DIELECTRIC PROPERTIES OF WHEAT AT MICROWAVE FREQUENCIES

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ABSTRACT

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Dielectric properties of a hard red spring wheat have been investigated at 2.45 and 9.40 GHz. The permittivity was determined for moisture contents from 0.5% to 26% and at temperatures from -20°C to 80°C. For all measurements, a consistent filling procedure was adopted to maintain the natural density of the sample.

On the basis of the criteria imposed by the nature of the test material and different measurement procedures available, a modified-infinite-sample technique was used. For this measurement technique, different possible errors for slotted line measurements were analyzed and theoretical formulas for errors due to the reflection coefficient and phase shift measurements were verified.

Waveguide sample holders, suitable for granular materials, were designed to make the measurements over wide ranges of moisture contents and temperatures. Sample holders were fitted with thermocouples to monitor the sample temperature. Moisture content of the sample was determined on a wet basis utilizing an air-oven method.

A computer program was developed to calculate and plot the dielectric properties as a function of moisture content and density. The program has been written with a

number of features; experimental points plotting, plotting of the points obtained from the least-square-error coefficients and the uncertainty plottings. The program can also take into account the experimental data obtained either from the slotted line measurements or the network analyzer measurements.

The dielectric constant and loss factor were found to vary nearly linearly with moisture content over the entire temperature measurement range. Dielectric losses for dry as well as wet wheat, at microwave frequencies, were found to be of dipolar origin with relaxation frequency below 2.45 GHz. No sudden change in the dielectric properties was observed at 0°C, thus indicating that water in wheat, up to 26% moisture content, is predominantly in the bound form.

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A_1, A_2, A_3 - depolarization factors along the main axes of the ellipsoid

a_0, a_1, a_2 - least-square curve coefficients

D - bulk-density of grain in g/cm^3

MC - moisture content in percent (in Figures 6.2 to 6.5)

M_D - moisture content on dry basis

$M\omega$ - moisture content on wet basis

R - voltage standing wave ratio

s - shift in voltage minimum

T - temperature in °C

T_1 - short circuit plane for slotted-line measurements

$T\varepsilon_1$ - face of the dielectric for slotted-line measurements

TEMP. - temperature in °C (in Figures 6.6 to 6.9)

v_i - fractional volume filling factor of the dispersed granules

w_d - weight of the dry material

w_ω - weight of the wet material

Z - normalized input impedance

Z_c - characteristic impedance of a uniform waveguide

Z_o - the intrinsic impedance of free space

α, β, γ - three dispersion regions for biological and agricultural materials

γ - reflection coefficient

$\varepsilon_r = \varepsilon' - j\varepsilon''$ - complex permittivity

ε' - real part of permittivity or dielectric constant

ε'' - imaginary part of permittivity or loss factor

ε_m, ε_o, ε_i - permittivity of mixture, host and included material, respectively

ε^* - effective permittivity of the material surrounding the inclusions

ε_s - value of the dielectric constant at a frequency low enough so that ε' achieves the highest value possible due to the assumed polarization mechanism

ε_∞ - value of the dielectric constant at a frequency high enough to make the dispersion of ε' due to the assumed polarization mechanism negligible

θ, ξ, ϕ - phase angle in radians

λ - free space wavelength

λ_c - cut-off wavelength

λ_g - guide wavelength

τ - relaxation time in seconds for a particular polarization mechanism

ω - angular frequency in radians $\omega = 2\pi f$

CHAPTER I

INTRODUCTION

1.1 General Objectives of the Research

Investigation of the dielectric properties of agricultural materials becomes increasingly important as the agricultural technology becomes sophisticated, as new uses for electromagnetic signals are developed, and as new methods, processes, and devices come into being which utilize or are influenced by the electrical nature of the materials (Nelson, 1971).

The area of the dielectric properties is a broad field even when limited to agricultural products, since it involves the dependence of the dielectric properties on frequency, temperature, moisture content, and density. Increased interest in using microwave energy for grain drying (Hamid et al., 1968), treatment of grain for the control of insects and larvae (Hamid et al., 1969) and seed treatment to improve germination (Nelson, 1965a) as well as for moisture measurement, has made information on dielectric properties of grain essential at the most popular ISM (Industrial, Scientific, and Medical) frequency of 2.45 GHz as well as at 9.40 GHz, most frequently used for moisture monitoring (Kraszewski, 1970). For proper design of a microwave applicator for grain processing or a microwave

sensor for moisture measurement, knowledge of the dielectric properties of grain as a function of moisture content and temperature is of primary importance. In addition to these, microwave measurements of the dielectric properties give very valuable information about the state of water in grain for different moisture contents and temperatures.

In this work, dielectric properties of wheat at microwave frequencies have been reported. Dielectric properties were determined at two frequencies, 2.45 and 9.40 GHz for several moisture contents, temperatures and densities. The experimental data have been presented graphically to illustrate the influence of temperature and moisture content at both frequencies.

1.2 State of the Art

A macroscopic description of the dielectric properties of a material is provided by the permittivity $\varepsilon_r = \varepsilon' - j\varepsilon''$. The dielectric constant, ε', is a measure of the ability of the material to store electric energy, while, ε'', the loss factor, is a measure of the energy absorbed from the applied electric field. The significant variables on which ε_r depends, in decreasing order of importance are the frequency, temperature, and the intensity of the applied electric field. Methods of measuring real and imaginary

parts of ε_r as a function of these variables are described comprehensively in the literature (von Hippel, 1954; Anderson, 1963; Altschuler, 1963; Bussey, 1967; and Hill et al., 1969).

The choice of the method depends, in general, on the type of the material to be measured, the frequency range, the range of temperatures, the accuracy required, the number of measurements required, the availability of equipment, and some additional factors related to each particular problem. Dielectric properties of grain and seeds as a function of frequency and moisture content were investigated at room temperature in the audio frequency (Stetson et al., 1970), radio frequency (Nelson, 1965b), and recently also in the microwave frequency range (Nelson, 1972).

As for any other type of material, the dielectric properties of agricultural products are functions of temperature, frequency and moisture content. The influence of frequency and temperature will be presented in the next section. In order to understand the influence of moisture content on the dielectric properties, it is essential to understand the forces that hold water in grain. A brief discussion about the nature of these holding forces, for different forms of water, is presented below.

Water may be held by substances which absorb it in

three different forms. A certain amount of water, held in the intergranular spaces and within the pores of the material, may be termed as free water (Hlynka and Robinson, 1954). For this form of water, the molecules of the absorbing substance are not involved except as a supporting structure.

Another form of water, referred as adsorbed water (Hlynka and Robinson, 1954), is more closely associated with the absorbing substance. In this case the properties of one substance are influenced by the properties of the other. The general term sorption is used to denote this interaction, while adsorption and desorption are used specifically to denote the processes of taking up and giving off water of sorption.

The last form of water combines in a chemical union with the absorbing substance and may only be removed under rigorous conditions.

All three forms of water, mentioned above, have different influence on the dielectric properties in the microwave frequency range. The picture is further complicated by the fact that in the case of biological materials the whole spectrum of the water binding forces exists.

The studies of the dielectric properties of

biological materials and their frequency and temperature dependence provide very valuable information regarding the structure and mechanism of polarization. From these properties one can determine the state of water (bound or free), dipole moment, shape, and the hydration process which are of primary importance in biochemistry and biophysics (Schwan, 1963).

The electrical properties of biological materials have been studied ever since suitable electrical techniques became available for this purpose. Earlier contributions, restricting the discussion to the "passive" electrical properties, did not help much toward an understanding of the factors responsible for the electrical properties of tissues. This was due to inadequate theory and experimental techniques. During the Second World War the frequency range was extended from 1 KHz to 10 MHz. After 1940 techniques became available for investigation of the electrical properties at ultra high and low frequencies. The frequency range so far explored extends from 5 Hz up to 30 GHz (Schwan, 1957).

Fig. 1.1 shows, as a typical example for biological materials, the frequency dependence of the dielectric constant of muscular tissue. It demonstrates three dispersions (α, β, γ), each characteristic of a separate relaxation mechanism. The dielectric constants at low frequencies

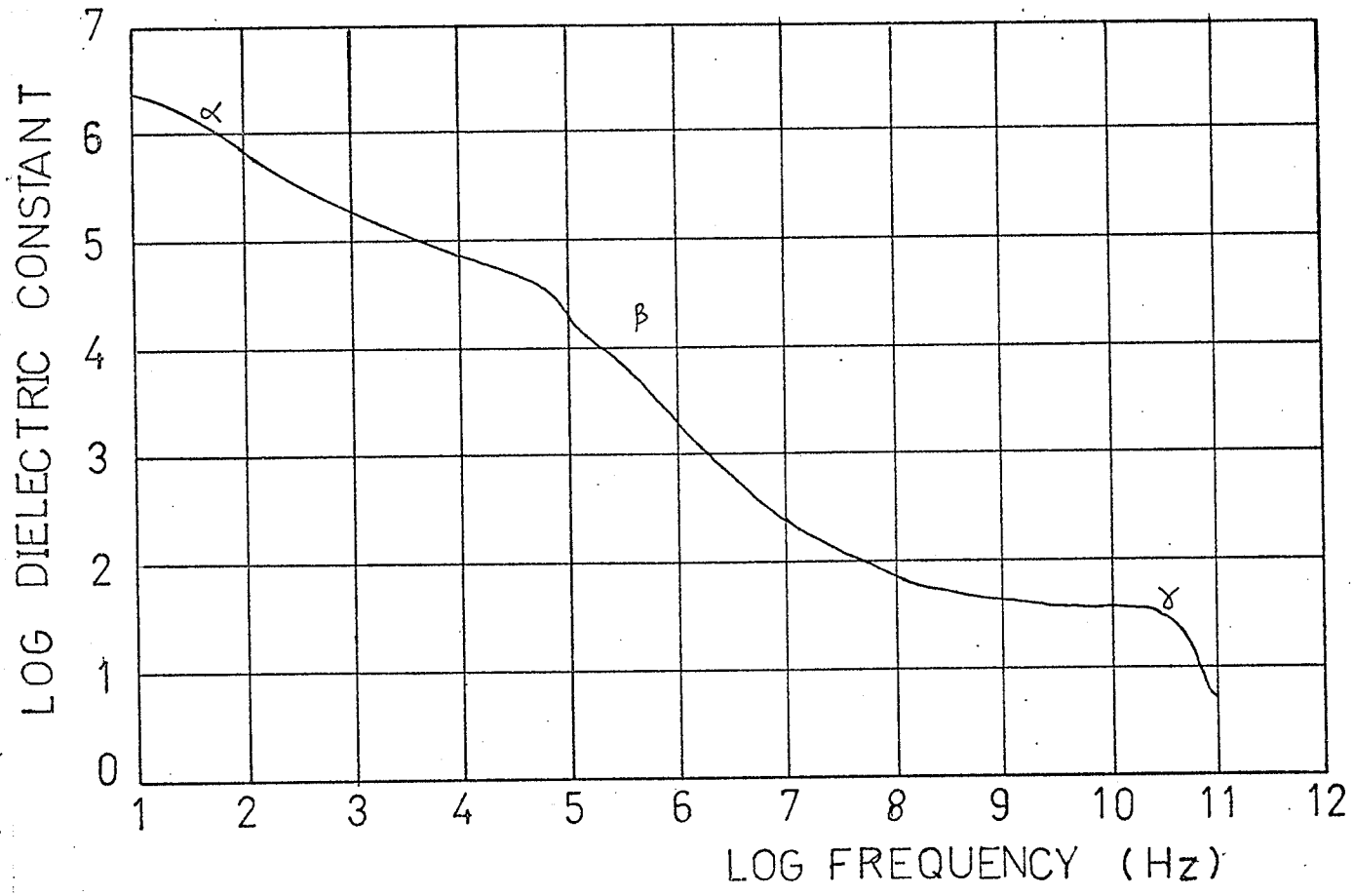

Fig. 1.1 Frequency dependence of the dielectric constant of muscular tissue.

are higher than those of any other type of material and are characteristic to the structure of the biological cell A study of the linear electric properties of biological systems is identical with an analysis of the mechanism responsible for the three anomalous dispersions. This behaviour applies to various types of biological materials, as compiled by Iskander (1972).

Discussions of the anomalous dispersion (decreasing of the dielectric constant with increasing frequency) and the dielectric theories of Debye, Onsager, Cole, Kirkwood, Fröhlich, and others are found in many references, including Böttcher (1952), von Hippel (1954), and Hill et al. (1969). Basically, all of these formulations deal with the polarization resulting from the orientation of the dipoles with the applied electric field. Two smaller contributions to the total polarization come from electronic polarization, the displacement of electrons of atoms with respect to the nucleus, and the atomic polarization, the displacement of nuclei with respect to one another. These two types of polarizations are termed as "distortion" or "deformation" polarization.

As frequency increases from low values, the polar molecules can follow the changes in direction of the electric field to a point and, as frequency continues to increase, the dipole motion can no longer keep up with the

changing electric field. As a result, the dielectric constant drops with increasing frequency in this region and energy is absorbed as a result of the phase lag between the dipole rotation and the field. At higher frequencies, the dielectric constant again levels off at the so-called optical value, the square of the index of refraction and the loss factor again drops to a low value.

Most of the agricultural products and biological materials are heterogeneous in nature. The fact that they usually contain water complicates matters since water appears in such systems in different forms (bound and free. The brief description of dielectric properties of heterogeneous mixtures containing water has been given by deLoor (1968), while the description about the dielectric behaviour of heterogeneous systems has been given by van Beek (1967).

Finally, the dispersion and absorption which result from polarizations at interfacial boundaries of heterogeneous systems, are called Maxwell-Wagner dispersion and absorption. These generally occur in non-homogeneous materials and are frequently seen in biological materials (Davies, 1969; Schwan, 1957,1959). Frequency dependence of the Maxwell-Wagner dispersion and absorption are similar in nature to that of the Debye dipolar dispersion and absorption, but these occur at lower frequencies.

CHAPTER II

TECHNIQUES FOR MEASURING THE PERMITTIVITY OF AGRICULTURAL PRODUCTS IN THE MICROWAVE FREQUENCY RANGE

2.1 Requirements for the Measurement Technique Imposed by the Tested Materials

Agricultural materials of interest are, in general, heterogeneous mixtures and contain water. This last fact complicates the picture because water in such heterogeneous systems may appear in different forms, i.e. as free water, bound water or water of crystalization.

The technique selected for measuring the permittivity of wet granular materials should fulfill several requirements, some of which are listed below:

1. It should be applicable in a wide freqency range and for a wide range of permittivities.

2. The required instrumentation, measurement procedure, and the necessary calculations should be relatively simple.

3. It should be possible to check the sample density and moisture content just before and after performing a test in a simple manner.

4. It should be possible to vary the sample temperature over a wide range.

5. Handling of the sample should be simple so that

a large number of independent measurements can be made.

6. It should be possible to protect the sample against changes of density and moisture content during measurement.

2.2 Survey of the Literature

Various techniques and measurement systems have been developed for measuring the dielectric properties of different kinds of materials (Schwan, 1957,1959; Nelson, 1972). In a particular case measurement method is usually determined by the nature of the test material and frequency and temperature range in which the measurement is to be made.

Several excellent reviews and discussions of the permittivity and permeability measurement methods have been published by von Hippel (1954), Altschuler (1963) and Vaughan (1969). In principle, permittivity measurements at microwave frequencies can be done in three different ways. These are the reflection, transmission, and perturbation methods. All these three types of methods have been described in detail by Altschuler (1963). A complete analysis of the reflection and transmission methods of measuring the permeability and permittivity of materials at microwave frequencies has been presented by Franceschetti (1967) and Franceschetti and Silleni (1964). An extensive review of

the experimental methods used, in measuring the dielectric properties, and the electric properties of various agricultural products at different frequency ranges has been presented by Nelson (1971).

2.3 Selection of the Measurement Technique

As mentioned before, there are three groups of methods of measuring the permittivity at microwave frequencies. These are the reflection, the transmission, and the perturbation methods. The most popular method of the first groupis based on the measurement of input impedance of a sample, short- and open-circuited at its far end. The method is usually used with samples inserted into waveguide or coaxial lines. Another method of this type is the very-long-sample method, which is based on the measurement of the input impedance of a relatively long sample so that the reflections from its far end can be neglected.

Transmission methods, which are based on measurements of the complex transmission coefficient of the sample in the waveguide or coaxial line, are less popular because of the complicated measuring arrangements required and the lower accuracy obtainable.

Perturbation methods are based on measurements of the incremental changes in the resonance frequency and Q-factor of a resonant cavity containing a very small sample

of the material under test. These methods require relatively complicated instrumentation and can be used only for very small samples.

On basis of the different methods available and the requirements listed in Sec. 2.1, the modified very-long-sample method (Rzepecka et al., 1973) was selected for permittivity measurements. In the past very-long-sample methods were used only for medium- and high-loss dielectrics. The modified method was even found to be suitable for dielectrics in granular and powdered form and relatively short samples. The reflections at the sample-load boundary were eliminated by using a matched load with the test sample being in immediate contact with the load. The matched load selected was made of high loss material coated with a silicon film to protect it against environmental effects.

In addition to being suitable for granular materials, this method can be used without restrictions over a relatively wide frequency range, using different waveguides and transmission lines, and over a wide range of permittivity. Another advantage in using the modified method is that the experimental set-up is relatively simple. Relatively good protection of the sample against changes in density, temperature, and moisture content can be realized easily. The method is particularly valuable when large number of

samples must be tested as a function of temperature, moisture content, and density or when a continuous monitoring of the permittivity is required during the irradiation by microwave power.

CHAPTER III

WAVEGUIDE TECHNIQUE

3.1 Principle of Operation and Theory

The permittivity of the test material, using the modified infinite sample (Rzepecka et al., 1973), is calculated from the measured complex reflection coefficient on a transmission line completely filled with the material and terminated by an appropriate matched load. The reflections at the sample-load boundary are eliminated by using a special matched load with the dielectric sample in immediate contact with the load, so that the sample is directly in contact with the high loss material of the matched load.

The characteristic impedance Z_c of a uniform waveguide operating in H mode (TE mode), based on transmission line theory, is a function of permittivity of the material, which in this case completely fills the line, i.e.

$$Z_c = Z_o / \sqrt{\varepsilon_r - (\lambda/\lambda_c)^2} \qquad (3.1)$$

where

$\varepsilon_r = (\varepsilon' - j\varepsilon'')$ is the permittivity of the material,

Z_o - the intrinsic impedance of free space,

λ - the free space wavelength,

and λ_c - the cut-off wavelength for the particular mode of propagation.

The theory underlying this technique follows from the fact that the normalized input impedance, Z, at an interface of two dielectrics in a waveguide as shown in Fig. 3.1 at z = 0, is given by

$$Z = Z_{c2} / Z_{c1} \tag{3.2}$$

where

Z_{c1} - characteristic impedance for the dielectric to the left of z = 0 plane,

and Z_{c2} - characteristic impedance for the dielectric to the right of z = 0 plane,

provided that

(a) the second dielectric is infinitely long,

(b) input impedance is measured in first dielectric,

(c) only one mode (TE) propagates along the line far away from the interface at z = 0, and

(d) the material is homogeneous (i.e. the permittivity is not a function of the x,y,z coordinates).

In most practical cases the first dielectric is air, for which equation (3.1) is reduced to the form

$$Z_{c1} = Z_o / \sqrt{1 - (\lambda/\lambda_c)^2} \tag{3.3}$$

If the matched load assures an infinite length behaviour of the waveguide which extends over z > 0, then the input impedance at z = 0, normalized with respect to

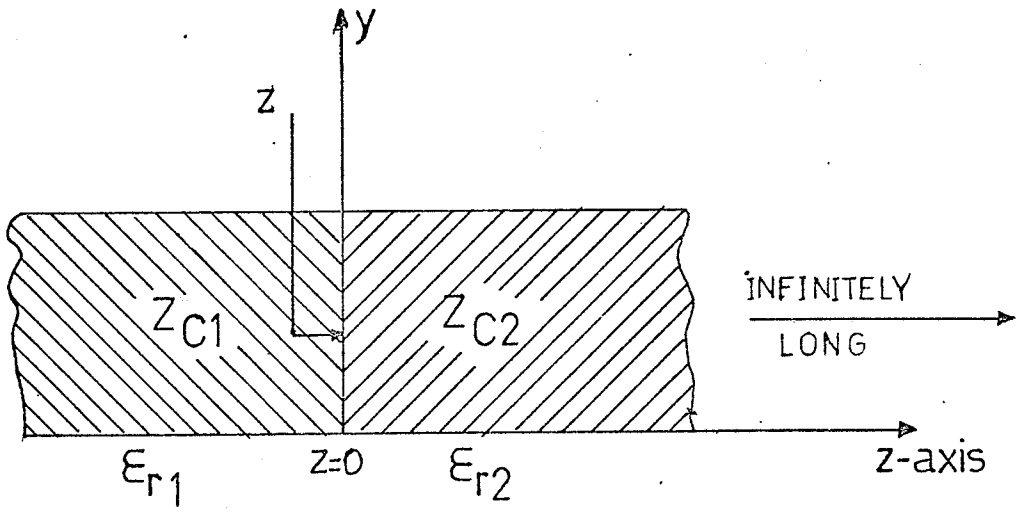

Fig.3.1 Interface between two dielectrics in the waveguide.

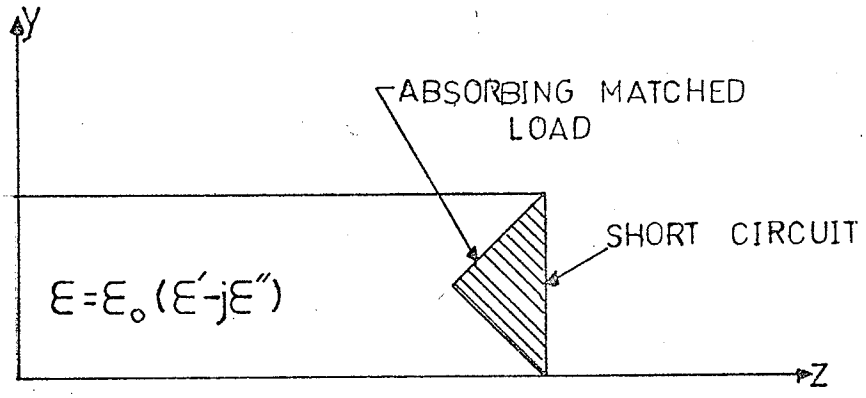

Fig. 3.2 Configuration of the waveguide sample holder for the modified infinite sample method.

characteristic impedance of the same line unloaded, from equations (3.1) to (3.3) may be expressed as

$$Z = \frac{\sqrt{1 - (\lambda/\lambda_c)^2}}{\sqrt{\varepsilon_r - (\lambda/\lambda_c)^2}} \tag{3.4}$$

for the structure shown in Fig. 3.2. Solving (3.4) for the permittivity

$$\varepsilon_r = \left(\lambda/\lambda_c\right)^2 + \left[1 - \left(\lambda/\lambda_c\right)^2\right] / Z^2 \tag{3.5}$$

The impedance Z can be calculated either from reflection coefficient data, obtained by using network analyzer, or from voltage standing wave ratio data, obtained by using a slotted line. If "R" is VSWR for the load and "s" is the shift in voltage minimum toward the load, then the characteristic impedance Z of the sample in the waveguide, normalized with respect to the characteristic impedance of the empty waveguide, is given by

$$Z = \frac{1 + j\ R \tan(2\pi s/\lambda_g)}{R + j \tan(2\pi s/\lambda_g)} \tag{3.6}$$

where λ_g is the empty waveguide wavelength. Substituting the above value of Z in equation (3.5) and solving for the real and imaginary parts

$$\varepsilon' = \left(\lambda/\lambda_c\right)^2 + \left[1 - \left(\lambda/\lambda_c\right)^2\right] \frac{R^2 \mathrm{Sec}^4\phi - (R^2 - 1)^2 \tan^2\phi}{(1 + R^2 \tan^2\phi)^2} \tag{3.7}$$

and

$$\varepsilon'' = \left[1 - \left(\lambda/\lambda_c\right)^2\right] \frac{2R(R^2 - 1)\sec^2\phi \tan\phi}{(1 + R^2\tan^2\phi)^2} \qquad (3.8)$$

where $\phi = 2\pi s/\lambda_g$.

