DIELECTRIC PARAMETERS OF GROUND BEEF AND
THEIR CORRELATION WITH PERTINENT VARIABLES

by

Don Van Dyke

D.V.M., Texas A. and M. University
(1964)

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Master of Science

at the

Massachusetts Institute of Technology

January, 1968

Signature of Author. . . . . . . . . . . . . . . . . . . . . . . . .
Department of Nutrition and Food Science, 15 January 1968

Certified by . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
Thesis Supervisor

Accepted by. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
Chairman, Departmental Committee
on Graduate Students

NOTICE: THIS MATERIAL MAY BE
PROTECTED BY COPYRIGHT LAW
(TITLE 17 U.S. CODE)
ABSTRACT

Dielectric Parameters of Ground Beef and Their Correlation with Pertinent Variables

by

Don Van Dyke

Submitted to the Department of Nutrition and Food Science on 15 January 1968 in partial fulfillment of the requirements for the degree of Master of Science.

A computer program for performing calculation is discussed. Sample holders used are described. Sample preparation is discussed.

Dielectric properties were determined for ground beef samples having varying chemical composition. Dielectric measurements were made at 300, 915, 1000, and 3000 megahertz (MHz) at 0-10°C, 25°C, and 80°C using the slotted coaxial line technique of von Hippel et al. Measurements were also made of the proximate analysis of each sample. The dielectric properties were reported as a function of temperature, frequency, and chemical composition of the sample.

It was found that the dielectric loss factor and dielectric constant increased with an increase in temperature, water, or ash. However, with an increase in protein, fat, or frequency, the results showed a decrease in the dielectric loss factor and the dielectric constant.

The chemical components of beef which have a dominant effect on the dielectric parameters are the water and ash contents. The effect of protein or fat, when compared with water and ash, on the dielectric parameters of beef was far less pronounced. Correlations among the chemical and physical variables and the dielectric behavior were obtained. These correlations enable one to predict the dielectric properties of beef of different composition or under various conditions within the range of variables studied.

Thesis Supervisor: Samuel A. Goldblith

Title: Professor of Food Science and Deputy Department Head
Apt. 56
215 Massachusetts Avenue
Arlington, Massachusetts
02174

15 January 1968

Mr. Edward Neal Hartley
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Dear Sir:

A thesis entitled, "Dielectric Parameters of Ground Beef and Their Correlation with Pertinent Variables" is hereby submitted in partial fulfillment of the requirements for the degree of Master of Science in Food Science and Technology.

Respectfully submitted,

Don Van Dyke
ACKNOWLEDGEMENTS

The author wishes to acknowledge his sincere thanks to all those who assisted and encouraged him during the course of this work. Special thanks are due his wife, Frances, for her devotion, enthusiasm, patience, and understanding; to Professor Samuel A. Goldblith for his continuous interest, helpful advice, and friendly guidance in all phases of the work; to Mr. William B. Westphal of the Laboratory for Insulation Research (M. I. T.) for instruction, advice, assistance, and direction in collecting the dielectric data; to Professor Daniel I.C. Wang for guidance in presentation of data; and to Miss Janet Anderson for her competence in typing the manuscript.

He wishes to thank Armour and Company for their grant to the Massachusetts Institute of Technology which made possible the particular work reported in this thesis.

Finally, he wishes to acknowledge his appreciation to the United States Air Force for affording him the opportunity of furthering his education and to those individuals who were instrumental in his being selected for graduate study.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Title Page</td>
<td>1</td>
</tr>
<tr>
<td>Abstract</td>
<td>2</td>
</tr>
<tr>
<td>Letter of Transmittal</td>
<td>3</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>4</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>5</td>
</tr>
<tr>
<td>List of Figures</td>
<td>8</td>
</tr>
<tr>
<td>List of Tables</td>
<td>10</td>
</tr>
<tr>
<td>I. Introduction</td>
<td>11</td>
</tr>
<tr>
<td>Energy Needed to Heat a Food</td>
<td>12</td>
</tr>
<tr>
<td>The Half Power Depth</td>
<td>13</td>
</tr>
<tr>
<td>Statement of the Problem</td>
<td>14</td>
</tr>
<tr>
<td>II. Charged Particles and Their Relationship to the Dielectric Constant, the Dielectric Loss Factor, and the Loss Tangent</td>
<td>16</td>
</tr>
<tr>
<td>Coulomb's Law</td>
<td>17</td>
</tr>
<tr>
<td>Electric Field Intensity</td>
<td>17</td>
</tr>
<tr>
<td>The Electric Potential</td>
<td>18</td>
</tr>
<tr>
<td>Capacitance and Dielectrics</td>
<td>19</td>
</tr>
<tr>
<td>The Dipole Moment</td>
<td>23</td>
</tr>
<tr>
<td>Polarization</td>
<td>25</td>
</tr>
<tr>
<td>&quot;Loss Tangent&quot; and &quot;Loss Factor&quot;</td>
<td>31</td>
</tr>
<tr>
<td>III. Electronic Heat in the Food Industry</td>
<td>35</td>
</tr>
<tr>
<td>Microwaves Region of the Electromagnetic Spectrum</td>
<td>36</td>
</tr>
<tr>
<td>Early Investigations Conducted in Regard to Dielectric Properties of Foods and Food Constituents</td>
<td>36</td>
</tr>
<tr>
<td>Development of Magnetrons for Heating Foods</td>
<td>38</td>
</tr>
<tr>
<td>Solid State Device for Generation of Microwaves</td>
<td>38</td>
</tr>
<tr>
<td>Industrial Applications of Dielectric Heating</td>
<td>40</td>
</tr>
<tr>
<td>Freeze Drying</td>
<td>40</td>
</tr>
<tr>
<td>Dielectric Defrosting</td>
<td>40</td>
</tr>
<tr>
<td>Microwave Cooking</td>
<td>42</td>
</tr>
<tr>
<td>Microwaves in the Catering Industry</td>
<td>44</td>
</tr>
<tr>
<td>Microwave Processing of Potato Chips</td>
<td>46</td>
</tr>
<tr>
<td>The &quot;Per Se&quot; Effects of Microwaves</td>
<td>47</td>
</tr>
</tbody>
</table>
V. Experimental Methods

The Precision Slotted Line Technique for Determining Dielectric Data 51
Equipment Needed in Order to Use the Precision Slotted Line Technique 55
Sample Holders and Sample Preparation 57
Temperature Control 62
Calculating $\varepsilon''$, $\varepsilon$', and Tan $\delta$ Experimental Data 63
Computer Program 70
Sample Preparation 75
Chemical Methods 76

V. Results and Discussion

Examination of Calculated Values of $\varepsilon''$ as a Function of Ash, Selected Water Content, and Temperature 93

Examination of the Calculated Values of $\varepsilon''$ as a Function of Ash at Different Temperatures and Protein Concentration 106

Examination of the Calculated Values of $\varepsilon''$ as a Function of Ash at Different Ether Soluble (Fat) Values and Different Temperatures 111

Comparison of the $\varepsilon''$ Values of Ground Beef and Aqueous Sodium Chloride Solutions 116

The Relative Dielectric Constant ($\varepsilon'$) 118

The Loss Tangent or Dissipation Factor (Tan $\delta$) 125

I. Conclusions

The Relative Dielectric Loss Factor ($\varepsilon''$) 131
The Relative Dielectric Constant ($\varepsilon'$) 132
The Loss Tangent or Dissipation Factor (Tan $\delta$) 133

The Effect of Chemical Composition upon the Power which can be Generated within the Sample and upon the Half Power Depth (Penetration) of the Sample 133

I. Recommendations for Future Work

Sample Preparation 137
Measurements at Different Temperatures 138
| Calculation of $\varepsilon''$, $\varepsilon'$, and Tan $\delta$ | 139 |
| Sample Thickness | 139 |
| Calibration of Dielectrometers | 140 |
| Computerized Evaluation of Chemical and Physical Variables | 141 |

VIII. Appendix

| Coaxial Line Method for Double Layer Dielectrics, Manual Calculation | 144 |
| Coaxial Line Method for Double Layer Dielectrics, Computer Solution | 147 |
| $X_{0E}$ Values Calculation | 149 |

IX. Bibliography
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>The Electric Dipole Moment</td>
<td>24</td>
</tr>
<tr>
<td>2.</td>
<td>Polarization of Molecules</td>
<td>26</td>
</tr>
<tr>
<td>3.</td>
<td>Electronic Dipole Moment Symbolized by the Vector Quantity $</td>
<td>μ</td>
</tr>
<tr>
<td>4.</td>
<td>Polarization of a Capacitor</td>
<td>30</td>
</tr>
<tr>
<td>5.</td>
<td>Current-Voltage Relation in an Ideal Capacitor</td>
<td>34</td>
</tr>
<tr>
<td>6.</td>
<td>Section of Coaxial Line Containing a Dielectric Sample TEM Mode as a Traveling and as a Standing Wave</td>
<td>52</td>
</tr>
<tr>
<td>7.</td>
<td>Change in Wave Length and Node Width of the Standing Wave as a Result of Inserting a Dielectric Sample (with Loss) into the Line</td>
<td>54</td>
</tr>
<tr>
<td>8.</td>
<td>Block Diagram of a Complete Standing Wave Measurement System</td>
<td>56</td>
</tr>
<tr>
<td>9.</td>
<td>Construction Detail of Sample Holder Used for Dielectric Measurements at 1000 MHz, with Water Tight Sleeve Attached</td>
<td>59</td>
</tr>
<tr>
<td>10.</td>
<td>Construction Detail of Sample Holder Used for Dielectric Measurements at 1000 MHz, before Tightening Clamping Rings, and without Outer Sleeve</td>
<td>60</td>
</tr>
<tr>
<td>11.</td>
<td>Photograph of Sample Holder Used for Dielectric Measurements of Ground Beef at 1000 MHz</td>
<td>61</td>
</tr>
<tr>
<td>12.</td>
<td>Graphs for Direct Determination of the Relative Dielectric Constant and the Relative Dielectric Loss Factor</td>
<td>72-75</td>
</tr>
<tr>
<td>13.</td>
<td>Computer Program</td>
<td>78</td>
</tr>
<tr>
<td>14.</td>
<td>Graphs of the Dielectric Loss Factor ($\epsilon''$) of Ground Beef as a Function of Water Content at Different Temperatures</td>
<td>87-90</td>
</tr>
</tbody>
</table>
15. Three-Dimensional Plot Showing Relationship of Bloom Content, Water Content, and $\epsilon_r$" 92

16. Graphs of the Calculated Dielectric Loss Factor ($\epsilon''_\infty$) of Ground Beef as a Function of Ash Content at Different Water Concentrations 94-105

17. Graphs of the Calculated Dielectric Loss Factor ($\epsilon''_\infty$) of Ground Beef as a Function of Ash Content, at Different Protein Concentrations, and at Different Temperatures 107-110

18. Graphs of the Calculated Dielectric Loss Factor ($\epsilon''_\infty$) of Ground Beef as a Function of Ash Content, at Different Ether Soluble (Fat) Concentrations and Different Temperatures 112-115

19. Graphs of the Calculated Dielectric Constant ($\epsilon'_\infty$) of Ground Beef as a Function of Ash Content at Different Temperatures and Different Water Concentrations 119-122

20. Graph of the Dielectric Loss Factor ($\epsilon''_\infty$) of Ground Beef as a Function of Ash Content at Different Water and Ash Concentrations Plotted with No Interpolation of Data 123

21. Graphs of the Calculated Tan $\delta$ of Ground Beef as a Function of Ash Content at Different Temperatures and Different Ash Concentrations 126-128
# LIST OF TABLES

<table>
<thead>
<tr>
<th>#</th>
<th>Table Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Frequencies Allocated by the FCC for Industrial-Scientific-Medical (ISM) Use (Anon., 1964)</td>
<td>37</td>
</tr>
<tr>
<td>2.</td>
<td>Dielectric and Chemical Data for Ground Beef</td>
<td>81</td>
</tr>
<tr>
<td>3.</td>
<td>Data on Aqueous Solutions of Sodium Chloride</td>
<td>117</td>
</tr>
<tr>
<td>4.</td>
<td>Factors Relating to the Energy Needed to Heat a Food Sample, and to the Penetration of Microwaves into the Food Sample</td>
<td>135</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION
In dielectric heating, the energy needed to heat a
given food substance to a desired effect may be expressed
as in Equation 1.1:

\[ \text{Energy Needed} = \text{Power} \times \text{Time} \]  
(Eq. 1.1)

where \( E \) = the energy needed in watt-hours (1 BTU 0.293
watt-hours).

The power which can be generated in a non-conductor
placed in an electromagnetic field has been presented in
equation form by several authors, Kinn (1947), Nelson
(1952), Harvey (1960), Allaire (1965a), Goldblith (1966),
and others.

\[ P = kE^2 \epsilon'' \tan \delta \cdot f \]  
(Eq. 1.2)

where \( P \) = power in watts per cubic meter, \( k = 55.61 \times 10^{-14} \);

where \( P \) = watts per cubic inch, \( k = 1.41 \times 10^{-12} \).

\( E \) = field intensity in volts per square meter.

\( f \) = frequency in hertz .

\* \( \epsilon'' \) = relative dielectric constant of the material.

**\( \tan \delta \) = loss tangent of the material.

Examination of the above equation indicates the heat
production is directly proportional to the dielectric loss

\* \( \epsilon'' \) is the relative dielectric constant of a material. It
is the ratio of the capacity current through the material to
the capacity current which would flow if the same field were
applied to free space (Brown, Hovler, and Bierwirth, 1947).

\( \epsilon'' \) is also often designated by \( K' \) where \( K' = \epsilon'' / \epsilon_0 \), the ratio
of the dielectric constant of the material to that of free
space. Since the latter value is considered as unity, \( \epsilon'' \), \( \epsilon \),
and \( K' \) are often (though incorrectly) used interchangeably.

**\( \tan \delta \), the tangent of the loss angle, is sometimes referred
to as the dissipation factor.
factor $\varepsilon''_r$ ($\varepsilon'_r \times \tan \delta$), the frequency, and the square of the electric field intensity.

The dielectric loss factor ($\varepsilon''_r$) is then a measure of efficiency of absorption of microwave energy by a given material.

The dielectric properties of some food substances have been determined (Dunlap and Makower, 1945, Morse and Rivercomb, 1947, Ede and Haddow, 1951, von Hippel, 1954, Schwan, 1956, Bengtsson et al, 1963, and Pace, 1966). However, much of this work was done at frequencies too low to be valid at what would seem to be the most useful frequency range for microwave heating (300 Mc to 3000 Mc).

From Equation 1.2, it is obvious that the higher the frequency used, the greater power produced in the material (if $\varepsilon''_r$ is relatively constant). As frequency is increased, however, penetration into the material decreases and a point is reached where heating becomes non-uniform as a result.

The Half Power Depth. In the analysis of penetration, it is convenient to separate the effect of energy radiated from one direction only, i.e., the plane wave, from that which supplies multiple reflections from all directions toward the absorbing material. In the latter case, incomplete absorption on one passage may become complete in successive passages.

The half power depth (HPD) of a material is the thickness of the material which will reduce power to one-half
of its value at the surface.

The half power depth for a given material may be calculated by use of the following equation (Goldblith, 1966):

$$ HPD = \frac{0.693}{(\epsilon'_\infty)^{1/2}} \tan \delta \cdot 55.61 \times 10^{-14} f $$

(Eq. 1.3)

in which $HPD =$ half power depth in centimeters.
\[ \epsilon'_\infty = \text{relative dielectric constant of the material.} \]
\[ \tan \delta = \text{dielectric loss tangent of the material.} \]
\[ f = \text{frequency of energy being used.} \]

From Equation 1.3, it is apparent that a knowledge of the relative dielectric constant ($\epsilon'_\infty$) and the loss tangent ($\tan \delta$) would permit mathematical computation of the half power depth of penetration at any given frequency. A complicating factor in predicting heat generation by the use of microwave energy is that $\epsilon'_\infty$ and $\tan \delta$ (hence $\epsilon''_\infty$) are functions of both the operating frequency and the ambient temperature.

Thus the mathematical computation of two parameters of great importance to industry, i.e., power absorption and penetration, is dependent upon a knowledge of the relative dielectric constant ($\epsilon'_\infty$), the dielectric loss ($\epsilon''_\infty$), and the loss tangent ($\tan \delta$).

**Statement of the Problem.** Since foods are complex biochemical systems, any single component may exert an influence upon the dielectric parameters of the entire system. The present work was undertaken to determine the influence of the major components (protein, fat, ash, and
moisture) of a food (beef) upon the dielectric parameters at three different temperatures.
CHAPTER II
CHARGED PARTICLES AND THEIR RELATIONSHIP TO THE DIELECTRIC CONSTANT,
THE DIELECTRIC LOSS FACTOR, AND THE LOSS TANGENT
Some basic ideas that enter into the treatment of charged particles must be reviewed to provide the necessary background for developing an understanding of the behavior of microwave energy in a dielectric or non-conducting material (adapted in part from Barrow, 1966).

1. **Coulomb's Law.** In 1785 the French physicist Coulomb found that the force between two charges in air varies inversely as the square of the distance between the charges and is directly proportional to the product of the magnitude of the two charges.

   \[ F = \frac{q_1 q_2}{d} \]  
   \[ \text{Eq. 2.1} \]

   Where \( F \) = force.

