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TECHNICAL REPORT

TR-76-27-FEL

DIELECTRIC PROPERTIES OF FOODS

Massachusetts Institute of Technology
Dept. of Nutrition and Food Science
Cambridge, Massachusetts

Project Reference: 1T762724AH99

November 1976

UNITED STATES ARMY
NATICK RESEARCH and DEVELOPMENT COMMAND
NATICK, MASSACHUSETTS 01760

Food Engineering Laboratory
Fel-45

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 76-27 - FEL	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DIELECTRIC PROPERTIES OF FOODS		5. TYPE OF REPORT & PERIOD COVERED Final 14 June 72 - 15 June 75
		6. PERFORMING ORG. REPORT NUMBER FEL-45
7. AUTHOR(s) Daniel I. C. Wang and Samuel A. Goldblith		8. CONTRACT OR GRANT NUMBER(s) DAAG17-72-C-0142
9. PERFORMING ORGANIZATION NAME AND ADDRESS Massachusetts Institute of Technology Dept. of Nutrition and Food Science Cambridge, Massachusetts		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1T762724AH99 6.2 CA-006
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Natick Research and Development Command DRXNM-WS Natick, MA 01760		12. REPORT DATE August 1975
		13. NUMBER OF PAGES 26
14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

DIELECTRIC PROPERTIES	MOISTURE	FREQUENCY
MEAT	COAXIAL LINE TECHNIQUE	FROZEN FOODS
FOOD	MICROWAVES	THAWING
TEMPERATURE	PENETRATION DEPTHS	COMPUTATIONS
MEASUREMENT	DEPTH	HEATING

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of the work reported herein was to provide dielectric properties data needed in the mathematical modelling of meat roasting in those cases involving the use of microwave energy.

Earlier measurements on the dependence of dielectric properties of meats on temperature at the microwave frequencies of 2450, 915 and 300 MHz have been extended to cover the range of -40° to $+120^{\circ}C$. A coaxial line technique, with a shorted sample holder for frozen samples and quarter-wavelength holders for

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20. (Abstract (Cont.)

samples above freezing is used for all measurements. The results are in general agreement with published data in the literature. For thawed samples, K' decreases with temperature and frequency but increases with moisture content. K" on the other hand increases with temperature and moisture content but decreases with frequency. Calculations using these dielectric data show that at high temperatures the differences in penetration depth and power absorption between the three frequencies are reduced.

SUMMARY

The dielectric properties of various types of meats have been determined as a function of frequency and temperature. The specific meat products which have been tested include raw beef, pork, chicken breast, chicken thigh, and turkey rolls. The frequencies which were employed in the dielectric measurements were 2450, 915, and 300 MHz. The temperature range in these measurements was from -40° to $+120^\circ$C. In addition, these precooked meats and their juices were also measured with respect to their dielectric properties at frequencies of 2450, 915, and 300 MHz and temperatures ranging from 5° to 65°C.

PREFACE

Microwave energy is a technique which could lead to substantial improvements in the cooking process. In order to apply this technology most effectively, it is necessary to have a knowledge of the properties of foods which affect this heating performance. The dielectric constant and dielectric loss factor are the two most important properties which need to be determined. This report describes the results of measurements of the properties for beef, pork, chicken and turkey as a function of microwave frequency and temperature.

The work was performed under Project No. 1T762724AH99, Food Technology, Tech Area AH99C, Food Service Technology, Technical Effort AH99CA, Studies on Garrison and Field Food Service Equipment. Dr. Robert V. Decareau and Mr. John C. Perry were the Project Officer and the Alternate Project Officer, respectively, for the US Army Natick Research and Development Command.

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DIELECTRIC PROPERTIES OF FOODS

Introduction

In the use of microwaves to heat foodstuffs, two parameters which determine the rate of heating are the amount of power (P) absorbed by the sample and the depth of penetration by the microwaves into the sample as measured by the half-power-penetration depth (HPD). Power absorption in watts per cubic centimeter is given by:[1]

$$P = 55.6 \times 10^{-14} E^2 f K'' \quad (1)$$

where E is the electric field strength in volts/cm, f the frequency in Hz and K" the relative dielectric loss. The half-power-penetration depth is defined as the depth in the sample at which the power level is reduced to 50% of the incident power at the surface. It can be calculated by:[2]

$$HPD = \frac{\lambda \ln 2}{2 (K')^{1/2}} \left[\frac{2}{(1+\tan^2\delta)^{1/2}-1}\right]^{1/2} \quad (2)$$

where HPD has the units of λ the wavelength, and the K' is the relative dielectric constant, $\tan^2\delta$ is the ratio K"/K' or the loss tangent. Given a microwave field of fixed intensity and frequency, the dependence of a food's heating characteristics on its dielectric properties K' and K" are indicated in Equations 1 and 2. Although there have been numerous published data on the dielectric properties of foods[3] and agricultural products,[4] there was until recently[5] no information on the dielectric properties of meat products from the frozen state up to sterilization temperatures. The purpose of this report is to provide a summary of the results of dielectric measurements from the start of this project in June 1972 to date.

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1. Goldblith, S.A. Adv. Food Res. 15:277, 1967

2. Püschner, H. Heating and Microwaves; Phillips, Technical Library, Springer-Verlag, New York, 1966.

3. Goldblith, S.A., and R.V. Decareau, An Annotated Bibliography on Microwaves; MIT Press, Cambridge, 1973.

4. Tinga, W.R., And S.O. Nelson. J. Microwave Power 8 (1):23, 1973.

5. Ohlsson, T., and N.E. Bengtsson. J. Microwave Power 10 (1):93, 1975.

II. Materials and Methods

A. Measurement technique and equipment.

Details of the measurement technique using the coaxial line[6] method have been described for high loss[7] as well as low loss[8] samples. For measurements in the temperature range of -40° to +65°C, klystron tubes were used to generate the 2450 and 915 MHz signals and an oscillator (General Radio, Concord, Massachusetts) was used to supply the 300-MHz signal. For the high temperature measurements, a crystal oscillator (Lektronics Lab, Philadelphia, Pennsylvania) which simultaneously puts out signals at 900 and 300 MHz was used so that the same sample holder could be used to measure one sample at the two lower frequencies. Figures 1 to 3, respectively, show sample holders used to measure frozen samples, thawed samples up to 65°C, and thawed samples from 80°C to 120°C. All holders are constructed of brass with a one-inch inner-diameter outer conductor and a 3/8-inch outer-diameter center conductor. All but the open circuited low loss holder for low temperatures had alumina bottom covers. A total of six sample holders were constructed for these measurements, each with specifications shown in Table 1.