Similarly Z can be related to γ, the reflection coefficient, by the relation

$$Z = \frac{(1 - |\gamma|)\tan\theta/2 - j(1 + |\gamma|)}{(1 + |\gamma|)\tan\theta/2 - j(1 - |\gamma|)} \qquad (3.9)$$

where γ has been expressed as $|\gamma|e^{-j\theta}$.

Substituting this in equation (3.5) and solving for the real and imaginary parts

$$\varepsilon' = \left(\lambda/\lambda_c\right)^2 + \left[1 - \left(\lambda/\lambda_c\right)^2\right] \frac{(1 - |\gamma|^2)^2 - 4|\gamma|^2\sin^2\theta}{(1 + |\gamma|^2 + 2|\gamma|\cos\theta)^2} \qquad (3.10)$$

$$\varepsilon'' = \left[1 - \left(\lambda/\lambda_c\right)^2\right] \frac{4|\gamma|(1 - |\gamma|^2)\sin\theta}{(1 + |\gamma|^2 + 2|\gamma|\cos\theta)^2} \qquad (3.11)$$

Either set of equations may be used to calculate the permittivity depending upon the measurement system used.

During the measurements one point of primary importance is the location of the sample within the waveguide sample holder. In particular, see Fig. 3.3, the face of dielectric nearest to the slotted line, $T_{\varepsilon 1}$, must lie exactly at T_1, a terminal plane as near to the end of the slotted

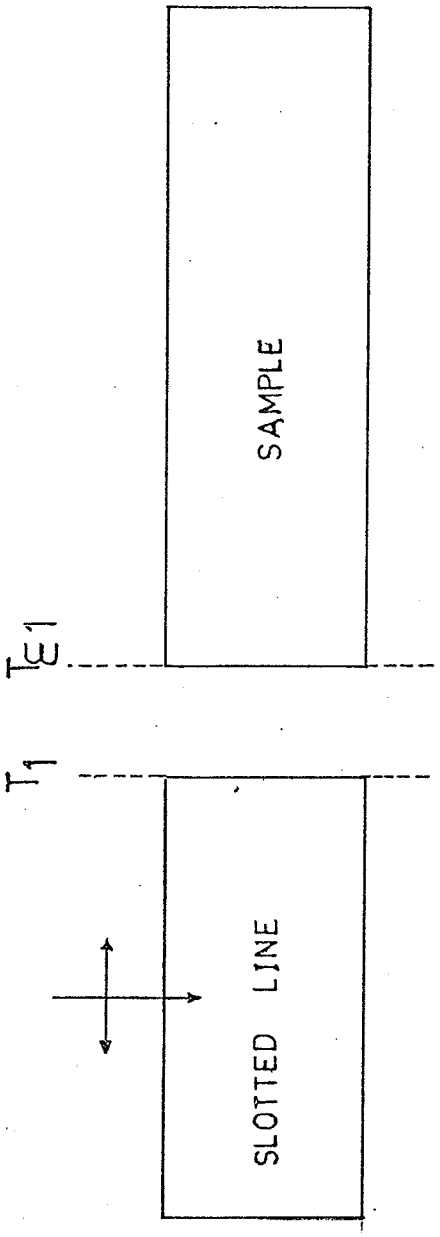

Fig.3.3 Location of sample in the waveguide.

line as possible, at which a short circuit can be placed accurately. In the case of rectangular waveguides coupled by flanges, this can be done by using a flat metal plate as a short circuit at T_1. The sample face must then be located exactly at the very end of the waveguide sample holder.

The region in which solutions for the input impedance and reflection coefficient (at the interface of two dielectrics) exist will now be considered. The conditions which must be satisfied by the input impedance are obtained from the physical properties of the test material. The real part of the permittivity, ε', which represents the dispersive part of the electrical energy, is larger than or equal to unity, while the imaginary part, ε'', which represents the dissipative part of the electrical energy, is larger than or equal to zero. By writing Z as $|Z|e^{-j\xi}$ in equation (3.5) and separating into real and imaginary parts

$$\varepsilon' = \left(\lambda/\lambda_c\right)^2 + \left[1 - \left(\lambda/\lambda_c\right)^2\right] \cos 2\xi \; / \; |Z|^2 \qquad (3.12)$$

$$\varepsilon'' = - \left[1 - \left(\lambda/\lambda_c\right)^2\right] \sin 2\xi \; / \; |Z|^2 \,. \qquad (3.13)$$

By rearranging equations (3.12) and (3.13)

$$\tan 2\xi = - \varepsilon'' \; / \; \left[\varepsilon' - \left(\lambda/\lambda_c\right)^2\right] \qquad (3.14)$$

and

$$|Z|^2 = a_1 / a_2 \tag{3.15}$$

where

$$a_1 = 1 - \left(\lambda/\lambda_c\right)^2$$

and

$$a_2 = \left\{\left|\varepsilon' - \left(\lambda/\lambda_c\right)^2\right|^2 + \varepsilon''^2\right\}^{\frac{1}{2}}$$

Thus the allowed values of ε' and ε'' result in the following conditions

$$\text{(a)} \quad 0 \geq \xi \geq -45° \tag{3.16}$$

$$\text{(b)} \quad |Z| \leq 1 \tag{3.17}$$

or in terms of the reflection coefficient

$$-1 \leq \frac{2|\gamma|}{1 - |\gamma|^2} \sin\theta \leq 0 \tag{3.18}$$

$$\frac{(1 + |\gamma|)^2 \tan^2\theta/2 + (1 - |\gamma|)^2}{(1 - |\gamma|)^2 \tan^2\theta/2 + (1 + |\gamma|)^2} \tag{3.19}$$

The region, in which the measured values of the reflection coefficient are located on the Smith Chart, is shown in Fig. 3.4.

3.2 Error Analysis

The principle and theory presented in Section 3.1 is valid only if the test material is homogeneous. Non-uniformities in the material may occur due to local density differences, local temperature gradients, or due to the

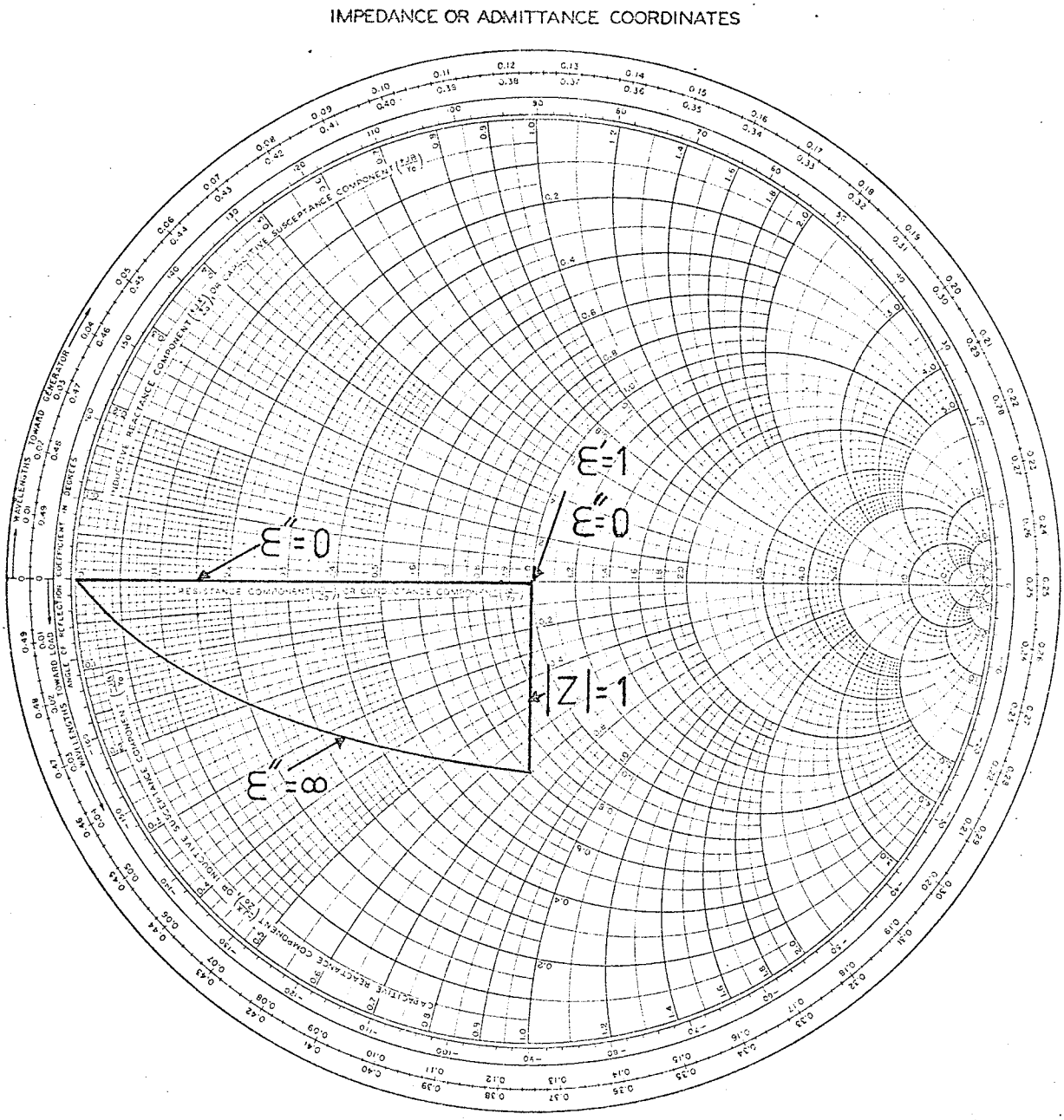

Fig.3.4 Input impedance region for dielectric materials.

presence of thermocouples used for the monitoring of temperature. These nonuniformities lead to errors in the permittivity measurement which are difficult to evaluate numerically. The only way to reduce these errors is to keep the different parameters affecting them under control during the measurements.

For a uniform material, the errors related to the uncertainty in the reflection coefficient depend on three main factors:

1. accuracy of the reflection coefficient measurement which is determined by the actual method and instrumentation used,

2. sample holder, which can introduce reflections resulting from the presence of control devices: thermocouples for temperature control and seals to retain moisture,

3. connection between the sample holder and the measurement set-up, as for instance, the presence of a waveguide to coaxial line transition (when a network analyzer and a waveguide type sample holder are used) or a choke flange with a thin dielectric diaphragm (when a slotted line is used).

In addition to the aforementioned factors, there are some principal sources of error in the measurement of the input impedance of the sample in the waveguide. Some of these sources are the errors in the measurements of

waveguide wavelength, voltage minima , and voltage standing wave ratio. A detailed discussion of these errors and the irreduction procedures can be found in standard textbooks on microwave measurements (. Altschuler , 1963; Montgomery, 1948). With the proper precautions used, these errors can be usually neglected when compared with those resulting from uncertainty in the reflection coefficient. It will be worthwhile to underline here that the so-called air gap errors (Bussey, 1967) do not exist in the present method since the granular material completely fills the waveguide cross-section. As mentioned before, sample face must be exactly located at the short circuit position. In the case of granular materials, this is quite difficult, particularly when the kernel size is comparable with the waveguide dimensions. In the present case the plane was defined as the flat end of the waveguide and the sample was held at this position with the help of mica diaphragm.

The uncertainties in ε' and ε'' resulting from errors in the reflection coefficient measurement may be found by differentiating equations (3.10) and (3.11) with respect to $|\gamma|$ and θ.

$$\frac{\Delta\varepsilon'_{\gamma}}{\Delta\gamma} = \frac{4}{D}\left\{\left[\varepsilon' - \left(\lambda/\lambda_c\right)^2\right]\left[1 - |\gamma|^2\right]\cos\theta + \varepsilon''\left[1 + |\gamma|^2\right]\sin\theta\right\} \tag{3.20}$$

$$\frac{\Delta\varepsilon'_{\theta}}{\Delta\theta} = \frac{4|\gamma|}{D}\left\{\left[\varepsilon' - \left(\lambda/\lambda_c\right)^2\right]\left[1 + |\gamma|^2\right]\sin\theta + \varepsilon''\left[1 - |\gamma|^2\right]\cos\theta\right\} \tag{3.21}$$

$$\frac{\Delta\varepsilon''_{\gamma}}{\Delta\gamma} = \frac{4}{D}\left\{\varepsilon''\left[1 - |\gamma|^2\right]\cos\theta + \left[\varepsilon' - \left(\lambda/\lambda_c\right)^2\right]\left[1 + |\gamma|^2\right]\sin\theta\right\} \tag{3.22}$$

$$\frac{\Delta\varepsilon''_{\theta}}{\Delta\theta} = \frac{4|\gamma|}{D}\left\{\varepsilon''\left[1 + |\gamma|^2\right]\sin\theta + \left[\varepsilon' - \left(\lambda/\lambda_c\right)^2\right]\left[1 - |\gamma|^2\right]\cos\theta\right\} \tag{3.23}$$

where

$$D = 4|\gamma|^2 \sin^2\theta + \left[1 - |\gamma|^2\right]^2$$

The total uncertainties in ε' and ε'' can be calculated from the following relations:

$$\Delta\varepsilon' = \frac{\Delta\varepsilon'_{\gamma}}{\Delta|\gamma|}\Delta|\gamma| + \frac{\Delta\varepsilon'_{\theta}}{\Delta\theta}\Delta\theta \tag{3.24}$$

and

$$\Delta\varepsilon'' = \frac{\Delta\varepsilon''_{\gamma}}{\Delta|\gamma|}\Delta|\gamma| + \frac{\Delta\varepsilon''_{\theta}}{\Delta\theta}\Delta\theta \tag{3.25}$$

where

$\Delta|\gamma|$ - the uncertainty in the modulus of the reflection coefficient,

$\Delta\theta$ - the uncertainty in the phase angle of the reflection coefficient.

The accuracy in the γ measurements for the Hewlett-Packard network analyzer, type 8410S-200, is specified as

$$\begin{aligned} \Delta|\gamma| &= \pm\, 0.03|\gamma|(1 + |\gamma|) \\ \Delta\theta &= \text{arc sin}[0.03(1 + |\gamma|)] \end{aligned} \tag{3.26}$$

for the frequency range 2 to 8 GHz and when the directivity error is cancelled. For the slotted lines with the precision regulated attenuators used in the test, the uncertainty in the reflection coefficient can be estimated to be equal to

$$\begin{aligned} \Delta|\gamma| &= 0.005 + \frac{0.002}{1 - |\gamma|^2 + 0.01} \\ \Delta\theta &= 0.025 \text{ radians} \end{aligned} \tag{3.27}$$

For both the network analyzer and the slotted line

techniques, the maximum errors in (the real and imaginary parts) the permittivity measurements resulting from the above mentioned values are shown in Figures 3.5and 3.6, respectively.

From the inspection of Figures 3.5and 3.6, it is easy to deduce that the error of phase shift is much more important than the error of reflection coefficient. Therefore, the position of minimum was measured as carefully as possible to reduce the error in the phase shift measurements.

3.3 Experimental Set-Up

Block diagrams of the experimental set-ups used at 2.45 and 9.40 GHz are shown in Figs. 3.7(a) and 3.7(b), respectively. The experimental apparatus constructed for making the measurements consisted essentially of five parts:

1. As a microwave oscillator, a Hewlett-Packard (HP) 8690A was used with a HP 8699B plug-in at 2.45 GHz and a HP 8694B plug-in at 9.40 GHz. At each frequency the internal 1,000 Hz amplitude modulation was employed.

2. The attenuation measuring circuit consisted of precision variable attenuators HP S382C and HP X382A at 2.45 and 9.40 GHz, respectively.