   \( q \) = charged body "point charge."

   \( d \) = distance.

   If \( q_1 \) and \( q_2 \) are of the same sign, the force will be positive and will be that of repulsion. If \( q_1 \) and \( q_2 \) are opposite signs, the force will be one of attraction.

2. **Electric Field Intensity.** Any region in which electric forces may be detected is called an electric field. The intensity (or strength) \( E \) of an electric field at any point is defined as the ratio of the force \( F \) acting on a small test charge, \( q \), at that point to the charge \( q \), or the force

   \[ E = \frac{F}{q} \]  
   \[ \text{Eq. 2.2} \]

   Where \( E \) = intensity of an electric field.

   \( F \) = force acting on test charge.

   \( q \) = test charge.
which would be exerted on a positive charge placed at that point. The electric field strength is a vector quantity. Its direction is the direction of the force on a positive charge.

If one considers the electric field about a point charge \(+q\), at distance \(d\) from this charge, a unit positive charge would be repelled, regardless of the direction of the unit charge from the point charge. The electric field about a point charge \(+q\) can therefore be considered as a sphere. At a distance \(d\) from the \(+q\) charge, the unit positive charge would be repelled by a force of \(q/d^2\). Therefore at a distance \(d\) from the \(+q\) charge the electric field intensity is given by \(q/d^2\). If one were to draw all of the positions possible at a distance \(d\) from a point positive charge which a unit positive charge could be placed, the surface area of a sphere of radius \(d\) would be drawn \((4\pi d^2)\). Thus the lines of force which can emanate from a charge \(+q\) is given by:

\[
\frac{q}{d^2} \times (4\pi d^2) = 4\pi q
\]

(Eq. 2.3)

Where \(q = +\) charge.

\(d = \) radius of the sphere.

The electric field of a unit positive charge can be represented by \(4\pi\) lines of force.

3. The Electric Potential. A unit positive charge in an electric field of intensity \(E\) experiences a force equal to \(E\). For a given displacement \(\Delta d\) of the unit charge, the work involved is the product of force (field strength) and the distance through which the charge is moved. As the unit
positive test charge is brought closer to the positive charge \( q \) which generates the electric field, the potential energy increases. The change \( dV \) for an infinitesimal change \( dd \) is:

\[
dV = -E \, dr \quad \text{(Eq. 2.4)}
\]
or

\[
E = \frac{dV}{dd} \quad \text{(Eq. 2.5)}
\]

Where \( E \) = field intensity.

\( dd \) = change in distance of unit positive test charge.

\( dV \) = change in electrical potential.

4. Capacitance and Dielectrics. A device on which electric charges may be stored is called a capacitor or condenser. A typical capacitor consists of two conductors, one of which is charged positively and the other negatively. Charging is usually accomplished by transferring the charge from one conductor to the other by means of a battery or other source of potential difference. When one refers to the charge on a capacitor, one refers to the magnitude of the charge on either conductor. Since the two conductors bear equal and opposite charges, the net charge is zero.

If air (or more properly, vacuum) is between the plates of the capacitor with a potential difference of \( V \) volts, there will be a potential drop of \( V \) volts across the capacitor and, according to the equation \( E = \frac{dV}{dd} \), the field between the plates will be \( V/d \), where \( d \) is the distance between the plates.

The ratio of the charges that capacitor plates acquire when charged by a battery to the area of the capacitor plates
is the charge density ($\sigma$):

$$\sigma = \frac{q}{A} \quad \text{(Eq. 2.6)}$$

Where $\sigma =$ charge density.

$q =$ total charge concentration in capacitor.

$A =$ surface area of the metal electrodes.

The previous result that each charge has associated with it $4\pi$ lines of force can now be carried over to imply $4\pi \sigma$ lines of force per square centimeter. The field strength is therefore:

$$E = 4\pi \sigma \quad \text{(Eq. 2.7)}$$

Where $E =$ field intensity.

$\sigma =$ charge density.

$\pi = 3.1416.$

The capacitance $C$ is defined as the ratio of the charge to the potential difference:

$$C = \frac{q}{V} \quad \text{(Eq. 2.8)}$$

Where $C =$ capacitance.

$q =$ charge.

$V =$ potential difference.

The capacitance can be related to the geometry of the condenser by substituting the results $q = \sigma A$ and ignoring the direction and sign of $E$:

$$V = Ed = 4\pi \sigma d \quad \text{(Eq. 2.9)}$$

Where $V =$ potential difference.

$E =$ field intensity.

$d =$ distance.

$\sigma =$ charge density.

to give:
\[ C_0 = \frac{\sigma A}{4\pi \sigma d} = \frac{A}{4\pi d} \]  \hspace{1cm} \text{(Eq. 2.10)}

Where \( C_0 \) = capacitance in vacuum (or air).

\( \sigma \) = charge density.

\( A \) = area of plate.

\( d \) = distance between plates

\( \pi \) = 3.1416.

If one now places a dielectric or non-conducting material between the two plates, the relations which have been obtained are altered.

Starting again with Coulomb's law and immersing the charges \( q_1 \) and \( q_2 \) in a dielectric material, it is found that the force between them is less at any given distance (\( d \)) than when such a dielectric medium is absent. Coulomb's law can be written to apply to both vacuum and dielectric media by writing it in the form:

\[ F = \frac{q_1 q_2}{\epsilon'_v d^2} \]  \hspace{1cm} \text{(Eq. 2.11)}

Where \( F \) = force.

\( q \) = charged body.

\( d \) = distance.

\( \epsilon'_v \) = dielectric constant.

where \( \epsilon'_v \) is a constant, at a given temperature, for any medium. It is known as "the relative dielectric constant," and represents the effect of the dielectric material in decreasing the force between the charges.

In order to compare the dielectric material with a vacuum (or air), consider the charge +q when it is immersed in a
dielectric material. The force on the unit positive charge (or electric field) at distance \( d \) would be \( \frac{q}{\varepsilon' \cdot d^2} \), and the total lines of force emanating for such a surrounded charge would be:

\[
\frac{q}{\varepsilon' \cdot d^2} \cdot (4\pi \cdot d^2) = \frac{4\pi \cdot q}{\varepsilon'} \quad \text{(Eq. 2.12)}
\]

The electric field is therefore lowered by the presence of the non-conducting materials by a factor equal to the relative dielectric constant \( \varepsilon' \).

Suppose the capacitor is charged until the same charge \( q \) as for vacuum accumulates on the plates. The charge per square centimeter is again \( \sigma = \frac{q}{A} \), but the lines of force per square centimeter, and therefore the electric field \( E \), are reduced to \( \frac{4\pi \sigma}{\varepsilon'} \). Again, ignoring the direction and sign of \( E \), \( E = \frac{V}{d} \). This implies that the applied voltage is:

\[
V = \frac{4\pi \sigma \cdot d}{\varepsilon'} \quad \text{(Eq. 2.13)}
\]

where \( V \) = applied voltage.

\( \sigma = \) charge density.

\( d = \) distance.

\( \varepsilon' = \) relative dielectric constant.

\( \pi = 3.1416 \).

and the capacitance \( C \) is:

\[
C = \frac{q}{V} = \frac{\sigma A}{4\pi \cdot \frac{d}{\varepsilon'}} = \varepsilon' \cdot \frac{A}{4\pi \cdot d} \quad \text{(Eq. 2.14)}
\]

by comparison with Eq. 2.10, where \( C_0 = \frac{A}{4\pi \cdot d} \), we see that the measured capacitances with and without dielectric material give \( \varepsilon' \) from the formula:
\[
\frac{C}{C_0} = \epsilon_r' \quad \text{(Eq. 2.15)}
\]

Where \( C \) = capacitance with dielectric material.
\( C_0 \) = capacitance in a vacuum.
\( \epsilon_r' \) = relative dielectric constant.

The dielectric material has therefore increased the capacitance of the condenser.

5. **The Dipole Moment.** Since molecules are made up of charged units, electrons, and the atomic nuclei, much of the behavior of molecules is understandable in terms of electrical interactions.

The principal characteristic of the charge distribution in a molecule that can be measured is the extent to which the center of the electron distribution of a molecule fails to coincide with the center of the positive-nuclear-charge distribution. This charge asymmetry is obtained as the dipole moment of the molecule.

The dipole moment of two equal and opposite charges is defined as the product of the charges of the distance separating them. The dipole moment has, furthermore, a direction as well as a magnitude, i.e., it is a vector quantity. It is frequently convenient to represent a dipole moment diagrammatically by an arrow showing the direction from the positive to the negative charge, and the magnitude by the length of the arrow.

In Figure 2.1, the effect of an assembly of charges at some distant point is investigated, and with this approach the dipole moment due to a collection of charges is defined
\( \sigma = \) charge.
\( d = \) distance.
\( \mu = \) electric dipole moment.

\( \mu = \sum q_i d_i \).
\( \mu = -(+q)d_1 - (-q)d_2 \).
\( \mu = +q(d_2-d_1) \).
\( \mu = +\sigma d \).

Figure 2-1. The Dipole Moment (Rarrow, 1966).
as \( \mu = \sum_i q_i d_i \), where \( q_i \) and \( d_i \) are the charges and vector lengths to the \( i \)th charges of the assembly.

In addition to a dipole moment that a molecule can have as a result of its asymmetric charge distribution, there is, for all molecules, the possibility of distorting the electronic distribution in a molecule by applying an electric field. In this way an induced dipole moment can be produced. The effectiveness of an applied field in making a molecule polar is determined by polarizability of the molecules. All molecules, symmetric or not, are polarizable and can have an induced dipole moment. On the other hand, there will be many symmetric molecules, like \( \text{H}_2 \), \( \text{CO}_2 \), and \( \text{CCl}_4 \), that necessarily have a zero "permanent" dipole moment.

6. Polarization. The concept of polarization is well developed by von Hippel (1954) who states that a dielectric material increases the storage capacity of a capacitor by neutralizing charges at the electrode surfaces which otherwise would contribute to the external field. This phenomenon is dielectric polarization. We may visualize it as the action of dipole chains which form under the influence of the applied field and bind countercharges with their free ends on the metal surfaces (Figure 2.2).

By writing Equation 2.8 as:

\[ V = \frac{q}{C} \]

Where \( q \) = charge.

\( C \) = capacitance of the dielectric material.

\( V \) = voltage.
Figure 2-2. Polarization of Molecules (from von Hippel, 1954).

- Dipole
- Free charge
- Bound charge
and Equation 2.14 as:

\[ C = \varepsilon'_0 (\text{Co}) \]

one obtains the following equation for voltage:

\[ V = \frac{q}{\varepsilon'_0} \cdot \frac{1}{C_0} \quad \text{(Eq. 2.16)} \]

One may interpret this equation as stating that only a fraction of the total charge \( q \), the free charge \( \frac{q}{\varepsilon'_0} \), contributes to the voltage whereas the remainder, the bound charge \( q \left(1 - \frac{1}{\varepsilon'_0}\right) \), is neutralized by the polarization of the dielectric.

Equation 2.6 may be further developed to obtain a clearer concept of the charge distribution and its effect in space. Charge densities \( \sigma \) are represented by field vectors. The total (or true) charge \( q \) concentrated in the capacitor is distributed over the surface area \( A \) of the metal electrodes with a density \( \sigma \) as:

\[ q = \int_A \sigma \, dA \quad \text{(Eq. 2.17)} \]

Where \( q = \) total charge.

\( A = \) surface area of electrodes.

\( \sigma = \) charge density.

One may represent this true charge density \( \sigma \) by a vector \( D \), the electric flux density (or dielectric displacement), such that the surface charge density shall be equal to the normal component of \( D^* \), or:

\[ \sigma \, dA \equiv D \cos \alpha \, dA = D \cdot n \, dA = D_n \, dA \quad \text{(Eq. 2.18)} \]

*By postulating that the surface charge densities are equal to the normal components of the field vectors instead of four times their magnitude, the author (von Hippel) has optioned for a rationalized system of units.
Similarly, one may develop equations for the bound charge component of the total charge density. One can allocate to the bound charge density a vector \( P \), called the polarization, as:

\[
\sigma \left(1 - \frac{1}{\varepsilon_n}\right) dA \equiv P \cdot n dA = P n dA \quad \text{(Eq. 2.19)}
\]

Where \( \sigma \) = charge density.

\( A \) = surface area of electrodes.

\( P \) = polarization.

Note that the polarization \( P \) refers to a vector quantity allocated to the bound charge density of the capacitor.

In Equation 2.16 one finds:

\[
\mu = +qd
\]

Where \( \mu \) = electric dipole moment.

\( q \) = charge.

\( d \) = distance.

Thus electric dipole moment can be symbolized by a vector of magnitude \( |\mu| \) pointing from the negative to the positive pole (Figure 2-3). This vector quantity is obtained in the dielectric material between the plates of the capacitor. The polarization vector \( P \) corresponds in magnitude to the surface charge density bound at the electrodes by the polarized dielectric, and it points in the direction of the applied field. The polarization \( P \) is therefore identical with the electric dipole moment per unit volume of the dielectric material (Figure 2-4).

The point of maximum polarization in a system would occur
Figure 2-3. Electric Dipole Moment Symbolized by the Vector Quantity $|\mu|$.

$\mu$ is the dielectric pole moment, $q$ is the charge, and $d$ is the distance.
Figure 2-4. Illustration of Polarization of a Capacitor.

FROM VON HIPPEL (1954)

UNIT CUBE OF DIELECTRIC

P BOUND CHARGES PLP UNIT AREA

PLATES OF CAPACITOR

DIELECTRIC MATERIAL
when all dipoles reacted to the applied field and aligned.
In practice, this maximum effect is difficult to reach because of hindrance from the simultaneous effect of mobility, thermal agitation, Brownian movement, and collisions. An average effect occurs but it is nonetheless a very extensive one. The net dipole moment will be inversely proportional to the absolute temperature, and at very low temperatures, complete orientation may occur. The polarization effect also depends on the size of the polar molecules, on the frequency, and on the viscosity or solidity of the surrounding medium. These relationships correctly imply that polarization may be hindered from its full degree, at least within the limits of orientation time, and that polarization, therefore, may lag behind the applied field.

7. "Loss Tangent" and "Loss Factor." Returning now to the capacitor analogy, it can be further shown that when absorptive polarization occurs, there will be two currents involved. The charging or capacitive current is $90^\circ$ out of phase with the applied voltage (current leads the voltage in a capacitive circuit), and another component of the current is in phase with the potential and represents an ohmic loss. These are measures of the absorption and are accounted for by an energy transfer from the field to the material manifested as heat. Because of this phase difference, the dielectric constant is usually written as a complex number. The real part of the dielectric constant represents the component of polarization which is in phase with the voltage, and the imaginary
part represents the component which is out of phase. In equation form (von Hippel, 1954):

\[ \xi^* = \xi' - j \xi'', \text{ and} \]
\[ \xi'' = \xi' \cdot \tan \delta \]

in which \( \xi^* \) is the complex dielectric constant.
\( \xi' \) (or \( \xi_v' \)) is the real part of the dielectric constant.
j is the square root of -1.
\( \xi'' \) (or \( \xi_v'' \)) is the imaginary part (loss factor of the dielectric constant).

\( \delta \) is the loss angle (\( \tan \delta \) is referred to as the "loss tangent" or "dissipation factor").

When an electric field is applied, the molecules of the substances in the field align themselves so as to add the unbalanced electron charges in the molecule to those existing on the electron plates. The greater the extent of this alignment and consequent electron unbalance, the higher will be the dielectric constant. Generally, as frequency is increased, it becomes more difficult for the molecules to reorient against the viscosity of the medium, and the dielectric constant decreases (Singleton, 1960).

The loss factor (\( \xi_v'' \), the imaginary part of the dielectric constant) has minima both at very low frequencies where the entire polarization (molecular and electronic) is in phase with the field and also at very high frequencies where polarization (now solely electronic) is again in phase with the field. Between these two minima, the loss factor reaches a maximum which occurs when:
in which \( \omega \) is \( 2\pi \) times the frequency.

\[ \tau \] is the relaxation time.

It follows that this maximum in power absorption occurs when the period of the relaxation and the period of the impressed field are equal (Fuoss, 1943).

One may set up vectors to represent the values involved when absorptive polarization occurs, as shown by von Hippel (1954) and Smyth (1955). When this is done, the total current is represented by the vector sum of the charging currents and loss currents (see Figure 2-5). There are two angles involved: \( \Theta \) is the power factor angle (power factor is the cosine of the phase angle between current and voltage when these are sinusoidal) and \( \delta \) is the angle between the total current and charging current vectors. The angle \( \delta \) is the loss angle and its tangent is referred to as the "dissipation factor" or "loss tangent."

\[
\tan \delta = \frac{\varepsilon''}{\varepsilon'} = \frac{\text{loss factor}}{\text{relative dielectric constant}} \quad \text{(Eq. 2.21)}
\]
Figure 2-5. Current-Voltage Relation in an Ideal Capacitor (A) and in a Capacitor Containing a Dielectric With Loss (B).

