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STANDARDIZATION ENGINEERING PRACTICES STUDY

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Report No. 2

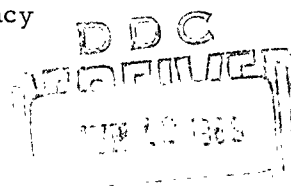
Contract No. DA 36-039 AMC-00008 (E)

Task 701: High Frequency Characteristics of Ceramic Materials

Second Quarterly Progress Report

1 December 1962 to 28 February 1963

U. S. Army Electronic Materiel Support Agency
Production Engineering Department
Standardization Division
Components and Materials Branch
Fort Monmouth, New Jersey



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Task 701: High Frequency Characteristics of Ceramic Materials

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Object: Conduct an investigation of available test procedures, such as the "resonant cavity" method and the "free space reflectometer" method, among others, which will provide reproducible values for the dielectric constant and dissipation factor of ceramic materials at 1.0, 3.0, 8.6, and 24 kMc.

The study should be based upon evaluation of those ceramic insulating materials having good dielectric properties which have met the qualification requirements of Military Specification MIL-I-10, "Insulating Materials, Electrical, Ceramic, Class L".

This investigation should also provide for a literature review of the test procedure, apparatus and data used in and resulting from a study conducted by Battelle Memorial Institute, wherein the slotted-line method, using a dielectrometer, was established as the test procedure. Results of the Battelle work should be correlated with results of this study. (Contract No. DA-36-039-SC-63136).

Report prepared by

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I. PURPOSE

Conduct an investigation of available test procedures, such as the "resonant cavity" method and the "free space reflectometer" method, among others, which will provide reproducible values for the dielectric constant and dissipation factor of ceramic materials at 1.0, 3.0, 8.6, and 24 kMc.

The study should be based upon evaluation of those ceramic insulating materials having good dielectric properties which have met the qualification requirements of Military Specification MIL-I-10, "Insulating Materials, Electrical, Ceramic, Class L".

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This project has been organized and divided up into the following tasks:

- Phase 1: Selection of Method
 - Part a: Background study
 - Part b: Selection of Test Method
- Phase 2: Select Optimum Sample
 - Part a: Sample size
 - Part b: Material
- Phase 3: Procure Samples
 - Part a: Prepare specifications
 - Part b: Procure materials
 - Part c: Fabrication
- Phase 4: Measure and Evaluate
 - Part a: Measurements and calculations
 - Part b: Evaluation and comparison of methods
 - Part c: Preparation of test specifications

II. ABSTRACT

Literature study and analytical calculations were continued in order to provide a background for selection of suitable experimental approaches worthy of trial. Notes on TM_{010} and TE_{011} cylindrical cavity methods are included. Ceramic samples of several ranges of dielectric constant were selected, ordered, and received in readiness for experimental measurements.

III. PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

CONFERENCES

1. S. Devita and others - U.S.A. Electronics Research & Development Laboratory, Fort Monmouth, New Jersey
2. A. Orlowski, A.A. Smith - at General Electric, Electronics Laboratory, Syracuse, New York
3. Dr. E.C. Henry - General Electric, Electronics Laboratory, Syracuse, New York

IV. DATA AND PROGRESS

A. SELECTION OF METHOD

1. Background Study

The stated purpose of this project is to conduct an investigation of available test procedures, other than the slotted-line method, for measuring dielectric constant and dissipation factor of ceramic materials at microwave frequencies. As stated under conclusions in the first quarterly report of this project, the approach should best serve the needs of the Electronic Materiel Support Agency and its relations with ceramics suppliers and users.

In order to weigh and evaluate available methods, considerable study of the literature was necessary. This report contains some of the observations from this literature. A few of the most appropriate resonant cavity test methods are discussed. Some of the most appropriate literature references are cited at the end of the report.

A preliminary analysis of the TM_{010} cavity method was necessary to obtain a better quantitative feeling for the effect of sample diameter on the test results. This involved tabulations of combinations of Bessel Functions. The graphical results of this survey are presented.

