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Indian Standard

RECOMMENDED METHODS OF TESTS FOR THE DETERMINATION OF DIELECTRIC PROPERTIES OF INSULATING MATERIALS AT FREQUENCIES ABOVE 300 MHz

PART I GENERAL

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INDIAN STANDARDS INSTITUTION
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Indian Standard

RECOMMENDED METHODS OF TESTS FOR THE DETERMINATION OF DIELECTRIC PROPERTIES OF INSULATING MATERIALS AT FREQUENCIES ABOVE 300 MHz

PART I GENERAL

Solid Electrical Insulating Materials Sectional Committee, ETDC 63

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RECOMMENDED METHODS OF TESTS FOR THE DETERMINATION OF DIELECTRIC PROPERTIES OF INSULATING MATERIALS AT FREQUENCIES ABOVE 300 MHz

PART I GENERAL

0. FOREWORD

0.1 This Indian Standard was adopted by the Indian Standards Institution on 15 April 1982, after the draft finalized by the Solid Electrical Insulating Materials Sectional Committee had been approved by the Electrotechnical Division Council.

0.2 The standard deals with the general requirements of the methods of measuring the dielectric properties of insulating materials of frequencies above 300 MHz. It applies to the procedures for the determination of relative permittivity and dielectric dissipation factor and of quantities related to them, such as loss index, of dielectric materials in the microwave frequency region.

0.3 This standard is one amongst a series of standards dealing with the dielectric properties of electrical insulating materials. Unlike the test methods employed at lower frequencies, the test methods for frequencies above 300 MHz involve the use of test specimen and/or test set up, the dimensions of which are larger than or comparable to the wave length of the electromagnetic field of the test frequency. This standard has since been brought out with a view to highlight these special considerations in addition to highlighting the factors influencing dielectric properties of insulating materials at higher frequencies. A survey on methods of measurements, and the choice of test methods are also given.

0.4 Lumped parameter methods can be used when the wave length of the applied electromagnetic field is large compared with the dimensions of the specimen. Distributed parameter methods shall be used when the spatial variation of the electromagnetic field over the specimen cannot be ignored.

0.5 This standard is being brought out in many parts. It is intended to cover the general requirements and resonance method of tests in the first two parts. Subsequent parts dealing with input impedance method of measurement, and optical methods are under consideration.

0.6 In the preparation of this standard, considerable assistance has been drawn from IEC Pub 377-1 (1973) 'Recommended methods for the determination of dielectric properties of insulating materials at frequencies above 300 MHz Part I General issued by the International Electrotechnical Commission.

0.7 For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis, shall be rounded off in accordance with IS : 2-1960†. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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1. SCOPE

1.1 This standard (Part I) covers the general requirements of the method of measurement of the dielectric properties of insulating materials at frequencies above 300 MHz.

1.2 This standard applies to the procedure for the determination of relative permittivity, and the dielectric dissipation factor and of quantities related to them, such as loss index, of dielectric materials in the microwave frequency region.

2. TERMINOLOGY

2.0 For the purpose of this standard, the following definitions shall apply. All these definitions apply only to dielectric materials having the permeability of absolute vacuum.

2.1 Relative Complex Permittivity ε_r^* — The relative complex permittivity ε_r^* of a dielectric material is:

$$\varepsilon_r^* = \varepsilon_r' - j\,\varepsilon_r'' = \frac{C_x^*}{C_0} \qquad (1)$$

where ε_r' is relative permittivity which is a real component of complex permittivity, j ε_r'' is the imaginary component of complex permittivity and C_x^* denotes the complex capacitance of a small capacitor in which the space between and around the electrodes is entirely and exclusively filled with the dielectric material in question, and C_0 is the capacitance of the same electrode configuration in absolute vacuum.

NOTE — The complex capacitance of a capacitor is defined by:

$$j\omega C_X^* = Y_X^* = G_X + j\omega C_X$$

where G_X is the real part (ac conductance) and jwC_X is the imaginary part of the complex admittance Y_X^* of the said capacitor.

