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**Massachusetts Inst of Tech
Cambridge Lab for Insulat—ETC**

**Dielectric Spectroscopy of High-Temperature
Materials.**

Westphal, W. B.

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AFML-TR-66**

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14	REPORT TITLE	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ACLF	WT
	Dielectric constant measurements						
	Dielectric loss measurements						
	High-temperature materials						
	Capacitance bridge						
	Resonant cavity						

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Errata Sheet

p. 11, Program 1, lines 4 and 5 from top have to be retyped so that cosine is moved 3 spaces to the right.

p. 21, ~~IT~~ MISCELLANEOUS INORGANICS AND MIXTURES, the tabulations should read:

Concrete pavement

California Highway Department

<u>Sample</u>	Density (g/cm ³)	H ₂ O (%)	(MHz)	0.1	1	10	100
S1	2.284	0	κ	9.05	7.97	7.01	6.57
			tan δ	.0946	.0913	.0730	.0536
S1		25.89	κ	176.5	69.2	23.5	13.2
			tan δ	.822	1.088	.734	.485

Asphalt pavement

California Highway Department

<u>Sample</u>	Density (g/cm ³)	H ₂ O (%)	(Hz)	10 ⁵	10 ⁶	10 ⁷	10 ⁸
S	2.06	0	κ	4.51	4.34	4.21	4.14
			tan δ	.0280	.0221	.0181	.0198
S		2.55	κ	42.0	17.7	9.03	6.54
			tan δ	.875	.638	.444	.233
L	2.46	0	κ	4.79	4.73	4.70	4.61
			tan δ	.0187	.0158	.0123	.0121
L		~0.36	κ	14.48	9.28	6.65	6.01
			tan δ	.368	.280	.190	.104

Dielectric Spectroscopy of High-Temperature Materials

W. B. Westphal and J. Iglesias

Laboratory for Insulation Research
Massachusetts Institute of Technology
Cambridge, Massachusetts

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FOREWORD

This report was prepared by the Massachusetts Institute of Technology, Laboratory for Insulation Research, Cambridge, Massachusetts, under USAF Contract F33615-70C-1220. 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. W. G. D. Frederick acting as project engineer.

This Final Report covers work conducted from February 1, 1970 to January 31, 1971, and was submitted on February 26, 1971 by the authors for publication.

This technical report has been reviewed and is approved.

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Air Force Materials Laboratory

ABSTRACT

Measuring techniques for extending dielectric-constant and loss measurements to liquid-nitrogen temperature at 10 MHz, to 2000°C at 100 MHz, and to 1600°C at 90 GHz are discussed. High-temperature measurements on spinel and sapphire are included in the dielectric data accumulated during this contract. Programs in Fortran IV are given for the general standing-wave method calculations and for covered high-loss samples one-quarter wavelength from the end of hollow waveguide.

TABLE OF CONTENTS

	Page
Introduction	1
Measurement and Instrumentation Techniques	1
Low-Frequency Bridges	1
extension for a Two-Terminal Bridge	3
Resonant Cavity for 100 MHz	4
Resonant Cavity Method for Soft Materials	6
90-GHz Equipment	7
Programming	8
References	10
Program I	11
Program II	13
Index to Dielectric Data	16

ILLUSTRATIONS

Figure		Page
1.	Schematic of precision low-frequency bridge.	2
2.	Photographs of bridge switch.	3
3.	Photographs of bridge extension: (a) for above ambient; (b) for below ambient.	3
4.	Reentrant cavity: (a) cross section; (b) photograph; (c) symmetry plane; (d) equivalent circuit of reentrant cavity.	5
5.	Equipment for measurement of Q of reentrant cavity.	6
6.	High-temperature pressure welding of resonant cavity; (a) foil formed on mandrel, two are made. Faces are welded by hot-pressing; (b) welding of flanges by hot-pressing with sample inside; (c) finished dielectric-filled cavity; (d) cavity in graphite container as used during measurements.	6

INTRODUCTION

In the first section of this report extensions of measurement techniques developed since March 31, 1970, are described. These include a method for using the dielectric-filled cavity technique with soft materials, details of design for a 100 MHz reentrant cavity, and the use of a light pipe for 3-mm measurements. The next section discusses programming for dielectric calculations. The final section lists measurement data on materials and is supplementary to AFML-TR-70-138.

MEASUREMENT INSTRUMENTATION AND TECHNIQUES

Low-Frequency Bridge*

Acquisition of a General Radio Type 1620-AP capacitance measuring assembly has allowed us to recalibrate the precision capacitor used in our two-terminal bridge for high-temperature measurements. The basic accuracy of 0.01% assures that capacitance measurement errors on solid samples will be negligible in comparison to thickness measurement errors.

Experience in measuring small (<2 pf) high-loss, three-terminal samples has indicated the need for more precise measurements than can be obtained with any known direct-reading bridge. For example, the accuracy in measuring a 1-pf, 1-megohm sample at 100 cycles is limited as follows:

The GR 1615 can be balanced only with $M = 10$ or greater which limit capacitance resolution to 0.01 pf (1%). In addition, capacitance of the conductance (G) network causes an unspecified error.

On the GR 1616, the capacitance resolution is not a significant error, but the specified possible error due to the capacitance of the G network is 0.03 pf (3%).

On our present laboratory bridges¹⁾ and the Cole-Gross bridge²⁾ errors due to the capacitance of the G network can be made small only by a sacrifice in sensitivity by increased loading of the detector terminals.

The Harris bridge avoids the above problems by using a two-phase source but the practical limit of air capacitors in the G phase is about 1000 pf, corresponding to a sample resistance of 1.6 megohms minimum at 100 cycles (if full voltage is applied to the sample).³⁾

A new bridge is under construction which should provide routine operation with capacitance errors due to the G network of 0.001 pf and provides an adjustment to reduce the error toward zero for any sample with extra bridge balances. The bridge shown schematically in Fig. 1 is designed for use in the frequency range 0.5 Hz (with 1 volt) to 1 kHz. Six digit resolution in C is provided by 2

* Work described in this section was jointly sponsored by ONR (Contract N00014-67A-0204-0003).

