Moisture Content Determination in Single Peanut Kernels With a Microwave Resonator

A. W. Kraszewski* and S. O. Nelson[1]

ABSTRACT

Principles are discussed for determining moisture content of individual peanut, *Arachis hypogaea* L., kernels by microwave resonator measurements, and data illustrating the application of these principles are presented. By measuring the shift in the resonant frequency and the change in the cavity transmission characteristics when a peanut kernel is inserted into the cavity, and taking the ratio of these two parameters, it is possible to obtain the moisture content of the kernel independent of its mass (size) and apparently independent of peanut type, as far as runner and virginia market types are concerned. Moisture contents in the range from 4 to 14 percent, wet basis, were determined with an uncertainty of 0.9 percent moisture, at the 95-percent confidence level.

Key Words: Moisture content, peanut, kernels, microwave measurements, microwave resonators.

During harvesting, storage, marketing, and processing of peanuts, *Arachis hypogaea* L., moisture content of the peanuts is an important factor. In the Southeast, peanuts are dug and then allowed to dry in the windrow to an average moisture content of 18 to 22%, wet basis, on the vines before they are combined. Sometimes they are allowed to dry naturally to less than 10.5% before being combined. If not, the artificial drying process must start immediately after combing to prevent mold growth and to reduce the moisture content to less than 10.5% for marketing. Peanuts can be stored safely at this moisture level if adequate ventilation is provided, but they are often dried to lower levels for storage.

Conventional electronic moisture meters for grain, seeds, and nuts provide a moisture content reading that is an average for the sample. This average does not provide any information about the range of individual kernel or seed moisture contents that may be present in a sample. The range of kernel moisture contents, if known, could be very useful in the storage, handling, and processing of peanuts. Thus, an instrument that could determine the moisture content of individual kernels within samples would be valuable both in research and in practical use in the peanut industry.

Hutchison and Holaday, (1978) developed a moisture profile meter for peanut samples by equipping a commercial crushing-roller grain moisture meter with a millivolt recorder and a device to feed individual peanut kernels to the crushing rollers. Recorded signal peaks, which resulted from the DC conductance of the kernels as they passed between the rollers, were correlated with moisture content and provided moisture content estimates for the individual kernels in a 50-kernel sample. Single-kernel moisture contents have also been determined by impedance measurements on individual peanut kernels with capacitive sensors at radio frequencies (Kandala and Nelson, 1990; Nelson *et al.*, 1990). Measurements of capacitance and conductance at two frequencies (1 MHz and 4.5 MHz) of a small parallel-plate capacitor with the peanut kernel between and in contact with the plates allowed nondestructive prediction of the kernel moisture content within ±1% of the values determined by a standard oven drying method. Dowell and Lamb (1991) evaluated a commercial single-kernel, crushing-roller, dc-conductance type instrument for use with peanuts and found that it had sufficient accuracy for potential use in the peanut industry.

Resonant cavity techniques are widely used in measuring the microwave properties of materials by measuring the shift in the resonant frequency and the change in the Q factor of the cavity when the object is inserted into the cavity (Altschuler, 1963). This technique has proven to be an interesting alternative to existing methods for kernel moisture determination in soybeans and corn (Kraszewski *et al.*, 1989; Kraszewski and Nelson, 1992), because it offers nondestructive and relatively fast measurements. The purpose of this research was to determine the effects of peanut kernels of various shapes, dimensions, types, and different moisture levels on the parameters of a microwave resonant cavity and to evaluate the feasibility for determining the moisture content of individual kernels by microwave measurements.

Materials and Methods

Peanuts

Shelled peanuts of the runner market-type (cv. Florunner) separated into two lots according to size (jumbo and medium), were obtained for this study from the USDA, ARS, National Peanut Research Laboratory, Dawson, Georgia, after the 1990 harvest season. Forty-six peanut kernels, including both medium and jumbo sizes, were randomly selected for the measurements. Some kernels were lightly sprayed with distilled water to increase their moisture contents to about 16% from the initial level of 10 to 12%. The weight of wet kernels ranged from 380 to 940 mg. These kernels were permitted to dry under ambient conditions for various time intervals between the microwave measurements, and after every drying period each kernel was individually sealed in a glass vial and kept at 4C to equilibrate, usually for 2-3 days, before it was measured again. In this way microwave measurements and kernel weights were recorded for each kernel 3 to 5 times before it was finally oven-dried to determine its dry mass. The dry mass was determined by placing individual kernels in copper moisture dishes (Nelson and Lawrence, 1989) and drying them in a forced-air oven for 6 hr at 130 C (ASAE, 1991). Kernels and moisture dishes were cooled in a desiccator over anhydrous $CaSO_4$ upon removal from the oven before being weighed. Subsequently, the kernel moisture content was calculated as a ratio of mass of water to mass of wet kernel as determined for each microwave measurement sequence.