†Rules for rounding off numerical values (*revised*).

As the wavelength of the applied electromagnetic field with increasing frequency approaches the dimensions of the specimen employed, the variation of the electric (and magnetic) field parameters throughout the specimen can no longer be ignored. Therefore, for a proper interpretation of the measured data, it is necessary to turn from lumped circuit analysis to wave analysis and transmission line theory. This means also growing sensitivity of results to inhomogeneity and anisotropy of specimens.

2.1.1 The relative complex permittivity ε_r^* of a dielectric material is proportional to the square of the ratio of the complex propagation coefficient $\gamma = a + j\beta$ of an electromagnetic wave in the dielectric material to that $\gamma_0 = j\,\beta_0$ in absolute vacuum:

$$\varepsilon_r^* = \left(\frac{\gamma}{\gamma_0}\right)^2 + \left(\frac{\lambda_0}{\lambda_c}\right)^2 \tag{2}$$

where λ_0 is the wavelength in free space and λ_c is the critical (or cut-off) wavelength of the mode used.

NOTE 1 — With plane waves of travelling electromagnetic wave (TEM) $\lambda_c = \infty$.

NOTE 2 — The relative permittivity ε_r of ambient dry air free from carbon dioxide at 293 K and normal atmospheric pressure equals 1·000 53, so that in practice measurements of capacitance in air (C_a), specific capacitance in air (C_a) and complex propagation coefficient in air (γ_a) taken in air instead capacitance in vacuum (C_0), specific capacitance in vacuum (C_0) and complex propagation coefficient in vacuum (γ_0) taken in absolute vacuum can be used to determine the relative permittivity ε_r of solid and liquids with sufficient accuracy.

NOTE 3 — The complex (absolute) permittivity of a dielectric material is the product of its relative complex permittivity ε_r^* and the electric constant (or permittivity of absolute vacuum) ε_0.

$$\varepsilon^* = \varepsilon_0\,\varepsilon_r^*$$

In the SI system, the absolute permittivity has the unit farad per metre (F/m); furthermore, the electric constant ε_0 has the following value:

$$\varepsilon_0 \approx 8{\cdot}54{\cdot}10^{-12} \approx \frac{1}{36\pi} \cdot 10^{-9}\ F/m \tag{3}$$

2.2 Relative Permittivity ε_r' — The relative permittivity ε_r' of a dielectric material is the real part of the relative complex permittivity, defined in **2.1**. According to equations 1 and 2:

$$\varepsilon_r' = \frac{C_x}{C_0} = (\lambda_0)^2 \left[\frac{\beta^2 - a^2}{(2\pi)^2} + \frac{1}{\lambda_c^2}\right] \tag{4}$$

NOTE — If the dielectric quantities are noted as real numbers, that is, ε_r' and tan δ instead of ε_r' and ε_r'', the prime is omitted:

$$\varepsilon_r' = \varepsilon_r$$

2.3 Loss Index ε_r'' — The loss index ε_r'' of a dielectric material is the imaginary part of the relative complex permittivity defined in **2.1.** According to equations 1 and 2:

$$\varepsilon_r'' = \frac{G_x}{j\omega C_0} = \left(\frac{\lambda_0}{\pi}\right)^2 . \frac{a\beta}{2} \tag{5}$$

2.4 Dielectric Dissipation Factor tan δ — The dielectric dissipation factor tan δ of a dielectric material is the tangent of the phase angle (loss angle δ) between the applied field strength 'F' and the resulting electric displacement D within the insulating material, both varying sinusoidally with time at one and the same angular frequency $\omega = 2\pi f$.

2.4.1 As the field components E and D within the dielectric in general are not accessible to measurement, the dielectric dissipation factor of a given volume (for example, of the dielectric material) is measured as the ratio of the electric energy dissipated to 2π times that reversibly stored in that volume per one half-period of oscillation. This ratio is also equivalent to:

$$\tan \delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{6}$$

2.4.2 The reciprocal of the dissipation factor tan δ is called quality factor (Q – factor):

$$\frac{1}{\tan \delta} = Q$$

3. FACTORS INFLUENCING DIELECTRIC PROPERTIES OF DIELECTRIC MATERIALS

3.1 The measured permittivity and dielectric dissipation factor of a given dielectric material are determined by the resulting dielectric polarization of the test specimen. Various external and internal physical parameters such as frequency, temperature, electrical field strength, ionizing radiation, moisture and other impurities, chemical structure, homogeneity and isotropy (physical and chemical structure), etc, affect the measured data.