2. The TM_{010} Cavity Filled with Dielectric

The TM_{010} cavity is cylindrical with axial electric field and circumferential magnetic field. This electric field is uniform in magnitude from one end of the cylinder to the other. The electric field is maximum at the center line of the cylinder. The electric field is zero at the cylindrical wall where $r=a$. Then $J_0(\beta_0 a) = 0$ where J_0 is a Bessel Function of first kind and zero order. The appropriate

root of this equation for the TM_{010} mode is the lowest; that is when

$$B_0 a = 2.4048 = \frac{2\pi a}{\lambda_0} = a\omega_0 \sqrt{\mu_0 \epsilon_0} = 2\pi f_0 a \sqrt{\mu_0 \epsilon_0}$$

AND $B_1 = B_0 \sqrt{\frac{\epsilon}{\epsilon_0}}$, for cavity filled with material

with dielectric constant ϵ/ϵ_0 .

$$\text{THEN } B_1 = \frac{2\pi a}{\lambda_0} \sqrt{\frac{\epsilon}{\epsilon_0}} = 2.4048 = \frac{2\pi f a}{30} \sqrt{\frac{\epsilon}{\epsilon_0}}$$

$$\text{AND } \frac{\epsilon}{\epsilon_0} = \left(\frac{2.4048}{2\pi a} \right)^2 = \left(\frac{2.4048 \times 30}{2\pi f a} \right)^2 \quad \text{WHERE } \lambda = \text{CM, WAVELENGTH}$$

$f = \text{KILOMEGACYCLES/SEC}$

Thus the resonant wavelength of the cavity is proportional to the radius and

to the square root of the dielectric constant of the filling. The cavity resonates

$$\text{empty when } \frac{2\pi a}{\lambda_0} = 2.4048 = \frac{2\pi f_0 a}{30}$$

The losses are determined from Q measurements with and without the dielectric filling.

$$Q'' = \frac{1}{Q} - \frac{1}{Q'}$$

Q' refers to losses when the same resonator is filled with a loss-free dielectric of the same permittivity and cannot be directly determined. The usual procedure is to correct a calculated Q for true depth of penetration by measurements on the empty cavity.

3. The Partially Filled TM_{010} Cavity

The presence of a centrally located cylindrical rod specimen does not destroy the circular symmetry of the electromagnetic field, but does modify the radial distribution. Two sets of field equations are required: one for the interior of the specimen, and one for the air space between specimen and cylindrical wall. The boundary conditions involve the disappearance of the tangential component of electric field at the metallic cylinder wall. Also, there must be continuity of both electric

and magnetic fields at the boundary of specimen surface and air space where $r=b$.

The conductivity of specimen is neglected, since, except for lossy dielectrics, the conductivity will have no significant effect on field distribution or resonant wavelength.

The relation of resonant wavelength in terms of dimensions and dielectric constant of the specimen and air space is a rather formidable equation:

$$\frac{K_1}{K_0} = \frac{\beta_1}{\beta_0} \times \frac{J_0(\beta_1 b)}{J_1(\beta_1 b)} \times \frac{J_1(\beta_0 b)}{J_0(\beta_0 b)} \left\{ \frac{\frac{Y_0(\beta_0 a)}{J_0(\beta_0 a)} - \frac{Y_1(\beta_0 b)}{J_1(\beta_0 b)}}{\frac{Y_0(\beta_0 a)}{J_0(\beta_0 a)} - \frac{Y_0(\beta_0 b)}{J_0(\beta_0 b)}} \right\}$$

where $\frac{K_1}{K_0}$ is relative dielectric constant of specimen

$\beta_0 = \frac{2\pi}{\lambda_0}$ the resonant free space wavelength of system

AND $\beta_1 = \beta_0 \sqrt{\frac{K_1}{K_0}}$

$a =$ cavity radius

$b =$ specimen radius

J_0, J_1 are Bessel functions of first kind

Y_0, Y_1 are Bessel functions of second kind

When b/a is small, this expression is approximated by:

$$\frac{K_1}{K_0} = 1 + 0.539 \frac{a^2}{b^2} \times \frac{f_0 - f}{f_0}$$

Testing of low loss ceramics requires sufficiently large values of b to get detectable values of $f_0 - f$. Larger samples cause the simplified formula to be incorrect. Some investigation of the magnitude of error is necessary. In order to carry out a preliminary phase of this investigation, the complete formula was used to calculate the approximate relationship of sample size (a/b), dielectric constant, and resonant frequency of the system. The cross-plot intersections on Figure 1 are the desired values which were then transferred to Figure 2.