In 1991, four additional lots, two each of the runner (cv. Florunner) and virginia market-types in jumbo and medium sizes, were obtained for verification tests. Ninety-one kernels were randomly selected, with weight of wet kernels ranging from 420 to 1030 mg among Florunners and 460 to 1280 mg among the virginia peanuts. Some of the kernels were lightly sprayed with distilled water to increase their moisture above the original 6% level. After that, all kernels were kept individually in glass vials at 4 C

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for 72 h to equilibrate, and another 24 h at 23C for temperature stabilization before microwave measurements. The previously described procedure was then followed in every detail.

Microwave Measurements

The microwave measurement cavity consisted of a section of standard S-band WR-284 rectangular waveguide (inside dimensions: 72 x 34 mm) 305 mm long. It was coupled with external waveguides through two identical coupling holes, 20.6 mm in diameter, at each end of the cavity. A Plexiglas tube of 15.8-mm outside diameter and 12.4-mm inside diameter was installed in the center of the cavity as shown in Fig. 1. The resonant frequency of the empty cavity operating in the H_{105} (TE_{105}) mode was 3175.9 MHz and its quality factor, Q_o, was 865 (Rizzi, 1988).

The cavity was located between two waveguide-to-coaxial transitions, which allowed it to be connected to an automatic network analyzer calibrated in the transmission mode. The analyzer generated 801 discrete frequencies within a range of 16 MHz spanning the resonant frequency of the cavity. This allowed measurement of the transmission through the cavity in increments of 20 kHz by reading the coordinates of a marker on the test set CRT display. The resonance of the cavity appears as a peak in transmission through the cavity. To determine the resonant frequency, the frequency of a signal coupled to the cavity is varied until the maximum transmission is observed. The second parameter of the resonance curve, as shown in Fig. 2, is its shape. The apparent Q factor of the cavity is lowered by coupling devices connected to the cavity, energy losses in the cavity walls and dielectric tubing, and losses in the sample introduced into the cavity. Thus, when a peanut kernel is introduced into the cavity, the resonant frequency will decrease and the Q factor will be lowered, causing a broader, flatter resonance curve, shifted to the left. A "marker to maximum" command automatically accomplished the determination of the resonant frequency with an accuracy better than 10 kHz and the transmission coefficient, S_{21}, through the cavity with an accuracy of 0.02 dB. The test setup is depicted in the block diagram of Fig. 3.

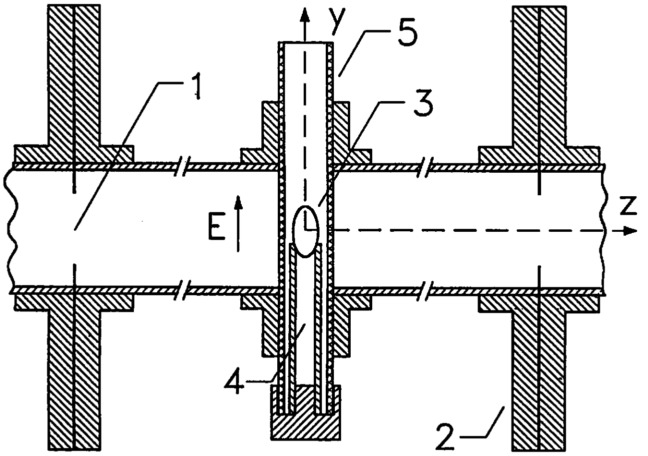

Fig. 1. Sectional view of the rectangular waveguide resonant cavity showing the coupling irises (1) held between circular waveguide flanges (2) at each end of the cavity and the peanut kernel (3) supported at the center by a plastic tube (4) inside the plastic tube (5) within the cavity.