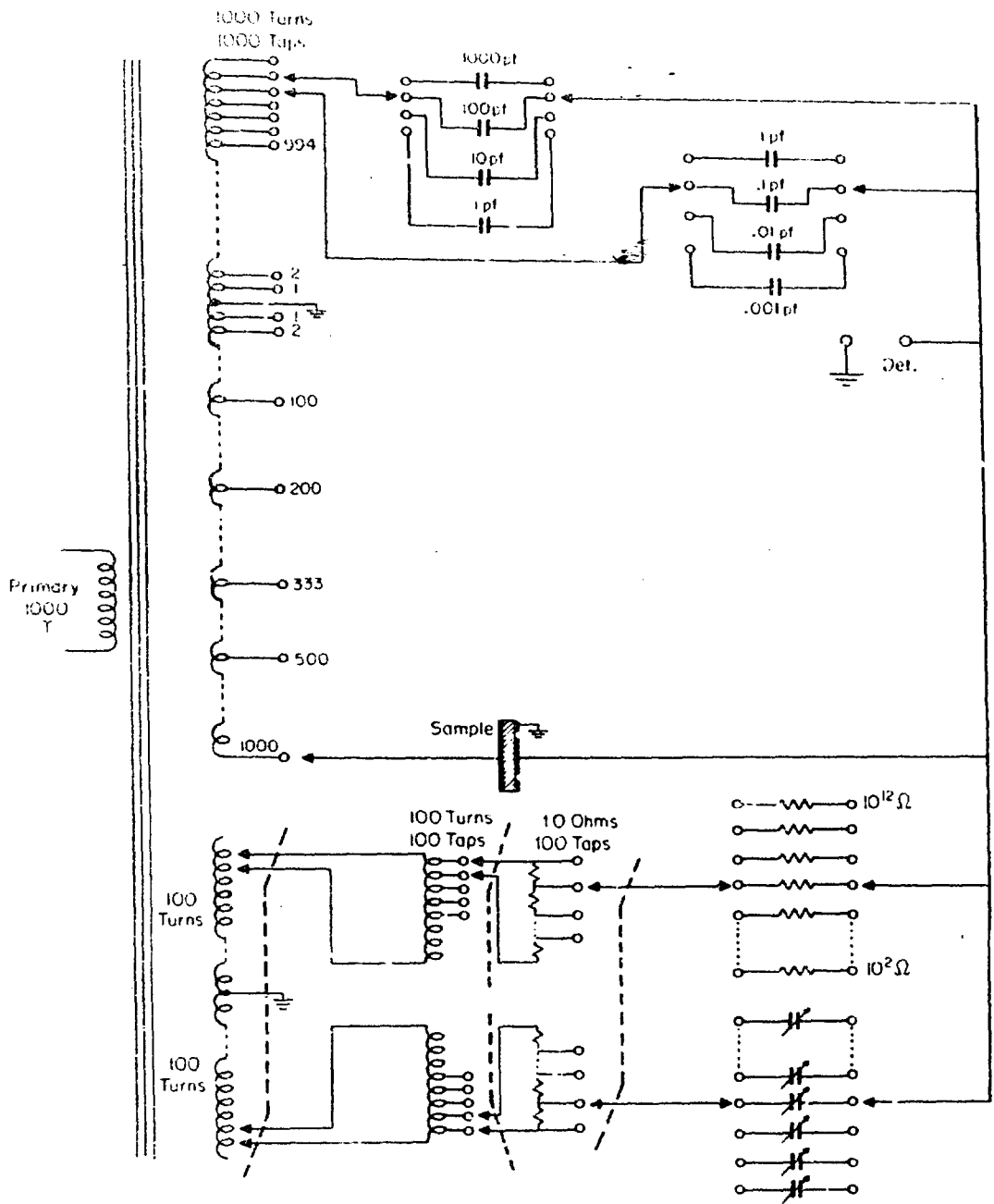


Fig. 1. Schematic of precision low-frequency bridge.

standard capacitors and 1000-turn transformer winding tapped at each turn. Six digit resolution in C is provided by using 100 turns of the transformer plus a 100-turn divider transformer plus a resistance potentiometer. These controls are duplicated with a symmetrical construction in the sample side of the bridge; here capacitors are adjusted to balance out the capacitance of the opposite conductivity network. Assuming that the transformer and C networks are ideal, successive balances made using phase-sensitive detectors and a series of samples with increasing loss should lead to a properly compensated C network. In Fig. 2, the



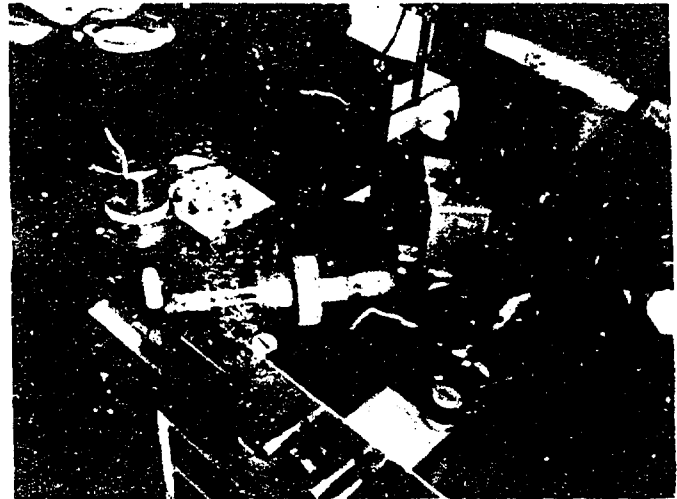
Fig. 2. Photographs of bridge switch.

construction of the 1000 point, 2-circuit capacitance switch is shown in present state. Contact fingers not shown will mount on the rotating cage and will contact pins in the phenolic drum. The holes for these pins are shown in a spiral pattern, 10 turns, 100 points per revolution.

Extension for a Two-Terminal Bridge

A basic problem exists in using our two-terminal wide-range bridge⁴⁾ for both hot and cold temperatures. For high temperatures the coaxial line connecting the sample to the bridge should go upward from the bridge to avoid heat transfer by convection to the bridge; for cold temperature the sample should be below the bridge. If separate sample holders are used for the two temperature regions, the sample must be transferred with risk of moisture contamination and two separate calibrations of sample holder capacitance are required. To avoid this problem, we have constructed an extension with a swivel joint in a horizontal line. As shown in Fig. 3, ordinary copper tube fittings, 2-1/2 inch size, were used for the outer conductor.

(a)



(b)

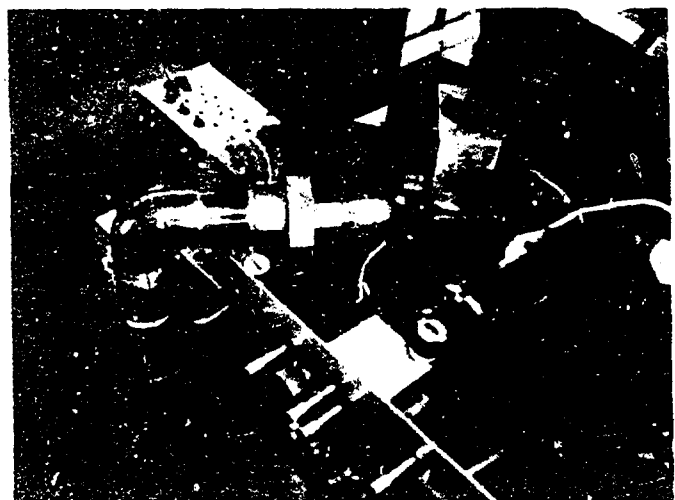


Fig. 3. Photographs of bridge extension: (a) for above ambient; (b) for below ambient.

The inner conductor size is 7/8 inch. These large conductors, combined with close proximity of switch and sample, result in nominal line loss correction of 0.0002 in $\tan \delta$ at 10 MHz.

Resonant Cavity for 100 MHz

As indicated in a previous report,⁵⁾ a high-temperature measuring system at 100 MHz would be a desirable addition in the temperature-frequency plot of this laboratory's capabilities. A doubly-reentrant cavity (Fig. 4a) offers the possibility of reasonably accurate loss measurements to 2000°C. Direct measurement of absolute value of κ' might not be accurate (because of expansion effects in the cavity), but comparisons between materials should be satisfactory. The equivalent lumped circuit of the cavity is visualized by cutting the outer conductor on the center plane. The shorted coaxial line sections at each end are less than $\lambda/4$ long; at one frequency their equivalent is a lumped inductor (Fig. 4d). The center capacitor is divided into two sections by the center plane; each capacitor has the value $2C$. Resonance obviously occurs when $2\omega^2 LC = 1$ in the equivalent series circuit when the outer conductor is reconnected. Calculations of theoretical losses for an empty cavity show the losses separated into 4 parts:

1. Resistance of outer conductor of coaxial line.
2. Resistance of inner conductor of coaxial line.
3. Resistance of shorting plane at end of line.
4. Resistance of electrodes.

In Table 1 are tabulated the results of calculations for 3 cavities, all copper at 25°C, inner conductor and electrode face of Pt at 25°C, and the same at 1600°C. The measured value of Q for the copper cavity includes the contact losses of the spring fingers joint, coupling losses to generator and detector, and dielectric loss in the heat-shielded material; the 25°C, 100-MHz value is 4350. Figure 5 shows the equipment used for determining Q by the frequency variation method.

Table 1. Losses in reentrant cavity at 100 MHz, $C_g = 33.9$ pf.

Conductors	R1	R2	R3	R4	Q
Copper, 25°C	0.22	0.92	2.61	0.10	6100
Part Cu, part Pt, 25°C	0.22	2.27	2.61	0.51	4175
" " 1600°C	0.22	6.00	2.61	1.34	2305
Copper, * 25°C	0.43	1.79	3.20	0.26	6400
* At 150 MHz $C_g = 14.6$ pf.					

