



Standard Test Method for Measuring Relative Complex Permittivity and Relative Magnetic Permeability of Solid Materials at Microwave Frequencies Using Waveguide¹

This standard is issued under the fixed designation D 5568; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers a procedure for determining relative complex permittivity (relative dielectric constant and loss index) and relative magnetic permeability of isotropic, reciprocal (nongyromagnetic) solid materials. If the material is nonmagnetic, this procedure may be used to measure permittivity only.

1.2 This measurement method is valid over a frequency range of approximately 1 MHz to 50 GHz. These limits are not exact and depend on the size of the specimen, the size and type of transmission line used as a specimen holder, and on the applicable frequency range of the network analyzer used to make measurements. The lower frequency is limited by the smallest measurable phase shift through a specimen, and the upper frequency limit is determined by the excitation of higher-order modes that invalidates the dominant-mode transmission line model. Any number of discrete measurement frequencies may be selected in this frequency range. To achieve maximum measurement accuracy, use of different transmission line sizes and types may be required. For example, use of a 7-mm diameter coaxial geometry can provide for measurements from 1 MHz to 18 GHz. However, air gaps that exist between the specimen and the transmission line's conductors introduce errors that may necessitate the use of a larger diameter coaxial transmission line and a series of rectangular wave guides of different size to cover this frequency range.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

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1.1 This test method covers a procedure for determining relative complex permittivity (relative dielectric constant and loss) and relative magnetic permeability of isotropic, reciprocal (non-gyromagnetic) solid materials. If the material is nonmagnetic, it is acceptable to use this procedure to measure permittivity only.

1.2 This measurement method is valid over a frequency range of approximately 100 MHz to over 20 GHz. These limits are not exact and depend on the size of the specimen, the size of rectangular waveguide transmission line used as a specimen holder, and on the applicable frequency range of the network analyzer used to make measurements. The practical lower and upper frequencies are limited by specimen dimension requirements (large specimens at low frequencies and small specimens at high frequencies). Being a non-resonant method, the selection of any number of discrete measurement frequencies in a measurement band would be suitable. Use of multiple rectangular waveguide transmission line sizes are required to cover this entire frequency range (100 MHz to 20 GHz). This test method can also be generally applied to circular waveguide test fixtures. The rectangular waveguide fixture is preferred over coaxial fixtures when samples have in-plane anisotropy or are difficult to manufacture precisely.

1.3 The values stated in SI units are to be regarded as the standard. The values given in parentheses are in English units. The equations shown here assume an $e^{+j\omega t}$ harmonic time convention.

1.4 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:²

D 1711 Terminology Relating to Electrical Insulation

¹ This test method is under the jurisdiction of ASTM Committee D09 on Electrical and Electronic Insulating Materials and is the direct responsibility of Subcommittee D09.12 on Electrical Tests.

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² ASTM STP 926 "Engineering Dielectrics, Volume 11B, Electrical Properties of Solid Insulating Materials: Measurement Techniques," 1987.

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

*A Summary of Changes section appears at the end of this standard.

3. Terminology

3.1 For other definitions used in this test method, refer to Terminology D 1711.

3.2 *Definitions:*

3.2.1 *relative complex permittivity (relative complex dielectric constant) (relative complex capacitance), ϵ_r^** —the ratio of the admittance of a given configuration of the material to the admittance of the same configuration with vacuum as dielectric:

$$\epsilon_r^* = \frac{Y}{Y_0} = \frac{Y}{j\omega C_0 v} = \epsilon'_r - j\epsilon''_r \quad (1)$$

where Y is the admittance with the material and $j\omega C_0 v$ is the admittance with vacuum. — the proportionality factor that relates the electric field to the electric flux density, and which depends on intrinsic material properties such as molecular polarizability, charge mobility, etc.:

$$\epsilon_r^* = \epsilon'_r - j\epsilon''_r = \frac{\vec{D}}{\epsilon_0 \vec{E}} \quad (1)$$

where:

ϵ_0 ≡ the permittivity of free space,

\vec{D} ≡ the electric flux density vector, and

\vec{E} ≡ the electric field vector.

3.2.1.1 *Discussion*—In common usage the word “relative” is frequently dropped. The real part of complex relative permittivity (ϵ'_r) is often referred to as simply relative permittivity, permittivity or dielectric constant. The imaginary part of complex relative permittivity (ϵ''_r) is often referred to as the loss index. In anisotropic media, permittivity is described by a three-dimensional tensor.

