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MEETINGS

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11/12–11/13: International Symposium on Automatic Control and Optimization of Food Processes. Paris, France. Contact: J.J. Bimbenet, 1, Avenue Des Olympiades, F91305 Massy, France.

11/13–11/19: International Symposium of Food Working Party of the European Federation of Chemical Engineering. Paris, France. Contact: V. Reynaud, Salon Du Gia, 42, Rue Du Louvre, F-75001, Paris, France.

December, 1986

12/16–12/19: Winter Meeting of the American Society of Agricultural Engineers. Hyatt Regency Hotel, Chicago, IL. Contact: M.A. Purschwitz, American Society of Agricultural Engineers, 2550 Niles Road, P.O. Box 410, St. Joseph, MI 49085.

CONTENTS

EFFECTS OF FEED MOISTURE AND BARREL TEMPERATURE ON THE RHEOLOGICAL PROPERTIES OF EXTRUDED COWPEA MEAL[1]

M. B. KENNEDY[2], R. D. PHILLIPS[3,4], V. N. M. RAO[5]
and M. S. CHINNAN[3]

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ABSTRACT

Decorticated cowpea meal was adjusted to 20, 30, and 40% moisture and extruded in a Wayne pilot-scale extruder at barrel temperatures of 150, 175 and 200°C. The resulting products were subjected to rheological evaluation using the Instron Universal Testing Machine equipped with standard tensile jaws, the Warner-Bratzler shear device and the Kramer Shear Press. Regression equations relating rheological properties to feed moisture and barrel temperature were computed from the data, and response surfaces were generated from these models. Tensile strength of extrudates was greatest for the dense products produced in the low moisture-low temperature region and declined at higher moistures and temperatures. Shear strength as determined by either the Warner-Bratzler or Kramer devices exhibited a ridge of high values extending from 20%-150°C to 30%-200°C, and declined for brittle, expanded products made at low moisture and high temperature and for soft products made at high moisture.

[1]Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warrant by the University of Georgia and does not imply approval of a product to the exclusion of others that may be suitable.

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INTRODUCTION

The importance of cowpeas as a source of protein and B vitamins in developing countries of West Africa has been well established (Dovlo *et al.* 1976). However, neither cowpeas nor other starchy legumes have been incorporated to a significant extent into a commercially manufactured foods in developed countries. These seeds contain approximately 50% starch and 25% protein, levels similar to those which might be chosen for cereal/oilseed meal blends. In addition, the protein quality is superior to that of cereals and comparable to that of oilseed meals. For these reasons, cowpeas would appear to be a promising food ingredient if coupled with an appropriate technology for conversion to food products.

Thermoplastic extrusion is particularly efficient and versatile process for producing finished or intermediate food products from raw ingredients (Harper 1981a,b). It is employed on a large scale in the production of precooked cereal and tuber flours, snacks, and ready-to-eat cereals from starchy substrates; and for producing texturized protein products from defatted oilseed meals. A number of experimental studies have featured the application of extrusion cooking to starchy legumes, including cowpeas, and the evaluation of the resulting products for nutritional and functional properties (Elias *et al.* 1976; Jorge Joao *et al.* 1981; Aguilera *et al.* 1984; Pham and Del Rosario 1984a, 1984b).

When the goal of extrusion is to cook and form the ingredients into a coherent food product, understanding the factors which control texture are of primary importance. Numerous researchers have examined the effects of extrusion conditions on the textural properties of extruded cereal and oilseed meals. Mercier and Feillet (1975) reported that the maximum shearing force required for extruded corn grits containing an initial moisture content[1] of 18.2% declined from 3000 to 1000 kg as extrusion temperature was increased from 170 to 250 °C. Cumming *et al.* (1972) used both tensile and shear tests to evaluate the texture of soybean meal extrudates as a function of extrusion temperature (110 to 200 °C) at 30% initial feed moisture. They reported that breaking tensile force increased to a maximum value at approximately 160 °C, then declined, while required shearing force increased in a sigmoidal fashion over the temperature range. Aguilera and Kosikowski (1976) studied the effects of feed moisture, process temperature and screw speed on Warner-Bratzler shear force values of extruded soybean meal. The resulting data were fit to a quadratic polynomial equation and presented as surface-response diagrams. The resulting model predicted that shear force declined with increasing moisture (25-45%), and with increasing temperature (120-170 °C) when moisture

[1]All moisture content values are expressed in terms of wet basis unless otherwise specified.

was > 35%. Below 35% moisture, shear force was relatively independent of extrusion temperature. Maurine and Stanley (1978) examined the effects of protein content (35-38%), and screw speed (60-100 rpm), as well as feed moisture (24-30%) and extrusion temperature (160-180 °C) on Warner-Bratzler values of extruded soy protein materials. They found that the required shearing force for these proteinaceous extrudates increased with increasing temperature rather than declined as was observed with starchy products (Mercier and Feillet 1975). Despite these and other efforts, a systematic model of the effects of extrusion variables on the texture of even the most studied substrate, soybean meal, does not exist (Holay and Harper 1982). Further, there is very little information on texture of starchy legume extrudates.

We have previously described the extrusion cooking of cowpea meals over a range of initial moistures and barrel temperatures, and have reported the general physical characteristics of the resulting products, including product temperature at the die, residence time, throughput, product moisture, expansion, bulk density, and tristimulus color values (Phillips *et al.* 1984). In this paper, we present the results of a study of the rheological properties of these extrudates.

MATERIALS AND METHODS

Extrusion Processing

The preparation of cowpea meal and the details of the extrusion process have been described previously (Phillips *et al.* 1984). Briefly, whole cowpea seed were decorticated and adjusted to moisture contents of 20, 30 and 40% by adding the required amounts of water, agitating for one hour and equilibrating for approximately 20 h at 10 °C. The hydrated seeds were chopped to a coarse meal in a Hobart Silent Cutter. The meals were extruded on a pilot scale extruder (Wayne Machine and Die Company, Totowa, NJ) equipped with a 19 mm dia (nominal) barrel (25:1 length to diameter ratio), a 5:1 compression ratio screw with constant pitch and increasing root diameter, and a cylindrical die, 4.76 mm dia × 22 mm length. The specific dimensions of the screw based on Harper's (1981a) terminology were: Lead (l) = 19.05 mm; Axial flight width (b) = 4.60 mm; Helix angle (θ) = 18 °; Feed section flight height (depth, H) = 3.48 mm; Metering section flight height = 0.69 mm; Half-diametral screw clearance (δ) = 0.01 mm. The void space between the screw nose and the tapered inner die surface was 0.482 cm^3, and the length of the cylindrical segment of the die was 17.80 mm. A schematic of the Wayne pilot scale extruder is given in Phillips *et al.* (1984). Extrusion was carried out at set (nominal) barrel temperatures of 150 °, 175 ° and 200 °C and a screw speed of 180 rpm. Product temperature was determined by a thermocouple mounted in the barrel adjacent to the die which was in contact with the product stream. The 20% moisture meal was fed into the extruder with a vibrating hopper; the 30% and 40% meals were doughy and had to be manually introduced into the feed port with the aid of a wooden plunger. In each case the machine was choke fed.

Triplicate extrusion runs corresponding to each of the nine combinations of initial moisture (20, 30, 40%) and set barrel temperature (150, 175, 200 °C) were performed. After steady state operation was achieved, as characterized by the absence of surging and hesitation and by constant barrel and product temperature, samples corresponding to 2-5 min operation were collected separately in open pans and allowed to cool for 5 min then sealed in polyethylene bags and stored at −20 °C until evaluated. Extrudates were labeled and will be referred to in terms of the initial moisture and set barrel temperature, e.g. 20-150 represents the product produced from feed material adjusted to 20% moisture content extruded at a barrel temperature of 150 °C.

Rheological Evaluations of Extrudates

Extrudates were evaluated at conditions as similar to those immediately following extrusion and cooling as possible (Phillips *et al.* 1984). They were thawed from −20 °C and allowed to equilibrate to room temperature in sealed bags. As the goal was to characterize the textural range of extruded products that could be made from cowpea meal, moisture was not adjusted prior to evaluation.

Tensile and shear properties of extrudates were determined using an Instron Universal Testing Machine, Table Model 1130 (Instron Corporation, Canton, MA), and the appropriate attachments. Tests were carried out on a minimum of six replicates from each extrusion run, yielding a set of 18 observations for each combination of initial moisture and barrel temperature. Force-deformation curves were recorded on a strip chart recorder at 20 cm/min. Force, F, was recorded in kg and converted to Newtons, N, and deformation, ΔL, was recorded in centimeters, and converted to meters.

Tensile properties were measured by mounting 5.5 cm lengths of extrudate in Instron standard fiber jaws and stretching at a rate of 5 cm/min until failure occurred. In cases in which the extrudate was too brittle to be held in the fiber jaws, sections were coated on each end with a rubber caulking compound to produce resilient "boots" which could then be mounted. Data from samples which failed near the jaws were discarded.

Mean diameter of each extrudate section was determined from six measurements taken with vernier calipers along the length of the sample.

The force required to shear individual strands to extrudate was measured using the Warner-Bratzler shear cell. Cross-head speed was 5 cm/min. Extrudate diameter at the narrow section where shearing occurred was determined with calipers. In addition, shear properties of bulk extrudate were measured using the Kramer Shear Press. One gram of extrudate segments was placed in the cell at right angles to the shearing bars, and the interdigitating plates were forced through the product at a speed of 12.7 cm/min.

The following rheological parameters were calculated from the data for each test to which they were applicable:

(1) Stress at failure

$$\sigma = F/A$$

Where A is the cross-section area, m^2

(2) Modulus of Elasticity

$$E = \sigma/(\Delta L/L)$$

Where L = original length (m)

(3) Total energy (mJ)

$$E_T = F\Delta L$$

Total energy is area under the force deformation curve and was determined by planimeter.

The results were analyzed using the SAS stepwise procedure (Helwig and Council 1979). The initial model was considered to be of fourth order of the following form:

$$y = b_0 + b_1T + b_2M + b_3T^2 + b_4M^2 + b_5TM + b_6T^2M + b_7TM^2 + b_8T^2M^2$$

Where T = nominal barrel temperature (°C)
M = % moisture in the feed;
y = F, σ, E, or E_T

The final models obtained from the SAS stepwise regression procedure were employed in generating response surfaces using the SAS plot/contour procedure (Helwig and Council 1979).