3. The slotted line used at 2.45 GHz was model 8011/B manufactured by Marconi, while that used at 9.40 GHz

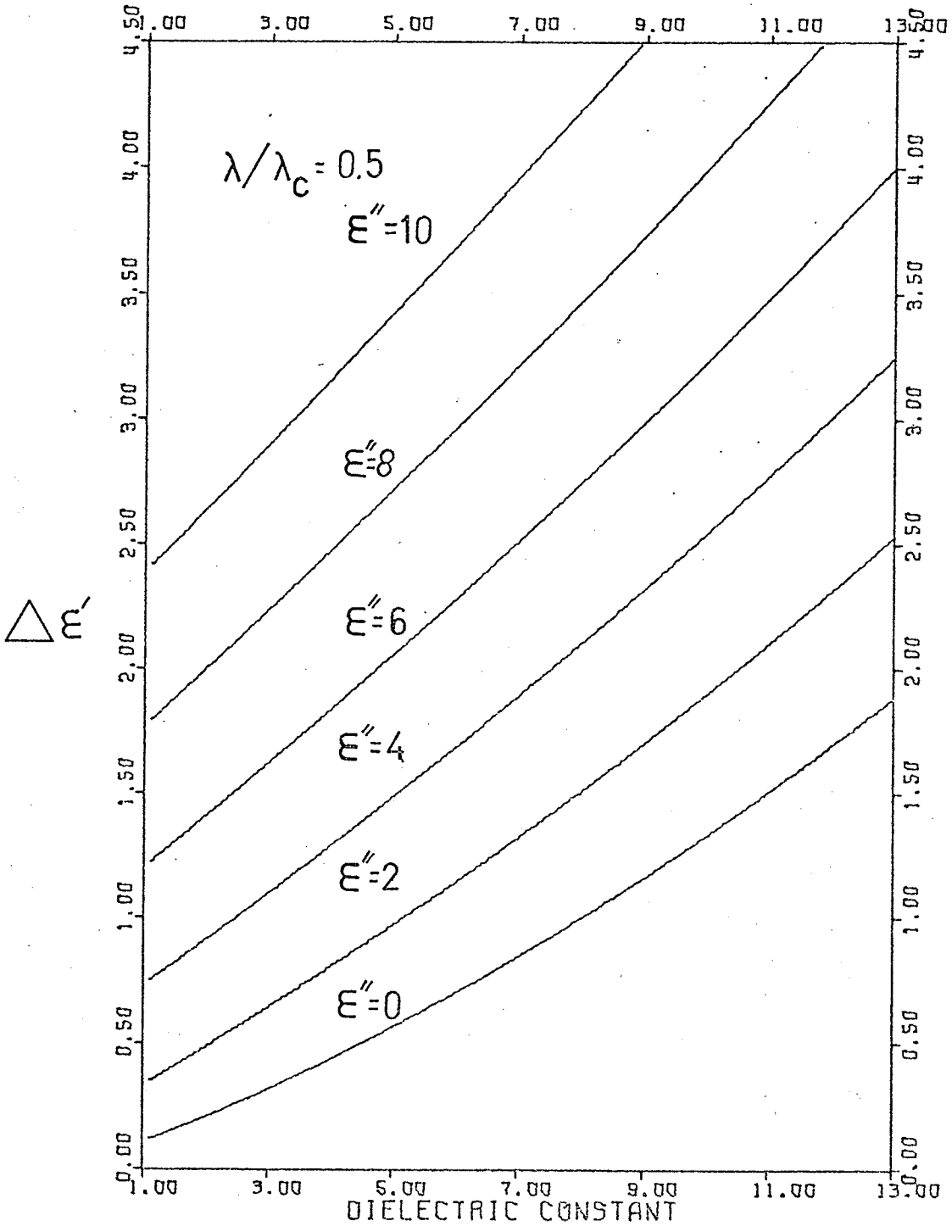

Fig. 3.5a Maximum error in ε' for HP Network Analyzer

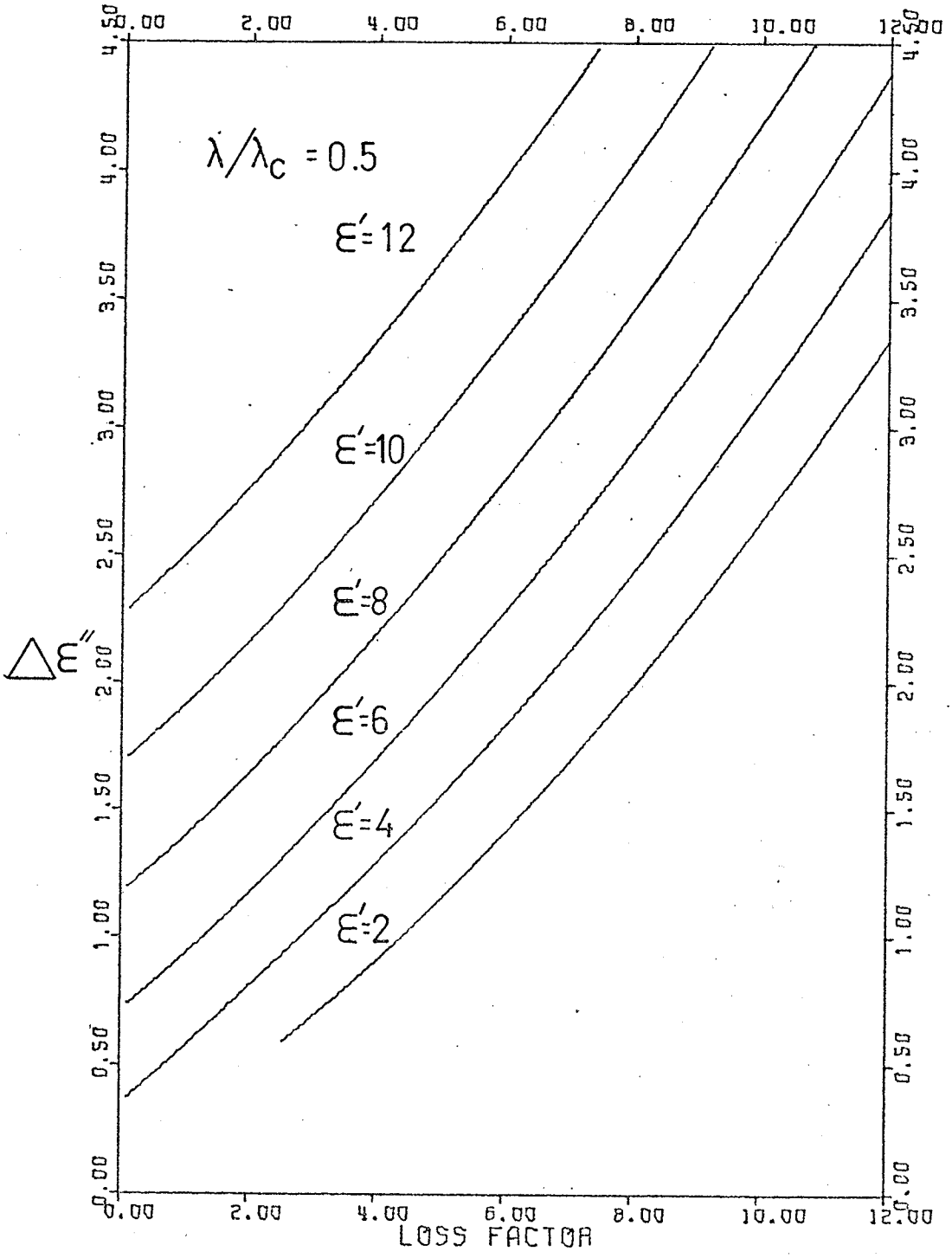

Fig.3.5b Maximum error in ε'' for HP Network Analyzer

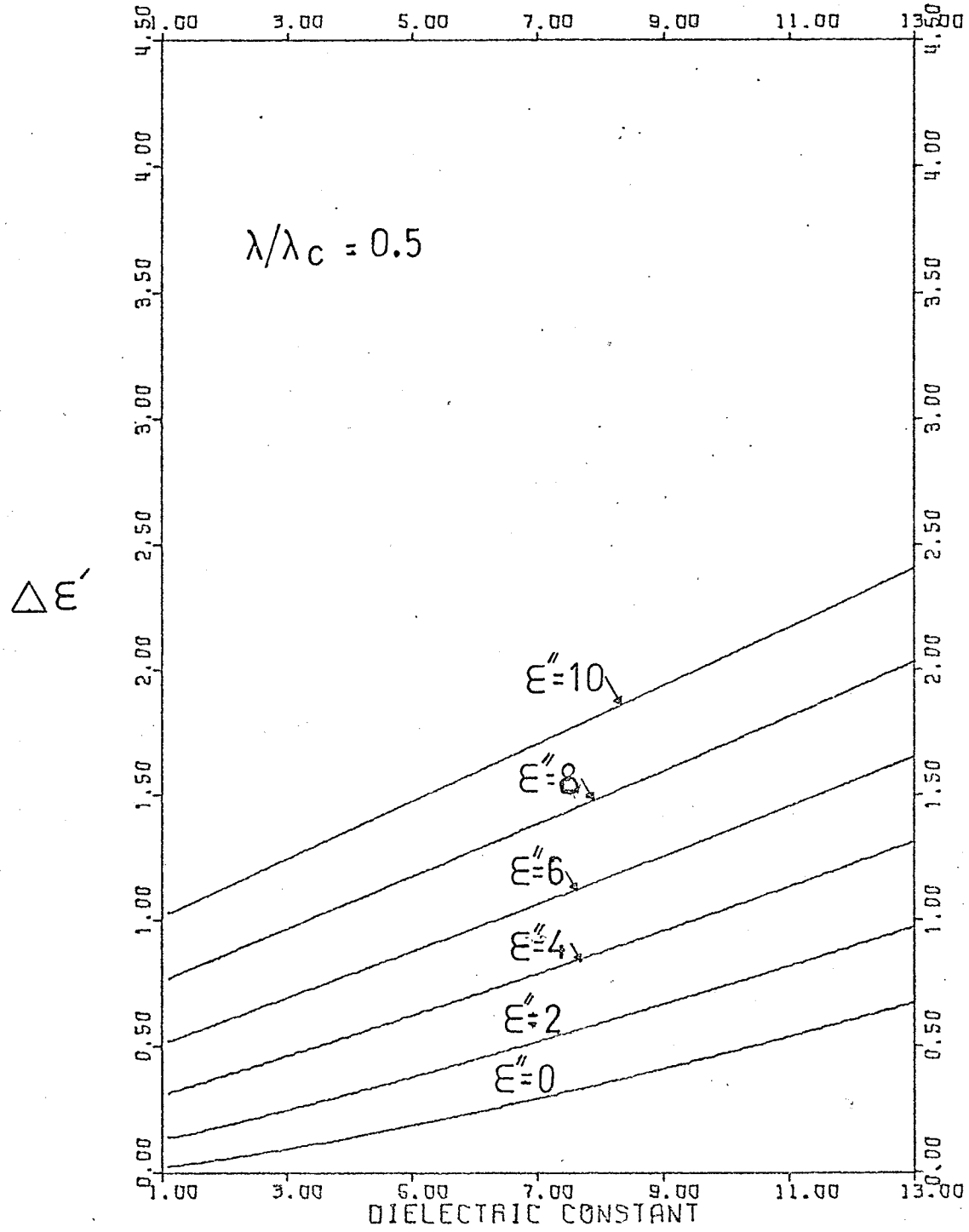

Fig.3.6a Maximum error in ε' for Slotted-line measurements

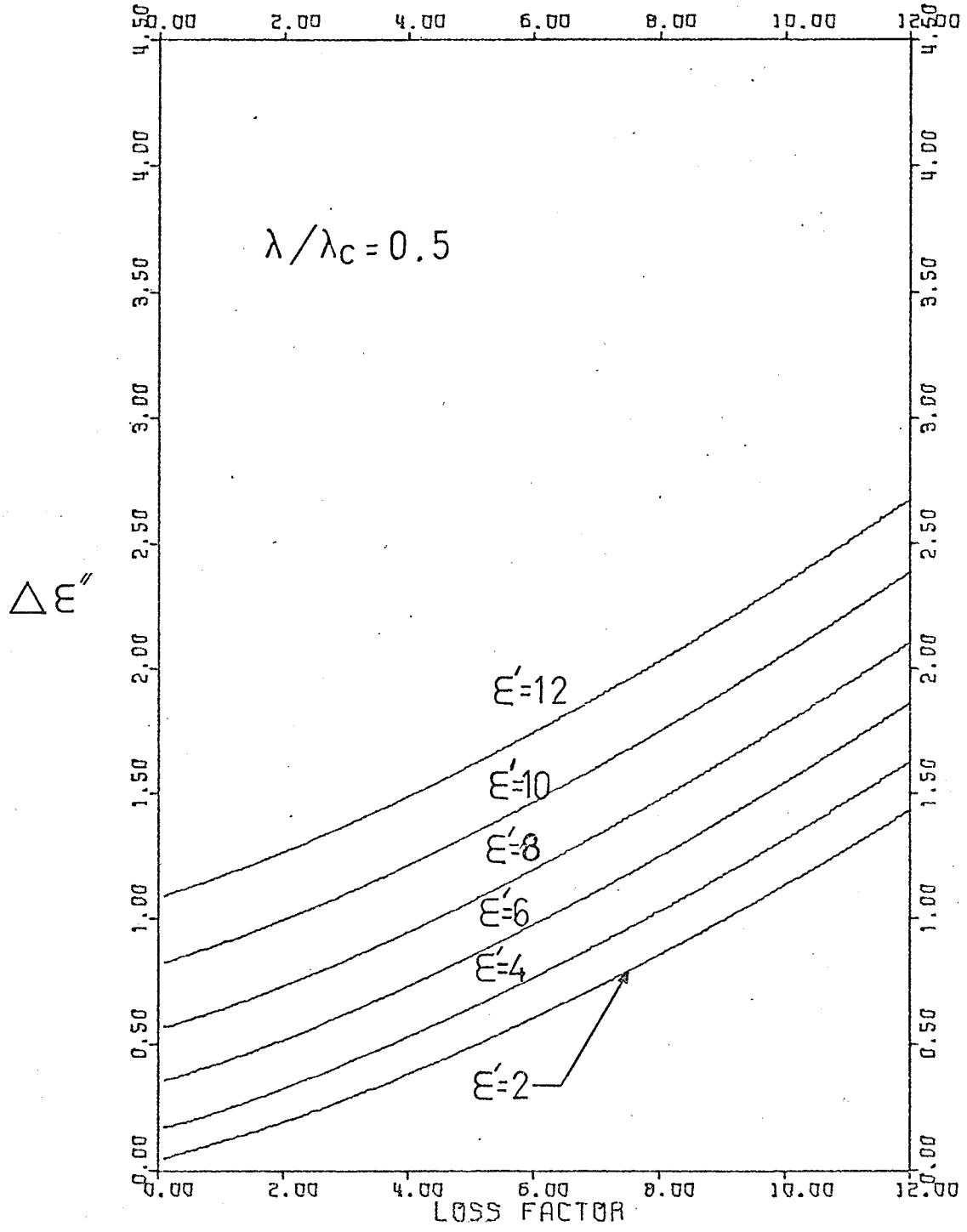

Fig.3,6b Maximum error in ε'' for Slotted-line measurements

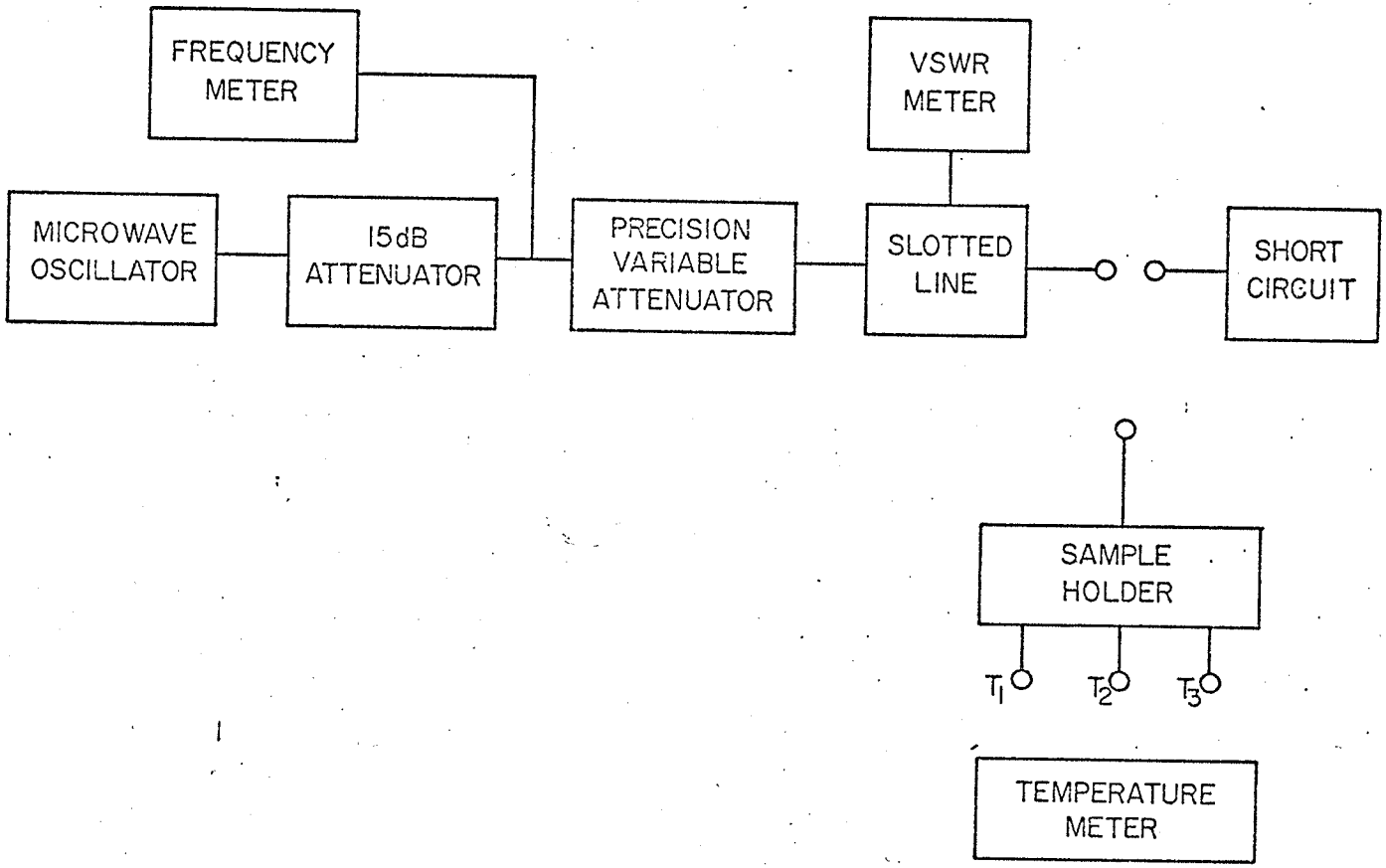

Fig. 3.7a Experimental set-up at 2.45 GHz

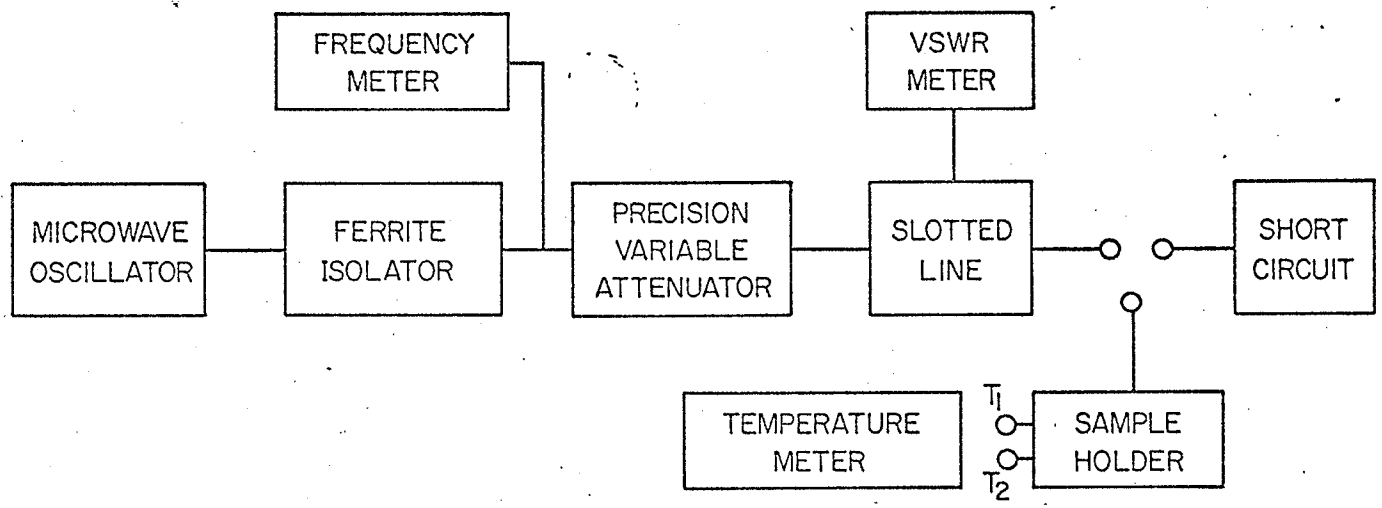

Fig. 3.7b Experimental set-up at 9.40 GHz

consisted of a HP 809C with a HP X810B.

4. Frequency measurements were done by a HP 5245L with heterodyne converters, a HP 5252C at 2.45 GHz and a HP 5255A at 9.40 GHz. The standing wave ratio was measured by a HP 415E SWR meter.

5. The voltage difference between the test thermocouple or the sample temperature was measured with a HP 419A DC null voltmeter.

CHAPTER IV

MATERIALS AND METHODS

4.1 Selection and Preparation of the Material

All measurements of dielectric properties were performed on Neepawa wheat, a hard red spring wheat, harvested during the Fall of 1971 and graded No. 1 Manitoba Northern by the Canadian Grain Commission. The experimental material was obtained from the Glenlea Research Station after it had been cleaned but not treated with any fungicide. The original equilibrium moisture content attained at 23°C and 40% relative humidity was 10.6% (wet basis) and the natural density was 1.35 g/cm^3.

The wheat was initially divided into five lots which were conditioned to moisture contents ranging from 2.8% to 23.0%. Later on the samples with 2.8% and 23.0% were reconditioned to 0.5% and 26.0%, respectively, to extend the range of measurements. Samples to have moisture content above 10.6% were conditioned by adding the proper amount of distilled water. The lots conditioned by adding water were stored in sealed containers at 2°C and 50% relative humidity, for at least 12 days to assure uniform moisture distribution. During this period lots were mixed frequently and thoroughly by rotating the sealed containers in such a manner as to obtain complete mixing to improve

the uniformity of moisture distribution. Lots to have moisture content below 10.6% were dried in a forced air oven at 60°C to reduce to minimum any possible chemical changes in the wheat at higher temperatures.

4.2 Moisture Content, Density, and Temperature Determination

Moisture content of the unground samples were determined by an oven drying method, as recommended in the 1972 ASAE yearbook (p. 384). Two samples from the lot were dried in an air oven at 130° ± 1°C for 19 hours. The samples before and after drying, were weighed by an analytical balance (Model No. Mettler H10T) with a maximum uncertainty of ±0.01 g. In terms of the weights of the dry and wet materials, moisture contents are given by

$$M_D = \frac{\left(w_\omega - w_d\right)}{w_d} \times 100 \qquad (4.1)$$

$$M_\omega = \left(\frac{w_\omega - w_d}{w_\omega}\right) \times 100 \qquad (4.2)$$

where:

w_ω - weight of wet material

w_d - weight of dry material

M_D - moisture content on dry basis

M_ω - moisture content on wet basis.

The total uncertainty in moisture determination (wet basis) is

$$\Delta M_\omega = \left|\frac{\partial M_\omega}{\partial w_\omega}\right| \Delta w_\omega + \left|\frac{\partial M_\omega}{\partial w_d}\right| \Delta w_d \qquad (4.3)$$

where

$$\frac{\partial M_\omega}{\partial w_\omega} = 100\ \frac{w_d}{w_\omega^2}$$

$$\frac{\partial M_\omega}{\partial w_d} = -\frac{100}{w_\omega}$$

and $\Delta w_\omega = \Delta w_d = 0.01$ g.

These result in maximum uncertainty in moisture determination being equal to ±0.2%. The moisture content was calculated on wet basis. Since a certain period was always required for measurements over a range of temperatures, moisture content of each sample was determined at the beginning and at the end of the measurement period.

Grain density was determined by weighing the amount of wheat required to fill the sample holder and dividing by its volume. A consistent filling procedure was used to avoid variation in compaction. The volumes of the sample holders used at 2.45 and 9.40 GHz were 740 ±1 cm^3 and 51.5 ±1 cm^3, respectively. Since the amount of sample required at 2.45 GHz was about 600 g, the analytical balance with a maximum capacity of 160 g could not be used. Instead, a Mettler top-loading balance, with a maximum uncertainty in weight measurement being equal to ±1 g, was used. This

results in maximum uncertainty in density determination of ±0.3% at 2.45 GHz. Uncertainties of ±1 cm^3 in volume and ±0.01 g in weight result in maximum uncertainty in density of ±2% at 9.40 GHz. For all samples, the natural density (e.g. without compression) of grain was maintained.

The temperature of the sample was taken as an average of the readings obtained for three thermocouples installed at equal distances. Thermocouples were made from copper-constantan wires and the readings were obtained as a difference in voltages for the sample-holder thermocouples and a reference thermocouple immersed in a medium of known temperature. The reference temperature was held constant at 0° ± 0.05°C. Uncertainty of ±0.01 mV in reading the voltages results in an estimated uncertainty of ±0.5°C in sample temperature.

CHAPTER V

WAVEGUIDE SAMPLE HOLDERS

Several criteria were considered in the design of the sample holders. These included temperature monitoring, prevention of moisture removal, uniformity of temperature at different points, and thermal insulation in the sample holder.

In order to obtain the information about the uniformity of the sample temperature, three thermocouples were positioned at different places along the sample holder. The overall length of the straight section of the waveguide was divided into two portions with a thermocouple at the centre. The remaining two thermocouples were positioned at the centre of each of these portions. Thus, the thermocouples were equally spaced along the sample holder.

When a thermocouple is positioned in a rectangular waveguide operating in the fundamental mode, as shown in Fig. 5.1, the reflections resulting from the insertion are reduced if the junction is fine and connecting wires thin. Since the wires are perpendicular to the electric field, the perturbation of the field is also very small. The small dimensions and perpendicular position of the thermocouple prevent any significant coupling with the

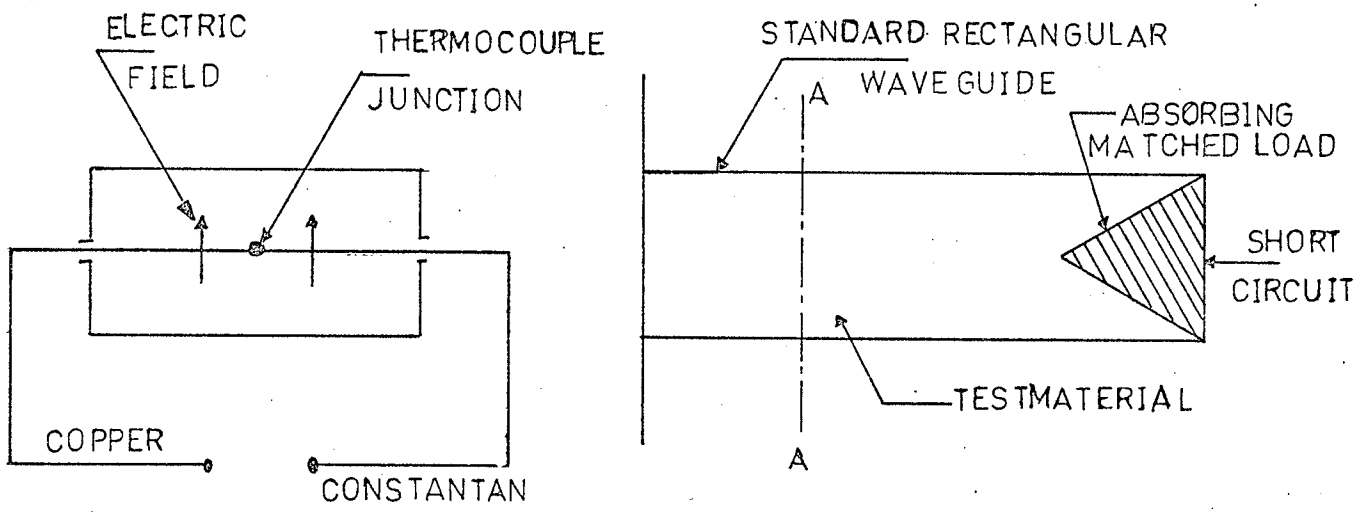

Fig.5.1 Experimental sample holder for waveguide technique

microwave field.

To retain the moisture content of the sample during the measurements, the sample holder was sealed with a thin mica sheet. At the same time, the mica sheet provided thermal insulation between the sample holder and the slotted line. This thin diaphragm of mica was positioned with a choke flange to minimize reflections.

During the preliminary tests of the waveguide sample holder for the uniformity of temperature, it was found that the rate of increase or decrease in temperature near the end was greater than that in other portions. To reduce this unwanted effect, 1/0.16 cm acrylic ring and non-metallic screws were used to attach the sample holder to the experimental set-up.