3.2.2 For the purposes of this test method, the media is considered to be isotropic, and therefore permittivity is a single complex number. —In common usage the word “relative” is frequently dropped. The real part of complex relative permittivity (ϵ_r') is often referred to as simply relative permittivity, permittivity or dielectric constant. The imaginary part of complex relative permittivity (ϵ_r'') is often referred to as the loss factor. In anisotropic media, permittivity is described by a three-dimensional tensor.

3.2.1.2 *Discussion*—For the purposes of this test method, the media is considered to be isotropic, and therefore permittivity is a single complex number at each frequency.

3.2.2 *relative complex permeability, μ_r^** , n —the proportionality factor that relates the magnetic flux density to the magnetic field, and which depends on intrinsic material properties such as magnetic moment, domain magnetization, etc.:

$$\mu_r^* = \mu'_r - j\mu''_r = \frac{\vec{B}}{\mu_0 \vec{H}} \quad (2)$$

where:

μ_0 ≡ the permeability of free space,

\vec{B} ≡ the magnetic flux density vector, and

\vec{H} ≡ the magnetic field vector.

3.2.2.1 *Discussion*—In common usage the word “relative” is frequently dropped. The real part of complex relative permeability (μ_r') is often referred to as relative permeability or simply permeability. The imaginary part of complex relative permeability (μ_r'') is often referred to as the magnetic loss factor. In anisotropic media, permeability is described by a three-dimensional tensor.

3.2.2.2 *Discussion*—For the purposes of this test method, the media is considered to be isotropic, and therefore permeability is a single complex number at each frequency.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 A list of symbols specific to this test method is given in Annex A1.

3.3.2 *calibration, n* —a procedure for connecting characterized standard devices to the test ports of a network analyzer to characterize the measurement system’s systematic errors. The effects of the systematic errors are then mathematically removed from the indicated measurements. The calibration also establishes the mathematical reference plane for the measurement test ports.

3.3.2.1 *Discussion*—Modern network analyzers have this capability built in. There are a variety of calibration kits that can be used depending on the type of test port. The models used to predict the measurement response of the calibration devices depends on the type of calibration kit. Most calibration kits come with a tape or disemedia that can be used to load the definitions of the calibration devices into the network analyzer. Calibration kit definitions loaded into the network analyzer must match the devices used to calibrate. Since both transmission and reflection measurements are used in this standard, a two-port calibration is required.

3.3.3 *network analyzer, n* —a system that measures the two-port transmission and one-port reflection characteristics of a multiport system in its linear range and at a common input and output frequency.

3.3.3.1 *Discussion*—For the purposes of this standard, this description includes only those systems that have a synthesized signal generator, and that measure the complex scattering parameters (both magnitude and phase) in the forward and reverse

directions of a two-port network ($S_{11}, S_{21}, S_{12}, S_{22}$).

3.3.4 *relative complex permeability*, μ^*_R —scattering parameter (S-parameter), S_{ij} , n —a term used to express the relationship between magnetic induction and magnetizing force defined by the ratio of the absolute permeability to the magnetic constant, given by

$$\mu^*_R = \mu'_R - j\mu''_R = \frac{|B|}{\mu_0 H} \quad (2)$$

where μ_0 is the permeability of free space.

3.3.5 *Discussion*—In common usage the word “relative” is frequently dropped. The real part of complex relative permeability (μ'_R) is often referred to as relative permeability or permeability. The imaginary part of complex relative permeability (μ''_R) is often referred to as the magnetic loss index. In anisotropic media, permeability is described by a three dimensional tensor.

3.3.5.1 For the purposes of this test method, the media is considered to be isotropic, and therefore permeability is a single complex number.

3.3.6 *scattering parameter (S-parameter)*, S_{ij} , n —a complex number consisting of either the reflection or transmission coefficient of a component at a specified set of input and output reference planes with all other planes terminated by a non-reflecting termination.

3.3.7 *Discussion*—As most commonly used, these coefficients represent the quotient of the complex electric field strength (or voltage) of a reflected or transmitted wave divided by that of an incident wave. The subscripts i and j of a typical coefficient—a complex number consisting of either the reflection or transmission coefficient of a component at a specified set of input and output reference planes with an incident signal on only a single port.