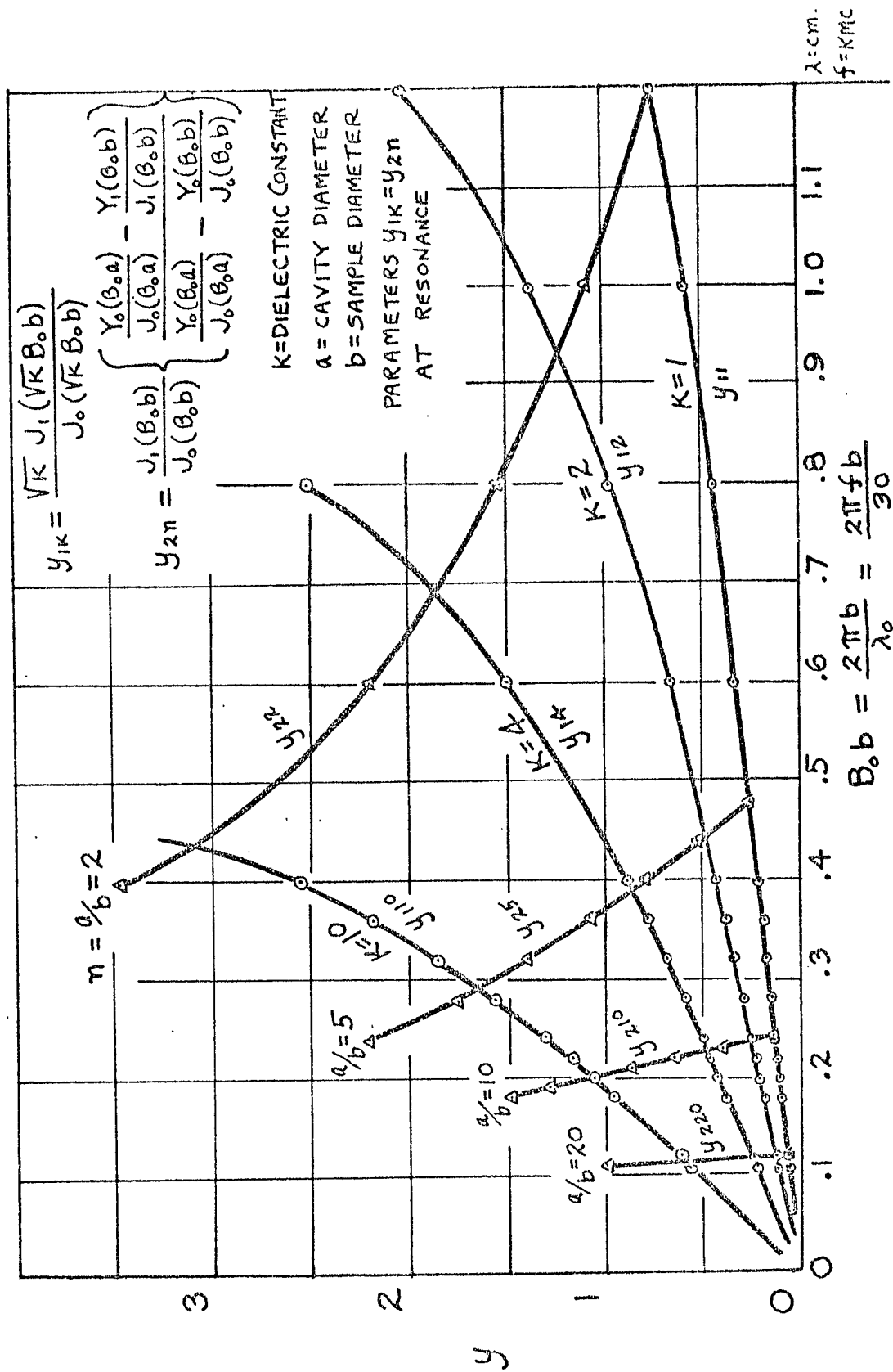


FIG. 1: GRAPHICAL ANALYSIS OF EFFECT OF SAMPLE DIAMETER, DIELECTRIC CONSTANT, AND FREQUENCY IN TM_{010} CAVITY

a = CAVITY RADIUS

b = SAMPLE RADIUS

f_k = SAMPLE FREQUENCY

f_1 = EMPTY CAVITY FREQUENCY

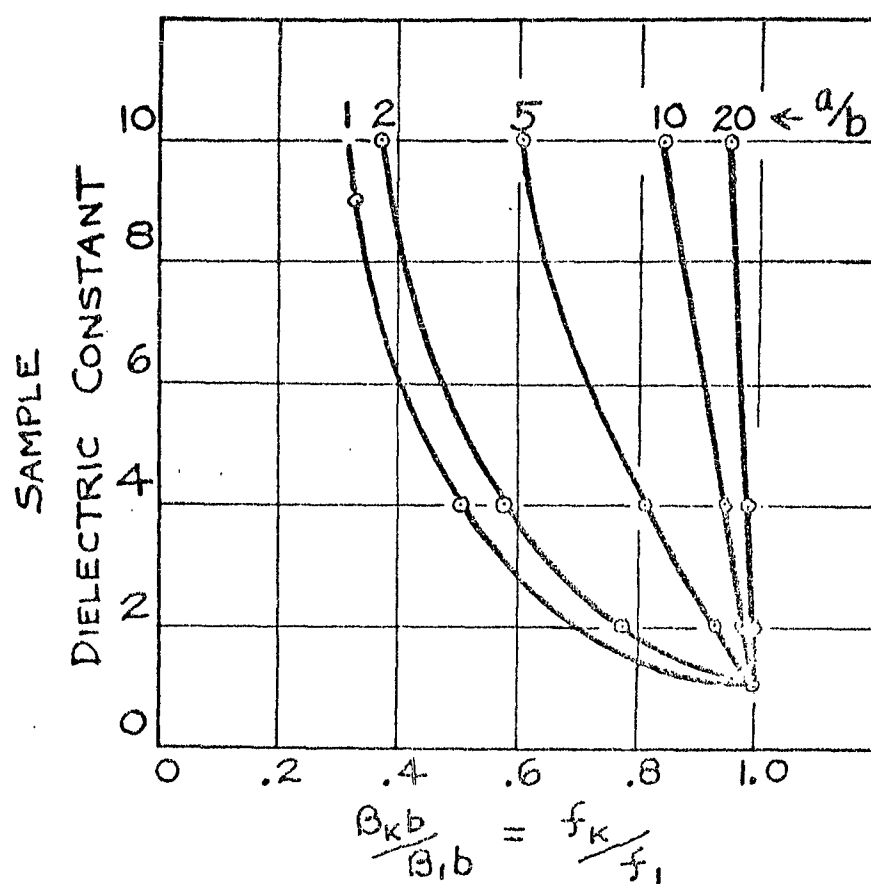


FIG. 2: RELATIONSHIP OF FREQUENCY,
DIELECTRIC CONSTANT, AND SAMPLE DIAMETER
AT RESONANCE FOR TM_{010} CAVITY

These graphs demonstrate how increased sample diameter decreases the resonant frequency for a given dielectric constant. For small sample diameter, frequency tends to drop in proportion to cross-sectional area (square of diameter). For intermediate diameters, the frequency drop continues to taper off and becomes proportional to the diameter rather than to the square of diameter. For large diameters, increasing diameter has a smaller and smaller effect, approaching zero when sample diameter approaches cavity diameter.

