Thin-layer microwave drying of peanuts

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St. John, C. and Otten, L. 1989. **Thin-layer microwave drying of peanuts.** Can. Agric. Eng. **31**: 265–270. The drying behavior of single layers of peanut pods and kernels fully exposed to different levels of microwave power at 2450 MHz was investigated. An experimental thin-layer microwave drying apparatus was designed and constructed to monitor weight loss during drying. Freshly dug and partially dried peanuts were subjected to effective power levels ranging from 250 to 1000 W. Airflow rate, temperature and relative humidity were kept constant at 0.1 m/s, 22°C, and 30%, respectively, to determine the effect of microwave power on drying rate.

Drying rates ranging from 10 to 94 times the normal rate of conventional wagon drying were achieved for pods and 8 to 32 times for kernels. Final seed temperatures ranged between 41 and 58°C. A two-term exponential thin-layer drying model accurately described the drying behavior of pods and kernels over the entire period. Overall equations were established to predict the drying of pods and kernels with respect to time and microwave power level.

INTRODUCTION

The initial processing step in peanut production following harvest is drying or "curing" of the whole peanuts in preparation for storage. Harvest procedures include digging and inverting the plants for drying from an initial pod moisture content of 100 - 150% to 25 - 35% (DB). Peanuts are then combined and loaded into conventional batch type dryers where forced air is used to lower the moisture content to 8 - 10%. In regions where adverse weather conditions prevail at harvest, the field drying stage is eliminated.

The curing step can have a significant effect on taste, texture and milling properties. To maintain an acceptable quality, peanuts are conventionally dried with the incoming air heated to no higher than 35°C (Beasley and Dickens 1963). This upper limit may have to be further reduced to prevent the relative humidity from becoming less than 60%. These temperature and humidity restrictions can result in drying times in excess of 30 h for peanuts of about 25% (DB) moisture content (Delwiche et al. 1986).

The main disadvantage of conventional batch drying is that drying proceeds from the surface inward on individual peanuts. This is expected to cause stress concentrations that tend to produce surface hardening, splits and cracks. Diffusion of moisture to the surface is then restricted by the reduced permeability of the outer layers. As a result, the maximum rate of moisture removal is limited when the equipment is operated in a manner to maximize quality. The use of microwaves to provide energy for moisture removal is a means of overcoming this disadvantage. Internal heat generation by the microwave process creates a positive temperature gradient inward and a moisture-driving potential outward in moist hygroscopic materials. The high efficiency with which microwave energy is coupled with the product and the selective heating of moisture-laden portions, results in accelerated and more even drying for many products.

OBJECTIVES

The aim of the research presented in this paper was to determine the drying behavior of single layers of peanut pods and kernels fully exposed to different levels of microwave power. Specific objectives are:

(1) To construct a thin-layer microwave dryer capable of providing meaningful and accurate data without interrupting the progress of drying.

(2) To develop equations to predict the drying rate of peanut pods and kernels for various initial moisture contents and energy input levels.

LITERATURE REVIEW

Otten and Levesque (1987) have presented a review of experimental and commercial microwave drying of grain corn, including a description of a pilot-scale dryer installed at Tifton, Georgia. This unit has been used by Delwiche et al. (1986) to investigate the effect of microwave vacuum drying on peanut quality. Microwave power levels at 2450 MHz ranged from 940 to 7600 W. Peanuts shelled at 8 – 28% (DB) were dried at nominal rates of 4, 8, 16 and 32 times the normal rate of conventional wagon drying. No significant ($P > 0.05$) differences were observed for kernel splitting and skin slippage potential among the microwave vacuum treated samples and conventionally dried control samples. However, slight ($P < 0.05$) differences were found among the treatment levels within the microwave group. Kernels dried at the lower microwave process rates showed less damage than those at higher process rates. The germination potential of microwave-dried nuts was significantly ($P < 0.01$) lower than the control samples, with germination decreasing with increasing microwave process rate.

Thin-layer drying

Reviews of existing grain drying theories have been presented by Fortes and Okos (1980) and Booker et al. (1974). Liquid and/or vapor diffusion have been assumed to be the primary mass transfer mechanisms in drying studies on cereal grains and other crops, including peanuts. The kinetics of moisture desorption is therefore represented by Fick's second law of diffusion.

