Technology, Laboratory for Insulation Research, Cambridge, Massachusetts, under USAF Contract F33615-67C-1612. This Contract was initiated under Project No. 7371, "Exploratory Development in Electrical, Electronic, and Magnetic Materials," Task No. 737101, "Dielectric Materials." The work was administered under direction of the AF Materials Laboratory, with Mr. D. Evans acting as project engineer.

This Final Report covers work conducted from Nov. 1, 1966 to March 31, 1970, and was submitted on May 21, 1970, by the authors for publication.

This technical report has been reviewed and is approved

DAVID J. IDEN
Lt. Colonel, USAF
Chief, Electromagnetic
Materials Branch
Materials Physics Division
Air Force Materials Laboratory

ABSTRACT

Extensions of the laboratory's measuring techniques for complex dielectric constants to wider ranges of temperature (4° to $2000^\circ K$) and frequency (.008 Hz to 90 GHz) are reviewed. Methods of interpreting dielectric data and computer programs for finding the components of complex spectra are discussed. Measurement data of general interest accumulated in the last three years appear in graphical and/or tabular form.

TABLE OF CONTENTS

ILLUSTRATIONS

INTRODUCTION

A review of the general properties of high-temperature insulators has been previously given (Tech. Rep. 203). Since that time we have measured new samples of BN, SiO_2, sapphire, and spinel ($MgAl_2O_4$), all of which have good high-temperature properties. These are listed in Section III and are indexed according to the same categories used in our previous review report 203. Sections I and II describe respectively measurement techniques and calculation procedures.

MEASUREMENT TECHNIQUES

Since our last summary report on measurement methods (Tech. Rep. 182), the frequency and temperature ranges have been extended and different techniques have been used on special materials. These are briefly described in this section. Figure 1 shows graphically the frequency and temperatures available for measurement. The letter designations refer to equipment or methods as listed in the following summary.

<u>Summary of Methods of Measurement</u>

A. Laboratory-built three-terminal low-frequency bridge used mainly on another contract. For a description see Tech. Rep. 6 under Contract N00014-67A-0204-0003.

B. Laboratory-built three-terminal high-frequency bridge, see above.

C. Laboratory-built three-terminal bridge with automatic frequency scanning and recording. See Tech. Rep. 4 of above contract.

D. Laboratory-built wide-range bridge, three-terminal 1 to 10^5 Hz, two-terminal 1 to $4x10^7$ Hz. See Tech. Rep. 201 under Contracts AF 33(616)-8353 and Nonr-1841(10)

E. Susceptance variation method with reentrant cavity: (a) 60 to 100 MHz, 2-inch disks; (b) 300 MHz, 1-inch disks.

F. Experimental Laboratory capacitance bridge, 50 MHz to 300 MHz.

G. Standing-wave method with open-circuited line: (a) disk sample, 300 MHz to 200°C; (b) coax sample, 100 to 300 MHz, R.T. only.

H. Reentrant cavity with twin coaxial sample. Used only for good sensitivity ($\tan \delta$ 3 to $5x10^{-5}$) on coaxial samples at 300 MHz, R.T. only.

I. Standing-wave method with coaxial sample $\lambda/4$ away from short, near R.T. only.

J. Standing-wave method with coaxial sample against short, -150 to +500°C.

K. Standing-wave method with cylindrical sample, -150° to 1000°C at 8.52 GHz, to 800°C at 14 and 24 GHz.

L. Coaxial cavity, frequency variation method, 1 to 3 GHz, -195° to +1400°C.

M. Dielectric-filled cylindrical cavity, -195° to 1500°C, 3 to 6 GHz, -195° to 1700°C, 9 GHz.

N. Transmission bridge, free-space method, 90 GHz, under development.

The obvious gap in high-temperature measurements near 10^8 Hz could be remedied by construction of a doubly reentrant cavity as proposed in a previous report.[1] A model (Fig. 2) useful to about 800°C, using silver instead of platinum and iridium foils, is under construction and will be studied for expected temperature gradients.

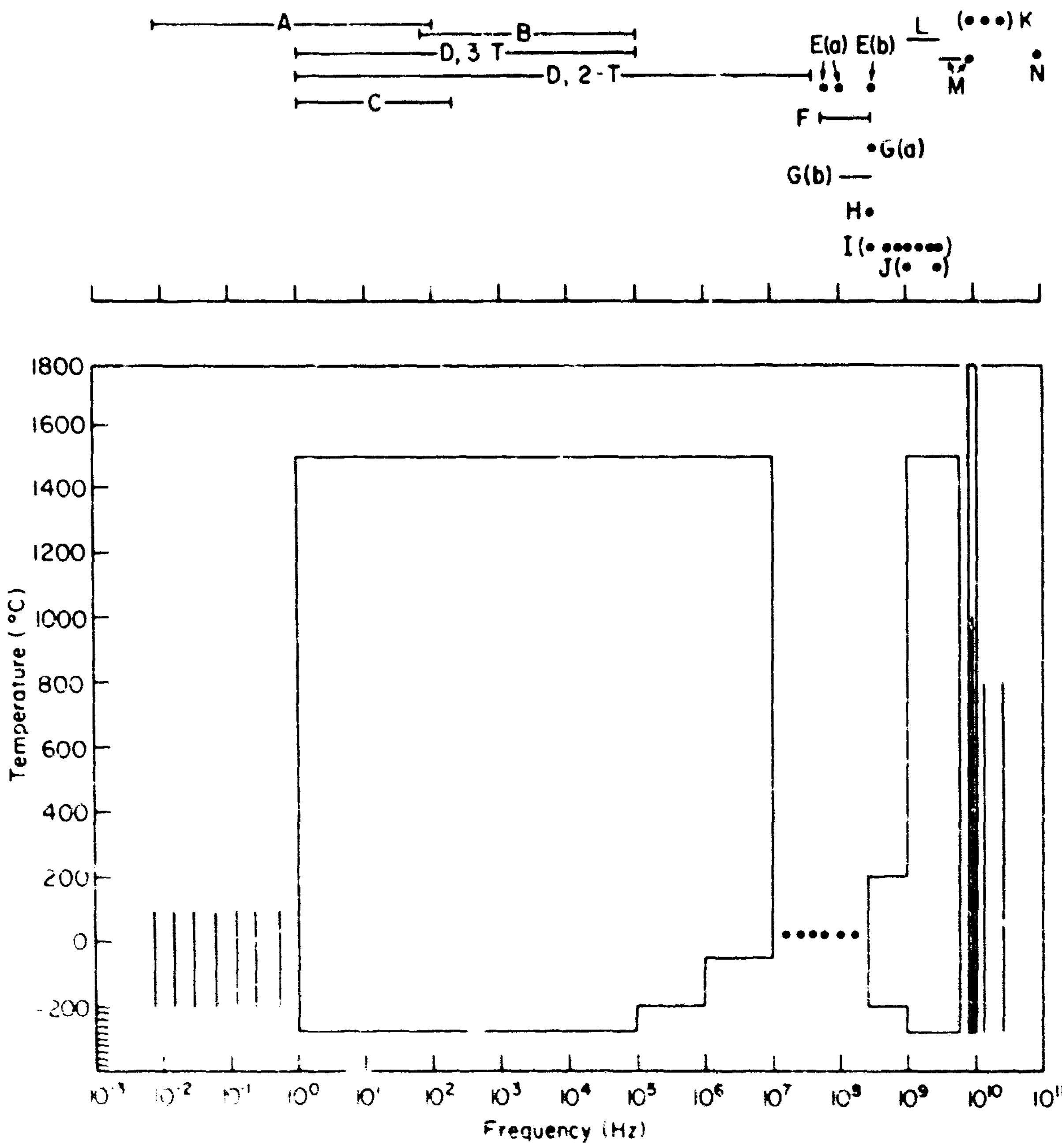


Fig. 1. Measurement methods and temperature ranges. See summary list for letter designations.

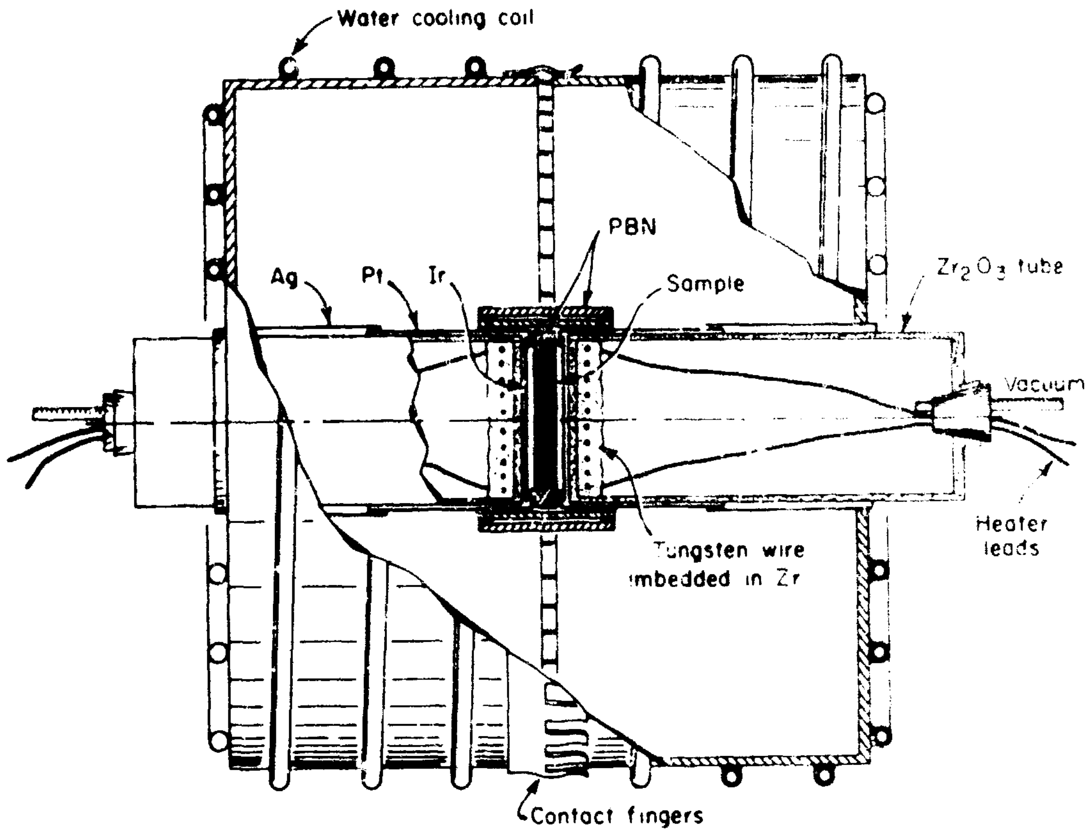


Fig. 2. High-temperature reentrant cavity (shown about 1/3 size for 100 MHz).

The 90-GHz measurements are still being developed.

For some of the data listed in Section III more than one method of measurement was used. An example is the Budd DiClad 522, which was supplied as doubly copper-clad sheet or as unclad sheet. With the clad sheet two-terminal and three-terminal samples were cut (Figs. 3a,b,c).

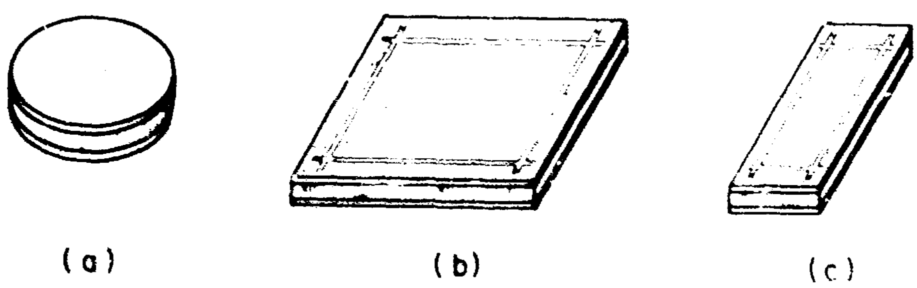


Fig. 3. Type of samples for copper-clad dielectrics. (a) Disk for two-terminal measurements. (b) Large square for precision three-terminal measurements. (c) Rectangular three-terminal sample for measurements in liquid-helium Dewar.

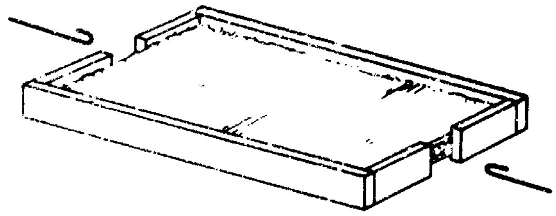


Fig. 4.
Microwave dielectric-filled cavity formed of doubly-clad sheet stock.

For microwave measurements, pieces of the same stock were soldered to close the periphery of a rectangular piece as shown in Fig. 4. The resultant dielectric-filled cavity having a width of 4.449 cm and a length of 15.30 cm resonated in the TE_{104} mode at 3.14 GHz. A thickness measurement of the plate is not involved in the computation of the dielectric constant

$$\kappa' = \frac{\lambda^2}{4} [(\frac{1}{w})^2 + (\frac{4}{\ell})^2]^{1/2}. \qquad (1)$$

The equivalent loss tangent for copper loss was computed:

$$\tan \delta_w = \frac{\frac{1}{w}(w + 2t) + (\frac{4}{\ell})^2(\ell + 2t)}{1.31\times10^4 \, wt \, \frac{\lambda}{s} [\frac{1}{w^2} + \frac{4}{\ell^2}]^{3/2}}, \qquad (2)$$

where s is the resistivity of the copper relative to its room-temperature resistivity. The value of $\tan \delta_w$ was 2.48×10^{-4} at 25°C and was small compared to dielectric loss at all temperatures.

Measurements on declad stock were made by using the three-terminal liquid displacement method[2] at 10^4 Hz and a rectangular cavity (as shown in Fig. 5) near 3 GHz.

Measurements were made with air-filled cavity (1), sample added (2), benzene (3), sample added (4). As in the three-terminal liquid displacement method, the four sets of data allow measurements of κ' without measurement of sample thickness:

$$\kappa'_s = \frac{[(\frac{\lambda_3}{\lambda_1})^2(\frac{\lambda_3}{\lambda_4})^2 - (\frac{\lambda_1}{\lambda_2})^2]}{(\frac{\lambda_3}{\lambda_4})^2 - (\frac{\lambda_1}{\lambda_2})^2} \kappa'_{air}. \qquad (3)$$

Equation 3 holds for any TE cavity but requires the same mode in all four measurements. Since the edge of the sample is in regions of low field strength, the length and width are not critical.