3.3.4.1 *Discussion*—As most commonly used, these coefficients represent the quotient of the complex electric field strength (or voltage) of a reflected or transmitted wave divided by that of an incident wave. The subscripts i and j of a typical coefficient S_{ij} refer to the output and input ports, respectively. For example, the forward transmission coefficient S_{21} is the ratio of the transmitted wave voltage at Reference Plane 2 (Port 2) divided by the incident wave voltage measured at Reference Plane 1 (Port 1). Similarly, the Port 1 reflection coefficient S_{11} is the ratio of the Port 1 reflected wave voltage divided by the Port 1 incident wave voltage at reference plane 1 (Port 1).

3.3.8.3.5 *transverse electric (TE_{mn}) wave*, n —an electromagnetic wave in which the electric field is everywhere perpendicular to the direction of propagation.

3.3.8.4

3.3.5.1 *Discussion*—The index m is the number of half-period variations of the field along the waveguide’s larger transverse dimension, and n is the number of half-period variations of the field along the waveguide’s smaller transverse dimension. The dominant wave in a rectangular waveguide is TE_{10} . The electric field lines of the TE_{10} mode are parallel to the shorter side.

3.3.9 *transverse electromagnetic (TEM) wave*

3.3.6 *cutoff frequency*, n —an electromagnetic wave in which both the electric and magnetic fields are perpendicular to the direction of propagation.

3.3.9.1 *Discussion*—In coaxial transmission lines the dominant wave is TEM. —the lowest frequency at which non-evanescent, dominant mode propagation can occur within a rectangular waveguide.

4. Summary of Test Method

4.1 A carefully machined test specimen is placed in an electromagnetic waveguide transmission line and connected to a calibrated network analyzer that is used to measure the S-parameters of the transmission line-with-specimen. A specified data-reduction algorithm is then used to calculate permittivity and permeability. If the material is nonmagnetic a different algorithm is used to calculate permittivity only. Error corrections are then applied to compensate for the existence of air gaps between the specimen and the transmission line’s conductors. line conductor surfaces.

5. Significance and Use

5.1 Design calculations for ~~Radio Frequency~~ radio frequency (RF), microwave and millimeter-wave components require the knowledge of values of complex permittivity and permeability at operating frequencies. This test method is useful for evaluating ~~batch type small experimental batch~~ or continuous production of material for use materials used in electromagnetic applications. ~~It may be used~~ Use this method to determine complex permittivity only (in non-magnetic materials) or both complex permittivity and permeability simultaneously.

6. Interferences

6.1 The upper limits of permittivity and permeability that can be measured using this test method are restricted by the transmission line and specimen geometries. No specific limits are given in this standard, but this test method is practically limited geometries, which can lead to unwanted higher order waveguide modes. In addition, excessive electromagnetic attenuation due to low-to-medium values of permittivity and permeability. In 7-mm coaxial lines, specimen permittivities <30 a high loss factor within the test specimen can prevent determination of permittivity and permeabilities <100 can be determined if the air gap between the specimen and the inner and outer conductors permeability. No specific limits are given in this standard, but this test

method is known. Rectangular wave guides yield higher limits, practically limited to low-to-medium values of permittivity and in general these upper limits increase as transmission line cross-sectional area increases. permeability.

6.2 The existence of air gaps between the test specimen and the transmission line introduces a negative bias into measurements of permittivity and permeability. In this test method compensation for this bias is required, and to do so requires knowledge of the air gap sizes. Air gap sizes are estimated from dimensional measurements of the specimen and the specimen holder, which can be measured with micrometers, feeler gauges, or other precision instruments. Several different error correction models have been developed, and a frequency independent series capacitor model is described in Annex A2. Air gap corrections are only approximate and therefore this test method is practically limited to low-to-medium values of permittivity and permeability.

7. Apparatus

7.1 *Experimental Setup* is given in Experimental Test Fixture—The test fixture includes a specimen holder connected to a network analyzer, as shown in Fig. 1 as a block diagram.

7.2 *Network Analyzer*—The network analyzer needs a full 2-port test set that can measure scattering parameters in both directions. Use a network analyzer that has a synthesized signal generator in order to ensure good frequency stability and signal purity. To define the Port 1 and Port 2 Reference Planes with respect to magnitude and phase, perform a two-port calibration of the network analyzer.