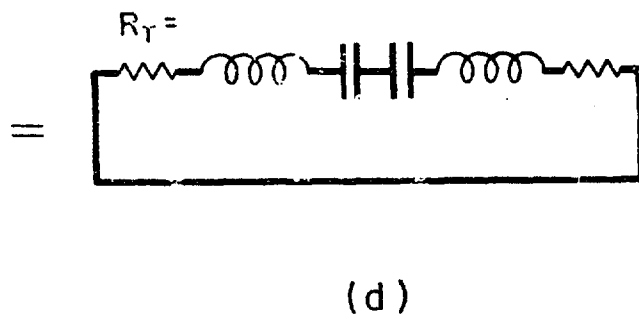
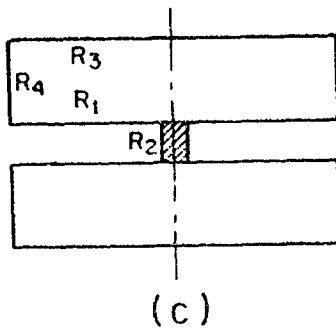
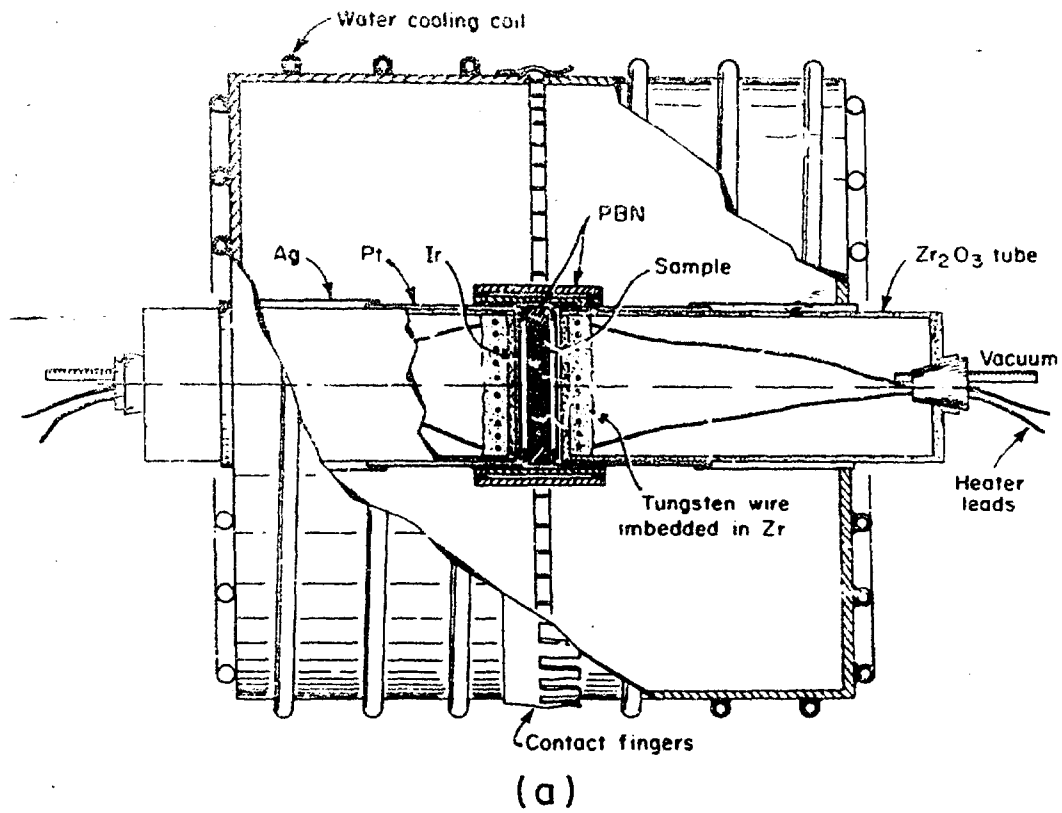


Fig. 4. Reentrant cavity; (a) cross section; (b) photograph; (c) symmetry plane; (d) equivalent circuit of reentrant cavity.

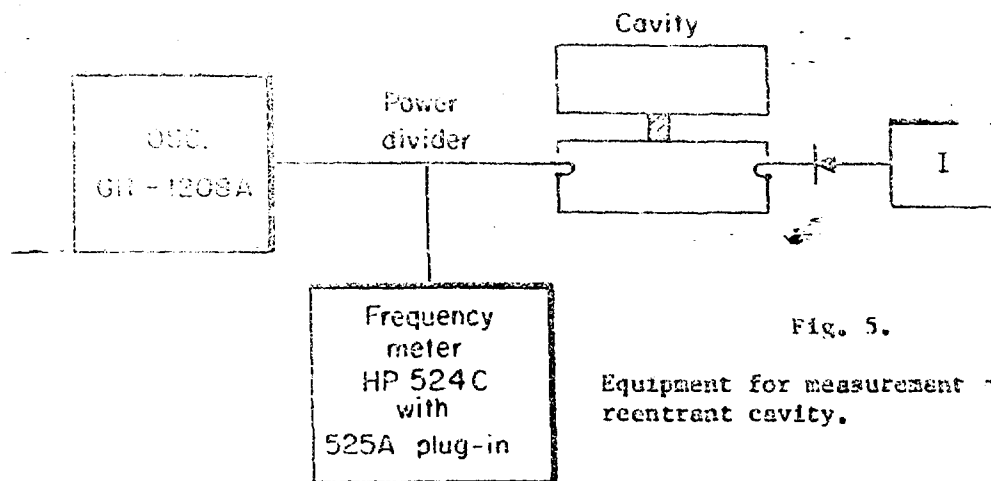


Fig. 5.

Equipment for measurement of Q of reentrant cavity.

Resonant-Cavity Method for Soft Materials

Our usual procedure for measuring materials above 1000°C has been to form a dielectric-filled cavity of the sample by wrapping it with Pt or Pt-Rh foil and

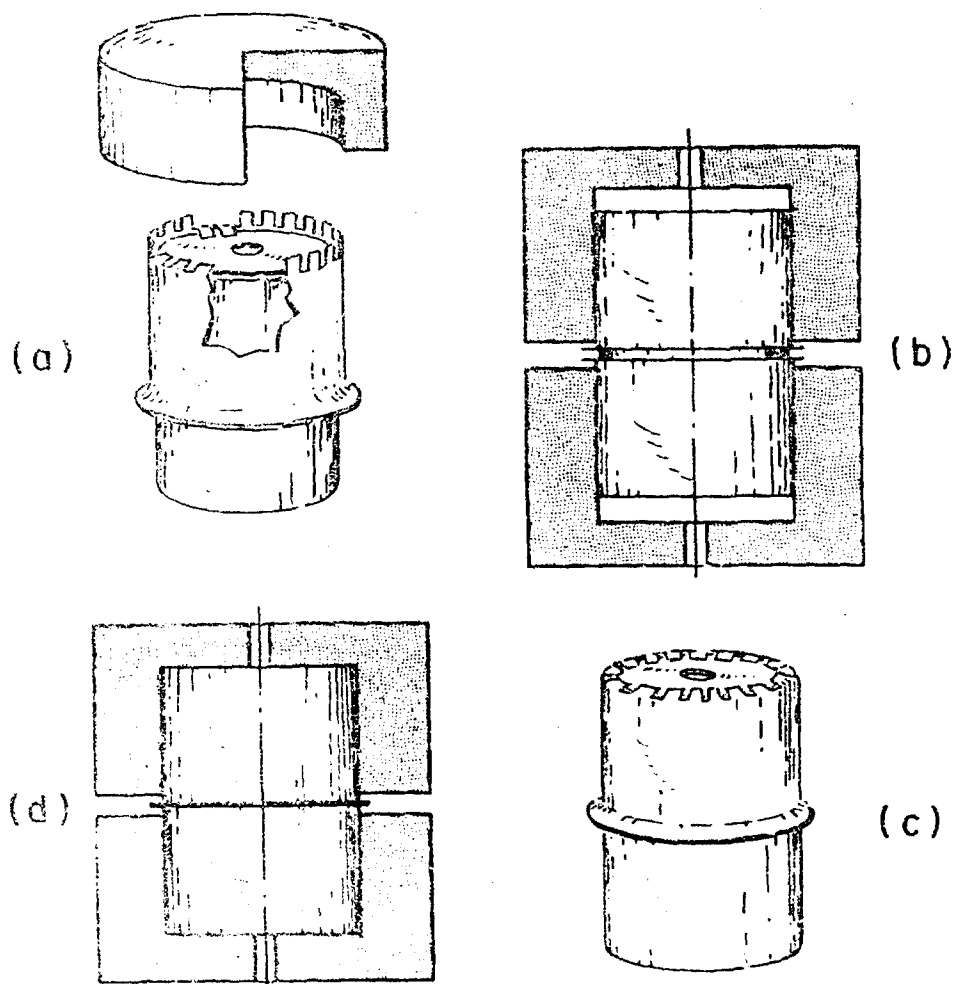


Fig. 6. High-temperature pressure welding of resonant cavity; (a) foil formed on mandrel, two are made. Faces are welded by hot-pressing; (b) welding of flanges by hot-pressing with sample inside; (c) finished dielectric-filled cavity; (d) cavity in graphite container as used during measurements.

welding the foil by hot-pressing against the sample faces. An alternate method is to make two flanged cups as shown in Fig. 6 using graphite plunger and die. With the sample in the cups, the rims are hot-pressed together. As usual, graphite cups surround the sample during measurement.