For measurements with H field, a single thickness (1/16 inch) unclad sample was located $\lambda/4$ from the end of a coaxial line (Fig. 6a) or circular waveguide (Fig. 6b). The sources of errors and their magnitudes are listed. Stacking samples improves the sensitivity for measuring small losses. For accurate measure-

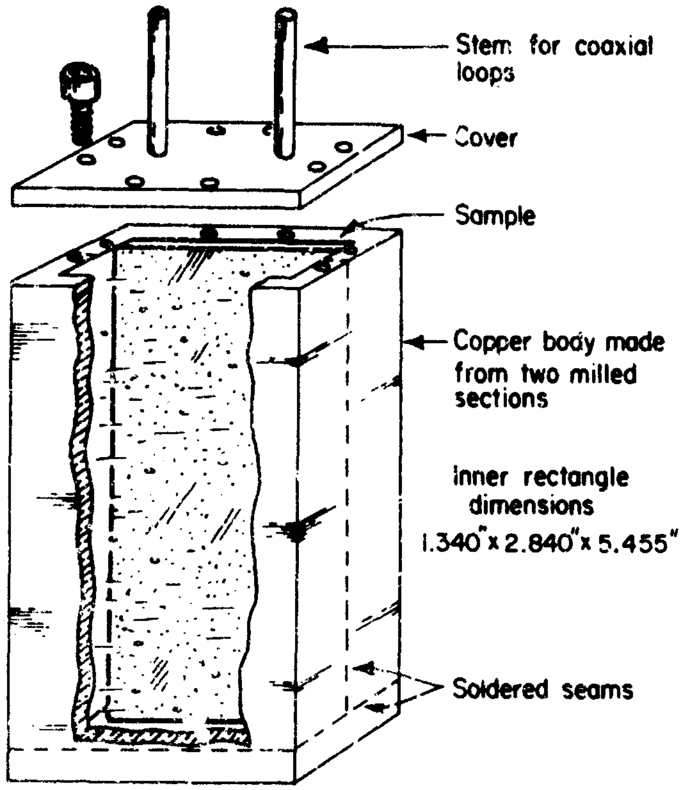
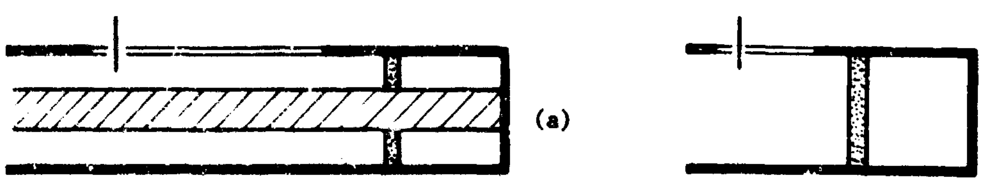


Fig. 5.

Rectangular cavity for microwave measurement on sheet using liquid displacement.



At 3 GHz:	% error κ	At 8.5 GHz; TE11	
Instrument repeatability 10 μ	.38	Instrument repeatability 5 μ	.11
1 mil uncertainty in clearance	.78	1 mil uncertainty in clearance	.06
1/2 mil " in thickness	.80	1/2 mil " in thickness	.80
	1.96		.97
tan δ sensitivity	.00015	tan δ sensitivity	.00015

Fig. 6. Standing-wave method with thin sample, located a quarter wavelength from end of line: (a) Coaxial line; (b) circular hollow waveguide TE_{11} mode.

ments appropriate density corrections are used. Liquid immersion has been proposed but not used here.

In measurements on another glass-Teflon material (Duroid) data with both ⊥ and ∥ fields were required as a function of temperature for 1-inch thick stock. For these measurements, a thick-wall (0.81-inch) circular cavity (Fig. 7) was made of copper. Two disks of 1-3/8 inch diameter were press-fitted into the cavity. An oversized copper plunger was cooled in liquid nitrogen and then pressed into the die. The dielectric-filled cavity thus formed was operated in the TM_{010} mode for E ⊥ measurements and in the TE_{111} mode for E ∥. As the material was heated,

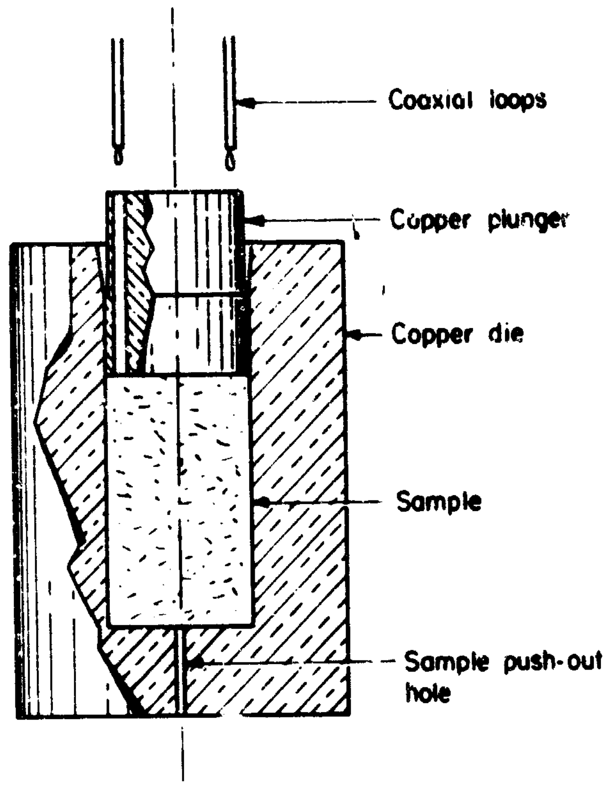


Fig. 7.

Thick-wall copper cavity for measurements or thick anisotropic laminates.

thermal expansion moved the plunger. This motion was monitored and thermal expansion of the copper was used in calculating the cavity dimensions for each temperature. The thermal expansion was large, and the sample remained 15% thicker after the run. In our knowledge, the precision and temperature range of this run are unique for this material.

COMPUTATIONS IN SPECTRUM ANALYSIS

The current trend for computers to program and control measurement procedure, to compute results and analyze them in terms of time or frequency has not yet led to completely automated dielectric spectroscopy. For the present we use the IBM 360 to compute values of dielectric constant and loss from instrument readings and to analyze frequency response.

Computation of κ', κ''

As an example of this first use we consider the calculation of dielectric constant and loss of a liquid contained as shown in Fig. 8 and measured by the standing-wave method in coaxial line (Program 1, Appendix). The sample holder is designed so that the region below the sample is $\lambda/4$ long. Sample-out data are AN, the node, and ΔXA the node width and wavelength λ. Sample-in data are SN, the node, and ΔXS the node width. The basic transmission-line equations give boundary impedances (Z_{B1}, Z_{B2},...) in terms of intrinsic-line constants (ZO_n γ_n) and line

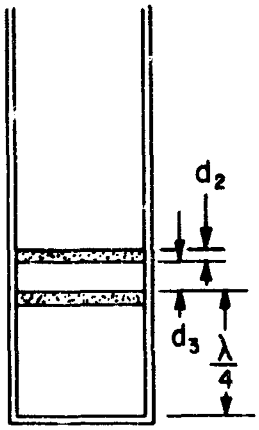


Fig. 8. Construction of sample holder section for high-loss liquids.

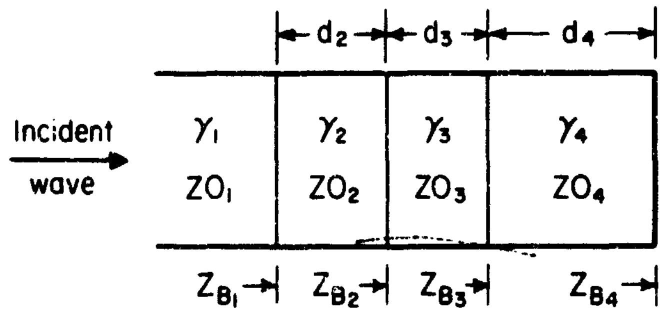


Fig. 9. Terminology for sections in liquid sample holder.

length d_n (Fig. 8). For Fig. 9 the general formulation for TE or TEM waves defines

$$\tanh \rho_{Bn} = \frac{Z_{Bn}}{ZO_n}, \quad \tanh \rho_{B(n+1)} \frac{Z_{B(n+1)}}{ZO_{(n+1)}}, \text{ etc.} \tag{4}$$

Then the impedance at a boundary Z_{Bn} is related to the impedance at the next boundary $Z_{B(n+1)}$:

$$\frac{Z_{Bn}}{\tanh[(\gamma d)_{(n+1)} + \rho_{(n+1)}]} = \frac{Z_{B(n+1)}}{\tanh \rho_{(n+1)}} . \tag{5}$$

The experimentally measured quantity is $\tanh \rho_{B1}$:

$$\tanh \rho_{B1} = \frac{E - j \tan 2\pi X_o/\lambda}{1 - j E \tan 2\pi X_o/\lambda} = \frac{X - jY}{1 - jXY} \equiv \frac{X - Z1}{1 - Z1X} = \frac{Z2}{Z3} = Z4, \tag{6}$$

where E, the inverse standing-wave ratio,

$$= \frac{\sin \pi\Delta X/\lambda}{(1 - \cos^2 \pi\Delta X/\lambda)^{1/2}} \equiv X, \tag{7}$$

and X_o is the distance from the first minimum to B1. In the above and the following equations the $\equiv$ sign separates computer program terminology on the right from previous notation:

$$\tanh \rho_{B2} = \frac{Z_{B2} \tanh (\gamma_2 d_2 + \rho_{B2})}{Z_{B1}} , \tag{8}$$

$$= \frac{\tanh \rho_{B1} - \frac{ZO_2}{ZO_1} \tanh \gamma_2 d_2}{\frac{ZO_2}{ZO_1} - \tanh \gamma_2 d_2 \cdot \tanh \rho_{B1}} . \tag{9}$$

Substituting γ_1/γ_2 for ZO_2/ZO_1,

$$\frac{ZO_2}{ZO_1} \tanh \rho_{B2} = \frac{\tanh \rho_{B1} - \frac{\gamma_1}{\gamma_2} \tanh \rho_2 d_2}{1 - \frac{\gamma_2}{\gamma_1} \tanh \gamma_2 d_2 \tanh \rho_{B1}} . \tag{10}$$

Neglecting losses in Section 2, the right-hand side reduces to

$$\frac{\tanh \rho_{B1} - j(1/\sqrt{\kappa_2'}) \tan(2\pi d_2 \kappa_2'/\lambda)}{1 - j \tanh \rho_{B1} \cdot \kappa_2' \tan(2\pi d_2 \kappa_2'/\lambda)} \equiv \tag{11}$$

$$\frac{Z4 + j\ K1}{1 + jK2 \cdot Z4} = \frac{Z6}{Z8} = \frac{1}{Z9} . \tag{12}$$

With Section 4 a quarter wavelength with negligible losses:

$$Z_{B2} = ZO_3 \coth \gamma_3 d_3 = ZO_2 \tanh \rho_{B2} . \tag{13}$$

Substituting the right-hand side from Eq. 10,

$$ZO_1 \frac{\tanh \gamma_3 d_3}{ZO_3} = Z9; \tag{14}$$

then

$$\gamma_3 d_3 \tanh \gamma_3 d_3 = \gamma_1 d_3 Z9 = j \frac{2\pi d_3}{\lambda} Z9 \equiv \frac{Z9}{K3} = Z11. \tag{15}$$

Assuming that $\gamma_3 d_3$ is small (<1 radian) and substituing u for $\gamma_3 d_3$, we get

$$u \tanh u \cong u^2 - \frac{u^4}{3} = Z11 . \tag{16}$$

Solving for u in terms of Z11,

$$u = [Z11 - \frac{1}{3} (Z11)^2]^{1/2} \equiv Z12SQ. \tag{17}$$

The complex dielectric constant at this point in the program would be

$$\kappa' - j\kappa'' = (Z12SQ \cdot K3)^2 . \tag{18}$$

Instead, the complex parts of u (A,B) are varied in steps until the equation

$$Z14 = u \tanh u = Z11 \qquad (19)$$

is nearly satisfied. The final steps are 0.001% in both A and B. Line 39 defines the error. First B(DO 600), then A(DO 700), is varied. The final print-out lists sample node and ΔX, the dielectric constant K1, the loss factor K2, the loss tangent TAN, and the two complex numbers Z11 and Z14 so the degree of matching can be confirmed. The total cost of calculating 68 data sets at $2.09 per minute of calculation was $1.47. Although the approximation of Eq. 16 is not good for samples longer than one radian, the iteration part of the program extends the range to at least 1.4 radians. For values greater than π/2, an underflow develops and stops the program.

A modification of the program (Program II, Apendix) uses arrays of node shifts (DN) and DX values; thus charts such as Fig. 10 can be prepared to any desired accuracy to eliminate the need of further use of the computer for a particular sample holder. In principle the iteration procedure of these programs can be used to refine other calculations for any length of sample. Previously published computation procedures[3] have been restricted in the upper limit of loss tangent.

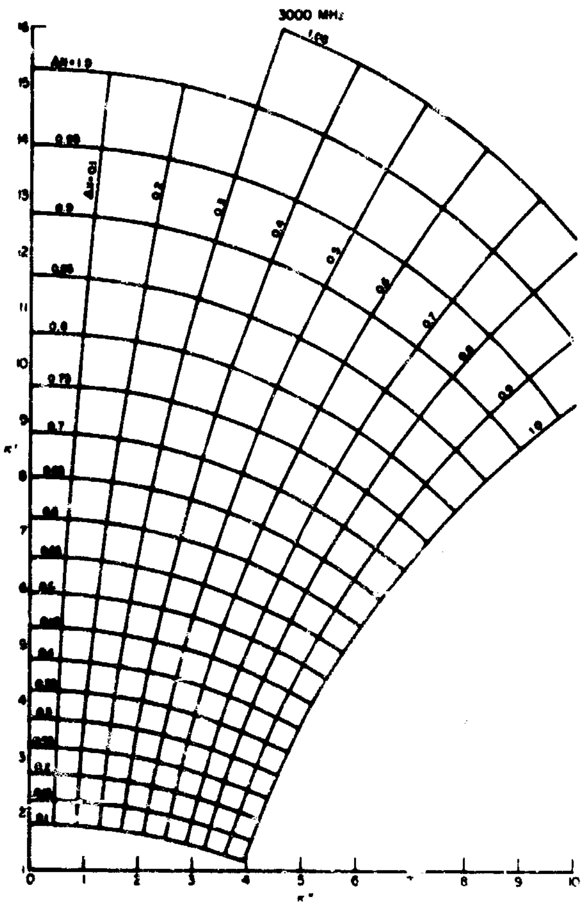


Fig. 10. Chart for finding κ', κ" in terms of node shift ΔN and node width ΔX.

Spectrum Analysis

In our frequency range the fundamental problem of dielectric analysis is to determine from the wide-band frequency response the number and type of subspectra. One approach in analysis is to represent the total spectrum as the sum of subspectra, each having a single relaxation time. Mathematically the composite spectrum is represented as the sum of its components:

$$\kappa'(\omega) = \kappa_\infty + \frac{\Delta\kappa_1}{1 + \omega^2\tau_1^2} + \cdots + \frac{\Delta\kappa_n}{1 + \omega^2\tau_n^2} \qquad (20)$$

and

$$\kappa''(\omega) = \frac{\Delta\kappa_1}{1 + \omega^2\tau_1^2}\,\omega\tau_1 + \cdots + \frac{\Delta\kappa_n}{1 + \omega^2\tau_n^2}\,\omega\tau_n + \frac{\sigma}{\omega\epsilon_o}\,, \qquad (21)$$

where κ_∞ is the high-frequency (near infrared) dielectric constant, σ is the d-c conductivity $(\text{ohm-cm})^{-1}$, n is the number of relaxators, ε_o is the dielectric constant of vacuum (fds/cm).

The purpose of Program III (Appendix), conceived and first executed by Dr. D. B. Knoll*) of this laboratory, is to find the number of components and compare the composite spectrum with the measured values. The initial portion of the program (to line 29) accepts a number (H) of capacitance and loss readings from a capacitance bridge and a second number (L) of readings from a low-frequency bridge. The parameters κ'(K1), κ''(K2), $\omega\kappa''$(K2W), κ''/ω(K2dW) are computed for each measurement frequency.