Therefore, to interpret consistently the results obtained from a test, it is necessary to know the state of the test specimen and to keep all the aforementioned parameters under control. In the following, the influences of frequency, temperature, moisture and other impurities, of physical and chemical structure and of electrical field strength on the measured dielectric properties are discussed separately.

NOTE — The permittivity and dielectric dissipation factor measured within the frequency range covered by this recommendation mostly originate from dipole polarization due to polar molecules and from atomic polarization.

3.1.1 *Frequency*

3.1.1.1 As, for technical materials, ε_r' and tan δ are not constant over the wide frequency range over which they are used, it is necessary to measure the dissipation factor and the permittivity at those frequencies at which the dielectric material will be used. For accurate interpolation between data measured at a few frequencies, it may sometimes be possible to obtain a Debye curve to fit over an absorption region; also, effective use may be made of a cole-cole plot.

3.1.2 *Temperature*

3.1.2.1 The polarizability of a dielectric material depends also on its temperature. Therefore the frequencies of the loss index maxima (and correspondingly of the dielectric dissipation factor) vary with temperature. Accordingly, the temperature coefficient of loss index can be positive or negative depending on the position of the loss index maximum with respect to the measuring frequency and the test temperature. Special attention is drawn to the fact that irreversible changes of the dielectric properties of the material investigated may occur in a short time, for example, during a measurement at elevated temperatures. In this respect *see* **3.1.3** and **3.1.4** also.

3.1.3 *Moisture and Other Impurities*

3.1.3.1 The polarizability is increased by absorption of water or by the formation of a water film on the surface of the dielectric, thus affecting the permittivity, the dissipation factor and the dc conductivity. Conditioning of test specimens is therefore of decisive importance and control of the moisture content, both before and during testing, is imperative if test results are to be interpreted correctly. The polarizability is also subject to impurities introduced by physical contamination or chemical additives, for example, solvents or plasticizers. Therefore care shall be taken to ensure that the material to be tested is not affected or affected only in a controlled way by the sampling procedures or by subsequent treatments for example, at elevated temperatures.

3.1.4 *Physical and Chemical Structure*

3.1.4.1 The direction of polarization of the electromagnetic field relative to the structure of the specimen under test strongly influences the result of the measurement. Different results may be obtained due to inhomogeneity (as in laminates) or to anisotropy, for example, in crystals, unless all measurements on the specimens are made in the same relation to some identifiable feature of the material. Specimens which have the same chemical composition but different chemical structures, for example, curable resins subjected to different curing conditions or polymers of a different degree of polymerization, will also give different results.

NOTE — Materials showing some periodicity in their structure such as laminates may have a frequency response different from that of their constituents if the wavelength is comparable with the period of this structure.

3.1.5 *AC - Field Strength*

3.1.5.1 In general, permittivity and dielectric dissipation factor are independent of field strength so long as no partial discharge occurs in the dielectric. With ferro-electric bodies, however, a field-dependent effect may still be observable at the lower microwave frequencies, but it rapidly vanishes as the frequency increases.

4. SURVEY ON MEASURING METHODS

4.1 Principles of Measuring Methods

4.1.1 *General* — The characteristic feature of methods for the determination of dielectric properties in the frequency range covered by this recommendation is that the electric and magnetic components of the field vary both in amplitude and phase from point to point of the specimen and of the measuring apparatus, because the wavelength of the radiation is comparable with the dimensions of the specimen and the apparatus. In non-magnetic materials, this effect first becomes obvious in the tens-of-MHz region and can no longer be ignored from 600 MHz upwards.