90-GHz Equipment

This bridge equipment, as originally built, was intended for use with relatively thin samples (<1 cm) and small diameter (5/8 inch), with an absorbing tube surrounding the sample. Measurements on fused silica and pyrolytic graphite have not yielded measurable loss values. Longer samples showed attenuation which varied depending on the absorber; this indicates the beams of energy are not narrow enough for long samples. Metallic tubes were substituted but have not been fully evaluated to find minimum satisfactory diameter and length combinations.

PROGRAMMING

Computation of κ' , κ'' in Standing-Wave Measurements

The computation procedure for covered samples less than 1.4 radians long and mounted over a quarter wavelength in coaxial line has been previously given.⁶⁾ The program has been developed for any length of sample in hollow waveguide with TE mode. The same program may be used for a sample without cover (by setting the constants $K1$ and $K2$ equal to zero) and with coaxial line [by setting $(\lambda/\lambda_c)^2$ equal to zero]. The input data consist of node width with sample-in corrected for loss in air-filled section of line (DS), the node position with sample-in (SN) and the node position with sample out (AN). The value of $2\pi X_0/\lambda$ in the program is written

$$2\pi[XE - AN + SN(I)]/LW.$$

There are three common ways of taking the sample-out node position:

(1) Sample and cover are both removed, so empty holder is used. Then $XE = -(D2 + D3)$, where $D2$ and $D3$ are the thickness of cover and sample, respectively.

(2) Sample is removed, cover is left in same position. Then XE is the calculated value of X_0 with cover and empty sample space:

$$XE = \frac{\lambda}{2\pi} \tan^{-1} \left[\frac{K1 - \tan(2\pi D3/\lambda)}{1 + K2 \tan(2\pi D3/\lambda)} \right].$$

(3) Sample holder (in which the top of the cover is located a distance d_h from the top of the holder) is removed and replaced by a shorting plane. Then $XE = d_h$.

When the sample over quarter wavelength holder is used as in the previous program,

$$XE = \frac{\lambda}{2\pi} \tan^{-1} \left[\frac{\cot(2\pi D3/\lambda) + K1}{1 - K2 \cot(2\pi D3/\lambda)} \right].$$

In the programs and in the above expressions:

$\lambda = LW =$ wavelength in air-filled section of waveguide [hollow (TE modes) or coax (TE mode)],

$$FC = \left(\frac{\lambda}{\lambda_c} \right)^2,$$

$$W = 1 + FC$$

$$K1 = - \frac{1}{(\kappa_2^2 W - FC)^{1/2}} \tan \left[\frac{2\pi D2}{\lambda} (\kappa_2^2 W - FC)^{1/2} \right],$$

$$K2 = (\kappa_2^2 W - FC)^{1/2} \tan \left[\frac{2\pi D2}{\lambda} (\kappa_2^2 W - FC)^{1/2} \right],$$

$$K3 = \frac{\lambda}{2\pi D3}.$$

Losses in the cover are neglected but the program can be readily changed to include these losses if necessary. The wall losses in sample-filled section are included in the results as computed. They are readily subtracted at the end of the computation.⁶⁾

REFERENCES

1. A. von Hippel and co-workers, "The Dielectric Relaxation Spectra of Water, Ice, and Aqueous Solutions and Their Interpretation. VI. New Measurements on Relaxation and Conduction of 'Pure' Ice I_h Single Crystals and Their Critical Evaluation," Tech. Rep. 6 (Contract N00014-67A-0204-0003), Lab. Ins. Res., Mass. Inst. Tech., May 1969, p. 15.
2. Dielectric Materials and Applications, A. von Hippel, Ed., The Technology Press at MIT and John Wiley & Sons, New York, 1954, p. 58.
3. W. P. Harris, "Operator's Procedure Manual for Harris Ultra Low Frequency Impedance Bridge," NBS Report 9627, U.S. Department of Commerce, National Bureau of Standards, October 1967.
4. R. E. Charles, K. V. Rao, and W. B. Westphal, "A Capacitance Bridge Assembly for Dielectric Measurements from 1 Hz to 40 MHz," Tech. Rep. 201, Lab. Ins. Res., Mass. Inst. Tech., October 1966.
5. W. B. Westphal and J. Iglesias, "Dielectric Measurements on High-Temperature Materials," Tech. Rep. AFML-TR-70-138, Lab. Ins. Res., Mass. Inst. Tech., July 1970.
6. Reference 5, pp. 6-9, 14,15.
7. Reference 2, p. 86.

PROGRAM I
THIN COVERED SAMPLE (<1.4 radians) OVER QUARTER WAVELENGTH
IN HOLLOW GUIDE

FORTRAN IV G LEVEL 18

MAIN

DATE = 71115

11/59/03

```

0001      INTEGER*4 I,J,K,N,NX
0002      REAL*8 K1,K2,K3,Y,XE,AN,SN,LW,DX,DS,DA,X,A,B,A2,B2,Z14RE,Z14IM,
      2BOLD,Z14IND,Z14ROD,ERROR1,EROLD,AOLD,AIM,RE,TAM,Z11RE,Z11IM,WE,
      3COSINE,FC,W,ZM,Y1,TAHA,TANB,PI1,PII2,ZR3,ONE,STEP(4)/1.0-2,1.0-3,
      41.0-4,1.0-5/,NOB,F(2)/1.00,-1.00/
0003      COMPLEX*16 Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11,Z12,Z13,Z14R,Z14I,
      Z14,Z12NEW,Z12RE,Z12IM,Z12SQ,G,H,Z15,Z2A,ZONE,ZONE
0004      REAL*8 SILLY(2),FAKE(2),FUN(2)
0005      EQUIVALENCE (SILLY(1),Z11),(FAKE(1),Z15),(FUN(1),Z12SQ)
0006      DIMENSION DS(10),SN(10),DATE(18)
0007      NAMELIST/IN/DS,SN,NX/CONST/DA,AN,XE,K1,K2,K3,FC,W,LW/OUT/K1,K2,
      2K3,LW/OUT2/Z1,Z2,Z4,Z9,A,B
0008      200 FORMAT(1X,18A4)
0009      77 READ(5,200,END=88) DATE
0010      201 FORMAT(1H1,20X,18A4)
0011      WRITE(6,201) DATE
0012      READ(5,IN)
0013      READ(5,CONST)
0014      WRITE(6,IN)
0015      WRITE(6,CONST)
0016      100 FORMAT(1H0,5X,2HNS,10X,2HDS,11X,2HK1,11X,2HK2,12X,3HTAN,20X,3HZ11,
      231X,3HZ14//)
      WRITE(6,100)
0017      ZONE=(1.00,0.00)
0018      ZOONE=(0.00,1.00)
0019      PII=31416.0-4
0020      PII2=62832.0-4
0021      ZR0=0.00
0022      ONE=1.00
0023      DO 10 I=1,NX
0024      IF(SN(I).EQ.AN) GO TO 10
0025      Y=PII2*(XE-AN+SN(I))/LW
0026      DX=DS(I)-DA
0027      IF(DX.LE.ZR0) GO TO 10
0028      COSINE=DCOS(PII*DX/LW)**2
0029      X=DSIN(PII*DX/LW)/DSQRT(2.00-COSINE)
0030      Y1=DTAN(Y)
0031      Z1=ZONE*Y1
0032      Z2A=ZONE*X
0033      Z2=Z2A-Z1
0034      Z3=ZONE-Z2A*Z1
0035      Z4=Z2/Z3
0036      Z5=ZOONE*K1
0037      Z6=Z4+Z5
0038      Z7=Z3ONE*K2
0039      Z8=ZONE+Z4*Z7
0040      Z9=Z8/Z6
0041      Z10=ZOONE/K3
0042      Z11=Z10*Z9
0043      Z11RE=SILLY(1)
0044      Z11IM=SILLY(2)
0045      Z12SQ=DSQRT(Z11+(1.00/3.00)*Z11**2)
0046      A=FUN(1)
0047      B=FUN(2)
0048      160 TAHA=DTANH(A)
0049      TANB=DTANH(B)
0050      A2=TAHA*(ONE+TANB**2)/(ONE+TAHA**2*TANB**2)
0051      B2=TANB*(ONE-TAHA**2)/(ONE+TAHA**2*TANB**2)
0052      Z14RE=A*A2-B*B2
0053      Z14IM=A*B2+B*A2
0054      ERROR1=DSQRT((Z14RE-Z11RE)**2+(Z14IM-Z11IM)**2)
0055      DO 400 K=1,4
0056      TAHA=DTANH(A)
0057      DO 400 J=1,2
0058      WE=ONE+STEP(K)*F(J)
0059      401 BOLD=B
0060      Z14ROD=Z14IM
0061      Z14ROD=Z14RE
0062      EROLD=ERROR1
0063