Temperature control was achieved using a constant temperature bath with a Haake E51 thermostated heater. Water was used in the bath for temperatures between 5° and 65°C. Mineral oil was used for higher temperatures. Sample holders were immersed, and ten minutes was allowed for temperature equilibration. For the below-freezing temperatures, a refrigerated bath (Tenney Engineering, Union, New Jersey) was used to circulate cooled denatured ethanol to the styrofoam insulated holder (Figure 1). Because of the size of the sample at these temperatures, one hour was allowed for temperature equilibration. Temperatures in the holder were monitored by a thermocouple with ice/water reference junction. At temperatures below ambient, dry nitrogen was used to purge the holder and remove moisture condensation which would otherwise markedly affect the measurements.

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6. Roberts, S., and A.J. von Hippel. Appl. Phys. 17(6):610, 1946.

7. To, E.C. MS Thesis. MIT, 1974.

8. Pace, W.E. MS Thesis, MIT, 1967.

Measurements were started at the low end of the range (5° or 80° respectively in the water or oil bath) working up. In low temperature measurements, the sample was cooled to -20°C first, then -40°C. Calculations were done by computer using the two programs of Westphal and Iglesias.[9]

B. Sample preparation.

All meat samples were brought fresh from local supermarkets. Turkey roll used was a commercial frozen product (Top Frost) which contained added salt. Sample preparation, storage, cooking, and rendering of the cooked juices as well as loading techniques have been described.[7] For the low temperature measurements, the frozen meat (unground) was allowed to thaw slightly in order to facilitate cutting into blocks. A specially designed borer 1.5 inches in diameter was used to bore out disks about two inches thick. These are cut into one-cm disks in a cutter with micrometer advance, and then cut to conform to the dimensions of the coaxial line using a doughnut-shaped cutter. Eight to ten disks were then stacked into the holder to give a sample thickness of about 10 cm. The exact sample thickness was obtained by difference in micrometer depth gauge measurements of the empty and filled holder. Thermal expansion of the sample was assumed negligible compared to its length. Moisture content of the samples was determined by vacuum oven drying, 4 to 8 hours at 95°C. Protein content was determined by micro-kjeldahl[10] and ash content by muffle-furnace at 450°C.[10] Fat content was determined by the method of Bligh and Dyer.[11]

III. Results and Discussion

The coaxial line technique and other forms of dielectric measurement methods such as resonant cavities are accurate only for samples with $\tan\delta$ less than one. In such cases the error is estimated at about 3%.[12] With foodstuffs, $\tan\delta$ of four is common at high temperatures and low frequencies. The accuracy of the method is then reduced, due partly to the fact that very thin samples have to be used, whose thickness have to be accurately known (Table 1).

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9. Westphal, W.B., and J. Iglesias. Technical Report AFML-TR-71-66, Air Force Materials Laboratories, Ohio, 1971.

10. Horwitz, W., ed. Official Methods of Analysis of the AOAC, 11th edition; AOAC, Washington, DC, 1970.

11. Bligh, E.G., and W.J.Dyer. Can. J. Biochem. Physiol. 37:911, 1959.

12. Westphal, W.B. personal communication, 1975.

The method's precision is determined largely by the degree of homogeneity of the sample and the reproducibility of packing the samples into the holder. The standard deviation of repeatedly packing the same meat sample into a holder has been found to be about 5% of the mean value,[7] and this should serve as an indicator of degree of sample preparation reproducibility. As a calibration check, water is measured at the three frequencies 2450, 915, and 300 MHz from 5° to 65°C (Table 2). The results were in agreement with values for water at these frequencies calculated using the Debye equations and literature parameters.[13]

Dielectric properties of the five meat samples are presented in Tables 3 through 7 and their proximate compositions are given in Table 9. As has been pointed out[7] the added salt in turkey gives this sample a significantly higher dielectric loss at all temperatures and frequencies except in the frozen state. Effects of salt on the dielectric constant of thawed samples were also not evident as found in the studies. Taking into account the differences in frequency and possible packing density, the data for beef and pork were in agreement with literature values.[5]

The proximate compositions of the four unsalted raw meats (beef, pork, chicken breast, and chicken thigh) are very similar (Table 8). Their moisture contents show a standard deviation of 2.3.% of their mean, and the less active dielectric components such as protein and fat show a total standard deviation of 2.6% from their combined mean. Similarly, the cooked meats and cooked meat juices of these meats show proximate compositions very similar to one another. However, as a result of cooking, the variations in the moisture and solids contents were larger than in the case for the raw meats. The standard deviation in the moisture content, the component which has the most effect on dielectric properties, was found to be 5.1% of their combined mean. Based on this, the data for unsalted meats (Tables 4 through 7) are pooled to give the dielectric properties of fresh meat products (Table 9). It should be mentioned that presenting the data collectively is not construed to mean that the dielectric properties of all meats are identical. The results were presented in this fashion only as a convenient way for achieving a reduced format.

The dependence of dielectric constant and dielectric loss of unsalted raw meats on temperature and frequency are shown in Figures 4 and 5, respectively. In all cases, the standard deviations in K' and K" of the different unsalted meats were less than 10%. Considering the sensitivity of the coaxial line method and an estimated error of 10%, the slight differences in the dielectric properties of unsalted meats was not detected.

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13. Collie, C.H., J.B. Hasted and D.M. Ritson. Proc. Phys. Soc. (London) 60(2):145, 1948.

The exact differences in K' measured at different frequencies were also hard to determine (Figure 4). In general, difference in K' measured at 2450 MHz and at 915 MHz is only a few percent and can be considered to be insignificant. It is clear from Figure 4 that K' decreases with temperature. Figure 5 shows that K" increases with temperature for 915 and 300 MHz, but is relatively less dependent on temperature for 2450 MHz. This fact can have important implications in heating applications, as will be discussed later.

The dependence of penetration depth on wavelength has often been stressed, and the effects of dielectric properties on absorption of power is all too often overlooked. Recently, Ohlsson and Bengtsson[5] pointed out that, as temperatures reach above 50°C, the penetration depths achieved by the three frequencies 2800, 900, and 450 MHz are almost the same. This is because at higher temperatures the lower frequency gives such high $\tan\delta$ that the factor in brackets in Equation 2 is substantially reduced, offsetting the larger wavelength and making HPD small. On the other hand, the variation of K" and $\tan\delta$ with temperature is small at the high frequencies, making the HPD relatively constant. Calculations of HPD from data in Table 9 show that at 5°C HPD for 2450, 915, and 300 MHz are, respectively, 1.0, 2.8, and 4.6 cm, but at 120°C these figures are 0.7, 1.2, and 1.6 cm, respectively (Figure 6). This is in support of earlier observations by the Swedish workers.[5]

Based on the measurements reported here, it can be seen that at 2450 MHz, the dielectric properties are relatively independent of moisture, temperature, and salt, as compared to the other two frequencies studied. As a result, power absorption and penetration depth, both functions of dielectric properties, are relatively independent of temperature, moisture, and salt. Choice of 2450 MHz as a heating frequency would give versatility, since different loads within a range of moisture, salt contents, and different temperatures would be heated with about the same power at about the same penetration.