7.3 *Computer*—Use a computer for network analyzer data acquisition and computation of permittivity and permeability from the measured scattering parameters. Any computer capable of these functions is sufficient for the purposes of this test method.—The network analyzer needs a full 2-port test set that can measure transmission and reflection scattering parameters. Use a network analyzer that has a synthesized signal generator in order to ensure good frequency stability and signal purity.

7.3 *Waveguide Calibration Kit*—To define Port 1 and Port 2 measurement reference planes, calibration of the waveguide test fixture is required. A calibration kit consists of well-characterized standard devices and mathematical models of those devices. Use a through-reflect-line (TRL), an open-short-load-through (OSLT), or any other calibration kit that yields similar calibration quality to calibrate the waveguide test fixture.

7.4 *Network Analyzer Calibration Kit*—To define Port 1 and Port 2 Measurement Reference Planes, calibration of the network analyzer is required. A network analyzer calibration kit consists of well characterized standard devices and mathematical models of those devices. A through-reflect-line (TRL), open-short-load-through (OSLT), or other calibration kit that yields similar calibration quality may be used to calibrate the network analyzer.

7.5 Specimen Holder:

7.5.1 Because parameters such as specimen holder length and cross-sectional dimensions are of critical importance to the calculation of permittivity and permeability, carefully measure and characterize the physical dimensions of the specimen holder.

7.5.2 Although not required, it is helpful if the specimen is nearly the same length as the specimen holder. This minimizes conductor losses that cause a positive bias to ϵ''_R results. If desired, use measurement techniques to remove conductor losses. Two possible procedures to remove specimen holder conductor losses are outlined in Appendix X2.

7.5.3 Either rectangular wave guides or beadless coaxial lines may be used as the specimen holder. Coaxial lines consist of two concentric cylindrical conductors that guide TEM waves. Coaxial lines have an advantage over rectangular wave guides in that

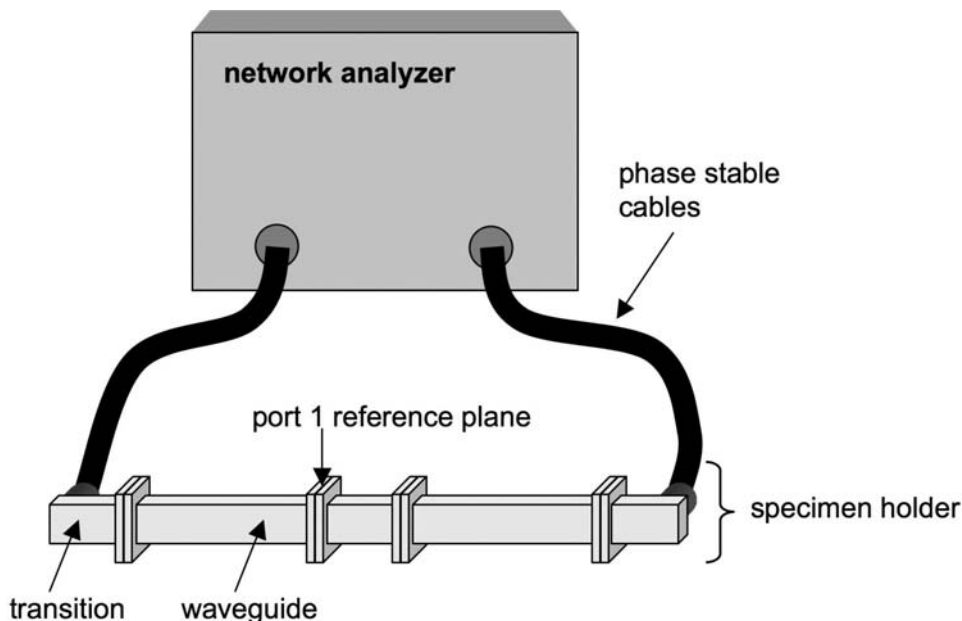


FIG. 1 Diagram of Experimental Fixture

they can be used to perform very broadband measurements. Coaxial lines have no lower cutoff frequency, and therefore can be used for measurements at relatively low frequencies. The upper frequency limit of a coaxial line is limited by overmoding, determined by the diameters of the outer and inner conductors. As these diameters become larger, the cutoff frequencies of higher-order modes become lower. The theoretical model used for this test method assumes that only the dominant mode of propagation exists (TEM for coaxial lines, TE_{10} for rectangular wave guides).