A. In an ideal capacitor, the charging current \( I_0 \) leads the voltage \( v_o \) by \( 90^\circ \).

B. In a capacitor containing a dielectric with loss, the current will lead the voltage not by \( 90^\circ \) but by \( 90^\circ - \delta \). The total current traversing the condenser is the sum of the charging current \( I_c \) and the loss current \( I_l \). The charging current is the product of the phase difference, the angular frequency, the capacitance, and the voltage. The loss current is the product of the conductance of the dielectric and the voltage. The angle \( \delta \) is the loss angle and the angle \( \theta \) is the power factor angle.
CHAPTER III

ELECTRONIC HEAT IN THE FOOD INDUSTRY
Electronic Heat in the Food Industry. Microwaves occupy "...a loosely defined region of the electromagnetic spectrum--beginning where traditional high frequency techniques no longer are appropriate and extending to somewhere below the frequency of infrared light (Fly, 1966). Table III-1 lists the frequencies allocated by the Federal Communications Commission for industrial, scientific, and medical use.

Microwaves are located between the infrared and the radio-frequency regions of the spectrum and possess characteristics of both. Like infrared, they can be reflected, refracted, and made to interact with matter. Like radio waves, they can be transmitted through various media and can be conducted through wave guides and coaxial lines (Mezey, Falkenbach, and Oxley, 1965).

Considerable work was done in the 1930's in attempts to apply RF (radio-frequency) energy to various industrial problems in the food industry. Frequencies used in these early investigations were in the 6 MHz to 40 MHz range (Kinn, 1947).

Proctor and Goldblith (1953) reported that most of the RF generators available prior to World War II and shortly thereafter produced energy at frequencies of 20 MHz to 150 MHz. In discussing the use of these frequencies, they (Proctor and Goldblith, 1953) cited problems relative to arcing which could be overcome at these frequencies only by lowering the voltage applied. Any lowering of voltage, however, requires a corresponding increase in frequency if
Table III-1

Frequencies Allocated by the FCC for Industrial-Scientific-Medical (ISM) Use (Anon., 1964)

<table>
<thead>
<tr>
<th>Wave Length</th>
<th>Frequency</th>
<th>Type of Heating</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.1 meters</td>
<td>13,560 KHz + 6.78 KHz</td>
<td></td>
</tr>
<tr>
<td>11.1 meters</td>
<td>27,120 KHz + 160.0 KHz</td>
<td>Dielectric</td>
</tr>
<tr>
<td>7.4 meters</td>
<td>40,680 KHz + 20.0 KHz</td>
<td></td>
</tr>
<tr>
<td>32.8 centimeters</td>
<td>915 MHz + 25.0 MHz</td>
<td></td>
</tr>
<tr>
<td>12.2 centimeters</td>
<td>2,450 MHz + 50 MHz</td>
<td>Microwave</td>
</tr>
<tr>
<td>5.2 centimeters</td>
<td>5,800 MHz + 75 MHz</td>
<td></td>
</tr>
<tr>
<td>1.4 centimeters</td>
<td>22,125 MHz + 125 MHz</td>
<td></td>
</tr>
</tbody>
</table>
the initial power level is maintained. Equipment and techniques to do this were not available prior to World War II.

Many advancements in the field of electronics were made in the 1930's and even more during World War II as a result of the demand for greater power at higher frequencies—first for communications and later for radar. With the advent of radar, there also came the use of the word "microwaves" when referring to frequencies above 300 MHz. Microwaves form the basis of radar, and in the World War II model sets, they were generated by tubes called magnetrons, capable of producing energy at frequencies of 1,050 to 3,000 MHz.

Morse and Revercomb (1947) reported on the use of magnetrons in heating foods and noted that the problems related to arcing, previously reported, were eliminated when frequencies were increased to 1,050 MHz.

Another important advancement in microwave technology was the development of improved magnetrons capable of continuous output of 5 kilowatts of power at 1,050 MHz (Nelson, 1947) and of 2 kilowatts and 5 kilowatts of power at 2,450 MHz (Schmidt, 1961). In May 1963, the development of a super power tube capable of delivering 425 kilowatts of power at 3,000 MHz and at an efficiency of 72 per cent was announced (Allaire and Sample, 1964). Curran (1966) has announced the availability in Great Britain of a 25 kilowatt magnetron operating in the 886-906 MHz wave band.

Bowers (1966) states that a tiny crystal of gallium
arsenide can be made to emit microwaves simply by applying a steady voltage across it. This phenomenon, known as the Gunn effect, may revolutionize microwave technology. The gallium arsenide source is much simpler than the klystron, and would be much cheaper to fabricate on a large scale. The Gunn oscillator is not the only solid-state device that looks promising as a generator of microwaves. Competitors exist, the strongest being the "Read diode." Its supporters claim that it has greater promise than the Gunn oscillator. It is a junction device that depends for its operation on "avalanche breakdown," that is, the creation of extra charge carriers by collisions with atoms. Other solid-state devices, some involving plasma effects in magnetic fields, are being watched with great interest, even though they appear to be less competitive than either the Gunn oscillator or the Read diode. Thus one is at an early stage of the advent of solid-state devices for microwave generation, and there are several contenders for the title of "most useful generator." Work in this area is very rapid and one will not have to wait long to know the winner.

As microwave technology has advanced, there has naturally been an increase in efficiency and a reduction in the unit cost of microwave power and equipment. One manufacturer has announced a microwave range for domestic use that will retail for less than $500.00 (White, 1966). With advancement of the art and the concurrent price reductions, an increased use of
microwave energy in the food industry is sure to come.

**Industrial Applications of Dielectric Heating.** Radio-frequency technique has long been considered for freeze drying. Copson (1958) states, "Electrical loss factor differences between water and ice indicated that for the all ice system an orderly process for the addition of sublimation energy to ice occurs. The interaction of the energy with the ice when dried food is also present indicates a selective heating of the ice portion which contributes intrinsic control in the drying process. As a consequence of the loss factor for ice, the penetration of the energy in depth is much greater than in the case of water, so that adequate heating is provided within the ice phase. Reduction in drying cycles of 75% over the conventional heating time was demonstrated. The energy required by the sublimation process was accounted for by the factors for increased microwave energy effect with larger loads and with ice. Sublimation rates were shown to be directly related to the microwave energy applied." Decareau (1961) states, "Microwave energy passes through the dry food layer and is absorbed directly by the ice. Thus, drying can be accomplished while the product's dry outer layer stays cool." However, there are a number of problems relating to voltage breakdown in vacuums, control of the system, and costs which must be overcome before microwave freeze drying becomes commercially competitive.

In dielectric defrosting, penetration of microwaves into the frozen material is extensive. The half power depth for
ice at 10.4°F. is reported as 1600 cm. for 915 MHz, and 780 cm. for 2450 MHz (Decareau, 1965). However, another important consideration which must be taken into account is the dielectric loss property of water. As soon as some defrosting has occurred, the values for water come into play. It is interesting to note that the half power depth for water at 34.7°F. is 4.1 cm. for 915 MHz, and 0.6 cm. for 2450 MHz. A "runaway" condition occurs if defrosting is not uniform. This means that as soon as some ice has melted, the water avidly absorbs energy for further defrosting essentially by conduction of heat from water to the remaining frozen material. Thus careful control of energy input is required if denaturing of tissue or coagulation of protein is to be avoided. Sherman (1946) reported that defrosting of thirty-pound cartons of perishable fruits like strawberries and raspberries have been defrosted with dielectric heat in a matter of minutes in contrast to four hours in warm water or one to seven days required at room temperature. Smaller two-pound cakes of frozen food were defrosted in less than three minutes. Bengtsson (1963) reported on the defrosting of meat and fish. In comparing continuous dielectric defrosting between flat electrodes at 35 mega-cycles per second (mcs) and continuous defrosting in a microwave oven of parabola type at 2450 mcs with regularly shaped blocks of frozen raw material, Bengtsson found end results satisfactory at both frequencies. The main difference found between frequencies was that higher power density, with
resulting shorter heat-treatment times, could be used at 2450 mcs whereas power penetration into the frozen material was low at this frequency, reducing the useful sample thickness to 4 cm. or less.

For defrosting foods such as frozen turkeys which are to be roasted immediately, the problem of some coagulation of the protein due to "runaway" conditions is not of great importance, since this occurs during the roasting process anyway.

In microwave cooking, the time requirement for adequate cooking of the food is directly proportional to the amount of food being heated. The fact that the cooking time is a function of the load size may be explained by microwave power concentration within the food. When dielectric materials are placed in the path of microwaves, or when microwaves are reflected from the metal walls back and forth through the dielectric substance, such a material will absorb energy from the waves in proportion to the loss of energy by the waves. If adequate power is available at the correct frequency, the process is further characterized by a very dramatic rate of heating throughout its volume. The energy change is one of absorption of the electromagnetic radiation of some or all of its energy by the substance being heated.

According to Copson (1956), foods requiring short heating periods with microwave energy, as in baking apples, potatoes, and cakes or in cooking fish, surface cooking is moderate and crusting absent. Thus, an apple retains a
nearly fresh appearance while being baked throughout. The facility with which dishes of food may be heated without crusting or deterioration has made such heating an important application of microwave cooking. Important improvements in nutrient retention are suggested in early reports. Products which cook quickly but ordinarily require a browning or crusting to meet taste acceptance posed a problem in microwave cooking. Chickens, steaks, and chops are examples. The problem was resolved by preparations which promote natural browning through Maillard reaction of normally present but now concentrated materials, such as glucose and glycine in cooking preparation. These studies have been reported in detail (Copson et al, 1955). It is general practice, however, to treat this class of foods as products requiring through-cooking, usually in a few minutes, plus short broiling or searing. Thus modern ovens contain browning heating elements. These two processes are sometimes carried out in conjunction with freezer storage or refrigeration. A third class of food with respect to microwave cooking practice is the group of roasted products, such as meat and poultry. These roasts generally require a cooking period of the order of 20 to 30 minutes, and this is ample for surface coloring without further treatment. Superficial fat layers absorb microwave energy, and the temperature may rise well above the boiling point of water, so that regular oven conditions are approached by the
roast itself and browning occurs. The effect of longer heating at these power levels in such products is, therefore, surface browning attributable to high temperatures, melting of fat, and development of some crispness. If heating is continued to the overdone stage, crusting occurs.

The dramatic rate of heating foods with microwaves makes this form of heating particularly suitable for catering service. The catering industry can play an important role in the development of foods and packaging which are specific for microwave ovens. Experience gained from these "Meal in a Moment" establishments should enable the food industry to make a smooth transition into large-scale home ownership of microwave ovens. Decareau (1964) states that frozen dinners as now packaged are completely unacceptable for microwave oven use, since packaging consists of an aluminum compartmented tray with a foil overwrap. Pot pies presently available are completely unacceptable for microwave oven use. There are two reasons for this: first, an aluminum container is used, which slows the heating rate and results in such uneven heating that dehydration occurs at the edges before the center is ready; and secondly, the crusts are unbaked, and the appearance of microwave baked crust is not normal. Most vegetables, with the exception of peas and corn, require long cooking time to yield an acceptable result. Other vegetables could be used if they were precooked before packaging. Breaded foods must be eliminated, because they become unacceptably soggy. Small
pieces of boiled potatoes, O'Brien potatoes, and creamed potatoes give good results. Thinly sliced meat items such as roast pork, lamb, or beef, or pot roast of beef, chicken slices, and turkey are examples of meats which give good results.

Microwave ovens are being used successfully for catering in several ways. One of the main advantages is that meals prepared and cooked beforehand can be provided rapidly, later at the serving area, by a minimum of unskilled staff. After cooking, the meals are evenly portioned out into individual plastic dishes suitable for use in the microwave ovens. Each meal in its dish is then overwrapped in transparent, moisture-proof "Cellophane" cellulose film and deep-frozen for storage against "caterers" orders. When required for delivery, the meals are packed into specially made moisture- and frost-repellent cartons with internal separators, for transport. At the catering premises, the meals are stored in deep-freeze cabinets, being transferred to ordinary refrigerators for controlled defrosting to meet daily requirements. When ordered for eating, the meals, still in their plastic dishes, are heated in ovens and served to the customers. The plastic dishes, plastic cutlery, and drinking cups are all disposable. A further advantage of the system is that because of the film overwrapping, the meals are untouched by hand (Anonymous, 1965). Using microwave ovens to reheat meals directly from the deep-frozen state can be done rapidly to meet special customer requirements,
but it takes as much microwave energy to raise the temperature from $-20^\circ C$ to $0^\circ C$ as it does to raise the temperature from $10^\circ C$ to $90^\circ C$. It is also difficult to reheat the different constituents of a deep-frozen meal to the same temperature in a fixed time (Anonymous, 1965).

Microwave heating is being investigated as a method of preparing brown-and-serve chicken parts for the institutional and consumer fields. The product is cooked from the inside out, so there is no raw center. Parts can be refrigerated or frozen until used, then browned and served quickly, with the crisp fresh crust or breading of fresh chicken (Anonymous, 1966).

The color of conventionally processed potato chips is determined primarily by the glucose content of the raw potatoes, and successful chipping has required the use of potatoes with relatively low glucose contents of the order of a tenth of one per cent or lower. Higher glucose contents result in chips that are unsaleably dark if finish fried at the high temperatures associated with conventional deep fat frying. Darkening of chips occurs at the terminal stage of finish frying, and if the chips are removed from the frying oil just at the onset of color development, they can be finish-dried without further darkening if the drying method is gentle. Microwaves provide this gentle, low temperature finish drying (O'Meara, 1966).

Recent work by Goldblith and Pace (1967) demonstrated that it is difficult to pump energy into low moisture
content chips. (This low moisture content is the reason this method of heating is gentle.) Secondly, there is an increase in loss factor with temperature, but this increase in loss factor as a function of temperature diminishes as the moisture content of the chips decreases and is not observed at the lowest moisture content chip measured (8.3 per cent moisture). At the 8.3 per cent moisture content, the difference between 1000 MHz and 3000 MHz is practically nil. More absorption of microwave energy takes place in the chip at the highest moisture content while at the highest temperature.

The "Per Se" Effects of Microwaves. The effect of microwaves on microbes or living tissue cells may be one of the more fascinating aspects of microwave research. For example, York (1967) reported that it appears that microwave energy has deleterious effect on several types of microbes at temperatures below lethality, i.e., less than 50°C. However, the proof in this paper is lacking.

Stodolnik-Baranska (1967) observed that lymphoblastoid transformation of lymphocytes in vitro after microwave irradiation. He conducted the experiments in culture media which had no rise in temperature during the exposure time. He noted that selective overheating of cells suspended in medium is theoretically possible under these conditions, but in view of the ratio of cell volume to the volume of the medium, however, and given the heat exchange characteristics of the medium and the cells, such "pin point" heating seems
improbable. Nevertheless, the concentration of salts in the cells is much more than in the surrounding medium. Thus, the heating effect may be real within the cells.

Olson (1965) reported the number of viable spores of Aspergillus niger, Penecillium sp., and Rizopus nigricans were greatly reduced at time-temperature exposure well below the thermal death point of these spores. He concluded that the excellent results with microwaves are probably not due to conventional thermal kill. He further states, however, that it is possible that the spores may present a preferential target for the microwave energy, and their internal temperatures may have far exceeded that of the surrounding media (bread). However, once again the experimental data are missing.

Robe (1966) citing work done in an industrial radio-frequency heating pilot plant by Yang, gave data indicating that pasteurization of wine and beer inoculated with yeast could be accomplished in less than one minute at 120° F. This contrasts with heating for 30 minutes at 140° F. by conventional heating or holding at 180° F. for one minute.

Goldblith and Wang (1967) exposed suspensions of Escherichia coli and Bacillus subtilis spores to microwave energy at 2450 MHz and compared the degree of inactivation to suspensions exposed to conventional thermal energy. For both E. coli and B. subtilis, the reduction in numbers of organisms by microwave exposure was shown to be nearly
identical to what is expected for the same time-temperature exposure using conventional heating. These authors also added ice to suspensions of *E. coli* and found no reduction in numbers when the final temperature was kept below the lethal thermal death point of the organisms. They concluded that at 2450 MHz, inactivation of these organisms is solely due to the thermal energy, and they found no evidence of "per se" effect of microwaves.

Data to be presented in this thesis should be helpful in leading one to predict that selective overheating may or may not occur in microbes depending upon the environment they are in, the characteristics of the microbe, heat exchange characteristics of the medium, and the cells, and how the energy is coupled into the material to be heated. Microbes in suspension heated in a microwave oven could well require thirty minutes at 140°F for pasteurization, while the same microbes may be inactivated in less than one minute under different techniques of coupling the energy into the media. This subject will be discussed further in another part of the thesis.

Pace (1967) has collected data from the literature and compiled an excellent table concerning the dielectric data for certain foods and food constituents.
CHAPTER IV

EXPERIMENTAL METHODS
The Precision Slotted Line Technique for Determining Dielectric Data. The required dielectric data for a material cannot be determined directly but can be calculated from data obtained by use of the precision slotted line as described by Roberts and von Hippel (1946), Dakin and Works (1947), Anonymous (1950), von Hippel (1954), Ginzton (1957), Sodeman (1958), Westphal (1963), Beatty (1965), Gilmore (1966), and Westphal (1966). This procedure utilizes a coaxial transmission line, limiting the electromagnetic field to the inclosure of the line, thereby eliminating boundary and stray effects and facilitating precision measurement of small samples of a given dielectric (Figure 4-1).