RESULTS AND DISCUSSION

Tensile Test

Table 1 contains measured (computed from experimental data) and predicted (from regression models) values for tensile parameters of extrudates, Table 2, regression coefficients of equations derived from the data, and Fig. 1, response surfaces generated from these models.

Variations in measured tensile properties values at a given set of conditions were large as seen in Table 1. The general physical properties of these extrudates have been described previously (Phillips *et al.* 1984). They exhibited inconsistencies in micro structure, including the tendency to form an annular void which sometimes opened to the outside of the rod-shaped extrudate, and surface breaks which would be especially noticeable in determining tensile properties on 5.5 cm long sections. The observed scatter was doubtless a major factor in the low values of R^2 obtained for the regression equations (Table 2). Despite these inconsistencies, the mean predicted values are, in most cases, reasonably close to the mean observed values. However, there are substantial deviations at higher moistures and barrel temperatures, especially for modulus of elasticity.

The force required to break individual strands of extrudate, and the stress at failure (force/cross section area) exhibited very similar patterns (Table 1, Fig. 1a,b). This reflected a consistency and homogeneity in the produce despite the large-scale structural inconsistencies mentioned above.

Tensile force and stress (Fig. 1a,b) were highest for the dense twisted extrudate produced at low levels of moisture and barrel temperature (Phillips *et al.* 1984) and declined as both independent variables increased. This decrease can be rationalized in terms of the increased tendency to expand and fissure as temperature increases and to become softer as moisture increases. For example at 20% initial moisture, increasing barrel temperature from 150 to 200 °C produced a more expanded, brittle and finally fissured product, while at 150 °C barrel temperature, increasing initial moisture from 20 to 40% produced a softer, more pliable, product. Proceeding from 20-150 to 30-175 the extrudates became both softer and more fissured and at 40-200, much softer and more granular (Phillips *et al.* 1984).

Cumming *et al.* (1972) extruded soy flour containing 30% moisture, dry basis, (23%, wet basis) over a range of barrel temperatures from 110° to 190 °C, and measured the tensile break force. The results were expressed as g force/g sample. If their results are recalculated (assuming the constant extrudate diameter to be 3.18 mm as implied by these authors) maximum force values range from .76 to 1.44 N compared to the range observed with cowpea extrudate of 1 to 16 N. Force was observed to increase with temperature from 110 to 160 °C then to decrease from 160 to 190 °C. Stress

Table 1. Measured and predicted values[1] of force at failure, stress at failure, total energy and modulus of elasticity from the tensile test applied to cowpea meal extrudates

Feed Moisture	Barrel Temperature	Force at Failure N		Stress at Failure kPa		Total Energy mJ		Modulus of Elasticity kPa	
		Measured	Predicted	Measured	Predicted	Measured	Predicted	Measured	Predicted
20%	150	16 ± 6	16	502 ± 224	509	110 ± 59	100	3579 ± 2954	3795
	175	11 ± 7	11	401 ± 250	367	20 ± 14	23	11367 ± 8156	11799
	200	4 ± 2	6	155 ± 81	214	9 ± 41	11	2624 ± 1666	3280
30%	150	9 ± 5	10	328 ± 179	351	117 ± 90	134	1128 ± 1424	1445
	175	7 ± 3	6	263 ± 98	258	75 ± 52	77	920 ± 651	1524
	200	5 ± 3	4	202 ± 97	174	35 ± 28	40	976 ± 1007	1880
40%	150	4 ± 3	3	152 ± 96	131	17 ± 12	25	968 ± 603	1505
	175	1 ± 1	2	83 ± 52	104	17 ± 14	25	360 ± 247	1276
	200	2 ± 1	2	114 ± 55	118	14 ± 6	18	611 ± 619	1920

[1]Mean ± SD

Table 2. Coefficients of regression equations predicting tensile properties of cowpea extrudate to initial feed moisture and nominal barrel temperature

Coefficient	Force at Failure N	Stress at Failure kPa	Total Energy mJ	Modulus of Elasticity kPa
b_0	8.961 E1	1.135 E3	4.002 E3	-2.338 E6
b_1	-4.000 E-1		-5.425 E1	2.754 E4
b_2	-1.274 E0		-1.039 E2	1.357 E5
b_3		-2.222 E-2	1.663 E-1	-7.899 E1
b_4				-1.918 E3
b_5			2.020 E0	-1.598 E3
b_6	2.713 E-5		-7.118 E-3	4.585 E0
b_7		-7.200 E-3	-1.523 E-2	2.259 E1
b_8		3.400 E-5	6.988 E-5	-6.482 E-2
R^2	.57	.45	.49	.56

Where: $y = b_0 + b_1T + b_2M + b_3T^2 + b_4M^2 + b_5TM + b_6T^2M + b_7TM^2 + b_8T^2M^2$

T = Nominal barrel temperature °C
M = % moisture in the feed

Regression models are significant at the 0.0001 level, and coefficients are significant at the 0.05 level.

was also calculated from these authors' data (assuming a constant diameter of 3.18 mm). The values increased from 123 kPa at 110 °C to 163 kPa at 150-160 °C then decreased to 88 kPa at 190 °C. Values for cowpea extrudate ranged from 83 to 500 kPa. These changes in force and stress over the latter part of the range agree with our findings.

Finkowski and Peleg (1981) extruded soy flour containing 22-29% moisture over temperature of 100 to 140 °C and at 50 and 150 rpm screw speed. Their extruder geometry was similar to that used in the present study except the screw had a 2:1 compression ratio. They also applied the tensile test to the resulting extrudates. Although it is difficult to identify the particular extrusion conditions which match the reported values of stress at failure in this paper, the range was 300 to 900 kPa (again recalculating from the authors' data). Although regression equations are not presented by the authors, they found moisture to be a more influential

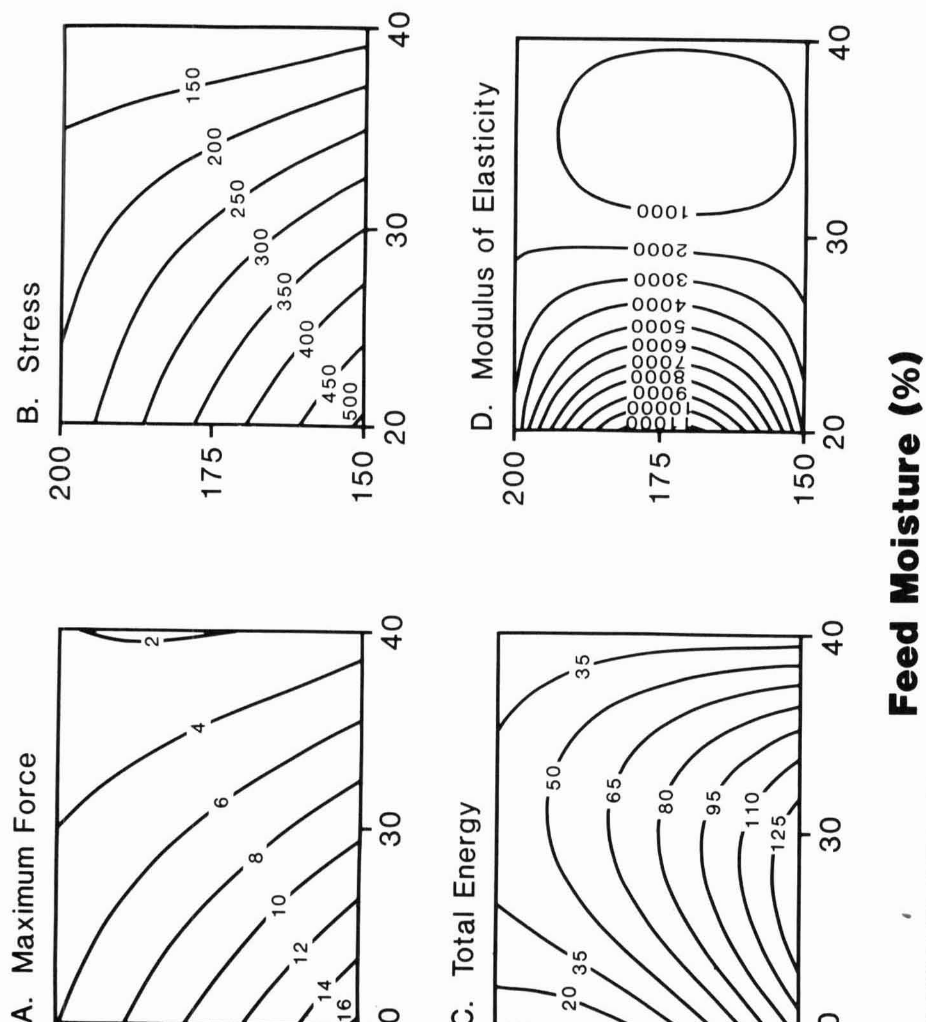

FIG. 1. RESPONSE SURFACE RELATING: A. force at failure (N); B. stress at failure (pKa); C. total energy (mJ); and D. modulus of elasticity (kPa) from the tensile test to feed moisture and barrel temperature.

factor in extrudate strength than temperature or screw speed. Although equipment and feed materials were similar, these stress values are much larger than those of Cumming *et al.* (1972) and overlap the high end of the range seen for extrudates in the present study. It is not known why these two studies on soy extrudates produced such different pictures for tensile properties. Furthermore, there is insufficient information in the literature to indicate what the tensile properties of soy extrudates versus those made from a starchy legume should be.

The total energy required to stretch-to-breaking strands of extrudate (Table 1, Fig. 1c) presented a somewhat different picture. The region requiring maximum energy to break strands of extrudate occurred at initial moistures of 20-30% and a barrel temperature of 150 °C. Values declined with increasing barrel temperature from this region, relatively rapidly at 20% and 40%, and more gradually at approximately 30% initial moisture. This shift in the maximum compared to force and stress may be interpreted in terms of the force pattern (Fig. 1a) and deformation. The 20% extrudates were relatively dry and brittle (Phillips *et al.* 1984) and exhibited sharp narrow force deformation curves, while the 30% moisture extrudate were more moist and deformable and exhibited lower, broader curves. The 40% moisture extrudate required relatively small energies to stretch regardless of extrusion temperature. That is, they were soft and ''short'' requiring little force to deform and breaking at intermediate deformations.