7.4.1 Because parameters such as specimen holder length and cross-sectional dimensions are of critical importance to the calculation of permittivity and permeability, carefully measure and characterize the physical dimensions of the specimen holder.

7.4.2 If a separate length of transmission line is used to hold the specimen, ensure that that empty length of line is also in place during calibration of the specimen holder.

7.4.3 The theoretical model used for this test method assumes that only the dominant mode of propagation exists (TE_{10} for rectangular wave guides). The existence of higher-order modes limits the applicability of the model. Use of rectangular wave guide has two distinct advantages over coaxial line: (1) test specimen is easier to machine, and (2) for a given gap size, air gap corrections are smaller for rectangular wave guides than for coaxial lines.

7.5.4 Be sure that the specimen holder dimensions are within proper tolerances for the transmission line size in use. If a 7-mm coaxial transmission line is used, let L_1 , D_1 , L_2 , and D_2 be the length and diameter of the inner conductor and the length and diameter of the outer conductor, respectively. Proper tolerances are then:

centerconductor: _____ (3)

$$D_1 = 3.040 \pm 0.005 \text{ mm } (0.1197 \pm 0.0002 \text{ in.});$$

outereconductor: _____ (4)

$$D_2 = 7.000 \pm 0.006 \text{ mm } (0.2756 \pm 0.00025 \text{ in.}), \text{ and}$$

$$L_2 \geq L_1 > L_2 - 0.00102 \text{ mm } (L_2 \geq L_1 > L_2 - 0.0004 \text{ in.}). \quad (5)$$

Dimensions and tolerances of other coaxial sizes are in the appropriate manufacturer's specifications. Dimensions and tolerances of standard rectangular wave guides are in various references. for rectangular waveguide or TE_{11} for circular waveguide). The existence of higher-order modes restricts the measurable bandwidth for a given waveguide test fixture.

7.4.4 Be sure that the specimen holder dimensions are within proper tolerances for the waveguide transmission line size in use. For an X-band rectangular waveguide transmission line the dimensions of the inner opening are denoted by "a" the width and "b" the height. Proper tolerances are then:

X-band waveguide width:

$$a = 22.86 \pm 0.10 \text{ mm } (0.900 \pm 0.004 \text{ in.}) \quad (3)$$

X-band waveguide height:

$$b = 10.16 \pm 0.10 \text{ mm } (0.900 \pm 0.004 \text{ in.}) \quad (4)$$

7.4.4.1 Dimensions and tolerances of other standard waveguides are in the appropriate manufacturer's specifications and U.S. military specifications.³

8. Test Specimen

8.1 Make the test specimen long enough to ensure good alignment inside the holder. Also, make the test specimen long enough to ensure that the phase shift through the specimen is much greater than the phase measurement uncertainty of the network analyzer at the lowest measurement frequency.

8.2 Accurately machine the specimen so that its dimensions minimize the air gap that exists between the conductor(s) and the specimen. In this respect, measure the specimen holder's dimensions in order to specify the tightest tolerances possible for specimen preparation. A test specimen that fits into coaxial transmission lines is a toroidal cylinder. Typical dimensional specifications for a 7-mm coaxial test specimen are given in Fig. 2. A test specimen for rectangular wave guides has rectangular shape. Fig. 3 gives dimensional specifications for a specimen that fits into X-band (8.2 to 12.4 GHz) wave guide. The given dimensional specifications provide nominal tolerances only. Keep physical variations of specimen dimensions as small as is practicable. Include specimen dimensions and uncertainties in the report.

8.1 Make the test specimen long enough to ensure good alignment inside the holder. Also, make the test specimen long enough to ensure that the phase shift through the specimen is much greater than the phase measurement uncertainty of the network analyzer at the lowest measurement frequency. If a specimen is expected to have low loss, sufficient length is also required to ensure accurate determination of the loss factor. Finally, for high loss specimens, the specimen length cannot be so long that high insertion loss prevents material property inversion.

8.2 Accurately machine the specimen so that its dimensions minimize the air gap that exists between the conductor surfaces and the specimen. In this respect, measure the specimen holder's dimensions in order to specify the tightest tolerances possible for

² Annual Book of ASTM Standards, Vol 10.01.

³ MIL-DTL-85/1F, 20 November 1998.