4.1.2 *Physical Effects Available for Measurement*

4.1.2.1 The permittivity and loss govern the following effects:

a) The propagation velocity of electromagnetic waves, and hence their wavelength within a given medium, is related inversely to the permittivity of the medium in question (*see* **2.1**),

b) At any discontinuity of the permittivity of a medium transmitting a wave, a fraction of the energy of the wave is reflected; the magnitude of the fraction depends on the ratio of the permittivities at the two sides of the discontinuity, and

c) Because the wave polarizes the medium, energy is lost continuously along its path of travel; the wave amplitude is therefore attenuated in proportion to the loss index of the medium.

4.1.2.2 *Effects not related to permittivity*

a) A beam of given frequency f and of given cross-section may propagate not only in one mode but in a variety of modes of different velocities and hence different wavelengths. The modes which exist in a particular case depend on the beam cross-section and on the beam-launching system, and

b) Reflection of energy and/or mode conversion (which also results in loss of energy in a given mode) takes place at any point at which the beam cross-section changes. Attenuation may still occur even in absolute vacuum due to diffraction losses from the beam or to the finite conductivity of the beam-guiding structure.

In order to separate the effects of the material properties from those of unwanted disturbances of the test-wave field, and thus obtain consistent and reproducible results, it is important to use for the measuring apparatus a uniform transmission system, that is one in which there are no significant discontinuities to cause reflections or losses. The properties of the system itself must be well known at the measuring frequency, and must either not change at all or change only in a predictable manner, after insertion of the test specimen. Only simple test arrangements should be used, both to reduce the number of uncertainties concerning the test conditions and to simplify the calculations.

4.2 Test Arrangement — The apparatus in which the test specimen is inserted may consist of:

4.2.1 *Resonance Apparatus* — A uniform transmission section is short-circuited at both ends and loosely coupled to a generator and receiver. Maximum energy transfer between generator and receiver is established when the separation of the short-circuits is a multiple of one-half the working wavelength. Details of this (the Resonance Method) will be given in Part 2 of this standard. Results are obtained in terms of Q (*see* **2.4.2**) and of frequency shift or dimensional shift to restore resonance after insertion of the test specimen, at constant resonator dimensions or constant test frequency respectively.

NOTE — As this method employs multiple beam reflection, it is especially suited to the detection of the lowest dissipation factors, even with small quantities of test material. To achieve the highest sensitivity possibile, fixed resonators may be used; such apparatus can be used only at a single frequency, which depends to some extent on the shape, size and dielectric properties of the test specimen.

4.3 Choice of the Test Method — The choice of the test method is affected by various considerations which may conflict with each other. In the following, these considerations are treated separately (*see* Fig. 1).

4.3.1 *Frequency or Wavelength*

4.3.1.1 At high frequencies it may be difficult to work to the required mechanical precision. At lower frequencies, guided waves are preferred due to reduction of size of test apparatus and of test specimens. Due to the skin effect of metallic conductors, in general the attenuation of waveguides rises with increasing frequency, thus making determination of loss index of low loss materials increasingly difficult.

NOTE — Hollow guides at the same working frequency show lower attenuation than coaxial guides. With circular hollow guides, the H_{01} mode has the outstanding property that attenuation decreases as frequency increases.

4.3.2 *Test Material Shape and Quantity*

4.3.2.1 Test specimens shall conform to the requirements of the test set-up. Therefore, in general, machining procedures are necessary (*see* respective measuring methods). As the material to be tested may be available not in bulk but only in plate, sheet (film), rod (wire) or tube form, the test method may be chosen also with respect to the shape and quantity of test material being at hand. An essential condition for dielectric measurements is that the specimen be of a single piece.

For resonance methods, the specimens may fill the cross-section of the beam. Due to the high inherent sensitivity with these methods, the techniques are applicable also to ball, rod or disk shaped specimens so long as suitable modes are employed. Sensitivity to small variations in the properties and the accuracy of results, however, greatly depend on the mode used, the ratio of volumes of resonator and specimen including the accuracy in obtaining this ratio.