References Cited

1. Goldblith, S.A. Adv. Food Res. 15:277, 1967

2. Püschner, H. Heating and Microwaves; Phillips, Technical Library, Springer-Verlag, New York, 1966.

3. Goldblith, S.A., and R.V. Decareau, An Annotated Bibliography on Microwaves; MIT Press, Cambridge, 1973.

4. Tinga, W.R., and S.O. Nelson. J. Microwave Power 8 (1):23, 1973.

5. Ohlsson, T., and N.E. Bengtsson. J. Microwave Power 10 (1):93, 1975.

6. Roberts, S., and A. J. von Hippel. Appl. Phys. 17 (6):610, 1946.

7. To, E.C. MS Thesis, MIT, 1974.

8. Pace, W.E. MS Thesis, MIT, 1967.

9. Westphal, W.B., and J. Iglesias. Technical Report AFML-TR-71-66, Air Force Materials Laboratories, Ohio, 1971.

10. Horwitz, W., ed. Official Methods of Analysis of the AOAC, 11th edition; AOAC, Washington, DC, 1970.

11. Bligh, E.G., and W.J. Dyer. Can. J. Biochem. Physiol. 37:911, 1959.

12. Westphal, W.B. personal communication, 1975.

13. Collie, C.H., J.B. Hasted and D.M. Ritson. Proc. Phys. Soc. (London) 60(2):145, 1948.

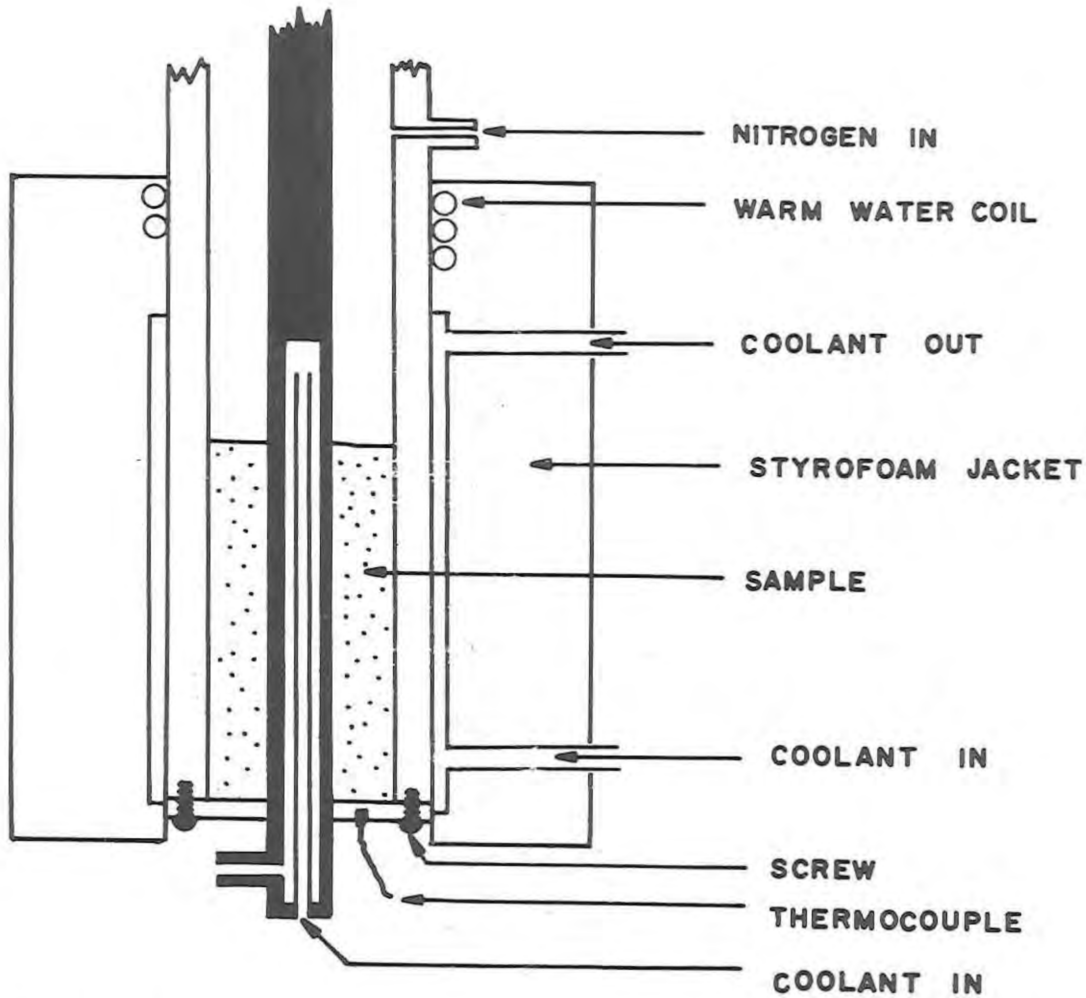

Figure 1: Schematic diagram of the open circulated low temperature holder for all three frequencies.