The sample holder, after being filled with wheat and sealed with a mica diaphragm, was connected using the acrylic ring to an empty section of the waveguide with non-metallic screws, as shown in Fig. 5.2. The whole unit was then wrapped in a few layers of thermal insulating material. This complete assembly was raised to the maximum or the minimum temperature by keeping it in a temperature control environment for 7 to 14 h so as to have uniform temperature of the sample. Once the maximum or minimum required temperature of the sealed sample holder with wheat sample was reached, the sample holder was taken

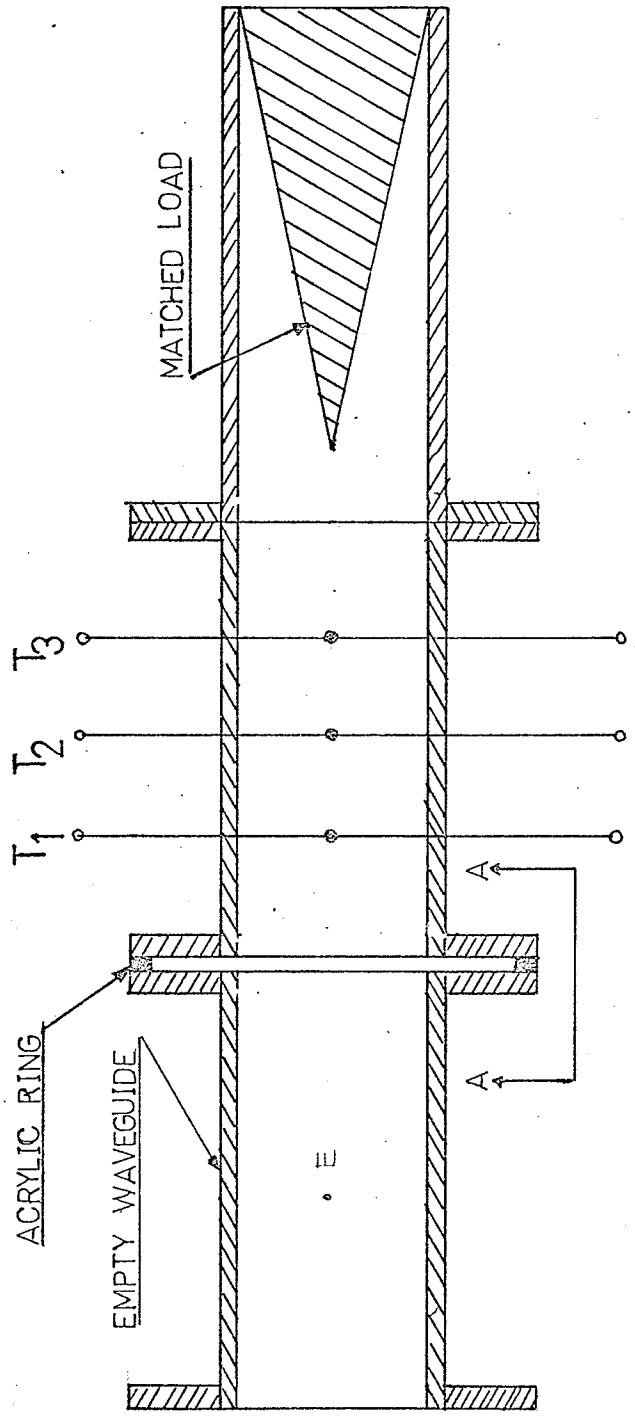

Fig. 5.2a Cut-view of the complete assembly.

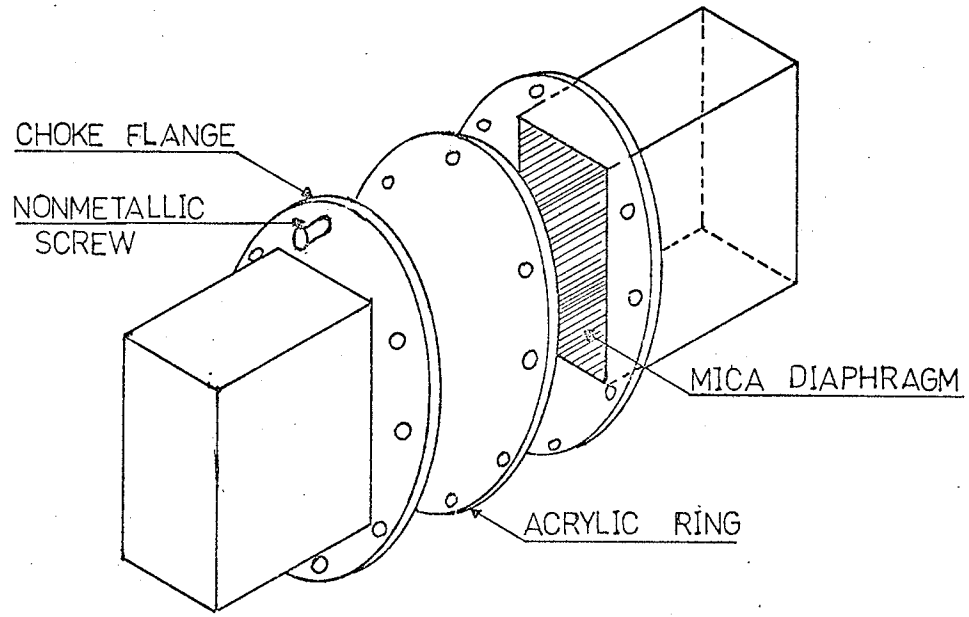

Fig.5.2b Isometric view of the segment AA of the complete assembly.

out of the temperature controlled chamber and connected to the warmed-up experimental set-up. The rate of increase or decrease in temperature at the beginning was about 2°C/min while, after some time, it was reduced to 0.2°C/min. Except for some time at the beginning, the rate was slow enough to permit the permittivity measurements as a function of temperature. The maximum temperature difference observed, at any time, between the two extreme ends of the sample was 1°C.

CHAPTER VI

EXPERIMENTAL PROCEDURE AND RESULTS

6.1 Electrical Measurement Procedure

Before making measurements of the dielectric properties, the sample holder was calibrated with all monitoring as well as protective elements attached to it, as described below.

The block diagram of the experimental set-up used, at 2.45 and 9.40 GHz, for the calibration of the sample holder is shown in Fig. 6.1. The set-up consisted of a microwave signal generator, frequency meter, variable precision attenuator, slotted line, and the SWR meter. As mentioned before, the uniform rate of increase or decrease of temperature was achieved using an empty section of the waveguide (brought to the maximum or minimum temperature along with the sample), an acrylic ring, and a thin mica diaphragm. The open end of the slotted line was connected to an empty section of the waveguide. The other end of the waveguide section, with a choke flange, was connected to an acrylic ring and a mica diaphragm. The waveguide section, acrylic ring and mica diaphragm were inserted between the sample holder and the slotted line to simulate the effect of these components on the shift of voltage minimum in the subsequent tests.

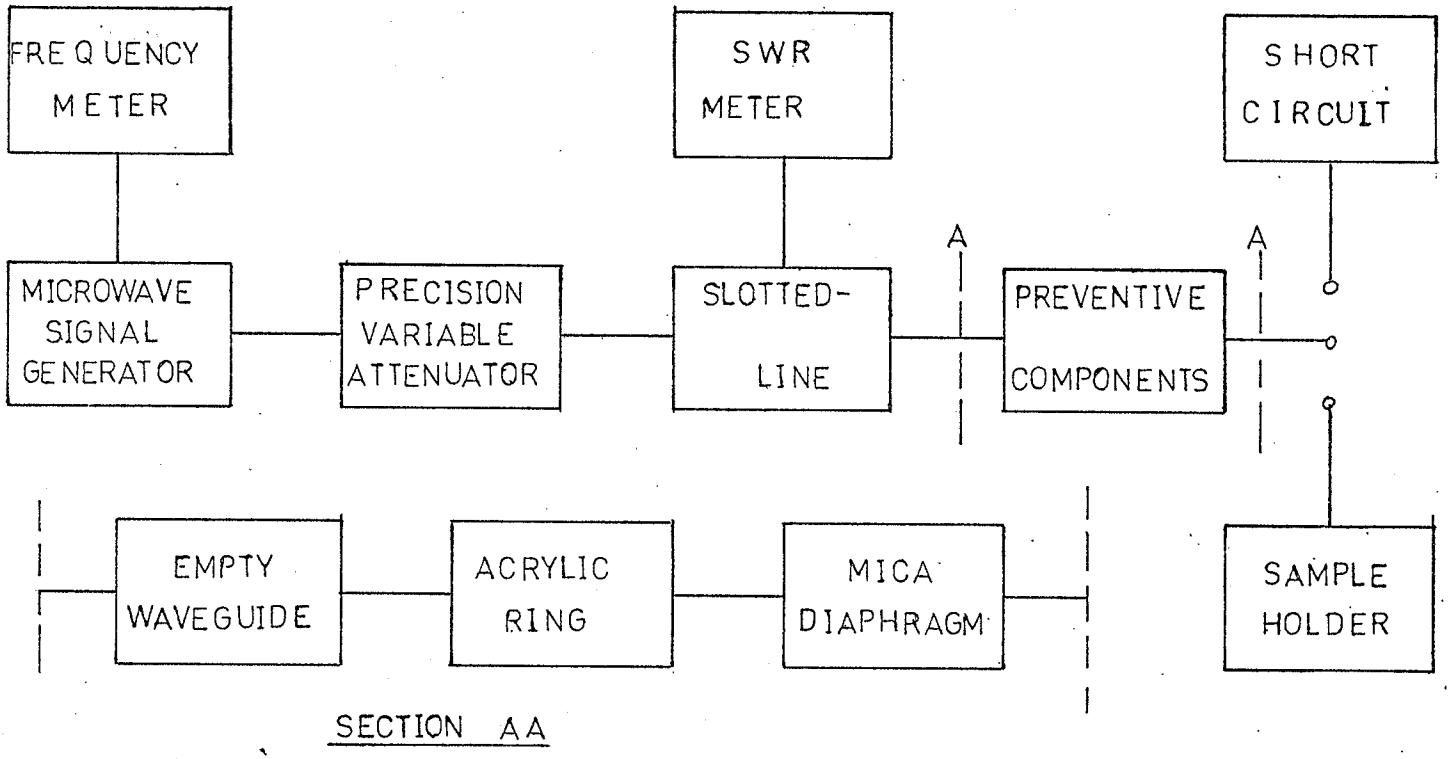

Fig. 6.1 Block diagram for the calibration set-up at both frequencies.

To calibrate the sample holder the following procedure was adopted:

1. The equipment, for calibration purposes, was connected as shown in Fig. 6.1.

2. The set-up, after being switched on, was allowed to warm up for about 5 min.

3. The signal generator was adjusted to the required operating frequency and the precision variable attenuator was set at 0 dB.

4. The open end of the experimental set-up was terminated with a short circuit.

5. The probe in the slotted line section was moved to a voltage maximum and the gain control on the amplifier was adjusted so that the pointer on the output meter was at full scale.

6. The probe was then brought to a voltage minimum and the reading on the output meter scale was noted.

7. Arithmetic mean of the two positions, as indicated on the dial gage or vernier scale, corresponding to equal signal levels on either side of the minimum, was taken as the true minimum.

8. The short circuit was then replaced by the empty sample holder (with thermocouples fitted in it), making sure that the open end of the sample holder lies exactly at the position of the short circuit.

9. The reading as obtained from the precision variable attenuator was used as the true VSWR in dB.

10. Steps 4 to 9 were repeated several times and arithmetic means were taken as true values for the short circuit voltage minimum and the standing wave ratio for the empty sample holder.

Once the calibration at the required operating frequency was complete, the sample holder containing thermocouples for monitoring the sample temperature was filled with grain of the required moisture content, prepared by using the procedure mentioned in Chapter IV. A consistent filling procedure was used to maintain the natural density of grain in the sample holder. The sample holder, filled with the grain of required moisture content, was sealed with a thin mica diaphragm. The sealed sample holder was then connected to an empty section of the waveguide, through the acrylic ring, with non-metallic screws. As mentioned before,(Chapter V), the acrylic ring, mica diaphragm, non-metallic screws, and the empty section of the waveguide were connected to achieve

1. thermal insulation,

2. uniform rate of increase or decrease of temperature, and

3. prevention of moisture removal from the sample.

The complete assembly after being wrapped in a few layers

of thermal insulating material, was raised to the maximum or minimum required temperature by heating or cooling in a temperature-controlled environment for a period of 7 to 14 h . The time period was selected to provide a uniform temperature distribution in the sample.

After the sample achieved the maximum or minimum required temperature, the complete assembly was brought out of the temperature-controlled environment and connected to the slotted line. The magnitude of the reflection coefficient was measured using the precision variable attenuator. The phase shift was determined as the shift in voltage minimum positions between the sample and the short circuit. As for the calibration, the minimum position was obtained as an average of the two positions, corresponding to equal signal levels on either side of the minimum. The temperature at different points in the sample was recorded as the voltage difference, obtained by comparison of the sample thermocouple with a reference thermocouple immersed in a medium of known temperature.

As the sample temperature gradually increased or decreased to the environment temperature, the corresponding voltage minimum position, attenuation, average sample temperature, and reference junction temperature were recorded on data sheets along with the frequency of operation, moisture content, and density. The complete

data thus obtained wereused to calculate the dielectric constant and loss factor, as a function of temperature and moisture content, using a FORTRAN IV G-level computer program given in the Appendix.

6.2 Experimental Results

The dielectric properties of Neepawa wheat were measured, over a temperature range extending from -20° to 80°C, at 2.45 and 9.40 GHz utilizing modified infinite-sample-method. The moisture content range, in which measurements were made, extended from 0.5% to 26% (wet basis).

For the measurements at 2.45 GHz, the sample holder was constructed from WR-284 standard waveguide with a standard flange and comprising a pyramidally-shaped matched load of about 18 cms in length. The total length of the sample holder was approximately 33 cm and contained three copper constantan thermocouples positioned inside the waveguide to monitor the sample temperature. The description of the position and orientation of these thermocouples has already been presented in Chapter V. The voltage standing wave ratio of the empty sample holder with the thermocouples and mica sheet, as obtained from the calibration, was 1.05 at 2.45 GHz.

A similar sample holder used at 9.40 GHz was designed

from WR-90 standard waveguide components with a total length of about 25 cm . The voltage standing wave ratio of the empty sample holder with the thermocouples and the thin diaphragm of mica sheet, in this case, was 1.08.

6.2.1 Dielectric Properties as a Function of Temperature

The directly measured quantities, for measurements as a function of temperature, were standing wave ratio and shift of the standing wave pattern minimum with respect to the calibration position. Since these quantities are directly related to the reflection coefficient $\left[|\gamma| = \frac{VSWR - 1}{VSWR + 1}\right.$, $\theta = \frac{4\pi\Delta\ell}{\lambda g}$; $\Delta\ell$ - shift of the minimum, λ_g - wavelength in the waveguide$\left.\right]$, ε' and ε'' can be calculated from equations (3.10) and (3.11) using the computer program given in the Appendix.The calculated values of ε' and ε'' as a function of temperature for various moisture contents at 2.45 GHz are marked by special symbols in Figures 6.2 and 6.3, while those for 9.40 GHz are marked in Figures 6.4 and 6.5. Second-order curves of the form $y = a_o + a_1x + a_2x^2$ fitted to the experimental data by minimizing the function $\sum_{i=1}^{n} \left(y_i - a_o - a_1x_i - a_2x_i^2\right)^2$ for ε' and ε'' at all moisture contents are shown as continuous curves in Figures 6.2 to 6.5.