```

PROGRAM I (cont.)

```

0065      B=R*WF
0066      TANB=DTAN(B)
0067      A2=TANA*(ONE+TANB**2)/(ONE+TANA**2*TANB**2)
0068      B2=TANB*(ONE-TANA**2)/(ONE+TANA**2*TANB**2)
0069      Z14RE=A*A2-B*B2
0070      Z14IM=A*B2+B*A2
0071      FRRDR1=DSORT((Z14RE-Z11RE)**2+(Z14IM-Z11IM)**2)
0072      IF(ERROR1.LE.EPOLD) GO TO 401
0073      Z14IM=Z14IOD
0074      Z14RE=Z14ROD
0075      B=ROLD
0076      ERROR1=EPOLD
0077      600 CONTINUE
0078      TANB=DTAN(B)
0079      DO 700 J=1,2
0080      WE=ONE+STEP(K)*F(J)
0081      402 AOLD=A
0082      Z14ROD=Z14RE
0083      Z14IOD=Z14IM
0084      EPOLD=ERROR1
0085      A=A*WE
0086      TANA=DTAN(A)
0087      A2=TANA*(ONE+TANB**2)/(ONE+TANA**2*TANB**2)
0088      B2=TANB*(ONE-TANA**2)/(ONE+TANA**2*TANB**2)
0089      Z14RE=A*A2-B*B2
0090      Z14IM=A*B2+B*A2
0091      FRRDR1=DSORT((Z14RE-Z11RE)**2+(Z14IM-Z11IM)**2)
0092      IF(ERROR1.LE.EPOLD) GO TO 402
0093      Z14RE=Z14ROD
0094      Z14IM=Z14IOD
0095      A=AOLD
0096      ERROR1=EPOLD
0097      700 CONTINUE
0098      IF(ERROR1.LE.1.0-6) GO TO 450
0099      400 CONTINUE
0100      450 Z12RE=ZONE*A
0101      Z12IM=ZOCNE*B
0102      Z12NEW=(Z12RE+Z12IM)**2
0103      Z13=-Z12NEW**K3**2
0104      G=ZONE*FC
0105      H=ZONE*W
0106      Z15=(G+Z13)/H
0107      Z14R=ZONE*Z14RE
0108      Z14I=ZOCNE*Z14IM
0109      Z14=Z14R+Z14I
0110      RE=FAKE(1)
0111      AIM=-FAKE(2)
0112      TAN=AIM/RE
0113      300 FORMAT(7X,F8.4,5X,F7.4,5X,F9.3,5X,F9.3,5X,F8.4,5X,E13.6,3X,E13.6,
0114      25X,E13.6,3X,E13.6)
0115      WRITE(6,300) SN(1),DS(1),RE,AIM,TAN,Z11,Z14
0116      WRITE(6,OUT2)
0117      10 CONTINUE
0118      GO TO 77
0119      88 CALL EXIT
0120      END

```

NOT REPRODUCIBLE

TYPICAL PRINT-OUT

NS	DS	K1	K2	TAN
0.6250	0.0700	30.705	4.965	0.1617
0.6310	0.0710	29.533	4.894	0.1657
	Z11			Z14
	-0.2717080-01	0.4506940-02	-0.2717070-01	0.4506930-02
	-0.2610680-01	0.4439130-02	-0.2610690-01	0.4439150-02
EOU				
K1=-0.1131899999999999		K2= -1.198499999999999		K3= 46.99499999999999
END				
		W= 4.499999999999999		

PROGRAM 11
 COVERED SAMPLE OF ANY LENGTH (1/2 HALF WAVELENGTHS)
 AGAINST SHORT IN HOLLOW GUIDE

```

FORTRAN IV C (LEVEL 18)          MAIN          DATE = 1112          17/37/44

0001      INYEGFR#4 I,J,K,N,NX
0002      REAL*8 K1,K2,K3,Y,XE,AN,SN,LW,DX,DS,DA,X,A,B,A2,B2,Z14RE,Z14IM,
2001D,Z14TOD,Z14ROD,ERROR1,EROID,AOLD,AIM,RE,TAM,Z11RE,Z11IM,WE,
3COS,INF,FC,W,7M,Y1,TANA,TANB,PI1,PI12,ZRO,ONE,STEP(221/0.100,5.0,2,
42.0-2.1,0-2.5,0-3.2,0-3.1,0-3.5,0-4.2,0-4.1,0-4.5,0-5.2,0-5.1,0-5.
55.0-6.2,0-6.1,0-6.1,0-7.1,0-8.1,0-9.1,0-10.1,0-11.1,0-127,NDB,
6F(2)/1.00,-1.00/SOLD
0003      COMPLEX*16 Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,Z9,Z10,Z11,Z12,Z13,Z14R,Z14I,
Z14,Z12NEW,Z12RE,Z12IM,Z12SO,G,H,715,72A,ZONE,700NE
0004      REAL*8 SILLY(2),FAKE(2)
0005      EQUIVALENCE (SILLY(1),Z11),(FAKE(1),Z15)
0006      DIMENSION DS(56),SN(56),N(56),DATE(18)
0007      NAMELIST/IN/DS,SN,N,NX/CONST/DA,AN,XE,K1,K2,K3,FC,W,LW/OUT/A,
ZB,Z14RE,Z14IM,K,J,ERROR1,KOUNT,WE
0008      200 FORMAT(1X,18A4)
0009      77 READ(5,200,FND=88) DATE
0010      201 FORMAT(1H1,20X,18A4)
0011      WRITE(6,201) DATE
0012      READ(5,IN)
0013      READ(5,CONST)
0014      WRITE(6,IN)
0015      WRITE(6,CONST)
0016      100 FORMAT(1H0,5X,2HNS,6X,2HDS,6X,1HW,5X,2HK1,9X,2HK2,9X,3HTAN,
Z18X,3HZ11,28X,3HZ14//)
0017      WRITE(6,100)
0018      ZONE=(1.00,0.00)
0019      ZONE=(0.00,1.00)
0020      PI1=31416.0-4
0021      PI12=62832.0-4
0022      ZRO=0.00
0023      ONE=1.00
0024      DO 10 I=1,NX
0025      IF(SN(I).EQ.AN) GO TO 10
0026      Y=PI12*(XE-AN+SN(I))/LW
0027      DX=DS(I)-DA
0028      IF(DX.LE.ZRO) GO TO 10
0029      COSINE=DCOS(PI1*DX/LW)*2
0030      X=DSIN(PI1*DX/LW)/DSORT(2.00-COSINE)
0031      Y1=DTAN(Y)
0032      Z1=ZONE*Y1
0033      Z2A=ZONE*X
0034      Z2=Z2A-Z1
0035      Z3=ZONE-Z2A*Z1
0036      Z4=Z2/Z3
0037      Z5=ZONE*K1
0038      Z6=Z4*Z5
0039      Z7=ZONE*K2
0040      Z8=ZONE+Z4*Z7
0041      Z9=Z6/Z8
0042      Z10=ZONE*(-K3)
0043      Z11=Z10*Z9
0044      Z11RE=SILLY(1)
0045      Z11IM=SILLY(2)
0046      ZM=DSORT(Z11RE**2+Z11IM**2)
0047      IF(N(I).EQ.1) GO TO 141
0048      IF(N(I).GE.2) GO TO 142
0049      141 IF(ZM.LE.ONE.AND.Z11RE.GE.ZRO) GO TO 150
0050      IF(ZM.LE.ONE.AND.Z11RE.LT.ZRO) GO TO 151
0051      IF(ZM.GT.ONE.AND.Z11RE.GE.ZRO) GO TO 152
0052      IF(ZM.GT.ONE.AND.Z11RE.LT.ZRO) GO TO 153
0053      142 IF(ZM.LE.ONE.AND.Z11RE.GE.ZRO) GO TO 170
0054      IF(ZM.LE.ONE.AND.Z11RE.LT.ZRO) GO TO 171
0055      IF(ZM.GT.ONE.AND.Z11RE.GE.ZRO) GO TO 172
0056      IF(ZM.GT.ONE.AND.Z11RE.LT.ZRO) GO TO 173
0057      150 R=ONE
0058      A=4.0-1*DX/LW
0059      GO TO 160
0060      151 R=2.0-1
0061      A=2.00*DX/LW
  