In discussing the theory of the Precision Slotted Line Technique, it is necessary that certain basic relationships be understood.

1. When electromagnetic energy is passed through a wave guide, the guide can propagate an infinite number of different types, or modes, of electromagnetic waves. The usual mode in coaxial lines is the principal TEM (transverse electromagnetic) mode (Figure 4-2,A).

2. If a metallic barrier is placed in the wave guide, a wave of energy striking the barrier will be reflected back towards its source. The convergence of incident and reflected waves then result in a standing wave (Figure 4-2,B). If one considers the amplitude of the incident wave as "A"
Figure 4-1. Section of a Coaxial Line Containing a Dielectric Sample.

A, the outer conductor; B, the center conductor; and C, the sample. The sample is positioned between the two conductors.

Figure 4-2. TEM Mode as a Traveling Wave (A) and as a Standing Wave (B).

E is the electric field strength and H is the magnetic field strength.
and the amplitude of the reflected wave as "B," then the reflection coefficient of the terminus will be the ratio of "B" to "A" or "B/A."

3. The field strength at any given point in the transmission line is simply the vector sum of the strengths of the incident and reflected waves at the particular point. A point on the line can be found where the vector sum $A+B$ is a maximum and is equal to $|A| + |B|$. Likewise, a point can also be found where the vector sum is at a minimum and is equal to $|A| - |B|$. These two phenomena give rise to the standing wave ratio (SWR):

$$\text{SWR} = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{|A| + |B|}{|A| - |B|} = \frac{1 + \gamma}{1 - \gamma} \quad \text{(Eq. 4.1)}$$

in which $E_{\text{max}}$ = voltage at maximum.

$E_{\text{min}}$ = voltage at minimum.

$A$ = amplitude (voltage) of incident wave.

$B$ = amplitude (voltage) of reflected wave.

$\gamma$ = reflection coefficient, $B/A$.

The Precision Slotted Line Technique is based on determining the impedance input in a transmission line as a result of inserting a dielectric into the line. The impedance can be calculated from measurements of the standing wave pattern in the line as taken with and without the dielectric sample in place. Insertion of the dielectric into the line results in a change in both the wave length and the node width of the standing wave (Figure 4-3).
Figure 4-3. Change in Wave Length and Mode Width of the Standing Wave as a Result of Inserting a Dielectric Sample (With Loss) Into the Line.

A. Air-filled line (with empty sample holder attached).

\[ N_{a1} \] - first minimum above the terminus.

\[ N_{a2} \] - second minimum above the terminus.

\[ n_{a \lambda} \] - half wave length.

\[ E \] - minimum power point.

\[ 2E \] - twice minimum power points.

\[ X_a \] - width of minimum as measured at the twice minimum power points.

B. Line with sample holder (containing sample) attached.

\[ N_s \] - first minimum above the terminus.

\[ n_{s \lambda} \] - half wave length.

\[ X_0 \] - distance (cm.) of the first minimum above the front face of the first dielectric.

\[ E \] - minimum power point.

\[ 2E \] - twice minimum power points.

\[ X_s \] - width of minimum as measured at the twice minimum power points.

\[ d_1 \] - distance (cm.) from top of sample holder to front face of first dielectric (sample cover).

\[ d_2 \] - thickness (cm.) of the first dielectric.

\[ d_3 \] - thickness (cm.) of the second dielectric (sample).

\[ B_1 \] - boundary between air-filled portion of line and front face of first dielectric.

\[ B_2 \] - boundary between bottom face of first dielectric and front face of second dielectric.
Equipment Needed in Order to Use the Precision Slotted Line Technique. In order to make the measurements (standing wave ratios, node locations, etc.) upon which the calculation of the dielectric properties of a material are based, an apparatus such as shown in Figure 4-4 is needed. The complete unit, or dielectrometer, consists of the following:

1. **Power Supply.** The power supply draws electrical power from the line and, if necessary, converts it to the voltage needed by the microwave generators (with the equipment used in the work cited herein, the line voltage of 110 volts, A. C., was the same as required by the generators and no conversion was necessary).

2. **Microwave Generator(s).** Oscillators or klystron tubes are used to convert the A. C. power into microwave energy at the specific frequencies for which they are designed.

3. **Attenuator.** An attenuator is used to regulate the power level of the signal picked up by the probe.

4. **Precision Slotted Line.** The precision slotted line consists of a precision milled coaxial line with a slot along one side of the outer conductor running parallel to the axis.

5. **Sample Holder(s).** The sample holders are precision devices which hold the sample to be measured. They attach to the microwave transmission line in such a way as to become an integral part of the line.

6. **Traveling Probe.** The probe is a fine wire,
Figure 4-4. Block Diagram of a Complete Standing Wave Measuring System.

A, power supply; B, microwave generator; C, attenuator; D, precision slotted line; E, sample holder; F, carriage for traveling probe; and G, detector.
micrometer driven, which protrudes through the slot in the outer wave guide. It is used to sample the wave so that its strength can be measured at any given point and thus supply the data which can be used to determine the standing wave ratio (SWR) and the position of the wave nodes.

7. Detector. The detector is an ammeter attached to the probe and affords the operator a knowledge of the relative wave strength at the site of the probe.

In the work cited in this thesis, dielectric measurements were made on a dielectrometer built by the Charles Engineering Company, Waltham, Massachusetts.

Sample Holders and Sample Preparation. The sample holders and the preparation and handling of the samples themselves are of extreme importance in obtaining accurate and reproducible dielectric measurements.

The sample holder forms an extension of the coaxial line and, in fact, becomes an integral part of the line. In order to preclude the creation of additional nodes in the line, it is essential that the sample holder and the fixed portion of the line be perfectly matched. The outside diameter of the inner conductor and the inside diameter of the outer conductor of the sample holder must be exactly the same as those of the line. Further, the junctions between the sample holder and the conductors of the line must result in no discontinuities nor can they be so tight as to force the center conductor into a position
which is not coaxial with the outer conductor.

Many solid non-food materials can be milled to exact dimensions and require no special holders. They are simply inserted into the line at the terminal end and the line is sealed off with a shorting plug*. Handling samples of food materials, however, is an entirely different matter and presents a continuous challenge.

**Sample Holder for Ground Beef.** The type holder used for measurements of the samples is illustrated in Figures 4-5 and 4-6, and a photograph (Figure 4-7) of the holder has been included.

The holder consists of two separate sections (top and bottom), and the sample is positioned between them. The extension of the center conductor is permanently attached to the bottom section of the holder. The sample is positioned on the bottom section of the holder by slipping it down over the center conductor. The top section of the holder is then added on top of the sample in a like manner. The two sections of the holder are then fastened together by a Whitley clamping ring.

The center conductor of the holder is copper with a 0.952 centimeter outside diameter. The outer conductor is

---

*A shorting plug is a disc of solid copper attached to the terminal end of the transmission line by a coupling. It provides a reflecting surface for the wave of energy so that a standing wave will be produced.*
FIG. 4.5 HOLDER WITH WATERTIGHT SLEEVE ATTACHED.
FIG. 4.6 UPPER AND LOWER SECTIONS OF HOLDER JUST BEFORE TIGHTENING CLAMPING RING, AND WITHOUT OUTER SLEEVE, LOWER SECTION MUST BE λ/4 CM IN LENGTH
Figure 4.7 Photograph of Sample Holder Used for Dielectric Measurements on Raw Potatoes at 1,000 MHz.
milled from copper to an inside diameter of 2.54 centimeters. Polystyrene is used as a base for the sample and as a sample cover, because it is a material whose dielectric properties are constant over the temperature and frequency range being used.

This holder allows the use of extremely thin (0.260 centimeter) samples. The use of such thin samples is desirable when dealing with lossy materials because samples of any appreciable thickness could result in a node actually being present in the sample itself, and measurements of the "apparent" first node \((N_s)\) above the sample would be totally in error. A disadvantage in using such thin samples is that very minute variations in sample thickness result in sizable errors in the final values.

While in the holder, the sample is surrounded (circumferentially) by a brass spacing ring 0.260 centimeter in thickness (same thickness as the sample). The ring prevents any compression of the sample by the holder when the top and bottom sections of the holder are fastened together. The sample must exactly fit the cavity provided for it in the holder.

**Temperature Control.** Data was collected at three temperature ranges, 0–1°C, 25°C ± 1°C, and 80°C ± 1°C. In order to obtain quick temperature equilibrium, a brass sleeve was devised to prevent the entrance of water through the Whitley clamping rings, and the entire holder
was submerged into water maintained at the appropriate temperature. In addition to immersing the holder in the water solution, water was pumped continuously through the inner portion of the center conductor of the bottom holder to a plug, as shown in Figure 4-5.

As noted in the legend to Figure 4-5, different lower (bottom) sections for the sample holder are used for making measurements at different frequencies. Changing the length of the line below the face of the sample is necessary in order to keep exact multiples of $\lambda/4$ distance between the face of the sample and the reflecting surface. A better method than changing the lower section of the holder, however, would be to have the lower section made in two parts so that only the part not adjacent to the sample would have to be changed when changing frequencies. This design would have the advantage of allowing measurements at all frequencies (within the frequency limits of the dielectrometer) without disturbing the sample.

Calculating $\varepsilon_n', \varepsilon_n'', \text{ and } \tan \delta$ from Experimental Data.

1. The air-filled sample holder is attached to the microwave transmission line in such a way as to become an integral part of the line. The different sample holders change the length of the line below the face of the sample and keep exact multiples of $\lambda/4$ distance between the face of the sample and the reflecting surface.

2. Measurements are made of the distance (cm.) of
the twice-minimum power points (the points along the axis of the transmission line where the power level is twice that at the minimum point (2E in Figure 4-3)) of the first minimum above the terminal end of the line. The difference in these two values is $\Delta X_a$, the width (cm.) of the minimum in the air-filled line as measured at the twice-minimum power points.

3. The measurements at the twice-minimum power points (as determined above) are averaged to obtain the position $N_a$, of the first measurable minimum in the air-filled line (Figure 4-3A). The value assigned to $N_a$ is the distance (cm.) of the minimum from the terminal end of the line.

4. The procedure described in "2" and "3" above is repeated at the next node (moving up the line towards the power source) and the position of this minimum, $N_{a_2}$, is determined (Figure 4-3B).

5. The distance (cm.) between two adjacent minima ($N_a$ and $N_{a_2}$ as located in "3" and "4" above) is $\lambda/2$, the half-wave length as measured in the air-filled line.

6. The sample whose properties are to be determined is then placed in the sample holder, and the holder is again attached so as to become an integral part of the line. Steps "2" and "3" described above are then repeated to find (a) $\Delta X_s$, the width of the minimum in the line containing the sample as measured at the twice-minimum power points, and (b) $N_s$, the position of the first measurable minimum in the
line containing the sample (this minimum is used below and corresponds to the minimum at Na). This concludes the actual measuring performed on the dielectrometer.

7. The change in position of corresponding nodes in the air-filled line as opposed to the line containing the sample is a function of the dielectric loss in the sample. This change and the change in the standing wave ratio (SWR) are the bases for the calculations.

8. The values so far determined (\(Na, Ns, \) and \(\lambda/2\), plus \(d\), the thickness or length (cm.) of the sample) are now used to calculate \(Xo\), the distance of the first minimum (in the line containing the sample) above the face of the first dielectric material (see Figure 4-3). This value is determined by use of the following equation (Westphal, 1963):

\[
Xo = \Delta N + Xo_E
\]

(Eq. 4.2)

where \(\Delta N = Ns - Na\), where \(Ns\) is the first node in the line containing the sample, and \(Na\) is the corresponding node in the air-filled line. \(\Delta N\) is the shift in the node towards the termination, passing from the empty line to a line containing the sample.

\(Xo_E\) = the distance of the node above the upper face of the bottom portion of the sample holder, i.e., the distance above the section which is \(\lambda/4\) in length. (For computing \(Xo_E\), see Appendix). \(Xo_E\)
is a constant for each frequency.

\( X_0 = \) the first node above the front face of the polystyrene cover.

9. The calculated value for \( X_0 \) is now used to determine \( \Delta X \), the corrected width of the minimum (in the line containing the sample) at the twice-minimum power points. This value, \( \Delta X \), is calculated from Equation 4.3 (Westphal, 1963):

\[
\Delta X = \Delta X_s - \left[ X_0 + n_s \frac{\lambda}{2} \right] \frac{\Delta X_a}{n_a} \frac{\lambda}{2}
\]

(Eq. 4.3)

in which \( \Delta X \) = corrected width of the minimum, in the line with the sample present, at the twice-minimum power points. (Note that \( \Delta X \) is a calculated value whereas \( \Delta X_s \) was a measured value)

\( X_s = \) width (cm.) of the minimum in the line containing the sample as measured at the twice-minimum power points, and

\( X_a = \) width (cm.) of the minimum in the air-filled line as measured at the twice-minimum power points.

In actual practice, it was found that \( \Delta X \) could be computed simply as \( \Delta X = \Delta X_s - \Delta X_a \), because loss due to the wall of the line and loss due to the sample holder itself were negligible.

The factor \( \frac{\Delta X_a}{n_a} \frac{\lambda}{2} \) of Equation 4.3 represents the loss tangent due solely to the wall of the line (\( \tan \delta_w \)). The total loss present (\( \tan \delta_t \)) is the summation of (a) the
loss due to the wall of the line (tan δw), (b) the loss due to the sample itself (tan δ), and (c) the loss due to the sample holder.

10. From ΔX and λ, the wavelength, the inverse standing wave ratio (E) can be calculated from the following equation (Westphal in von Hippel, 1954):

$$E = \frac{E_{\text{min}}}{E_{\text{max}}} = \frac{\pi \Delta X}{\lambda} - C$$  \hspace{1cm} (Eq. 4.4)

in which $E = \text{the inverse standing wave ratio}$.

$\pi = 3.1416$.

$C = \text{a correction factor (found in tables such as on page 65, Westphal, 1963)}$.

$\lambda = \text{wavelength (}2 \times \frac{\lambda}{2}\text{)}$.

11. The impedance ratio at the first boundary, $B_1$ (the boundary between the air-filled portion of the line and the upper or front face of the first dielectric, the sample cover, see Figure 4-3), can be calculated from the inverse standing wave ratio and the wavelength by use of the following equation (Westphal, 1963):

$$\tan \frac{Z_{B_1}}{Z_{O_1}} = \frac{E - j \tan \frac{360^\circ}{\lambda} X_0}{1 - j E \tan \frac{360^\circ}{\lambda} X_0}$$  \hspace{1cm} (Eq. 4.5)

in which $Z_{B_1} = \text{impedance at boundary 1}$,

$Z_{O_1} = \text{impedance in line above boundary 1}$,

$E = \text{inverse standing wave ratio}$, and

$j = \sqrt{-1}$.
12. The impedance ratio at the secondary boundary, \( B_2 \), is then determined. \( B_2 \) is the boundary between the bottom face of the first dielectric (the sample cover) and the upper face of the second dielectric (the sample). For this calculation we use the following equation (adapted from Westphal, 1966):

\[
\tan \frac{Z_{B_2}}{Z_{o_2}} = \frac{\tan \frac{Z_{B_1}}{Z_{o_1}} - j \frac{1}{\sqrt{\epsilon_2'}}}{1 - j\sqrt{\epsilon_2'} \tan \frac{Z_{B_1}}{Z_{o_1}} \tan \left( \frac{360^\circ d_2}{\lambda} \sqrt{\epsilon_2'} \right)}
\]

(Eq. 4.6)

in which \( Z_{B_2} \) = impedance at boundary 2,

\( Z_{o_2} \) = impedance above boundary 2,

\( \epsilon_2' \) = dielectric constant of the first dielectric;

in this case, polystyrene was used and \( \epsilon_2' = 2.56 \), a constant value, and

\( d_2 \) = thickness or length (cm.) of the first dielectric (sample cover).

13. From the impedance ratio at boundary 2 and the thickness or length of the sample \( (d_3) \), the dielectric constant and the loss tangent of the sample may be calculated as follows (adapted from Westphal, 1966):

(a) \[
\frac{Z_{B_2}}{Z_{o_2}} = \cotanh \frac{X}{\lambda} \]

\[
\frac{j 2\pi d_3}{X}
\]

(Eq. 4.7)

in which \( d_3 = \) thickness or length (cm.) of the second dielectric (the sample).
(b) The value of $X$, the product of the sample thickness and its reflection coefficient, can then be found quite simply by use of tables of $\cotanh \frac{X}{X}$ such as found in Westphal (1963).

(c) Then, $\varepsilon''$, the dielectric constant of the sample is found from:

$$\left( \frac{x}{2\pi d_3} \right)^2 = \frac{\varepsilon'_o - j \varepsilon''}{\varepsilon''} \quad (Eq. 4.8)$$

in which $X = \text{the product of the sample thickness and its reflection coefficient}$,

$\varepsilon'_o = \text{the dielectric constant of the sample}$,

$\varepsilon'' = \text{the dielectric loss factor of the sample}$, and

$\varepsilon'' = \text{the dielectric constant of free space (taken as 1)}.$

The solution of the above equation gives a numerical value multiplied by the cosine of the angle $= \varepsilon''$, the relative dielectric constant of the sample.