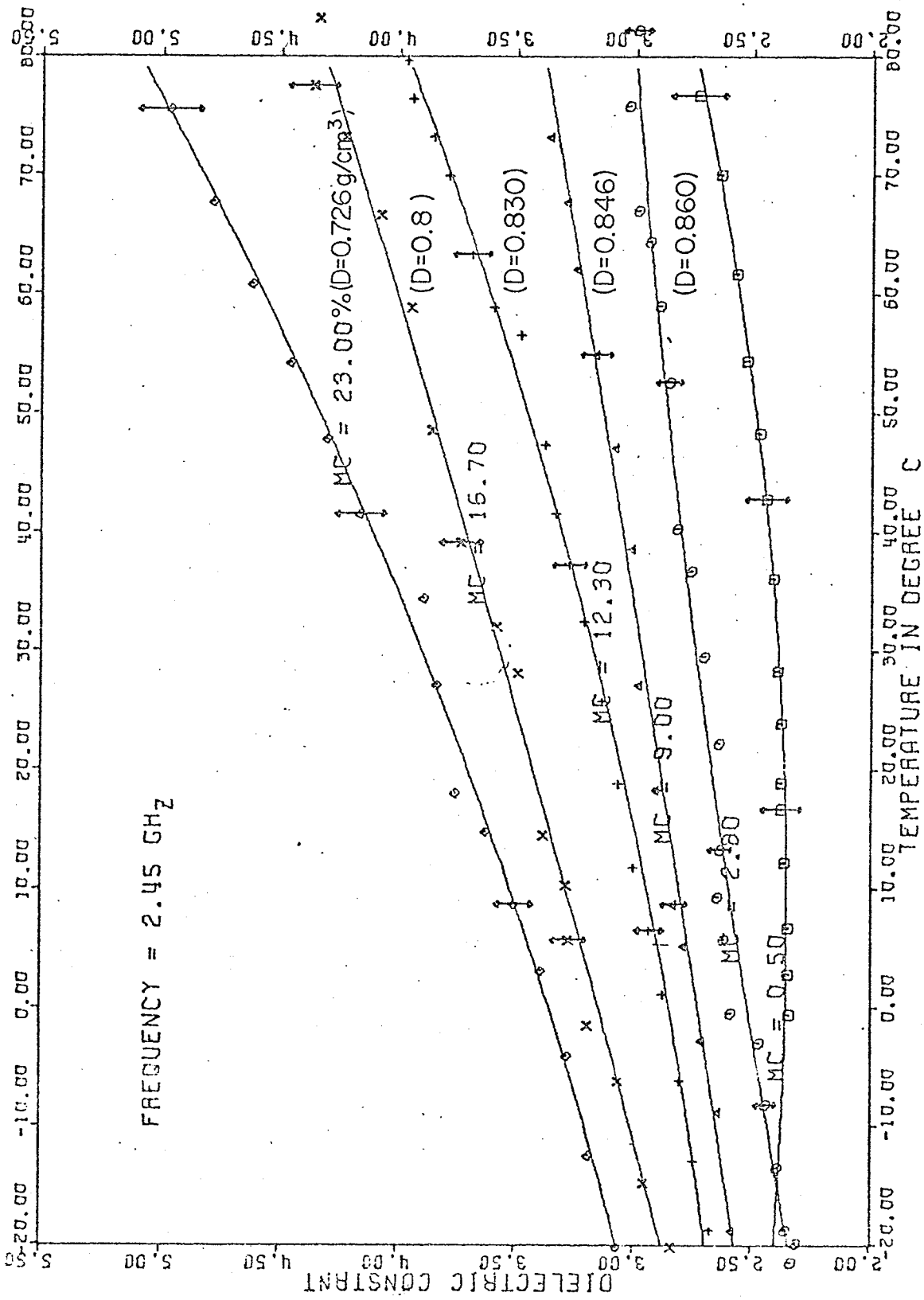

Fig. 6.2 Dielectric constant vs. temperature at 2.45 GHz

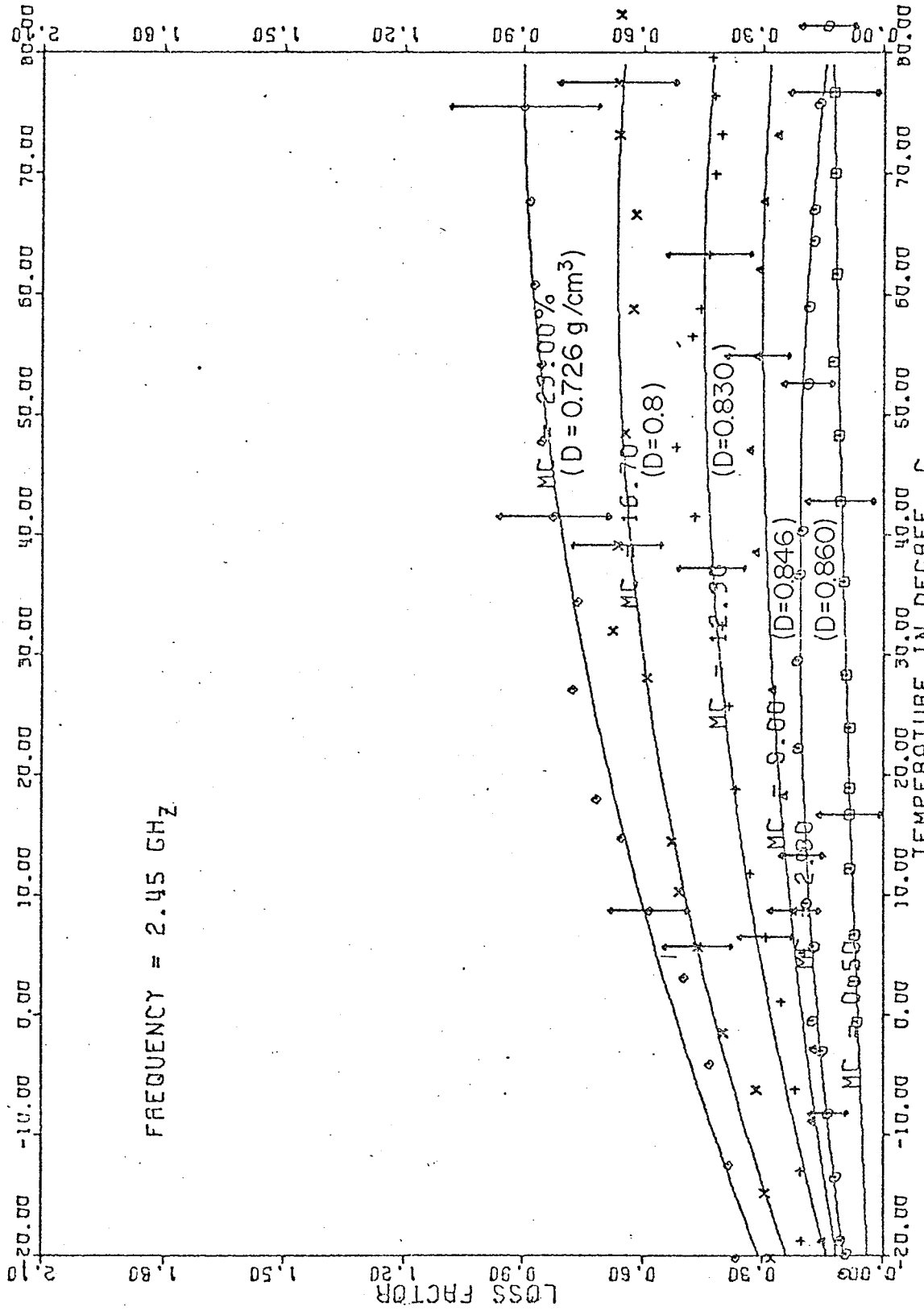

Fig.6.3 Loss factor vs. temperature at 2.45 GHz

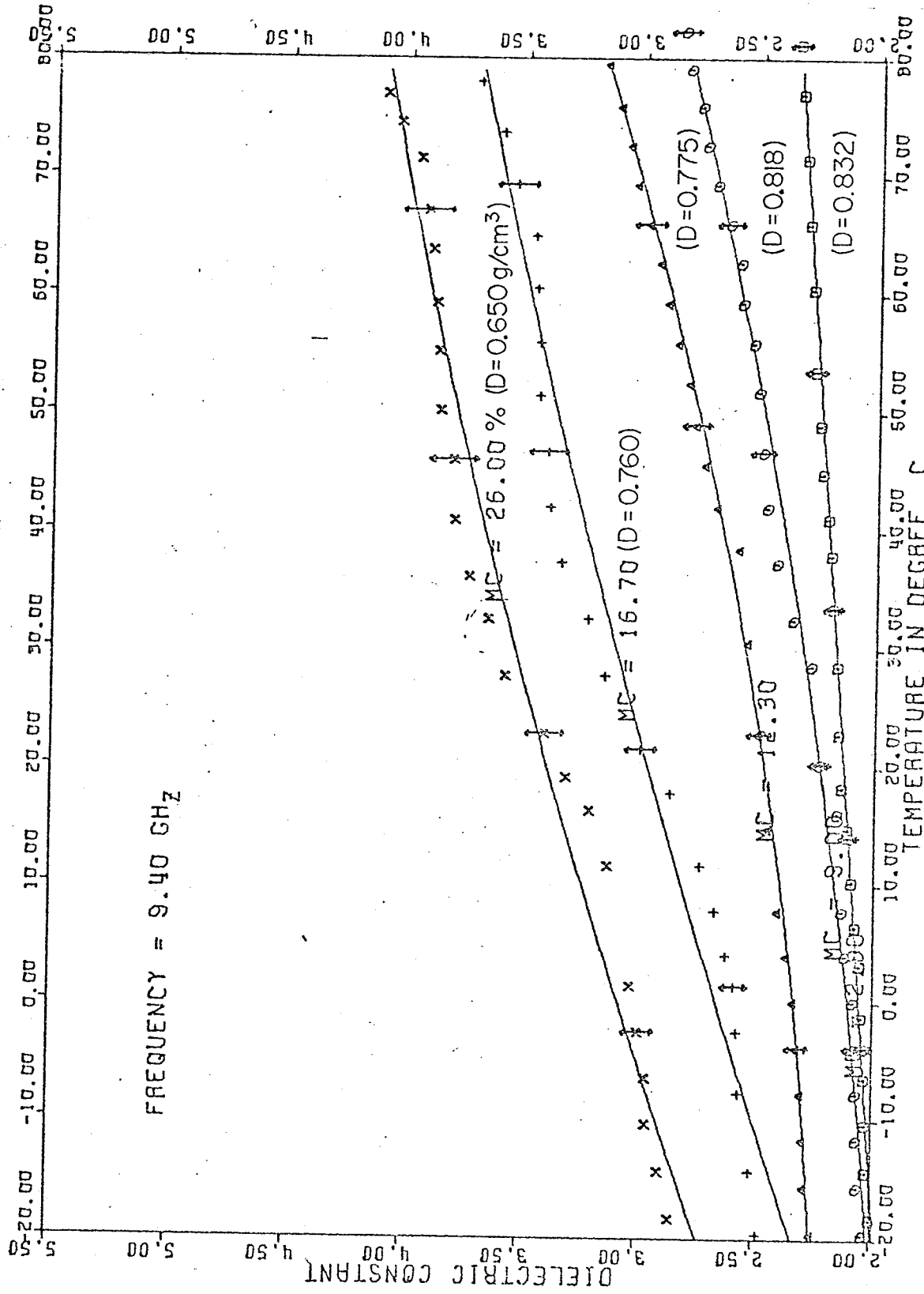

Fig.6.4 Dielectric constant vs. temperature at 9.40 GHz

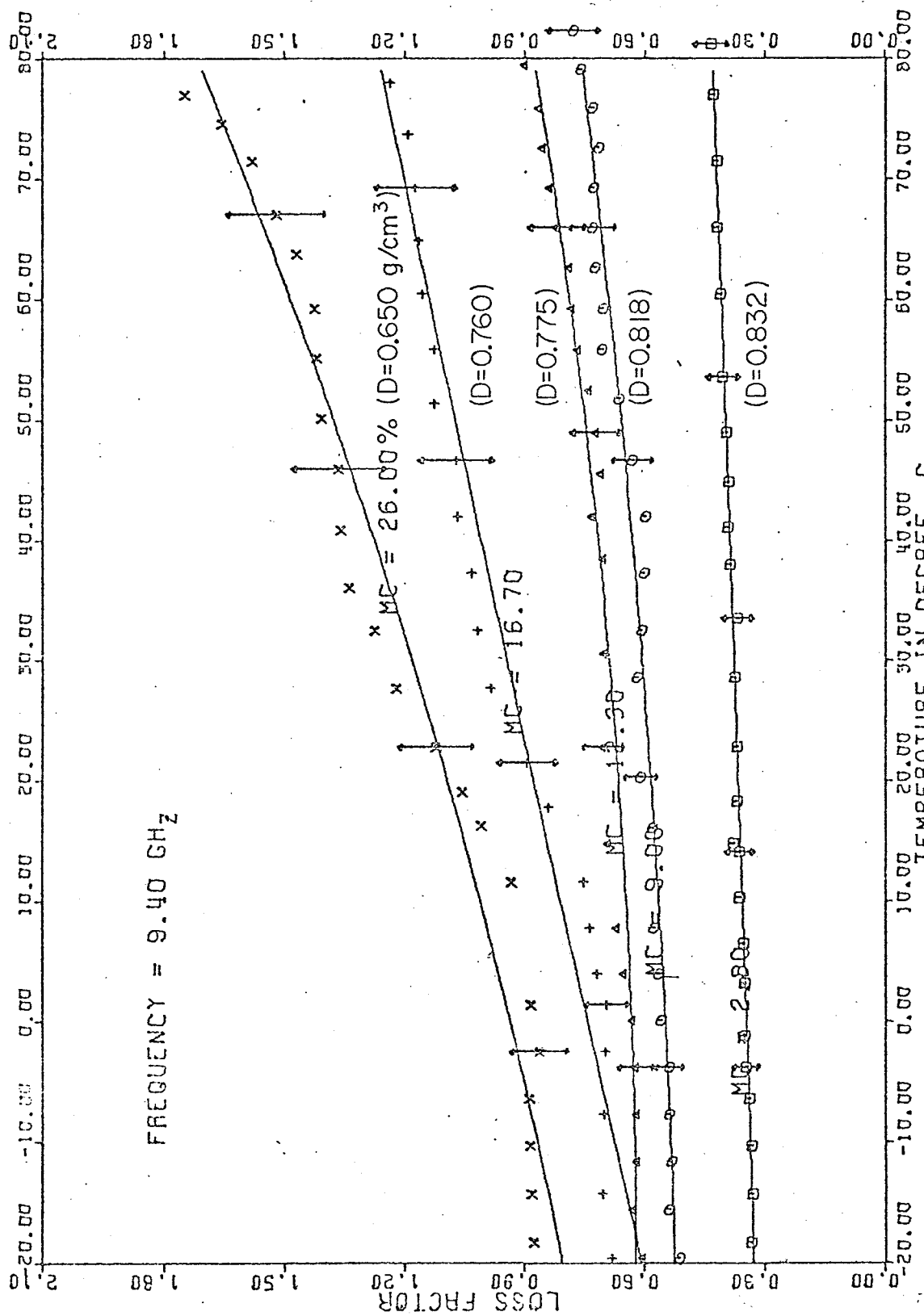

Fig. 6.5 Loss factor vs. temperature at 9.40 GHz

The vertical lines through every fifth data point represent the maximum estimated uncertainty in measurements as calculated from the relations given in Section 3.2. The moisture content and the corresponding density values are also indicated. All the calculations and the plotting were done with the help of the computer program given in Appendix utilizing an IBM 360/65 computer and the attached Calcomp Plotter.

6.2.2 Dielectric Properties as a Function of Moisture Content

The measured values of the dielectric properties, as a function of temperature at various moisture contents, were utilized to determine the relationships between the dielectric properties and moisture content. The relationships between the dielectric constant and moisture content, at various temperatures, were obtained as follows:

1. The values of dielectric constants were calculated at different observed sample temperatures for a particular moisture content, from the observed data.

2. These observed dielectric constants and temperatures were utilized to determine the second-order curve coefficients by minimizing the relation $\sum_{i=1}^{n} \left\{ y_i - a_o - a_1 x_i - a_2 x_i^2 \right\}^2$.