```


PROGRAM II (cont.)

```

0062      GO TO 160
0063      R=ONE
0064      A=6.07*DX/LW
0065      GO TO 160
0066      153 R=18.0-1
0067      A=DX/LW
0068      GO TO 160
0069      170 NDB=N(I)
0070      R=(NDB-ONE)*PII+7854.0-4
0071      A=4.07*DX/LW
0072      GO TO 160
0073      171 NDB=N(I)
0074      R=NDB*PII-7854.0-4
0075      A=4.07*DX/LW
0076      GO TO 160
0077      172 NDB=N(I)
0078      R=(2.07*NDB-1.00)*157(8.0-4-1.0-1/NDB)
0079      A=DX/LW
0080      GO TO 160
0081      173 NDB=N(I)
0082      R=(2.07*NDB-1.00)*15708.0-4+1.0-1/NDB
0083      A=DX/LW
0084      160 TAHA=DTANH(A)
0085      TANB=DTAN(B)
0086      A2=TAHA*(ONE+TANR**2)/(ONE+TAHA**2*TANB**2)
0087      R2=TANR*(ONE-TAHA**2)/(ONE+TAHA**2*TANB**2)
0088      Z14RE=(A*A2+B*B2)/(A**2+B**2)
0089      Z14IM=(A*B2-B*A2)/(A**2+B**2)
0090      FRRORI=DSORT((Z14RE-Z11RE)**2+(Z14IM-Z11IM)**2)
0091      DO 400 K=1,2
0092      SOLD=STEP(K)
0093      TAHA=DTANH(A)
0094      DO 600 J=1,2
0095      420 WE=ONE+STEP(K)*F(J)
0096      KOUNT=0
0097      401 KOUNT=KOUNT+1 0098      IF(KOUNT.GT.10) GO TO 411
0099      GO TO 425
0100      411 STEP(K)=STEP(K)*10.00
0101      GO TO 420
0102      425 ROLD=R
0103      Z14ROD=Z14IM
0104      Z14ROD=Z14RE
0105      FROLD=FRRORI
0106      B=R*WE
0107      TANB=DTAN(B)
0108      A2=TAHA*(ONE+TANR**2)/(ONE+TAHA**2*TANB**2)
0109      R2=TANR*(ONE-TAHA**2)/(ONE+TAHA**2*TANB**2)
0110      Z14RE=(A*A2+B*B2)/(A**2+B**2)
0111      Z14IM=(A*B2-B*A2)/(A**2+B**2)
0112      FRRORI=DSORT((Z14RE-Z11RE)**2+(Z14IM-Z11IM)**2)
0113      IF(FRRORI.LE.EROLD) GO TO 401
0114      Z14IM=Z14ROD
0115      Z14RE=Z14ROD
0116      R=ROLD
0117      FRRORI=FROLD
0118      STEP(K)=SOLD
0119      600 CONTINUE
0120      TANB=DTAN(B)
0121      DO 700 J=1,2
0122      421 WE=ONE+STEP(K)*F(J)
0123      KOUNT=C
0124      402 KOUNT=KOUNT+1
0125      IF(KOUNT.GT.10) GO TO 412
0126      GO TO 428
0127      412 STEP(K)=STEP(K)*10.00
0128      GO TO 421
0129      428 ROLD=A
0130      Z14ROD=Z14RE
0131      Z14ROD=Z14IM
0132      FROLD=FRRORI
0133      A=A*WE
0134      TAHA=DTANH(A)
0135      A2=TAHA*(ONE+TANR**2)/(ONE+TAHA**2*TANB**2)
0136      R2=TANR*(ONE-TAHA**2)/(ONE+TAHA**2*TANB**2)
0137      Z14RE=(A*A2+B*B2)/(A**2+B**2)
0138      Z14IM=(A*B2-B*A2)/(A**2+B**2)
0139      FRRORI=DSORT((Z14RE-Z11RE)**2+(Z14IM-Z11IM)**2)

```

PROGRAM IJ (Cont.)

```

0140      IF(ERROR1.LE.ERO10) GO TO 432
0141      Z14R=Z14ROD
0142      Z14I=Z14IOD
0143      A=AOLD
0144      ERROR1=EROLD
0145      STEP(KI)=SOLD
0146      700 CONTINUE
0147      IF(ERROR1.LE.1.D-6) GO TO 450
0148      400 CONTINUE
0149      450 Z12R=ZONE*A
0150      Z12I=ZNONE*B
0151      Z12NEW=(Z12R+Z12I)**2
0152      Z13=-Z12NEW*K3**2
0153      G=ZONE*FC
0154      H=ZONE*W
0155      Z15=(G+Z13)/H
0156      Z14R=ZONE*Z14RE
0157      Z14I=ZNONE*Z14IM
0158      Z14=Z14R+Z14I
0159      RE=FAKE(1)
0160      AIM=-FAKE(2)
0161      TAN=AIM/RE
0162      300 FORMAT(2X,F7.4,3X,F7.4,3X,I2,3X,F7.4,3X,F9.6,3X,F9.6,3X,E13.6,
22X,E13.6,3X,E13.6,2X,E13.6)
0163      WRITE(6,300) SN(I),DS(I),N(I),RE,AIM,TAN,Z11,Z14
0164      10 CONTINUE
0165      GO TO 77
0166      88 CALL EXIT
0167      END

```

TYPICAL PRINT-OUT

NS	DS	N	K1	K2	TAN
7.0000	0.0100	1	1.1471	0.002666	0.002324
7.0000	1.0000	1	1.1138	0.453739	0.407376
6.5000	0.0100	1	1.7884	0.004175	0.002335
6.5000	1.0000	1	1.5719	0.650037	0.413534
6.0000	0.0100	1	3.7139	0.011904	0.003704
6.0000	1.0000	1	2.0000	1.525029	0.762020
7.5000	0.0100	2	6.9674	0.001903	0.000273
7.5000	1.0000	2	6.9787	0.325143	0.046591
7.0000	0.0100	2	7.3665	0.002279	0.000309
7.0000	1.0000	2	7.2929	0.375678	0.051513
6.5000	0.0100	2	8.0271	0.005175	0.000645
6.5000	1.0000	2	7.6436	0.681794	0.089198
6.0000	0.0100	2	11.0249	0.039429	0.003576
6.0000	1.0000	2	7.4015	1.728636	0.233552

Z11

Z14

0.2414320 C1	-0.2091410-01	0.2414320 01	-0.2091410-01
0.8459020 00	-0.9386930 00	0.8459020 00	-0.9386930 00
-0.1543920 01	-0.2053830-01	-0.1543920 01	-0.2053830-01
0.3352290-02	-0.9350780 00	0.3352200-02	-0.9350780 00
0.1034650 00	-0.2770130-02	-0.1034650 00	-0.2770130-02
0.7152890-01	-0.3936980 00	0.7152920-01	-0.3936980 00
0.9572150 00	-0.2783620-02	0.9572160 00	-0.2783630-02
0.7807970 00	-0.3949790 00	0.7807970 00	-0.3949790 00
0.2414320 01	-0.2091410-01	0.2414320 01	-0.2091410-01
0.8459020 00	-0.9386930 00	0.8459020 00	-0.9386940 00
-0.1543920 01	-0.2053830-01	-0.1543920 01	-0.2053830-01
0.3352290-02	-0.9350780 00	0.3351370-02	-0.9350780 00
-0.1034650 00	-0.2770130-02	-0.1034660 00	-0.2770140-02
0.7152890-01	-0.3936980 00	0.7152880-01	-0.3936980 00