Analytical solutions to the diffusion equation, which are available for several geometries and initial and boundary conditions, have been applied to thin-layer drying studies. Young and Whitaker (1971) and Whitaker and Young (1972) used this approach in their studies of the drying behavior of peanut pods and kernels, respectively.

The diffusion-based modeling approach involves the use of a finite number of terms of the following infinite series solution to the diffusion equation.

$$MR = A_0 \exp(-k_0 t) + A_1 \exp(-k_1 t) + \ldots \qquad (1)$$

The solution applies regardless of a particle's geometry or boundary conditions but a constant diffusivity is assumed. The general form of the solution can be used to describe the expected average moisture history and the relative effect of various drying parameters (Sharaf-Eldeen et al. 1979). The particular constants and parameters must be chosen to fit the experimental data and the number of terms used is determined by the accuracy and computational ease required.

Henderson (1974), Sharaf-Eldeen et al. (1979) and Levesque et al. (1986) analyzed thin-layer drying data for corn using two-term approximations of Eq. 1. They indicated that the parameters and coefficients must be related to the conditions of both the product and the drying medium in order to achieve satisfactory prediction of the drying process. Hutchinson and Otten (1983) also achieved excellent fits to experimental drying data for soybeans and white beans using the two-term exponential approximation.

Despite excellent fits of experimental data that have been obtained with the diffusion equation, many of the inherent assumptions are known to be invalid for agricultural products and foods. For example, the normal assumption of homogeneity does not hold for most biological materials. Thus, Mensah et al. (1979) found that the resistance of soybean seedcoats to moisture transfer was approximately six times that of the cotyledons. Similarly, Henderson and Pabis (1962) and Sharaf-Eldeen et al. (1979) have indicated the presence of internal temperature gradients during the initial stages of drying. Furthermore, most researchers agree that the diffusivity is moisture-dependent (Brooker et al. 1974). The success in predicting drying behavior that has been achieved using diffusion theory may be attributed to the fact that the solutions decay exponentially with time in a manner similar to experimental drying curves (Fortes and Okos 1980). Purely empirical drying equations often give the best results in predicting drying behavior of cereal grains (Brooker et al. 1974). The most notable empirical relationship is the Page equation, which has been widely used in the analysis of thin-layer drying data for crops

$$MR = \exp(-Kt^{N}) \qquad (2)$$

Overhults et al. (1973) and White et al. (1981) found that Page's equation gave good predictions of drying curves for soybeans. Hutchinson and Otten (1983) obtained excellent fits of experimental drying data for soybeans and white beans. The drying constants K and N were described as functions of temperature, humidity, air velocity and initial moisture content.

EXPERIMENTAL APPARATUS AND PROCEDURE

Microwave drying equipment

The thin-layer drying apparatus is illustrated schematically in Fig. 1. The microwave generator consisted of a variable output 2450-MHz magnetron tube which was connected to a 430-mm cube stainless steel oven cavity by a short waveguide. Power transducers were connected to two radiofrequency power meters which measured the values of forward and reverse power. A cavity tuner located downstream of the power transducers was used to obtain the maximum transmitted energy with minimum reflected energy at all voltage settings.

Air circulation for removal of vapor from the cavity was provided by the laboratory air supply and entered the cavity near its base. A 330-mm-diameter sample container with a mesh bottom, made of stainless steel, was used to contain the peanut sample during the drying process. A baffle installed at the level of the sample tray forced the inlet air to flow up through the sample. Water vapor exited the cavity through two screened holes in its roof. The airflow rate was monitored using a rotameter.

Weighing system

The mass of the sample during the drying period was obtained by measuring the strain in a stainless steel cantilever beam from which the sample container was suspended. The beam was wrapped with aluminum tape to protect the strain gages from exposure to the microwaves. The output voltage from the Wheatstone bridge circuit was measured and recorded by the datalogger.

Standard masses were used to determine the relationship giving sample mass as a function of the input voltage. Although the calibration curve was linear, the slope and/or intercept changed slightly over a period of time. To eliminate this variation a new calibration was made before each test run. The accuracy of weighing beam was estimated to be ±0.1 g.

Experimental design

The designs for the drying experiments were randomized complete blocks (RCB) arranged as 4 × 1 factorials and replicated three times. Four microwave energy input rates were investigated at each pod and kernel initial moisture level. Target microwave incident power levels were 300, 600, 800, and 1100 W. Initial moisture levels were 120 and 40% (DB) for unshelled pods and 80 and 60% for kernels.