3. Steps 1 and 2 were repeated for other moisture

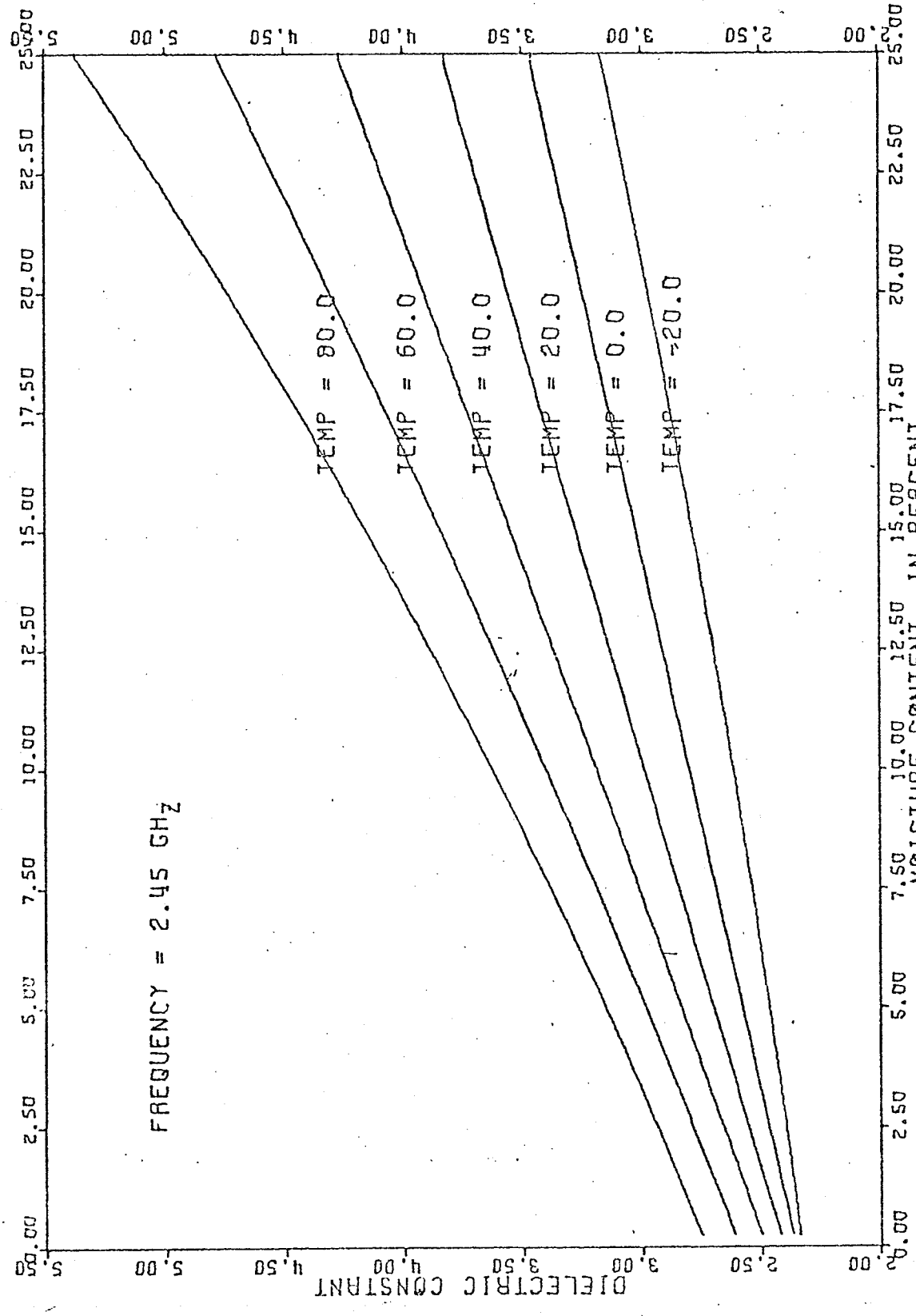

Fig. 6.6 Dielectric constant vs. moisture content at 2.45 GHz

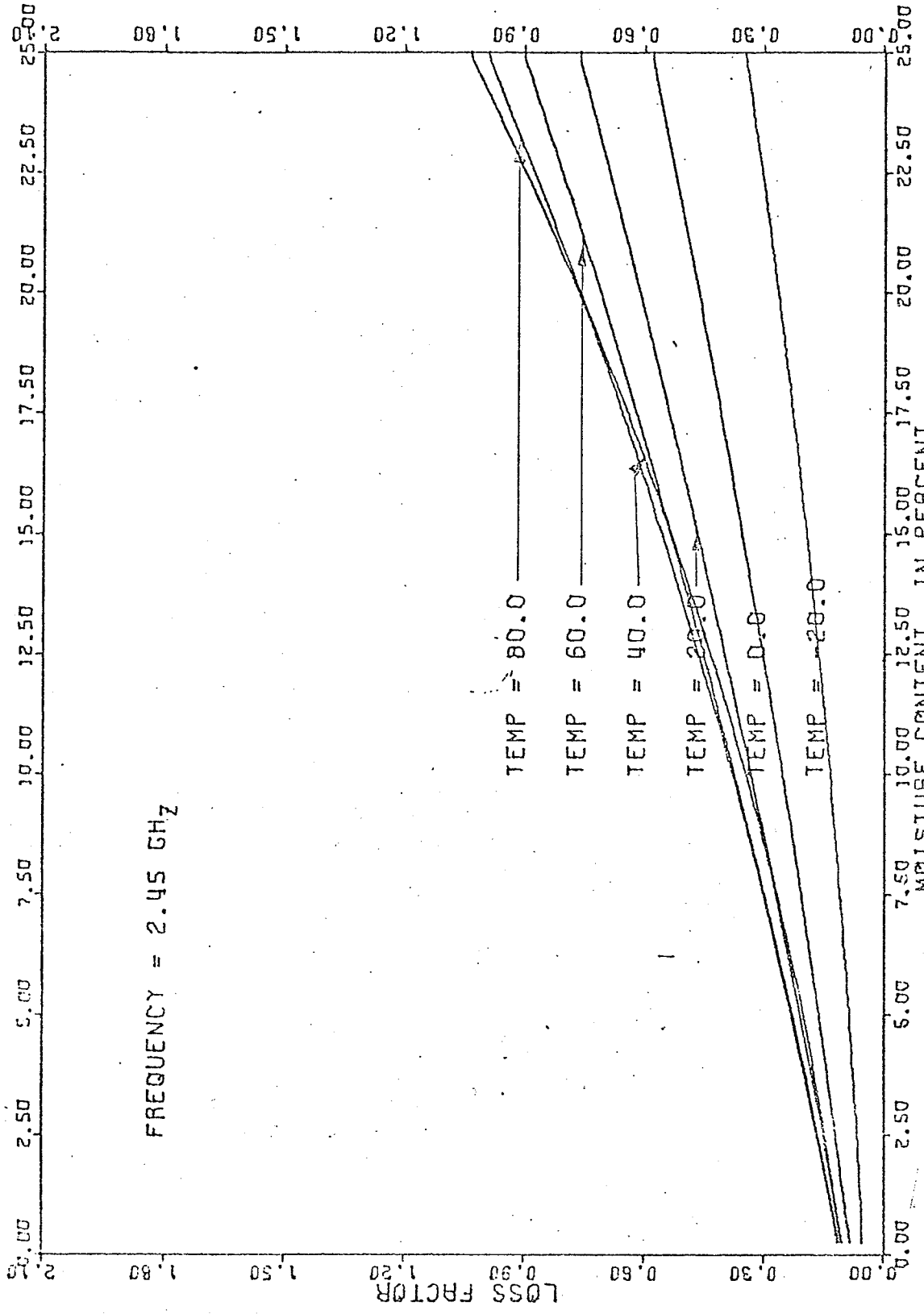

Fig. 6.7 Loss factor vs. moisture content at 2.45 GHz

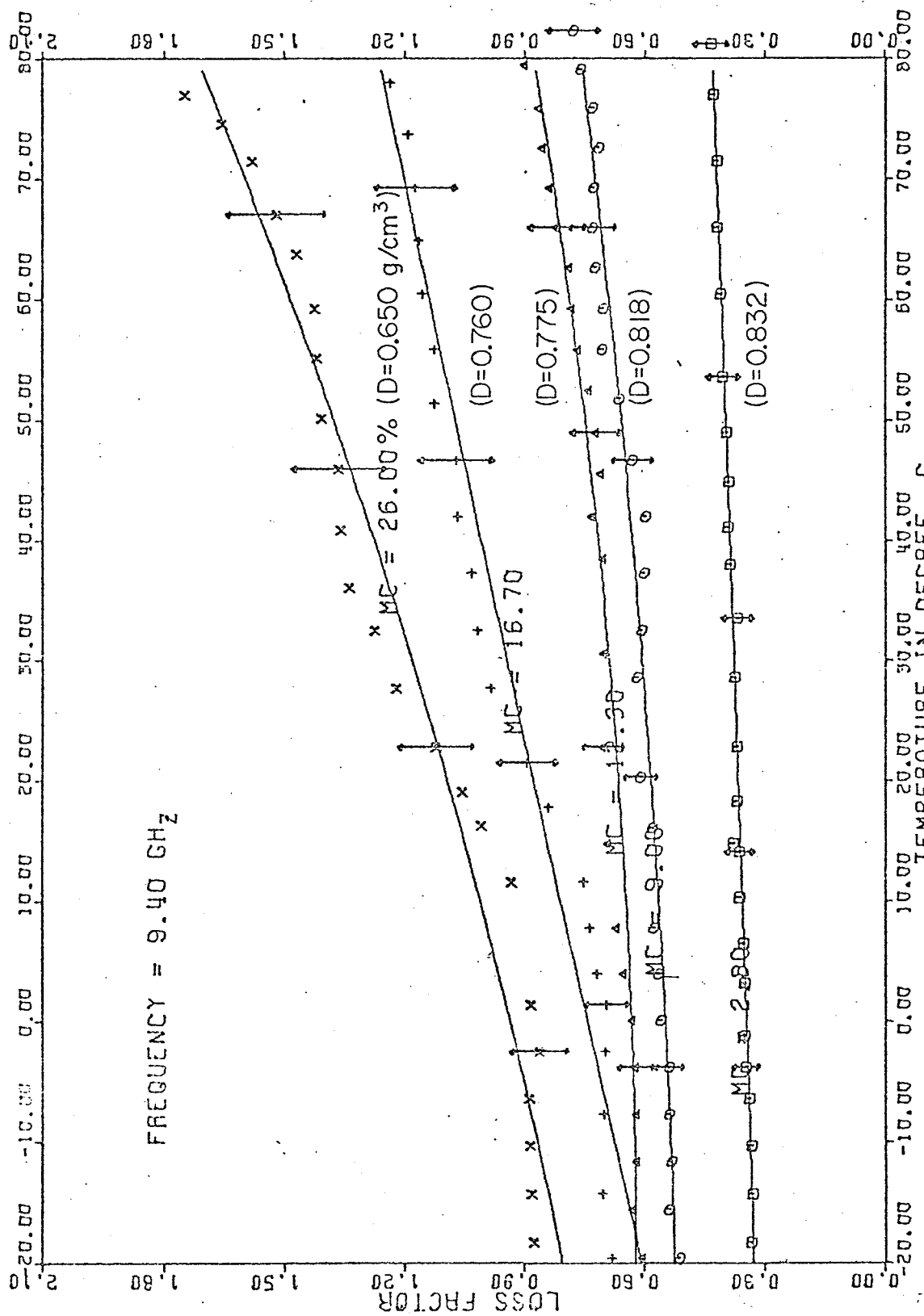

Fig. 6.5 Loss factor vs. temperature at 9.40 GHz

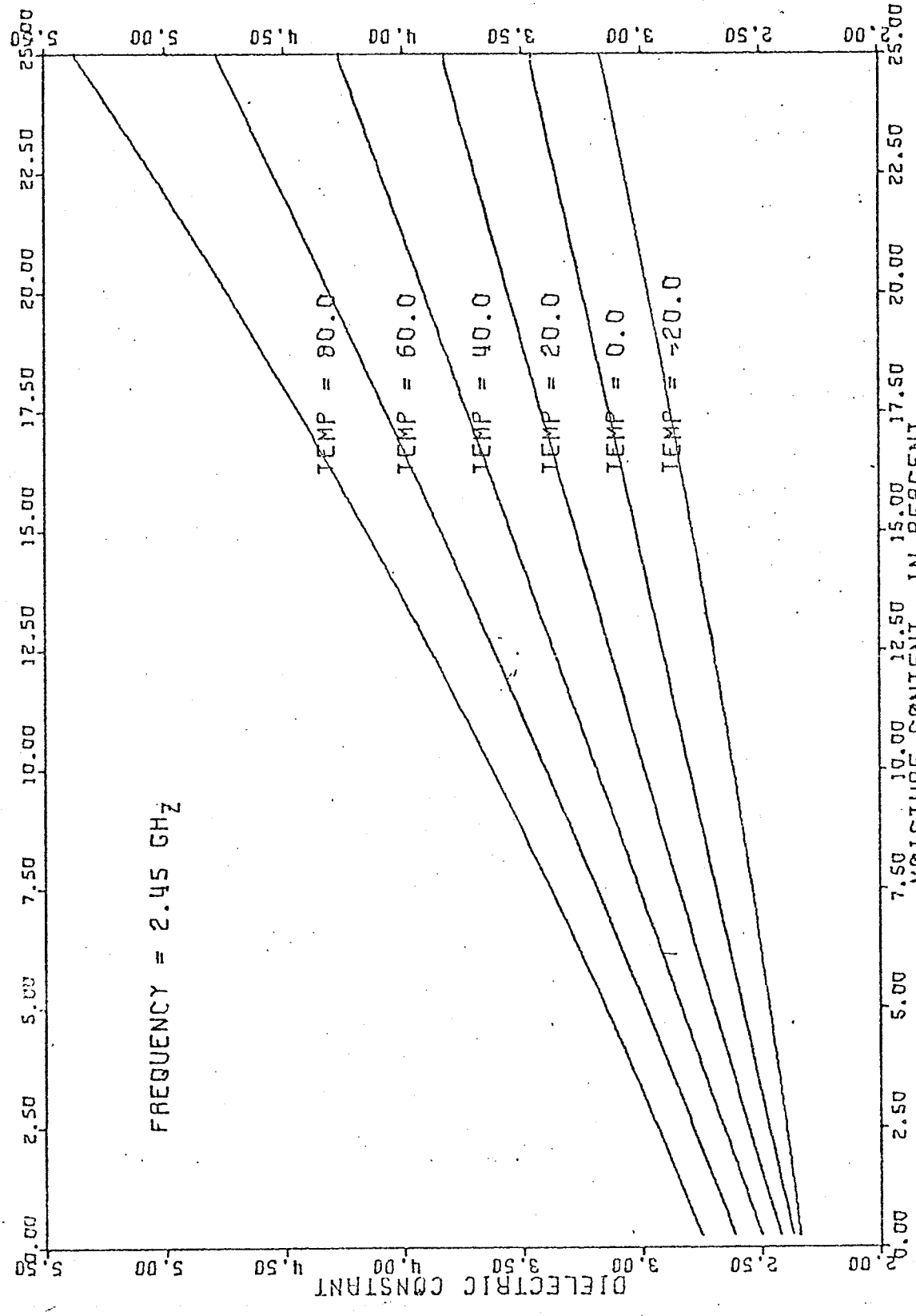

Fig. 6.6 Dielectric constant vs. moisture content at 2.45 GHz

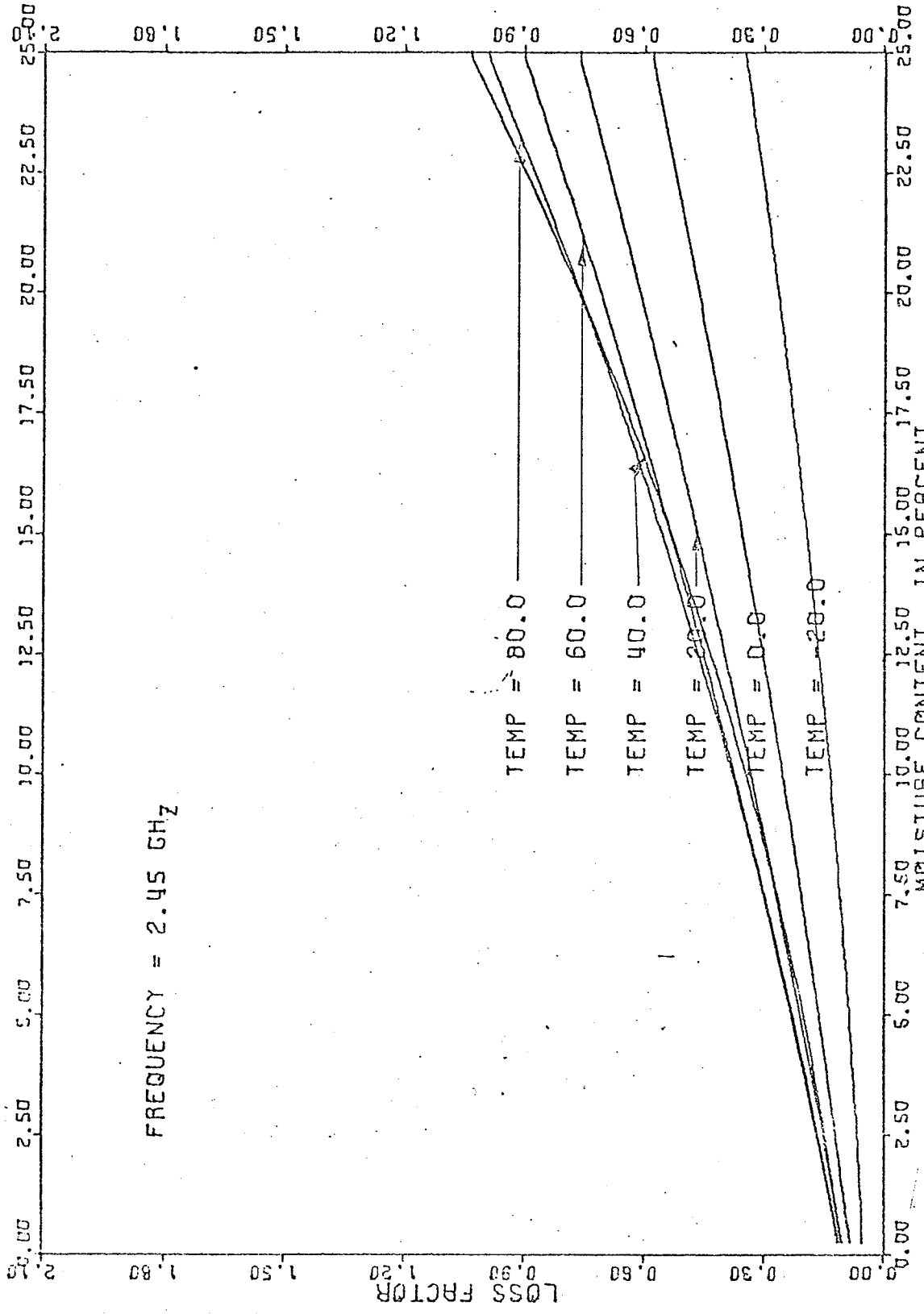

Fig. 6.7 Loss factor vs. moisture content at 2.45 GHz

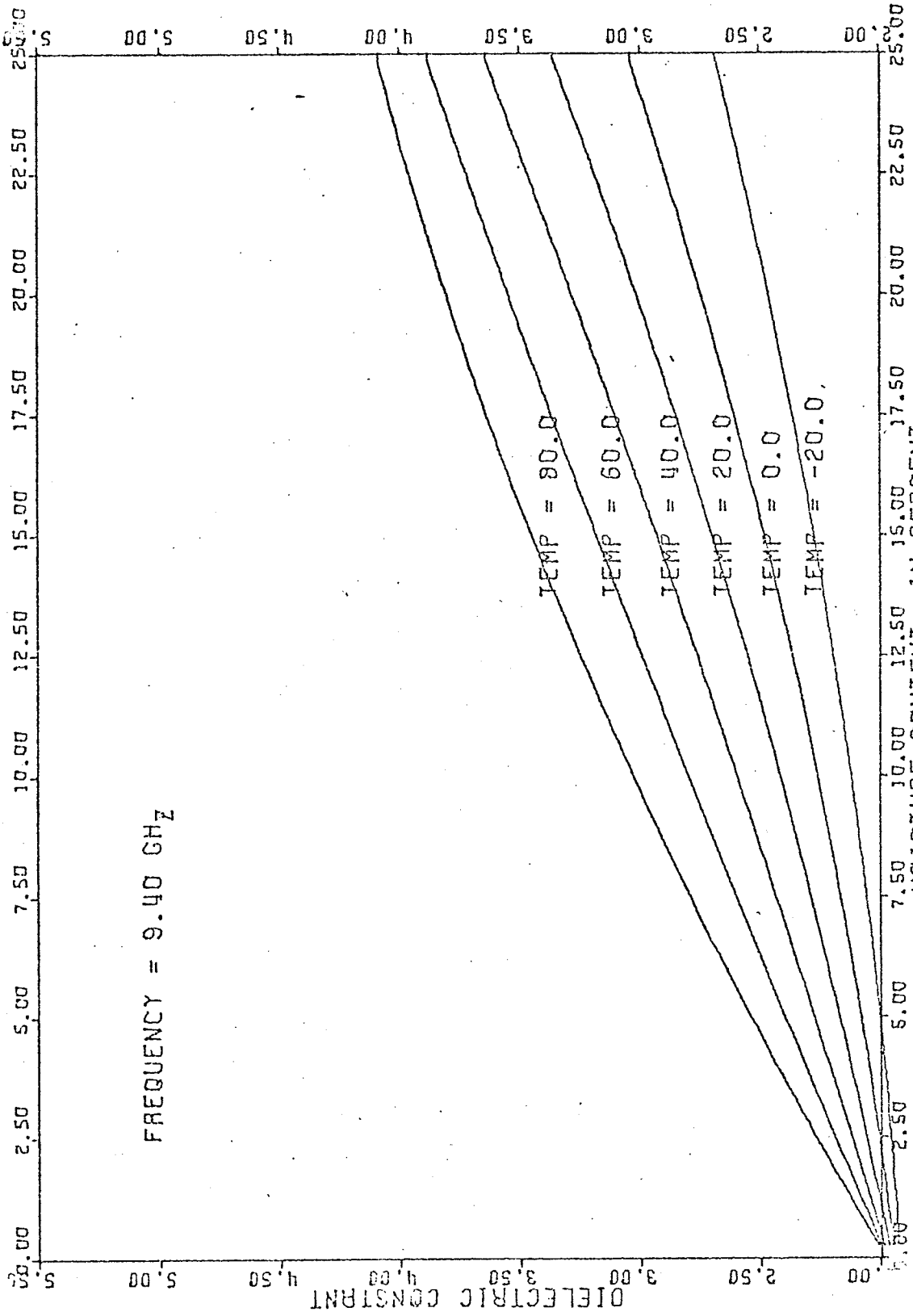

Fig.6.8 Dielectric constant vs. moisture content at 9.4GHz

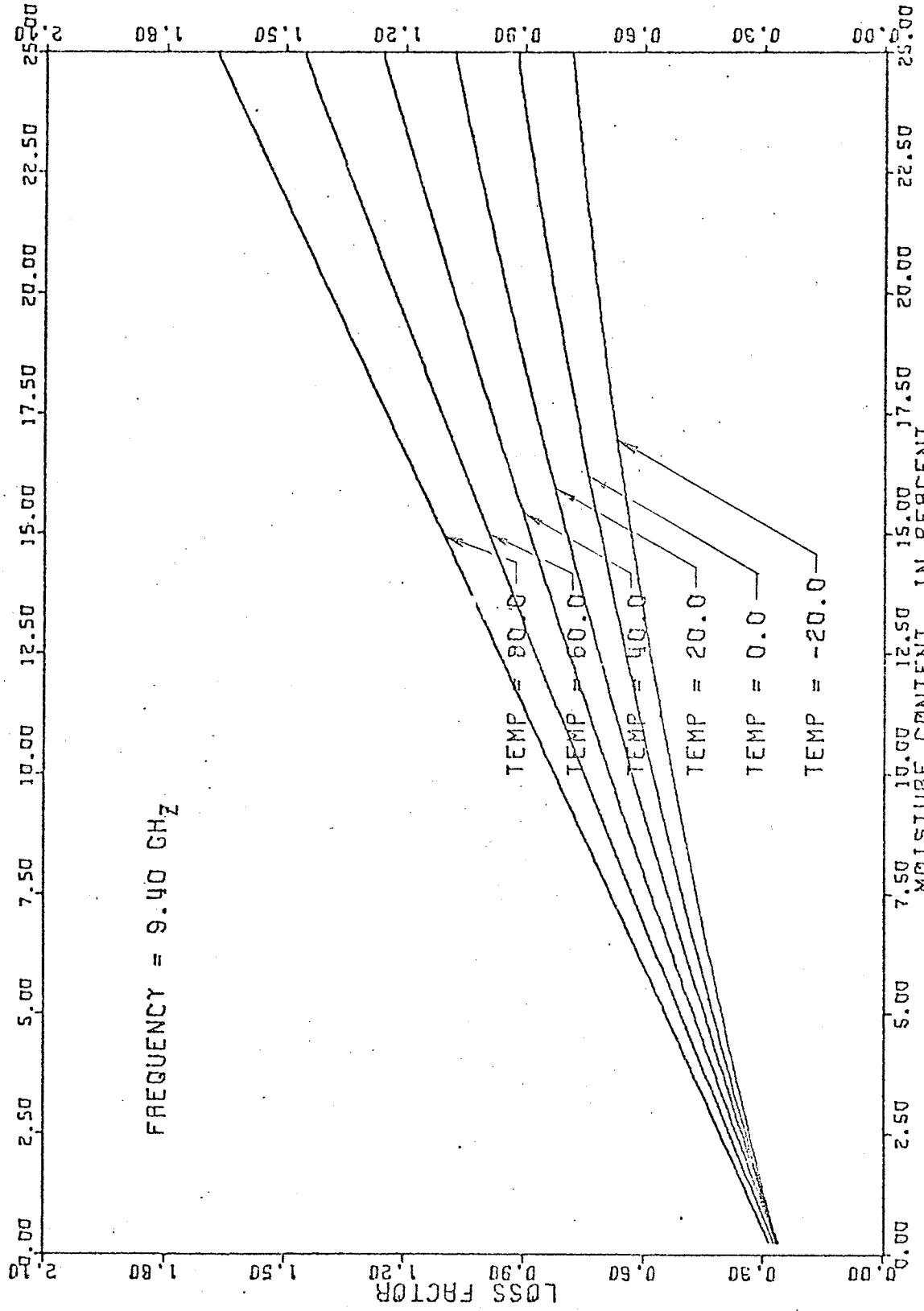

Fig.6.9 Loss factor vs. moisture content at 9.40 GHz

contents.

4. Second-order curve coefficients calculated in step 3 were then used to determine the dielectric constants, at the preselected temperature, for all moisture contents.

5. Using the data calculated in step 4, the dielectric constant as a function of moisture content was calculated at the particular temperatures.

6. Steps 4 and 5 were repeated for six different temperatures.

The above mentioned steps were repeated for the calculation of the loss factor. Six different temperatures selected were -20°, 0°, 20°, 40°, 60°, and 80°C. The curves for dielectric constant and loss factor as a function of moisture content are shown in Figs. 6.6 and 6.7, respectively, for 2.45 GHz while those for 9.40 GHz are plotted in Figs. 6.8 and 6.9.

CHAPTER VII

DISCUSSION OF THE EXPERIMENTAL RESULTS

7.1 Introduction

Dielectric properties of agricultural materials vary with frequency and temperature and are also highly dependent upon moisture content and density.

A brief general discussion of the influence of frequency, temperature, moisture content, and density on the dielectric properties of agricultural products is presented below.

7.1.1 Frequency Dependence of the Dielectric Properties

The dielectric properties are dependent upon the frequency of the alternating field. For a heterogeneous mixture the complete frequency range, from few Hz to visible light region, can be basically divided into four dispersion regions. Each of these regions corresponds to the absence of the influence of a different mechanism of polarization.

The polarization by an alternating electric field in heterogeneous systems, like grain, can be classified under three main headings:

1. Interfacial polarization due to the localized accumulation of free charge carriers, against a defect or a boundary layer, which induces its image charge on an

electrode and gives rise to a dipole moment.

2. Orientational or dipolar polarization due to the partial alignment of the permanent dipoles in the field direction.

3. Induced or distortional polarization in the field direction due either to:

(a) displacement of electrons relative to a nucleus, or

(b) displacement of ions from their zero field equilibrium positions.

As the frequency of the applied electric field increases, the contributions to the polarization from these mechanisms vary. Similar to human tissues (Schwan, 1963), agricultural products also exhibit three dispersion regions, α, β, and γ (Fig. 1.1).

The only mechanism possible for α-dispersion is the interfacial polarization. The dielectric losses, corresponding to frequencies up to few kilo-Hertz, are referred to as the Maxwell-Wagner type. An extensive review of the Maxwell-Wagner losses was presented by van Beek (1967).

The occurrence of dielectric losses corresponding to β and γ dispersions can be explained as follows: at low frequencies the polarization easily follows the alternating field, thus its contribution to the dielectric

constant is large, and no losses occur. For frequencies higher than the relaxation frequency, the field alternates too fast for the polarization to follow and there is no contribution to the dielectric constant, and also no energy is lost in the medium. Between these two extremes the dipole reorientation starts lagging, and the energy is dissipated. The dielectric constant and the loss factor as a function of frequency for this mechanism are illustrated in Fig. 7.1. Debye (1929) empirically developed a mathematical formulation which can be expressed as

$$\varepsilon = \varepsilon'_\infty + (\varepsilon'_s - \varepsilon'_\infty) \; / \; (1 + j\omega\tau) \qquad (7.1)$$

Separating into real and imaginary components yields

$$\varepsilon' = \varepsilon'_\infty + (\varepsilon'_s - \varepsilon'_\infty) \; / \; (1 + \omega^2\tau^2) \qquad (7.2)$$

$$\varepsilon'' = (\varepsilon'_s - \varepsilon'_\infty) \; \omega\tau \; / \; (1 + \omega^2\tau^2) \qquad (7.3)$$

where

ε'_s - low frequency value of the dielectric constant,

ε'_∞ - high frequency value,

τ - relaxation time, the period associated with the time for the dipoles to revert to random orientation.

The loss factor, ε'', peaks when $\omega = 2\pi f = 1/\tau$, and, at relaxation frequency ε'' has the value $(\varepsilon'_s - \varepsilon'_\infty) \; / \; 2$ and ε' has the value $(\varepsilon'_s + \varepsilon'_\infty) \; / \; 2$. Further details about other models and examples of pure liquids following

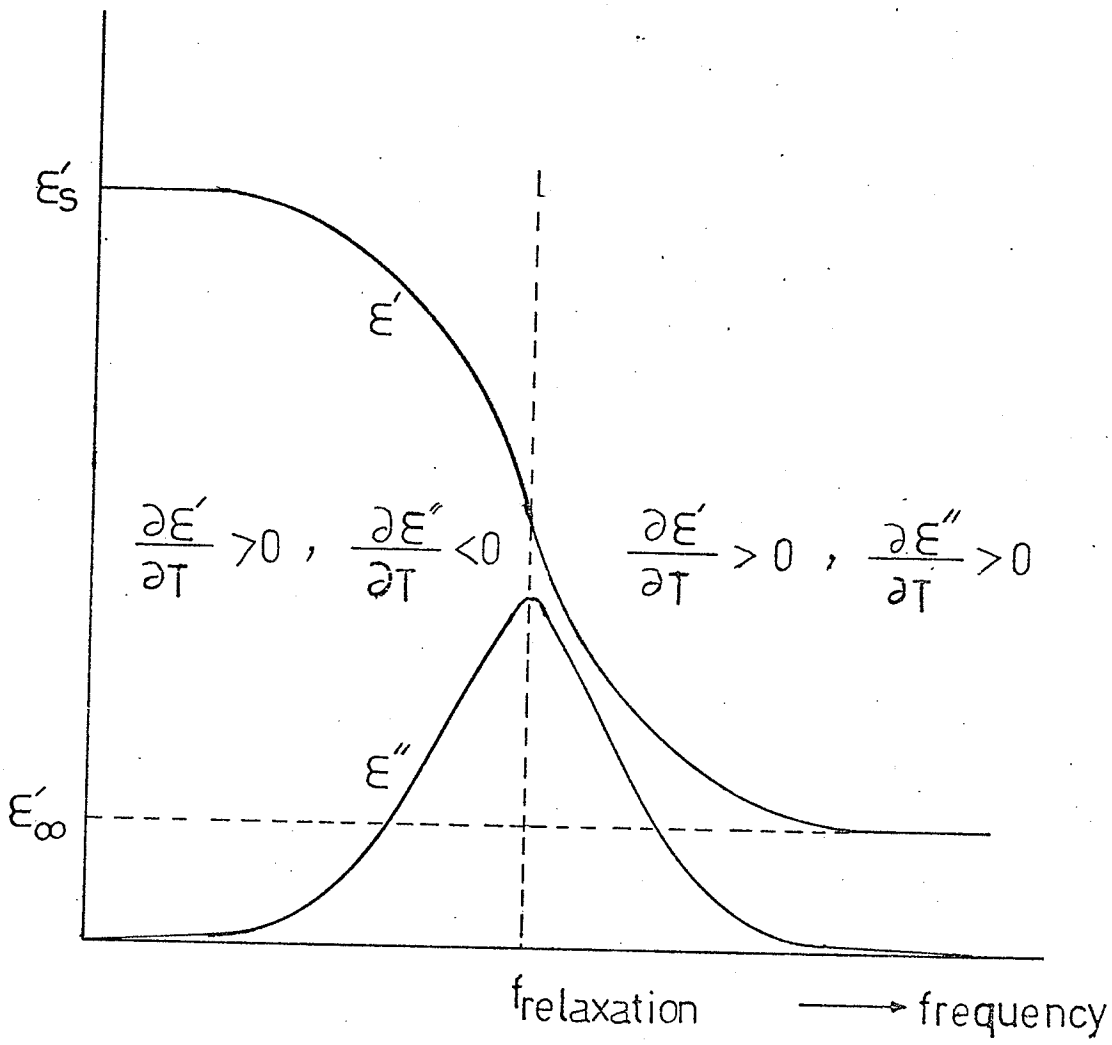

Fig. 7.1 Dispersion and absorption curves for polar materials following Debye relaxation process.

Debye dispersion can be found in many references, including Anderson (1963), and Hill et al. (1969).

For wheat, the dielectric losses corresponding to β-dispersion, in the megahertz range, are probably caused by the adsorbed water while those corresponding to γ-dispersion in the gega-hertz range, can be related to the loosely bound water.

Two smaller contributions to the total polarization come from electronic polarization, the displacement of electrons of atoms with respect to the nucleus, and atomic polarization, the displacement of nuclei with respect to one another.

7.1.2 Temperature Dependence of the Dielectric Properties

Dielectric properties of materials are also temperature dependent. In polar materials the relaxation frequency increases with temperature, and examination of equation (7.1) reveals that the dielectric constant will, therefore, always increase with temperature in the region of dispersion. In the absence of dielectric losses, the dielectric constant for such materials decreases with increasing temperature (Böttcher, 1952).

According to deLoor (1968), for dipolar materials

$$\frac{\partial \varepsilon'}{\partial T} > 0 \quad \text{for all frequencies} \qquad (7.4)$$

$$\frac{\partial \varepsilon''}{\partial T} < 0 \text{ for } f < f \text{ relaxation}$$
$$\frac{\partial \varepsilon''}{\partial T} > 0 \text{ for } f > f \text{ relaxation.} \qquad (7.5)$$

Temperature dependence of the dielectric properties of agricultural products containing water is mainly controlled by the presence of adsorbed water and loosely bound water. It is well known that for free water dielectric losses drop to negligible values below 0°C (freezing point of free water).

Fig. 7.2 shows the dispersion characteristics of free water for different temperatures, and although pure free water rarely appears in agricultural materials, this figure gives a general idea of water relaxation phenomena, which for free water occur at microwave frequencies.