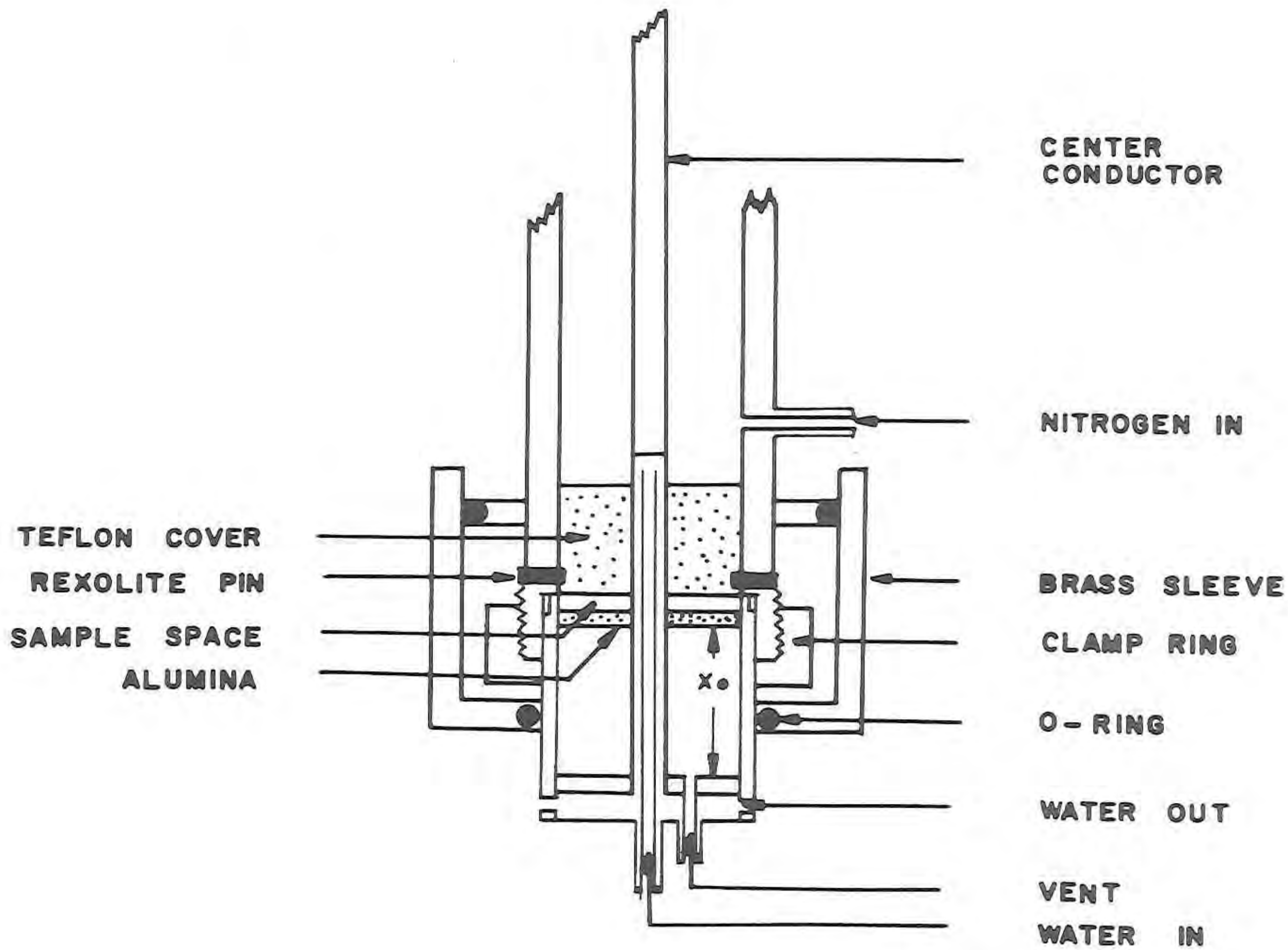

Figure 2: Schematic diagram of the quarter wavelength holder for 2450 MHz, 5 to 65°C.

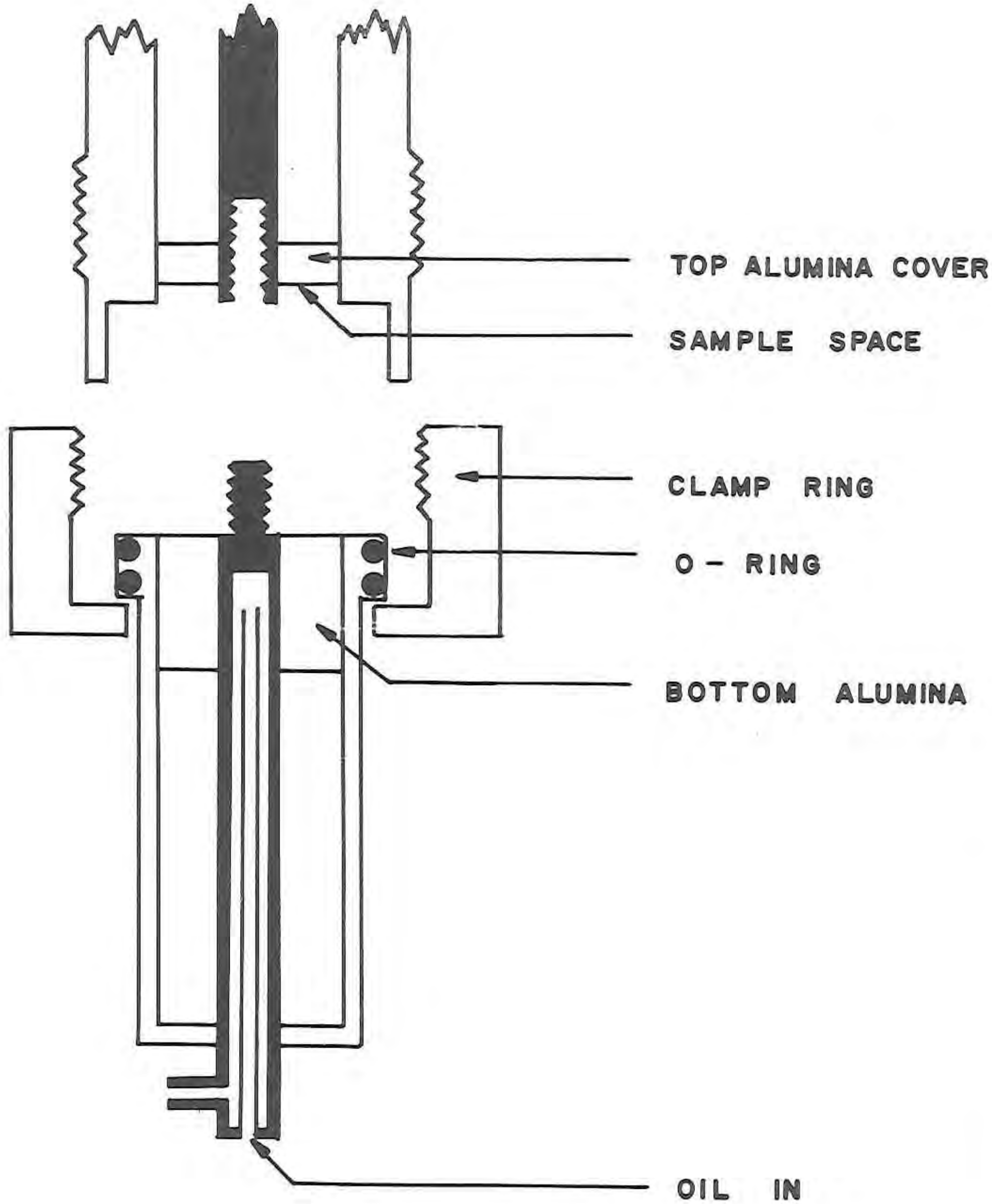

Figure 3: Schematic diagram of the quarter wavelength holder for 900, 300 MHz, 80 to 120°C.