The sample size, airflow rate through the cavity, and inlet air temperature and humidity were held constant throughout the drying experiments. Each sample was 300 g. The airflow rate was 8.24×10^{-3} m^3/s which corresponds to an apparent air velocity of approximately 0.10 m/s through the product layer. The inlet air temperature averaged 22°C at a relative humidity of 30%.

Drying procedure

The treatment combinations in each replication were processed according to the randomization plan. The plastic bag containing the specified sample was removed from cool storage, which was kept at 4°C, at least 12 h before the microwave drying treatment and equilibrated at room temperature inside the bag to assure a uniform temperature and moisture level throughout the seed mass. The unshelled peanuts or kernels were then weighed to ±0.001 g before they were spread in a single layer in the sample container. The energy input rate was set by adjusting the voltage to the desired value. The air supply was turned on immediately after the start of the drying cycle.

The sample mass was measured with the cantilever system at 5-min intervals for the first hour. The interval was increased by 5 min after each hour of drying until the experiment was terminated. During the measurements the airflow was stopped. The approximate drying time for each treatment was determined from preliminary drying tests. Upon completion of a drying experiment the sample was immediately weighed on the laboratory balance to verify the accuracy of the experimental balance and then visually inspected for physical damage. Next, the sample was air-dried in an air-convection oven as recommended by the American Society of Agricultural Engineers Standard (1986) to obtain the dry matter weight. The oven was maintained at 100°C and the respective drying times for pods and kernels were 40 and 72 h. All moisture content data were calculated on a dry basis (DB).

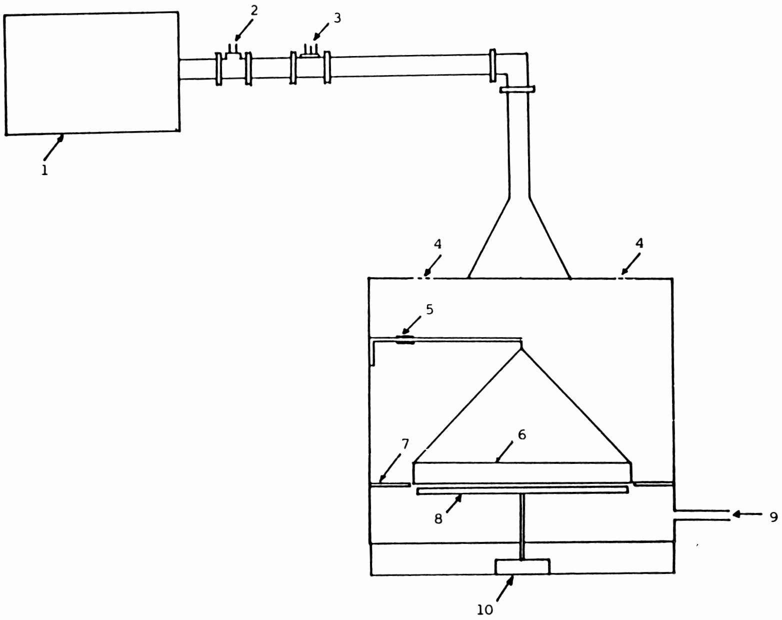

Figure 1. Schematic diagram of microwave drying equipment. 1, microwave generator; 2, power transducers; 3, tuner; 4, water vapor outlets; 5, strain gauges; 6, sample container; 7, baffle; 8, container support; 9, air inlet; 10, motor.

Statistical analysis

The Statistical Analysis System (SAS) software (SAS Institute Inc. 1986) was used for data analysis. Regression analyses were performed by the general linear modeling (GLM) procedure where an equation could be expressed in linear form and by the nonlinear least squares (NLIN) procedure where linearization was not possible. The RSQUARE procedure was used in a preliminary analysis to determine which variables provided the highest linear correlation to the response. The ANOVA procedure was used to perform analyses of variance and test hypotheses about variables contained in the experimental design model. The F-tests were considered significant at the 5% level.

RESULTS AND DISCUSSION

Microwave drying conditions effects

Both the transmitted and reflected power values varied cyclically during the course of drying runs at all voltage settings. While both quantities of power appeared to be material dependent, they displayed no overall changes with length of exposure or sample initial moisture content at a given voltage output. In general, more power was absorbed by pods than by kernels. Effective power input to the cavity was the difference between the average transmitted and reflected power values. Effective power levels at stipulated generator voltage settings were 250, 575, 700 and 1000 W for pods, and 250, 500, 675, and 775 W for kernels. Final seed temperatures, which were obtained by placing subsamples in a thermos flask, increased with the voltage setting from about 41 to 58°C.