(d) Finally, the loss tangent ($\tan \delta$) of the sample is calculated:

$$\frac{\varepsilon''}{\varepsilon'} = \tan \delta \quad (Eq. 4.9)$$

where $\varepsilon'_o = \text{the relative dielectric constant of the sample}$,

$\varepsilon'' = \text{the dielectric loss factor of the sample}$, and

$\tan \delta = \text{the tangent of the angle given in the solution to Eq. 4.8}.$
**Computer Program.** It is obvious that calculation of a large quantity of experimental data would become cumbersome. It was decided therefore to construct graphs for each frequency used (see Figures 4-8 through 4-11) setting the relative dielectric constant ($\varepsilon'_r$) on the ordinate, and the dielectric loss factor ($\varepsilon''_r$) on the abscissa. Proper construction of the graphs necessitated computing combinations of $X_0$ and $\Delta X$ through the range of values which were found in the experimental data. The program was written in Fortan IV, and a 360 IBM computer was used.

The equations previously developed (Eqs. 4.2 through 4.8) have been given the following symbols in the program (Figure 4-12).

\[
\frac{\pi \Delta X}{\lambda} - C = X
\]

\[
360 \frac{X_0}{\lambda} = Y
\]

\[
j \tan \frac{360 X_0}{\lambda} = Z1
\]

\[
X - Z1 = Z2
\]

\[
1 - j \tan \frac{360 X_0}{\lambda} = Z3
\]

\[
\frac{Z2}{Z3} = Z4
\]

\[
\frac{1}{\sqrt{\varepsilon_2}} \cdot \tan \frac{2\pi d_2}{\lambda_1} \sqrt{\varepsilon'_2} = k1
\]

\[
j k1 = Z5
\]

\[
Z4 + Z5 = Z6
\]
\[- \left( \sqrt{\xi_2'} \right) \left( \tan \frac{2\pi d_2}{\lambda_1} \right) \gamma_2' \right) = k_2 \]

\[ j k_2 = z_7 \]
\[ 1 + z_7 = z_8 \]
\[ z_8 = z_9 \]
\[ z_9 = z_{10} \]
\[ 2\pi \frac{d_3}{\lambda} = k_3 \]
\[ \frac{1}{k_3} = z_{10} \]
\[ z_9 \cdot z_{10} = z_{11} \]
\[ z_{11} - \frac{1}{3} z_{11}^2 = z_{12} \]
\[- \left( k_3 z_{12} \right)^2 = z_{13} = \text{solution to problem} \]

After careful examination of the manual calculations provided in the appendix work sheet, and careful examination of the work sheet showing what values the various symbols used in programming the computer represent in terms of the manual calculations, the equations presented in this chapter become easier to understand, and the advantage of preparing graphs which enable direct determination of the relative dielectric constant and the dielectric loss factor (and therefore the loss tangent, \( \tan \iota \)) becomes clear.

\textbf{Sample Preparation}. Several pounds of lean bottom round beef were ground and carefully mixed to obtain as uniform composition as possible. A portion of the meat was subjected to freeze drying, packed in cans, sealed under vacuum, and stored at \(-40^\circ C\). The remainder of the ground beef was stored at \(-40^\circ C\).
Figure A-9. Graph for Direct Determination of the Relative Dielectric Constant $\kappa''$.
Figure 4-10. Graph for Direct Determination of the Relative Dielectric Constant ($\kappa'$) and the Relative Dielectric Loss Factor ($\kappa''$).
Figure 4-11. Graph for Direct Determination of the Relative Dielectric Constant ($\varepsilon'' = \varepsilon''''$) and the Relative Dielectric Loss Factor ($\kappa'' = \kappa''''$).
Freeze-dried samples had a moisture content of 1.8 per cent and were used as the "dry" sample. The 19.9 per cent moisture sample was prepared by allowing the "dry" sample to equilibrate in an atmosphere of 94 per cent RH. (The 94 per cent relative humidity was obtained by preparing a saturated solution of \( \text{NH}_4\text{H}_2\text{PO}_4 \), placing the solution in the bottom of a desiccator, placing the sample above the solution, sealing the desiccator, drawing a partial vacuum in the desiccator until the boiling point of the solution is reached, sealing, and allowing the sample to equilibrate for 48 hours at 40° C.) Samples with moisture concentrations between 19.9 per cent and the "fresh" beef moisture content of 70.3 per cent were obtained by partially reconstituting the freeze-dried beef and mixing thoroughly.

The ash content of selected samples was varied by the addition of sodium chloride, as indicated in Table V-1.

The proximate analysis of all samples is listed in Table V-1.

**Chemical Methods.**

1. **Nitrogen Content.** The determination of nitrogen content of the dried beef sample was made by the Micro-Hjeldahl method as found in Sections 28.009-28.011, pages 643 and 644 of *Official Methods of Analysis of the Association of Official Agricultural Chemists, Ninth Edition*. Values reported were the average of duplicate analyses.

2. **Moisture and Volatiles.** The determination of per-
centage content of moisture and volatiles in all samples was made by the Vacuum Oven method as found in Section 26.002, page 358 of *Official Methods of Analysis of the Association of Official Agricultural Chemists, Ninth Edition*. Values reported were the average of duplicate analyses.

3. **Mineral Content (Ash)**. The determination of percentage content of ash in the dried beef sample was made in accordance with the method described in Section 29.012, page 419 of *Official Methods of Analysis of the Association of Official Agricultural Chemists, Ninth Edition*. Values reported were the average of duplicate analyses.

4. **Total Lipid Content**. A two to one methanol-chloroform solution was used to extract the lipid material. After gentle drying, the residue was dissolved in ethyl ether. After again gently drying, this portion was weighed and reported as the ether soluble fraction.
C When sample with cover

C

Portran IV C Level 0, MOD 0 Main

Date = 67223
CHAPTER V.

RESULTS AND DISCUSSION
Ground beef samples having varying percentages of ash, protein, fat, and water content were prepared as described earlier. The relative dielectric constant ($\varepsilon_r'$), loss tangent or dissipation factor (tan $\delta$), and the relative dielectric loss factor ($\varepsilon_r''$) were determined at 0-1°C, 25°C ± 1°C, and 30°C ± 1°C. Results of these determinations are listed in Table V-1.

The Dielectric Loss Factor ($\varepsilon_r''$). The variables under consideration in this research are frequency, temperature, and chemical composition of the beef.

Figures 5-1 through 5-4, constructed from data listed in Table V-1, show the relative dielectric loss factor ($\varepsilon_r''$) of the ground beef samples as a function of water content and temperature. As temperature is increased, the relative dielectric loss factor ($\varepsilon_r''$) increases. The increase in the relative dielectric loss factor ($\varepsilon_r''$) due to the increase in temperature becomes much more marked as the percentage of water increases above 20 percent. As the water content increases from 1.8 percent to 20 percent water, there is very little increase in the relative dielectric loss factor ($\varepsilon_r''$). From a level of 20 percent water to approximately 45 percent water, there is a dramatic increase in the relative dielectric loss factor ($\varepsilon_r''$). From approximately 45 percent water to 70 percent water, the relative dielectric loss factor ($\varepsilon_r''$) appears to have reached a plateau. (At 3000 MHz, the slope has decreased, though not actually reaching a plateau.)

Examination of Figures 5-1 through 5-4 indicates that the
### Table V-1

#### Dielectric and Chemical Data for Ground Beef

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temp. °C.</th>
<th>( f ), MHz</th>
<th>( \epsilon' )</th>
<th>Tan δ</th>
<th>( \epsilon'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a)</strong> Sample 1</td>
<td>0-1</td>
<td>300</td>
<td>30.1</td>
<td>0.507</td>
<td>59.4</td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>915</td>
<td>14.9</td>
<td>0.306</td>
<td>48.7</td>
<td></td>
</tr>
<tr>
<td>0.99% Ash</td>
<td>1000</td>
<td>14.1</td>
<td>0.296</td>
<td>47.5</td>
<td></td>
</tr>
<tr>
<td>21.40% Protein</td>
<td>3000</td>
<td>5.2</td>
<td>0.247</td>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td>7.30% Ether Soluble</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70.20% Water</td>
<td>25</td>
<td>300</td>
<td>46.0</td>
<td>0.789</td>
<td>58.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>17.9</td>
<td>0.372</td>
<td>48.2</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>17.2</td>
<td>0.380</td>
<td>45.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>6.2</td>
<td>0.274</td>
<td>22.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>105.1</td>
<td>1.460</td>
<td>72.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>28.4</td>
<td>0.687</td>
<td>41.4</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>27.1</td>
<td>0.664</td>
<td>40.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>6.6</td>
<td>0.279</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td><strong>(b)</strong> Sample 1</td>
<td>0-1</td>
<td>300</td>
<td>140</td>
<td>1.320</td>
<td>106</td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>915</td>
<td>35.0</td>
<td>0.674</td>
<td>52.0</td>
<td></td>
</tr>
<tr>
<td>(with 3% NaCl added)</td>
<td>1000</td>
<td>33.0</td>
<td>0.743</td>
<td>44.2</td>
<td></td>
</tr>
<tr>
<td>3.87% Ash</td>
<td>3000</td>
<td>8.67</td>
<td>0.303</td>
<td>28.6</td>
<td></td>
</tr>
<tr>
<td>20.80% Protein</td>
<td>25</td>
<td>300</td>
<td>220</td>
<td>1.660</td>
<td>132.5</td>
</tr>
<tr>
<td>7.09% Ether Soluble</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68.20% Water</td>
<td>915</td>
<td>48.0</td>
<td>0.827</td>
<td>58.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>43.9</td>
<td>0.943</td>
<td>46.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>9.82</td>
<td>0.335</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>342</td>
<td>1.850</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>84.0</td>
<td>0.913</td>
<td>92.0</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>78.1</td>
<td>1.421</td>
<td>55.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>21.80</td>
<td>0.770</td>
<td>28.3</td>
<td></td>
</tr>
<tr>
<td><strong>(C)</strong> Sample 1</td>
<td>0-1</td>
<td>300</td>
<td>178</td>
<td>1.320</td>
<td>135</td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>915</td>
<td>48.4</td>
<td>0.824</td>
<td>58.8</td>
<td></td>
</tr>
<tr>
<td>(with 6% NaCl added)</td>
<td>1000</td>
<td>44.4</td>
<td>0.939</td>
<td>47.3</td>
<td></td>
</tr>
<tr>
<td>6.60% Ash</td>
<td>3000</td>
<td>12.60</td>
<td>0.454</td>
<td>27.8</td>
<td></td>
</tr>
<tr>
<td>20.02% Protein</td>
<td>25</td>
<td>300</td>
<td>267</td>
<td>1.340</td>
<td>201</td>
</tr>
<tr>
<td>6.89% Ether Soluble</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>66.40% Water</td>
<td>915</td>
<td>68.2</td>
<td>1.111</td>
<td>62.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>65.9</td>
<td>0.900</td>
<td>73.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>16.25</td>
<td>0.527</td>
<td>30.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>375</td>
<td>1.260</td>
<td>298</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>86.0</td>
<td>0.789</td>
<td>109.8</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>80.2</td>
<td>0.892</td>
<td>90.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>22.8</td>
<td>0.663</td>
<td>34.4</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Temp. (\degree C.)</td>
<td>(\nu), MHz</td>
<td>(\ell')</td>
<td>(\tan \delta)</td>
<td>(\ell'')</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------</td>
<td>--------------</td>
<td>-----------</td>
<td>----------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>(D) Sample 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>28.4</td>
<td>0.481</td>
<td>59.1</td>
</tr>
<tr>
<td>1.83% Ash</td>
<td></td>
<td>915</td>
<td>14.1</td>
<td>0.402</td>
<td>35.1</td>
</tr>
<tr>
<td>39.15% Protein</td>
<td></td>
<td>1000</td>
<td>13.5</td>
<td>0.386</td>
<td>35.0</td>
</tr>
<tr>
<td>13.60% Ether Soluble</td>
<td></td>
<td>3000</td>
<td>4.24</td>
<td>0.212</td>
<td>20.0</td>
</tr>
<tr>
<td>45.20% Water</td>
<td>25</td>
<td>300</td>
<td>44.3</td>
<td>0.893</td>
<td>49.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>17.8</td>
<td>0.493</td>
<td>36.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>16.0</td>
<td>0.457</td>
<td>35.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>4.40</td>
<td>0.214</td>
<td>20.5</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>94.7</td>
<td>1.480</td>
<td>64.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>29.7</td>
<td>0.703</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>29.0</td>
<td>0.793</td>
<td>36.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>5.41</td>
<td>0.250</td>
<td>21.7</td>
</tr>
<tr>
<td><strong>(E) Sample 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>113.5</td>
<td>2.520</td>
<td>45</td>
</tr>
<tr>
<td>(with 2% NaCl added)</td>
<td></td>
<td>915</td>
<td>23.7</td>
<td>0.654</td>
<td>36.3</td>
</tr>
<tr>
<td>3.75% Ash</td>
<td></td>
<td>1000</td>
<td>24.4</td>
<td>0.706</td>
<td>34.6</td>
</tr>
<tr>
<td>38.40% Protein</td>
<td></td>
<td>3000</td>
<td>7.27</td>
<td>0.367</td>
<td>19.8</td>
</tr>
<tr>
<td>13.35% Ether Soluble</td>
<td>25</td>
<td>300</td>
<td>154</td>
<td>2.960</td>
<td>52.0</td>
</tr>
<tr>
<td>44.40% Water</td>
<td></td>
<td>915</td>
<td>35.4</td>
<td>0.903</td>
<td>39.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>34.2</td>
<td>0.977</td>
<td>35.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>8.12</td>
<td>0.372</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>225</td>
<td>1.800</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>76.4</td>
<td>1.150</td>
<td>66.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>70.1</td>
<td>1.080</td>
<td>65.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>17.5</td>
<td>0.748</td>
<td>23.4</td>
</tr>
<tr>
<td><strong>(F) Sample 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>140</td>
<td>2.170</td>
<td>64.5</td>
</tr>
<tr>
<td>(with 6% NaCl added)</td>
<td></td>
<td>915</td>
<td>37.0</td>
<td>1.000</td>
<td>37.0</td>
</tr>
<tr>
<td>7.39% Ash</td>
<td></td>
<td>1000</td>
<td>33.8</td>
<td>1.060</td>
<td>31.8</td>
</tr>
<tr>
<td>37.00% Protein</td>
<td></td>
<td>3000</td>
<td>10.4</td>
<td>0.484</td>
<td>21.5</td>
</tr>
<tr>
<td>12.88% Ether Soluble</td>
<td>25</td>
<td>300</td>
<td>210</td>
<td>2.530</td>
<td>83.0</td>
</tr>
<tr>
<td>42.70% Water</td>
<td></td>
<td>915</td>
<td>50.2</td>
<td>1.130</td>
<td>44.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>47.3</td>
<td>1.126</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>14.6</td>
<td>0.614</td>
<td>23.8</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>334</td>
<td>1.550</td>
<td>215</td>
</tr>
<tr>
<td></td>
<td></td>
<td>915</td>
<td>83.0</td>
<td>1.010</td>
<td>81.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1000</td>
<td>77.3</td>
<td>0.990</td>
<td>78.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3000</td>
<td>18.9</td>
<td>0.815</td>
<td>23.2</td>
</tr>
<tr>
<td>Sample</td>
<td>Temp. C.</td>
<td>$f$, MHz</td>
<td>$\varepsilon''$</td>
<td>Tan $\delta$</td>
<td>$\varepsilon'$</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------</td>
<td>----------</td>
<td>---------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0-1</td>
<td>300</td>
<td>27.2</td>
<td>0.739</td>
<td>36.6</td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.10% Ash</td>
<td>915</td>
<td>10.6</td>
<td>0.442</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>43.00% Protein</td>
<td>1000</td>
<td>10.0</td>
<td>0.425</td>
<td>23.5</td>
<td></td>
</tr>
<tr>
<td>15.10% Ether Soluble</td>
<td>3000</td>
<td>3.73</td>
<td>0.207</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>39.80% Water</td>
<td>25</td>
<td>300</td>
<td>40.0</td>
<td>1.040</td>
<td>38.5</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>13.8</td>
<td>0.488</td>
<td>28.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>12.7</td>
<td>0.508</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>4.30</td>
<td>0.224</td>
<td>19.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>90.6</td>
<td>1.850</td>
<td>49.0</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>24.8</td>
<td>0.759</td>
<td>32.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>23.8</td>
<td>0.767</td>
<td>31.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.00</td>
<td>0.240</td>
<td>20.8</td>
<td></td>
</tr>
</tbody>
</table>

| Sample 3                      | 0-1     | 300      | 62.5          | 2.020       | 31.0        |
| Proximate Analysis            |         |          |               |             |             |
| (with 2% NaCl added)          | 915     | 12.5     | 0.513         | 24.4        |
| 4.02% Ash                     | 1000    | 12.4     | 0.526         | 23.6        |
| 43.40% Protein                | 3000    | 6.64     | 0.325         | 20.4        |
| 15.10% Ether Soluble          | 25      | 300      | 72.8          | 1.970       | 37.0        |
| 36.78% Water                  | 915     | 23.5     | 0.790         | 29.8        |
|                               | 1000    | 21.7     | 0.805         | 27.0        |
|                               | 3000    | 7.48     | 0.354         | 21.1        |
|                               | 80      | 300      | 121           | 2.420       | 50.0        |
|                               | 915     | 42.1     | 1.040         | 40.3        |
|                               | 1000    | 38.8     | 1.070         | 36.2        |
|                               | 3000    | 16.0     | 0.658         | 24.3        |