The arrays of data are scanned (lines 31-83) to determine if measurement errors exist. Three criteria are involved in starting from the high frequency end for any combination of relaxators as in Eqs. 20 and 21:

$$1.\quad \omega\kappa''(I) > \omega\kappa''(I+1), \tag{22}$$

$$2.\quad \kappa'(I) < \kappa'(I+1), \tag{23}$$

$$3.\quad \frac{\kappa'(I+1) - \kappa' I}{\omega\kappa'' I - \kappa''(I+1)} = \tau > 0. \tag{24}$$

Print-out statements 42, 48, 56, 61, 71, 82 advise users of errors or equalities.

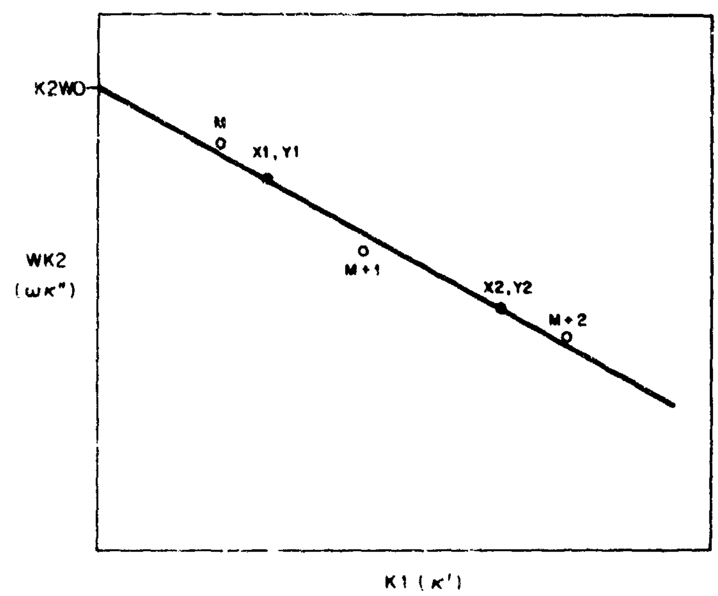


Fig. 11.
Terminology for initial line fit to three experimental points.

The Subroutine LINE fits a line to three successive experimental points according to Fig. 11.

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*) Present address: Texas Instruments Corporation, Materials Research Group, Dallas, Texas.

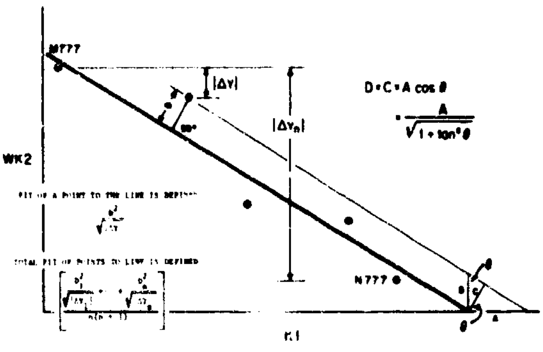

Fig. 12. Terminology for fit between line and experimental points.

Subroutine EROS is concerned with fit of the line to the points. The distance D(I) from a point (I) to line is shown in Fig. 12. In the figure $\frac{A}{B} = \tau \tan \theta$; $C = A \cos \theta = A/(1 + \tan^2\theta)^{1/2}$:

$$D(I) = C = \frac{\kappa'(I) + \tau\omega\kappa''(I) - \tau\kappa''\omega(0)}{(1 + \tau^2)^{1/2}} , \tag{25}$$

$$SE = [D(I)]^2/(|\Delta Y|)^{1/2}, \tag{26}$$

$$ERRER = \left[\frac{[D(I)]^2}{(|\Delta Y_1|)^{1/2}} + \frac{[D(I+1)]^2}{(|\Delta Y_2|)^{1/2}}\right]^{1/2} . \tag{27}$$

More points are added to the array until ERRER increases. Subsequently both the slope (line 107) and high-frequency termination (line 116) are varied in steps to improve the fit. The final slope (line 141) determines τ_1. The first calculation of κ_∞ follows using the high-frequency values of κ'. From (20),

$$\kappa'(I) = \kappa_\infty + \frac{\Delta\kappa_1}{1 + [\omega(I)\tau_1]^2} , \tag{28}$$

$$\kappa'(I+1) = \kappa_\infty + \frac{\Delta\kappa_1}{1 + [\omega(I+1)\tau_1]^2} . \tag{29}$$

Eliminating ΔK_1 between Eq. 28 and 29 and solving for κ_∞ (line 155) yields

$$\kappa_\infty = \frac{\kappa'(I)\{1 + [\omega(I)\tau_1]^2\} - \kappa'(I+1)\{1 + [\omega(I+1)\tau_1]^2\}}{[\omega(I)\tau_1]^2 - [\omega(I+1)\tau_1]^2}. \tag{30}$$

Solving for K_1 yields (line 147):

$$\Delta K_1 = \frac{\kappa'(I+1) - \kappa'(I)}{\frac{1}{1 + [\omega(I+1)\tau_1]^2} + \frac{1}{1 + [\omega(I)\tau_1]^2}} . \tag{31}$$

The high-frequency residue is regarded as the low-frequency contribution of a relaxator far outside the measuring range. The change in κ' with frequency in the measurement range is negligible, but the change in loss is obtained from the measured increment in κ'' for two frequencies minus the same increment due to the first spectrum component. Neither the time constant nor ΔK value of the off-range spectrum is known but their product is (line 162):

$$\Delta\kappa_h\tau_h = \frac{(\omega\kappa'')I - (\omega\kappa'')I{+}1 - \Delta K_1\tau_1 \left[\frac{\omega_I^2}{1 + (\omega_I\tau_1)^2} - \frac{\omega_{I+1}^2}{1 + (\omega_{I+1}\tau_1)^2}\right]}{\omega_I^2 - \omega_{I+1}^2} . \tag{32}$$

This high-frequency residue (HC) has a low-frequency counterpart (LC) at the other end of the measurement range. Here again neither the ΔK nor τ of an out-of-range spectrum can be found but their ratio $\Delta K_\ell/\tau_\ell$ appears with the same effect as a d-c conductance component. From two successive values of κ''/ω this component can be computed (line 173):

$$\frac{\Delta K_\ell}{\tau_\ell} = \frac{\left(\frac{\kappa''}{\omega}\right)_I - \left(\frac{\kappa''}{\omega}\right)_{I+1} - \Delta K_1\tau_1 \left[\frac{1}{1 + (\omega_I\tau_1)^2} - \frac{1}{1 + (\omega_{I+1}\tau_1)^2}\right]}{\frac{1}{\omega_I^2} - \frac{1}{\omega_{I+1}^2}} . \tag{33}$$

If no data have been taken at frequencies $< \frac{1}{2\pi\tau_1}$, the analysis is complete in that the number and magnitude of the relevant components have been determined. If lower frequency measurements exist, the contribution of HC and relaxator 1 are subtracted from each data point. These are now treated as new experimental points and the line fitting procedure is called again (205).

The approximate values of all unknowns LC, ΔK_n, $\tau_n \cdots \Delta K_1$, τ_1, HC, κ_∞ are refined in steps in subroutine ERROR to achieve the best overall fit to the experimental points. Since the capacitance errors are usually less than conductance errors in our measurements, differences in the κ' fit are multiplied by 2, then added to differences in the κ'' fit to establish the total error criteria (lines 16 to 18).

Obviously many modifications and uses of the program are possible. They are used to study the effect on measurement errors, to help decide the possibilities of hidden spectra and distributed time constants. There is a basic resolution problem in fitting a smooth curve to a series of experimental points with scatter that does not occur with "ideal" data. This makes the results of any curve-fitting program, such as ERROR, have some degree of dependence on the magnitude of the starting components. The difficulties arise because the function relating the total error to the magnitude of one-component is not a smooth function. In the future more automatic measurements will be made with decreased frequency separation. Then it may be feasible to smooth experimental errors before analysis.

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1. Semiannual Progress Report, April-September, 1967, Contract F33615-67C-1612.
2. See, for example, Standard D-1531, Carl Andeen et al., American Society for Testing Materials.
3. B. C. Gray, "Programming for Dielectric Constants," Electronic Industries, p. 106, August 1961; P. H. G[illegible] and B. A. Schoomer, Jr., "A Speedy Method of Computing Dielectric Properties," ibid., September 1963, p. 90.

FORTRAN IV G LEVEL 1, MOD 3 MAIN DATE = 70077 02/13/10

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              REAL*8 K1,K2,K3,Y,XE,AN,SN,LW,DX,DS,DA,X,A,B,A2,B2,Z14RE,Z14IM,
             2BOLD,Z14IOD,Z14ROD,ERROR1,EROLD,AOLD,AIM,RE,TAM,Z11RE,Z11IM,COSINE
              COMPLEX*16 Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11,Z12,Z13,Z14R,Z14I,
             2Z14,Z12NEW,Z12RE,Z12IM,Z12SQ
              REAL STEP(4)/0.01,0.001,0.0001,0.00001/,F(2)/1.,-1./
              DIMENSION DS(200),SN(200),DATE(18)
              NAMELIST/IN/DS,SN,NX/CONST/DA,AN,XE,K1,K2,K3,LW/OUT/K1,K2,K3,LW
          200 FORMAT(1X,18A4)
           77 READ(5,200,END=88) DATE
          201 FORMAT(1H1,20X,18A4)
              WRITE(6,201) DATE
              READ(5,IN)
              READ(5,CONST)
          100 FORMAT(1H0,5X,2HNS,10X,2HDS,11X,2HK1,11X,2HK2,12X,3HTAN,20X,3HZ11,
             231X,3HZ14//)
              WRITE(6,100)
              DO 10 I=1,NX
              Y=6.2832*(XE-AN+SN(I))/LW
              DX=DS(I)-DA
              COSINE=DCOS(3.1416*DX/LW)**2
              X=DSIN(3.1416*DX/LW)/DSQRT(2.-COSINE)
              Z1=(0.,1.)*DTAN(Y)
              Z2=X-Z1
              Z3=1.-Z1*X
              Z4=Z2/Z3
              Z5=(0.,1.)*K1
              Z6=Z4+Z5
              Z7=(0.,1.)*K2
              Z8=1.+Z4*Z7
              Z9=Z8/Z6
              Z10=(0.,1.)/K3
              Z11=Z10*Z9
              Z11RE=REAL(Z11)
              Z11IM=AIMAG(Z11)
              Z12SQ=CDSQRT(Z11+(1./3.)*Z11**2)
              A=REAL(Z12SQ)
              B=AIMAG(Z12SQ)
              A2=DTANH(A)*(1.+DTAN(B)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
              B2=DTAN(B)*(1.-DTANH(A)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
              Z14RE=A*A2-B*B2
              Z14IM=A*B2+B*A2
              ERROR1=DABS((Z14RE-Z11RE)/Z11RE)+DABS((Z14IM-Z11IM)/Z11IM)
              DO 400 K=1,4
              DO 600 J=1,2
          401 BOLD=B
              Z14IOD=Z14IM
              Z14ROD=Z14RE
              EROLD=ERROR1
              B=B*(1.+STEP(K)*F(J))
              A2=DTANH(A)*(1.+DTAN(B)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
              B2=DTAN(B)*(1.-DTANH(A)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
              Z14RE=A*A2-B*B2
              Z14IM=A*B2+B*A2
              ERROR1=DABS((Z14RE-Z11RE)/Z11RE)+DABS((Z14IM-Z11IM)/Z11IM)
              IF(ERROR1.LE.EROLD) GO TO 401
              Z14IM=Z14IOD
              Z14RE=Z14ROD
              B=BOLD
              ERROR1=EROLD
          600 CONTINUE
              DO 700 J=1,2
          402 AOLD=A
              Z14ROD=Z14RE
              Z14IOD=Z14IM
              EROLD=ERROR1
              A=A*(1.+STEP(K)*F(J))
              A2=DTANH(A)*(1.+DTAN(B)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
              B2=DTAN(B)*(1.-DTANH(A)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
              Z14RE=A*A2-B*B2
              Z14IM=A*B2+B*A2
              ERROR1=DABS((Z14RE-Z11RE)/Z11RE)+DABS((Z14IM-Z11IM)/Z11IM)
```

PROGRAM I (cont.)

```
            IF(ERROR1.LE.EROLD) GO TO 400
            Z14RE=Z14ROD
            Z14IM=Z14IOD
            A=AOLD
            ERROR1=EROLD
        700 CONTINUE
        400 CONTINUE
            Z12RE=(1.,0.)*A
            Z12IM=(0.,1.)*B
            Z12NEW=(Z12RE+Z12IM)**2
            Z13=-Z12NEW*K3**2
            Z14R=(1.,0.)*Z14RE
            Z14I=(0.,1.)*Z14IM
            Z14=Z14R+Z14I
            AIM=-AIMAG(Z13)
            RE=REAL(Z13)
            TAM=AIM/RE
        300 FORMAT(2X,F8.4,5X,F7.4,5X,F9.3,5X,F9.3,5X,F8.4,5X,E13.6,3X,E13.6,
           25X,E13.6,3X,E13.6)
            WRITE(6,300) SN(I),DS(I),RE,AIM,TAM,Z11,Z14
         10 CONTINUE
            WRITE(6,OUT)
            GO TO 77
         88 CALL EXIT
            END
```

TYPICAL PRINT-OUT

NS	DS	K1	K2	TAN
9.5316	0.1478	75.084	13.954	0.1859
9.5280	0.1973	74.785	19.207	0.2568
9.5191	0.2270	75.403	24.938	0.3307
9.5381	0.2686	68.876	28.039	0.4071

Z11		Z14	
-0.976104D-01	0.187611D-01	-0.976107D-01	0.187611D-01
-0.971049D-01	0.258146D-01	-0.971058D-01	0.258145D-01
-0.977869D-01	0.335343D-01	-0.977862D-01	0.335342D-01
-0.889420D-01	0.374858D-01	-0.889429D-01	0.374857D-01

PROGRAM II

```
ORTRAN IV G LEVEL 1, MOD 3              MAIN              DATE = 70103              20/37/02

            REAL*8 K1,K2,K3,Y,XE,LW,DX,DN,D,X,A,B,A2,B2,Z14RE,Z14IM,COSINE,
           2BOLD,Z14IOD,Z14ROD,ERROR1,EROLD,AOLD,AIM,RE,TAM,Z11RE,Z11IM
            COMPLEX*16 Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11,Z12,Z13,Z14R,Z14I,
           2Z14,Z12NEW,Z12RE,Z12IM,Z12SQ,Z2A
            COMPLEX*16 ZONE,ZONEI
            REAL STEP(4)/0.01,0.001,0.0001,0.00001/,F(2)/1.,-1./
            DIMENSION DATE(18),DN(9)
            NAMELIST/IN/DN,XE,LW,ND,NX,K1,K2,K3/OUT/K1,K2,K3,LW,X,Y,Z1,Z2,Z3,
           2Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11
            ZONE=(1.,0.)
            ZONEI=(0.,1.)
        200 FORMAT(1X,18A4)
         77 READ(5,200,END=88) DATE
        201 FORMAT(1H1,20X,18A4)
            WRITE(6,201) DATE
            READ(5,IN)
        100 FORMAT(1H0,5X,2HDX,10X,2HDN,11X,2HK1,11X,2HK2,12X,3HTAN,20X,3HZ11,
           231X,3HZ14//)
            WRITE(6,100)
            DX=0.
            D=0.01
            DO 500 L=1,NX
            DX=DX+D
            IF(DX.EQ.0.) GO TO 500
            COSINE=DCOS(3.1416*DX/LW)**2
            X=DSIN(3.1416*DX/LW)/DSQRT(2.-COSINE)
        800 FORMAT(2X,F7.4)
```