The modulus of elasticity values are given in Table 1 and also illustrated by the response surface in Fig. 1d. The mean predicted values differ greatly from the mean observed values for high feed moisture contents. However, some general statements about the modulus of elasticity of the extrudates can still be made. The maximum modulus value occurred at 20% initial moisture and 175 °C barrel temperature, and declined for all values of moisture and temperature from that point (Fig. 1c). This maximum modulus corresponded to the highly expanded cowpea extrudate (Phillips *et al.* 1984). At 20-200, the force had declined so as to produce a lower modulus, while at 20-150 the product was more capable of stretching prior to failure. A similar explanation can be applied to the other extrudates. Obviously for the modulus to be about the same for all the 30% moisture extrudate, deformation declined at about the same rate as stress did. This was the case due to the greater frequency of fissures and flaws in the product as temperature increased (Phillips *et al.* 1984). Modulus values for extruded soybean meal were calculated from the data of Finkowski and Peleg (1981). They ranged from 7,000 kPa to 61,000 kPa compared to approximately 400-11,000 kPa in this study.

Warner-Bratzler Shear Test

Measured and predicted values of shear parameters from the Warner-Bratzler (W-B) test are given in Table 3, coefficients for the regression equations computed from this data in Table 4, and the resulting response surfaces in Figure 2. As with the tensile data, experimental variation at each extrusion condition is rather large (Table 3), resulting in low values

Table 3. Measured and predicted values of maximum force, maximum stress and total energy from the Warner-Bratzler Shear Test applied to cowpea meal extrudates

Feed Moisture	Barrel Temperature	Maximum Force Measure. N	Maximum Force Pred. N	Maximum Stress Measure. kPa	Maximum Stress Pred. kPa	Total Energy Measure. mJ	Total Energy Pred. mJ
20%	150°C	136 ± 36	134	4228 ± 1363	4116	323 ± 133	312
20%	175°C	68 ± 36	69	2413 ± 1538	2591	137 ± 102	133
20%	200°C	40 ± 12	38	1182 ± 585	1066	101 ± 48	91
30%	150°C	96 ± 30	97	3845 ± 1172	3755	255 ± 71	253
30%	175°C	91 ± 18	86	4155 ± 1024	4265	189 ± 51	173
30%	200°C	89 ± 27	89	4870 ± 1142	4775	157 ± 59	148
40%	150°C	24 ± 13	21	2247 ± 636	1174	62 ± 31	51
40%	175°C	31 ± 18	31	1983 ± 1451	1834	77 ± 44	71
40%	200°C	34 ± 15	31	2446 ± 1179	2494	73 ± 24	61

Mean ± SD

of R^2 for regression models (Table 4). However, predicted values for each parameter are generally in good agreement with observed means. As with the tensile test, generally maximum force occurs with extrudates produced at 20% initial moisture and 150 °C barrel temperature. When force is corrected for extrudate diameter (stress), this trend becomes clearer (Fig. 2b). A saddle-shaped ridge of high shear strength extends from 20-150 to 30-200. This area represents tough extrudates which vary from dense and hard at 20-150 to expanded and layered in structure at 30-200 (Phillips *et al.* 1984). The pattern is very different from that seen for tensile stress. Since a relatively narrow cross-section of extrudate is examined in the

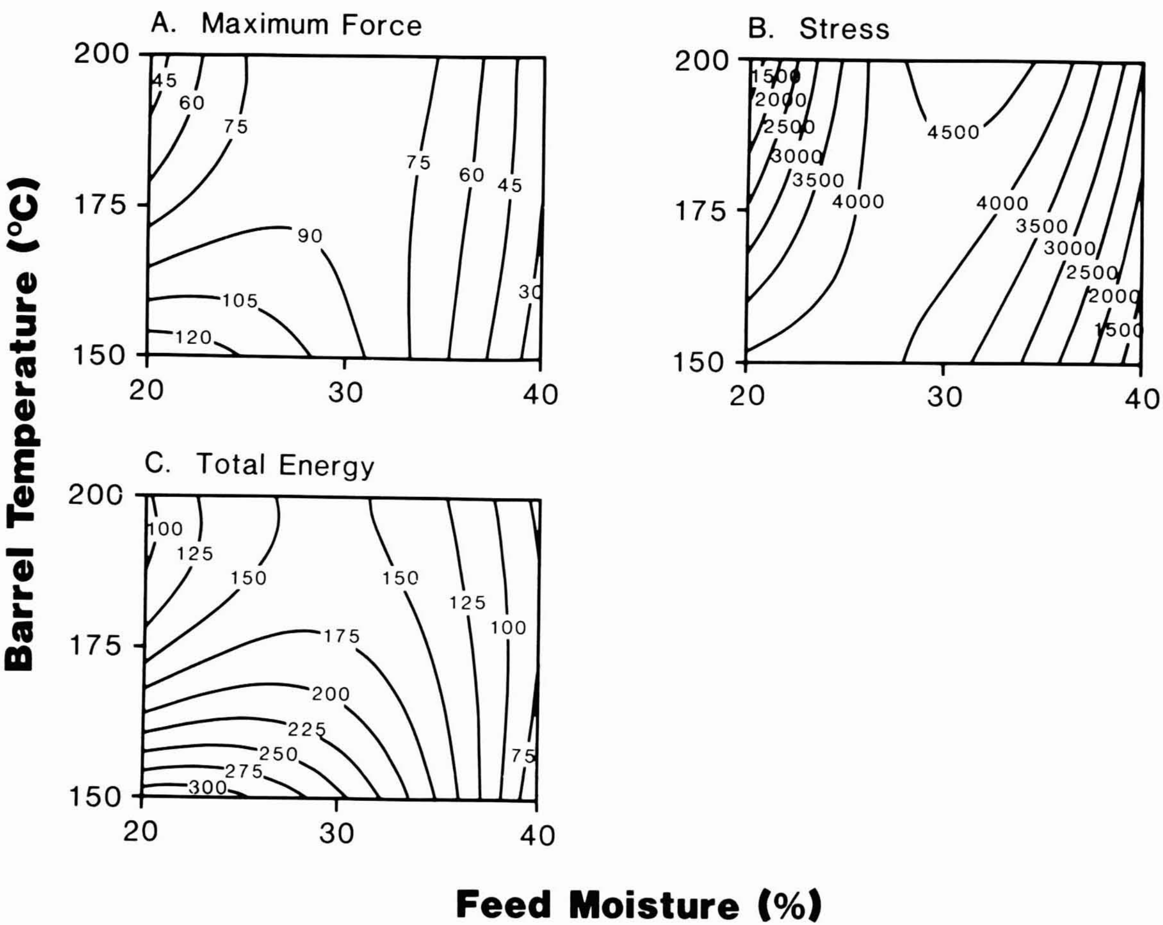

FIG. 2. RESPONSE SURFACE RELATING: A. maximum force (N); B. maximum stres (kPa); and C. total energy (mJ) from the Warner-Bratzler Shear test to feed moisture and barrel temperature.

Table 4. Coefficients of regression equations relating Warner-Bratzler Shear Test Properties of extruded cowpea meal to initial feed moisture and nominal barrel temperature

Coefficient	Maximum Force N	Maximum Stress kPa	Total Energy mJ
b_0	3.441 E3	6.568 E4	8.764 E3
b_1	-3.170 E1	-4.500 E2	-9.537 E1
b_2	-1.269 E2	-3.530 E3	-2.079 E2
b_3	6.265 E-2		2.467 E-1
b_4	8.808 E-1	4.545 E1	-7.123 E-1
b_5	1.146 E0	2.699 E1	2.598 E0
b_6	-1.747 E-3		-6.762 E-3
b_7	-7.135 E-3	-3.770 E-1	
b_8			
R^2	0.69	0.58	0.59

Where: $y = b_0 + b_1T + b_2M + b_3T^2 + b_4M^2 + b_5TM + b_6T^2M + b_7TM^2 + b_8T^2M^2$

and y = Maximum Force, Maximum Stress, or Total Energy
T = Nominal Barrel Temperature °C
M = % Moisture in the Feed

Regression models are significant at the 0.0001 level, and coefficients are significant at the 0.05 level.

shear test, breaks and flaws could be more easily avoided than with the tensile test. For this reason the Warner-Bratzler results are probably a more reliable representation of extrudate texture than those from the tensile test. The decline in shear strength at higher feed moisture and at low feed moisture and high barrel temperature can be explained by the soft, "short" texture of products from the former conditions and the expanded, brittle nature of the latter (Phillips *et al.* 1984). The smaller rate of decline in tensile stress compared to that of shear stress in the low moisture-high temperature region (Fig. 1b) reveals the greater impact of product brittleness on shearing failure. Total energy required to shear strands of extrudate is relatively larger than that required to stretch-to-breaking, but the general shape of the response surfaces is similar (Fig. 1c,2c). However, the high-shear ridge is still evident in the greater skewing of the diagram in a low moisture/low temperature-to-intermediate moisture/high temperature direction, and in the slower decline in energy contours on the shear energy surface.

The Warner-Bratzler shear test is probably the rheological evaluation most often applied to extruded products. A number of authors have studied the texture of soy extrudates using it. Cumming *et al.* (1972) extruded defatted soy meal at an initial moisture of 23% (wet basis) and barrel temperature of 110 to 200 °C. The W-B shear force values were corrected for density by these authors, and exhibited a sigmoidal pattern increasing from low to high temperatures. If the density correction is removed, force and stress increase more or less linearly between 110° and 160 °C then decline. The values of force vary from 22 to 36 N, while stress (assuming a constant 3.18 mm diameter) varies from 2,800 to 4,500 kPa. Thus the force values are somewhat smaller than those found for cowpea extrudates, while stress is about the same due to the smaller diameter of the soy extrudates. Aguilera and Kosikowski (1976) extruded soybean flakes at initial moistures of 25, 35, and 45% and process temperatures of 120, 145, and 170 °C. Force values ranged from 2 to 65 N. The data was fit to a regression model, and represented as a surface response diagram. Moisture was found to be the major contributor to texture, and the response surface bore little resemblance to the one found for cowpea products. Maurice and Stanley (1978) extruded soybean meal with initial moistures of 24 to 30% and barrel temperatures of 160 to 180 °C. Shear force values ranged from 7 to 70 N, which are closer to those observed in this study. The data was fit to a regression model and it was found that protein content (confounded with moisture) was the most important factor in W-B force. The model reported herein for cowpea extrudates is more complex, with both temperature, moisture, and interactions of the two contributing to shear force and stress.

