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BDX-613-991

A METHOD OF INSPECTING
DIELECTRIC MATERIALS
AT MICROWAVE FREQUENCIES

PDO 6984830, Final Report

G. D. O'Dell, Project Leader

Internal Distribution November 1973

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC

**Kansas City
Division**

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**Project Leader:
G. D. O'Dell
Department 846**

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A METHOD OF INSPECTING DIELECTRIC MATERIALS AT MICROWAVE FREQUENCIES

BDX-613-991, UNCLASSIFIED Final Report, Internal Distribution
November 1973

Prepared by G. D. O'Dell, D/846, under PDO 6984830

A successful method of screening high-dielectric-constant, nonmagnetic, high-loss-factor materials at microwave frequencies has been developed to provide material control by incoming inspection. This is accomplished by measuring the S-parameters of the material--reliance on the manufacturer's permittivity data and X-ray examination for voids and inclusions is no longer necessary. Use of an automatic network analyzer makes 100-percent inspection economically feasible.

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Atomic Energy Commission
Contract Number AT(29-1)-613 USAEC

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SUMMARY

This work was conducted to establish a reliable test technique for inspecting high-loss-factor, nonmagnetic, high-dielectric-constant materials in the C and D microwave bands. S-parameter measurements were successfully used to screen these materials in incoming inspection.

The material is machined to the required configuration, inserted into a test fixture closely resembling the next assembly, and fully characterized by S-parameter measurements. This technique is suitable not only for this narrow class of materials, but for almost any other dielectric, and can be performed at any frequency where S parameters can be accurately measured.

Before this method was developed, the material was inspected by X-ray examination for voids, inclusions, and lot variations. X-ray inspection and reliance on the manufacturer's permittivity ratings did not provide adequate safeguard against subtle changes in product operating characteristics.

Complex permittivity was believed a suitable criterion for screening this material; however, complex permittivity is not a directly measurable quantity, and it does not account for the effects of higher-order propagation modes that sometimes occur at microwave frequencies. A literature review disclosed no suitable permittivity measurement technique.

Although complex permittivity may partly characterize the material, the geometry of the part becomes a contributing factor at microwave frequencies. Therefore, S-parameter measurement is more suitable because it includes the effects of higher-order modes and standing waves which are functions of both the part geometry and the material properties. Since S parameters provide all of the information necessary to define the material, complex permittivity need not be determined. X-ray screening is no longer necessary because the S parameters include the effects of voids or inclusions in the material.

Although manually-operated test equipment can be used to measure S parameters, such a method is very time consuming. Therefore, a Hewlett-Packard 8542 Automatic Network Analyzer was used in this investigation and is recommended for incoming inspection. The high operating speed and convenience of the automatic analyzer makes 100-percent inspection economically feasible and provides valuable engineering and quality-control support.

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DISCUSSION

SCOPE AND PURPOSE

The objective of this work was to develop a satisfactory method of measuring dielectric properties to establish incoming inspection methods necessary to support product requirements. The specific application is a nonmagnetic, lossy, high-dielectric-constant material used to produce slugs for the receiver section of an rf microwave assembly.

Such a test capability is necessary because permittivity data supplied by the manufacturers of these materials have not proven adequate to provide the material consistency necessary to prevent changes in product operating characteristics.

Permittivity is not a directly measurable quantity, but must be derived from other measurements; therefore, such data do not provide convenient inspection criteria. Since the purpose of this work was to develop a direct practical approach, more-complex methods were of interest only as they influenced that purpose. For example, a rigorous iterative solution including the effects of higher-order propagation modes and standing waves was considered beyond the scope of this effort because it would not provide a practical inspection method.

Although the required tests can be performed on manually-operated equipment, a manual method is impractical for 100-percent inspection because of the time required. Therefore a Hewlett Packard 8542 Automatic Network Analyzer was used.

PRIOR WORK

Effort in this area before this work was essentially confined to a literature review that did not disclose a suitable method of measuring the dielectric constant and loss-tangent factors that comprise complex permittivity. Although the slugs used in evaluation units were satisfactory, X-ray examination and reliance on the manufacturer's permittivity data did not provide the criteria necessary to control the material.

ACTIVITY

Problem Analysis

Nonmagnetic, lossy, high-dielectric-constant materials may be accurately screened for product acceptance either by complete S-parameter characterization or by calculations of the complex permittivity based on the S-parameters. These measurements are complicated by both the frequency of measurement and properties of the material. The measurement of high-dielectric-constants at microwave frequencies results in additional complications due to the presence of higher-order modes that result from the material characteristics and the part configuration.