4.3.2.2 Having equal specimen length (in order to have equal sensitivity in measurement) means that test apparatus using guided waves in their fundamental mode requires less test material than that using unguided waves; likewise, coaxial waveguides require still less than hollow guides at the same working frequency. With waveguide equipment, it is essential to fit the test specimen to the waveguide dimensions as closely as possible.

4.3.3 *Dielectric Properties of Test Material*

4.3.3.1 *Permittivity* — Insulating materials having relative permittivities up to about 100 may be tested by any one of the methods enumerated. It must be borne in mind, however, that, due to the presence of the dielectric, higher order mode set up by any imperfections may propagate within the specimen, thus causing erroneous readings. With relative permittivities from about 100 upwards, transmission methods may be preferable by virtue of the high accuracy obtainable. With anisotropic materials, the results obtained depend on the positioning of the axes of the specimens with respect to the polarization axis of the beam. Therefore, the specimens must be cut to match the test conditions with respect to the mode employed.

4.3.3.2 *Dielectric dissipation factor and loss index* — Resonance methods are most suited for detecting very small losses. With impedance methods, the lower limit is imposed by the attenuation of the empty transmission system. The upper limits of losses measurable are set with resonance methods, by the off-set of the resonance effect.

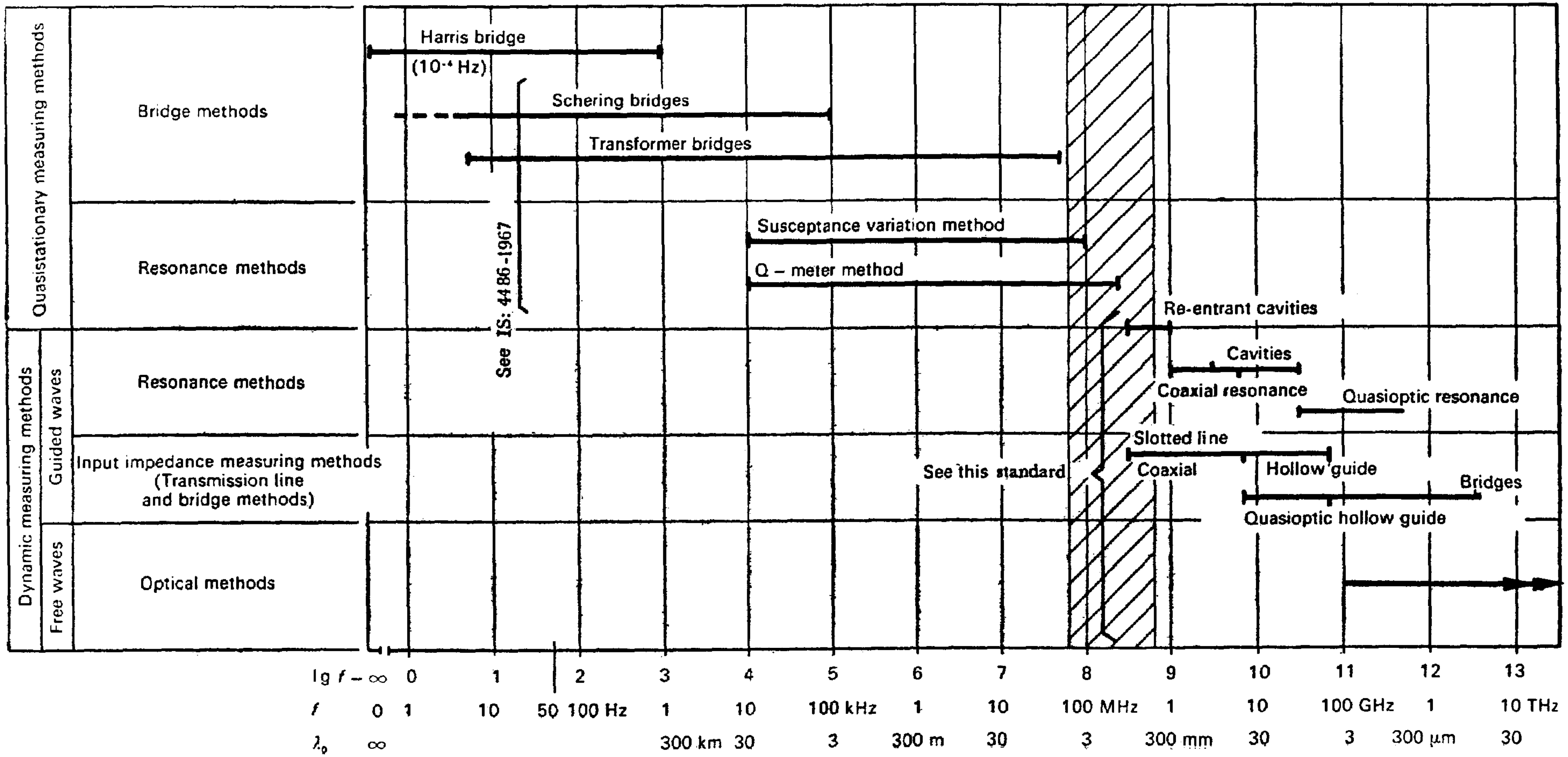

FIG. 1 AC MEASURING METHODS

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4.3.4 *Mechanical Requirements* — Mechanical requirements concern the dimensional precision and the surface finish of the wave guiding structure as well as of the specimen, and also the accuracy to which length or angle readings can be taken.

a) Dimensional precision is especially important when non-standard waveguide equipment is being used (for example, cavities) or if waveguides are used close to their cut-off frequency, and in matching of specimens to the waveguide dimensions (the respective methods will be dealt with in Part 2 of this standard). With methods using unguided waves, these requirements apply to the beam launching system and to the surface flatness of the specimen as well. All moving parts must move smoothly and without any back-lash.