```
      WRITE(6,800) DX
      DO 10 I=1,ND
      IF(DN(I).EQ.0.) GO TO 10
      Y=6.2832*(XE-DN(I))/LW
      Z1= ZONEI * DTAN(Y)
      Z2=X-Z1
      Z2A=Z1*X
      Z3=ZONE-Z2A
      Z4=Z2/Z3
      Z5=ZONEI*K1
      Z6=Z4+Z5
      Z7=ZONEI*K2
      Z8=ZONE+Z4*Z7
      Z9=Z8/Z6
      Z10=ZONEI/K3
      Z11=Z10*Z9
      Z11RE=REAL(Z11)
      Z11IM=AIMAG(Z11)
      Z12SQ=CDSQRT(Z11+(1./3.)*Z11**2)
      A=REAL(Z12SQ)
      B=AIMAG(Z12SQ)
      A2=DTANH(A)*(1.+DTAN(B)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
      B2=DTAN(B)*(1.-DTANH(A)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
      Z14RE=A*A2-B*B2
      Z14IM=A*B2+B*A2
      ERROR1=DABS((Z14RE-Z11RE)/Z11RE)+DABS((Z14IM-Z11IM)/Z11IM)
      DO 400 K=1,4
      DO 600 J=1,2
  401 BOLD=B
      Z14IOD=Z14IM
      Z14ROD=Z14RE
      EROLD=ERROR1
      B=B*(1.+STEP(K)*F(J))
      A2=DTANH(A)*(1.+DTAN(B)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
      B2=DTAN(B)*(1.-DTANH(A)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
      Z14RE=A*A2-B*B2
      Z14IM=A*B2+B*A2
      ERROR1=DABS((Z14RE-Z11RE)/Z11RE)+DABS((Z14IM-Z11IM)/Z11IM)
      IF(ERROR1.LE.EROLD) GO TO 401
      Z14IM=Z14IOD
      Z14RE=Z14ROD
      B=BOLD
      ERROR1=EROLD
  600 CONTINUE
      DO 700 J=1,2
  402 AOLD=A
      Z14ROD=Z14RE
      Z14IOD=Z14IM
      EROLD=ERROR1
      A=A*(1.+STEP(K)*F(J))
      A2=DTANH(A)*(1.+DTAN(B)**2)/(1.+DTANH(A)**2*DTAN(B)** 2)
      B2=DTAN(B)*(1.-DTANH(A)**2)/(1.+DTANH(A)**2*DTAN(B)**2)
      Z14RE=A*A2-B*B2
      Z14IM=A*B2+B*A2
      ERROR1=DABS((Z14RE-Z11RE)/Z11RE)+DABS((Z14IM-Z11IM)/Z11IM)
      IF(ERROR1.LE.EROLD) GO TO 402
      Z14RE=Z14ROD
      Z14IM=Z14IOD
      A=AOLD
      ERROR1=EROLD
  700 CONTINUE
  400 CONTINUE
      Z12RE=ZONE*A
      Z12IM=ZONEI*B
      Z12NEW=(Z12RE+Z12IM)**2
      Z13=-Z12NEW*K3**2
      Z14R=ZONE*Z14RE
      Z14I=ZONEI*Z14IM
      Z14=Z14R+Z14I
```

PROGRAM II (CONT.)

```
      AIM=-AIMAG(Z13)
      RE=REAL(Z13)
      TAN=AIM/RE
  300 FORMAT(14X,F8.4,5X,F9.3,5X,F9.3,5X,F8.4,5X,E13.6,3X,E13.6,
     25X,E13.6,3X,E13.6)
      WRITE(6,300) DN(I),RE,AIM,TAN,Z11,Z14
   10 CONTINUE
  500 CONTINUE
      WRITE(6,CUT)
      GO TO 77
   88 CALL EXIT
      END
```

PRINT-OUT

DX	DN	K1	K2	TAN
0.0100				
	1.0000	14.384	0.128	0.0089
	1.0500	15.728	0.142	0.0090
	1.1000	17.231	0.159	0.0092
	1.1500	18.923	0.180	0.0095
	1.2000	20.845	0.206	0.0099
	1.2500	23.054	0.237	0.0103
	1.3000	25.621	0.278	0.0108
	1.3500	28.643	0.329	0.0115
	1.4000	32.140	0.398	0.0124
0.0200				
	1.0000	14.382	0.255	0.0177
	1.0500	15.726	0.284	0.0180
	1.1000	17.228	0.318	0.0185
	1.1500	18.919	0.360	0.0190
	1.2000	20.841	0.411	0.0197
	1.2500	23.048	0.475	0.0206
	1.3000	25.613	0.555	0.0217
	1.3500	28.634	0.658	0.0230
	1.4000	32.099	0.797	0.0248

Z11		Z14	
-0.486634D 00	0.505513D-02	-0.486633D 00	0.505514D-02
-0.540838D 00	0.581521D-02	-0.540827D 00	0.581521D-02
-0.603588D 00	0.677495D-02	-0.603592D 00	0.677497D-02
-0.677235D 00	0.801064D-02	-0.677236D 00	0.801065D-02
-0.765076D 00	0.963883D-02	-0.765076D 00	0.963882D-02
-0.871886D 00	0.118448D-01	-0.871887D 00	0.118449D-01
-0.100484D 01	0.149379D-01	-0.100486D 01	0.149378D-01
-0.117528D 01	0.194655D-01	-0.117530D 01	0.194655D-01
-0.140214D 01	0.264735D-01	-0.139439D 01	0.264736D-01
-0.486532D 00	0.101087D-01	-0.486524D 00	0.101097D-01
-0.540711D 00	0.116283D-01	-0.540709D 00	0.116283D-01
-0.603426D 00	0.135470D-01	-0.603419D 00	0.135470D-01
-0.677023D 00	0.160172D-01	-0.677033D 00	0.160172D-01
-0.764794D 00	0.192718D-01	-0.764778D 00	0.192717D-01
-0.871498D 00	0.236808D-01	-0.871482D 00	0.236808D-01
-0.100429D 01	0.298615D-01	-0.100427D 01	0.298615D-01
-0.117445D 01	0.389066D-01	-0.117445D 01	0.389065D-01
-0.140081D 01	0.529018D-01	-0.139109D 01	0.529020D-01

PROGRAM III

```
FORTRAN IV G LEVEL 1, MOD 3              MAIN              DATE = 70098              13/12/07

              IMPLICIT REAL (K)
              DIMENSION FR(50),K1EX(50),K2EX(50),DATE(18),G(50),C(50),N(50),
             2F(50),GS(50),R(50),M(50),K1EXP(50),K2EXP(50),K1S(50),K2S(50),
             2X(50),XI(50),K1(50),K2(50),W(50),K2W(50),K2DW(50),B(50),PX(50)
              INTEGER H,Z,Z123
              REAL STEP(4)/0.1,0.02,0.005,0.001/
              REAL STEPP(8)/0.01,-0.01,0.004,-0.004,0.0015,-0.0015,0.0006,
             2-0.0006/
              NAMELIST/IN/CO,C,G,F,N,FR,R,M,H,L/TA/TAU/M7/M777/M9/M1/L9/L1/LE/
             2L1E
       10     READ(5,200,END=350)DATE
      200     FORMAT(1X,18A4)
              READ(5,IN)
              WRITE(6,201)DATE
      201     FORMAT(1H1///20X,18A4//)
              IF(H.EQ.0) GO TO 41
              DO 40 I=1,H
              GS(I)=G(I)*R(I)*M(I)/(10.*(1.+(R(I)/2000.)+G(I)*(1.E6+1000.*R(I)))
             6)
       40     CONTINUE
              IF(L.EQ.0) GO TO 38
       41     DO 50 I=1,L
              A=1.0/(1.0+(F(I)/1.01)*(1.0-F(I))*1.0E6*G(H+I))
              GS(H+I)=(G(H+I)*A*(N(I)+F(I)/1.01)*(1.0+1.0F4*A*G(H+I)*(N(I)+F(I)/
             21.01)))/(1.0+1.E4*A*G(H+I)*(N(I)+F(I)/1.01)-100.0*A*G(H+I)*(N(I)+
             2F(I)/1.01)**2)
       50     CONTINUE
       38     MN=H+L
              DO 222 I=1,MN
              K1EX(I)=C(I)/CO
              K2EX(I)=GS(I)/(6.2832*FR(I)*CO*1.E-12)
              K1(I)=K1EX(I)
              K2(I)=K2EX(I)
              W(I)=FR(I)*6.2832
              K2W(I)=K2(I)*W(I)
              K2DW(I)=K2(I)/W(I)
      222     CONTINUE
              Z123=1
              L1=MN
      413     Z=3
              MEXIT=0
              M111=L1-1
              DO 224 I=Z123,M111
              M750=I
              IF(K2W(I).EQ.K2W(I+1)) GO TO 25
              GO TO 35
       25     K2W(I+1)=1.1*(K2W(I))
       20     FORMAT(1X,'FOUND K2W(I+1)=K2W(I) FIX UP TAKEN K2W(I+1)=1.1*K2W(I)
             2')
              WRITE(6,20)
       35     TAU=(K1(I+1)-K1(I))/(K2W(I)-K2W(I+1))
              IF(0.LT.TAU) GO TO 225
      224     CONTINUE
              GO TO 388
      225     M1=M750
              WRITE(6,M9)
              M222=L1-M1
              DO 260 I=1,M222
              J=L1-I
              IF(K2W(J).EQ.K2W(J+1)) GO TO 26
              GO TO 36
       26     K2W(J+1)=1.1*(K2W(J))
       21     FORMAT(1X,'FOUND K2W(J+1)=K2W(J) FIX UP TAKEN K2W(J+1)=1.1*K2W(J)
             2')
              WRITE(6,21)
       36     TAU=(K1(J+1)-K1(J))/(K2W(J)-K2W(J+1))
              IF(0.0.LT.TAU) GO TO 265
      260     CONTINUE
      265     L1E=J+1
```

PROGRAM III (CONT.)

```
      WRITE(6,LE)
      L1=L1E
      L1D=L1E-1
      DO 650 I=M1,L1D
      CHECK=K1(I+1)-K1(I)
      IF(0.0.LT.CHECK) GO TO 650
      IF(K2W(I).EQ.K2W(I+1)) GO TO 27
      GO TO 37
   27 K2W(I+1)=1.1*(K2W(I))
   22 FORMAT(1X,'FOUND K2W(M+1)=K2W(M) FIX UP TAKEN K2W(M+1)=1.1*K2W(M)
     2')
      WRITE(6,22)
   37 TAU=(K1(I+1)-K1(I))/(K2W(I)-K2W(I+1))
      IF(0.0.LT.TAU) GO TO 650
      L1C=I+1
      DO 651 J=L1C,L1E
      CHECK=(K1(J)-K1(I))/K1(I)
      IF(CHECK.LT.(-0.01)) GO TO 652
  651 CONTINUE
  650 CONTINUE
      GO TO 251
  652 L1=L1C-1
      WRITE(6,L9)
  251 M777=M1
      K2WO=0.0
  777 CALL LINE (M777,K1,K2W,TAU,K2WO,L1,MN)
      IF(Z.EQ.3) GO TO 304
      IF(TPREVS.LT.TAU) GO TO 304
  788 M777=M777+1
      M777P=M777+2
      IF(M777P.GE.L1) GO TO 888
      WRITE(6,TA)
      GO TO 777
  304 IF(TAU.LE.0.0) GO TO 788
      M777P=M777+2
      IF(L1.LE.M777P) GO TO 290
  991 N777=M777+2
      ERRER=0.0
      CALL EROS (M777,N777,TAU,K2WO,K1,K2W,ERRER)
  229 IF(N777.EQ.L1) GO TO 290
  227 ERRER1=ERRER
      N777=N777+1
      ERRER=0.0
      CALL ERCS (M777,N777,TAU,K2WO,K1,K2W,ERRER)
      IF(ERRER.LE.ERRER1) GO TO 229
      TAUOLD=TAU
      K2WOLD=K2WO
      DO 400 J=1,8
  228 ERRERT=ERRER
      TAUT=TAU
      TAU=TAUT*(1.+STEPP(J))
      ERRER=0.0
      CALL EROS (M777,N777,TAU,K2WO,K1,K2W,ERRER)
      IF(ERRER.LE.ERRER1) GO TO 229
      IF(ERRER.LT.ERRERT) GO TO 228
      TAU=TAUT
      ERRER=ERRERT
  301 ERRERN=ERRER
      K2WON=K2WO
      K2WO=K2WON-K2W(M777)*STEPP(J)*0.1
      ERRER=0.0
      CALL ERCS (M777,N777,TAU,K2WO,K1,K2W,ERRER)
      IF(ERRER.LE.ERRER1) GO TO 229
      IF(ERRER.LT.ERRERN) GO TO 301
      K2WO=K2WON
      ERRER=ERRERN
  400 CONTINUE
      TAU=TAUOLD
      IF(Z.EQ.3) GO TO 401
      IF(TPREVS.LT.TAU) GO TO 401
  402 M777=N777
      GO TO 777
  401 K2WO=K2WOLD
```

```
      IF(L1.LE.N777) GO TO 291
      MOLD=M777
      M777=N777
      CALL LINE (M777,K1,K2W,TAU,K2WO,L1,MN)
      IF(TAU.LT.TAUOLD) GO TO 303
      GO TO 678
  303 IF(3.LT.Z) GO TO 304
      M1=M777
      WRITE(6,M9)
      GO TO 304
  678 M777=MOLD
      TAU=TAUOLD
  291 X(Z+1)=TAU
      TPREVS=TAU
      KK=0.0
      N776=N777-1
      DO 960 I=M777,N776
      B(I)=(K1(I+1)-K1(M777))/(1./(1.+(W(I+1)*TAU)**2)-1./(1.+(W(M777
     2)*TAU)**2))
      KK=KK+B(I)
  960 CONTINUE
      X(Z)=KK/(N777-M777)
      IF(X(Z).LT.0.0) GO TO 402
      IF(3.LT.Z) GO TO 921
      XXKINF=0.0
      DO 910 I=M777,N776
      XKINF=(K1(M777)*(1.+(W(M777)*TAU)**2)-K1(I+1)*(1.+(W(I+1)*TAU)
     2**2))/((W(M777)*TAU)**2-(W(I+1)*TAU)**2)
      XXKINF=XXKINF+XKINF
  910 CONTINUE
      X(1)=XXKINF/(N777-M777)
      XXHC=0.0
      HSTORD=0.0
      DO 920 I=M777,N776
      XHCXHC=((K2W(M777)-K2W(I+1))-B(I)*TAU*(W(M777)**2/(1.+(W(M777)*
     2TAU)**2)-W(I+1)**2/(1.+(W(I+1)*TAU)**2)))/(W(M777)**2-W(I+1)**2)
      IF(XHCXHC.LT.0.0) GO TO 483
      IF(HSTORD.EQ.0.0) GO TO 482
      IF(HSTORD.LT.XHCXHC) GO TO 483
  482 HSTORD=XHCXHC
  483 XXHC=XXHC+XHCXHC
  920 CONTINUE
      X(2)=XXHC/(N777-M777)
  921 XXLC=0.0
      XSTORD=0.0
      DO 922 I=M777,N776
      XLCXLC=(K2DW(M777)-K2DW(I+1)-B(I)*TAU*(1./(1.+(W(M777)*TAU)**2)
     2-1./(1.+(W(I+1)*TAU)**2)))/(1./W(M777)**2-1./W(I+1)**2)
      IF(XLCXLC.LT.0.0) GO TO 481
      IF(XSTORD.EQ.0.0) GO TO 480
      IF(XSTORD.LT.XLCXLC) GO TO 481
  480 XSTORD=XLCXLC
  481 XXLC=XXLC+XLCXLC
  922 CONTINUE
      X(Z+2)=XXLC/(N777-M777)
      IF(MEXIT.EQ.1) GO TO 999
      DO 320 I=M777,L1
      SK1SK1=X(Z)/(1.+(W(I)*TAU)**2)
      IF(3.LT.Z) GO TO 307
      SK1SK1=SK1SK1+X(1)
  307 K1(I)=K1(I)-SK1SK1
      SK2W=X(Z)*W(I)**2*TAU/(1.+(W(I)*TAU)**2)
      K2W(I)=K2W(I)-SK2W
      SK2DW=X(Z)*TAU/(1.+(W(I)*TAU)**2)+X(2)
  322 K2DW(I)=K2DW(I)-SK2DW
  320 CONTINUE
      GO TO 370
  290 MEXIT=1
      N777=L1
      GO TO 291
  370 DO 710 I=M777,L1
      M751=I
```