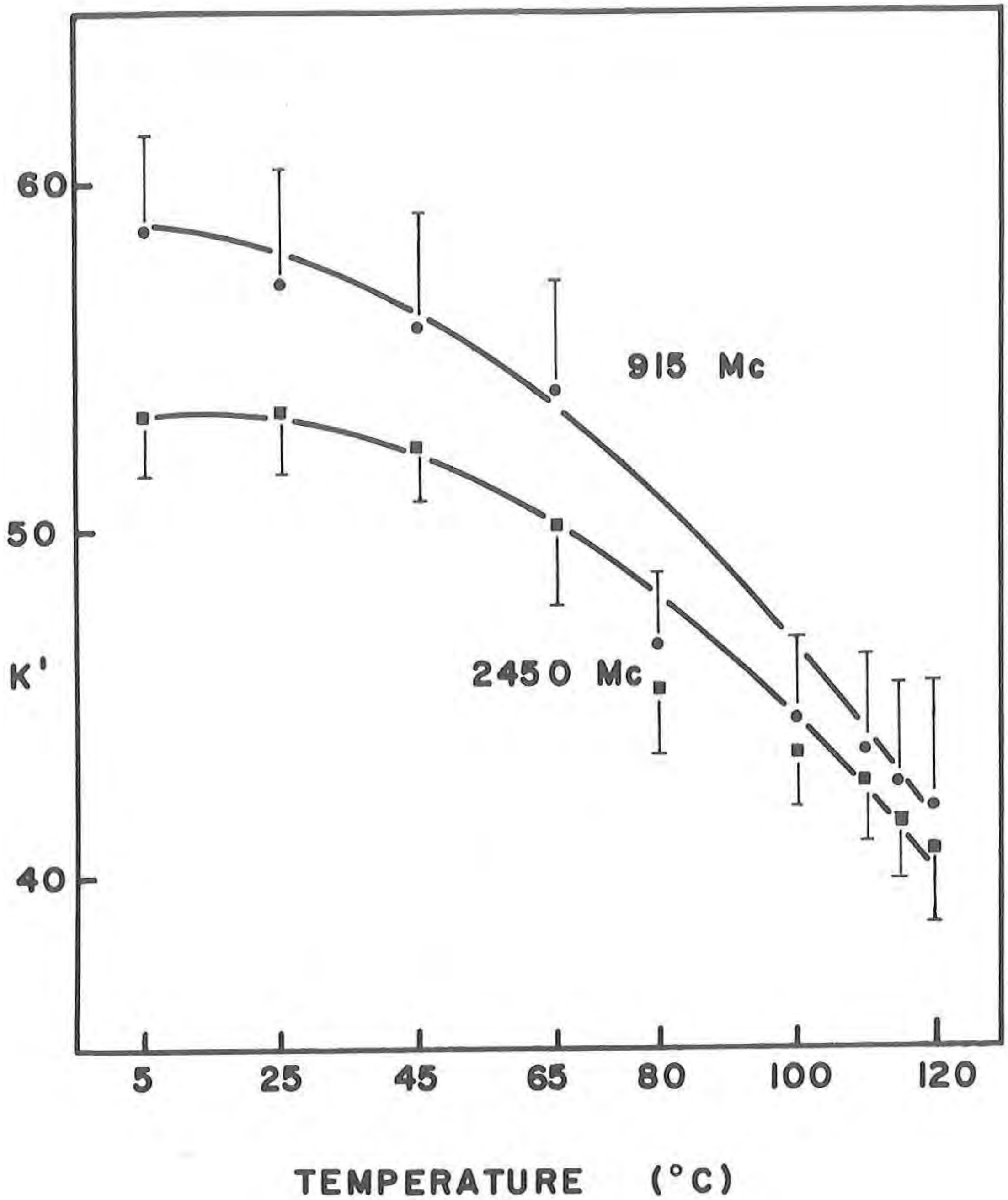

Figure 4: Dielectric constant K' of unsalted meats at 2450 and 915 MHz, 5 to 120°C. Mean and standard deviations.

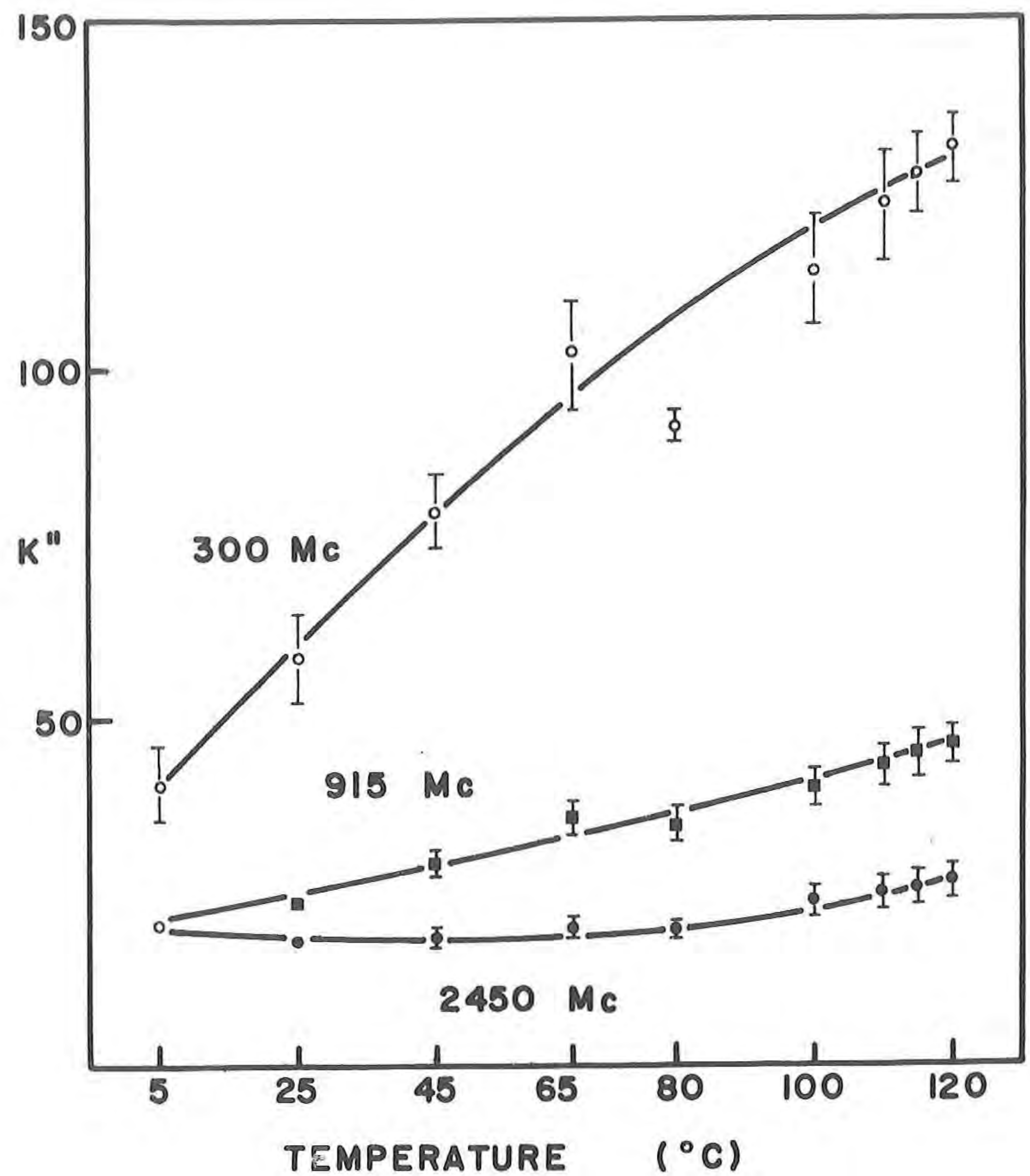

Figure 5: Dielectric loss K" of unsalted meats at 2450, 915, and 300 MHz, 5 to 120°C. Mean and standard deviations.