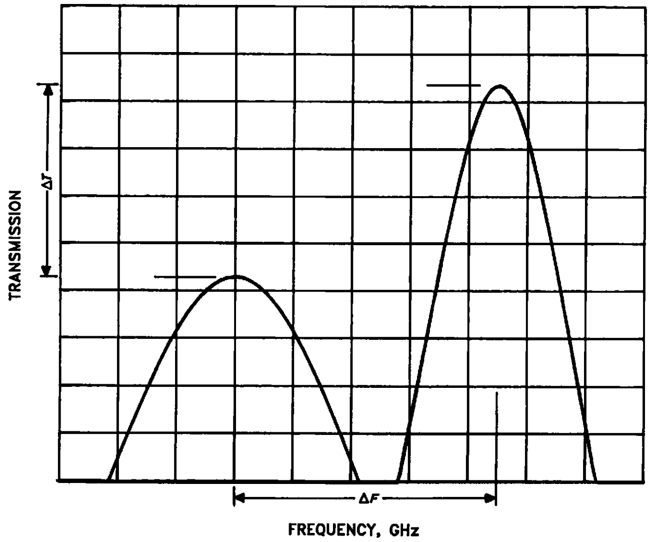

Fig. 2. Resonant curves for empty cavity (right) and cavity loaded with kernel (left).

In the following experiments, the shift of resonant frequency is denoted $\Delta F = f_0 - f_s$, where subscripts o and s refer to the empty cavity and cavity loaded with a sample (kernel) at the center of the cavity, respectively. Energy dissipated in the kernel is expressed as a change in the cavity Q factor:

$$\frac{1}{Q_s} - \frac{1}{Q_0} = \frac{1}{Q_0}\left(\frac{V_0}{V_s} - 1\right) = \frac{\Delta T}{Q_0}$$

Here V denotes the voltage transmission coefficient at resonance, $\Delta T = (10^k - 1)$ is the transmission factor, and $k = 0.05\ (S_{210} - S_{21s})$, with S_{21} being the voltage transmission coefficient at resonance, expressed in decibels.

Basic Relationships

The resonant cavity parameters with a kernel located at the center of the cavity are related to the kernel material permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, the kernel volume, and the kernel shape by the following expressions (Altschuler, 1963):

$$\Delta F = 2\,(\varepsilon' - 1)\,K f_0 \left(\frac{v_s}{v_0}\right) \tag{1}$$

$$\Delta T = 4\,\varepsilon''\,K^2\,Q_0 \left(\frac{v_s}{v_0}\right) \tag{2}$$

where v_0 is the volume of the empty cavity (749 cm^3), v_s is the volume of the peanut kernel, and K is the kernel shape factor, the value of which is dependent upon kernel shape, orientation, and permittivity. The shape factor can be determined for some simple regular shapes (Altschuler, 1963), e.g., $K = \frac{3}{\varepsilon' + 2}$ for a sphere and $K = 1$ for a rod parallel to the electric field lines. Equations 1 and 2 have been used widely for material permittivity measurements, provided that the material sample is well defined in dimensions and shape, the values of f_0, Q_0 and v_0 are known for a given cavity, and the values of K and v_s are precisely determined for the sample, under the assumption that the volume of the sample is much smaller than the volume of the cavity, and the sample itself has low loss ($\varepsilon'^2 >> \varepsilon''^2$). All these conditions are relatively easy to satisfy for solid dielectric materials that can be conveniently machined and measured. However, for biological materials like tissues, seeds and kernels, these conditions cannot usually be fulfilled satisfactorily, and the resonant cavity techniques are not useful for permittivity measurements of those materials.