There have been few reports in which intact, starchy extrudates were subjected to rheological examination. Mercier and Feillet (1975) measured breaking strength of corn grits, extruded at an initial moisture of 18.2%, and at temperatures of 65 to 250 °C with a device similar to the Warner-Bratzler cell (judging from its description), and reported values of shear force, which decreased from ~2800 to 800 kg (~8000 to ~27500 N) as temperature increased from 170 to 250 °C. These values are ten to one hundred times those observed for cowpea extrudates. No information on product diameter was included, making the more meaningful comparison of stress values impossible, however, it is doubtful that diameters could be large enough to make stress values similar to those in the present study. This indicates that starch may contribute to large values of shear force, even in expanded products. Faubion and Hoseney (1982a) found that extruded wheat starch had higher shear force values than extruded wheat flour, and that addition of gluten reduced the strength of extrudates. The values of stress computed from these data, however, ranged only from 175 to 291 kPa.

Kramer Shear Press

The Kramer Shear Press is used to examine rheological properties of bulk samples. Since, in this test, force is not related to produce cross-sectional area it is considered empirical in nature. Nevertheless, it gives useful information of the combined compression and shear behavior of materials. Measured and predicted values of maximum force and total energy from the Kramer test are given in Table 5, coefficients of the regression equations in Table 6, and the surface response diagrams in Fig. 3. General observations made for data from the other tests also apply here. Coefficients of determination are somewhat higher, probably because the use of larger samples eliminates some scatter in the data. Actual values of force and total energy are about ten times larger than for the Warner-Bratzler test for the same reason. The shear force and total energy diagrams (Fig. 3a,b) resemble the corresponding ones for W-B shear test, with the high-strength ridge being evident.

Table 5. Measured and predicted values of maximum force, and total energy from the Kramer Shear Test applied to cowpea meal extrudates

Feed Moisture	Barrel Temperature	Maximum Force Measure. N/g	Pred.	Total Energy Measure. mJ/g	Pred.
20%	150°C	1185 ± 269	1160	3544 ± 957	3521
20%	175°C	755 ± 348	728	1896 ± 696	1953
20%	200°C	512 ± 139	480	1185 ± 585	1163
30%	150°C	826 ± 262	776	1669 ± 525	1728
30%	175°C	993 ± 225	938	1635 ± 509	1535
30%	200°C	882 ± 186	820	1639 ± 406	1699
40%	150°C	259 ± 175	175	578 ± 284	561
40%	175°C	279 ± 186	186	581 ± 306	644
40%	200°C	342 ± 240	240	690 ± 379	663

Mean ± SD

Aguilera *et al.* (1984) milled and air classified navy beans to produce high starch (17% protein, 50% starch) and high protein (40% protein, 16% starch) flours. Blends of high starch navy bean fraction and corn grits

Table 6. Coefficients of regression equations relating Kramer Shear Test Properties of extruded cowpea meal to initial feed moisture and nominal barrel temperature

Coefficient	Maximum Force N/g	Total Energy mJ/g
b_0	9.732 E4	8.878 E4
b_1	-1.057 E3	-7.267 E2
b_2	-6.560 E3	-3.697 E3
b_3	2.778 E0	1.298 E0
b_4	1.038 E2	3.612 E1
b_5	7.300 E1	2.747 E1
b_6	-1.944 E-1	-3.377 E-2
b_7	-1.171 E0	-2.199 E-1
b_8	3.145 E-3	
R^2	0.68	0.72

Where: $y = b_0 + b_1T + b_2M + b_3T^2 + b_4M^2 + b_5TM + b_6T^2M + b_7TM^2 + b_8T^2M^2$

and y = Maximum Force, or Total Energy
T = Nominal Barrel Temperature °C
M = % Moisture in the Feed

Regression models are significant at the 0.0001 level, and coefficients are significant at the 0.05 level.

and of high protein navy bean fraction and soy flour were extruded on a Wenger X5 machine. The starchy products were extruded at initial moistures of 10-12% and product temperatures of 85-90°C. Hardness, defined as peak force per unit mass (kg/gm) was measured using the Kramer Shear Press. Values declined from 394 to 15 N (kg × 9.81) as high starch bean flour was increased from 0 to 100% in the mixture. The extrudates were described as highly expanded which would explain the relatively lower hardness. The high protein extrudates were rehydrated and autoclaved prior to texture analysis, making comparison with cowpea extrudates meaningless.

The purpose of this work was to investigate the texturization of cowpea meal, and to measure the textural properties of the resulting products. We have attempted, insofar as possible, to compare these results with those for other experimentally produced extrudates. The literature is so sketchy in this area, even for soy extrudates as to make such comparisons dif-

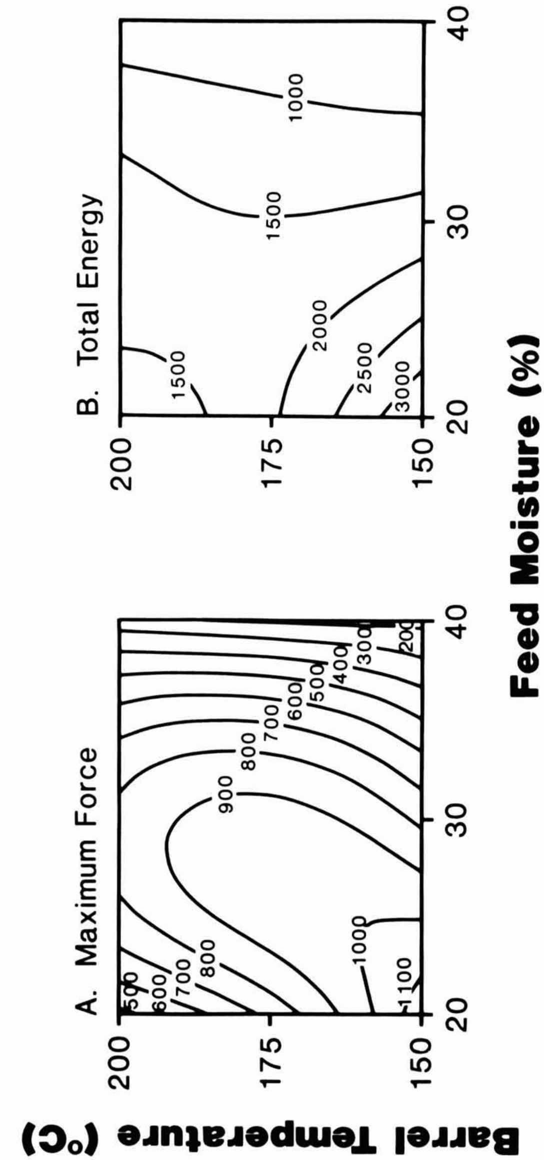

FIG. 3. RESPONSE SURFACE RELATING: A. maximum force (N) and total energy (mj) from the Kramer Shear test to feed moisture and barrel temperature.

ficult. The particular combination of major texture producing species in cowpea meal, proteins and starches, and their unique characteristics, are responsible for the resulting textures. For this reason, these products would not be expected to duplicate those made from other ingredients. However, their potential can be assessed only by such comparisons.

The contribution of protein to the texture of starchy (e.g., cereal grain) extrudates, and of carbohydrate to proteinaceous extrudates has not been extensively studied. In the latter case, starch has been considered to interfere with texture information in extruded peanut flour products (Aguilera *et al.* 1980). Faubion and Hoseney (1982a, 1982b) reported that increasing levels of gluten reduced expansion in wheat flour extrudates, while addition of soy isolate at the 5-7% level increased expansion. They also observed that, while wheat flour extrudates required lower shearing force (Warner-Bratzler) than wheat starch extrudates, the addition of soy isolate to wheat starch increased the required shearing force of the resulting extrudates. Paton and Spratt (1984) examined reconstituted wheat systems, and found that addition of gluten increased expansion under some conditions of moisture and temperature, but decreased it under others. The mechanism by which these interactions occur have yet to be elucidated. The known properties of cereal and legume proteins, and the findings that denaturation of soy protein prior to extrusion interferes with texture formation (Rhee *et al.* 1981), suggest that the greater solubility of globulins allow them to become mobilized in the extruder barrel and to contribute to texture while relative inert prolamins and glutelins may act as a physical interference. Current work in this laboratory is seeking to assess the role of the protein and starch fractions in cowpea meal extrusion.

SUMMARY AND CONCLUSIONS

A major research effort is underway in our laboratory to assess the potential of cowpeas, a high-protein, starchy legume, for producing extruded food products. The objective of this study was to examine the rheological properties of cowpea extrudates produced over a range of initial moistures and barrel temperatures. Cowpea meal was successfully extruded into coherent products when initial moisture content ranged from 20 to 40%, and the extruder barrel temperature ranged from 150° to 200 °C. The expanded, brittle products resulting at 20% initial moisture, and 175-200 °C resembled commercial puffed snack foods, although shear stress values were higher (Falcone 1983). Extrudates produced from 30% moisture dough were tough and chewy, resembling intermediate moisture meat products. Extrudates made from 40% moisture dough were soft, gummy and bread-like.

These findings demonstrate the potential of this underutilized legume as an ingredient for producing a variety of extruded foods. However much remains to be done before cowpea meal will be accepted as a raw material for manufactured food production. It will be necessary to examine, at higher resolution, the effects of initial moisture and barrel temperature on texture. Blending with other ingredients, may be necessary to optimize textures of products made under various conditions. In addition, no effort was made in this study to examine sensory properties of the extrudates, although flavor and subjective mouth-feel are of great importance in the acceptability of foods. It is intended that future work will address these questions.