INDEX TO DIELECTRIC DATA

	Page
I. INORGANIC COMPOUNDS	
Aluminum oxide, single crystal, Union Carbide	17
" " multicrystalline, G.E. A-923	17
A-1004	17
Boron nitride, hot-pressed, Battelle Memorial Institute	18
Magnesium aluminate (spinel), single crystal, Union Carbide	18
Silica slipcast, Dynasil	18
Silica fiber, Philco Ford	18,19
Silica fiber phosphate, Whittaker Corp.	20
Silicon nitride, Admiralty Materials Lab.	20
II. MISCELLANEOUS INORGANICS AND MIXTURES	
Concrete pavement, California Highway Department	21
Asphalt pavement, " " "	21
III. ORGANIC COMPOUNDS	
(Listed according to source)	
Budd, copper-clad laminate	22,23
Carborundum, EKONOL (polyester resin)	23
Dodge Industries, FLUORGLAS E 650/2-1200	24
E.I. du Pont de Nemours, Nonex honeycombs	24
IV. LIQUIDS	
(Listed according to source)	
Hercules Inc., VUL-CUP, a, ¹ -bis(t-butyl peroxy) diidopropylbenzene	25
" DI-CUP, dicumyl peroxide	25
Pennwalt Corp., Lucidol Div., Lucidol, t-butyl perbenzoate	25
" " Lupersol 130, 2,5-dimethyl-2,5-di(t-butylperoxy) hexyne-3	25
U.S. Peroxygen Div., Argus Chemical Corp., USP 333	26
Wallace & Tiernan Inc., Lupersol 101, 2,5-dimethyl-2,5-di(t-butylperoxy)hexane	26

I. INORGANIC COMPOUNDS

Aluminum oxide, single crystal

Union Carbide, Electronics Div.

Sapphire Al_2O_3

Density at 25°C = 3.9840 g/cm³

Freq. 3.45 - 3.33 GHz

E ⊥ C

T°C	κ	tan δ
25	9.39	<.0001
80	9.41	<.0001
240	9.49	<.0001
377	9.62	<.0001
526	9.83	<.0001
617	9.95	<.0001
713	10.08	<.00015

Aluminum oxide, multicrystalline

General Electric Company

A-923 (97% Al_2O_3)

Density 3.740 g/cm³

A-1004 (94% Al_2O_3)

Density 3.649 g/cm³

Freq. 3.74 - 3.37 GHz

Freq. 3.80 - 3.61 GHz

T°C	κ	tan δ	T°C	κ	tan δ
25	9.31	.00039	25	9.02	.00076
99	9.41	.00042	100	9.11	.00078
184	9.58	.00053	200	9.26	.00081
281	9.72	.00070	300	9.40	.00093
356	9.84	.00090	400	9.55	.00109
430	9.96	.00112	500	9.69	.00128
562	10.17	.00160	600	9.84	.00177
705	10.42	.00215	650	9.92	.00335
800	10.63	.00265	700	10.00	.0093
903	10.86	.0033			
973	10.98	.0040			
1025	11.17	.0045			
1050	11.22	.0050			
1109	11.38	.0060			
1132	11.41	.010			

Boron nitride
(hot-pressed, after vacuum treatment)

Battelle Memorial Institute

Density in g/cm^3

8.52 GHz, 25°C

Sample	Density	κ	$\tan \delta$
115H7	—	4.37	.00030
118H7	2.132	4.67	.00025

Magnesium aluminate (spinel) MgOAl_2O_3

Union Carbide, Electronics Div.

Single crystal

Density at 25°C = 3.57389 g/cm^3

Freq. 4.23 - 4.07 GHz

T°C	$\kappa \pm 02$	$\tan \delta$
25	8.28	.0001
150	8.42	.0002
231	8.54	.0002
297	8.64	.0003
421	8.85	.0010
455	8.91	.0025

Silica, slip-cast

Dynasil Corp. of America

8.6 GHz, 25°C

Sample	Density (g/cm^3)	κ	$\tan \delta$
DSCX-3	1.970	3.395	.00058
DSCX-8E	2.038	3.513	.00054

Silica fiber composites

Philco-Ford Corp., Aeronutronic Div.

Sample 1-VH-O-M-1, 25°C	(Hz)	10^5	10^6	10^7	7.5×10^7	1.8×10^8
As received,	κ	2.779	2.777	2.777	2.775	2.772*
density 1.536 g/cm^3	$10^4 \tan \delta$	4.6	8.3	6.4	13.4	17*
After 18 hrs.	κ			2.77	2.77	2.77*
vacuum oven 20°C	$10^4 \tan \delta$			4.6	9.1	11.5*

* Extrapolated values.

Silica fiber composites (cont.)

Philco-Ford Corp., Aeronutronic Div.

Sample 1-XB-O-M

Density 1.653 g/cm³

	T ^o C	8.52 GHz κ	tan δ	
As received, Face 1 up	25	2.919	.0062	
Face 2 up	25	2.956	.0064	
After vacuum oven				
80 ^o C, 10 days				
Face 2 up	25	2.938	.00162	
Face 1 up	25	2.895	.00169	
	115	2.89	.0012	
	246	2.89	.0006	
	357	2.90	.0005	
	438	↓	.0006	
	535		.0008	
	608		.0010	
	710		.0014	
	805		.0020	
	908		.0026	
	972		.0028	
	1000		↓ *	.0031*
	25		2.89	.00042

* Extrapolated values.

Silica fibers in aluminum phosphate matrix
ChemCeram

Whittaker Corp.

Sample	T ^o C	8.52 GHz		Density (g/cm ³)
		κ	tan δ	
1, as received	25	2.73	.0051	1.547
2, as "	25	2.70	.0060	1.543
2, dried*	25	2.68	.0043	(wt. loss .049%)
2, room humidity	25	2.70	.0050	
	116	2.70	.0050	
	235	2.71	.0053	
	410	2.71	.0080	
	495	2.71	.0105	
	580	2.72	.0140	
	673	2.72	.0177	
	760	2.72	.0228	
	827	2.73	.0265	
	916	2.74	.0315	
	967	2.75	.038	
	25	2.71	.0047	

* 4 days at 120^oC in vacuum oven.

Silicon nitride ceramic
At 8.52 GHz, density 2.449 g/cm³

Admiralty Materials Laboratory

T ^o C	κ	tan δ
25	5.54	.0036
170	5.54	.00375
323	5.54	.0040
446	5.55	.00365
586	5.55	.0030
674	5.56	.0050
714	5.57	.0054
864	5.58	.00615
912	5.59	.00630
991	5.63	.00665
509	5.55	.0034
348	5.54	.0040

11. MISCELLANEOUS INORGANICS AND MIXTURES

Concrete pavement

California Highway Department

Sample	Density	(Hz)	0.1	1	10	100
S1	Dry	K	9.05	7.97	7.01	6.57
		tan δ	.0946	.0913	.0736	.0586
S1	Wet	K	176.5	69.2	23.5	13.2
		tan δ	.822	1.088	.734	.485

Asphalt pavement

California Highway Department

Sample	Density	(Hz)	10 ⁵	10 ⁶	10 ⁷	10 ⁸
S	Dry	K	4.51	4.34	4.21	4.14
		tan δ	.0280	.0221	.0181	.0198
S	Wet	K	42.0	17.7	9.03	6.54
		tan δ	.875	.638	.444	.233
L	Dry	K	4.79	4.73	4.70	4.61
		tan δ	.0187	.0158	.0123	.0121
L	Wet	K	14.48	9.28	6.65	6.01
		tan δ	.368	.280	.190	.104