Peanuts have kernels of a rather regular prolate ellipsoidal shape with some runner market types having a major-to-minor-axis ratio ranging between 1.6 and 2. This places their shape factor, K value, somewhere between that for a sphere (ratio of 1) and a long rod (ratio > 5), when a kernel is placed with its major axis parallel to the electric field inside the cavity (along the plastic tube in Fig. 1). Whatever the exact value of the shape factor, assume that it is similar for all kernels under consideration. Taking the ratio of the two measured cavity parameters, expressed by equations 1 and 2, one obtains

$$X = \frac{\Delta F}{\Delta T} = \frac{\varepsilon' - 1}{\varepsilon''}\,\frac{1}{K}\,\frac{f_0}{2Q_0} = \varphi\,(M)\,\frac{C}{K} \tag{3}$$

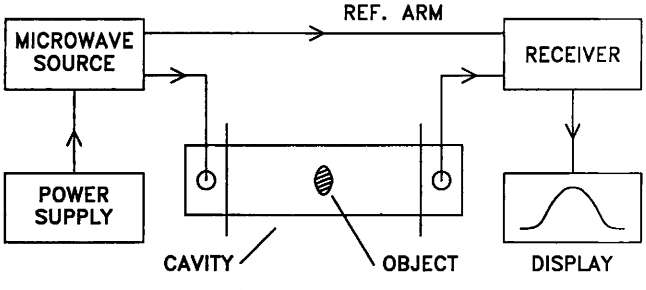

Fig. 3. Block diagram of the measuring setup.

where $C=\frac{f_0}{2Q_0}$ is a constant for a given resonant cavity and $\varphi(M)=\frac{\varepsilon'-1}{\varepsilon''}$ is a permittivity function of the kernel moisture content, and the ratio $X=\frac{\Delta F}{\Delta T}$ is known directly from the microwave cavity measurements. It may be noted that the ratio expressed by equation 3 does not depend upon the mass (size) of the peanut kernel located in the cavity. Thus, the ratio X may be considered a size-independent function. The nature of the permittivity function requires further explanation.

It may be observed that dispersion (change in phase) and dissipation (change in amplitude) of electromagnetic waves inside the resonant cavity loaded with a sample of material both depend upon dimensions and the relative permittivity (dielectric properties) of the material. When moisture content of a kernel of given mass, placed at the center of the cavity, changes, a change is reflected in the parameters of the resonant cavity (resonant frequency and Q factor). Because the relative permittivity of water differs greatly from that of most hygroscopic dielectric materials, its effect can be separated from the effect of dry dielectric material. A calibration equation allowing the determination of moisture content, M, from microwave cavity measurements may be written in a general form:

$$M = A\ \varphi^{-1}(X) \qquad (4)$$

where $\varphi^{-1}(X)$ is the inverse of the permittivity function $\varphi(M)$ and A is a constant. Verification of this relationship with experimental data on peanut kernels is presented below.

Experimental Results

For the 46 peanut kernels of the Florunner cultivar measured at various moisture levels in the S-band resonant rectangular cavity (total of 184 data points), the ratio of the shift of resonant frequency ΔF and the transmission factor ΔT versus the moisture content is shown in Fig. 4. The following equation fits the experimental results with a high statistical significance:

$$\frac{1}{X} = 0.008437\,M + 0.000159 \qquad r = 0.9843 \qquad (5)$$

where r is the correlation coefficient. Solving for M provides the calibration equation for the kernel moisture content in percent, wet basis, equivalent to equation 4, as

$$M = \frac{118.5}{X} - 0.02 \qquad (6)$$

Equation 6 may then be used to calculate the moisture content of individual kernels from the resonant cavity measurements. To verify their accuracy, another set of 91 peanuts of jumbo and medium sizes of two market types, runner and virginia, harvested the following year, was tested in the same resonator. A total of 318 data points in the moisture content range from 4 to 14% was collected. The moisture contents of the kernels were determined by the standard oven method and compared with those calculated from equation 6. Moisture content values predicted by equation 6 are compared with the reference values in Fig. 5. The distribution of differences between oven moisture content and calculated values is shown in Fig. 6. The predicted values of peanut moisture content agreed well with those determined by the standard method, with a bias of −0.21% moisture and standard deviation of differences, or standard error of performance (SEP), of 0.466% moisture content. It should be noted that the uncertainty in the standard oven moisture determinations is generally ±0.2% moisture content.