```
      BBBB=1.0/W(I)
      IF(X(Z+1).LE.BBBB) GO TO 711
  710 CONTINUE
  711 M777=M751
      IF(L1.LT.(M777+1)) GO TO 999
      WRITE(6,M7)
      Z=Z+2
      GO TO 777
  999 NX=Z+2
      IF(0.0.LT.X(NX)) GO TO 731
      X(NX)=XSTORD
  731 IF(0.0.LT.X(2)) GO TO 666
      X(2)=HSTORD
  666 NP=NX-2
      DO 551 J=3,NP,2
      XRE=X(J)
      X(J)=X(J+1)
      X(J+1)=XRE
  551 CONTINUE
      DO 441 I=1,NX
      PX(I)=X(I)
  441 CONTINUE
      X(1)=PX(NX)
      NXC=NX-1
      DO 331 J=1,NXC
      X(J+1)=PX(NX-J)
  331 CONTINUE
      DO 333 I=1,NX
      XI(I)=X(I)
  333 CONTINUE
      MMM=2
      CALL ERROR(NX,M1,K1S,X,K2S,FR,K1EX,K2EX,SUM,K1EXP,K2EXP,L1,SUMK1,
     2SUMK2)
      SUMOLD=SUM
      SUM1=0.
      DO 500 J=1,4
  701 DO 700 L=1,MMM
      SUM2=SUM1
      DO 600 I=1,NX
      XOLD=X(I)
      X(I)=X(I)*(1.+STEP(J))
      CALL ERROR(NX,M1,K1S,X,K2S,FR,K1EX,K2EX,SUM,K1EXP,K2EXP,L1,SUMK1,
     2SUMK2)
      IF(SUM.LT.SUMOLD) GO TO 601
      X(I)=XOLD
      X(I)=X(I)*(1.-STEP(J))
      CALL ERROR(NX,M1,K1S,X,K2S,FR,K1EX,K2EX,SUM,K1EXP,K2EXP,L1,SUMK1,
     2SUMK2)
      IF(SUM.LT.SUMOLD) GO TO 601
      X(I)=XOLD
      SUM1=SUMOLD
      GO TO 600
  601 SUM1=SUM
      SUMOLD=SUM
  600 CONTINUE
  700 CONTINUE
      IF(SUM1.LT.SUM2) GO TO 900
      GO TO 555
  900 MMM=1
      GO TO 701
  555 MMM=1
      SUM1=SUM2
  500 CONTINUE
  507 FORMAT(1H0,13X,8HXINITIAL,5X,9HXCOMPUTED//)
      WRITE(6,507)
  115 FORMAT(1X,2HLC,8X,E12.5,3X,E12.5)
      WRITE(6,115) XI(1),X(1)
      NT=NX-3
      DO 112 I=2,NT,2
  113 FORMAT(1X,7HKS-KINF,3X,E12.5,3X,E12.5)
      WRITE(6,113) XI(I),X(I)
  114 FORMAT(1X,3HTAU,7X,E12.5,3X,E12.5)
```

PROGRAM III (CONT.)

```
          WRITE(6,114) XI(I+1),X(I+1)
      112 CONTINUE
      111 FORMAT(1X,2HHC,9X,E12.5,3X,F12.5)
          WRITE(6,111) XI(NX-1),X(NX-1)
      508 FORMAT(1X,4HKINF,6X,E12.5,3X,E12.5)
          WRITE(6,508) XI(NX),X(NX)
      509 FORMAT(//1H0,5X,2HFR,12X,4HK1EX,13X,3HK1S,12X,4HK2EX,13X,3HK2S,
         211X,6HK1EX %,11X,6HK2EX %//)
          WRITE(6,509)
      510 FORMAT(1X,E12.5,3X,E12.5,3X,E12.5,3X,E12.5,3X,E12.5,3X,F12.5,3X,
         2F12.5)
          WRITE(6,510) (FR(I),K1EX(I),K1S(I),K2EX(I),K2S(I),K1EXP(I),
         2K2EXP(I),I=M1,L1)
      801 FORMAT(73X,5HSUM =,F11.5,5X,F11.5)
          WRITE(6,801) SUMK1,SUMK2
          IF(L1E.EQ.L1) GO TO 10
          Z123=L1+1
          L1=L1E
          GO TO 413
      888 GO TO 10
      350 CALL EXIT
          END
```

TOTAL MEMORY REQUIREMENTS 002F7A BYTES

FORTRAN IV G LEVEL 1, MOD 3 ERROR DATE = 70098 13/12/07

```
          SUBROUTINE ERROR (NX,M1,K1S,X,K2S,FR,K1EX,K2EX,SUM,K1EXP,K2EXP,
         2L1,SUMK1,SUMK2)
          IMPLICIT REAL (K)
          DIMENSION K1S(50),X(50),K2S(50),FR(50),K1EX(50),K2EX(50),
         2K1EXP(50),K2EXP(50)
          NJ=NX-3
          NW=NX-1
          SUM=0.
          SUMK1=0.
          SUMK2=0.
          DO 100 I=M1,L1
          K1S(I)=X(NX)
          K2S(I)=X(NW)*6.2832*FR(I)+X(1)/(6.2832*FR(I))
          DO 101 J=2,NJ,2
          K1S(I)=K1S(I)+X(J)/(1.+(6.2832*FR(I)*X(J+1))**2)
          K2S(I)=K2S(I)+X(J)*6.2832*FR(I)*X(J+1)/(1.+(6.2832*FR(I)*X(J+1))
         2**2)
      101 CONTINUE
          DK1=(K1EX(I)-K1S(I))/K1EX(I)*2
          DK2=(K2EX(I)-K2S(I))/K2EX(I)
          SUM=SUM+ABS(DK1)+ABS(DK2)
          K1EXP(I)=DK1*50.
          K2EXP(I)=DK2*100.
          SUMK1=SUMK1+ABS(K1EXP(I))
          SUMK2=SUMK2+ABS(K2EXP(I))
      100 CONTINUE
          RETURN
          END
```

TOTAL MEMORY REQUIREMENTS 000486 BYTES

FORTRAN IV G LEVEL 1, MOD 3 EROS DATE = 70098 13/12/07

```
          SUBROUTINE EROS (M777,N777,TAU,K2WO,K1,K2W,ERRER)
          IMPLICIT REAL (K)
          DIMENSION K1(50),K2W(50),D(50),DS(50)
          DO 200 I=M777,N777
          D(I)=(K1(I)+TAU*K2W(I)-TAU*K2WO)/SQRT(1.+TAU**2)
      200 CONTINUE
          M778=M777+1
          SE=0.0
```

PROGRAM III (CONT.)

```
      IF(K2W(M777).EQ.K2W(M778)) GO TO 202
      SE=(D(M777)**2/SQRT(ABS(K2W(M777)-K2W(M778))))
  202 DO 201 I=M778,N777
      IF(K2W(M777).EQ.K2W(I)) GO TO 110
      DS(I)=(D(I)**2/SQRT(ABS(K2W(M777)-K2W(I))))
      GO TO 115
  110 DS(I)=0.
  120 FORMAT(1X,'EROS K2W(M777)=K2W(I) FIX UP DS(I)=0.')
      WRITE(6,120)
  115 SE=SE+DS(I)
  201 CONTINUE
      IF(K2W(M777).EQ.K2W(M778)) GO TO 204
      ERRER=SQRT(SE/((N777-M777)*(N777-M777+1)))
      GO TO 205
  204 ERRER=SQRT(SE/((N777-M777-1)*(N777-M777)))
  205 RETURN
      END
```

TOTAL MEMORY REQUIREMENTS 000668 BYTES

FORTRAN IV G LEVEL 1, MOD 3 LINE DATE = 70098 13/12/07