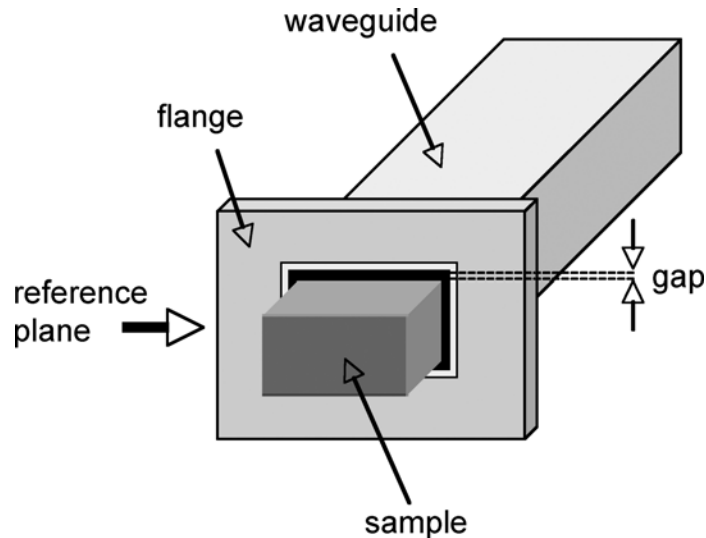


FIG. 2 Drawing of Sample Being Inserted into Waveguide

specimen preparation. Keep physical variations of specimen dimensions as small as is practicable and include specimen dimensions and uncertainties in the report.

9. Preparation of Apparatus

9.1 Inspect Network Analyzer Test Ports—Insure that the recession of both test ports' center conductor shoulder behind the outer conductor mating plane meets the minimum specifications. For a 7-mm connector, the recession is 0.005 to 0.021 mm (0.0002 to 0.008 in.) with the collet removed.—Insure that the recession of both test ports' center conductor shoulder behind the outer conductor mating plane meets the minimum specifications. Refer to network analyzer manufacturer's documentation to provide connector specifications.

9.2 Flexing and Tightening Cables and Connectors—Cable flexing and improperly tightened connectors introduce phase and magnitude errors into S-parameter data. For this reason, bend the test cables as little as possible, and under no circumstances bend the test cables smaller than the manufacturer's minimum recommended radius. Use of phase-stable cables is highly recommended. Insofar as possible, return the network analyzer cables to the same position during measurement of calibration standards and specimen. Use the proper a torque wrench to tighten connectors. Use a 1.36 newton meter (12 in.-pound) with the manufacturer's recommended torque wrench to tighten 7-mm coaxial connectors.

9.3 Inspect and Clean Specimen, Specimen Holder, and Connectors—Handle specimens with laboratory gloves (nylon, plastic, or latex) to avoid depositing oil onto a specimen.—If contamination is a concern, handle specimens with laboratory gloves. Clean specimens, connectors, and transmission lines using lint-free swabs and isopropyl alcohol (not less than 99 % pure). Blow out specimens, connectors, and transmission lines using filtered, pressurized air (not breath). Examine specimens for cracks and chips on their edges. Note any damage to specimens.

9.4 Network Analyzer Setup:

9.4.1 Turn on the network analyzer at least 1 h before beginning calibration and measurements.

9.4.2 For measurements made in a 50-Ω coaxial setup, set system and line impedances to 50 Ω. For rectangular wave guide measurements, set system and line impedances to 1 Ω. Set delay to either coaxial delay or rectangular wave guide delay, as appropriate. Set relative velocity factor to 1.000.

9.4.3 Put network analyzer into step frequency mode. Set the start frequency and stop frequency as desired. Set the number of measurement points to the desired value.

9.4.4 If available, set the network analyzer's variable intermediate frequency (IF) bandwidth to less than 30 Hz, otherwise set the network analyzer data averaging factor to a value >200.

9.4.5 Perform a two-port network analyzer calibration in accordance with the manufacturer's procedures.

9.4.1 Turn on the network analyzer before beginning calibration and measurements. Refer to manufacturer documentation for minimum warm-up period.

9.4.2 Put network analyzer into step frequency mode. Set the start frequency and stop frequency as desired. Set the number of measurement points to the desired value.

9.4.3 If available, set the network analyzer's variable intermediate frequency (IF) bandwidth to less than 30 Hz, otherwise set the network analyzer data averaging factor to a value >200.

9.4.4 Perform a two-port test fixture calibration using a waveguide calibration kit in accordance with the manufacturer's procedures and in accordance with 7.3.