Properties Suitable for Analysis

The interaction of electromagnetic fields with matter can be described in terms of three fundamental properties: polarization, magnetization, and conduction. These properties are described by the dielectric constant or permittivity, the permeability, and the conductivity. The latter two properties do not adequately describe this rather narrow class of dielectric materials.

Since the material is nonmagnetic, the permeability is very nearly that of free space ($\mu_0 = 4\pi \times 10^{-7}$ henries/m), with a frequency-dependent variation of about 10^{-10} to 10^{-12} . This leads to the simplifying assumption that the relative permeability has a constant value of one. The conductivity, if measurable at the desired frequency, provides only a partial description of the material properties. However, it can be derived from the permittivity.

The remaining property, permittivity, most adequately describes the material under consideration. Permittivity is not a directly measurable quantity, but must be obtained from other properties such as the VSWR, S parameters, or isolation of a test specimen within a coaxial line or waveguide. S-parameters measured with a Hewlett Packard 8542-A Automatic Network Analyzer were used for this project.

S-Parameter Definition. S-parameters are transmission and reflection coefficients defined in terms of incident and reflected rf energy for a device that is terminated in its characteristic impedance. They differ from hybrid and other common parameters used at lower frequencies which are defined in terms of voltages and currents measured with open-circuit or short-circuit terminations. Flow graph and matrix representations for the basic two-port S-parameters are shown in Figures 1 and 2, with a and b quantities referring to the incident and emergent waves, respectively.

Figure 1. Two-Port S-Parameter Flow Graph

$$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \begin{bmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

Figure 2. Two-Port Network Matrix

Material Definition by S-Parameters. The most adequate description developed for microwave dielectric properties is based on direct use of two-port S-parameter measurements. The disadvantage of this technique is that the S-parameter data must be statistically analyzed each time a new type of material is selected. The principal advantage is that samples of almost any geometry can be treated by the same measurement technique.

Material Definition by Complex Permittivity. The second approach taken was to derive the permittivity from S-parameter measurements. All of the literature-reported permittivity measurement methods evaluated during this work yielded unsatisfactory results. These methods are discussed only for future reference if similar work should be required. Permittivity can be regarded as a measure of the collective effect of the individual electrical dipole moments within the material. A dipole is formed by the separation of unlike electrical charges by a finite distance. The dipole moment is defined as the product of the charge in coulombs and the separation between charges in meters. The charges making up these dipoles may be visualized as the nuclei and electron clouds of the material. Permittivity is most often defined in terms of field quantities. In one of Maxwell's constitutive equations, the electric flux density ($\vec{D}$) in coulomb/m² is related to the electric field intensity ($\vec{E}$) in volts/m by ϵ , which is the permittivity for a

given material ($\bar{D} = \epsilon \bar{E}$). Since dielectric losses must be considered, permittivity will be a complex quantity, with the real and imaginary parts ϵ' and ϵ'' , as shown in Equation 1:

$$\epsilon = \epsilon' - j\epsilon'' \quad (1)$$

In defining the electrical properties of a dielectric material, the relative dielectric constant and the loss tangent or dissipation factor usually are given. These quantities are derived from the complex permittivity where ϵ_r is the relative dielectric constant and ϵ_0 is the free space permittivity:

$$\epsilon_r = \frac{\epsilon'}{\epsilon_0} \quad (2)$$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ farads/meter,}$$

and the loss tangent is defined as

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad (3)$$

This definition is by no means universal; others can be found in the literature. The relative permittivity or relative dielectric constant is generally the quantity referred to in tables of material properties as the dielectric constant. This normalized portion of the complex permittivity is associated with the ability of the dielectric material to store electrical energy. The loss tangent is used to describe the energy loss characteristics of the dielectric.

Definition of Material Properties

Emerson and Cummings HP-155 carbon-filled plastic was chosen as a representative nonmagnetic, lossy, high-dielectric-constant material for this evaluation. The electrical properties listed in Table 1 were supplied by the vendor. A chemical analysis performed at Bendix confirmed the non-ferrous nature of the material. An X-ray analysis was used to examine the material for voids and inclusions.

Electrical Properties. The permittivity data presented in Table 1 were provided by the vendor. The vendor also lists the dc resistivity as between 1000 and 10000 ohm-cm, revised from earlier data listed as 10 to 100 ohm-cm.