Increased dielectric constant also has an essentially linear effect on the depression of frequency for small sample diameters. As sample diameter increases, the upward curvature increases. When the sample fills the cavity, the frequency decrease is proportional to the square root of dielectric constant.

The loss tangent is also a rather complicated expression, as follows:

$$\tan \delta = \frac{\frac{a^2}{b^2} + F^2 \left(\frac{K_1}{K_0} - 1 \right)}{\frac{K_1}{K_0} \times F^2 \left[1 + \frac{J_1^2(\beta_1 b)}{J_0^2(\beta_1 b)} \right]} \times \left[\frac{1}{Q} - \frac{1}{Q'} \right]$$

WHERE $F = \left[Y_0(\beta_0 a) \times J_0(\beta_0 b) - Y_0(\beta_0 b) \times J_0(\beta_0 a) \right] \frac{\pi \beta_0 a}{2}$
 When sample radius b is small, the approximate simplified expression

becomes:

$$\tan \delta = \frac{0.269}{K_1/K_0} \times \frac{a^2}{b^2} \left(\frac{1}{Q} - \frac{1}{Q'} \right)$$

Again Q' refers to a calculated cavity Q for lossless specimen with dielectric constant $\frac{K_1}{K_0}$, corrected for actual depth of penetration obtained from a Q measurement of the empty cavity.