External kernel damage was observed to be minimal; however, internal inspection revealed evidence of uneven drying in up to 10% of the kernel samples dried to an average moisture content of 9% (DB) at higher power levels. These kernels displayed significant internal shrinkage. Physical quality improved as the effective power decreased and no visual damage was detected in kernels dried at 250 W.

Drying behavior and model selection

Preliminary tests revealed that peanut samples could be microwave dried to below 2% (DB) moisture content in a 20-h period. Consequently, it was assumed that prolonged microwave drying of peanuts at all power levels would remove all moisture and the value of M_e was taken as zero in the moisture ratio computations.

Plots of moisture content versus time exhibited decaying exponential type characteristics. Single-term exponential models, including Page's equation, were examined as potential microwave drying models but they failed to adequately predict both pod and kernel drying behavior during the entire drying period. However both two- and three-term approximations of the general series solution to the diffusion equation adequately described the experimental data. Additional terms did not improve the accuracy of fit.

In terms of a higher coefficient of determination, the three-term model generally provided a slightly better fit to the experimental data than the two-term model. However, in following scattered observations more closely, the curve predicted by the three-term model exhibited a polynomial effect rather than a truly exponential decay during the later drying stages (Fig. 2). The two-term approximation was considered to represent the microwave drying process more accurately than the three-term approximation, and would be computationally more efficient since one less constant needed to be evaluated.

The two-term exponential equation was the model proposed by Sharaf-Eldeen et al. (1979) and expressed as:

$$MR = A \exp(-kt) + (1-A) \exp(-Bkt) \qquad (3)$$

Equation 3 was fitted to the drying data for each pod and kernel test. The drying parameter k and the coefficients A and B were selected to minimize the squares of deviation of the model from the data using the NLIN procedure. R^2 values were consistently higher than 0.995.

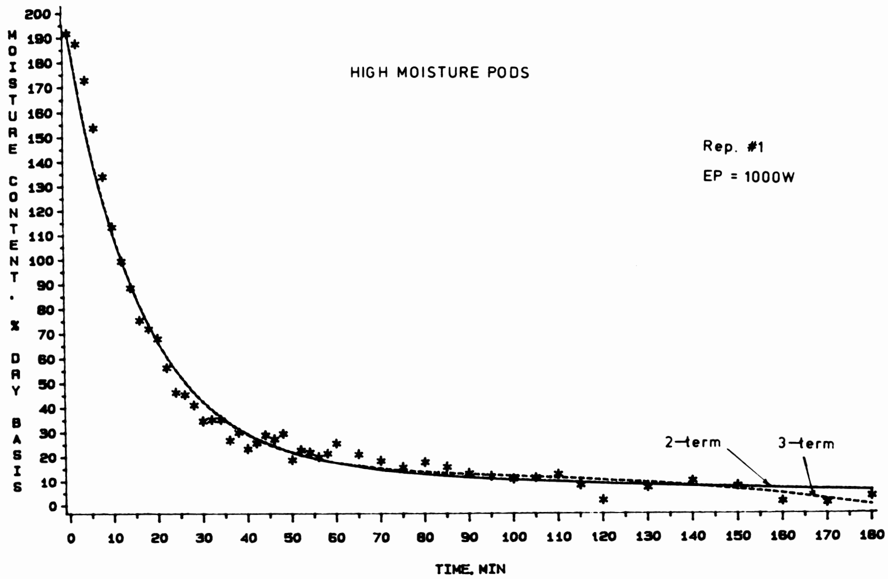

Figure 2. Comparison of two- and three-term exponential models fitted to peanut pod drying data of replicate 1 at 1000 W.

Drying rate

The drying rates were compared on the basis of the time required to dry samples from the initial moisture levels to the 10% (DB) marketable moisture level. The drying time for each test was predicted from its two-term exponential equation.

The drying times in each block of experiments increased with a decrease in effective power and hence, a decreasing drying rate. Drying times also tended to increase with the block number in each experiment, indicating a possible effect of the time of treatment application on the drying rate. Analyses of variance performed on the drying times for each pod and kernel moisture level showed that differences in drying time among effective power levels were significant at the 1% level in all cases. Differences in drying time among blocks were less significant, with the difference being insignificant for the low moisture pod experiment.