Table 1. Vendor-Supplied Permittivity Data

	Frequency		
	1.0 MHz	1.0 GHz	8.6 GHz
Relative Dielectric Constant, ϵ_r	136.0	90.0	30.0
Loss Tangent, $\tan \delta$	0.1	0.6	0.5

The manufacturer's permittivity data at 8.6 GHz were obtained with a free-space interferometer vertically polarized at 45 degrees to the surface of a sheet material sample.¹ The 1.0-GHz data were obtained with a commercial dielectrometer which uses cylindrical disc samples in a circular waveguide. The 1.0-MHz data are theoretical--extrapolated from measured data at other frequencies. Although available for only three frequencies, these permittivity data are sufficient for comparison to the measurements of this investigation.

Both the high loss tangent and dielectric constant restrict the methods possible for complex permittivity measurement. The principal disadvantage of lossy material is that the attenuation of even a short sample masks the effects of terminations attached to the coaxial line containing the sample. This prohibits the use of short-circuit methods commonly used in determining permittivity.

The influence of placing a high-permittivity material in an electric field differs little from that of a conductor ($\epsilon = \infty$). For permittivities higher than 30 the dipole moment changes little with increasing permittivity. This eliminates the possibility of determining the permittivity by perturbation methods with small specimens.

Chemical Properties. A chemical analysis was conducted as a first step toward definition of the HF-155 dielectric material. The major reason for this was to determine the principal constituents of the material and the composition of any foreign matter or inclusions.

The chemical analysis identified the HF-155 rod as an alkyd thermoset resin with a carbon filler. Alkyd resins usually are formulated by using a polyhydric alcohol and phthalic anhydride with a drying oil as a modifier.

A thermogravimetric analysis (TGA) showed a 40-percent carbon char content, due mostly to the carbon filler. The ash content of the resin and filler was 0.44 percent. An emission spectrographic analysis of the ash indicated that cobalt was the major component. Cobalt naphthenate is a catalyst commonly used with drying oils. The elements and amounts present in the ash are listed in Table 2.

Table 2. Elemental Analysis of Ash From HF-155 Lot 9-12-2A

Elements	Content, Percent Weight
Co	0.004 to 0.04
Si, Fe	0.0015 to 0.004
Ca, V, Al	0.0004 to 0.0015
Mg, Ti, Cr	0.0015 to 0.0004
Ni, Mn	0.00004 to 0.00015
Cu	0.000015 to 0.00004

This analysis is significant in that carbon, the major additive to the plastic resin, is nonferrous. (This allows the assumption that the permeability of the dielectric is equal to that of free space.) The ash content is of interest because this is a likely source of any inclusions found in the material.

X-Ray Analysis. Four batches of HF-155 material received from the vendor since September 15, 1969, were available for analysis. Vendor data on electrical properties, together with batch designations and dates on manufacture, are listed in Table 3.

As of October 1971, numerous X-rays had been taken of material from each of the above batches. The results of these tests are still useful in defining physical composition of each batch. The detected voids and inclusions are important to the extent that they modify the dielectric properties of the material. The batch properties are summarized in Table 4.

This wide variance of HF-155 homogeneity will be considered later with regard to its effects on dielectric properties of the material.

Frequency Dependence

Both the permittivity and the methods available for measuring it change with frequency.

Table 3. Vendor HF-155 Test Results

Shape	Lot	Batch Date	GHz	ϵ_r	$\tan \delta$	Volume Resistivity (ohm-cm)
Bar*	9-12-1A	9-15-69	8.6	19.1	0.43	42
Bar*	9-12-2A	9-15-69	8.6	21.4	0.52	40
Sheet**	155	11-14-69	8.6	28.2	0.45	50
Sheet**	5-14-71	May 1971	8.8	25.3	***	***
<p>*Bar Stock was 0.5 inch square by 12 inches (12.7 by 305.8 mm) **Sheet Stock was 12 inches square by 0.5 inch thick (305.8 by 12.7 mm) ***Significant voids and metallic chips</p>						