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AN ENERGY USE ANALYSIS OF A FRESH AND FROZEN FISH PROCESSING COMPANY

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ABSTRACT

An energy use analysis was performed on a fresh and frozen fish processing company to identify current levels of energy consumption and establish an energy conservation program. Electrical energy constituted 79% and 87% of the fish and ice plants' energy consumption, respectively. Baseload electricity in the fish plant was 88% and 30% in the ice plant. The fish plant's intensity index was 1,882.3 BTU/lb (4,371.9 KJ/Kg) of product while the ice plant's 172.5 BTU/lb (399.6 KJ/Kg) of ice. The trucking fleet had a fuel intensity index of 29,910.6 BTU/mile (19,630.6 KJ/Km) and was the largest energy consumer accounting for 60% of the company's total energy usage. Proposed energy conservation measures can lead to significant reductions in the current levels of energy consumption.

INTRODUCTION

The concepts energy and energy management have acquired significant importance in industrialized nations especially after the Arab oil embargo of 1973. The United States is the world's largest energy user, with an expected total energy consumption of 76 quadrillion British Thermal Units (BTU)(8.02×10^{19} Joules) in 1985. Out of this total, 28.5 quadrillion

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BTU (3.01×10^{19} Joules) are expected to be consumed by the industrial sector (Energy Information Administration 1985).

The food processing industry is among the six most energy intensive U. S. industry groups, accounting for 7-9% of the total energy used in the industrial sector; whereas the fresh and frozen packaged fish industry (SIC[1] 2092) consumes 0.6-0.8% of this industry group's energy requirements (U. S. Dept. of Commerce 1983a). Over the 1971-1981 period, the fresh and frozen packaged fish industry boosted the value of its product shipments from $1 billion to $3.3 billion, respectively (U. S. Dept. of Commerce 1983b). However, it experienced a 633% increase in the dollar value of its purchased fuels and electrical energy, while its energy requirements rose 72% over the same period (Casper 1977; U. S. Dept. of Commerce 1983a).

Previous studies on energy use in the fish industry include that of Cleland and Earle (1980), who conducted an energy survey in a New Zealand fish processing firm in which no energy management program had been implemented. In their study they reported an average intensity index of 1,600 BTU/lb (3,717 KJ/Kg) of chilled and frozen fish product. By introducing a long-term energy management program, the company's overall energy savings were estimated as 30% of the intensity index. Wall *et al.* (1982) investigated the energy consumption trends of an Australian fish processing company which manufactured canned, chilled and frozen fish products. They reported an intensity index of 3,005 BTU/lb (6,981 KJ/Kg) of fish product, with fuel oil use making up 57.5% (1,726 BTU/lb or 4,009 KJ/Kg) of this index. By implementing an energy conservation program, the company was expected to save 25% of its annual energy consumption.

Despite the publication of these studies, energy management information on the fish processing industry has been scarcely reported in the current scientific literature. In addition, studies have not integrated the other important sectors related to the industry (e. g., ice production, product distribution).

The objectives of this study were: (1) to identify and quantify the levels of energy consumption in three profit centers (sectors) of a medium-sized mid-Atlantic fresh and frozen fish processing company; and (2) to provide the company with specific energy saving measures to reduce its current energy requirements.

MATERIALS AND METHODS

The present study was carried out in a fresh and frozen fish processing, ice manufacturing and trucking company in which no energy management

[1]Standard Industry Code

program had previously been implemented. The company averages an output of 700 tons of fish and 15,000 tons of ice per year and has 70 full- and part-time employees. The firm's current facility layout has existed since 1981 when the ice manufacturing plant was constructed and the fish plant was upgraded.

The fish plant manufactures filleted, dressed, and gilled and gutted fish; as well as ground fish scrap which is sold as animal feed. The ice manufacturing plant produces bulk and bagged ice. The former is mainly distributed to fishing vessels, while the latter is basically marketed at the retail level. In addition, the trucking division consists of six refrigerated trailer-trucks with an average payload of 56,000 lb (25,424 Kg). These vehicles transport the finished products to several market places in the midwestern and southeastern United States.

Figure 1 and Fig. 2 illustrate the unit process operation and the energy sources in the production of both fish products and ice, respectively. This study included energy and production data from January, 1981 to December, 1983.

Energy and Power Inputs

All energy inputs (i. e., electricity, natural gas, #2 fuel oil) to the fish and ice plants and their related costs were obtained from monthly utility statements. Energy use by the trucking fleet was determined from the company's records. These inputs were all converted to both British Thermal Units and Joules using conversion factors reported by Henry *et al.* (1980), Murphy and McKay (1982) and Turner (1982). In addition, a load factor study was performed to determine the ratio of the average power use to the peak power demand, as a mean to estimating the efficiency at which the electric power demand is used in both plants. This was carried out according to the methodology suggested by Dranetz Technologies (1983), Turner (1982) and Wall *et al.* (1982).

Product Output

The rates of production by both plants were obtained from sales and inventory records and reported in pounds. The traveled mileage for the trucking fleet was also recorded.

Intensity Indexes

Intensity indexes (energy-to-product ratios) were determined by dividing the energy inputs of each profit center by its corresponding production rate. The indexes of the fish and ice plants were reported in both BTU per lb and kilojoules per kg of product, while the trucking fleet's was expressed in BTU per mile and kilojoules per km.

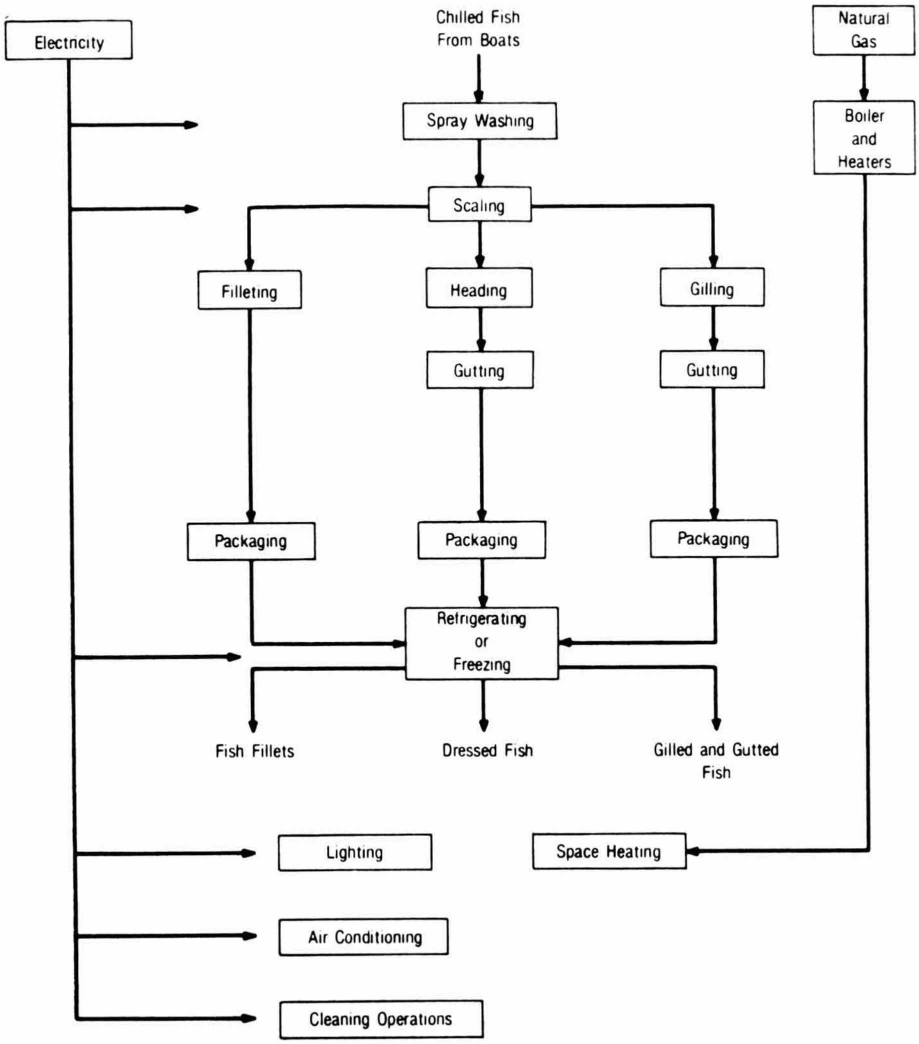

FIG. 1. PROCESS FLOWCHART FOR THE PRODUCTION OF FRESH AND FROZEN FISH PRODUCTS AND RELATED ENERGY INPUTS.

Statistical Analyses

Simple linear regression analyses were performed in order to determine: (1) the linear coefficient of determination (R^2) between the use of natural gas and the heating degree-days recorded in the geographical area of the company; (2) the baseload natural gas; and (3) the space heating requirements for the fish plant per heating degree-day. These statistical analyses were conducted on both a yearly and a three-year basis as reported by Haimes and Secor (1980).