```
      SUBROUTINE LINE (M777,K1,K2W,TAU,K2W0,L1,MN)
      IMPLICIT REAL (K)
      DIMENSION K1(50),K2W(50)
      M=M777
   40 FORMAT(1X,I3,3X,I3)
      WRITE(6,40) M,L1
      IF(M.EQ.L1) GO TO 9
      M1=M+1
   45 FORMAT(1X,E12.5)
      WRITE(6,45) (K1(I),I=1,M1)
      IF(M1.EQ.L1) GO TO 10
      X1=(2*K1(M)+K1(M+1))/3.
      X2=(K1(M+1)+2*K1(M+2))/3.
      Y1=(2*K2W(M)+K2W(M+1))/3.
      Y2=(K2W(M+1)+2*K2W(M+2))/3.
      IF(Y1.EQ.Y2) GO TO 10
      TAU=(X2-X1)/(Y1-Y2)
      IF(TAU.EQ.0.0) GO TO 30
      K2W0=Y1+X1/TAU
      GO TO 31
   30 K2W0=0.
   31 M777=M1
      GO TO 9
   10 IF(K2W(M).EQ.K2W(M+1)) GO TO 11
      TAU=(K1(M+1)-K1(M))/(K2W(M)-K2W(M+1))
      GO TO 12
   11 WRITE(6,20)
   20 FORMAT(1X,'LINE K2W(M+1)=K2W(M) FIX UP DO NOT CHANGE TAU')
      GO TO 9
   12 M777=M1
    9 RETURN
      END
```

TOTAL MEMORY REQUIREMENTS 00040E BYTES

INDEX TO DIELECTRIC DATA

II. MINERALS, ROCKS, SOILS, MISCELLANEOUS INORGANICS

III. ORGANIC COMPOUNDS

(Listed according to mfg. or source of sample)

IV. LIQUIDS

Note: In the following data sheets κ (or κ') is the dielectric constant relative to air; κ'' is the loss factor; tan δ is the loss tangent; ρ is the resistivity in ohm-cm.

Aluminum oxide, single crystal

Sapphire Al_2O_3

Union Carbide Corporation
Electronics Division
8888 Balboa Ave.
San Diego, Calif. 92123

Loss tangents at 8.5 GHz, 25°C: $E \perp c$, <.00002

$E \parallel c$, <.00005

Dielectric constants at ~3 GHz:

T°C	$E \perp c$	$E \parallel c$
25	9.390*	11.584*
-75	9.292	11.433
-195	9.257	11.357

Variation of dielectric constant at 25°C with inclination of electric field direction with respect to optic axis was calculated from elliptic polarization function:

$$\kappa = \left[\frac{11.584^2 \times 9.39^2\ (1 + \cot^2\theta)}{11.584^2 + 9.39^2\ \cot^2\theta}\right]^{1/2}$$

θ°	κ
10	11.494
20	11.246
30	10.895
40	10.507
50	10.1295
60	9.820
70	9.584
80	9.439

Average κ for random oriented full-density ceramic:

κ_{av} = 10.071 from $\kappa_{av} = (9.39 \times 9.39 \times 11.584)^{1/3}$

or 10.121 for approximate value, $\frac{11.584 + 2 \times 9.390}{3}$

* These values are in reasonable agreement with optically measured values of 11.56 and 9.406 [E. E. Russell and Bell, J. Opt. Soc. Amer. 57, 543 (1967)].

Aluminum oxide, multicrystalline

AT-100 (near 100% Al_2O_3, fine grained)

Density, g/cm^3: (10^2 to 10^8 Hz) - 3.956

(4; 8 GHz) - 3.955

General Electric Company
Electronic Components Division
Microwave Tube Business Section
One River Road
Schenectady, N.Y. 12305

Frequency in Hz

T°C		10^2	10^3	10^4	10^5	10^6	10^7	8.5×10^9
25	κ	9.98	9.98	9.98	9.98	9.98	9.98	9.96
	10^6 tanδ	7	<1	<1	<1	<1.5	<7	48
100	κ	10.09	10.09	10.09	10.09	10.09	10.09	
	10^6 tanδ	52	6	<1	<1	<1.5	<7	
200	κ	10.21	10.21	10.21	10.21	10.21	10.21	
	10^6 tanδ	603	128	45	20	10	<7	
300	κ	10.42	10.37	10.355	10.35	10.35	10.35	
	10^4 tanδ	61.3	16.3	5.27	2.28	.62	.12	
400	κ	10.84	10.68	10.57	10.46	10.44	10.44	
	tanδ	0307	.0133	.00407	.00103	.00034	.00006	
500	κ	12.60	11.28	10.86	10.71	10.63	10.62	
	tanδ	.289	.069	.0237	.0044	.00082	.0002	

A-976 (near 100%)

Frequency in Hz

T°C		10^2	10^3	10^4	10^5	10^6	10^7	8.5×10^9
25	κ	9.90	9.90	9.90	9.90	9.90	9.90	9.81
	10^6 tanδ	70	34	20	10	<10	<10	66
100	κ	10.01	10.01	10.00	10.00	10.00	10.00	
	10^5 tanδ	15	7	3	1.5	<1	<1	
200	κ	10.14	10.12	10.11	10.11	10.11	10.1	
	10^5 tanδ	66	23	8	6	3	<1	
300	κ	10.32	10.29	10.26	10.26	10.26	10.26	
	10^4 tanδ	25	11	3.8	1.1	.4	.2	
400	κ	10.65	10.50	10.43	10.42	10.41	10.41	
	10^4 tanδ	395	102	27.8	8.7	2.9	1.0	
500		11.30	10.81	10.65	10.59	10.58	10.56	
	10^3 tan	461	118	22.4	4.59	1.97	1.1	

Density of disk - 3.919; density of cylinder - 3.917

Aluminum oxide, multicrystalline

A-1000 (99.8% Al_2O_3, fine grained) **General Electric Company**

Density, g/cm^3: (10^2 to 10^8 Hz) - 3.900

($8.5x10^9$) - 3.896

Frequency in Hz

T^oC		10^2	10^3	10^4	10^5	10^6	10^7	$8.5x10^9$
25	κ	10.08	10.08	10.07	10.04	9.98	9.96	9.77
	tan δ	.00048	.00048	.00135	.00354	.00664	.00612	.00258
100	κ	10.20	10.16	10.15	10.15	10.15	10.15	
	tan δ	.00184	.00077	.00037	.00058	.00208	.0061	
200	κ	10.39	10.36	10.33	10.33	10.31	10.29	
	tan δ	.00344	.00198	.00101	.00045	.00051	.00170	
300	κ	10.65	10.55	10.51	10.47	10.45	10.44	
	tan δ	.0193	.0059	.00226	.00079	.00049	.00065	
400	κ	11.86	10.89	10.68	10.63	10.60	10.58	
	tan δ	.213	.0461	.00936	.00206	.00076	.00057	
500	κ	33.3	13.98	11.28	10.83	10.80	10.76	
	tan δ	1.212	.525	.130	.0201	.00341	.00135	

A-919 (97% Al_2O_3, magnesia-free)

Density, g/cm^3: (10^2 to 10^8 Hz) - 3.747

($8.5x10^9$ Hz) - 3.750

Frequency in Hz

T^oC		10^2	10^3	10^4	10^5	10^6	10^7	$8.5x10^9$
25	κ	10.33	9.95	9.62	9.45	9.38	9.37	9.35
	tan δ	.0240	.0251	.0206	.0082	.00139	.00030	
100	κ	10.29	9.88	9.60	9.51	9.49	9.49	.00069
	tan δ	.0316	.0252	.0123	.00303	.00048	.00025	
200	κ	9.74	9.62	9.60	9.59	9.59	9.59	
	tan δ	.0210	.0046	.00089	.00021	.00006	<.0001	
300	κ	10.32	9.89	9.79	9.78	9.77	9.77	
	tan δ	.0760	.0237	.00475	.00097	.00033	.00010	
400	κ	14.38	11.13	10.18	9.96	9.90	9.89	
	tan δ	1.65	.295	.0590	.0128	.00195	.00063	
500	κ	16.56	13.67	11.44	10.37	10.08	10.03	
	tan δ		6.83	.860	.122	.0203	.0035	

Aluminum oxide, multicrystalline

A-923 (97% Al_2O_3) General Electric Company

Density, g/cm^3: (10^2 to 10^8 Hz) - 3.740

(8.5x10^9 Hz) - 3.740

Frequency in Hz

T°C		10^2	10^3	10^4	10^5	10^6	10^7	8.5x10^9
25	κ	10.26	10.23	10.10	9.61	9.28	9.27	9.24
	tan δ	.00227	.00432	.0173	.0357	.00952	.00165	.00067
100	κ	10.33	10.30	10.19	9.72	9.40	9.39	
	tan δ	.00330	.00352	.0178	.0320	.0118	.00157	
200	κ	10.18	9.73	9.55	9.53	9.50	9.50	
	tan δ	.0349	.0238	.0073	.00200	.0089	.00040	
300	κ	10.38	9.84	9.74	9.65	9.64	9.64	
	tan δ	.0678	.0232	.0074	.00313	.00167	.00112	
400	κ	12.50	10.48	9.97	9.82	9.80	9.79	
	tan δ	.205	.082	.0228	.00735	.0035	.0017	
500	κ	16.72	13.93	10.98	10.08	9.95	9.91	
	tan δ	8.03	1.20	.240	.0444	.00976	.0037	

A-1004 (94% Al_2O_3)

At 25°C: 2x10^4 Hz, κ = 10.10, tan δ= .0426; 5x10^4 Hz, κ = 9.76, tan δ = .0536;

3x10^5, κ = 9.19, tan δ = .0341.

Density, g/cm^3: (10^2 to 10^8 Hz) - 3.645

(8.5x10^9 Hz) - 3.649

Frequency in Hz

T°C		10^2	10^3	10^4	10^5	10^6	10^7	8.5x10^9
25	κ	10.48	10.41	10.26	9.51	9.10	9.00	9.01
	tan δ	.00226	.00716	.0319	.0534	.0142	.00228	.00125
100	κ	10.63	10.55	10.48	9.89	9.19	9.10	
	tan δ	.00355	.00555	.0208	.0505	.0271	.0515	
200	κ	10.49	9.73	9.34	9.25	9.21	9.20	
	tan δ	.0450	.0439	.0171	.0047	.00163	.00105	
300	κ	10.52	9.81	9.55	9.44	9.37	9.36	
	tan δ	.0767	.043	.0132	.0059	.0022	.0020	
400	κ	12.63	10.39	9.78	9.54	9.43	9.36	
	tan δ	.227	.0887	.033	.0136	.0072	.0040	
500	κ	19.19	12.59	10.55	10.03	9.83	9.74	
	tan δ	1.16	.452	.121	.0298	.0133	.0071	

Boron nitride

Pyrolytic — Raytheon Company

Data supplementary to p. 40, Tech. Rep. 203

Post-treated samples, measured at 8.52 GHz, 25°C

Density (g/cm^3)	κ	tan δ
1.233	2.994	.00008 ± .00002
1.237	3.013	.00005 ± .00003

Sample 2A + 2B, density at 25°C 1.381

5.07 to 5.00 GHz

T°C	κ	tan δ
25	3.199	<.0002
200	3.212	<.0002
400	3.226	<.0002
600	3.241	.0002 ± .0001
800	3.255	.0002 ± .0001
1000	3.272	.0002 ± .0001
1200	3.288	.0002 ± .0001
1300	3.297	.0003 ± .0002
1400	3.309	.0007 ± .0004

Test for anisotropic effects at 8.52 GHz, 25°C, by rotation and reversal of sample:

$\kappa_{max} = 3.0018$

$\kappa_{min} = 2.9894$

Pyrolytic laminate — Union Carbide

8.52 GHz E ‖ laminate

T°C	κ	tan δ
25	5.15 ± .05	.00025 ± .00005
173		.00025 ± .0001
225		
341		
470		
610		
800		
978		.0003 ± .0001

Boron nitride, hot-pressed

Grade HP, 25°C

The Carborundum Company
Refractories & Electronics Division
Whirlpool Technical Center
Niagara Falls, N.Y., 14302

All tan δ values multiplied by 10^4

Sample No.	Density (g/cm^3)	Field direct.	(Hz)	10^2	10^3	10^4	10^5	10^6	10^7	10^8
1	2.120	unknown	κ	4.59	4.56	4.54	4.54	4.54	4.54	4.54
			tanδ	8.5	3.58	2.30	2.3	2.3	2.8	3.5
2	1.762	⊥	κ	4.14	4.02	3.97	3.96	3.96	3.96b	
			tanδ	414	174	41.6	9.9	3.4	2.0	
3	2.131	∥	κ	4.71	4.64	4.54	4.46	4.40	4.32	
			tanδ	100	110	120	125	141	123	
			(Hz)	$3x10^8$	10^9	$3x10^9$	$8.5x10^9$		$1.4x10^{10}$	$2.4x10^{10}$
4	(various not meas.)	unknown	κ	4.59	4.59	4.59	4.39		4.62	4.57
			tanδ	2.7	3.5	4.2	6.55		6.0	6.0
5	1.999	unknown	κ							
			tanδ							
6	2.033	⊥	κ	4.47	4.468	4.457				
			tanδ	5.3	4.6	6.0				
7	1.748	mixed	κ	3.88	3.880	3.876				
			tanδ	4.1	4.7	4.0				
8	2.111	⊥	κ				4.584			
			tanδ				6.0			
9	2.061	⊥	κ				4.552			
			tanδ				7.1			
9	"	∥	κ				4.507			
			tanδ				7.7			
10	2.117	⊥	κ						4.75	
			tanδ						8.0	
11	2.063	⊥	κ						4.55	
			tanδ						8.7	
11	"	∥	κ						4.51	
			tanδ						8.8	
12	2.118	⊥	κ							4.69
			tanδ							8.5
13	2.066	⊥	κ							4.61
			tanδ							7.9
13	"	∥	κ							4.48
			tanδ							9.2

Boron nitride, hot-pressed

Grade A, 25°C

Carborundum

All tan δ values are multiplied by 10^4

Sample No.	Density (g/cm^3)	Field direct.	(Hz)	10^2	10^3	10^4	10^5	10^6	10^7	10^8
1	2.084	unknown	κ	4.13	4.12	4.090	4.087	4.086	4.080	4.08
			tanδ	11.8	10.4	7.9	4.3	3.1	2.7	2.6
2	2.040	$\perp$	κ	4.40	4.40	4.39	4.39	4.39	4.38	
			tanδ	8.7	6.3	6.0	3.1	1.8	1.0	
3	2.066	$\parallel$	κ	3.99	3.99	3.98	3.98	3.98	3.97	
			tanδ	6.9	5.6	4.5	3.0	2.4	1.1	
			(Hz)	$3x10^8$	10^9	$3x10^9$	$8.5x10^9$	$1.4x10^{10}$	$2.4x10^{10}$	
4 (various not meas.)		unknown	κ	4.46	4.46	4.46		4.6	4.61	
			tanδ	4.0	3.3	3.4		5.8	3.5	
5	2.099	unknown	κ				4.605			
			tanδ				20			
6	2.091	$\perp$	κ	4.62	4.615	4.599				
			tanδ	2.6	3.7	3.8				
7	2.097	mixed	κ	4.36	4.359	4.352				
			tanδ	2.2	1.3	1.5				
8	2.069	$\perp$	κ				4.586			
			tanδ				6.4			
9	2.077	$\perp$	κ				4.550			
			tanδ				3.6			
9	"	$\parallel$	κ				4.268			
			tanδ				4.5			
10		$\perp$	κ					4.268		
			tanδ					4.5		
11	2.093	$\perp$	κ					4.53		
			tanδ					4.5		
11	"	$\parallel$	κ					4.28		
			tanδ					10.4		
12	2.090	$\perp$	κ						4.56	
			tanδ						5.3	
13	2.095	$\perp$	κ						4.54	
			tanδ						4.6	
13	"	$\parallel$	κ						4.24	
			tanδ						3.2	

Boron nitride, hot-pressed, with silica

Grade M, 25°C

Carborundum

All tan δ values multiplied by 10^4

Sample No.	Density (g/cm^3)	Field direct.	(Hz)	10^2	10^3	10^4	10^5	10^6	10^7	10^8