Table 4. Physical Description of Four HF-155 Batches

Batch	Description
9-12-1A	4 Bars: small high-density particles in each, voids in one bar
9-12-2A	3 Bars: small high-density particles in each, few voids, the largest 0.085-inch diameter (2.16 mm)
HF-155	2 Bars: few voids, the largest 0.065 inch diameter (1.65 mm) Rod: high-density inclusions 0.040 by 0.020 inch (1.016 by 0.508 mm) 9 Slugs: few voids 0.025-inch diameter (0.635 mm) maximum with many high-density particles less than 0.010 inch (0.254 mm) maximum
5-14-271	Many high-density particles with maximum dimension of 0.035 inch (0.889 mm)

Permittivity Variation With Frequency. There is a change in permittivity of all materials with frequency. Typical curves of the complex dielectric constant versus frequency may be found in the literature, with Debye² relaxation and resonance dispersions being the most common. The change in permittivity with frequency is particularly acute in the vicinity of 1.0 GHz and higher.³ Generally, ϵ'' changes more with frequency than ϵ' .⁴ Recalling from Table 1 that the dielectric constant of HF-155 material as listed by the vendor is 30 at 8.6 GHz, 90 at 1 GHz, and 136 at 1 MHz, the loss tangent over the same frequency range varies from 0.6 to 0.1. This extreme variance with frequency requires permittivity measurement at the intended operating frequency.

Frequency Restrictions on Measurement Methods. The C- and D-frequency bands were chosen for this investigation. The methods of permittivity measurement used at lower frequencies are not suitable in this range. At low frequencies, capacitive resonance methods often treat the material as the dielectric between parallel capacitor plates. However, increased skin effect and lower circuit Q make measurements based upon lumped circuit reactance variations unsuitable at frequencies above 100 MHz. At slightly higher frequencies the sample may be measured within a half-wavelength coaxial line. Above 1.0 GHz, distributed parameters must be considered in permittivity measurement. Although impedance measurements are usually made under short-circuit conditions, such a method is not suitable for HF-155 because of high losses which mask the effects of the terminations and the decreasing wavelength in the material caused by a combination of high frequency and high dielectric constant. Waveguides are used at frequencies above several GHz because higher-order propagation modes make coaxial methods impractical.

Higher-Order Modes

All of the measurements of material properties in this investigation were made with the specimens placed in a coaxial transmission line. Waveguide measurements at these frequencies are prohibitive because of the sample size required to fill the guide. All of the dielectric constant measurement methods found in the literature for coaxial measurements are based on the propagation of a dominant TEM mode. The validity of this assumption, and consequently the accuracy of permittivity calculations based on it, depends on suppression of higher-order modes.

TEM Assumption. In a transverse electromagnetic wave (TEM), both the electric and the magnetic fields exist entirely in the plane transverse to the direction of propagation. This is the mode present in coaxial transmission lines. Higher-order modes [either transverse electric (TE) or transverse magnetic (TM)], exist when either the magnetic or electric field has a component in the direction of propagation. Coaxial transmission lines will support higher-order modes under the proper conditions.

Solutions for complex permittivity based on the assumption of TEM propagation are desirable because of the complexity involved in developing either field solutions or mathematical models which include the effects of higher-order modes. For example, the National Bureau of Standards has devoted three years to developing a method of measuring coaxial transmission line open capacitance, a comparatively simple geometry, by means of an iterative solution of the effects of higher-order modes.

Higher-Order Mode Generation. Higher-order modes can be generated within a coaxial line by almost any type of discontinuity. For TEM signal propagation in a coaxial line, insertion of a lossy, high-dielectric-constant material represents a pronounced discontinuity. Any inhomogeneity in the material, either density variations, voids, or inclusions, also may cause higher-order modes. Higher-order modes are caused also by irregularly-shaped samples or those with nonparallel interfaces or gaps between dielectric specimens and coaxial conductors.

Some of the energy of the traveling TEM wave is transferred to higher-order modes upon encountering a discontinuity within the transmission system. Energy transmission by higher-order modes is possible in a coaxial line above the frequency where the circumference at the mean magnetic path between conductors is one wavelength. This frequency is known as the cutoff frequency, above which higher-order modes travel with little attenuation. Past the area of disturbance in the coaxial line, both TEM and higher-order modes are propagated. Below the cutoff frequency the disturbance in the field pattern is confined to the area of discontinuity, decaying rapidly away from the source of disturbance. Since each of the methods of permittivity calculation evaluated in this report is based on the assumption of a pure TEM mode, measurements at frequencies above the cutoff frequency must be avoided.