NOTE 1 — Waveguides should not be used below a frequency equalling 1·25 times the cut-off frequency of the respective mode.

NOTE 2 — Tolerances of characteristic dimensions shall conform to at least $\pm \frac{\lambda g}{1\,000}$, where λg is the propagating wavelength.

b) High surface finish is required especially with all metallic beam guiding structures, as due to the pronounced skin effect any disturbance of a smooth surface will cause further increase of attenuation.

c) With all methods employing standing waves, determination of the standing wave pattern must be correct at least to a quantity of the order of $\pm \frac{\lambda g}{1\,000}$, where λg is the propagating wavelength. Consequently, in the millimetre range of wavelengths, it is advisable to turn to optical methods.

4.3.5 *Temperature*

4.3.5.1 Temperature influences the consistency of measurements with methods using guided waves in that it changes not only the characteristic length of the measuring assembly, but also the match of the specimen to the waveguide and, with hollow guides, the cut-off wavelength as well.

5. TESTING PROCEDURE

5.1 Preparation of Specimens

5.1.1 The specimen shall be cut from the solid material or prepared by an appropriately standardized technique in order to obtain the desired shape. The subsequent measurements of the dimensions of the specimen shall be made accurately with a tolerance of $\pm \left(\frac{\lambda g}{1000} + 0{\cdot}005 \text{ mm} \right)$.

5.2 Conditioning

5.2.1 Conditioning shall be made in accordance with the relevant specifications.

6. TEST REPORT

6.1 In the test report, the following information shall be given where relevant :

a) Type and designation of the insulating material as well as the form in which it is delivered. Method of sampling, shape, dimensions of the test specimen and date of sampling. Exact information on the treatment of the specimen at the contact areas is important;

b) Method and duration of conditioning the specimens;

c) Temperature and relative humidity during the test and temperature of the specimen;

d) Measuring apparatus and test method applied;

e) Applied microwave power;

f) Applied frequency or free space wavelength;

g) Applied wave mode (Information on the position of a preferred axis of the specimen with respect to the direction of the electric field applied is very important);

h) Relative permittivity ε_r (average value);

j) Dielectric dissipation factor tan δ or dielectric loss index ε_r'' (average values); and

k) Date of test.