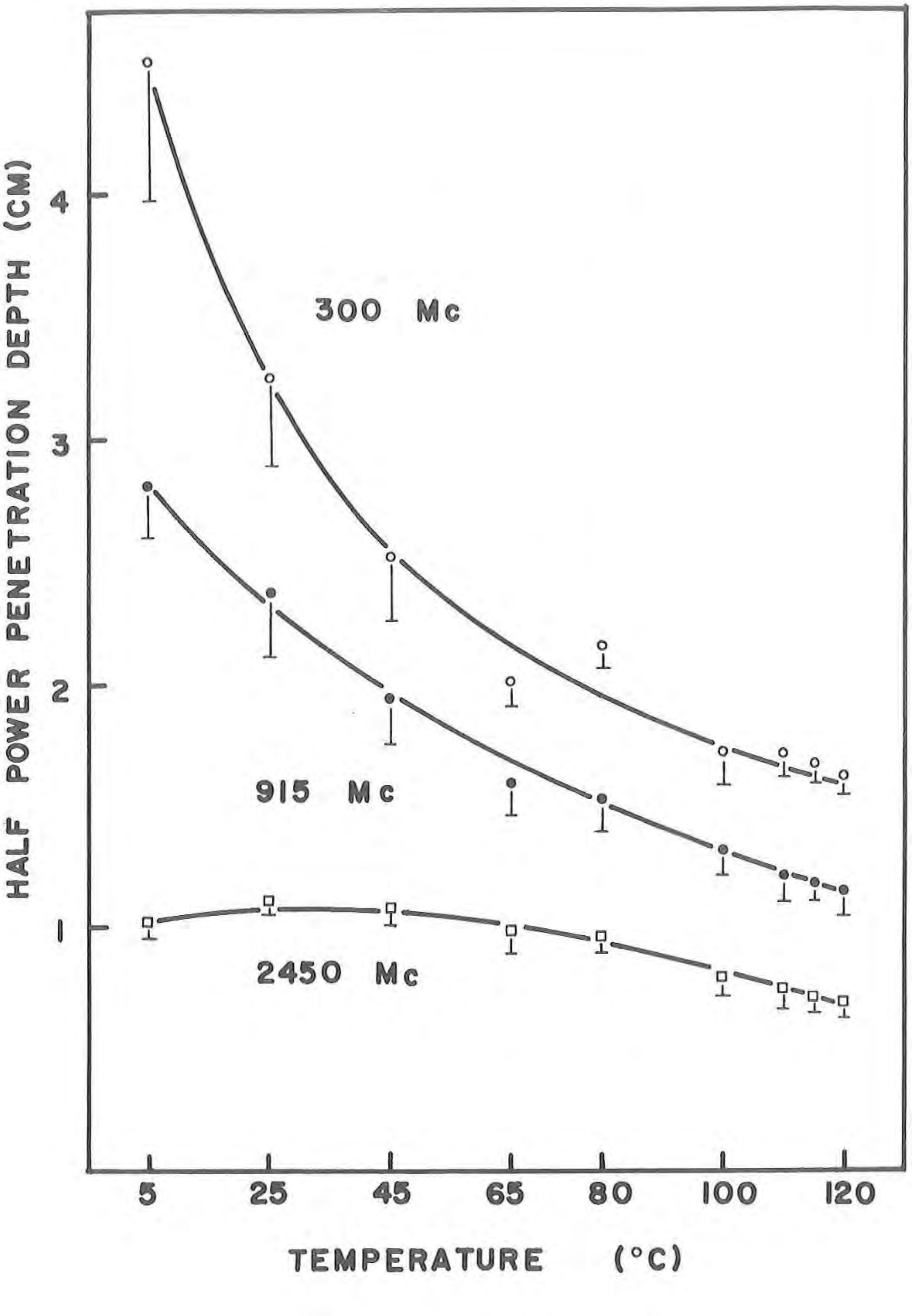

Figure 6: Half Power Penetration Depth of raw unsalted meats at 2450, 915, and 300 MHz, 5 to 120°C. Mean and standard deviation.

Table I. Dimensions and Specifications of Coaxial Sample Holders

Frequency (MHz)	Temp (°C)	Top Cover			Bottom Cover		Sample
		Material	K'	Thickness	Thickness	Xo (cm)*	Thickness
2450	5 - 65	Teflon	2.05	0.9472	0.1587	2.1	0.110
915	5 - 65	Teflon	2.05	0.9472	0.1587	7.3	0.154
300	5 - 65	Teflon	2.05	0.9472	0.1587	23.0	0.140
2450	65 - 120	Alumina	9.57	0.9159	0.1587	2.1	0.104
900,300	65 - 120	Alumina	9.57	0.9159	1.905	16.0	0.152
2450,915,300	-40 - 0	-	-	-	-	0	10

*Distance from bottom cover to short (see Figure 2)

Table 2: Dielectric Properties of Water Measured at Three Frequencies and Seven Temperatures

Temp.	2450 MHz			915 MHz			300 MHz		
°C	K'	K"	TAN	K'	K"	TAN	K'	K"	TAN
5	81.2	13.8	0.170	85.6	5.98	0.070	81.1	2.22	0.027
15	80.4	11.7	0.146	82.3	4.47	0.054	77.4	1.69	0.022
25	76.7	8.88	0.116	78.1	3.41	0.044	73.5	1.40	0.019
35	73.6	6.99	0.095	74.6	2.64	0.035	69.4	1.09	0.016
45	70.6	5.77	0.082	71.1	2.17	0.031	65.7	0.89	0.014
55	*	*	*	67.7	1.75	0.026	61.8	0.83	0.013
65	64.6	3.99	0.062	64.0	1.41	0.022	58.0	0.77	0.013

*Data not taken

Table 3 : Dielectric Properties of Beef Products at Three Frequencies and Different Temperatures