In the coaxial-line experiments of this work, samples were inserted in a 10-cm section of APC-7 airline. The mean magnetic path in an APC-7 airline with an inner radius of 7 mm is approximately 1.60 cm, which corresponds to a frequency of 19 GHz. Frequencies at which the mean magnetic path is equal to one wavelength are shown in Table 5 for the range of dielectric constant values attributed to HF-155 by the vendor. The calculation for an air dielectric is also given for comparison.

The restrictions imposed on the measurement frequency by the influence of the dielectric constant on cutoff frequency are apparent in Table 5.

Table 5. Upper Frequency Limits for Dominant TEM Mode Transmission

Relative Dielectric Constant (ϵ_r)	Cutoff Frequency (GHz) $f = C / \sqrt{\epsilon_r} \cdot \lambda$
1 (air)	19
30	3.5
70	2.3
90	2.0
136	1.61

Evidence of High-Order Modes. The extent to which a TEM assumption is true is shown by the basic attenuation definition for a dielectric material. For TEM propagation in a coaxial line, the attenuation (A) through a dielectric in dB/cm is given as follows:⁵

$$A = 8.686 \left(\frac{2\pi}{\lambda_0} \right) \left\{ 0.5 \left(\frac{\epsilon'}{\epsilon_0} \right) [(1 + \tan^2 \delta)^{0.5} - 1] \right\}^{0.5} \text{ dB/cm.} \quad (4)$$

Table 6 lists Bendix measured and calculated values of attenuation in HF-155 for 8.45-cm samples in a 10-cm airline.

The data shown in Table 6 were obtained with a Hewlett Packard Model 8542 Series Automatic Network Analyzer. The sample filled the airline as completely as possible, thus taking the form of a cylinder with the same outer diameter as the inner diameter of the conductor shell. A hole was provided at the center of the sample just large enough for the center conductor of the airline. Some, but not all, of the experimental data derived from the calculated theoretical values can be attributed to inhomogeneity in the material. The attenuation at 0.2 GHz was less than 10 dB, making the presence of standing waves the most likely cause of the discrepancy. The same sample at 1.0 GHz had an attenuation greater than 25 dB, which should have eliminated much of the effect of standing waves in the material. The remaining portion

of this difference can be attributed only to the presence of higher-order modes. Although not conducted during this project, investigations using a 20-centimeter airline with 16-cm HF-155 samples, if such samples can be machined, should resolve the extent of higher-order-mode propagation more fully by reducing the possibility of standing waves in the sample.

Table 6. Measured and Calculated Attenuation Values for HF-155 Material

Frequency (GHz)	Attenuation (dB/cm)	
	Calculated	Measured
0.2	0.21	1.13
1.0	5.06	3.01
8.6	20.82	9.38

Measurement Solution

The methods used for HF-155 sample preparation, fixturing, and measurement are described below. The material properties were determined either directly from S-parameter measurements or by calculating permittivity from these measurements.

Data Acquisition

Transmission line measurements, in a broad sense, include all measurements in which parallel beams of electromagnetic energy strike perpendicularly on dielectric boundaries. Samples in the form of a distributed dielectric medium loading a coaxial line fulfill this requirement. HF-155 samples were prepared and the distributed parameters were measured in a coaxial transmission line.

Sample Preparation. Material samples were machined into two shapes, one cylindrical, and the other of the same dimensions as the receiver slug used in a production assembly. The dimensions of the receiver slug are those shown in Figure 3. The cylindrical-sample dimensions are given in Figure 4.

Figure 3. Receiver Slug Dimensions

Figure 4. Cylindrical Dielectric Test Specimen

Both sample types were inserted in a standard 10-cm APC-7 airline. For the cylindrical samples the airline used as a test fixture was disassembled and slightly modified for the slug measurements. Test fixturing for the receiver slug samples was obtained by machining a small counter-bore in one of the APC-7 connectors on the airline, as shown in Figure 5.

Figure 5. APC-7 Connector Modified to Contain Test Specimen

S-parameter measurements of the sample in slug form most nearly approximate the characteristics of the material for a particular function, while the measurements of cylindrical samples are better suited for permittivity calculations. Because of the short length of the slugs, transmission loss through the sample is less than 5.0 dB, indicating substantial effect of standing waves within the material. Because of the short sample length, any higher-order modes generated are more readily coupled from one face of the sample to another. Higher-order-mode propagation is unique for a particular slug, being determined by the permittivity of the material, the dimensions of the sample, and the fit within a mating part of a product assembly. Although the airline test fixture does not duplicate the dielectric environment of the application, the simulation is approximate. While they do not represent the subtleties of the material in its final application, cylindrical samples are better than the receiver slugs for permittivity measurements. When sufficiently long, they provide enough attenuation to eliminate standing waves in the material. The possible coupling of higher-order modes between faces of the sample also is eliminated with a longer sample, increasing the validity of calculations based on the TEM assumption.