1	2.143	unknown	κ	3.71	3.70	3.69	3.69	3.69	3.68	3.68
			tanδ	4.0	2.78	2.22	2.07	1.63	1.8	2.3
2	2.107	⊥	κ	4.34	4.33	4.32	4.30	4.30	4.30	
			tanδ	16.9	14.3	10.5	6.6	3.7	1.9	
3	2.109	∥	κ	3.76	3.76	3.76	3.75	3.75	3.75	
			tanδ	7.4	7.0	6.7	4.6	3.4	3.6	

Sample No.	Density (g/cm^3)	Field direct.	(Hz)	$3x10^8$	10^9	$3x10^9$	$8.5x10^9$	$1.4x10^{10}$	$2.4x10^{10}$
4	(various not meas.)		κ	4.24	4.24	4.24		4.32	
			tanδ	2.8	3.1	3.7		5.5	
5	2.145		κ				4.328		
			tanδ				4.1		
6	2.137	⊥	κ	4.27	4.27	4.255			
			tanδ	3.8	4.9	4.9			
7	2.118	mixed	κ	3.99	3.992	3.983			
			tanδ	3.9	4.5	5.2			
8	2.095	⊥	κ				4.192		
			tanδ				6.6		
9	2.120	⊥	κ				4.332		
			tanδ				6.2		
9		∥	κ				3.668		
			tanδ				8.5		
10	2.125	⊥	κ					4.23	
			tanδ					5.4	
11	2.123	⊥	κ					4.295	
			tanδ					11.0	
11	"	$\vert$	κ					3.63	
			tanδ					7.8	
12	2.066	⊥	κ						4.22
			tanδ						5.1
13	2.121	⊥	κ						4.28
			tanδ						7.9
	"	∥	κ						3.54
			tanδ						10.5

Boron nitride, hot-pressed

Grade HBR

Union Carbide Corporation
Carbon Products Division
270 Park Ave.
New York, N,Y,m 10017

E ⊥ direction of pressing

T^oC		10^2	10^3	10^4	10^5	10^6	10^7
25	κ	4.77	4.77	4.76	4.76	4.76	4.76
	10^4 tan δ	18.2	7.1	4.9	1.5	1.4	0.9
100	κ	4.85	4.80	4.78	4.78	4.78	4.78
	10^4 tan δ	165	45.4	9.4	4.1	2.1	0.6
200	κ	5.26	4.96	4.85	4.82	4.81	4.81
	10^4 tan δ	596	277	101	39	5.4	23
300	κ	5.75	5.25	5.00	4.89	4.85	4.85
	10^4 tan δ	855	526	231	109	33.8	12.5
400	κ	6.75	5.70	5.21	5.00	4.88	4.87
	10^4 tan δ	28.0	11.57	4.95	2.3	1.2	.37
500	κ	8.07	6.46	5.62	5.31	5.08	4.93
	tan δ	1.994	.389	.109	.0419	024	.014

Boron nitride, hot-pressed

Grade HD 0092,

Density 1.9745 g/cm^3

At 8.52 GHz

κ_{min} = 3.993 tan δ = 0.00025

κ_{max} = 4.091 tan δ = 0.00026

T^oC	At 4.54 to 4.47 GHz κ	tan δ
25	4.08	.00026
113	4.08	.0003
185	4.09	.0005
322	4.09	.00055
423	4.10	.00040
530	4.11	.00035
639	4.12	.00040
752	4.13	.00045
863	4.13	.00050
943	4.14	.00050
1021	4.15	.00055
1096	4.16	.00080
1170	4.16	.0013
1219	4.17	.0019
1287	4.18	.0034
1373	4.19	.0040
1427	4.20	.0028
1446	4.22	.0023
1460	4.24	.0044
1470	4.24	0046

Grade HD 0093

Density 1.9165 g/cm^3

At 3.52 GHz

κ' = 3.998 ± 0.002

tan δ = 0.00052

T^oC	At 4.53 to 4.44 GHz κ	tan δ
25	4.003	.0005
207	4.048	.0004
393	4.072	.00045
513	4.088	.0004
593	4.101	.0007
798	4.146	.0030
852	4.166	.0052
891	4.204	.0040
1018	4.320	.0028
1077	4.479	.0057
1094	4.485	.0071
1110	4.54	.01
943	4.25	.0026
860	4.19	
25	4.01	

Density check after run 1.916

Boron nitride, hot pressed

Grade HD 0094, at 8.52 GHz

Sample 2: density 1.303 g/cm^3

T^oC	κ	tan δ
25	3.004	.00033

Sample 1: density 1.307 g/cm^3

T^oC		
25	3.016	.00033
93	3.02±.03	.00030
192		.00035
339		.00037
471		.00040
602	3.04±.03	.00040
705		.00047
754		.00060
793		.00095
843		.0020
954		.0085
999		.0135

Union Carbide

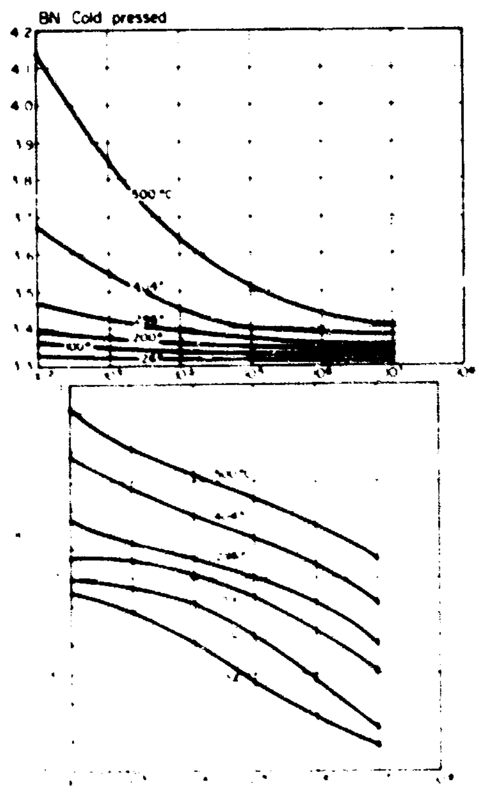
At 5.30 to 5.26 GHz

Density: 1.303 g/cm^3

T^oC	κ	tan δ
25	3.004	.00033
120	3.008	.00037
203	3.012	.00039
325	3.018	.00044
404	3.021	.00043
498	3.026	.00046
601	3.032	.00046
721	3.039	.00065
812	3.047	.00186
884	3.053	.00447
908		>.01

Boron nitride, cold-pressed

Union Carbide



Rod sample, at 8.52 GHz

Density: 1.474 g/cm^3

At 25^{o}C:

$\kappa' = 3.412$; tan $\delta = .00046$

Magnesium aluminate (spinel) $MgOAl_2O_3$

Single crystal **Union Carbide**

Density at 25.0°, 3.57389 g/cm^3

At 8.52, 25°C: $\kappa' = 8.26 \pm .04$

$$\tan\delta = .00009 \pm .00002$$

Magnesium orthosilicate, multicrystalline **General Electric**

F-118 Density: disk 3.087, cylinder 3.071 g/cm^3

	25°C		100°C		200°C		300°C		400°C		500°C		550°C	
Freq. Hz	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ
10^2	6.625	.00098	6.70	.00445	6.80	.00134	6.91	.00636	7.23	.0662	8.78	.421		
10^3	6.62	.00027		.00065	6.79	.00076	6.89	.00198	7.04	.0127	7.44	.0890		
$2x10^3$				.00086										
$3x10^3$				.00098	6.78	.00057								
$4x10^3$				.00108										
$5x10^3$				.00110										
$6x10^3$				.00107										
$8x10^3$				.00102										
10^4	6.62	.00013	6.70	.00090	6.78	.00044	6.88	.00090	6.98	.00334	7.20	.0188		
10^5	6.62	.000110	6.69	.00024	6.78	.00064	6.87	.00051	6.96	.00123	7.14	.0049		
$5x10^5$					6.77	.00098								
10^6	6.62	.000072	6.69	.00016	6.77	.00074	6.85	.00046	6.96	.00069	7.09	.00329		
10^7	6.62	.00011	6.69	.00024	6.77	.00025	6.84	.00083	6.95	.00023	7.08	.00149		
10^8														
$8.5 x10^9$	6.59	.00083	6.64	.00086	6.73	,00092	6.81	.00100	6.90	.00109	6.98	.00119	7.03	.00124
$1.4x10^{10}$														
$2.4x10^{10}$														

F-202

	25°C		100°C		200°C		300°C		400°C		500°C		550°C	
Freq. Hz	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ		
10^2	6.77	.000515	6.86	.00107	6.99	.00277	7.26	.02835	9.74	.508	14.73	4.29		
10^3	6.76	.000293	6.85	.00063	6.98	,00202	7.14	.0076	7.70	.142	10.08	.822		
10^4	6.76	.000240	6.84	.00056	6.96	.00124	7.08	.0037	7.34	.0293	8.13	.178		
10^5	6.76	.000233	6.83	.00035	6.95	.00077	7.06	.0017	7.22	.00705	7.40	.0474		
10^6	6.76	.000245	6.83	.00032	6.94	,00067	7.06	.00120	7.18	.0025	7.31	.00975		
10^7	6.76	.00025	6.83	.00025	6.94	.00052	7.05	.00098	7.15	.00153	7.28	.00394		
10^8														
$8.5x10^9$	6.74	.00080	6.81	.00090	6.92	.0015	7.02	.0014	7.13	.0019	7.23	.0027	7.28	.0031
$1.4x10^{10}$														
$2.4x10^{10}$														

Density of disk 3.087, cylinder 3.086 g/cm^3

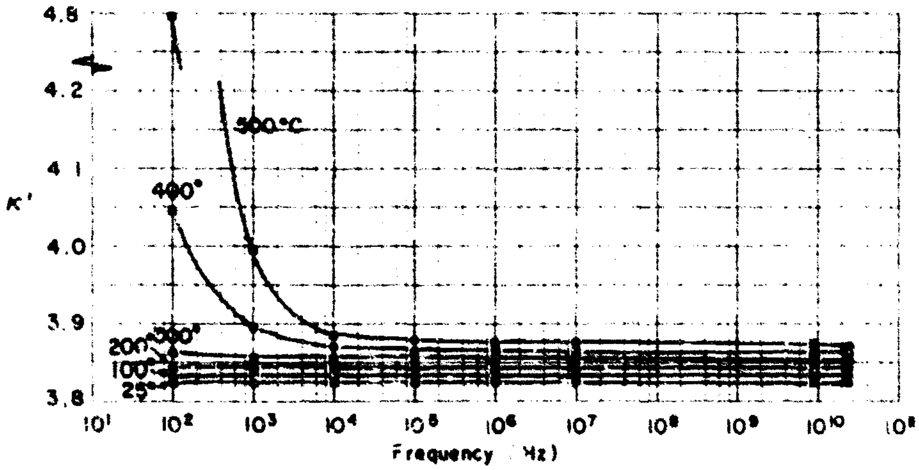
Mercuric compounds, hot-pressed

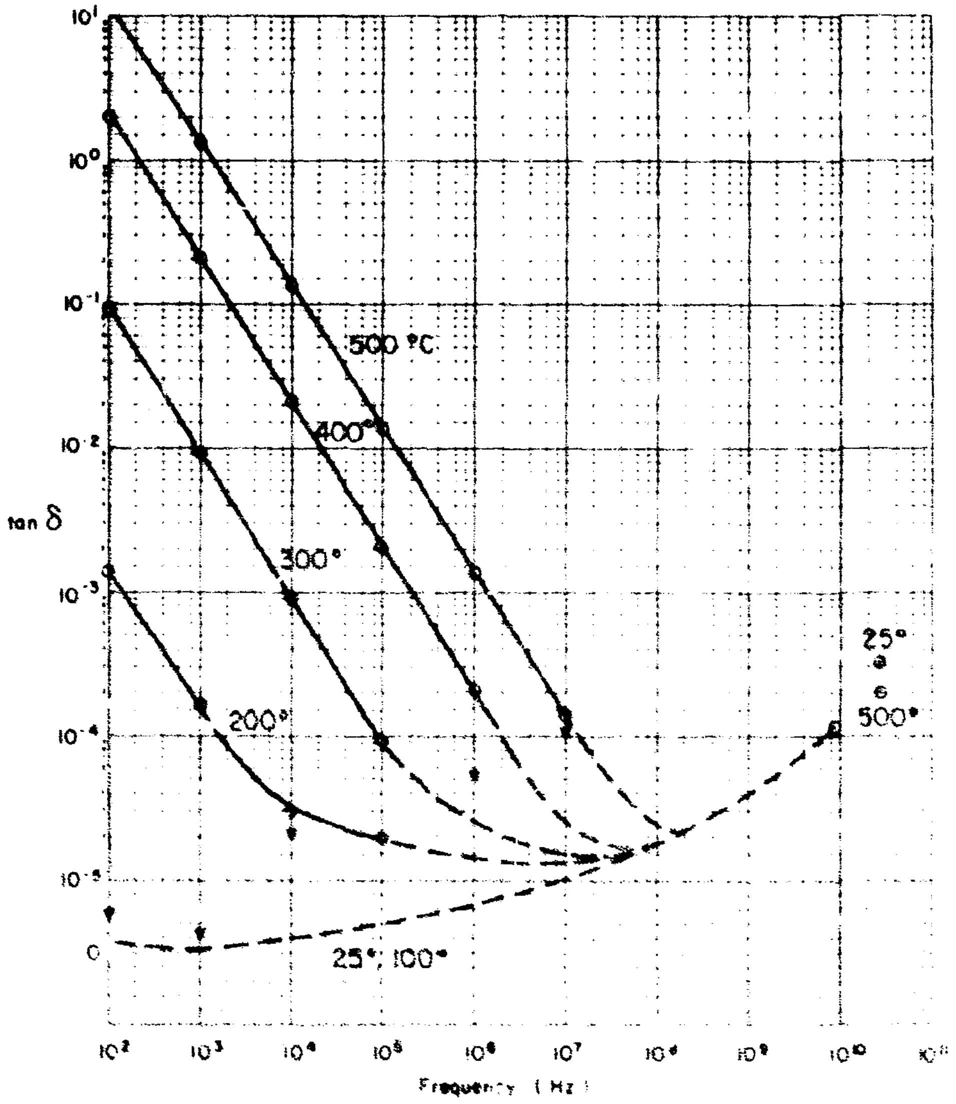
Theort. density	Compound	Sample No.	Density (g/cm^3)	T^oC		10^2	10^3	10^4	10^5	10^6	10^7	$8.5x10^9$
6.27	HgI_2	1	-	25	κ		13.7			11.8		13.4
					tan δ		.191			.0034		.0037
		2	5.48	25	κ		14.3			12.57		
					tan δ		.208			.0026		
		3	5.49	25	κ							13.9
					tan δ							< .003
		4	5.56	25	κ	16.11	13.15	12.41	12.39	12.38	12.37	
					tan δ	.828	.154	.0268	.00427	.00117	.00043	
				50	κ	44.35	16.87	13.50	12.98	12.90	12.85	
					tan δ	2.33	.888	.168	.0264	.0047	.00095	
				25	κ	15.45	13.03	12.45	12.42	12.41	12.40	
					tan δ	.713	.185	.0334	.0057	.00149	.00076	
7.15	HgCl	1	5.36	25	κ	7.49	7.48	7.48	7.48	7.46	7.45	
					tan δ	.0013	.00044	.00029	.00034	.00040	.00029	
				50	κ	7.62	7.61	2.59	7.58	7.57	7.57	
					tan δ	.00328	.00095	.00046	.00021	.00028	.00039	
				25	κ	7.58	7.58	7.57	7.57	7.56	7.56	
					tan δ	.00050	.00027	.00018	.00021	.00034	.00046	
7.73	HgS	1	5.19	25	κ	9.75	9.72	9.68	9.64	9.62	9.58	
					tan δ	.0038	.0035	.0029	.0021	.0017	.0011	
				50	κ	9.64	9.61	9.58	9.56	9.53	9.49	
					tan δ	.00324	.00225	.00188	.00174	.00181	.00144	
				25	κ	9.63	9.62	9.62	9.61	9.58	9.57	
					tan δ	.00207	.00177	.00162	.00165	.00147	.00119	

Silicon dioxide, high purity glasses

Dynasil 4000

Dynasil Corporation of America
Berlin, New Jersey 08009





Silicon dioxide, high-purity glasses (cont.)

Spectrosil A

Thermal American Fused Quartz Co.
Montville, N.J. 07045

$25^{o}C$, 8.52 GHz: $\kappa' = 3.826 \pm .003$

$10 \tan \delta = 1.9 \pm .4$

Spectrosil B

25^{C}, 8.52 GHz: $\kappa' = 3.825 \pm .003$

$10^4 \tan \delta = 1.5 \pm .2$

Frequency in Hz

$T^{o}C$		10^2	10^3	10^4	10^5	10^6	10^7
25	κ	3.823	3.823	3.823	3.823	3.823	3.823
	$10^6 \tan \delta$	<4	<4	6	7	<40	<130
100	κ	3.83	3.83	3.83	3.83	3.83	3.83
	$10^6 \tan \delta$	<4	<4	<8	<10	<40	<130
197	κ	3.84	3.84	3.84	3.84	3.84	3.84
	$10^6 \tan \delta$	264	44	15	<20	<40	<130
300	κ	3.86	3.86	3.86	3.86	3.86	3.86
	$10^4 \tan \delta$	151	15.9	2	<.4	<.6	<1.3
398	κ	3.89	3.86	3.86	3.86	3.86	3.86
	$10^2 \tan \delta$	15.9	1.76	.219	.04	<.02	<.02
486	κ	3.98	3.89	3.87	3.87	3.87	3.87
	$\tan \delta$	.79	.0883	.00954	.0015	.0005	.0002

Vitreosil, optical grade

$25^{o}C$, 8.52 GHz, $\kappa' = 3.811 \pm .005$; $10^4 \tan \delta = 1.17 \pm .2$

Vitreosil, commercial grade

$25^{o}C$, 8.52 GHz, $\kappa' = 3.805 \pm .01$; $10^4 \tan \delta = .80 \pm .13$

Silicon dioxide, sintered

Slip-cast

Brunswick

Density 1.957 g/cm^3

	25°C		100°C		200°C		300°C		400°C		500°C	
Freq.,Hz	κ	10^4tanδ	κ	10^4tanδ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ
10^2	3.38	7.1	3.39	11.0	3.44	.0190	4.42	.896	7.91	9.51	19.1	33.8
$3x10^2$	3.38	8.6										
10^3	3.38	8.8	3.38	7.8	3.41	.99364	3.64	.178	5.09	1.66	7.57	9.00
$2x10^3$	3.38	7.3										
$5x10^3$			3.38	7.7								
10^4	3.37	6.2	3.38	7.6	3.41	.00158	3.47	.0246	3.90	.334	5.10	1.47
$5x10^4$			3.38	8.3					3.5			
10^5	3.37	4.5	3.37	8.3	3.41	.00099	3.46	.00465	3.54	.055	3.90	.290
$2x10^5$			3.37	7.5								
10^6	3.37	3.7	3.37	6.1	3.40	.00081	3.45	.00158	3.49	.0089	3.61	.0483
$6x10^6$			3.37	3.6								
10^7	3.37	2.5	3.37	3.2	3.40	.00068	3.45	.0008	3.49	.0021	3.55	.0112
$8.5x10^9$	3.364	6.6										

Silicon dioxide, with 2.5% chromium oxide

Brunswick

Slip-cast,

Density 1.928 g/cm^3

	25°C		100°C		200°C		300°C		400°C		500°C	
Freq.,Hz	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ	κ	tan δ
10^2	3.33	.00345	3.43	.0057	3.57	.0292	4.59	.935	8.73	9.39	36.7	42.4
10^3	3.33	.00257	3.42	.0043	3.51	.0113	3.72	.179	5.17	1.76	13.5	10.1
10^4	3.32	.00174	3.36	.0034	3.48	.0071	3.59	.0292	3.95	.324	6.09	2.41
10^5	3.32	.00152	3.34	.0027	3.40	.0054	3.51	.0109	3.63	.0537	4.39	.425
10^6	3.31	.00093	3.33	.0020	3.38	.0040	3.49	.0101	3.56	.0149	3.82	.094
10^7	3.31	.00035	3.32	.0017	3.34	.0022	3.42	.0076	3.53	.0106	3.68	.032
$8.5x10^9$	3.29	.00112										

Silicon dioxide, sintered

Code 7941

Density 1.923 g/cm^3

Corning Glass

Freq., ~8.5 GHz

T°C	κ	tan δ
25	3.323	.0005
279	3.351	.0009
517	3.378	.0014
769	3.408	.0023
910	3.431	.0028
1043	3.451	.0037
1205	3.455	.0051
1372	3.513	.0091

Corning Multiform Glass

At 8.52 GHz, 25°C, density = 1.906 g/cm^3

κ = 3.27; tan δ = .00063

Quartz fiber

Sample AS-3DX-1R

Source: Philco Ford Corp.
Newport Beach, Calif. 92663

Manufacturer: Fiber Materials Inc.
Graniteville, Mass. 01829

Freq., 8.52 GHz

T°C	κ	tan δ
25*	3.02	.0054
25	2.98	.0019
98	2.97	.0018
198	2.96	.0016
307	2.95	.0015
418	2.95	.0014
497	2.945	.0014
591	2.95	.0016
729	2.96	.0022
828	2.975	.0029
905	2.99	.0035
995	3.01	.0042

* As received, other values after vacuum bake for 24 hours at 125°C.

Glasses

Sample EE 9

Sample EE 10

Owens-Illinois
Toledo, Ohio 43601

EE 9 Freq., 8.52 GHz			EE 10 Freq., 8.52 GHz		
T^oC	κ	tan δ	T^oC	κ	tan δ