<p>| Sample 3                      | 0-1     | 300      | 65.00         | 1.980       | 32.8        |
| Proximate Analysis            |         |          |               |             |             |
| (with 5% NaCl added)          | 915     | 18.50    | 0.723         | 25.6        |
| 6.70% Ash                     | 1000    | 18.40    | 0.710         | 24.0        |
| 42.20% Protein                | 3000    | 8.27     | 0.402         | 20.5        |
| 14.60% Ether Soluble          | 25      | 300      | 77.40         | 1.950       | 39.5        |
| 35.79% Water                  | 915     | 32.50    | 0.986         | 33.0        |
|                               | 1000    | 29.40    | 0.980         | 30.0        |
|                               | 3000    | 12.30    | 0.569         | 21.4        |
|                               | 80      | 300      | 150           | 2.86        | 52.4        |
|                               | 915     | 52.0     | 1.100         | 52.5        |
|                               | 1000    | 53.2     | 1.240         | 43.0        |
|                               | 3000    | 16.5     | 0.671         | 24.6        |</p>
<table>
<thead>
<tr>
<th>Sample</th>
<th>$\text{Temp.}^\circ\text{C.}$</th>
<th>$f$, MHz</th>
<th>$\varepsilon''$</th>
<th>$\tan \delta$</th>
<th>$\varepsilon''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J) Sample 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>12.8</td>
<td>0.715</td>
<td>17.9</td>
</tr>
<tr>
<td>2.31% Ash</td>
<td>915</td>
<td>7.3</td>
<td>0.422</td>
<td>17.3</td>
<td></td>
</tr>
<tr>
<td>49.50% Protein</td>
<td>1000</td>
<td>7.1</td>
<td>0.433</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td>17.25% Ether Soluble</td>
<td>3000</td>
<td>2.68</td>
<td>0.212</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>30.90% Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>300</td>
<td>18.2</td>
<td>0.947</td>
<td>19.2</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>9.4</td>
<td>0.479</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>9.0</td>
<td>0.450</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>3.24</td>
<td>0.226</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>30.0</td>
<td>1.470</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>15.3</td>
<td>0.692</td>
<td>23.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>15.8</td>
<td>0.753</td>
<td>21.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>3.79</td>
<td>0.272</td>
<td>13.9</td>
<td></td>
</tr>
<tr>
<td>(K) Sample 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>1.42</td>
<td>0.292</td>
<td>4.85</td>
</tr>
<tr>
<td>2.67% Ash</td>
<td>915</td>
<td>1.30</td>
<td>0.216</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td>57.28% Protein</td>
<td>1000</td>
<td>1.0</td>
<td>0.250</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>19.90% Ether Soluble</td>
<td>3000</td>
<td>1.12</td>
<td>0.244</td>
<td>4.60</td>
<td></td>
</tr>
<tr>
<td>19.90% Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>300</td>
<td>1.84</td>
<td>0.328</td>
<td>5.62</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>1.81</td>
<td>0.292</td>
<td>6.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1.60</td>
<td>0.336</td>
<td>4.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>1.20</td>
<td>0.256</td>
<td>4.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>3.11</td>
<td>0.463</td>
<td>6.73</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>3.00</td>
<td>0.500</td>
<td>6.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>2.7</td>
<td>0.483</td>
<td>5.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>1.48</td>
<td>0.203</td>
<td>7.30</td>
<td></td>
</tr>
<tr>
<td>(L) Sample 6*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeze-Dried Sample</td>
<td>0-1</td>
<td>300</td>
<td>0.0443</td>
<td>0.028</td>
<td>1.60</td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>915</td>
<td>0.0422</td>
<td>0.279</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>3.34% Ash</td>
<td>1000</td>
<td>0.043</td>
<td>0.268</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>70.10% Protein</td>
<td>3000</td>
<td>0.0060</td>
<td>0.0046</td>
<td>1.30</td>
<td></td>
</tr>
<tr>
<td>24.45% Ether Soluble</td>
<td>25</td>
<td>300</td>
<td>0.0442</td>
<td>0.279</td>
<td>1.58</td>
</tr>
<tr>
<td>1.80% Water</td>
<td>915</td>
<td>0.0462</td>
<td>0.283</td>
<td>1.63</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>0.0450</td>
<td>0.0298</td>
<td>1.51</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>0.0210</td>
<td>0.0140</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>0.1170</td>
<td>0.0616</td>
<td>1.90</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>0.0294</td>
<td>0.0525</td>
<td>1.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>0.0940</td>
<td>0.073</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>0.0230</td>
<td>0.0143</td>
<td>1.61</td>
<td></td>
</tr>
</tbody>
</table>

The technique used in the thesis to measure samples was not designed for samples with moisture contents below 15%. Sample six will have a relatively high error, but is presented to show the approximate relationship of a very dry sample to those with higher moisture.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Temp. °C</th>
<th>2πr MHz</th>
<th>tan δ</th>
<th>ξ'</th>
<th>ξ''</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Sample 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>11.0</td>
<td>0.545</td>
<td>20.2</td>
</tr>
<tr>
<td>.50% Ash</td>
<td>915</td>
<td>4.4</td>
<td>0.217</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>10.70% Protein</td>
<td>1000</td>
<td>4.4</td>
<td>0.308</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>49.45% Ether Soluble</td>
<td>3000</td>
<td>2.08</td>
<td>0.164</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>39.30% Water</td>
<td>25</td>
<td>300</td>
<td>17.0</td>
<td>0.709</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>6.4</td>
<td>0.298</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>5.8</td>
<td>0.358</td>
<td>16.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>2.25</td>
<td>0.167</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>45.5</td>
<td>1.60</td>
<td>28.4</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>12.2</td>
<td>0.468</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>10.3</td>
<td>0.568</td>
<td>18.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>3.32</td>
<td>0.184</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>(b) Sample 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>20.2</td>
<td>0.624</td>
<td>32.4</td>
</tr>
<tr>
<td>.66% Ash</td>
<td>915</td>
<td>6.1</td>
<td>0.244</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td>14.30% Protein</td>
<td>1000</td>
<td>5.6</td>
<td>0.257</td>
<td>21.8</td>
<td></td>
</tr>
<tr>
<td>34.84% Ether Soluble</td>
<td>3000</td>
<td>2.28</td>
<td>0.149</td>
<td>15.24</td>
<td></td>
</tr>
<tr>
<td>50.20% Water</td>
<td>25</td>
<td>300</td>
<td>31.9</td>
<td>0.928</td>
<td>33.4</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>7.2</td>
<td>0.288</td>
<td>25.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>6.8</td>
<td>0.301</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>2.62</td>
<td>0.167</td>
<td>15.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>56.0</td>
<td>1.540</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>17.3</td>
<td>0.641</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>14.8</td>
<td>0.589</td>
<td>25.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>3.76</td>
<td>0.192</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>(c) Sample 9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>26.4</td>
<td>0.659</td>
<td>40.1</td>
</tr>
<tr>
<td>.83% Ash</td>
<td>915</td>
<td>10.4</td>
<td>0.359</td>
<td>29.0</td>
<td></td>
</tr>
<tr>
<td>17.89% Protein</td>
<td>1000</td>
<td>9.6</td>
<td>0.367</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td>38.09% Ether Soluble</td>
<td>3000</td>
<td>4.05</td>
<td>0.250</td>
<td>16.2</td>
<td></td>
</tr>
<tr>
<td>53.30% Water</td>
<td>25</td>
<td>300</td>
<td>39.6</td>
<td>0.970</td>
<td>40.8</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>11.7</td>
<td>0.394</td>
<td>29.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>11.8</td>
<td>0.451</td>
<td>26.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.0</td>
<td>0.314</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>72.4</td>
<td>1.770</td>
<td>40.9</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>20.3</td>
<td>0.620</td>
<td>32.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>22.3</td>
<td>0.832</td>
<td>26.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.25</td>
<td>0.343</td>
<td>15.3</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Temp. °C</td>
<td>f, MHz</td>
<td>ζ&quot;</td>
<td>Tan δ</td>
<td>ζ'</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------</td>
<td>--------</td>
<td>-----</td>
<td>-------</td>
<td>----</td>
</tr>
<tr>
<td><strong>Sample 10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>28.1</td>
<td>0.827</td>
<td>34.0</td>
</tr>
<tr>
<td>1.06% Ash</td>
<td>915</td>
<td>12.3</td>
<td>0.391</td>
<td></td>
<td>31.5</td>
</tr>
<tr>
<td>22.80% Protein</td>
<td>1000</td>
<td>11.4</td>
<td>0.428</td>
<td></td>
<td>26.6</td>
</tr>
<tr>
<td>24.80% Ether Soluble</td>
<td>3000</td>
<td>4.67</td>
<td>0.212</td>
<td></td>
<td>22.0</td>
</tr>
<tr>
<td>52.00% Water</td>
<td>25</td>
<td>300</td>
<td>41.0</td>
<td>1.110</td>
<td>36.8</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>13.7</td>
<td>0.435</td>
<td></td>
<td>31.6</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>12.9</td>
<td>0.480</td>
<td></td>
<td>26.9</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.35</td>
<td>0.241</td>
<td></td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>77.0</td>
<td>1.830</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>24.8</td>
<td>0.659</td>
<td></td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>24.1</td>
<td>0.884</td>
<td></td>
<td>27.3</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.73</td>
<td>0.249</td>
<td></td>
<td>23.0</td>
</tr>
<tr>
<td><strong>Sample 11</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proximate Analysis</td>
<td>0-1</td>
<td>300</td>
<td>29.2</td>
<td>0.650</td>
<td>45.0</td>
</tr>
<tr>
<td>1.60% Ash</td>
<td>915</td>
<td>14.2</td>
<td>0.447</td>
<td></td>
<td>31.8</td>
</tr>
<tr>
<td>34.30% Protein</td>
<td>1000</td>
<td>13.7</td>
<td>0.460</td>
<td></td>
<td>29.8</td>
</tr>
<tr>
<td>11.92% Ether Soluble</td>
<td>3000</td>
<td>4.85</td>
<td>0.211</td>
<td></td>
<td>23.0</td>
</tr>
<tr>
<td>52.00% Water</td>
<td>25</td>
<td>300</td>
<td>44.8</td>
<td>0.863</td>
<td>52.0</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>16.6</td>
<td>0.499</td>
<td></td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>16.2</td>
<td>0.526</td>
<td></td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>5.91</td>
<td>0.242</td>
<td></td>
<td>24.4</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>300</td>
<td>97.0</td>
<td>1.770</td>
<td>54.6</td>
</tr>
<tr>
<td></td>
<td>915</td>
<td>27.8</td>
<td>0.738</td>
<td></td>
<td>37.7</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>25.9</td>
<td>0.785</td>
<td></td>
<td>33.0</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>6.07</td>
<td>0.218</td>
<td></td>
<td>27.8</td>
</tr>
</tbody>
</table>
FIG. 5.1 THE DIELECTRIC LOSS FACTOR ($\varepsilon''$) OF GROUND BEEF AS A FUNCTION OF WATER CONTENT, MEASURED AT 300 MHz AND THREE DIFFERENT TEMPERATURES.
FIG. 5.2 THE DIELECTRIC LOSS FACTOR ($\epsilon_r''$) OF GROUND BEEF AS A FUNCTION OF WATER CONTENT, MEASURED AT 915 MHZ AND THREE DIFFERENT TEMPERATURES.
FIG. 5.3 THE DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF AS A FUNCTION OF WATER CONTENT, MEASURED AT 1000 MHZ AND THREE DIFFERENT TEMPERATURES.
FIG. 5.4 THE DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF AS A FUNCTION OF WATER CONTENT, MEASURED AT 3000 MHZ AND THREE DIFFERENT TEMPERATURES.
relative dielectric loss factor \( \varepsilon'' \) decreases with an increase in frequency over the ranges studied. At the lowest moisture level studied (1.8 per cent), all four frequencies had \( \varepsilon'' \) values near zero. Maximum \( \varepsilon'' \) values were 6.6, 29.5, 30, and 105 for 3000, 1000, 915, and 300 MHz respectively.

As the percentage of water in the beef decreases, all other components, ash, fat, and protein increase, and the contribution of these components to the relative dielectric loss factor \( \varepsilon'' \) cannot be determined from Figures 5-1 through 5-4. These graphs merely indicate that water content has an important bearing on the relative dielectric loss factor \( \varepsilon'' \).

From the data in Table V-1, it may be seen that when sodium chloride was added to samples, the relative dielectric loss factor \( \varepsilon'' \) increased dramatically. Graphs constructed as in Figure 5-30 were prepared from data listed in Table V-1. From these graphs one could not separate the effects of water content from the effects of the ash content upon the dielectric parameters of the sample. It was found possible to ascertain the effect of ash alone on \( \varepsilon'' \) by using a three-dimensional plot wherein one plotted the percentage ash on the abscissa, and the percentage water on the ordinate, then added a vertical or third-dimensional axis by using "hat pins" or some similar device, the height of which would indicate the relative dielectric loss factor \( \varepsilon'' \). Thus one could obtain the relationship of various levels of ash and water to the relative dielectric loss factor \( \varepsilon'' \). A photograph showing the graph so constructed is shown in Figure 5-5.
Figure 3-1. Three-dimensional plot showing relationship of Ash content, water content, and $\epsilon_n$. 

H$_2$O(%) 

Ash(%)
From graphs constructed as in Figure 5-5, it was possible to interpolate (by using similar triangles) the relative dielectric loss factor ($\varepsilon''_r$) as a function of ash content alone, at selected water contents and temperatures. Figures 5-6 through 5-17 indicate results of these calculations of the data given in Table V-1.

**Examination of the Calculated Values of the Relative Dielectric Loss Factor ($\varepsilon''_r$) as a Function of Ash, Selected Water Contents, and Temperatures (Figures 5-6 through 5-17).**

After examination of Figures 5-6 through 5-17, one may draw the following conclusions:

1. At a given frequency, ash content, and temperature, an increase in water concentration results in an increase in $\varepsilon''_r$ value.

2. At a given frequency, temperature, and water content, an increase in ash results in an increase in $\varepsilon''_r$ value.

3. At a given frequency, water content, and ash concentration, an increase in temperature results in an increase in $\varepsilon''_r$ value.

4. At a given temperature and chemical composition, lower frequencies have higher $\varepsilon''_r$ values. Maximum and minimum ranges for $\varepsilon''_r$ values from Figures 5-6 through 5-17 were 1.8-23 for 3000 MHz, 4-86 for 1000 MHz, 4-86 for 915 MHz, and 10-355 for 300 MHz.

There appears to be a linear relationship between the ash content and the $\varepsilon''_r$ value for a given water content and temperature from 0.5 per cent ash to approximately 3.5-4.0 per cent ash. At 3.5-4.0 per cent ash, the slope of the curve declines
FIG. 5.6 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 300 MHZ AND 0°C.
FIG. 5.7 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 300 MHZ AND 25°C.
FIG. 5.8 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATION. MEASUREMENTS MADE AT 300 MHZ AND 80°C.
FIG. 5.9 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 915 MHZ AND 0–1°C.
FIG. 5.10 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 915 MHz AND 25°C.
FIG. 5.11 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 915 MHZ AND 80°C.
FIG. 5.12 THE CALCULATED DIELECTRIC LOSS FACTOR \( (\varepsilon''_r) \) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 1000 MHZ AND 0-1°C
FIG. 513  THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 1000 MHz AND 25°C.
FIG 5.14 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF, AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 1000 MHZ AND 80°C.
FIG. 5.15 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS. MEASUREMENTS MADE AT 3000 $\text{mH}_2\text{O}$ AND 0-1°C.
FIG. 5.16 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONS MEASUREMENTS MADE AT 3000 MHZ AND 25°C.
FIG. 5.17 THE CALCULATED LOSS FACTOR ($\varepsilon_r''$) AS A FUNCTION OF ASH CONTENT, AT DIFFERENT WATER CONCENTRATIONIS, MEASUREMENTS MADE AT 3000 MH$_2$ AND 80°C.
Somewhat as the ash value is increased to approximately 6.5-7.0 per cent. This decline in slope is much more pronounced at 30°C than at the lower temperatures. (There appeared to be two exceptions to this: at 0-1°C and 25°C the 3000 MHz sample indicated a linear relationship between ash per cent and $\varepsilon''$ values from 0.5 per cent to 7.0 per cent ash.)

There may be a decrease in the slope as one reaches levels of ash below one per cent. This effect depends upon how one draws the curves, and does not manifest itself in the bulk of the data.

**Examination of the Relative Dielectric Loss ($\varepsilon''$) as a Function of Ash at Different Temperatures and Protein Concentrations (Figures 5-18 through 5-21).** If again one constructs three-dimensional graphs as in Figure 5-5, using the values listed in Table V-1 for the dielectric loss factor ($\varepsilon''$) as the height of the vertical axis, one may calculate the values for ash content at selected temperatures and protein concentrations by using the method of similar triangles.