It is also convenient and informative to express microwave drying rates in terms of the drying-rate factor (X), which is defined as being the number of times microwave drying is faster than the nominal average conventional drying rate of 0.5% (WB)/h. Use of rate factors also enables comparisons to be made between pod and kernel drying rates for the different initial moisture levels.

The treatment mean drying times for the various experiments were converted to the rate factors displayed in Table I. Drying-rate factors ranged from 8 for low-moisture kernels dried at 250 W to 94 for low-moisture pods dried at 1000 W. The drying-rate factors of pods were almost double those of kernels for most effective power levels in both high- and low-moisture experiments. Both pod and kernel high-moisture drying-rate factors were higher than their low-moisture counterparts at the three lower power levels, but lower at the highest power level. In fact, high-moisture drying-rate factors increased linearly with effective power whereas increases in low moisture drying rates displayed a tendency to be exponential.

The amount of moisture removed per kilowatt-minute of effective energy did not vary significantly with either the energy input rate or the initial moisture level, and averaged 1.6 g for pods and 0.8 g for kernels. The higher energy input rates only increased the rate of moisture removal.

Table I. Peanut moisture removal rates calculated on a wet basis

Effective power (W)	Mean drying time (min)	Rate factor (X)
	High-moisture pods	
1000	109.5	50
700	147.3	37
575	179.2	30
250	320.3	17
	Low-moisture pods	
1000	24.9	94
700	61.8	38
575	101.1	23
250	227.9	10
	High-moisture kernels	
775	183.7	23
675	216.7	20
500	301.1	14
250	437.7	10
	Low-moisture kernels	
775	106.4	32
675	204.8	17
500	316.2	11
250	432.5	8

Microwave drying equations

A general equation based on the two-term exponential model (Eq. 3) was established for each pod and kernel initial moisture level to predict the drying curve from the effective power level. From a theoretical basis the parameters A and B are related to the geometry, composition and initial moisture level of the peanuts and were considered constant. The drying parameter k, however, should be related to the drying conditions.

The experimental drying data from the three replicates of each energy input rate at all pod and kernel moisture levels were combined after adjustment for the respective initial moisture value. The NLIN procedure was used to determine the values of A, B, and k which provided the best fit of the model to each data combination. R^2 values were consistently higher than 0.99. The average values of A and B were calculated for each pod and kernel moisture level. The series of regressions were then repeated for each data combination to determine the drying parameter k and A and B at their average values.

The RSQUARE procedure was used to examine a number of potential linear models to describe the dependence of k on the effective power (EP) for each pod and kernel moisture level. The independent variables investigated were EP, EP^2, 1/EP, $1/\mathrm{EP}^2$ and ln(EP). The most promising models for the paremeter k were selected on the basis of goodness of fit as indicated by the coeffecient of determination. After substituting these functions into the appropriate two-term exponential equation, nonlinear least square regressions were performed over the entire set of drying data for each pod and kernel moisture level in order to calculate the coefficients relating the variables in the selected models to the parameter k. In general, very little improvement was achieved by increasing the number of terms in the drying parameter expressions and the more complex models were eliminated.

Equation 3 was fitted to the peanut pod and kernel drying data with an R^2 of at least 0.99. The corresponding drying parameters are given in Table II.

The model provided a good fit for each set of data as well as for the combined data of three replications. Figure 3 displays a typical plot of combined data obtained at 575 W and the predicted drying curve. This good agreement reveals that use of the general solution form of the diffusion equation can be extended to modeling of drying processes in which heat and moisture transfer is effected by microwave energy.

The profound influence of effective power on the drying behavior is illustrated in Fig. 4. As was expected, drying proceeded more rapidly as the effective power increased. However, differences in drying behavior tended to be smaller at higher power levels in high-moisture content experiments. Similar observations were also made for the low moisture content experiments.

CONCLUSIONS

The microwave drying process was very effective in removing moisture from high- and low-moisture peanut pods and kernels. Pods were dried at rates ranging from 10 to 94 times the normal rate of conventional wagon drying and kernels at 8 - 32 times.

The two-term aproximation of the general series solution to the diffusion equation predicted the microwave drying behavior of both pods and kernels with good accuracy over the entire drying period.