25	5.84	.0070	25	8.17	.0082
97	5.86	.0070	97	8.25	.0082
199	5.90	.0071	202	8.36	.0083
314	5.97	.0072	292	8.47	.0084
421	6.02	.0074	416	8.63	.0089
506	6.08	.0077	501	8.76	.0096
607	6.17	.0081	605	8.98	.0123
32	5.82	.0069	27	8.19	.0080

II. MINERALS, ROCKS, SOILS, MISCELLANEOUS INORGANICS

Rocks

Hawaian, high-density basalt*

50% relative humidity

Density 2.717 g/cm^3

	Sample 1	Sample 2	Sample 3	Sample 3	Sample 3	Sample 4
Freq. (Hz)	$3x10^8$	10^7	$3x10^8$	10^9	$3x10^9$	$8.5x10^9$
κ	8.36	9.90	9.30	9.08	8.85	8.40
tan δ	.043	.080	.034	.033	.037	.04
μ'/μ_o	1.174	1.17	1.113	1.10	1.08	1.01
tan δ_m	.0077	<.002	.0075	.026	.072	.06

Hawaian low-density basalt*

50% relative humidity

Freq. (Hz)	10^7	$3x10^8$	10^9	$3x10^9$
κ	4.9	3.74	3.51	3.30
tan δ	.068	.085	.0481	.053
μ'/μ_o	1.047	1.047	1.040	1.035
tan δ_m	<.002	.0040	.0[illegible]2	.002

* Data supplementary to Tech. Rep. 203, Lab. Ins. Res., Mass. Inst. Tech., Jan. 1967.

Rocks (cont.)

Deep ocean basalt

No change after heating to 200°C

Freq. (Hz)	10^5	10^6	10^7	$8.5x10^9$
κ	188	153	124	10.2
tan δ	93.5	11.6	.146	.560
ρ	1025	1015	995	36.9

Soils

Hawaian soil saturated with distilled H_2O*

% H_2O on dry weight basis = 127.5

% H_2O on volume basis = 63.0

Density 1.303 g/cm^3

Freq. (Hz)	10^3	10^4	10^5	10^6	$9.5x10^6$	$7x10^7$
κ	29,700	988	230	1295	81.5	64.2
tan δ	135	43.9	20.05	3.32	.776	.185

Hawaian soil* with approximately 25% H_2O on dry weight basis. Density ≅ .88 g/cm^3.

Freq. (Hz)	10^2	10^3	10^4	10^5	10^6	10^7	$3x10^8$	$1x10^9$	$3x10^9$	$8.5x10^9$
κ	10560	940	68.0	21.66	12.04	6.88	5.12	4.90	4.45	3.97
tan δ	2.30	4.43	7.25	2.67	.827	.389	.105	.079	.81	.135

Synthetic basalt and lunar rocks, Apollo 11 and 12, see:

D. H. Chung, W. B. Westphal, and G. Simmons, "Dielectric Properties of Apollo 11 Lunar Samples and Their Comparison with Earth Materials," J. Geophys. Res. 75, 1970 (in press).

D. H. Chung, W. B. Westphal, and G. Simmons, "Dielectric Properties of Apollo 12 Lunar Samples," a paper (T64c) presented at American Geophys. Union Meeting, April 23, 1970, Washington D.C.

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* Data supplementary to Tech. Rep. 203, Lab. Ins. Res., Mass. Inst. Tech., Jan. 1967.

Miscellaneous inorganics

Corning Code 0330 — Corning Glass

3 GHz	25°C
κ	tan δ
6.58	.0055

Isomica 4950 — General Electric Company

Vacuum baked for 36 hrs. at 125°C, E ∥ sheet

Freq. (MHz)	κ	tan δ
300	5.33	.0013
8520	5.31	.00207
8520	5.32*	.0025*

* 50% relative humidity.

III. ORGANIC COMPOUNDS

(Listed according to manufacturer or source)

Artificial concrete — American Concrete Products

Material measured to be isotropic in κ within .5%

Freq. (MHz)	150	300	1000	3000
κ	6.06	6.04	6.02	6.0
tan δ	.0107	.0134	.0125	.0123

Conformal coating 1517-36-3 — Amicon Corporation

25°C, 50% relative humidity

Freq. (Hz)	κ	tan δ
10^2	4.31	.0206
10^3	4.21	.0204
10^6	3.76	.0298

Volume resistivity 3.7×10^{13} ohm-cm

Surface resistivity $>6 \times 10^{14}$ ohms per square

Polyethylene, irradiated

At 25°C

Source: Amphenol Corp.

Freq. (Hz)	κ'	$\tan\delta$
10^3	$2.28 \pm .02$	$.59 \pm .05$
10^6		$.82 \pm .05$
10^8		$2.3 \pm .3$
4×10^8	$2.27 \pm^{.02}_{.01}$	$2.9 \pm .5$
10^9		$2.8 \pm .3$
3×10^9		$2.6 \pm .3$
8.5×10^9	$2.260 ^{+.01}_{-.005}$	$2.5 \pm .2$

Polypropylene

Avisun Corporation
Post Road
Markus Hook, Pa. 19061

		Natural		Plateable 12-270A	
Freq., Hz	T°C	κ	$10^4 \tan\delta$	κ	$10^4 \tan\delta$
10^2	25	2.26	1.50	2.41	15.2
2×10^2			1.30		
4×10^2			1.18		
10^3			1.36	2.41	11.8
3×10^3			1.50		
10^2			1.65	2.39	10.5
2×10^4			1.68		
5×10^4			1.66		
10^5		2.25	1.51	2.38	8.70
10^6		2.25	0.96	2.37	7.25
10^7		2.25	1.26	2.36	6.55
10^8		2.25	2.04	2.36	8.2
3×10^8		2.25	2.8	2.35	12.4
10^9		2.25	4.7	2.35	17.5
3×10^9		2.25	4.0	2.35	15.7
5×10^9	25	2.245	3.7	2.344	12.1
	-55	2.265	3.0	2.352	6.0
	-75	2.271	2.7		
	-195	2.308	0.7 ± 0.3	2.375	2.8
8.5×10^9	25	2.245	3.6	2.343	12.3

Polypropylene (cont.) — Avisun Corporation

Natural, at 8.52 GHz

Sample	Density (g/cm^3)	T^{o}C	κ	tan δ
1 stacked sheet pcs		25	2.246	.00033
2 stacked injection molded pcs		25	2.236	.00035
3 rod	.9073	25	2.245	.00037

Polypropylene, plateable — Avisun Corporation

12-270A, at 8.52 GHz

Sample	Density	T^{o}C	κ	tan δ
4 stacked injection molded pcs	.9500	25	2.442	.00145
5 rod	.9303	25	2.343	.00123

Polytetrafluoroethylene, fiberglas laminate — The Budd Company, Polychemicals Division

DiClad-522,
E ⊥ sheet

All values of tan δ multiplied by 10^4

T^{o}C	Freq. (Hz)	10	10^2	10^3	10^4	10^5	10^6	10^7	$5.5x10^7$	$9x10^7$	$3.14x10^9$*
25	κ	2.739	2.740	2.738	2.737	2.735	2.734	2.733	2.732	2.731	2.712
	1 tan δ	8.6	7.0	6.7	6.1	6.3	6.95	7.7	10.0	11.7	22.5
100	κ		2.710	2.705	2.704	2.698	2.696	2.683			2.680
	1 tan δ		11.1	8.10	8.25	7.17	7.07	7.7			31
250	κ		2.554	2.534	2.522	2.503	2.502	2.49			
	1 tan δ		79.0	36.3	20.35	14.9	11.6	10.6			
-78	κ		2.796	2.793	2.790	2.784	2.78	2.78			2.752
	1 tan δ		4.2	5.9	6.8	7.1	7.7	9.8			17
-195	κ	2.801	2.799	2.794	2.792	2.787					2.758
	1 tan δ	.0005	2.2	4.5	5.1	5.4					12
-269	κ	2.709	2.789	2.784	2.783	2.780					
	1 tan δ	.0003	1.2	2.0	2.2	2.1					

* Copper cavity

E ‖ sheet

T^{o}C	Freq. (Hz)	$3x10^8$	10^9	$3x10^9$	$8.5x10^9$	$1.4x10^{10}$	$2.4x10^{10}$
25	κ	3.155	3.153	3.152	3.146	3.133	3.127
	tan δ	28	30	33	40	48	52
100	κ				3.11		
	tan δ				39		
-250	κ				3.03		
	tan δ				36		
-54	κ				3.17	3.13	
	tan δ				35	39	
-195	κ				3.22	3.12	
	tan δ				28	31	

Polytetrafluoroethylene film

Zitex

Density 0.463 g/cm^3

25^oC, 8.52 GHz: κ = 1.194, tan δ = .00010

Chemplast Inc.
150 Day Road
Wayne, N.J. 07470

Custom Materials

Custom Materials Inc.

Custom load 4101

Freq. (GHz)	T^oC	κ	tan δ_e	μ'/μ_o	tan δ_m
3	25	13.8	.050	2.69	.451
8.5	25	13.3	.031	1.65	.747
8.5	-67	13.7	.006	1.57	.748
8.5	85	14.5	.051	1.68	.735

Custom 707-4

25^oC, 8.52 GHz: κ = 4.04, tan δ = .00090

Custom 707-(3.75)

25^oC, 8.52 GHz: κ = 3.753, tan δ = .00076

Sylgard 182

Dow Corning

1 MHz

T^oC	κ	tan δ
25	2.86	.00132
70	2.72	.00080
25 again	-	.00109
25 (after 24 hrs. in H_2O) wt. gain .019%	2.86	.00142

Sylgard 184

Dow Corning

At 25^oC

Freq. (Hz)	50	10^3	10^5	10^6
κ	2.86	2.86	2.84	2.84
10^4 tan δ	2	10.2	18.4	14.0

Sylgard 184

Dow Corning

2nd sample at 1 MHz

T^oC	κ	tan δ
25	2.88	.00123
70	2.70	.00071
25	-	.00040
25 (after 24 hrs in H_2O) wt. gain .025%	2.89	.00129

"Kapton"* E. I. Dupont de Nemours

Type 500 H film

At 25°C, 45% relative humidity

Electric field in plane of sheet, $\kappa \pm .05$, $\tan\delta \pm .0005$

			After 48 hrs. at 100°C	
Freq. (GHz)	κ	$\tan\delta$	κ	$\tan\delta$
0.3	3.43	.0074	-	-
1	3.40	.0076	3.30	.0041
3	3.37	.0080	3.28	.0044
8.5	3.33	.0087	3.26	.0047
24	3.25	.0098	-	-

After 12 to 18 hrs. vacuum bake at 425°C, 2 microns, 8.52 GHz:

$\kappa = 3.03 \pm 0.1$, $\tan\delta = .0015 \pm .0003$

"Eccogel" 1265 Emerson & Cuming

	Freq. (Hz) 60		10^3		10^6	
T°C	κ	$\tan\delta$	κ	$\tan\delta$	κ	$\tan\delta$
25	7.60	.025	7.20	.0595	4.05	.1115
70					6.02	.0545
25 again					-	.0897
25 (after 24 hrs. in H_2O) wt. gain 1.08%					5.38	.128

"Eccofoam FH" Emerson & Cuming

3.938 lb/cu.ft.

8.52 GHz		24 GHz	
κ	$\tan\delta$	κ	$\tan\delta$
1.0856	.00161	1.0798	.00165

RTV-11 General Electric Company

At 1 MHz

T°C	κ	$\tan\delta$
25	3.25	.00285
70	3.05	.00372
25	-	.00242
25 (after 24 hrs in H_2O) wt. gain .035%	3.31	.00543

* Supplementing data given in Tech. Rep. 203.

Scotchcast 221 — 3-M

At 1 MHz

T^oC	κ	tan δ
25	3.06	.0273
70	3.73	.1373
25	-	.0245
25 (after 24 hrs. in H_2O) wt. gain .274%	3.12	.0352

Polyimide foams — Monsanto

At 8.52 GHz

	Density (lbs/cu.ft.)	T^oC	κ	tan δ
HD-139	8.4	25	1.1439	.00277
		150	1.128	.00040
		304	1.118	.00045
		25	1.126	.0014
HD-140	16.7	25	1.301	.00507
		154	1.264	.00094
		307	1.260	.00121
		25	1.260	.00037
HD-144	21.8	25	1.412	.00635
		148	1.355	.00135
		303	1.382	.00190
		28	1.351	.0068

Radar tape — Quantum Inc.
Lufbery Ave.
Wallingford, Conn.

At 14.2 GHz

T^oC	κ	tan δ
25	3.56	.0132
150	3.37	.0055
320	3.32	.0074
477	3.36	.0130

Duroid (1" thick sheet)

Rogers Corporation

$T^{o}C$	3.7 GHz E // κ	tan δ	4.3 GHz E $\perp$ κ	tan δ	Cavity length (inches)
25	2.476	.00156	2.317	.00125	2.015
81.5	2.458	.00176	2.301	.00153	2.042
106.8	2.447	.00178	2.289	.00140	2.055
125	2.438	.00176	2.282	.00142	2.067
152	2.425	.00166	2.268	.00149	2.083
176	2.412	.00160	2.255	.00155	2.106
202	2.399	.00159	2.239	.00167	2.127
250	2.370	.00165	2.203	.00202	2.159
310	2.301	.00182	2.130	.0024	2.320
362	2.031	.00225	1.878	.0015	2.869

IV. LIQUIDS

Fluorocarbon derivative P-10 — Allied Chemical Corp. Specialty Chemical Div.

At 25°C

Freq. (GHz)	κ	tan δ
1	1.92	.0050
3	[illegible]	.0140
8.52	1.89	.029
14	1.87	.038

Fluorinated ethers — E. I. Dupont de Nemours & Co. Organic Chemicals Department

At 27°C

T°C = <6 to 28

Freq. (Hz)	FPS-1418 b.p. 148°C κ	FPS-1418 tan δ	FPS-1419 b.p. 101°C κ	FPS-1419 tan δ	FPS-1420 b.p. 153°C κ	FPS-1420 tan δ
10^2	1.890	$3x10^{-6}$	1.859	$1.6x10^{-5}$	2.570	$3.23x10^{-3}$
10^5	1.890	$3x10^{-6}$	1.859	$2x10^{-6}$	2.570	$1.6x10^{-5}$
10^8	1.888	.00243	1.857	$4.2x10^{-4}$	2.53	.0126
10^9	1.851	.0142	1.833	.0042	2.420	.0952
$3x10^9$	1.838	.0124	1.832	.0076	2.213	.0995
$8.5x10^9$	1.797	.0068	1.798	.0084	2.026	.0907

Mullet oil — U. S. Bureau of Fisheries

Freq. (GHz)	24 ± 0.5°C κ	24 ± 0.5°C tan δ	10 ± 1°C κ	10 ± 1°C tan δ
1	2.54	.068	-	-
8.5	2.52	.0507	2.50	.0458
14	2.42	.0468	2.39	.0443
24	2.35	.0384	2.36	.0380

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13. ABSTRACT

Extensions of the laboratory's measuring techniques for complex dielectric constants to wider ranges of temperature (4° to 2000°K) and frequency (.008 Hz to 90 GHz) are reviewed. Methods of interpreting dielectric data and computer programs for finding the components of complex spectra are discussed. Measurement data of general interest accumulated in the last three years appear in graphical and/or tabular form.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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High-temperature materials						
Relaxation spectrum analysis						

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