Automatic Network Analyzer Measurement. The automatic network analyzer used for this work is essentially an application of a minicomputer to control the task of performing microwave measurements. This combination permits rapid acquisition, computation, and display of accurate microwave measurement data for a wide range of frequencies.

In calibrating for both slug and cylindrical-sample measurements, the APC-7 airline used as a fixture was left attached to and treated as a part of the S-parameter test set. This calibration procedure removes any measurement error caused by imperfections in the airline test fixture.

With this method of calibration, the insertion of samples for measurement results in a phase angle error for each of the measured S-parameters unless the reference planes are adjusted. The samples for the receiver-slug measurements were merely inserted at the calibration interface, with phase error being ignored because of the short sample length. For the cylindrical samples, the reference planes of measurement were extended mathematically to the ends of the sample within the airline to remove the phase error. These reference-plane extensions were obtained by physical and electrical measurement of the center airline conductor and each cylindrical sample.

Electrical Properties by S-Parameter Measurement

Slug Measurements. Receiver slugs of the proposed product configuration were machined from each of the four available batches of material listed in Table 3, and 10 slugs from each batch were measured on the Hewlett Packard 8542-A Automatic Network Analyzer. The results of these measurements are shown in Table 7.

Table 7. Summary of S-Parameter Data for Receiver Slugs

Batch	S-Parameter Type			
	S11 = S22		S12 = S21	
	Magnitude $\bar{X}$ σ	Angle $\bar{X}$ σ	Magnitude $\bar{X}$ σ	Angle $\bar{X}$ σ
9-12-1A	0.36 0.01	232 1.8	0.86 0.01	152 0.95
9-12-2A	0.36 0.02	233 2.6	0.83 0.02	151 0.95
155	0.38 0.01	233 1.2	0.86 0.01	151 0.95
5-14-271	0.39 0.02	230 2.6	0.85 0.02	150 0.95

These data are repeatable to the second decimal place for the S-parameter magnitudes and within one degree for the angles. There appears to be little difference between batches, as shown by the $\pm 3\sigma$ range for the magnitude of the reflection coefficient, $|S_{11}|$, in Table 8.

Table 8. S_{11} Batch Variations

Batch	$\pm 3\sigma$ Range for $ S_{11} $
9-12-1A	0.33 to 0.39
9-12-2A	0.30 to 0.42
155	0.35 to 0.41
5-14-271	0.33 to 0.45

These reflection and transmission measurements provide a valid basis for material selection at a given frequency. Future HF-155 material lots could be screened on the basis of deviation from the S-parameter norms established for material proven acceptable in operating production units.

Since S_{13} is very nearly equal to S_{21} and similarly, $S_{11} \approx S_{22}$, statistical comparison of device properties need only be based on two S-parameters, with the redundant measurements in each case providing added statistical information.

Modified Slug Measurements. Further tests were conducted with modified receiver slugs of HF-155 to determine the effects of voids and inclusions on electrical properties. Two receiver slugs were measured, and then modified before subsequent measurement. One specimen was modified by drilling five holes slightly greater than 0.0625-inch (1.59 mm) diameter perpendicular to the axis of the slug. These holes were later filled with a ferrous material. The second slug was altered by drilling two holes of the same diameter along the axis of the slug.

Several conclusions can be drawn from these measurements:

- Signal transmission is not affected appreciably by voids with major dimensions perpendicular to the axis of the slug.
- Voids running the length of the dielectric sample substantially modify transmission properties and can be detected by S-parameter measurements.

- Increased amounts of ferrous inclusions in the dielectric are reflected in the measured S-parameters of the material as they approach those of a pure conductor.
- Acceptable slugs, including those containing voids, have reflection coefficients which decrease with frequency. However, a significant amount of metallic impurity will reverse this trend.