7.1.3 Influence of Density on the Dielectric Properties

Agricultural materials of interest are in the form of heterogeneous mixtures of a granular material with air. The macroscopic behaviour of a mixture of a granular material with dielectric constant ε_i dispersed in a continuum with dielectric constant ε_o can be described by the theoretical formulas given in literature including Böttcher (1952) and deLoor (1968). It has been shown (deLoor, 1968), that for ellipsoidal granules of equal size and eccentricity,

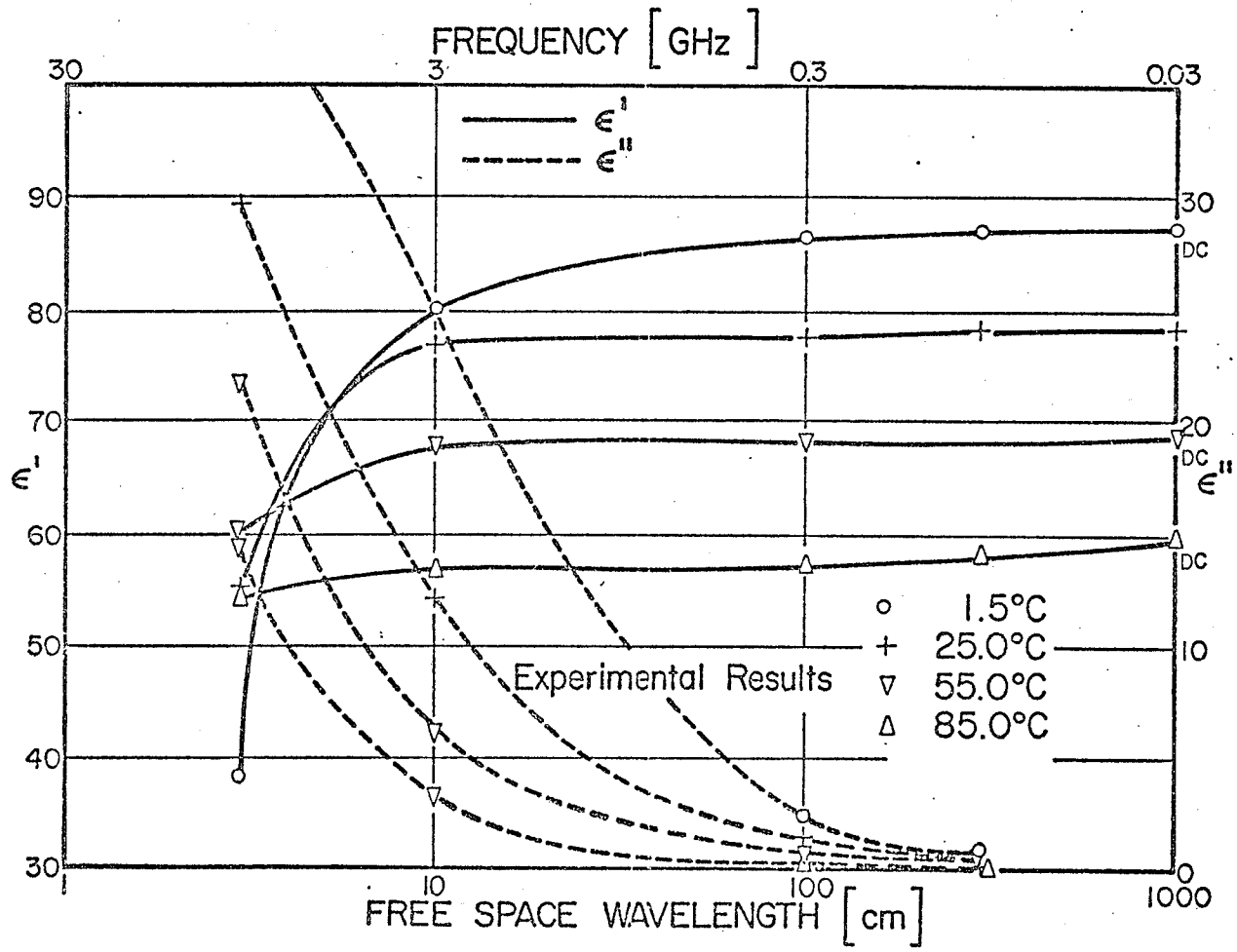

Fig. 7.2 Permittivity of free water as a function of frequency for different temperatures.

the macroscopic permittivity of the mixture can be expressed as

$$\varepsilon_m = \varepsilon_o + \left(v_i/3\right)\left(\varepsilon_i - \varepsilon_o\right) \sum_{j=1}^{3} 1/\left[1 + \left\{\left(\varepsilon_i/\varepsilon^*\right) - 1\right\}A_j\right] \tag{7.6}$$

where

v_i - volume filling factor of the dispersed granules,

A_j - depolarization factors along the main axes of the ellipsoid,

ε^* - effective internal permittivity.

The variation of the dielectric constant with the volume filling factor is shown in Fig. 7.3. From this figure, it is evident that an increase in the volume filling factor of the material with higher dielectric constant results in an increase of the dielectric constant of the mixture.

It is, therefore, evident that the dielectric constant of wheat should increase with density. This fact, i.e. increase of dielectric constant with sample density, has been confirmed by Nelson (1972). According to Nelson (1972), the dielectric constant increases almost linearly with density. The loss factor was also found to increase linearly, except for a small portion in which it first decreased and then increased. These non-linearities in the dielectric constant and the loss factor might be because of the variation of effective internal permittivity, ε^* in equation (7.6), with the density.

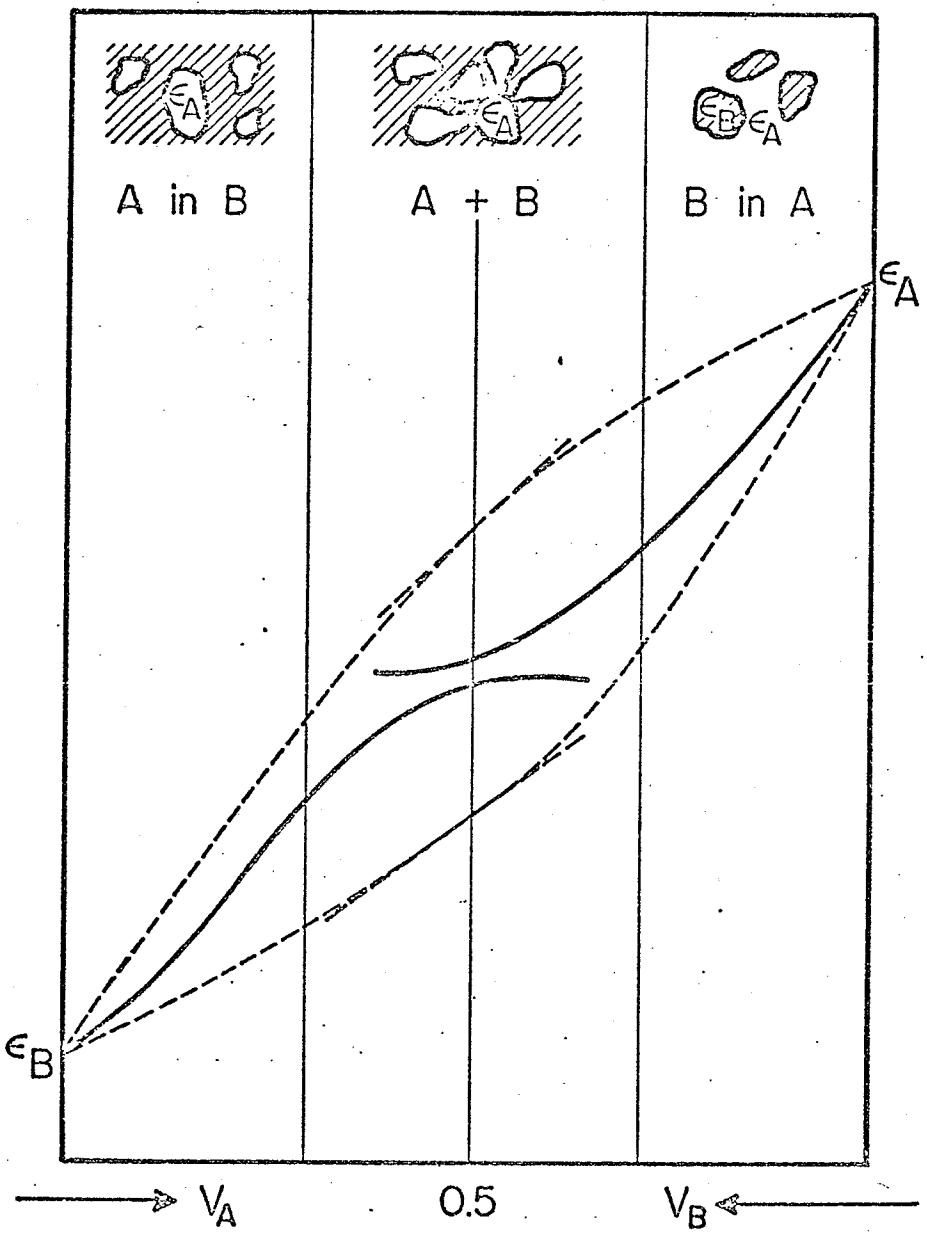

Fig. 7.3 Permittivity of a heterogeneous mixture as a function of content.

7.1.4 Moisture Content Dependence

As mentioned in the previous section, agricultural materials are heterogeneous mixtures of a granular material with air. The fact that these materials contain water complicates the picture because water in such systems may appear in three different forms; free water, adsorbed water, or water of crystallization.

The macroscopic dielectric behaviour of a heterogeneous mixture has already been briefly described in the previous section. From the equation (7.6) it is clear that the dielectric properties should increase with increase in the moisture content. According to deLoor (1968), the maximum and minimum limits of the dielectric constant of the mixture can be obtained by substituting in equation (7.6) $\varepsilon^* = \varepsilon_m$ and $\varepsilon^* = \varepsilon_o$. Losses in the heterogeneous mixture on the other hand depend upon the relative proportions of the adsorbed water and the relatively free water. The dielectric constant for bound water is 5.5 and temperature independent, while that for free water is approximately 80, and is temperature dependent.

In addition to a reduction in the dielectric constant, adsorbed water also results in a spread of the relaxation frequency. According to deLoor (1968), when one of the components of a heterogeneous mixture shows losses of dipolar origin, the relaxation frequency of the mixture is

always the same or higher than that of the relaxing component.

7.2 Discussion

In order to draw quantitative comparisons, experimental results are presented in analytical form in Tables 7.1 to 7.4. These results were obtained for the natural densities of the grain at various moisture contents.

The dielectric constants, at 2.8% moisture content for 2.45 and 9.40 GHz (Tables 7.1 and 7.2), are 2.851 and 2.058, respectively, while the loss factors are 0.163 and 0.348, respectively. The same type of behaviour, the decrease of the dielectric constant and the increase of the loss factor with increasing frequency, is also evident for other moisture contents. The values of the dielectric constant and the loss-factor agree fairly well, at 2.45 GHz, with the data presented by Nelson (1972) for room temperature. At 9.40 GHz the values reported here differ from those presented by Nelson (1972) by more than the experimental uncertainty, but differences may be accounted for by differences in the experimental material and the sample density.

Higher values of the dielectric constant at 2.45 GHz than at 9.40 GHz and increase of the loss factor with frequency, for all corresponding moisture contents and

TABLE 7.1

RELATIONSHIPS BETWEEN DIELECTRIC PROPERTIES AND TEMPERATURE FOR 1971 NEEPAWA HARD RED SPRING WHEAT AT VARIOUS MOISTURE CONTENTS AT 2.45 GHz

PROPERTY	MOISTURE CONTENT %	REGRESSION EQUATION	TEMPERATURE OF MAXIMUM LOSS °C
Dielectric Constant	0.5	$2.352 - 0.0008T + 0.735 \times 10^{-4}T^2$	
	2.8	$2.521 + 0.0082T - 0.268 \times 10^{-4}T^2$	
	9.0	$2.733 + 0.008T + 0.370 \times 10^{-5}T^2$	
	12.3	$2.854 + 0.009T + 0.635 \times 10^{-4}T^2$	
	16.7	$3.155 + 0.013T + 0.119 \times 10^{-4}T^2$	
	23.0	$3.362 + 0.016T + 0.754 \times 10^{-4}T^2$	
Loss Factor	0.5	$0.064 + 0.112 \times 10^{-2}T - 0.434 \times 10^{-5}T^2$	None
	2.8	$0.163 + 0.254 \times 10^{-2}T - 0.359 \times 10^{-4}T^2$	35
	9.0	$0.202 + 0.365 \times 10^{-2}T - 0.334 \times 10^{-4}T^2$	55
	12.3	$0.281 + 0.591 \times 10^{-2}T - 0.519 \times 10^{-4}T^2$	57
	16.7	$0.425 + 0.786 \times 10^{-2}T - 0.638 \times 10^{-4}T^2$	62
	23.0	$0.523 + 0.942 \times 10^{-2}T - 0.581 \times 10^{-4}T^2$	81

TABLE 7.2

RELATIONSHIPS BETWEEN DIELECTRIC PROPERTIES AND TEMPERATURE FOR 1971 NEEPAWA HARD RED SPRING WHEAT AT VARIOUS MOISTURE CONTENTS AT 9.40 GHz

PROPERTY	MOISTURE CONTENT %	REGRESSION EQUATION	TEMPERATURE OF MAXIMUM LOSS °C
Dielectric Constant	2.80	$2.058 + 0.004T + 0.200 \times 10^{-6} T^2$	
	9.00	$2.105 + 0.005T + 0.400 \times 10^{-4} T^2$	
	12.30	$2.336 + 0.005T + 0.660 \times 10^{-4} T^2$	
	16.70	$2.665 + 0.016T - 0.349 \times 10^{-4} T^2$	
	26.00	$3.086 + 0.016T - 0.473 \times 10^{-4} T^2$	
Loss Factor	2.80	$0.348 + 0.001T + 0.100 \times 10^{-5} T^2$	None
	9.00	$0.553 + 0.001T + 0.141 \times 10^{-5} T^2$	--
	12.30	$0.637 + 0.001T + 0.236 \times 10^{-4} T^2$	--
	16.70	$0.748 + 0.007T - 0.370 \times 10^{-5} T^2$	--
	26.00	$0.939 + 0.007T + 0.313 \times 10^{-4} T^2$	--

temperatures, suggest the existence of a relaxation frequency above 9.40 GHz. Similar properties were reported by Roebuck et al. (1972) for potato starch.

At both measurement frequencies, the dielectric constant has a positive temperature coefficient, $\frac{\partial \varepsilon'}{\partial T}$, from -20°C to 80°C for all moisture contents above 2.8%. For 0.5% moisture content the temperature coefficient is almost zero at 2.45 GHz, thus resulting in a constant value of ε' from -20°C to 80°C.

At 2.45 GHz the loss factor first increases and then decreases with temperature indicating the existence of an apparent maximum. The temperature of maximum losses, as shown in Table7.1, increases with moisture content from 35°C for 2.8% moisture content to 81°C for 23% moisture content. The temperature coefficient, $\frac{\partial \varepsilon''}{\partial T}$, over the entire measurement temperature range was found to be positive. In comparison, there is no apparent maximum for loss factor at 9.40 GHz and it continues to increase steadily. Positive temperature coefficient, $\frac{\partial \varepsilon''}{\partial T}$, suggests the existence of dielectric losses of dipolar origin, at microwave frequencies, with a relaxation frequency below the microwave region.

The temperature coefficient, $\frac{\partial \varepsilon'}{\partial T}$, remains almost constant up to 12.3% moisture content and changes suddenly from 0.009 to 0.013, at 2.45 GHz and 0.005 to 0.016 at

9.40 GHz, when moisture content increases from 12.3% to 16.7%. This sudden change of temperature coefficient indicates the existence of two ranges of water binding forces (Stuchly, 1970), the first for low moisture content in which water in the wet substance is bonded by the large forces of absorption, and the second in which water is loosely held in the kernels.

From Figs. 6.4 and 6.5, it is found that for moisture contents above 12.3% experimental points are oscillating around the smooth curve. These oscillations might be because of moisture migration near the open end of the sample, which were not observable for lower moisture contents (private communication, Kraszewski, A., Inst. of Physics, Polish Academy of Sciences, Zielna 37, 00 108 Warszawa, Poland). The most probable reason for this migration is the temperature difference at different points in the sample, particularly when the sample temperature differs from the environment temperature by a large amount. The dielectric constant and the loss factor at both frequencies and for moisture contents up to 26% change smoothly through 0°C, the freezing temperature of free water. This indicates that water is in the adsorbed form even for 26% moisture content. Similar behaviour has been observed for starch by Guilbot et al. (1960) and for granular potato starch by Stuchly (1970) and Roebuck et al. (1972).

According to equation (7.6), the dielectric constant as well as the loss factor should increase with moisture content. It is found, from Tables 7.3 and 7.4, that both the dielectric constant and the loss factor are linear functions of moisture content for all temperatures and at both frequencies. Similar behaviour, i.e. linear increase of the dielectric constant with moisture content, was also observed by Nelson (1965b) at lower frequencies and for a narrower range of moisture content.

Linear relationships between the dielectric properties and moisture content seem to be result from the natural sample density because non-linear relations were observed for constant sample density (private communication, Rzepecka, M.A., Department of Electrical Engineering, Univ. of Manitoba, Winnipeg, Manitoba, 1972). The linear relationship between the dielectric properties and moisture content should prove to be of great advantage in the design of the microwave moisture meters.

7.3 Suggestions for Further Studies

7.3.1 Study of the Nature of Water in Wheat and Other Seeds

A considerable number of electrical instruments have been designed for estimating the moisture content of various materials, including cereal grains and their products.

TABLE 7.3

RELATIONSHIPS BETWEEN DIELECTRIC PROPERTIES AND MOISTURE CONTENT FOR 1971 NEEPAWA HARD RED SPRING WHEAT AT VARIOUS TEMPERATURES AT 2.45 GHz

PROPERTY	TEMPERATURE °C	REGRESSION EQUATION
Dielectric Constant	-20.00	2.335 + 0.025 MC
	0.00	2.353 + 0.044 MC
	20.00	2.401 + 0.059 MC
	40.00	2.480 + 0.070 MC
	60.00	2.590 + 0.076 MC
	80.00	2.731 + 0.078 MC
Loss Factor	-20.0	0.052 + 0.006 MC
	0.0	0.077 + 0.016 MC
	20.0	0.094 + 0.021 MC
	40.0	0.103 + 0.023 MC
	60.0	0.105 + 0.021 MC
	80.0	0.099 + 0.016 MC

TABLE 7.4

RELATIONSHIPS BETWEEN DIELECTRIC PROPERTIES AND MOISTURE CONTENT FOR 1971 NEEPAWA HARD RED SPRING WHEAT AT VARIOUS TEMPERATURES AT 9.40 GHz

PROPERTY	TEMPERATURE °C	REGRESSION EQUATION
Dielectric Constant	-20.0	1.924 + 0.013 MC
	0.0	1.939 + 0.023 MC
	20.0	1.953 + 0.039 MC
	40.0	1.963 + 0.060 MC
	60.0	1.971 + 0.086 MC
	80.0	1.976 + 0.118 MC
Loss Factor	-20.0	0.260 + 0.031 MC
	0.0	0.252 + 0.036 MC
	20.0	0.249 + 0.041 MC
	40.0	0.250 + 0.045 MC
	60.0	0.256 + 0.050 MC
	80.0	0.267 + 0.055 MC

The electrical properties of grain do not depend solely upon moisture content but are also functions of temperature and density. The influence of temperature and moisture content on the dielectric properties of wheat are shown in Figs. 6.2 to 6.9 at two different frequencies. These properties were, however, obtained for natural density (without compaction) of the grain. Since the permittivity varies with the grain density, it would be useful to examine the density dependence of the dielectric constant and the loss factor of the grain.

The dielectric constant at 2.45 GHz was found to be higher than that at 9.40 GHz while, the loss factor was higher at 9.40 GHz, thus suggesting the existence of a relaxation frequency above 9.40 GHz. Determination of the dielectric properties for frequencies higher than 9.40 GHz should help to explain these facts. The measurements should be performed over a broad frequency and temperature range to include, if possible, the relaxation frequency and the freezing point of free water.

In addition to the above-mentioned studies, the dielectric properties at temperatures much lower than -20°C and over a broad moisture content range are required to determine how far the water remains in the bound form.

Finally, the activation energies and thus the nature of binding forces can be examined from the

dependence of the frequency of maximum losses on an inverse of temperature.

7.3.2 Study of the Geometrical Model for Optimum Application of the Mixture Theory for Grain and Seeds

Relating, satisfactorily, the dielectric constant of a mixture to the dielectric constant of its components is a major problem in the dielectric mixture theory (Tinga, 1969). The first factor in developing the geometrical model is the shape of the kernel and the relative size of its axes. This requires an extensive study of the shape and size of kernels at different temperatures and moisture contents.

In addition to the kernel's shape and size study, knowledge about some other topics is also needed. These topics are:

1. Air and water volumes at different moisture contents and specific gravities.

2. Specific gravity of adsorbed water as a function of moisture content.

3. Void volume and specific gravity of grain and seeds as a function of moisture content.

From these studies and with the help of experimental data of the dielectric properties of grain and seeds as functions of temperature, moisture content and frequency, a suitable geometrical model can be developed.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

8.1 Summary

The need for the knowledge of the dielectric properties of wheat at microwave frequencies is discussed, and the potential for the utilization of electromagnetic methods is considered. The definition, different mechanisms of the dielectric polarization, and the literature available on these topics is presented. Other topics discussed in the introduction include different types of dielectric materials and their temperature dependence, dielectric properties of biological matetials, and a brief introduction to the mixture theory.

Methods and techniques for the determination of the dielectric properties of different materials in the microwave frequency range are reviewed. On basis of the criteria imposed by the nature of the agricultural materials and different measurement procedures available, a waveguide measuring system is described in some detail.

Basic principles are verified and the mathematical relationships for the calculation of the dielectric properties of the material from the slotted section or network analyzer measurements are presented. Different possible errors are reviewed and the theoretical formulas for the errors due

to the reflection coefficient and phase shift measurements are derived.

The test material selected, methods of sample preparation, and measurement methods for moisture content, grain density, and temperature determination are also described.

The design of a sample holder suitable for granular materials is presented. Special methods used for retaining moisture content and maintaining the uniform rate of increase or decrease in temperature of the sample are also mentioned.

To calculate and plot the permittivity values obtained from the observed parameters, a computer program with a number of unique features was developed. The program takes into account the readings obtained with different systems (network analyzer or slotted line). The average of voltages, obtained from the comparison of the copper-constantan thermocouples installed in the sample holder and the reference junction thermocouples, along with the reference junction temperature were fed directly to calculate the exact temperature of the sample. Other convenient features of the program include the calculation and plotting of all the experimental points, plotting of the values obtained with the least-square second-order-fit coefficients through the experimental points, and the uncertainty plottings for the dielectric constant and loss factor as a function of

temperature at various moisture contents. The dielectric properties were calculated and plotted as a function of moisture content based on the values available as a function of temperature at various moisture contents. A complete description of the computer program used is included as an Appendix.

Results obtained at 2.45 and 9.40 GHz for temperatures -20°C to 80°C and moisture contents from 0.5% to 26% are presented in analytical as well as graphical form. Dielectric properties are presented as a function of temperature at various moisture contents and as a function of moisture content at different temperatures. Sample densities at different moisture contents are given in the plottings.

The experimental curves were examined, as a function of frequency, temperature, and moisture content, in the light of the basic polarization mechanisms and the mixture theory. For this purpose, a brief review of the mixture theory for heterogeneous systems is also presented.

Suggestions for further studies include the influence of density on the dielectric properties of wheat, measurement of the dielectric properties for frequencies higher than 9.40 GHz over wide ranges of moisture contents and temperatures, and studies involving the variation of air and water volumes for different moisture contents and temperatures.

8.2 Conclusions

The following conclusions are drawn on basis of theexperimental results obtained and the data available in theliterature:

1. Modified-infinite-sample method serves very well for the determination of dielectric properties of high loss granular materials, such as grain.

2. Standard waveguide components can be easily modified for:

   (a) monitoring the sample temperature,

   (b) prevention of moisture removal from the sample, and

   (c) thermal insulation of the sample.

3. The dielectric constant and loss factor for wheat with natural density (without compaction) vary almost linearly with moisture content, over a wide range of temperature.

4. The existence of two ranges of water bonding forces is confirmed, the first for low moisture content in which the water in the wet substance is bonded by the large forces of adsorption, and the second in which the water is loosely held in the kernels.

5. Dielectric losses at microwave frequencies for dry or almost dry wheat are very small and are of dipolar origin with relaxation frequency well below the microwave region.

6. Dielectric losses at microwave frequencies for wet wheat are also of dipolar origin with relaxation frequency below the microwave origin.

7. Partially free water has a relaxation frequency above 9.40 GHz.

8. Up to 26% moisture content, water is predominantly in the bound form and dielectric properties do not change substantially at the freezing point of free water.