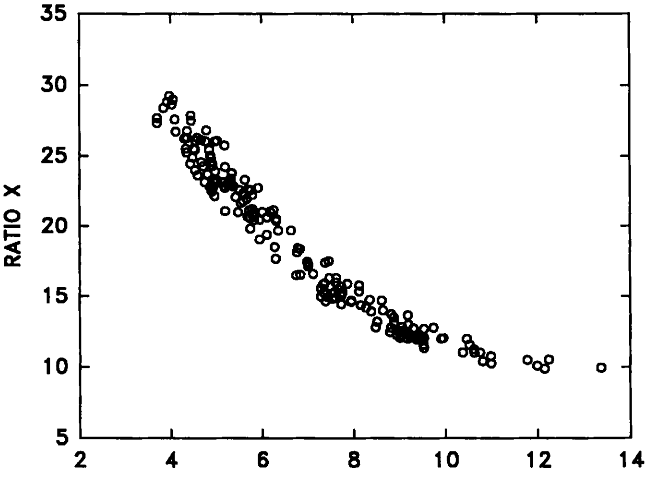

Fig. 4. Dependence of the ratio $X = \frac{\Delta F}{\Delta T}$ on moisture content in single Runner peanut kernels harvested in 1990.

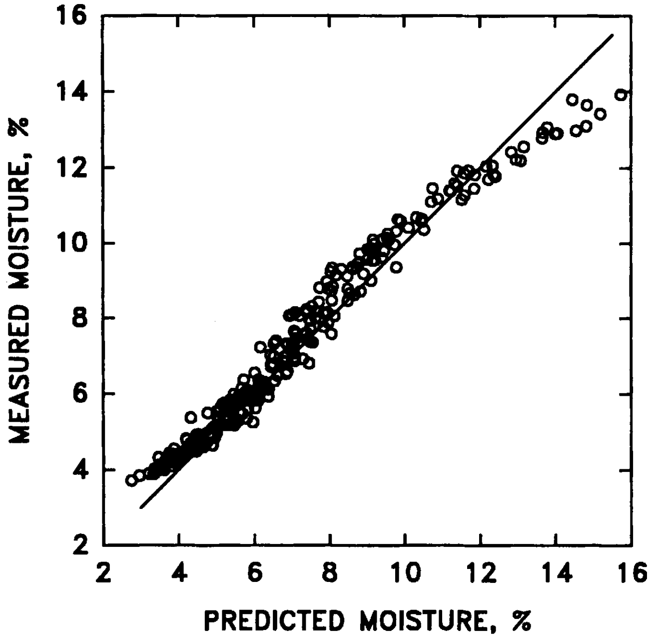

Fig. 5. Predicted moisture content of mixed medium and jumbo size peanut kernels versus moisture content determined by standard oven method.

Uncertainty Analysis

The accuracy of the system calibration is affected by an uncertainty of the measuring system, σ_M, consisting of the repeatability of the results for the same kernel of given moisture content and an uncertainty of the "real" values of the moisture content determination, σ_c, i.e., repeatability of the results provided by the standard oven method used for the system calibration. Since both of these magnitudes are of a random character, the uncertainty in using the microwave resonant cavity for moisture content determination

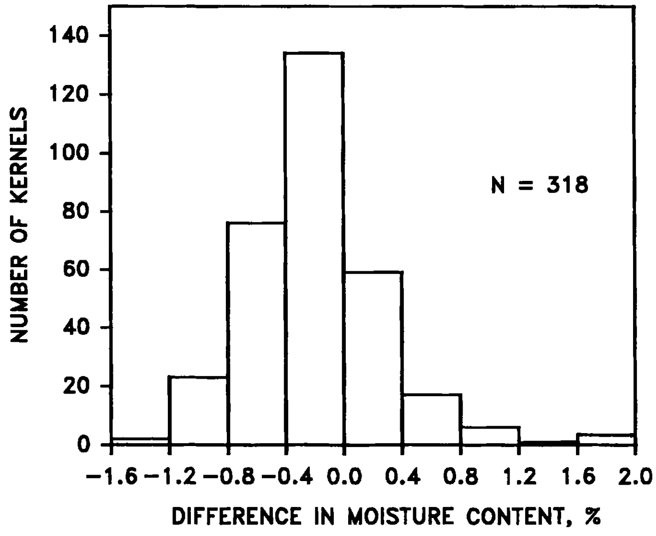

Fig. 6. Distribution of differences between oven moisture content and moisture content calculated from the calibration equation 6 for 318 data points on Runner and Virginia peanuts harvested in 1991.