Permittivity Calculation

Three basic methods of permittivity calculation were investigated, each based on the assumption of the TEM mode as the dominant mode of transmission in the material. Standing waves were suppressed in each case by using a sample long enough to provide at least 20-dB transmission loss. A permittivity definition based on two-port network considerations is presented first, followed by the infinite-sample and transmission methods. Results of each of the calculations are summarized in Table 9. The effects of both higher-order modes and standing waves in the material are evident from the inconsistency of the results. Although there was some correlation of loss-tangent among these methods, there is not sufficient correlation to determine a value for the dielectric constant.

Table 9. Calculated Permittivity Values

Calculation Method	Frequency (GHz)	Dielectric Constant ϵ_r	Loss Tangent (ϵ'/ϵ'')
Two-Port	1.0	32.94	0.592
Infinite-Sample	1.0	16.98	1.48
	1.7	11.57	2.24
	2.0	10.58	2.17
Transmission	1.0*	1.51	0.06
	1.7	8.11	0.639
	2.0	15.18	0.639
* Δl of samples insufficient			

Two-Port Network Method. One definition of the complex permittivity is given by Altschuler⁵ in terms of two-port network parameters. It is based on the two conditions: that the terminal planes of the measurement device are located at the air-dielectric interface, and that single-mode (TEM) propagation exists. From the admittance (Y_e) representation in terms of S-parameters:

$$Y_e = \frac{(1-S_{11})^2 - S_{12}^2}{(1+S_{11})^2 - S_{12}^2}, \quad (5)$$

and for the TEM mode,

$$Y_e = \frac{1}{\epsilon_0} (\epsilon' - j\epsilon''). \quad (6)$$

Infinite-Sample Method. Although the accuracy is limited, this method given by Altschuler is a useful first approximation. An infinite sample is considered one sufficiently long so that no energy reflected from the air-dielectric interface at the end of the sample is measurable at the input of the sample. As previously stated, a 20 dB or greater one-way attenuation through the material was assumed sufficient to restrict the formation of standing waves in the material. Values obtained with this method, as shown in Table 9, were calculated by Equation 7, where θ is the angle of S_{11} :

$$\frac{\epsilon}{\epsilon_0} = \frac{VSWR - j \tan \theta}{1 - j VSWR (\tan \theta)} \quad (7)$$

Transmission Method. This measurement technique developed by Westphal⁵ uses the change in attenuation ($\Delta\alpha$) in dB and the change in transmission ($\Delta\phi$) in degrees produced by a reduction in sample length (Δl) in cm. Using these measured properties, values of ϕ and β are calculated by Equations 8 and 9.

$$\alpha = \frac{\Delta\alpha}{8.68 \Delta l}, \text{ and} \quad (8)$$

$$\beta = \frac{\Delta\phi}{57.296 \Delta l} + \frac{2\pi}{\lambda_0}, \quad (9)$$

where

α = attenuation constant per unit length,

β = phase constant per unit length, and

λ = free-space wavelength.

In the expression for β the Δl quantity from the second term has been deleted as suggested by Magid.⁶ The relative permittivity and the loss tangent are then defined in terms of Equations 10 and 11.

$$\epsilon_r = \left(\frac{\lambda_0}{2\pi} \right)^2 (\beta^2 - \alpha^2), \text{ and} \quad (10)$$

$$\tan \delta = \frac{2\alpha\beta}{(\beta^2 - \alpha^2)} \quad (11)$$

As with previous methods, a one-way transmission loss of 20.0 dB or more is used to reduce standing waves in the dielectric. The calculation shown in Table 9 for the 1.0 GHz data was done with a smaller Δl than the data at 1.7 and 2.0 GHz, and is therefore less significant.

ACCOMPLISHMENTS

Since complex permittivity measurement was found insufficient to determine the performance of lossy, high-dielectric-constant materials in applications at microwave frequencies, a method was developed for acceptance and screening these materials by means of S-parameter measurements with a network analyzer.

Although such measurements can be made on manually operated equipment, manual operation is not practical for 100-percent inspection of normal lot quantities; therefore, the automatic network analyzer was used for this work, and is recommended for incoming material inspection.

The S-parameter measurement method is more suitable than the permittivity data for material testing because it includes the effects of higher-order modes and standing waves in the dielectric, which are functions of the sample geometry, as well as its material properties. For this test method, the lossy material is machined into final form as required for the next assembly, inserted into a fixture resembling the next assembly as closely as possible, and fully characterized by S-parameter measurement. The S-parameter method also is capable of detecting significant voids and inclusions within the material. Parts such as microwave receiver slugs can be quickly screened by 100-percent inspection if desired, ensuring proper performance in final assemblies.

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