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APPENDIX

COMPUTER PROGRAM

In anticipation of a large number of experimental points, a computer program was developed to calculate the values of ε' and ε'' and their uncertainties as a function of temperature at various moisture contents. The program was designed for the general case and accomodates input data taken from the network analyzer or slotted line system.

Calculations were programmed for computation on an IBM 360/65 computer attached with a Calcomp Plotter 750/563 using FORTRAN IV programming language. This program, with present dimensions, can be used for a maximum of seven sets of moisture contents and each of these moisture contents can contain a maximum of forty data points at different temperatures.

```
FORTRAN IV G LEVEL  20.1                MAIN                DATE = 73078          21/20/39

                C   MAIN PROGRAM FOR CALCULATING DIELECTRIC PROPERTIES FROM
                C    THE REFLECTION COEFFICIENT OR STANDING WAVE RATIO MEASUREMENTS
                C   INPUT DATA DESCRIPTION
                C         M          NUMBER OF DATA SETS (MOISTURE CONTENTS)
                C         F          FREQUENCY IN GEGA HERTZ FOR PLOTTING
                C         TMIN       MINIMUM TEMPERATURE TO BE PLOTTED
                C         TINC       INCREMENTAL TEMPERATURE PER INCH
                C         ERMIN      MINIMUM EPSR TO BE PLOTTED
                C         EIMIN       MINIMUM EPSI TO BE PLOTTED
                C         ERINC      INCREMENTAL EPSR PER INCH
                C         LEMC1      CUT-OFF WAVELENGTH IN CENTIMETERS
                C         LEMG1      WAVEGUIDE WAVELENGTH IN CENTIMETERS
                C         KKK        CONTROL INTEGER     ONE FOR NETWORK ANALYZER
                C                    AND ANY OTHER NUMBER FOR SLOTTED LINE
                C         N          NUMBER OF TEMPERATURE POINTS
                C          MC        MOISTURE CONTENTS IN PERCENT
                C         TREF       REFRENCE JUNCTION TEMPERATURE IN FAHRENHEIT
                C         REFL       VSWR OR RETURN LOSS IN DB
                C         ANGL       PHASE SHIFT IN CMS OR IN DEGREES
                C         TEMPE      AVERAGE VOLTAGE IN MILLI-VOLTS
0001                      COMPLEX XA,YA,Z1,Z
0002                      COMPLEX CMPLX
0003                      INTEGER KKK(7)
0004                      INTEGER NN(7)
0005                      DIMENSION IB(7000),DEPSR(7,40),DEPSI(7,40),T(102),E(102)
0006                      REAL REFL(7,40),ANGL(7,40),TEMPE(7,40),MC(7)
0007                      REAL EPSI(7,40),EPSR(7,40),AA(2,2),BB(2,2),CC(2,2),DD(2,2),EE(2,2)
0008                      REAL LEMC,LEMG,LEM,TREF(7),X(40),Y(40),D(10),A(10,10),XX(220)
0009                      REAL YY(220),B(10),C(40,10)
0010                      REAL LEMC1(7),LEMG1(7)
0011                      REAL DTR(7,3),DTI(7,3),DMR(7,3),DMI(7,3)
0012                      READ40,M
0013                40    FORMAT(4I4)
0014                      READ48,F
0015                       READ48,TMIN,TINC,ERMIN,ERINC,EIMIN,EIINC
0016                      DO 120 LL=1,M
0017                      READ48,LEMC1(LL),LEMG1(LL)
0018                      READ40,KKK(LL)
0019                      READ40,N
0020                      NN(LL)=N
0021                      READ48,MC(LL),TREF(LL)
0022                      READ48,(REFL(LL,I),I=1,N)
0023                      READ48,(ANGL(LL,I),I=1,N)
0024                120   READ48,(TEMPE(LL,I),I=1,N)
0025                48    FORMAT(8F8.3)
                    C
                    C
0026                      DO 130 LL=1,M
0027                      PRINT110,MC(LL)
0028                110   FORMAT('1',20X,'MOISTURE CONTENTS = ',F8.3)
0029                      LEMC=LEMC1(LL)
0030                      LEMG=LEMG1(LL)
0031                      XE=(LEMC/LEMG)**2.
0032                      LEM=LEMC/SQRT(1.+XE)
0033                      FREQ=30.0/LEM
0034                      PRINT140,FREQ
0035                140   FORMAT('0',20X,'MEASUREMENT FREQUENCY = ',F8.3,'GHZ')
0036                      PRINT20
```

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 0037        20    FORMAT('0',10X,'TEMP C',5X,'REFLECTION COEFF',5X,
                  1'PHASE ANGLE',8X,'EPSR',11X,'EPSI',10X,'DEPSR',10X,'DEPSI')
 0038              N=NN(LL)
 0039              DO 99 L=1,N
 0040               K=KKK(LL)
 0041              IF(K.EQ.1)GO TO 940
 0042              RE=REFL(LL,L)
 0043              R=(RE-1.)/(RE+1)
 0044              ANG=(2.*3.1416/LEMG)*ANGL(LL,L)
 0045              TEMP=TEMPE(LL,L)
 0046              TEMP1=TREF(LL)+44.28*TEMP-1.184*TEMP*TEMP
 0047              TEMPE(LL,L)=(TEMP1-32.)*5./9.
 0048              GO TO 640
 0049        940    R=1-REFL(LL,L)/20.
 0050              R=(10.**R)/10.
 0051              RE=(1+R)/(1-R)
 0052              ANG=-ANGL(LL,L)*2.*3.1416/180.
 0053              ANG=ANG/2.
 0054              TEMPE(LL,L)=(TEMPE(LL,L)-32.)*5./9.
 0055        640    X1=TAN(ANG)
 0056              X2=RE*X1
 0057              XA=CMPLX(RE,-X1)
 0058              YA=CMPLX(1.,-X2)
 0059               Z1=XA/YA
 0060              Z=Z1*Z1
 0061              XE=(LEMC/LEMG)**2.
 0062              YE=(1/XE)
 0063              Z=Z/(1.+YE)
 0064              ZZ=1/(1.+XE)
                C
                C         EPSR      DIELECTRIC CONSTANT
                C         EPSI      LOSS-FACTOR
                C
 0065              EPSR(LL,L)=ZZ+REAL(Z)
 0066              EPSI(LL,L)=-AIMAG(Z)
 0067              R1=R*R
 0068              AA(1,1)=(1.-R1)*COS(ANG)
 0069              AA(2,2)=AA(1,1)
 0070              AA(1,2)=(1.+R1)*SIN(ANG)
 0071              AA(2,1)=AA(1,2)
 0072              BB(1,1)=EPSR(LL,L)-YE/(1+YE)
 0073              BB(2,2)=BB(1,1)
 0074              BB(1,2)=EPSI(LL,L)
 0075              BB(2,1)=BB(1,2)
 0076              CC(1,1)=1.
 0077              CC(1,2)=0.
 0078              CC(2,1)=0.
 0079              CC(2,2)=R
 0080              DB=4.0*R1*SIN(ANG)*SIN(ANG)+(1.-R1)**2.
 0081               DE=4./DB
                C
 0082              DO 145 I=1,2
 0083              DO 145 J=1,2
 0084              SUM=0.0
 0085              DO 146 K=1,2
 0086        146   SUM=SUM+AA(I,K)*BB(K,J)
 0087        145   DD(I,J)=SUM
 0088         21   FORMAT('0',10X,F8.3,7X,F8.3,9X,F8.3,8X,F8.3,7X,F8.3,7X,F8.3,
```

```
                      17X,F8.3)
CC89                  DO 148 I=1,2
0090                  DO 148 J=1,2
0091                  SUM=0.0
0092                  DO 149 K=1,2
0093            149   SUM=SUM+DD(I,K)*CC(K,J)
0094            148   EE(I,J)=SUM*CE
0095                  K=KKK(LL)
0096                   IF(K.EQ.1)GO TO 98
                C        DER        MAXIMUM ERROR IN REFLECTION COEFFICIENT
                C        DET        MAXIMUM ERROR IN PHASE SHIFT
                C
0097                  DER=0.005+0.002/(1.01-R1)
0098                  DET=0.025
0099                  GO TO 97
0100            98    DER=0.03*R*(1+R)
0101                   DET=ARSIN(DER/R)
                C
                C        DEPSR      UNCERTAINTY IN DIELECTRIC CONSTANT
                C        DEPSI       UNCERTAINTY IN LOSS-FACTOR
                C
0102            97     DEPSR(LL,L)=EE(1,1)*DER+EE(1,2)*DET
0103                   DEPSI(LL,L)=EE(2,1)*DER+EE(2,2)*DET
0104                  PRINT21,TEMPE(LL,L),R,ANG,EPSR(LL,L),EPSI(LL,L),
                     1DEPSR(LL,L),DEPSI(LL,L)
0105            99    CONTINUE
                C
0106                  DO 160 I=1,N
0107                  Y(I)=EPSR(LL,I)
0108            160    X(I)=TEMPE(LL,I)
0109                  CALL CURV(X,Y,10,3,40,N,A,B,C,D)
0110            210    PRINT170,D(1),D(2),D(3)
0111            170    FORMAT('0',10X,'EPSR = ',E14.6,'+',E14.6,'T  +',F14.6,'T*T'//)
                C
                C
                C        DTR        LEAST SQUARE CURVE COEFFICIENTS FOR EPSR VS
                C                    TEMPERATURE IN CENTIGRADE
                C
0112                  DO 460 I=1,3
0113            460   DTR(LL,I)=D(I)
0114                  DO 230 I=1,N
0115                  Y(I)=EPSI(LL,I)
0116            230   X(I)=TEMPE(LL,I)
0117                  CALL CURV(X,Y,10,3,40,N,A,B,C,D)
0118            260   PRINT270,D(1),D(2),D(3)
0119            270    FORMAT('0',10X,'EPSI = ',E14.6,'+',E14.6,'T  +',F14.6,'T*T'//)
                C
                C        DTI        COEFFICIENTS FOR EPSI VS TEMPERATURE
                C
0120                  DO 780 I=1,3
0121            780   DTI(LL,I)=D(I)
0122            130   CONTINUE
                C
                C
0123                   CALL PLOTS(IB,7000)
0124                   CALL FACTOR(1.0)
0125                  CALL PLOT(3.0,1.5,-3)
0126                  CALL AXIS(0.,0.,'TEMPERATURE IN DEGREE  C',-24,10.,0.,TMIN,TINC)
```

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```
0127              CALL AXIS(0.,7.,'    ',3,10.,0.,TMIN,TINC)
0128              CALL AXIS(0.,C.,'DIELECTRIC CONSTANT',19,7.,90.,ERMIN,ERINC)
0129              CALL AXIS(10.,C.,'    ',-3,7.,90.,ERMIN,ERINC)
0130              CALL SYMBOL(1.,6.,.14,12HFREQUENCY = ,0.,12)
0131               CALL NUMBER(999.,999.,.14,F,0.,2)
0132              CALL SYMBOL(999.,999.,.14,3H GH,0.,3)
0133              CALL SYMBOL(999.,5.9,.14,1HZ,0.,1)
                C
0134              DO 8 LL=1,M
0135               N=NN(LL)+1
0136               EPSR(LL,N)=ERMIN
0137               TEMPE(LL,N)=TMIN
0138               N=NN(LL)+2
0139               EPSR(LL,N)=ERINC
0140              TEMPE(LL,N)=TINC
0141               N=NN(LL)
0142              DO 9 I=1,100
0143               T(I)=I-21
0144          9   E(I)=DTR(LL,1)+DTR(LL,2)*T(I)+DTR(LL,3)*T(I)*T(I)
                C
0145              T(101)=TMIN
0146               T(102)=TINC
0147              E(101)=ERMIN
0148               E(102)=ERINC
0149               CALL LINE(T,E,100,1,0,0)
                C
0150               MN=LL*10+5
0151               TE=(T(MN)-TMIN)/TINC
0152              EP=(E(MN)-ERMIN)/ERINC
0153              CALL SYMBOL(TE,EP,.14,5HMC = ,0.,5)
0154               CALL NUMBER(999.,999.,.14,MC(LL),0.,2)
0155               N=NN(LL)+2
                C
0156               DO 14 I=1,N
0157               T(I)=TEMPE(LL,I)
0158          14  E(I)=EPSR(LL,I)
0159              N=NN(LL)
0160              MM=LL-1
0161               CALL LINE(T,E,N,1,-1,MM)
                C
0162               DO 10 I=5,N,5
0163               TE=(TEMPE(LL,I)-TMIN)/TINC
0164               EP=(EPSR(LL,I)-ERMIN)/ERINC
0165               DEP=DEPSR(LL,I)/(2*ERINC)
0166              CALL PLOT(TE,EP,-3)
0167              CALL SYMBOL(0.,DEP,.07,6,0.,-2)
0168               CALL SYMBOL(0.,-DEP,.07,6,180.,-2)
0169          10  CALL PLOT(-TE,-EP,-3)
0170          8   CONTINUE
                C
                C
0171               CALL PLOT(15.,0.,-3)
0172              CALL AXIS(0.,0.,'TEMPERATURE IN DEGREE  C',-24,10.,0.,TMIN,TINC)
0173              CALL AXIS(0.,7.,'    ',3,10.,0.,TMIN,TINC)
0174               CALL AXIS(0.,0.,'LOSS FACTOR',11,7.,90.,EIMIN,EIINC)
0175              CALL AXIS(10.,C.,'    ',-3,7.,90.,EIMIN,EIINC)
0176              CALL SYMBOL(1.,6.,.14,12HFREQUENCY = ,0.,12)
0177               CALL NUMBER(999.,999.,.14,F,0.,2)
```

```
0178                CALL SYMBOL(999.,999.,.14,3H GH,0.,3)
0179                CALL SYMBOL(999.,5.9,.14,1HZ,0.,1)
                C
0180                DO 11 LL=1,M
0181                N=NN(LL)+1
0182                 EPSI(LL,N)=EIMIN
0183                N=NN(LL)+2
0184                 EPSI(LL,N)=EIINC
0185                 DO 12 I=1,100
0186                 T(I)=I-21
0187          12    E(I)=DTI(LL,1)+DTI(LL,2)*T(I)+DTI(LL,3)*T(I)*T(I)
0188                MM=1
0189                EMAX=E(1)
0190                DO 55 I=2,100
0191                 IF(EMAX.GE.E(I))GO TO 55
0192                EMAX=E(I)
0193                 MM=I
0194          55    CONTINUE
0195                 PRINT56,T(MM)
0196          56    FORMAT('0','TEMPERATURE OF MAXIMUM LOSS = ',F8.3)
                C
0197                E(101)=EIMIN
0198                E(102)=EIINC
0199                CALL LINE(T,E,100,1,0,0)
0200                 MN=LL*10+5
0201                 TE=(T(MN)-TMIN)/TINC
0202                 EP=(E(MN)-EIMIN)/EIINC
0203                CALL SYMBOL(TE,EP,.14,5HMC = ,0.,5)
0204                 CALL NUMBER(999.,999.,.14,MC(LL),0.,2)
                C
0205                 DO 15 I=1,N
0206                 T(I)=TEMPE(LL,I)
0207          15     E(I)=EPSI(LL,I)
0208                 N=NN(LL)
0209                MM=LL-1
0210                 CALL LINE(T,E,N,1,-1,MM)
0211                 DO 13 I=5,N,5
0212                TE=(TEMPE(LL,I)-TMIN)/TINC
0213                 EP=(EPSI(LL,I)-EIMIN)/EIINC
0214                DEP=DEPSI(LL,I)/(2*EIINC)
0215                CALL PLOT(TE,EP,-3)
0216                CALL SYMBOL(0.,DEP,.07,6,0.,-2)
0217                 CALL SYMBOL(0.,-DEP,.07,6,180.,-2)
0218           13    CALL PLOT(-TE,-EP,-3)
0219          11    CONTINUE
              C
              C
0220                 CALL PLOT(15.,0.,-3)
0221                CALL AXIS(0.,0.,'MOISTURE CONTENTS IN PERCENT',-28,10.,0.,0.,2.5)
0222                CALL AXIS(0.,7.,'    ',3,10.,0.,0.,2.5)
0223                 CALL AXIS(0.,0.,'DIELECTRIC CONSTANT',19,7.,90.,ERMIN,ERINC)
0224                CALL AXIS(10.,0.,'    ',-3,7.,90.,ERMIN,ERINC)
0225                CALL SYMBOL(1.,6.,.14,12HFREQUENCY = ,0.,12)
0226                 CALL NUMBER(999.,999.,.14,F,0.,2)
0227                CALL SYMBOL(999.,999.,.14,3H GH,0.,3)
0228                CALL SYMBOL(999.,5.9,.14,1HZ,0.,1)
                C
0229                TT=-20.0
```

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FORTRAN IV G LEVEL  20.1              MAIN              DATE = 73078      21/20/39

0230                  DO 1001 I=1,6
0231                  DO 150 LL=1,M
0232                  Y(LL)=DTR(LL,1)+DTR(LL,2)*TT+DTR(LL,3)*TT*TT
0233            150   X(LL)=MC(LL)
0234                   CALL CURV(X,Y,10,3,40,M,A,B,C,D)
0235                   PRINT450,TT,D(1),D(2),D(3)
0236            450    FORMAT('0',4F10.3)
                C
0237                  DO 1000 J=1,100
0238                   XX(J)=J/4.
0239            1000  YY(J)=D(1)+D(2)*XX(J)+D(3)*XX(J)*XX(J)
0240                  XX(101)=0.
0241                   XX(102)=2.5
0242                  YY(101)=ERMIN
0243                   YY(102)=ERINC
0244                  CALL LINE(XX,YY,100,1,0,0)
0245                  MN=LL*10+5
0246                   TE=XX(MN)/2.5
0247                   EP=(YY(MN)-ERMIN)/ERINC
0248                   CALL SYMBOL(TE,EP,.14,7HTEMP = ,0.,7)
0249                  CALL NUMBER(999.,999.,.14,TT,0.,1)
0250            1001  TT=TT+20.
                C
0251                  CALL PLOT(15.,0.,-3)
0252                   CALL AXIS(0.,0.,'MOISTURE CONTENTS IN PERCENT',-28,10.,0.,0.,2.5)
0253                   CALL AXIS(0.,7.,'    ',3,10.,0.,0.,2.5)
0254                  CALL AXIS(0.,0.,'LOSS FACTOR',11,7.,90.,EIMIN,EIINC)
0255                  CALL AXIS(10.,0.,'    ',-3,7.,90.,EIMIN,EIINC)
0256                  CALL SYMBOL(1.,6.,.14,12HFREQUENCY = ,0.,12)
0257                   CALL NUMBER(999.,999.,.14,F,0.,2)
0258                  CALL SYMBOL(999.,999.,.14,3H GH,0.,3)
0259                  CALL SYMBOL(999.,5.9,.14,1HZ,0.,1)
            C
0260                  TT=-20.0
0261                   DO 1002 I=1,6
0262                  DO 151 LL=1,M
0263                  Y(LL)=DTI(LL,1)+DTI(LL,2)*TT+DTI(LL,3)*TT*TT
0264            151   X(LL)=MC(LL)
0265                   CALL CURV(X,Y,10,3,40,M,A,B,C,D)
0266                   PRINT450,TT,D(1),D(2),D(3)
            C
0267                  DO 1003 J=1,100
0268                  XX(J)=J/4.
0269            1003  YY(J)=D(1)+D(2)*XX(J)+D(3)*XX(J)*XX(J)
0270                   XX(101)=0.
0271                   XX(102)=2.5
0272                  YY(101)=EIMIN
0273                   YY(102)=EIINC
0274                  CALL LINE(XX,YY,100,1,0,0)
0275                  TE=XX(40)/2.5
0276                  EP=0.5*I
0277                  CALL SYMBOL(TE,EP,.14,7HTEMP = ,0.,7)
0278                  CALL NUMBER(999.,999.,.14,TT,0.,1)
0279            1002    TT=TT+20.0
            C
0280                   CALL PLOT(15.,0.,999)
0281                  STOP
0282                  END
```

FORTRAN IV G LEVEL 20.1 CURV DATE = 73078 21/20/39

```
0001            SUBROUTINE CURV(X,Y,MM,M,NN,N,A,B,C,D)
0002            DIMENSION X(NN),Y(NN),D(MM),A(MM,MM),B(MM),C(NN,MM)
0003            DO 6 I=1,N
0004          6 C(I,1)=1.0
0005            DO 7 J=2,M
0006            DO 7 I=1,N
0007          7 C(I,J)=C(I,J-1)*X(I)
0008            DO 8 I=1,M
0009            DO 8 J=1,M
0010            A(I,J)=0.0
0011            DO 8 K=1,N
0012          8 A(I,J)=A(I,J)+C(K,I)*C(K,J)
0013             DO 10 I=1,M
0014            B(I)=0.0
0015            DO 10 K=1,N
0016         10 B(I)=B(I)+C(K,I)*Y(K)
0017            CALL MINV(A,M,MM)
0018            DO 11 I=1,M
0019            SUM=0.0
0020            DO 12 J=1,M
0021         12 SUM=SUM+A(I,J)*B(J)
0022         11 D(I)=SUM
0023            RETURN
0024            END
```

FORTRAN IV G LEVEL 20.1 MINV DATE = 73078 21/20/39

```
0001            SUBROUTINE MINV(A,N,M)
0002            DIMENSION A(M,M),IPVOT(30),INDEX(30,2),PIVOT(30)
0003            DO 17 J=1,N
0004         17 IPVOT(J)=0
0005            DO 135 I=1,N
0006            T=0.
0007            DO 9 J=1,N
0008            IF(IPVOT(J)-1)13,9,13
0009         13 DO 23 K=1,N
0010            IF(IPVOT(K)-1)43,23,81
0011         43 IF(ABS(T)-ABS(A(J,K)))83,23,23
0012         83 IROW=J
0013            ICOL=K
0014            T=A(J,K)
0015         23  CONTINUE
0016         9  CONTINUE
0017            IPVOT(ICOL)=IPVOT(ICOL)+1
0018            IF(IROW-ICOL)73,109,73
0019         73 DO 12 L=1,N
0020            T=A(IROW,L)
0021            A(IROW,L)=A(ICOL,L)
0022         12 A(ICOL,L)=T
0023         109  INDEX(I,1)=IROW
0024            INDEX(I,2)=ICOL
0025            PIVOT(I)=A(ICOL,ICOL)
0026            A(ICOL,ICOL)=1.
0027            DO 205 L=1,N
0028         205 A(ICOL,L)=A(ICOL,L)/PIVOT(I)
0029         347 DO 135 LI=1,N
0030            IF(LI-ICOL)21,135,21
0031         21 T=A(LI,ICOL)
0032            A(LI,ICOL)=0.
0033            DO 89 L=1,N
0034         89 A(LI,L)=A(LI,L)-A(ICOL,L)*T
0035         135 CONTINUE
0036         222  DO 401 I=1,N
0037            L=N-I+1
0038            IF(INDEX(L,1)-INDEX(L,2))19,401,19
0039         19 JROW=INDEX(L,1)
0040            JCOL=INDEX(L,2)
0041            DO 549 K=1,N
0042            T=A(K,JROW)
0043            A(K,JROW)=A(K,JCOL)
0044            A(K,JCOL)=T
0045          549 CONTINUE
0046         401 CONTINUE
0047         81 RETURN
0048            END
```