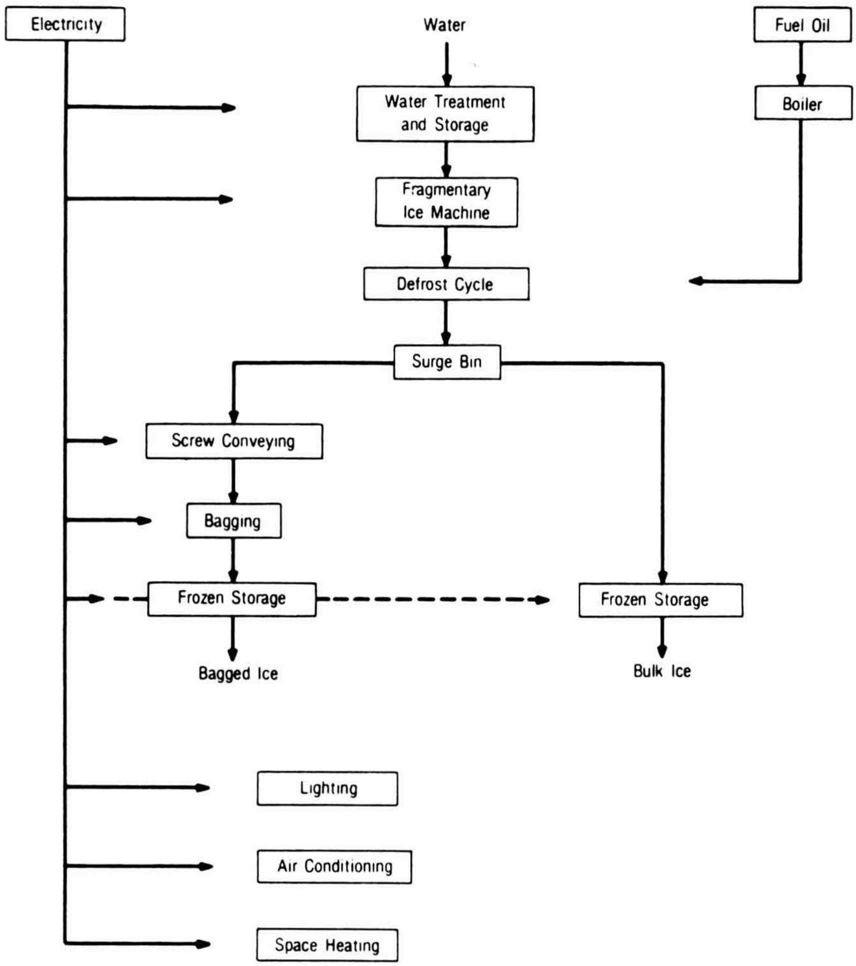

FIG. 2. PROCESS FLOWCHART FOR THE MANUFACTURE OF BULK AND BAGGED ICE AND RELATED ENERGY INPUTS

In additon, multiple linear regression analyses were conducted to determine the electricity baseload in both plants as suggested by Cleland *et al.* (1981).

Energy Conservation Program

Once all the data were processed and the regression analyses performed, an energy conservation program was developed. This program contained a series of energy-saving measures which were prioritized by the financial impact of each one on the firm's energy requirements. Savings that would result from upgrading load factors were first estimated by assuming that a 0.67 load factor (the highest value in record) could be maintained in the fish plant, while a value of 0.60 could be attained by the ice plant throughout the year except in June, July and August when a 0.80 value was used in the calculations as suggested by Mashburn (1985). Then, the actual kilowatt-hours and the proposed load factors were used to estimate a new peak demand and finally, the difference between the actual and the calculated peak demands was multiplied by the average demand cost of $10.40/kw from 1981 through 1983.

RESULTS AND DISCUSSION

Fish plant

The energy consumption by source and related costs at the fish processing plant are shown in Table 1. Electrical energy consumption made up 80% of the plant's total energy requirements. Electrical energy is primarily utilized to operate the refrigeration equipment for the chilling and freezing of whole fish and processed fish products. In addition, it is used to a lesser extent to power motor drives and air conditioning equipment, to generate hot water for cleaning purposes and to supply lighting.

Lighting is generated by both incandescent and fluorescent lamps. The former are located in the processing and loading areas while the latter are largely situated in the plant's offices and the cutting and sorting room.

Natural gas is solely consumed for space heating purposes, primarily from November through April. Heating is accomplished by three natural gas burners; two located in the cutting and sorting room while a third is used in the offices. The former area is also equipped with weatherstripping to minimize heat gains through doorways.

Table 1 also shows the unit costs for both gas and electrical energy sources. The latter energy not only is the most consumed energy source, but also possesses the highest cost per MMBTU. Consequently, measures directed at reducing and optimizing its use were first considered since they could produce the largest energy savings. Additionally, steps towards optimizing the consumption of natural gas were also considered since its use experienced the largest increase (32.2%) in unit cost from 1981 to 1983. It has been forecasted by the Energy Information Administration (1985) that real natural gas prices will rise progressively from 1986 as domestic production will sharply decline.

The output of fish products exhibited a gradual increase during this three-year period; however, no pattern relating month or season to quantity of processed fish could be identified. The primary reason for this being that fish availability in the area varied continuously making it difficult to schedule production rates.

The annual intensity index ranged between 1,691.7 and 2,105.3 BTU per lb (3,930.5-4,890.6 KJ/Kg) of fish product. The former resulted from a combined effect of higher yields of fish products and a lower use of electrical energy during the last 3 quarters of 1982. On the other hand, the latter ratio was primarily the result of poor fish catches, while energy consumption did not decrease accordingly. The latter and a high electricity baseload (88%) suggested that the facility was under-utilized. Cleland and Earle (1980) reported an intensity index and an electricity baseload of 1,600BTU per lb (3,717 KJ/Kg) and 80% respectively, in a similar fresh and frozen fish processing factory. These values were determined prior to undertaking a proposed set of energy conservation measures. In addition, Wall *et al.* (1982) stated that it is not an uncommon practice in the industry to design plants in order to cope with fish landing peaks.

Table 1. Annual energy consumption, production rate, and energy-related data for the fresh and frozen fish processing plant.

	1981	1982	1983
Natural Gas Use (MMBTU)	560.4	513.8	576.1
% of Total Energy Use	21.30	21.80	20.10
Average Unit Cost ($/MMBTU)	5.09	5.67	6.73
Electrical Energy Use (MMBTU)	2,075.0	1,845.7	2,287.1
% of Total Energy Use	78.70	78.20	79.90
Average Unit Cost ($/MMBTU)	8.63	8.89	8.76
Total Product Output (thousand pounds)	1,251.8	1,394.7	1,547.7
Mean Intensity Index (BTU/lb)	2,105.3	1,691.7	1,849.9
Total Energy Usage (MMBTU)	2,635.4	2,359.5	2,863.2
Total Energy Costs ($)	20,761.44	19,325.53	23,900.37
Electric Demand Costs ($)	14,357.86	14,626.97	16,067.93

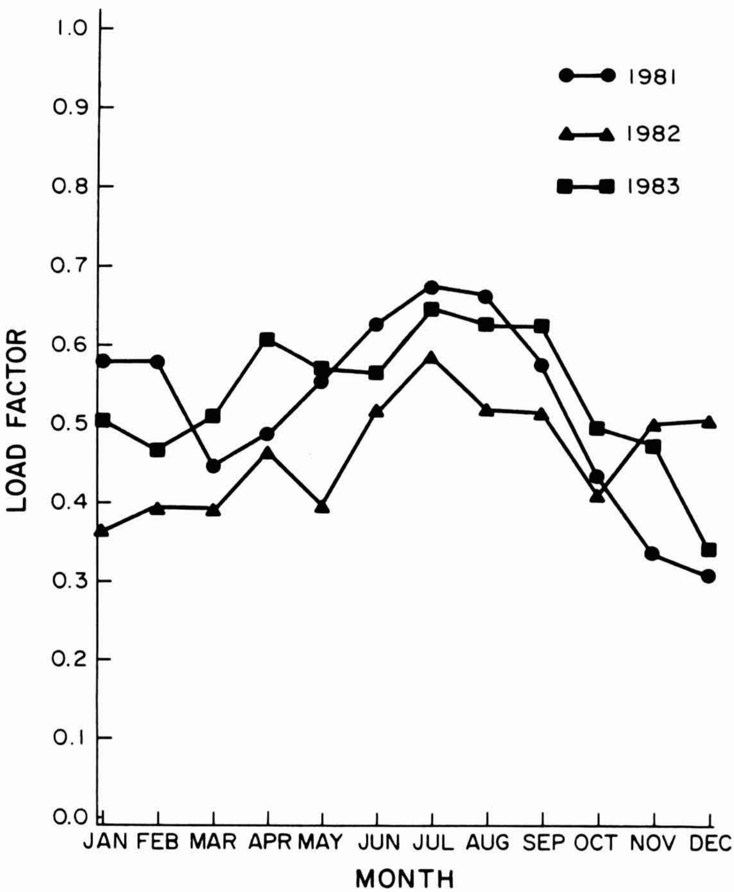

FIG. 3. ELECTRICAL LOAD FACTORS OF THE FISH PLANT FROM 1981 TO 1983

Electric demand charges represented between 40-43% of the total energy and power bill. Table 1 shows that during 1982 the overall energy costs declined 7% with respect to 1981; however, the net demand charges rose 2%. Due to the effect of demand charges on energy and power expenditures, a load factor study was performed to verify the plant's degree of efficiency on power demand utilization. Figure 3 is a plot of the load factors that occurred from 1981 to 1983. These ranged from 0.31 (December, 1981) to 0.67 (July, 1981). Fifty percent of these were below the minimum suggested value of 0.50 (Dranetz Technologies 1983). Both a demand and a production leveling program could help improve and maintain a load factor of at least 0.67 which would generate substantial savings on demand and energy charges. Wall *et al.* (1982) reported that an Australian fish company paid an extra $1,800 in annual demand charges for failing to keep its load factor at 0.54.

Predicted data related to the use of natural gas in the plant are contained in Table 2. All four models analyzed by simple linear regression analyses

Table 2. Natural gas baseload and consumption per heating degree-day by linear regression analysis.

	1981	1982	1983	1981-83
Natural Gas Use (MBTU/heating degree-day)	147.8	172.0	136.7	148.3
Mean Baseload (MBTU/month)	2,219.6	1,500.0	3,100.0	2,134.1
R^2	0.96	0.94	0.79	0.90
F-test	325.56	139.69	38.75	311.35
n	12	12	12	36

were significant at the 95% level. From this table it is observed that the 1981 model had both the strongest linear fit (F = 325.56), as well as the highest coefficient of determination ($R^2 = 0.96$). In addition, the lowest use of natural gas occurred in 1983 (136.7 MBTU or 144.4 MJ per heating degree-day); however, it was also the year with the highest baseload (3,100 MBTU or 3.27 GJ per month). The opposite occurred in 1982 where the model had the steepest slope (172.0 MBTU or 181.6 MJ per heating degree-day) and the smallest intercept (1,500 MBTU or 1.58 GJ per month). These wide fluctuations suggested a poor natural gas use control during the summer and the lack of a schedule for the use of space heating equipment.

An overall simple linear regression analysis, comprising the 1981-1983 data, yielded a strong linear fit ($R^2 = 0.90$), a natural gas use of 148.3 MBTU or 156.6 MJ per heating degree-day and a baseload of 2,134.12 MBTU or 2.25 GJ per month (Fig. 4). The high coefficient of determination stresses the linear relationship between the consumption of natural gas at the fish plant solely for space heating purposes and the heating degree-days recorded at the plant's location.