in a single peanut kernel may be defined as

$$\sigma_s = \pm\sqrt{\sigma_M^2 + \sigma_c^2} \qquad (7)$$

The uncertainty in the measuring system can be determined by differentiation of equation 6, which gives for the moisture content uncertainty

$$\sigma_M = -\frac{M}{X}\,\Delta X \qquad (8)$$

where the uncertainties in the parameter measurements are defined as

$$\Delta X = X\left(\frac{\delta f_0 + \delta f_s}{f_0 - f_s} + B\,\frac{\delta S_0 + \delta S_s}{10^k - 1}\right) = X\left(\frac{n_1 \delta f}{\Delta F} + B\,\frac{n_2 \delta S}{\Delta T}\right) \qquad (9)$$

where $B = \frac{2.303}{20} 10^k = 0.115\,(\Delta T + 1)$, and δf and δS are the elementary errors in the resonant frequency measurement and the transmission coefficient measurements, respectively, with $n = 0, 1, 2, 3, \ldots$ The discrete character of the measurements causes a similar distribution of errors. Because there is no continuous spectrum of readings available, the error in the resonant frequency measurement, δf, may have a value of $\delta f_i/2$ or any multiple n thereof, where δf_i is the increment of the frequency change in the measuring system. The incremental error in the transmission coefficient measurement, δS_{21}, was evaluated experimentally for a given mode of the cavity operation as 0.02 dB.

For the average values of $M = 9.0\%$, $\Delta F = 12.5$ MHz and $\Delta T = 0.95$, $B = 0.224$, and for $n_1 = 2$ and $n_2 = 0$, σ_M will have a value of 0.029% moisture. For $n_1 = 0$ and $n_2 = 2$, σ_M will be 0.085% moisture. These incremental errors can be added to evaluate the uncertainty in moisture measurements of discrete character, and together with a given uncertainty in the standard oven method, σ_c, are used to determine the system uncertainty, σ_s, according to equation 7. Such calculations have been performed for several cases of practical importance and presented in Fig. 7, for $n_1 = n_2$ and for various values of $\sigma_c = 0$, 0.1 and 0.2% moisture. The standard error of performance for peanuts grown in 1991, 0.466% moisture, corresponds to approximately $n_1 = n_2 = 8$. This means that the coordinates of the resonant curve have been measured twice (empty cavity and cavity loaded with a kernel), with the uncertainty of 3 to 4 discrete steps for every component in equation 9. The second conclusion is that the uncertainty in moisture content determination by the standard oven method is not a limiting factor for the microwave method of moisture assessment in individual peanut kernels.

Discussion and Conclusions

Measurements on a microwave resonant cavity, in which a peanut kernel is inserted, were proven useful for determining the moisture content of the kernel. The expected uncertainty in moisture content determination in the range from 4 to 14 percent is 0.91 percent moisture at the 95-percent confidence level. Thus, by measuring two parameters of the resonant cavity loaded with a peanut kernel, its moisture content can be determined immediately and without any contact between the kernel and the measuring instrument. The measurement can be simplified by using a grid on a calibrated screen of the measuring instrument, as shown in Fig. 8. Lines of constant moisture content are drawn on a screen calibrated for the resonant frequency shift in MHz (horizontal axis) and for the change in transmission coefficient S_{21} in decibels (vertical axis). When the coordinates of the peak of the resonant curve for an empty cavity (Fig. 2) are located in the upper right-hand corner of the screen (reference point), the position of the resonant-curve peak for the cavity loaded with a peanut of arbitrary size, will immediately indicate the moisture content of the peanut kernel. Although of limited accuracy, this method could be used for immediate sorting of peanut kernels in samples

Verification measurements were carried out with kernels harvested one year later than the runner-type kernels used for calibration. Moisture content of virginia market-type peanut kernels used in the verification tests, although not used for calibration and of some difference in kernel shape, were predicted quite well. Bias of the verification measurements is related to permanent errors and could reflect differences in kernel densities, peculiarities of growing season (chemical composition), differences in shape, and other factors related to year and location of production. Low values of the bias for moisture content determination may indicate that the microwave resonator technique is not influenced by kernel differences due to peanut type, origin, and year of harvest. The standard error of performance (SEP) reflects the calibration uncertainty, measurement uncertainty, and uncertainty of the standard oven method used for calibration. The measurement uncertainty is also