ACKNOWLEDGEMENTS

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Table II. Drying parameters for $MR = A \exp(-kt) + (1-A) \exp(-Bkt)$

Sample	A	B	k
(1) *High moisture*			
Pods	0.828224	0.087194	$0.0276956 + 4 \times 10^{-8}\,\mathrm{EP}^2 - 768.911/\mathrm{EP}^2$
Kernels	0.579980	0.147369	$-0.088026 + 0.0189844 \ln(\mathrm{EP})$
(2) *Low moisture*			
Pods	0.721118	0.152084	$0.027054 - 1.07\times10^{-4}\mathrm{EP} + 1.826 \times 10^{-7}\,\mathrm{EP}^2$
Kernels	0.516878	0.169495	$0.737861 - 1.6431 \times 10^{-3}\,\mathrm{EP} - 96.6975/\mathrm{EP} + 1.18 \times 10^{-6}\,\mathrm{EP}^2$

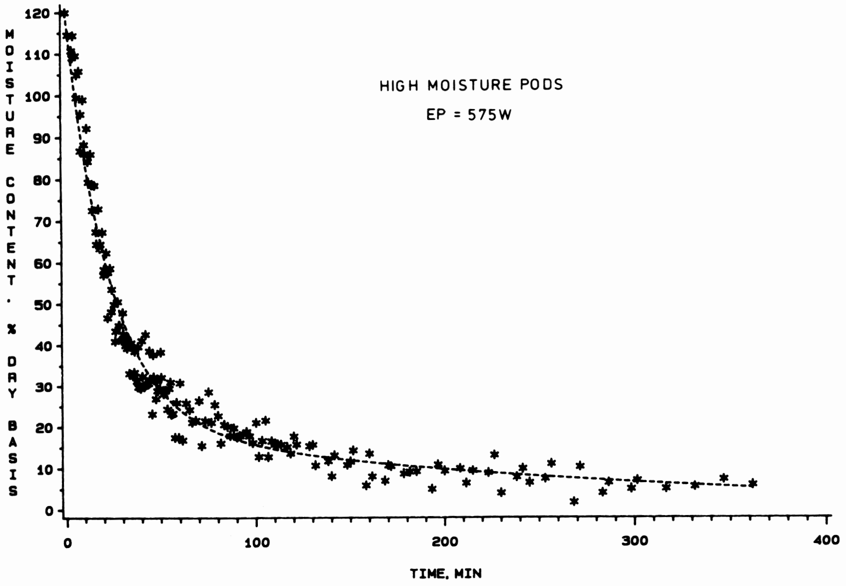

Figure 3. Typical plot of data obtained by combining observations of three replications for drying of high-moisture pods at 575 W.

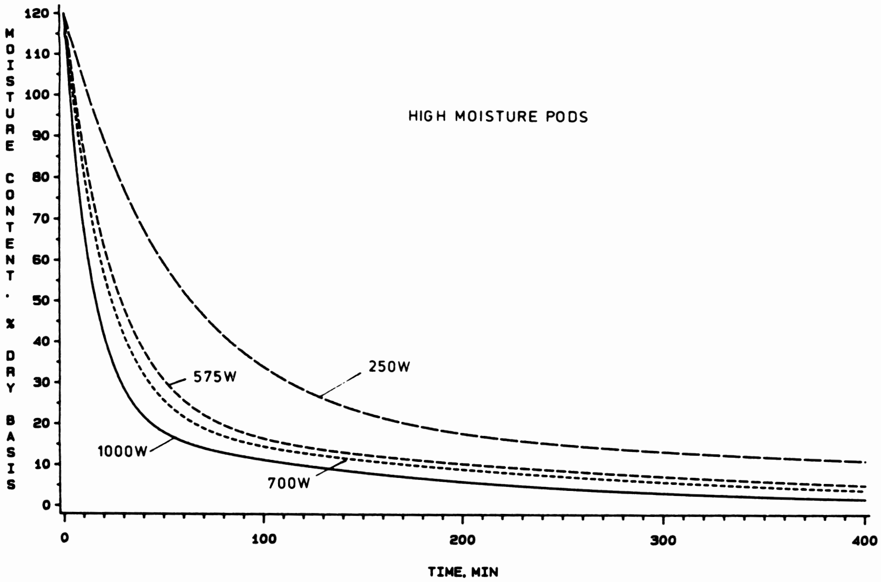

Figure 4. Effect of effective microwave power on high-moisture pod drying behavior.