Temp.	2450 MHz			915 MHz			300 MHz		
°C	K'	K"	TAN	K'	K"	TAN	K'	K"	TAN
Sample: Raw Beef									
-40	3.5	0.13	0.037	3.6	0.21	0.058	3.9	0.34	0.087
-20	4.4	0.51	0.120	4.8	0.54	0.110	5.4	0.97	0.180
5	52.9	19.3	0.365	57.2	19.8	0.346	59.3	47.6	0.803
25	52.4	17.3	0.330	54.5	22.4	0.411	55.1	66.9	1.21
45	51.0	17.5	0.342	53.1	27.7	0.521	49.8	87.5	1.76
65	47.6	18.1	0.380	50.6	33.2	0.656	43.9	112	2.55
80	44.1	19.5	0.442	45.7	33.1	0.720	54.3	110	2.03
100	43.2	22.3	0.523	43.0	37.5	0.870	52.8	128	2.47
110	42.6	22.8	0.535	41.8	39.8	0.950	51.9	133	2.56
115	40.5	24.2	0.598	41.1	40.9	0.990	51.4	135	2.63
120	39.7	25.1	0.632	40.5	42.0	1.04	50.9	140	2.75
Sample: Cooked Beef									
5	29.0	10.9	0.377	33.5	12.2	0.365	38.0	23.5	0.619
25	31.1	10.3	0.331	35.3	15.0	0.425	39.1	38.1	0.975
45	29.9	10.1	0.338	34.9	18.3	0.525	37.7	52.7	1.40
65	26.9	9.9	0.369	31.7	19.9	0.627	35.8	57.1	1.60
Sample: Cooked Beef Juice									
5	68.9	24.0	0.349	82.0	29.8	0.363	87.4	63.6	0.728
25	65.1	22.0	0.337	76.8	35.8	0.466	80.1	94.1	1.17
45	60.0	22.1	0.369	71.3	44.1	0.619	74.7	125	1.67
65	54.3	23.7	0.437	65.7	52.9	0.805	62.4	164	2.63

Table 4: Dielectric Properties of Pork Products at Three Frequencies and Different Temperatures

Temp.	2450 MHz			915 MHz			300 MHz		
°C	K'	K"	TAN	K'	K"	TAN	K'	K"	TAN
Sample: Raw Pork									
-40	3.5	0.13	0.037	3.6	0.15	0.042	4.0	0.29	0.073
-20	4.0	0.56	0.140	4.4	0.63	0.140	5.5	1.14	0.210
5	51.1	18.6	0.363	55.7	19.3	0.345	61.6	36.5	0.592
25	51.4	16.9	0.329	54.3	22.7	0.418	61.4	53.2	0.866
45	50.9	17.7	0.348	53.1	28.2	0.531	61.4	74.0	1.21
65	48.9	19.6	0.400	52.2	34.2	0.654	58.7	92.2	1.57
80	43.3	18.2	0.420	44.6	38.4	0.860	54.7	91.5	1.67
100	41.9	21.7	0.518	42.0	44.0	1.05	51.3	109	2.12
110	40.8	22.3	0.547	40.5	47.0	1.16	49.2	118	2.40
115	40.0	22.8	0.570	39.6	48.4	1.22	48.0	122	2.54
120	38.6	23.6	0.620	38.6	49.8	1.29	46.5	126	2.71
Sample: Cooked Pork									
5	28.8	10.6	0.367	31.4	10.6	0.337	37.6	20.5	0.545
25	30.2	10.1	0.333	32.1	12.7	0.396	38.9	29.9	0.768
45	29.7	10.3	0.346	31.9	15.8	0.494	39.7	39.8	1.00
65	28.0	10.6	0.378	30.2	17.7	0.585	39.2	47.3	1.21
Sample: Cooked Pork Juice									
5	69.0	26.2	0.382	82.7	30.8	0.371	89.9	69.3	0.770
25	66.0	25.2	0.381	78.0	38.2	0.489	80.2	104	1.30
45	61.7	26.9	0.435	73.1	46.9	0.641	76.9	139	1.81
65	56.8	28.7	0.505	67.3	58.8	0.873	67.8	178	2.63

Table 5: Dielectric Properties of Chicken (Breast) at Three Frequencies and Different Temperatures

Temp.	2450 MHz			915 MHz			300 MHz		
°C	K'	K"	TAN	K'	K"	TAN	K'	K"	TAN
Sample: Raw Chicken (Breast)									
-40	3.5	0.15	0.043	3.7	0.22	0.059	4.0	0.40	0.100
-20	4.0	0.51	0.130	4.6	0.87	0.190	5.3	1.31	0.250
5	54.6	27.0	0.380	61.8	21.7	0.351	67.9	40.0	0.588
25	55.2	19.3	0.349	61.1	25.8	0.422	67.4	57.5	0.854
45	54.1	19.9	0.367	59.7	31.7	0.530	66.6	78.8	1.18
65	52.1	21.8	0.418	57.8	38.5	0.665	64.8	104	1.60
80	47.9	20.2	0.422	49.6	32.5	0.650	56.7	95.0	1.67
100	45.6	25.5	0.559	47.6	38.0	0.790	55.0	111	2.02
110	44.9	27.1	0.604	46.9	42.2	0.900	53.8	125	2.32
115	43.5	28.0	0.644	46.2	43.5	0.930	53.0	128	2.42
120	43.1	28.9	0.671	45.9	46.1	1.00	52.5	133	2.54
Sample: Cooked Chicken (Breast)									
5	37.7	14.5	0.385	40.4	14.8	0.365	49.3	29.0	0.589
25	39.1	13.7	0.351	41.0	17.7	0.432	50.7	42.0	0.827
45	37.1	13.6	0.365	40.9	21.9	0.535	51.1	55.5	1.09
65	34.2	13.9	0.406	38.3	24.5	0.640	48.8	63.3	1.30
Sample: Cooked Chicken (Breast) Juice									
5	65.9	27.1	0.411	85.5	32.1	0.375	92.2	65.6	0.712
25	65.9	25.0	0.379	81.7	38.8	0.474	87.4	96.4	1.10
45	61.6	26.9	0.436	77.1	47.4	0.615	82.4	130	1.58
65	55.9	28.7	0.513	71.2	56.8	0.798	71.0	167	2.36

Table 6: Dielectric Properties of Chicken (Thigh) at Three Frequencies and Different Temperatures

Temp. °C	2450 MHz K'	2450 MHz K"	2450 MHz TAN	915 MHz K'	915 MHz K"	915 MHz TAN	300 MHz K'	300 MHz K"	300 MHz TAN
Sample: Raw Chicken (Thigh)									
-40	3.5	0.15	0.043	3.7	0.22	0.059	4.0	0.40	0.100
-20	3.9	0.54	0.140	4.7	0.54	0.110	5.4	1.10	0.200
5	54.4	19.3	0.355	59.7	19.3	0.323	65.8	38.4	0.582
25	54.7	17.6	0.322	58.5	22.9	0.391	67.9	57.7	0.849
45	53.6	18.2	0.338	57.2	28.1	0.492	64.6	76.6	1.19
65	51.7	20.0	0.386	55.6	34.4	0.618	64.0	102	1.61
80	46.3	19.7	0.425	46.9	34.1	0.720	50.3	91.0	1.82
100	43.8	24.0	0.548	45.3	39.8	0.870	48.8	107	2.19
110	42.3	26.2	0.619	44.1	43.2	0.960	48.3	119	2.46
115	42.0	26.6	0.633	43.8	45.0	1.02	48.0	125	2.60
120	41.5	27.0	0.651	43.1	46.1	1.07	47.5	127	2.67
Sample: Cooked Chicken (Thigh)									
5	39.7	13.9	0.350	42.7	13.5	0.315	49.9	26.6	0.532
25	40.9	12.8	0.313	42.7	16.1	0.376	50.2	37.8	0.752
45	39.5	12.8	0.323	42.5	20.1	0.472	50.3	51.3	1.02
65	34.5	12.8	0.372	39.0	22.5	0.576	47.7	59.2	1.24
Sample: Cooked Chicken (Thigh) Juice									
5	67.4	23.7	0.352	78.7	24.5	0.311	82.7	53.1	0.641
25	67.5	20.8	0.308	76.0	29.7	0.391	76.9	76.8	0.997
45	63.1	21.4	0.338	71.2	36.7	0.514	70.2	106	1.51
65	57.8	22.5	0.389	66.2	43.7	0.660	63.3	133	2.09