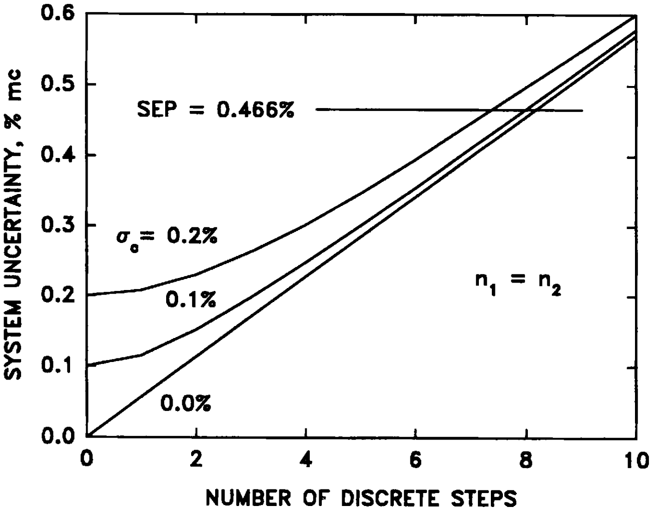

Fig. 7. Estimated system uncertainty as a function of number of discrete steps in measurement uncertainty ($n_1 = n_2$) for indicated values of the calibration uncertainty, σ_c.

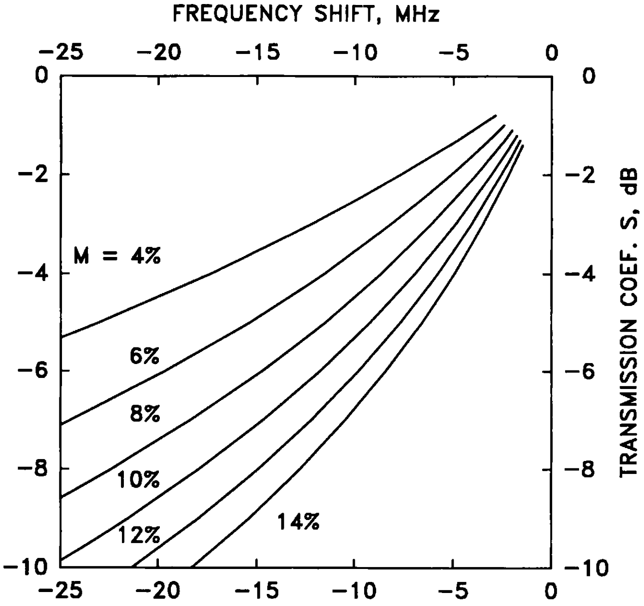

Fig. 8. Grid of constant moisture content lines on the instrument screen calibrated for the resonant frequency shift (horizontal axis) in MHz and the change in transmission coefficient S_{21} in decibels (vertical axis).

related to the discrete nature of the measurements, and, as shown in Fig. 6, preserves the random character of the errors.

The measuring circuit can be simple and requires only commercially available devices. As changes in the resonant frequency and the transmission factor of the empty cavity and the cavity loaded with a kernel are the measured values, long-term stability of the measuring system is not required. A practical instrument should be able to measure instantly the difference between two resonant frequencies with an accuracy of ±0.05 MHz and the differences between two transmission coefficients with an accuracy of ±0.03 dB. The absolute value of either of these parameters is of no importance, since their differences would be used in routine moisture content measurements.

Although results of static measurements are reported in this paper, peanut kernels could be individually introduced into the cavity, measured and released automatically at a high rate, determined only by the characteristics of a transport system and time needed for measurement (approx. 20 ms). Microprocessors could govern kernel delivery and release from the cavity and provide the computations needed for moisture content determination. A print-out of individual values and/or values averaged over the number of kernels being tested and the distribution for values for a given lot could be provided.

Measurements on a microwave resonant cavity with and without a single peanut kernel positioned at the center of the cavity can be used to determine the moisture content of the kernel independent of variations in kernel dimensions, type, and year of harvest, when the kernel is very small ($< 10^{-3}$) with respect to the volume of the cavity. Measurements of resonant frequency shift and change in transmission coefficient with a network analyzer permitted the prediction of moisture content of single peanut kernels with 0.9-percent moisture uncertainty at the 95-percent confidence level over a moisture content range from 4 to 14 percent.

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