INDIAN STANDARDS

ON

SOLID ELECTRICAL INSULATING MATERIALS

IS :

350-1968	Organic, backing, impregnating, insulating varnishes for electrical purposes (*first revision*)
352-1973	Air-drying insulating varnishes for electrical purposes (*first revision*)
1271-1958	Classification of insulating materials for electrical machinery and apparatus in relation to their thermal stability in service
1576-1967	Solid pressboard for electrical purposes
1951-1961	Polyvinyl chloride sleeving for electrical purposes
2188-1962	Methods of test for paper for electrical purposes
2259-1963	Methods of test for determination of insulation resistance of solid insulating materials
2260-1973	Preconditioning, conditioning and testing of solid electrical insulating materials (*first revision*)
2448 (Part I)-1963	Adhesive insulating tapes for electrical purposes : Part I Tapes with cotton textile substrates
2448 (Part II)-1968	Adhesive insulating tapes for electrical purposes : Part II Tapes with PVC substrates
2464-1963	Built-up mica for electrical purposes
2584-1963	Method of test for electric strength of solid insulating materials at power frequencies
2824-1975	Method for determining the comparative tracking index of solid insulating materials under moist conditions (*first revision*)
3202-1965	Code of practice for climate proofing of electrical equipment
3352-1965	Varnished cotton cloth and tapes for electrical purposes
3396-1979	Methods of test for volume and surface resistivity of electrical insulating materials (*first revision*)
3765-1966	Varnish impregnated cotton sleevings for electrical purposes
4248-1967	Non-ignitable and self-extinguishing boards (with mineral base) for electrical purposes
4249-1967	Classification and methods of tests for non-ignitable and self-extinguishing properties of solid electrical insulating materials
4486-1967	Recommended methods for the determination of the permittivity and dielectric dissipation factor of electrical insulating materials at power, audio and radio frequencies including metre wavelengths
4819-1968	Thin vulcanized fibre sheet (including leatheroid) for electrical purposes
4820-1968	Vulcanized fibre sheets for electrical purposes
5596-1970	Methods of test for determining deleterious substances in fibrous insulating materials
5711-1970	Vulcanized fibres rods and tubes for electrical purposes
6230-1970	Woven asbestos tape for electrical insulating purposes
6659-1976	Electronic grade ceramic materials (*first revision*)
7084-1973	Bitumen based filling compounds for electrical purposes
7571-1974	Methods of tests for ceramics for telecommunication and allied purposes

IS:

7755-1975 High tension insulating cotton tape impregnated with bitumen based compounds

7809 Pressure sensitive adhesive tapes for electrical purposes:

(Part I)-1975 General requirements

(Part II)-1977 Methods of test

(Part III/Sec 1)-1977 Requirements for individual materials, Section 1 Plasticized PVC tapes with non-thermosetting adhesive

(Part III/Sec 2)-1981 Specification for individual materials, Section 2 Requirements for polyester film tapes (PETP) with thermosetting adhesive

(Part III/Sec 3)-1981 Specification for individual materials, Section 3 Requirements for polyester film tapes (PETP) with non-thermosetting adhesive

(Part III/Sec 4)-1977 Requirements for individual materials, Section 4 Cellulosic paper, creped with thermosetting adhesive

(Part III/Sec 5)-1977 Requirements for individual materials, Section 5 Cellulosic paper with thermosetting adhesive

8264-1976 Air drying and anti-tracking insulating varnishes for electrical purposes

8504 (Part I)-1977 Guide for determination of thermal endurance properties of electrical insulating materials: Part I Temperature indices and thermal endurance profiles

8516-1977 Methods of test for determining electrolytic corrosion with insulating materials

8570-1977 Press paper for electrical purposes

9229 Insulating materials based on built-up mica or treated mica paper:

(Part I)-1979 Definitions and general requirements

(Part II)-1979 Methods of test

(Part III/Sec 1)-1979 Specification for individual materials, Section 1 Rigid mica material for commutator separators

9335 (Part I)-1979 Cellulosic papers for electrical purposes : Part I Definitions and general requirements