III. ORGANIC COMPOUNDS

Copper-clad laminate PE1153

The Budd Co., Polychem Division

E I			10^2	10^3	10^4	10^5	10^6	10^7	
3-terminal, liquid im- mersion, unclad *	25	κ			2.420				
		$\tan \delta$							
Declad †	25	κ			2.451				
		$\tan \delta$							
3-terminal, clad	26	κ	2.650	2.465	2.438	2.432			
		$\tan \delta$	.0945	.0279	.00484	.00093		
	-195	κ	2.416	2.415	2.414	2.411			
		$\tan \delta$	.00030	.00033	.00036	.00022		
	-54	κ	2.433	2.421	2.417	2.413			
		$\tan \delta$	.00042	.00050	.00052	.00031		
2-terminal, clad, meas. 12-21-70	25	κ	2.495	2.475	2.471	2.469	2.468	2.468	
		$\tan \delta$	.01816	.00307	.00083	.00050	.00055	.00035
3-terminal, clad, 2nd sample	25	κ	2.843	2.504	2.457	2.449			
		$\tan \delta$	.141	.0491	.00811	.00126		
	96	κ	2.486	2.398	2.389	2.384			
		$\tan \delta$	.0708	.01343	.00230	.00050		
	250	κ	2.257	2.240	2.232	2.222			
		$\tan \delta$	.0263	.00568	.00238	.00111		
	25	κ	2.759	2.510	2.459	2.451			
		$\tan \delta$	.0970	.0390	.00748	.00115		
	2-terminal, clad	-54	κ	2.484	2.484	2.484	2.479	2.464	2.456
			$\tan \delta$.00034	.00044	.00065	.00062	.00059	.00110
		-195	κ	2.490	2.487	2.485	2.484	2.482	2.470
			$\tan \delta$.00029	.00038	.00053	.00028	.00049	.00091
25		κ				2.462	-	2.458	
		$\tan \delta$				.00050	-	.00033
96		κ	2.474	2.464	2.461	2.460	2.458	2.455	
		$\tan \delta$	.01193	.00226	.00084	.00059	.00052	.00068
250		κ	2.333	2.319	2.312	2.309	2.298	2.295	
		$\tan \delta$	.01013	.00340	.00177	.00147	.00097	.00070
25		κ	2.422	2.415					
		$\tan \delta$	.00995	.00189				
E II									
2-terminal, unclad	25	κ	2.434	2.533	2.431	2.428	2.416	2.413	
		$\tan \delta$	.0037	.00094	.00061	.00035	.00052	.0005

* Refers to sheet stock received without copper.

† Refers to a sample made by mechanically stripping the copper-clad sheet.

Resonant-Cavity Measurements:

~ 8.5 GHz, sample constrained in parallel direction, allowed to expand with temperature against a force 30 lb/sq in the perpendicular direction. Unclad stock.

T ^o C	E I		E II		Thickness cm
	κ	tan δ	κ	tan δ	
-194	2.466	.00063	2.420	.00095	1.911
-54	2.437	.00070	2.397	.00104	1.917
23	2.421	.00091	2.383	.00130	1.924
96	2.396	.00117	2.367	.00147	1.948
250	2.296	.0012	2.246	.00185	2.093

Standing-wave method, 25^oC

E II, one piece unclad 2.387 .00128

EKONOL (polyester resin)

The Carborundum Company

Frequency, Hz	T ^o C	κ	tan δ	
10 ²	25	3.210	.00289	
10 ³	↓	3.210	.00316	
10 ⁴		3.185	.00336	
10 ⁵		3.168	.00348	
10 ⁶		3.156	.00325	
10 ⁷		3.148	.00220	
10 ⁸		3.140	.00215	
8.5x10 ⁹		↓	3.120	.00281
		99	3.11	.0030
	155	3.08	.0040	
	207	3.07	.0061	
	284	3.04	.0104	
	350	3.03	.0230	
	420	3.03	.0230	
	217	2.99	.0067	
	25	2.96	.0025	

FLUORGLAS E 650/2-1200
 TFE-fiberglass laminate

Dodge Industries, Inc.

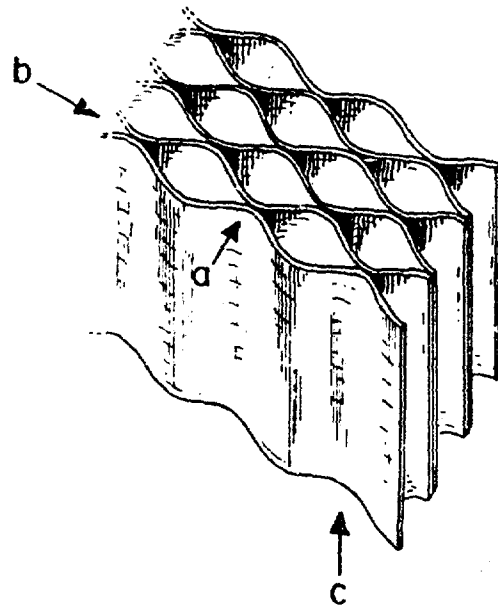
Freq., GHz	T ^o C	E ⊥		E ||	
		κ	tan δ	κ	tan δ
8.5	23	2.505	.0014	2.847	.0036
4	-195	2.533	.00082	2.896	.00172

Nonex honeycombs
 At 8.52 GHz

E. I. du Pont de Nemours and Company

Sample No.	Density	<u>a direction</u>		<u>b direction</u>		<u>c direction</u>	
		E ⊥ double-layer seam	κ	tan δ	E || double-layer seam	κ	tan δ	E || holes
1	1.398	1.0348	.00089	1.0441	.00141	1.0855	.00212
2	2.892	1.0519	.00165	1.0669	.00229	1.0951	.00350
3	3.938	1.0788	.00176	1.1258	.00326	1.1444	.0041
4	4.039	1.0808	.00187	1.1020	.00278	1.1265	.0047
5	4.124	1.0827	.00274	1.1045	.00359	1.1351	.0046
6	4.259	1.0863	.00197	1.1340	.00382	1.1270	.0045
7	4.701	1.0928	.00315	1.1115	.00297	1.1455	.0047
8	5.603	1.0990	.00205	1.1781	.00468	1.1869	.0065
8*	5.603	1.1010	.00330	1.1667	.00628		

* At 100°C, all other values at 25°C



IV. LIQUIDS

VUL-CUP
a,a¹-bis(t-butyl peroxy) diisopropylbenzene

Hercules Inc.
DI-CUP
dicumyl peroxide

25°C		
Freq., Hz	κ	tan δ
10 ²	2.633	.0011
10 ³	↓	.00011
10 ⁴		.000013
10 ⁵		10 ⁻⁵
10 ⁶		.00005 ± 2
1.8x10 ⁷		
6x10 ⁹	↓	
10 ⁸	2.63	.005 ± 2
10 ⁹	2.60	.0206
3x10 ⁹	2.56	.0378
8.5x10 ⁹	2.40	.056

25°C		
Freq., Hz	κ	tan δ
10 ²	2.79	.0073
10 ³	↓	.00081
10 ⁴		.000115
10 ⁵		.000064
10 ⁶		.00040
1.8x10 ⁷		2.97	.0032
6x10 ⁹	2.73	.0025
10 ⁸	2.70	.0050
10 ⁹	2.57	.0082
3x10 ⁹	2.515	.0078
8.5x10 ⁹	2.495	.0044

99°C		
Freq., Hz	κ	tan δ
10 ⁹	2.26	.0116
3x10 ⁹	2.24	.0184

Lucidol
t-butyl perbenzoate

25°C		
Freq., Hz	κ	tan δ
10 ²	-	-
10 ³	-	-
10 ⁴	12.17	.17
10 ⁵	12.17	.017
10 ⁶	12.1	.0027
10 ⁷	12.0	.0095
10 ⁸	11.2	.0044
10 ⁹	5.70	.252
3x10 ⁹	4.07	.337
8.5x10 ⁹	3.23	.460

Pennwalt Corp., Lucidol Div.
Lupersol 130
2,5-dimethyl-2,5-di(t-butylperoxy)hexyne-3

25°C		
Freq., Hz	κ	tan δ
10 ²	2.656	.00123
10 ³	↓	.000123
10 ⁴		.000012
10 ⁵		.000023
10 ⁶		.00012
10 ⁷		2.655	.00121
10 ⁸	2.65	.0066
10 ⁹	2.56	.0235
3x10 ⁹	2.50	.0344
8.5x10 ⁹	2.39	.0505

99°C		
Freq., Hz	κ	tan δ
10 ⁹	2.33	.0076
3x10 ⁹	2.32	.0154

Freq., Hz	25°C	
	κ	tan δ
10^2	3.818	.0170
10^3	↓	.00170
10^4		.00017
10^5		.000027
10^6		.00021
10^7		3.81	.00157
10^8	3.75	.0146
10^9	3.60	.0842
3×10^9	3.30	.130
8.5×10^9	2.80	.1735

Lupersol 101

Wallace & Tiernan Inc.

2,5-dimethyl-2,5-di(t-butylperoxy)hexane

Freq., Hz	25°C	
	κ	tan δ
10^4	2.66	.000088
10^5	2.66	.000144
10^6	2.66	.000053
10^7	2.65	.00049
10^8	2.64	.0050
10^9	2.62	.0217
3×10^9	2.58	.0387
8.5×10^9	2.41	.057
2.4×10^{10}	2.26	.045
	99°C	
10^9	2.02	.0040
3×10^9	2.02	.0068