4. The TE₁₀₃ Rectangular Cavity

The previous quarterly report described our TE₁₀₃ waveguide cavities. The

9200 Mc cavity has been modified to accommodate various diameter rod samples. Figure 3 is a photograph of the modified cavity. Sections of the widest cavity sides were removed and replaced with 0.500 inch thick copper plates. The length of the plate was designed so that the ends coincide with the regions of maximum electric field.

The two copper plates were drilled for copper adaptor bushings. Each bushing was drilled to accommodate a specific sample rod diameter with a reasonable clearance allowance. The inner surface of the copper plates and bushings were given a reasonably good polish with fine polishing paper.

This cavity, although rectangular, is very similar in many respects to the TM_{010} cavity and much of the same analysis concerning sample diameter is applicable in a general sort of way to this cavity. A test investigation of the effect of sample size will be made using the modified TE_{103} cavity.

5. The TE_{011} Cavity Filled with Dielectric

The TE_{011} cavity is cylindrical with circumferential electric field and axial (and radial) magnetic field. The electric field is zero along the central axis, rises to a maximum at a finite radius, and falls to zero again at the cylindrical cavity wall. The electric field is zero at both ends of the cylinder, reaching a maximum half-way between.

The lowest resonant frequency corresponds to the first root of

$$J_1(ma) = 0 \quad \text{WHERE} \quad ma = 3.832$$

$$\text{AND} \quad \beta^2 = \omega^2 \mu k - m^2 = \omega^2 \mu k - \left(\frac{3.832}{a}\right)^2$$

The cut off wavelength is:

$$\lambda_c = \frac{2\pi a}{3.832} \sqrt{\frac{k}{k_0}} = 1.64 a \sqrt{\frac{k}{k_0}} = \frac{30}{f_c} \text{ CM}$$

$f \equiv \text{KILOMEGACYCLE:}$
KMC

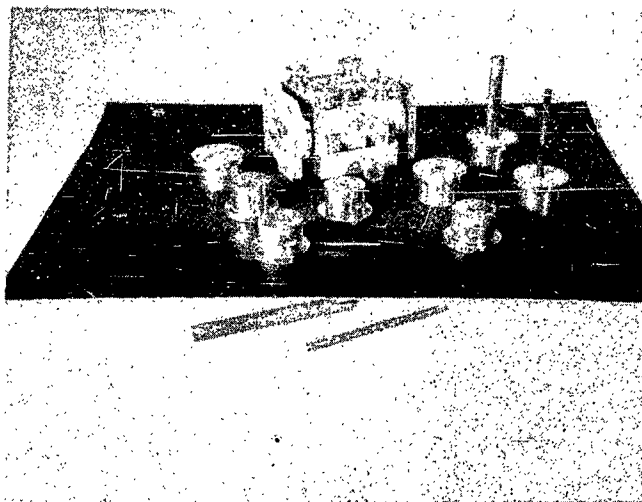


Figure 3: TE_{103} Rectangular Cavity Modified with copper side plates and bushing inserts to accommodate several rod sample diameters.

Also $\beta^2 = \frac{1}{\lambda_g^2} = \frac{K}{K_0} \left[\frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2} \right]$, which indicates that the closer the exciting wavelength approaches the cut-off value, the longer will be the wavelength λ_g within the cavity and with it the resonant length of the cavity.

The TE_{011} cavity has been used with a tuning plunger for dielectric measurements with some indication that precision is possible with low-loss materials. In this application, if the sample radius approaches the cavity radius, a precise fit is not critical since the electric field vanishes at the cylinder walls. Also, the cavity wall current flow path is circular and normal to the axis. This allows the design of clearance between plunger edge and wall since no current flows from wall to plunger.

The resonant response of the TE_{011} cavity may be delineated by variation of the length of the cavity about the resonant value, obtaining Q from the half-power points.

Care is necessary to distinguish between the TE_{011} and the TE_{11} , TM_{01} , TE_{21} , and TM_{11} modes. Although frequency measurements and calculations will serve, the usual procedure is to provide a pyramid of resistance wires on one of the end piston surfaces. This tends to eliminate excitation of the unwanted resonance modes which contain either radial or longitudinal components of electric field.

Horner, Taylor, Dunsmuir, Lamb, and Jackson have described application of the TE_{011} cavity to dielectric measurements. The equations for dielectric constant and $\tan \delta$ are covered in some detail for the case when the sample is a disk with radius essentially equal to cavity radius.