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NOMENCLATURE

A	parameter in two- and three-term exponential models,
A_0, A_1	parameters in series solution of diffusion equation,
B	parameter in two- and three-term exponential models,
DB	dry basis,
EP	effective power (W),
K	drying parameter in Page's equation,
k	drying parameter in two- and three-term exponential models ($\min^{-1}$),
k_0, k_1	parameters in series solution to diffusion equation ($\min^{-1}$),
M	average moisture content (% DB),
M_0	initial moisture content (% DB),
M_e	equilibrium moisture content (% DB),
MR	moisture ratio = $(M-M_e)/(M_0-M_e)$ (decimal),
N	parameter in Page's equation,
t	time (min),
X	drying-rate factor,
WB	wet basis.

REFERENCES

American Society of Agricultural Engineers 1986. Moisture measurements-peanuts - S410.1:97-98. *In* ASAE Yearbook of Standards. 33rd ed. ASAE, St. Joseph, MI.

BEASLEY, E. O. and J. W. DICKENS. 1963. Engineering research in peanut drying. North Carolina Exp. Sta. Tech. Bul. no. 155.

BROOKER, D. B , F. W. BAKKER-ARKEMA, and C. W. HALL. 1974. Drying cereal grains. AVI Publishing Co. Inc., Westport CI. 279 pp.

DELWICHE, S. R., W. L. SHUPE, J. L. PEARSON, T. H. SANDERS, and D. M. WILSON. 1986. Microwave vacuum drying effect on peanut quality. Peanut Sci. 13:21-27.

FORTES, M. and M. R OKOS. 1980. Drying theories: their bases and limitations as applied to foods and grains. *In* A. S. Mujumdar, ed. Advances in drying. Hemisphere Publishing Corporation, Washington, DC.

HENDERSON, S. M. and S. PABIS. 1962. Grain drying theory. III. The air/grain temperature relationship. J. Agric. Eng. Res. 7(1):21-26.

HENDERSON, S. M. 1974. Progress in developing the thin-layer drying equation. Trans. ASAE. (Am. Soc. Agric. Engrs.) 17(6):1167-1168, 1172.

HUTCHINSON, D. and L. OTTEN. 1983. Thin-layer air drying of soybeans and white beans. J. Food Technol. 18:507-522.

LEVESQUE, M. P., L. OTTEN, and G. E. TIMBERS. 1986. Effects of kernel properties on thin-layer drying of shelled corn. *In* A. S. Mujumdar, ed. Drying 86. Vol. II. Hemisphere Publishing Corporation, Washington, DC.

MENSAH, J. K., G. L. NELSON, J. L. BLAISELL, and G. J. GEANKOPLIS. 1979. Hygroscopic properties and moisture diffusivities of soybean seed coat and cotyledons. Paper no. 79-3058. ASAE, St. Joseph, MI. 49085.

OTTEN, L. and M. LEVESQUE. 1987. Reduction of fuel in grain drying. Report prepared for the Agricultural Energy Centre, Ontario Ministry of Agriculture and Food, Guelph, ON. 242 pp.

OVERHULTS, D. G., G. M. WHITE, H. E. HAMILTON, and I. J. ROSS. 1973. Drying soybeans with heated air. Trans. ASAE. (Am. Soc. Agric. Engrs. (16(1):112-113.

Statistical Analysis System Institute Inc. 1985. SAS user's guide: Statistics. Cary, NC.

SHARAF-ELDEEN, Y. I., M. Y. HAMDY, H. M. KEENER, and J. L. BLAISDELL. 1979. Mathematical description of fully exposed grains. Paper no. 79-3034. ASAE, St. Joseph, MI.

WHITAKER, T. B. and J. H. YOUNG. 1972. Simulation of moisture movement in peanut kernels: evaluation of the diffusion equation. Trans. ASAE (Am. Soc. Agric. Engrs.) 15(1):167-171, 174.

WHITE, G. M., T.C. BRIDGES, O. J. LOEWER, and I. J. ROSS. 1981. Thin-layer drying model for soybeans. Trans. ASAE (Am. Soc. Agric. Engrs.) 23(6):1643-1646.

YOUNG, J. H. and T. B. WHITAKER. 1971. Evaluation of the diffusion equation for describing thin-layer drying of peanuts in the hull. Trans. ASAE (Am. Soc. Agric. Engrs.) 14(2):309-312.