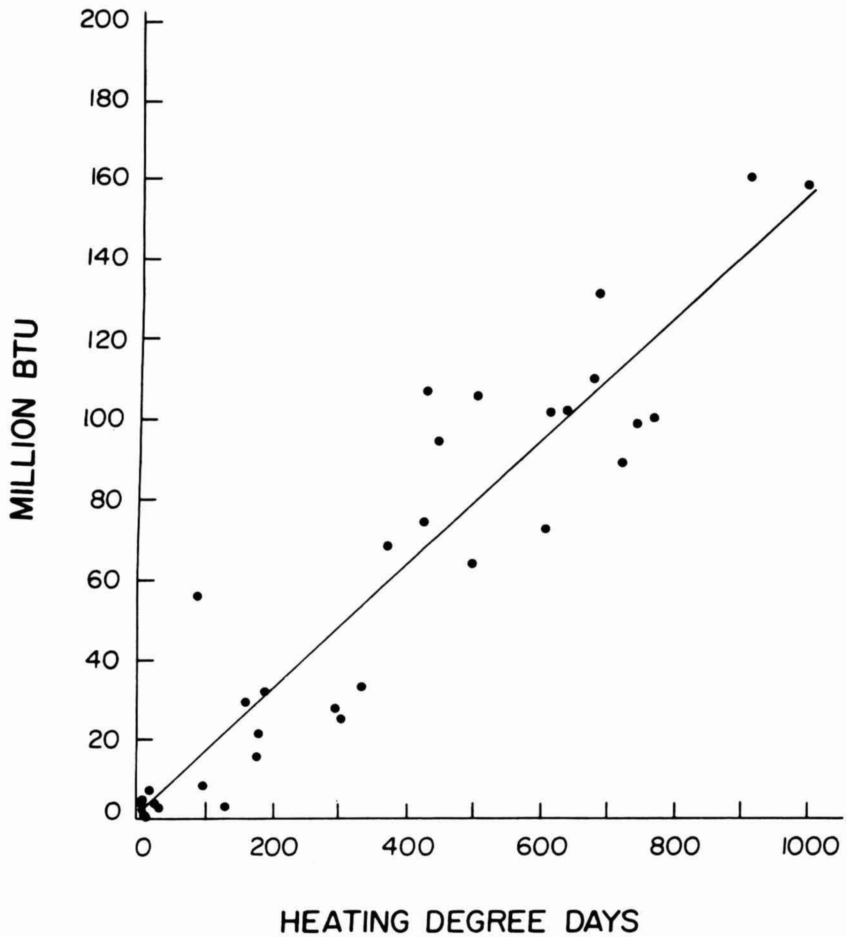

FIG. 4. NATURAL GAS CONSUMPTION BY THE FISH PLANT VERSUS HEATING DEGREE-DAYS

Ice Plant

Electrical energy is the main source of energy in the ice plant, representing over 80% of its energy requirements. The plant's four 125 hp (93.2 KW) ammonia reciprocating compressors are the largest single electricity-consuming components, comprising 80-85% of the plant's total electricity use. Table 3 reveals that the use of this energy source gradually increased over the years, primarily due to higher production rates. Fuel oil is solely consumed to heat water for the defrost cycle (Fig. 2) during periods other than summer, when the temperature of the incoming water is high enough to be used directly in the cycle. Table 3 also shows that the use of fuel oil declined over the same period as the bulk of the ice production was concentrated from July to September of 1982 and 1983 relative to 1981. During these months consumption of fuel oil was practically nonexistent.

Fuel oil possessed the highest unit cost in 1981 and 1982 relative to that of electrical energy; however, in 1983 the latter was the most expensive energy source due to reductions in the price of crude oil in the U. S. market and increased electric tariffs (McCarley and Fichman 1983). Because the use of fuel oil is mostly seasonal and in limited quantities while consumption of electrical energy is continuous and makes up most the plant's energy

Table 3. Annual energy consumption and energy-related data for the ice manufacturing plant.

	1981	1982	1983
Fuel Oil Use (MMBTU)	871.6	617.2	615.4
% of Total Energy Use	17.30	12.70	10.40
Average Unit Cost ($/MMBTU)	8.82	8.69	7.98
Electrical Energy Use (MMBTU)	4,154.2	4,260.8	5,279.3
% of Total Energy Use	82.70	87.30	89.60
Average Unit Cost ($/MMBTU)	7.63	8.05	8.25
Total Product Output (thousand pounds)	29,002.0	29,645.8	32,801.8
Mean Intensity Index (BTU/lb)	173.3	164.5	179.7
Total Energy Usage (MMBTU)	5,025.7	4,878.1	5,894.7
Total Energy Costs ($)	39,388.73	39,670.76	48,446.59
Electric Demand Costs ($)	29,133.27	40,356.24	41,672.71

requirements, those measures directed at diminishing and optimizing the use of the latter were first studied.

The annual intensity index over the period covered by the survey did not fluctuate drastically. The 1981's and 1983's indexes were somewhat higher than in 1982 because of an excessive use of fuel oil and electrical energy, respectively. The former was in part the result of a large number of heating degree-days (3,827) (U. S. Dept. of Commerce 1983c), while the latter was largely the result of poor control on the plant's electrical energy use. This resulted in considerable peaks in the intensity indexes during the winter months; as a consequence, these high ratios increased the average yearly index. Casper (1977) reported that the intensity index of the Manufactured Ice industry (SIC 2097) was 250-300 BTU/lb (581-697 KJ/Kg) in the mid-1970's. However, this ratio has decreased in recent years due to more energy efficient equipment and a shift to higher production rates of fragmentary ice.

The impact of demand charges on the energy and power costs can be observed in Table 3. In addition, a load factor study was also conducted in the ice plant. Load factors experienced an extreme fluctuation, ranging from 0.22 (October, 1982) to 0.81 (July, 1983)(Fig. 5). Small values commonly occurred in December and January, while peaks took place from June through August. These events were closely related to changes in production rates which shifted from low in winter to high in the latter months. This facility has the potential of accomplishing high load factors because the consistency of its loads is not strongly influenced by the availability of raw materials as is the case in the fish plant. Therefore, production rates would be easier to program preventing demand from peaking substantially.

Trucking Fleet

The trucking fleet had its most active period during the fourth quarter of the year, when it transported 45% more product, consumed 36% more diesel fuel and recorded the highest truck load factor (0.80) than the second most active period (1st quarter). The fleet's fuel intensity index ranged between 25,550 and 31,780 BTU/mile (16,768-20,857 KJ/Kg). These values are 26 to 57% higher than the 20,202 BTU/mile (13,259 KJ/Kg) reported by Mayer and Rawitscher (1978) for refrigerated trailer-truck fleets with similar characteristics (Table 4). The difference between these indexes and the lack of both consistent truck routes and a maintenance program suggests that fuel savings could be accomplished through both a truck fuel conservation and a scheduling program.

Energy Conservation Program

Fuel Economy Ratio. Table 5 reveals that the trucking fleet consumes most (63%) of the company's energy requirements, with an average trailer-truck fuel intensity index of 29,910.6 BTU/mile (19,630.6 KJ/Kg). Therefore, in order to generate significant energy savings, it was recommended to upgrade this index through: (1) a driver's incentive program

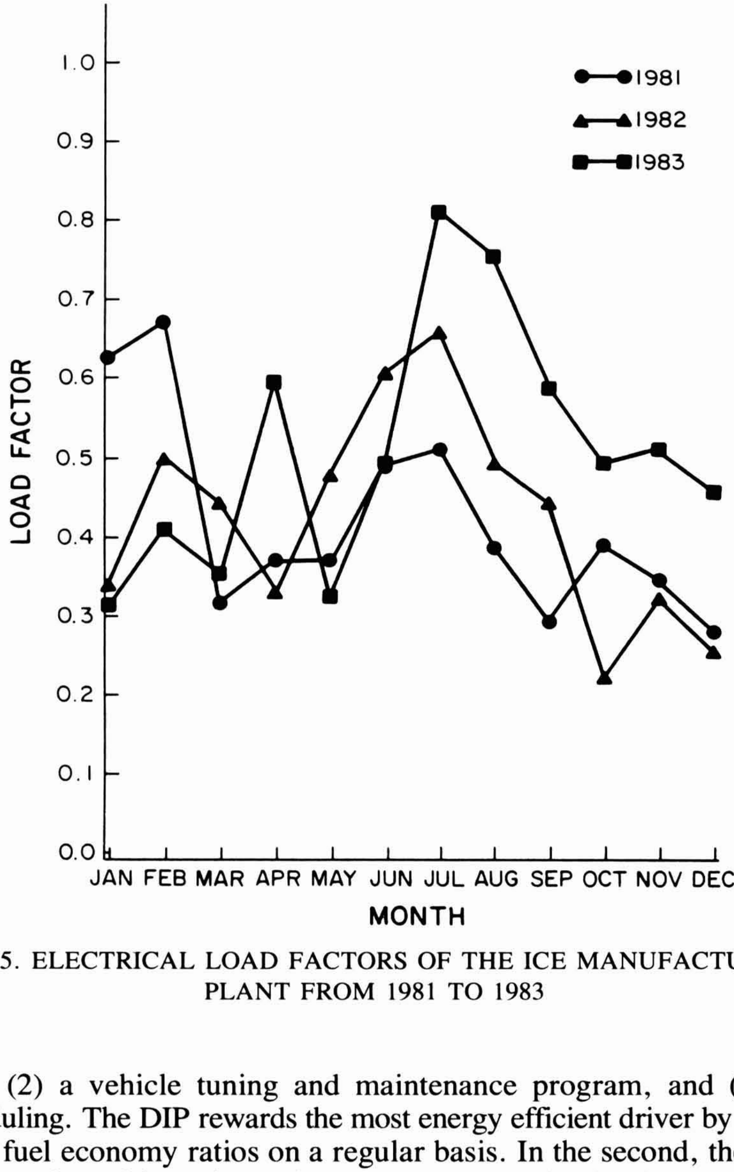

FIG. 5. ELECTRICAL LOAD FACTORS OF THE ICE MANUFACTURING PLANT FROM 1981 TO 1983

(DIP), (2) a vehicle tuning and maintenance program, and (3) route rescheduling. The DIP rewards the most energy efficient driver by monitoring his fuel economy ratios on a regular basis. In the second, the vehicle as well as the refrigeration unit are tuned and maintained. Young (1984) investigated the use of personal computers and two commercially available software packages in minimizing driving times through route scheduling. His findings demonstrated the usefulness of this approach in reducing fuel costs in trucking fleets.