The most striking feature illustrated in Figures 5-18 through 5-21 is that at a given frequency, ash content, and temperature, an increase in protein will decrease the $\varepsilon''$ value (due to decrease in water). It is also apparent that:

1. At a given temperature, frequency, and protein concentration, an increase in ash content results in an increase in the $\varepsilon''$ value.

2. At a given temperature, ash, and protein concentration, an increase in frequency results in a decrease in the $\varepsilon''$ value.
FIG. 518 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT DIFFERENT PROTEIN CONCENTRATIONS MEASURED AT 300 MHZ AND THREE DIFFERENT TEMPERATURES.
FIG. 519  THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT DIFFERENT PROTEIN CONCENTRATIONS. MEASURED AT 915 MHZ AND THREE DIFFERENT TEMPERATURES.
FIG. 5.20 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$) OF GROUND BEEF AS A FUNCTION ASH CONTENT, AT DIFFERENT PROTEIN CONCENTRATIONS MEASURED AT 1000 MH AND THREE DIFFERENT TEMPERATURES.
FIG. 5.21 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r^*$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT DIFFERENT PROTEIN CONCENTRATIONS. MEASURED AT 3000 MH₂ AND THREE DIFFERENT TEMPERATURES.
3. At a given frequency, protein and ash content, the \( \varepsilon'' \) value increases with an increase in temperature.

The slope of the curves in Figures 5-18 through 5-21 all have a similar appearance (with the exception of the 25°C curve at 3000 MHz). As noted earlier (in discussing \( \varepsilon'' \) as a function of ash, selected water content, and temperature), the slope of the curves now under consideration (5-18-5-21) decreases after reaching approximately 3.5-4.0 per cent ash. Since an increase in protein results in a decrease in \( \varepsilon'' \), it appears that the protein content "per se" of the beef sample plays a relatively small role and is of importance to the \( \varepsilon'' \) value primarily because of the decrease in the percentage of water present as protein percentage is increased and in altering the density of the sample. Further evidence of the relatively small contribution to the \( \varepsilon'' \) values of protein is the extraordinary low values for \( \varepsilon'' \) in the freeze-dried sample, which showed 70.1 per cent protein by analysis.

**Examination of the Relative Dielectric Loss (\( \varepsilon'' \)) as a Function of Ash at Different Ether Soluble (Fat) Values and Different Temperatures (Figures 5-22-5-25).** By again using three-dimensional graphs as in Figure 5-5, using the values listed in Table V-1 for the dielectric loss factor (\( \varepsilon'' \)) as the height of the vertical axis, one may calculate the values for ash content at selected temperatures and ether soluble concentrations by the method of similar triangles.

The most striking feature illustrated in Figures 5-22 through 5-25 is that an increase in fat in the beef sample decreases the
FIG. 5.22 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT THREE DIFFERENT ETHER SOLUBLE (FAT) CONCENTRATIONS, MEASURED AT 300 MHZ AND THREE DIFFERENT TEMPERATURES.
FIG. 5.23  THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon_r''$)
AS A FUNCTION OF ASH CONTENT, AT THREE
DIFFERENT ETHER SOLUBLE (FAT) CONCENTRATIONS,
MEASURED AT 915 MHZ AND THREE DIFFERENT
TEMPERATURES.
FIG. 5.24 THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$)
AS A FUNCTION OF ASH CONTENT, AT THREE
DIFFERENT ETHER SOLUBLE (FAT) CONCENTRATIONS,
MEASURED AT 1000 MHZ AND THREE DIFFERENT
TEMPERATURES.
FIG. 5.25  THE CALCULATED DIELECTRIC LOSS FACTOR ($\varepsilon''_r$) AS A FUNCTION OF ASH CONTENT AT THREE DIFFERENT ETHER SOLUBLE (FAT) CONCENTRATIONS, MEASURED AT 3000 MHZ AND THREE DIFFERENT TEMPERATURES.
value. The "per se" effect of fat on \( \varepsilon' \) appears to be relatively insignificant in determining \( \varepsilon'' \), and its primary importance is that an increase in the percentage fat in a sample will cause a resulting decrease in the percentage of water in the sample and alter the density of the sample. Further evidence of the relatively insignificant contribution of fat to the \( \varepsilon'' \) value of beef is the extraordinary low values for \( \varepsilon'' \) in the freeze-dried sample which had a 2.45 per cent ether soluble (fat) content by analysis.

Comparison of the Relative Dielectric Loss Factor (\( \varepsilon'' \)) of Ground Beef with Aqueous Sodium Chloride. Data presented in this thesis indicates that water and ash are the two chemical components of meat that play the more dominant role in determining the relative dielectric loss factor (\( \varepsilon'' \)). Data from von Hippel (1954) for aqueous sodium chloride at 25° C. is given in Table V-2. In this table, as the salt concentration is increased, the \( \varepsilon'' \) value increases. The \( \varepsilon'' \) decreases as frequency is increased in comparing 300 MHz to 3000 MHz. The increase in \( \varepsilon'' \) values for these aqueous sodium chloride solutions agree well with experimental data presented in this thesis for meat. Meat samples are complicated by density considerations which, according to Dunlap and Makower (1945), may alter dielectric properties. (These authors did not state to what extent density altered dielectric properties.)

Data reported for the dielectric loss factor \( \varepsilon'' \) for fresh ground beef measured at 3000 MHz in this thesis are below those values reported for beef by von Hippel (1954). After careful review, it is the opinion of the author that for "lossy" samples
Table V-2
Data on Aqueous Solutions of Sodium Chloride

<table>
<thead>
<tr>
<th>Aq. NaCl</th>
<th>$\xi_{\nu}'$</th>
<th>Tan $\delta$</th>
<th>$\xi_{\nu}''$</th>
<th>$\xi_{\nu}'$</th>
<th>Tan $\delta$</th>
<th>$\xi_{\nu}''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 Molar</td>
<td>76</td>
<td>0.78</td>
<td>59.3</td>
<td>75.5</td>
<td>0.240</td>
<td>18.1</td>
</tr>
<tr>
<td>0.3 Molar</td>
<td>71</td>
<td>2.40</td>
<td>140.2</td>
<td>69.3</td>
<td>0.435</td>
<td>30.1</td>
</tr>
<tr>
<td>0.5 Molar</td>
<td>69</td>
<td>3.90</td>
<td>268.2</td>
<td>67.0</td>
<td>0.625</td>
<td>41.9</td>
</tr>
</tbody>
</table>

such as beef, the slotted line technique, using thin samples (as used in this thesis) is an improvement over other methods, and should yield more accurate results. However, this illustrates a need for development of standards which could be used to verify technique and equipment before dielectric measurements are performed. The development of suitable standards will be discussed further under "Recommendations for Future Work."

The Relative Dielectric Constant ($\varepsilon'_\omega$). Examination of the data presented in Table V-1 indicates that the chemical and physical factors that affect the dielectric loss factor ($\varepsilon''_\omega$) have a similar affect upon the dielectric constant ($\varepsilon'_\omega$).

If again one constructs three-dimensional graphs as in Figure 5-5, using the values listed in Table V-1 for the relative dielectric constant ($\varepsilon'_\omega$) as the height of the vertical axis, one may extrapolate the values for the dielectric constant ($\varepsilon'_\omega$) as a function of ash content, at selected water percentages, and temperatures. Figures 5-26 through 5-29 were constructed from such extrapolated data.

After examination of Figures 5-26 through 5-29, one may make the following observations:

1. At a given chemical composition and frequency, the relative dielectric constant ($\varepsilon'_\omega$) increases with an increase in temperature.

2. At a given water content, temperature, and frequency, an increase in ash results in an increase in the dielectric constant.

3. At a given ash content, temperature, and frequency, an
FIG. 5.26  THE CALCULATED DIELECTRIC CONSTANT ($\varepsilon_r'$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT MEASURED AT 300 MHZ THREE DIFFERENT TEMPERATURES AND THREE DIFFERENT WATER TEMPERATURES.
FIG. 5.27 THE CALCULATED DIELECTRIC CONSTANT ($\varepsilon_r'$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, MEASURED AT 915 MHZ AT THREE DIFFERENT TEMPERATURES AND THREE DIFFERENT CONCENTRATIONS
FIG. 5.28 THE CALCULATED DIELECTRIC CONSTANT \( (\varepsilon'_r) \) AS A FUNCTION OF ASH CONTENT, MEASURED AT 1000 MHZ AND THREE DIFFERENT TEMPERATURES AND THREE DIFFERENT WATER CONCENTRATIONS.
FIG. 5.29 THE CALCULATED DIELECTRIC CONSTANT ($\varepsilon'_r$) AS A FUNCTION OF ASH CONTENT, MEASURED AT 3000 MH$_2$ AND THREE DIFFERENT TEMPERATURES AND THREE DIFFERENT WATER CONCENTRATIONS
FIG. 5.30 THE DIELECTRIC LOSS FACTOR ($\varepsilon_r''$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, MEASURED AT 3000 MHz AND THREE DIFFERENT WATER CONCENTRATIONS, AND THREE DIFFERENT TEMPERATURES.
increase in water content results in an increase in the dielectric constant.

4. At a given chemical composition and temperature, an increase in frequency will result in a decrease in the relative dielectric constant ($\varepsilon''$). From Figures 5-26 through 5-29, the minimum $\varepsilon''$ values listed for 300 MHz, 915 MHz, 1000 MHz, and 3000 MHz are 31.9, 22.3, 21.7, and 16.9 respectively. Maximum $\varepsilon''$ values found in Figures 5-26 through 5-29 are 298, 109.8, 90, and 34.4 for 300 MHz, 915 MHz, 1000 MHz, and 3000 MHz respectively.

5. The increase in the dielectric constant which results from an increase in temperature is least at ash concentrations found in most foods (i.e., below two per cent ash).

The temperature and frequency effect upon the dielectric constant is in agreement with many reports in the literature, although the values calculated for 3000 MHz in this thesis are lower than those reported by von Hippel (1954) for beef steak, and by Schwan (1956) for muscle. Review of the slotted line technique, using thin samples for the "lossy" samples used in this work, leads the author to conclude that the method used in the current work would give accurate results. Again the need for accepted standards for dielectric work on "lossy" material such as foods would help to erase any doubt one might have concerning the technique and equipment used for determining dielectric parameters.

Examination of Figures 5-26 through 5-29 indicates that the response of the relative dielectric constant ($\varepsilon''$) to an increase in ash value is linear over the concentrations and
temperature ranges studied, and it is apparent that the slope of the curves at lower temperatures and lower water concentrations is considerably less than the slope of those samples which have higher water concentrations and which were performed at higher temperatures.

The Loss Tangent or Dissipation Factor (\(\tan \delta\)). From data given in Table V-1, three-dimensional graphs were constructed as was done in Figure 5-5. The ash content was plotted on the abscissa, the water content on the ordinate, and the value for \(\tan \delta\) was represented by the height of the vertical axis. By the method of similar triangles, values were calculated for \(\tan \delta\) at specific water concentrations, temperature, frequency, and ash content. These calculated values were used to construct Figures 5-31 to 5-33. After examination of Figures 5-31 to 5-33, the following observations may be made:

1. At a given frequency, ash content, and temperature, an increase in water content does not result in an increase in values for \(\tan \delta\). (In contrast to observations for values of \(\varepsilon''\) and \(\varepsilon'\), noted previously.)

2. At a given temperature, frequency, and water content, an increase in ash from approximately 1 per cent to 3.5-4.0 per cent results in an increase in \(\tan \delta\) values. Above 3.5-4.0 per cent ash, values for \(\tan \delta\) increase slightly, remain relatively constant, or decrease.

3. At a given frequency, water content, and ash concentration, an increase in temperature results in an increase in
FIG. 5.31 THE CALCULATED LOSS TANGENT ($\tan \delta$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT THREE DIFFERENT TEMPERATURES, FOUR DIFFERENT FREQUENCIES, AND CONSTANT WATER CONTENT (37.5% $\text{H}_2\text{O}$).
FIG. 5.32 THE CALCULATED LOSS TANGENT ($\tan \delta$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT THREE DIFFERENT TEMPERATURES, FOUR DIFFERENT FREQUENCIES, AND CONSTANT WATER CONTENT (52.5% H$_2$O)
FIG. 5.33 THE CALCULATED LOSS TANGENT ($\tan \delta$) OF GROUND BEEF AS A FUNCTION OF ASH CONTENT, AT THREE DIFFERENT TEMPERATURES, FOUR DIFFERENT FREQUENCIES, AND CONSTANT WATER CONTENT (66% H₂O)
tan \( \delta \) values, except for the 300 MHz frequency, which had variable response in tan \( \delta \) values as a result of changes in temperature.

4. At a given temperature and chemical composition, lower frequencies have higher tan \( \delta \) values. The tan \( \delta \) values for 915 MHz and 1000 MHz for a given temperature closely approximate each other.
CHAPTER VI.

CONCLUSIONS
From the data of this thesis, the following conclusions may be drawn for the dielectric properties of ground beef.

The Relative Dielectric Loss Factor ($\varepsilon_\infty$).

1. At a given frequency, ash content, and temperature, an increase in water concentration results in an increase in $\varepsilon_\infty$ values.

2. At a given frequency, temperature, and water content, an increase in ash results in an increase in $\varepsilon_\infty$ values.

3. At a given frequency, water content, and ash concentration, an increase in temperature results in an increase in $\varepsilon_\infty$ values.

4. The effect of protein on the $\varepsilon_\infty$ value appears to be less pronounced than the effect of water or ash. It is difficult to quantitatively estimate the relationship of protein content to $\varepsilon_\infty$ values because a variation in protein inevitably varies the water or ash content.

5. The "per se" effect of fat upon $\varepsilon_\infty$ values is relatively small and would appear to be related to its effect on the water and ash contents and to any affect the fat may have on the density of the sample. As with protein, the effect of fat upon $\varepsilon_\infty$ values is difficult to quantitatively estimate because addition of fat changes other variables.

6. At a given temperature and chemical composition, lower frequencies have higher $\varepsilon_\infty$ values. For example, from Figures 5-6 to 5-17, it may be seen that at 0-1°C for 0.5 per cent ash content and 37.5 per cent water content, the $\varepsilon_\infty$ value was 1.8,
4, 4, and 10 for 3000 MHz, 1000 MHz, 915 MHz, and 300 MHz respectively. At 7 per cent ash content and 66 per cent water content, $\varepsilon_r'$ values at 80° C. were 23, 80, 86, and 355 for 3000 MHz, 1000 MHz, 915 MHz, and 300 MHz respectively.

**The Relative Dielectric Constant ($\varepsilon_r'$).**

1. At a given frequency and chemical composition of sample, an increase in temperature results in an increase in $\varepsilon_r'$ values.

2. At a given frequency, temperature, and water content, an increase in the ash content results in an increase in $\varepsilon_r'$ values.

3. At a given frequency, temperature, and ash concentration, an increase in water percentage will result in an increase in $\varepsilon_r'$ values.

4. At any given temperature and chemical composition of sample, a decrease in frequency results in an increase in $\varepsilon_r'$ values. For water values between 37.5 per cent and 66 per cent, minimum and maximum $\varepsilon_r'$ values were: (a) 16.9 to 34.4 for 3000 MHz, (b) 21.7 to 90 for 1000 MHz, (c) 22.3 to 109.8 for 915 MHz, and (d) 31.9 to 298 for 300 MHz.

5. At ash concentrations within the range of most foods (below 2 per cent), the effect of an increase in temperature upon the $\varepsilon_r'$ values is much less than at high ash concentrations (above 4 per cent).

6. If both water concentration and temperature (0-1° C. and 37.5 per cent H₂O) are low, increasing ash has very little effect upon the $\varepsilon_r'$ values.
The Loss Tangent or Dissipation Factor (Tan δ).

1. In contrast to observations for values of $\tan''$ and $\tan'$, an increase in water content at a given frequency, ash content, and temperature does not result in an increase in values for tan δ.

2. At a given temperature and chemical composition, lower frequencies have higher tan δ values. For 300 MHz, maximum and minimum values for tan δ for the water and ash concentrations studies in Figures 5-31 to 5-34 were: (a) 0.489 to 2.72 for 300 MHz, (b) 0.322 to 1.13 for 915 MHz, (c) 0.311 to 1.17 for 1000 MHz, and (d) 0.208 to 0.815 for 3000 MHz.

3. For the values under study for preparation of Figures 5-31 to 5-34, an increase in ash concentration up to approximately 3.5 to 4.0 per cent resulted in an increase in tan δ values if temperature, frequency, and water content remained constant. Above 3.5-4.0 per cent ash, an increase in ash content showed no consistent correlation with tan δ values.

4. An increase in temperature results in an increase in tan δ values. The 300 MHz frequency is an exception to this statement, and no correlation between temperature and tan δ was found at this frequency.

The Effect of Chemical Composition of the Sample upon the Power which can be Generated within the Sample and upon the Half Power Depth (Penetration) of the Sample. Data for calculating the factors in Table VI-1 came from data presented in Table V-1 and is based upon Equations 1.2 and 1.3 from Chapter I:

\[ P = K E^2 \ (\tan'' \cdot f) \]  
\[ \text{(Eq. 1.2)} \]
\[ HPD = \frac{0.693}{\left(\varepsilon_r'\right)^2 \tan \delta \cdot 55.61 \times 10^{-14} f} \quad (Eq. 1.3) \]

From Equation 1.2 it is seen that the "power" factor is proportional to \( \varepsilon_r' \). From Equation 1.3 it may be seen that the "Half Power Depth" is inversely proportional to \( \varepsilon_r' \) \( \tan \delta \) \( f \).