Bussey of the Bureau of Standards proposes the TE_{011} cavity using a rod sample

with movable end plate. The frequency can be tuned to the same value with and without the sample. Sample diameter can be changed to cover a wide range of dielectric constants and losses. Loss observations may be made in several ways.

Bussey's cavity for 9200 Mc was 1.88 inches diameter and 1.16 inches long for samples about 0.25 inch diameter. One end plate is micrometer adjusted. Bussey has developed calibration curves from a computer program to simplify conversion of test results to dielectric constant and loss tangent values.

Figures 4 and 5 are some of Bussey's tabulated results where he compared several TE_{011} methods with the slotted-line method. These results demonstrate 1% or better agreement on dielectric constant and 15% or better agreement on loss tangent as compared to the slotted-line method.

Figure 4

Comparison of Results, Cavity
(9200 Mc) and Slotted-Line (8650 Mc)

<u>Sample</u>	<u>Dielectric Constant</u>		<u>Loss Tan x 10⁴</u>				
	Method:	Z	Cav	Z	Δf	ΔT	ΔL
Poly		2.54	2.53	6.2	6.0	5.7	5.6
Tef		2.02	2.02	2.6	2.4	2.6	2.7
Nyl		3.05	3.06	105	100	97	102
Z:	Slotted-Line Method						
Δf , ΔT and ΔL refer to ways of measuring cavity Q, see text							

Figure 5

Performance on Low-Loss AL₂O₃
with 0.25" diameter Sample, 9200 Mc

<u>Sample</u>	<u>Dielectric Constant</u>	<u>Loss Tan x 10⁴</u>			
		Q-method:	f	T	L
90	9.38		1.4	1.4	1.5
91	9.80		.49	.51	.33
Sapph	9.36		.22	.18	.15

Both tests made by H. E. Bussey, National Bureau of Standards

(See Reference No. 3)

B. SELECTION AND PROCUREMENT OF OPTIMUM SAMPLES

1. Sample Size and Material

The following materials have been received:

1. Manufacturer Code BH-8, QPL designation L514, nominal rod diameters 0.080", 0.125", 0.188", 0.250", and 0.500".
2. Code BA-1, QPL designation L432, nominal rod diameters 1/8", 1/4", 3/8", 1/2".
3. Code BA-2, QPL designation L411, 2-1/8" dia. disks, 1/8" thick
4. Code BA-3, QPL designation , 3" x 2" x 1/4"
5. Code BA-4, QPL designation , 2-1/8" dia. disks, 1/8" thick
6. Code BA-5, QPL designation , 2-1/8" dia. disks, 1/8" thick
7. Code BA-6, QPL designation , 2-1/8" dia. disks, 1/8" thick
8. Code BK-1, QPL designation , 1, 2, 3, 4, 5, 9, 15, 3.2, 6.4 min. dia.
9. Code BK-2, QPL designation , 1/2", 1", dia. disks

Other materials will be added as necessary, although investigation of test methods requires concentration on samples of several sizes from a few materials which cover the range of dielectric properties.

V. CONCLUSIONS

The following conclusions are in addition to those listed in the first quarterly report:

1. Small sample perturbation methods in resonant cavities require relatively simple calculations compared to slotted-line methods. However, larger samples may be necessary for low-loss ceramics.
2. Larger samples with higher dielectric constants, in partially filled cavities, require more complicated calculations. It is possible that the calculations can be tabulated or plotted so that the test values can be referred to tables or curves to find the dielectric constant and dissipation factor with a minimum of calculations.
3. Bussey of the Bureau of Standards and others have found the TE_{011} cavity to be particularly interesting for low-loss ceramics and this method will be investigated further.

VI. PROGRAM FOR NEXT INTERVAL

Proceed with Phase 4: Measurements and calculations including design and construction of additional test cavities.

Trip to National Bureau of Standards, Boulder, Colorado is planned.

Dr. E.G. Schwarz will investigate free space methods.

VII. TECHNICAL PERSONNEL

E. F. Hansen	Project Leader
E. G. Schwarz	Microwave Dielectric Measurements
H. D. Bell	Microwave Measurements
Dr. H. Hair	Microwave Dielectric Measurements Consultant
Dr. E. C. Henry	Ceramics Consultant

Manhours

First Quarter	163
Second Quarter	169

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