Table 7: Dielectric Properties of Turkey Products at Three Frequencies and Different Temperatures

Temp.	2450 MHz			915 MHz			300 MHz		
°C	K'	K"	TAN	K'	K"	TAN	K'	K"	TAN
Sample: Raw Turkey Roll									
-40	3.5	0.13	0.037	3.6	0.17	0.047	3.8	0.29	0.076
-20	4.1	0.61	0.150	4.5	0.73	0.160	5.3	1.21	0.230
5	55.2	21.6	0.406	60.2	26.4	0.438	67.3	58.1	0.860
25	53.7	21.5	0.399	59.9	33.2	0.555	67.0	86.2	1.29
45	52.5	23.8	0.453	58.3	42.8	0.734	65.4	118	1.81
65	50.7	26.8	0.629	56.6	53.1	0.937	61.6	159	2.59
80	45.2	25.0	0.553	48.8	69.0	1.41	46.4	179	3.87
100	44.5	27.1	0.609	47.9	78.7	1.64	43.3	205	4.74
110	42.4	29.2	0.689	47.4	83.4	1.76	42.9	218	5.10
115	41.8	29.9	0.715	47.2	85.8	1.81	41.1	224	5.45
120	39.8	30.3	0.761	49.9	88.2	1.88	40.4	231	5.73
Sample: Cooked Turkey Roll									
5	38.2	16.1	0.421	41.6	19.7	0.472	46.5	44.9	0.966
25	39.7	16.7	0.420	43.0	26.1	0.607	47.1	66.7	1.42
45	37.3	17.2	0.459	41.4	32.4	0.782	44.8	27.5	1.96
65	34.4	17.8	0.517	37.7	36.9	0.980	36.5	92.8	2.55
Sample: Cooked Turkey Roll Juice									
5	70.3	29.7	0.422	78.5	44.3	0.565	86.3	115	1.33
25	67.5	30.9	0.457	74.5	57.5	0.771	82.1	166	2.02
45	62.9	35.4	0.563	69.5	74.0	1.06	72.9	224	3.07
65	56.8	40.1	0.705	62.9	90.6	1.42	62.9	285	4.53

Table 8 : Proximate Compositions for all Samples in Percent by Weight. Unsalted Meat Values are Mean ± Standard Deviation for Beef, Pork, Chicken

State	Sample	Moisture	Protein	Fat	Ash
Cooked	Turkey Roll	66.5	28.7	4.0	1.5
	Beef	63.9	29.4	5.3	1.1
	Pork	57.2	31.1	10.4	1.3
	Chicken (Breast)	66.3	32.5	1.5	1.2
	Chicken (Thigh)	69.1	27.5	5.7	1.0
	Unsalted Meats	64.1±5.1	30.1±2.2	5.7±3.6	1.2±0.1
Raw	Turkey Roll	73.8	22.1	2.8	1.4
	Beef	74.1	22.7	2.6	1.1
	Pork	69.9	23.2	5.7	1.2
	Chicken (Breast)	73.6	25.2	1.3	1.2
	Chicken (Thigh)	75.3	21.1	3.5	1.0
	Unsalted Meats	73.2±2.3	23.1±1.7	3.3±1.9	1.1±0.1
Cooked Juice	Turkey Roll	91.9	5.0	1.4	2.1
	Beef	93.1	4.6	1.5	1.3
	Pork	91.1	3.8	5.8	1.4
	Chicken (Breast)	92.3	5.9	1.0	1.2
	Chicken (Thigh)	86.4	4.4	8.3	0.9
	Unsalted Meats	90.7±3.0	4.7±0.9	4.2±3.5	1.2±0.2

Table 9: Dielectric Properties of Unsalted Meats (Beef, Pork, Chicken) at Three Frequencies, Mean ± Standard Deviation

Temp.	2450 MHz		915 MHz		300 MHz	
°C	K'	K"	K'	K"	K'	K"
Sample: Raw Unsalted Meats						
-40	3.50	0.14±0.01	3.64±0.06	0.19±0.03	3.90±0.09	0.34±0.06
-20	4.08±0.19	0.55±0.04	4.60±0.16	0.66±0.14	5.30±0.08	1.14±0.13
5	53.4±1.6	19.5±0.9	58.6±2.7	20.0±1.1	63.7±3.9	40.6±4.9
25	53.4±1.8	17.8±1.1	57.1±3.3	23.5±1.6	63.0±6.0	58.8±5.8
45	52.4±1.7	18.3±1.1	55.8±3.3	28.9±1.9	60.6±7.5	79.2±5.9
65	50.1±2.2	19.9±1.5	54.1±3.3	35.1±2.3	57.9±10	103 ±8.2
80	45.4±2.1	19.4±0.9	46.7±2.1	34.5±2.7	52.5±4.1	91.6±2.5
100	43.6±1.5	23.4±1.7	44.5±2.5	39.8±3.0	50.6±4.4	114 ±9.6
110	42.7±1.7	24.6±2.4	43.3±2.8	43.1±3.0	49.2±4.2	124 ±6.9
115	41.5±1.6	25.4±2.3	42.7±2.9	44.5±3.1	48.3±4.6	128 ±5.6
120	40.7±2.0	26.2±2.3	42.0±3.7	46.0±3.2	47.5±4.7	132 ±6.5
Sample: Cooked Unsalted Meats						
5	33.8±5.7	12.5±2.0	37.0±5.4	12.7±1.8	43.7±6.8	24.9±3.7
25	35.3±5.5	12.2±2.3	37.8±4.9	15.4±2.1	44.7±6.6	37.0±5.1
45	34.1±5.0	11.7±1.8	37.6±5.0	19.0±2.6	44.7±7.0	49.8±6.9
65	30.9±4.0	11.8±1.9	34.8±4.5	21.1±3.0	42.9±6.4	56.7±6.8
Sample: Cooked Juice of Unsalted Meats						
5	67.8±1.5	25.3±1.7	82.2±2.8	29.3±3.3	88.1±4.1	62.9±7.0
25	66.1±1.0	25.3±2.2	78.1±2.5	35.6±4.2	81.2±4.4	92.8±12
45	61.6±1.3	24.3±3.0	73.2±2.8	43.8±4.9	76.1±5.1	125 ±14
65	56.2±1.5	25.9±3.3	67.6±2.5	53.1±6.7	66.1±4.0	160 ±19