After examination of Table VI-1, one may conclude for the three samples shown:

1. **Low Moisture Samples (Sample 1).**
   a. Of the three samples shown in Table VI-1, low moisture samples will be the most difficult to heat by microwaves.
   b. The "Half Power Depth" is greatest for low moisture samples.
   c. The 3000 MHz frequency appears to be the better choice of frequencies (of those considered) if one wishes to heat low moisture samples. This is in agreement with work by Goldblith and Pace, 1967.

2. **High Moisture Samples (Sample 2).**
   a. It is much easier to generate heat within the high moisture sample than within the low moisture sample.
   b. The relative advantage of using 3000 MHz for heating the high moisture samples has decreased from that shown for low moisture samples.
   c. The "Half Power Depth" decreases with an increase in frequency.

3. **High Moisture, High Ash Samples (Sample 3).**
### Table VI-1

Factors Relating to the Energy Needed to Heat a Food Sample

and to the Penetration of Microwaves into the Food Sample

(all samples at 25° C.)

<table>
<thead>
<tr>
<th>Sample</th>
<th>( f ), MHz</th>
<th>( \epsilon' \epsilon'' f )</th>
<th>((\epsilon'')/(\tan \phi))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>0.55 x 10^9</td>
<td>0.233 x 10^9</td>
</tr>
<tr>
<td>Low ( H_2O ) (19.9%)</td>
<td>915</td>
<td>1.66 x 10^9</td>
<td>0.650 x 10^9</td>
</tr>
<tr>
<td>No NaCl added</td>
<td>1000</td>
<td>1.60 x 10^9</td>
<td>0.736 x 10^9</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>4.44 x 10^9</td>
<td>1.670 x 10^9</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>13.8 x 10^9</td>
<td>1.80 x 10^9</td>
</tr>
<tr>
<td>High ( H_2O ) (70.1%)</td>
<td>915</td>
<td>16.4 x 10^9</td>
<td>2.36 x 10^9</td>
</tr>
<tr>
<td>No NaCl added</td>
<td>1000</td>
<td>17.0 x 10^9</td>
<td>2.56 x 10^9</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>18.4 x 10^9</td>
<td>3.9 x 10^9</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>80.1 x 10^9</td>
<td>5.70 x 10^9</td>
</tr>
<tr>
<td>High ( H_2O ) (66.4%)</td>
<td>915</td>
<td>63.4 x 10^9</td>
<td>8.00 x 10^9</td>
</tr>
<tr>
<td>6.6% Ash</td>
<td>1000</td>
<td>65.9 x 10^9</td>
<td>7.70 x 10^9</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td>48.7 x 10^9</td>
<td>8.67 x 10^9</td>
</tr>
</tbody>
</table>

B. Factors Relating (Inversely) to the Half Power Depth,
a. The high water, high ash sample is the most favorable sample for the generation of heat by microwaves.

b. All frequencies show great ability to generate heat within these samples. The order in which the various frequencies produce heat within the sample is now inversely related to the frequency.

c. For all frequencies the "Half Power Depth" (and hence penetration into the sample) is least in the high moisture, high ash samples, and may place severe restrictions upon sample thickness.
CHAPTER VII.

RECOMMENDATIONS FOR FUTURE WORK
The following presentation will be useful to future experimentalists in analyzing the dielectric behavior of foods under conditions similar to those undertaken in this thesis.

1. **Sample Preparation.** Freeze-dried samples sealed under vacuum and stored at $-40^\circ$ C. are recommended. These samples can be rehydrated to the desired moisture content. When rehydrating, follow procedures described in Chapter IV, "Experimental Methods." Thorough mixing of the sample to assure an even distribution of moisture throughout the sample is necessary.

This method of storage allows one to prepare a large, homogeneous sample for use throughout the course of the investigation. Once the chemical composition of the prepared sample is known, manipulations of the ratios of the various chemical components can be made by adding particular components such as fat, water, etc., to the sample.

Samples prepared with a fixed moisture content (say 50 per cent) and a fixed ash content (say 2 per cent) can be prepared in which the ratios of other major chemical components can be varied. This will allow a more definitive examination of variables other than ash and water. Normally, the last step which should be performed in preparing samples is the addition of the desired amount of water.

2. **Measurements at Different Temperatures.** It is recommended that a wide range of temperatures be studied on the dielectric behavior of foodstuffs. This is possible through
the use of equipment commercially available. This type of equipment contains thermal control devices allowing measurements to be taken from -40° C. to 160° C. When making measurements at low temperatures (below the dew point), one must be careful to continually purge the upper portion of the sample holder with nitrogen to prevent condensation of moisture around the center conductor.

When performing measurements at high temperatures an occasional check of the solder of the lower section of the sample holder is recommended. Any water which enters into the sample holder will cause erroneous results.

3. **Calculation of $\epsilon''$, $\epsilon'$, and tan $\delta$.** It is recommended that one determine the maximum and minimum values for $\epsilon''$ and $\epsilon'$ which are likely to be found in the experimental data, and prepare graphs as found in Figures 4-8 through 4-11 to allow direct determination of dielectric values from measurements taken on the dielectrometer. Twenty seconds of computer calculations is equivalent to forty hours by manual calculation. It is, therefore, recommended that a standard computer program be kept on file for routine calculations.

4. **Sample Thickness.** When measuring "lossy" samples such as fresh ground beef, it is recommended that the height of the sample be reduced to 0.15 cm. from 0.26 cm. when making determinations at 2450 MHz or 3000 MHz. This height is also recommended for samples which have an ash content above 3 percent, regardless of the frequency used. This will make the
physical collection of data much more rapid. If the computer
program is used for calculating $\varepsilon_r''$ and $\varepsilon'_r$ as in Figures 4-8
to 4-11, then the change in sample height will necessitate con-
struction of additional graphs.

When measuring low loss samples such as dried beef, thick
samples of approximately $1/4 \lambda$ are required.

5. **Study of Density.** From data calculated by von Hippel
(1954) at 1000 MHz, the $\varepsilon_r''$ value for polystyrene 50 per cent,
carbon 50 per cent is 21.8 when the polystyrene is molded at
1000 p.s.i. However, $\varepsilon_r''$ drops to a value of 16.5 if molded
at 10,000 p.s.i. Just the opposite trend was found at 3000 MHz.
The $\varepsilon_r''$ value for polystyrene molded at 1000 p.s.i. is 11.6
and increases to 15.5 if molded at 10,000 p.s.i.

From these analyses, it may be possible to measure the
dielectric properties of relatively dry food samples "molded"
at different pressures. This approach may allow a correlation
between density and dielectric parameters. This technique is
recommended for future studies.

6. **Calibration of Dielectrometers.** If standards of known
dielectric parameters are available, one may become proficient
with the experimental equipment prior to experimentation. Such
standards would also be of value for reference during the course
of an investigation. It is recommended that the following stan-
dards be employed.

a. For studies on frozen food, either water or saline
solutions are adequate. According to Hopkins (1960), at $-20^\circ$ C.,
sodium chloride has no effect on the dielectric parameters of frozen material.

b. For comminuted, ground, or flesh type samples, silicon rubber samples with a given percentage of carbon added can be prepared with dielectric properties in the range of foods.

c. If a solid standard is necessary, polystyrene 50 per cent plus carbon 50 per cent has dielectric properties within the range of foods and would be a satisfactory standard.

Standards with physical properties similar to the food sample would allow an exact duplication of technique between the known standard and the unknown sample, thus increasing the probability that studies of dielectric parameters performed by various workers and methods are comparable.

7. Computerized Evaluation of Chemical and Physical Variables. Data collected in this thesis, plus other similar data can conceivably lead to prediction of dielectric parameters from a knowledge of chemical composition, frequency, temperature, and density. Mathematical predictions of the most economic technique for heating dielectric material with microwaves can be ascertained. This can greatly facilitate design of heating equipment and make "tailoring" of foods for heating by microwaves more feasible.

If dielectric parameters can be accurately predicted from knowledge of the chemical and physical variables of foods, then preliminary mathematical feasibility studies can be undertaken which can predict areas in which the most fruitful work is likely
to be accomplished. For example, from data such as presented in this thesis, it is possible, through computer analysis, to determine the temperature and frequency at which the greatest tendency for selective heating of microorganisms occurs in a given food. (The chemical composition of the microorganism differs from the chemical composition of the food under study.) Next, the heat exchange characteristics between microorganisms and their environment should be computed. If results of such mathematical calculations (which would necessarily contain several assumptions) indicate that selective heating of microorganisms can occur in such an environment, then experimental investigation can be undertaken with the great advantage of having the mathematically predicted frequency and temperature at which fruitful results are more likely to occur. If such mathematical computations indicate that fruitful results are not likely for the system under question, then experimental expense could conceivably be avoided. (Milk, beer, or wine would be interesting systems to investigate.)

Mathematical examination to predict conditions for selective heating of microorganisms on a relatively dry material, such as the surface of bread crust, should also be undertaken.
CHAPTER VIII.

APPENDIX
Coaxial Line Method for Double Layer Dielectrics

Sample No. 1: 72.2% H₂O  
Substance: Gr. Beef  
Temp.: 80° C. ± 1° C.  

\[ d_2 = 0.936 \quad \lambda = 30 \]

\[ d_3 = 0.260 \quad \varepsilon'_\infty = 41 \]

\[ \varepsilon''_\infty = 27.6 \]

\[ \tan \delta = 0.674 \]

\[ N_3 - N_\lambda = \Delta N \]

\[ X_0 = \Delta N + X_{0E} \]

\[ \Delta X_{\eta_1} = \frac{-0.767}{0.099} \]

\[ \Delta X_{\eta_2} = \frac{-3.572.8}{0.111} \]

\[ N_0 = +0.053 \]

\[ N_5 = +0.053 \]

\[ X_0 = \Delta N + X_{0E} \]

\[ X_0 = 3.5470 - 40.293 = -41.780 \]

\[ + 4.940 \]

\[ \frac{-0.454}{0.454} \]
\[ \Delta X = \Delta X_3 - \left[ \chi_0 + \kappa \cdot \gamma \right] \frac{\Delta X_1}{\Delta X_2} \]
\[ \Delta X = 1.74 - \left[ 0.7 \cdot 10^6 \cdot 1.5 \times 10^5 \right] \frac{0.0005}{1.5 \times 10^5} \]
\[ \Delta X = 1.45 \]
\[ E = \frac{\Sigma \Delta X}{2} - C = 0.170 \]
\[ \tan \alpha = E - j \frac{360^\circ \chi_0}{\Delta X} \]
\[ \alpha^\prime \quad \alpha^\prime = \tan \frac{360^\circ \chi_0}{\Delta X} \]
\[ \tilde{\alpha} \tilde{\alpha} = \frac{E - j \frac{\chi_0}{\Delta X}}{1 - j \frac{\chi_0}{\Delta X}} \]

Solve for This Complex Equation
\[ \tan \alpha = \frac{E + j (2 \cdot c - \gamma) \frac{\gamma}{\chi_0}}{1 + j (2 \cdot c - \gamma) \frac{\gamma}{\chi_0}} \]
\[ \tan \alpha = \frac{(0.170) + j \left( \frac{2 \cdot 10^6}{0.0005}\right) (0.0005)}{1 + j \left( \frac{2 \cdot 10^6}{0.0005}\right) (0.0005)} \]
\[ \alpha = \alpha_0 = 0.172 - j 0.492 \]
\[ \frac{0.172 - j 0.492}{1 - j \{2 \cdot 10^6 (0.0005)} \]
\[ \tan \alpha = \frac{E - j \frac{\gamma}{\chi_0}}{1 - j \left( \frac{\gamma}{\chi_0}\right)} \]
\[ \tilde{\alpha} \tilde{\alpha} = \frac{0.172 + j (0.364)}{1 - j \{2 \cdot 10^6 (0.0005)} \]
\[ \alpha = \alpha_0 = 0.172 - j 0.572 \]
Constants Used for Thin Fins, etc.

1) $c' = 0.225$ ft

2) $\frac{320.0}{2} = \sqrt{L_2} = 0.347$

3) $\sqrt{L_2} = 1.2$

4) $\sqrt{L_2} = 0.239$

For Complex Equations

$A + jB = R \angle \theta$

$R = \sqrt{A^2 + B^2}$

$\theta = \tan^{-1} \frac{B}{A}$

\[
\frac{R_1}{R_2} = \frac{A_1}{A_2} \frac{B_2}{B_1}
\]

\[
\theta_1 = \tan^{-1} \frac{B_1}{A_1} \quad \theta_2 = \tan^{-1} \frac{B_2}{A_2}
\]

\[
\theta = \tan^{-1} \frac{B}{A}
\]

See Chart of Complex

\[
\begin{align*}
A_1 &= \sqrt{(0.11)^2 + (0.30)^2} = 0.347 \\
A_2 &= \sqrt{(0.07)^2 + (0.50)^2} = 0.523 \\
\theta_1 &= \tan^{-1} \frac{0.30}{0.11} = 75.5^\circ \\
\theta_2 &= \tan^{-1} \frac{0.50}{0.07} = 66.4^\circ \\
\theta &= \tan^{-1} \frac{0.30}{0.11} = 75.5^\circ
\end{align*}
\]

$\theta_1 = 120^\circ$,

$\theta_2 = -45^\circ$

$\theta = \tan^{-1} \frac{0.30}{0.11} = 75.5^\circ$

\[
\frac{C' \cdot j^{x - 2}}{C''} = \sqrt{\left(\frac{C_1}{C_2}\right)^2} = 0.33 \cdot 180^\circ - 30^\circ
\]

\[
C_2' = (44.2) \cdot (C_2'' = 2)
\]

\[
\frac{C_1}{C_2} = 0.33
\]
Coaxial Line Method for Double Layer Dielectrics

Sample No. 1: 72.2% H₂O  
d₂ = 0.935  

d₁ = d₂ + d₃  

Substance: Gr. Reef  
d₃ = 0.260 cm.  

Temp.: 80° C. ± 1° C.  

X₀E = 4.944  

\[ \tan \delta = 0.674 \]

\[ X_e = \chi_H + X_{0E} \]

\[ L_s = \chi_e - \left[ \chi_0 \frac{\chi}{L_s} \right] \frac{\Delta X_2}{m \frac{\chi}{L_s}} \]

\[ E = \frac{E_{max}}{E_{min}} = \frac{\chi}{\alpha} \]

\[ L_{in} S_{in} = \frac{E_{in}}{1 - j \chi E_{in} \frac{3 \chi_2 X_2}{M}} = \frac{2\chi_1}{\chi} = \chi_1 \]

\[ L_{in} S_{in} = \frac{L_{in}}{1 - j \chi E_{in} \frac{3 \chi_2 X_2}{M}} \]

\[ Z_{in} = j \chi_1 \]

\[ Z_{in} : Z_{21} = Z_{12} \]

\[ 1 + j \chi_1 = \chi_2 \]
\[ \frac{c_0 \sqrt{\kappa}}{x} \cdot \frac{d}{dx} \lambda \partial^2 + h \sqrt{\beta^2} = \frac{j}{\sqrt{\pi} \sigma} \int \frac{1}{x^2} \left( \frac{2\pi \sigma}{\lambda} \right) = Z_0 \]

\[ X \partial_x h_x = j \left( \frac{2\pi \sigma}{\lambda} \right) = Z_0 \]

\[ X = Z_{12}, \quad Z_{10} = \frac{j}{k_3} \]

\[ Z_{11} = Z_1 \cdot Z_{12} \]

\[ Z_{12} = Z_{11} - \frac{V_0}{2}, Z_{22} \]

\[ \frac{C_{12} - j C_{12}'}{C_{12}} = - \left( \frac{x \lambda}{2 \pi \sigma} \right)^2 = Z_{13} \]
$X_{0E}$ may be calculated from the following equation:

$$-j \bar{\varepsilon}_r \frac{2 \pi X_{0E}}{\lambda} = \frac{j \frac{1}{\sqrt{\varepsilon_r}} \tan \left( \frac{2 \pi d_2}{\lambda} \sqrt{\varepsilon_r} \right) - j \cos \frac{2 \pi d_3}{\lambda}}{1 + \sqrt{\varepsilon_r} \tan \left( \frac{2 \pi d_3}{\lambda} \sqrt{\varepsilon_r} \right) \cos \frac{2 \pi d_3}{\lambda}}$$

$d_2$ = thickness of cover 0.963 cm.

$d_3$ = thickness of sample space = 0.260 cm.

$\varepsilon_r'$ = relative dielectric constant of polystyrene material of cover

$\lambda$ = wave length

For $\lambda = 100$ cm:

$$\tan = 0.0628 \left( 0.963 \sqrt{2.5} \right) = 0.0965$$

$$\cos = \frac{1.00}{2 \pi (0.260)} = 61.2$$

$$\cot = \frac{2 \pi X_{0E}}{\lambda} = \frac{10.40}{61.2} = 0.170 = 80.91' = 80.55^\circ$$

$X_{0E} = 2.2316 \lambda$
CHAPTER IX.

BIBLIOGRAPHY