These measures are expected to improve the fuel intensity index to at least 25,550 BTU/mile (16,768 KJ/mile), which would translate into savings of 1,563.6 MMBTU (1,651.2 GJ) per year (an 11.5% reduction from

Table 4. Summary of transportation parameters and fuel intensity index for two fish companies' trucking fleets.

	Present Study	Mayer & Rawitscher (1978)
Gross vehicle weight (lbs)	72,000-75,000	73,280-80,000
Net weight (lbs)	16,000	11,559
Payload (lbs)	56,000-59,000	61,721-68,441
Average load factor	0.73	0.74
Fuel type	diesel	diesel
Miles per gallon	4.1-5.1	6.45
Fuel intensity index (BTU/mile)	25,550-31,780	20,201.55

Table 5. Summary of results for the energy survey at the fresh and frozen fish processing company comprising 1981-1983 data.

	Fish Plant	Ice Plant	Trucking Fleet
Mean Production Rate (thousand pounds/yr)	1,398.1	30,484.7	-
Mean Energy Usage (MMBTU/yr)	2,619.4	5,266.2	13,630.0
% of Total Energy Use	12.17	24.48	63.35
Intensity Index	1,882.3[1]	172.5[1]	29,910.6[2]
Electricity Baseload (MMBTU/month)	145.1	132.0	-
% of Electricity Use	87.83	30.10	-
Natural Gas Baseload (MBTU/month)	2,134.1	-	-
Natural Gas Use (MBTU/heat. degree-day)	148.3	-	-

[1] In BTU per lb of product
[2] In BTU per mile

current consumption levels). These measures were supported by the fact that the six trailer-trucks on the fleet possess similar characteristics as far as the trailer size, refrigeration unit and truck engine BHP is concerned.

Therefore, the fleet's energy consumption would be a primary function of the driver's performance and the traveled route.

Load Factor Leveling. A load factor leveling program is primarily a scheduling procedure; consequently, both the programming of production rates and the acquisition of demand load controllers were recommended to reduce costly demand and electrical energy charges. These devices have the capability of shedding discretionary loads when pre-established demand and energy consumption levels are reached (Greenwood and Laabs 1980). Due to both the large electricity baseload of the fish plant (Table 5) and the diverse number of loads (i. e., lights, fans, refrigeration compressors, pumps, air conditioner) to be shed, a "Load Control Panel" was advised for this facility. These panels are designed to automatically control, monitor, shed and sequence between 8 to 30 loads, which in turn will help maintain a steady load factor of 0.67. Provided this value is observed throughout the year, savings on demand charges could range between 20 to 23%. Further reductions on the fish plant's baseload can be accomplished by somehow augmenting and leveling production rates to increase the net use of these facilities.

On the other hand, because the the ice plant had a smaller baseload (30%) and less loads to shed, a power and demand monitor was suggested for installation. This device would allow load factors to be maintained at suggested levels by shedding loads when pre-determined levels of demand are exceeded. In addition, timer-sequencers can be installed in the refrigeration compressors to prevent them from working at partial loads. It was considered from the physical and operating characteristics of the plant that a 0.80 load factor can be attained from June through August and a 0.60 value for the remainder of the year. Calculated annual gross savings of 35-40% can be generated if load factors are reached and kept at suggested values.

Lighting. This component is also part of the electricity baseload of both plants. It was recommended to replace incandescent light sources (20-30 lumens/watt) with fluorescent lamps (70-80 lumens/watt) for indoor and task lighting. This measure has the purposes of both reducing electric and power operating costs and improving illumination levels. In addition, low-wattage mercury vapor lamps should be installed for outdoor lighting instead of the currently used incandescent bulbs.

It was advised that the illumination levels in the cutting and sorting room be maintained between 70-90 footcandles (Turner 1982). Fluorescent lamps in the cold room and freezer should be replaced with special low-temperature light sources such as high pressure sodium. This will provide: (1) better illumination levels per watt; (2) improved operational capability; (3) longer lamp life and (4) reduced lamp heat load.

In addition, a light turn on/out schedule should be followed to minimize electrical energy wastage. This measure should be adopted along with an employee awareness, education and cooperation program.

Turner (1982) indicated that these measures are likely to generate mean gross savings of 20-25% in lighting costs at industrial facilities. Assuming that all the recommendations in this area are implemented, these percentages are likely to be achieved at the company under analysis.

Thermal Insulation. The installation of additional thermal insulation in offices and processing areas can both generate savings in the use of natural gas and reduce its baseload. Haimes and Secor (1980) reported a specific case in which a window insulation/replacement program at an industrial facility, resulted in net energy savings of 2,545 MMBTU (2,687.5 GJ) per year. This, after a natural gas consumption per heating degree-day analysis was performed on the company's energy data.

Further energy use reductions in this area can be accomplished by adopting both a temperature resetting program and a space heating equipment switch on/off schedule.

The thermal insulation of ammonia pipelines in the refrigeration system was considered a potential area for reducing electric energy and demand consumption by the refrigeration compressors. This observation was based on the fact that substantial amounts of ice build-up were observed on them.

Turner (1982) reported that elastomeric cellular plastic foams are normally used in refrigeration systems, due to their low thermal conductivities at low operational temperatures, and their capability of reducing up to 90% of undesirable heat gains.

SUMMARY AND CONCLUSIONS

Any successful energy conservation program contains three key elements: (1) good management, (2) proper maintenance and tuning operations, and (3) monitoring of the implemented energy conservation measures (ECM).

In this study, an energy use analysis was performed on a fresh and frozen fish processing company to quantify current levels of energy consumption, and identify potential ECM's. The company's six trailer-truck fleet was the largest energy user, with an average energy consumption of 13,630 MMBTU (14,313.3 GJ) per year. In addition, electrical energy was the most expensive and the most widely used energy source in both the fish processing and ice manufacturing plants, with annual average energy consumption levels of 2,619.4 MMBTU (2,766.1 GJ) and 5,266.2 MMBTU (5,561.1 GJ), respectively.

Rescheduling of truck routes and the implementation of a driver incentive (DIP) and maintenance programs were considered the most cost effective ECM's, with combined potential savings of 1,563.6 MMBTU (1,651.2 GJ) per year.

Other ECM's that were identified included: (1) demand leveling through load factor upgrading; (2) lighting, by switching to higher lumens per watt light sources and a light turn on/out schedule; and (3) thermal insulation in offices, process areas and refrigeration systems.

NOMENCLATURE

1 GJ = 1×10^9 Joules

1 MJ = 1×10^6 Joules

1 KJ = 1×10^3 Joules

1 MMBTU = 1×10^6 BTU

1 MBTU = 1×10^3 BTU

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DIELECTRIC PROPERTIES OF RICE BRAN

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ABSTRACT

The dielectric properties of rice bran have been of interest because of their correlation with moisture content and because to a large extent they determine the absorption of energy in dielectric heating applications. The dielectric properties, namely, dielectric constant, loss tangent, dielectric loss factor and a.c. conductivity of rice bran were measured experimentally at a frequency of 13.56 MHz by a resonance method using a Q-meter along with a coaxial, cylindrical sample holder. In order to study the effects of various factors, namely, the moisture content, temperature and bulk density of rice bran, the experiments were designed and performed based on Response Surface Methodology. The dielectric constant, dielectric loss factor and a.c. conductivity were found to have positive nonlinear relationships, while the loss tangent had a positive linear relationship within the ranges of factors studied, namely 3.95 to 14.05% (w.b.) moisture content, 26.5 to 53.5°C temperature, and 299.5 to 400.5 kg/m³ bulk density.

INTRODUCTION

One of the most valuable by-products of the rice milling industry is rice bran, since it is considered to be a potential source of oil. Moreover its high content of protein, sugars and other carbohydrates make it a good

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feed as well as a food supplement. As rice bran contains valuable B-group vitamins, amino acids, phosphoric acid compound etc., it is also useful in the medical field.

The dielectric properties of rice bran have been of interest for two principal reasons. First, they are useful for some rapid quality determinations, such as the measurements of moisture content. Secondly, they determine to a large extent the absorption of energy in high-frequency dielectric heating and microwave heating applications that are useful in the stabilization of rice bran. A review of the literature revealed that very few attempts have been made in the past to determine the dielectric properties of rice bran.

In the present investigation, the various dielectric properties, namely, the dielectric constant (ϵ'), loss tangent ($\tan \delta$), dielectric loss factor (ϵ'') and a.c. conductivity (σ) of rice bran at different moisture contents, temperatures and bulk densities were determined. These properties were measured at a fixed frequency of 13.56 MHz since this is one of the approved frequencies at which many of the commercially available dielectric heaters are working.

Basically, the dielectric constant of a material is related to its capacity of storing energy in an electric field in the material, whereas the loss factor is related to the capacity of the material for absorbing energy from the electric field. The dielectric constant of a material is frequently considered to be the ratio of the capacitance of a capacitor with the material as its dielectric, to the capacitance of the capacitor with air or more properly vaccum as the dielectric. The loss factor is an index of the material's energy dissipation characteristics when exposed to radiofrequency (RF) electric fields. The loss tangent value is also indicative of a material's energy dissipation characteristics. The conductivity is the reciprocal of the specific volume resistivity, which is the resistance between opposite faces of a centimeter cube of the material (Nelson and Stetson 1976).

MATERIALS AND METHODS

Experimental Set-up

The experimental set-up for the determination of dielectric properties consisted mainly of a circuit magnification meter (Q-meter), coaxial cylindrical sample holder and an indicating temperature controller. A constant input voltage to the Q-meter was ensured by providing a voltage stabilizer. A precision condenser with a least count of 0.02 pF was connected in parallel to the sample holder in the circuit which facilitated the measurement of capacitance accurately.

The coaxial sample holder used for measurement is shown in Fig. 1.

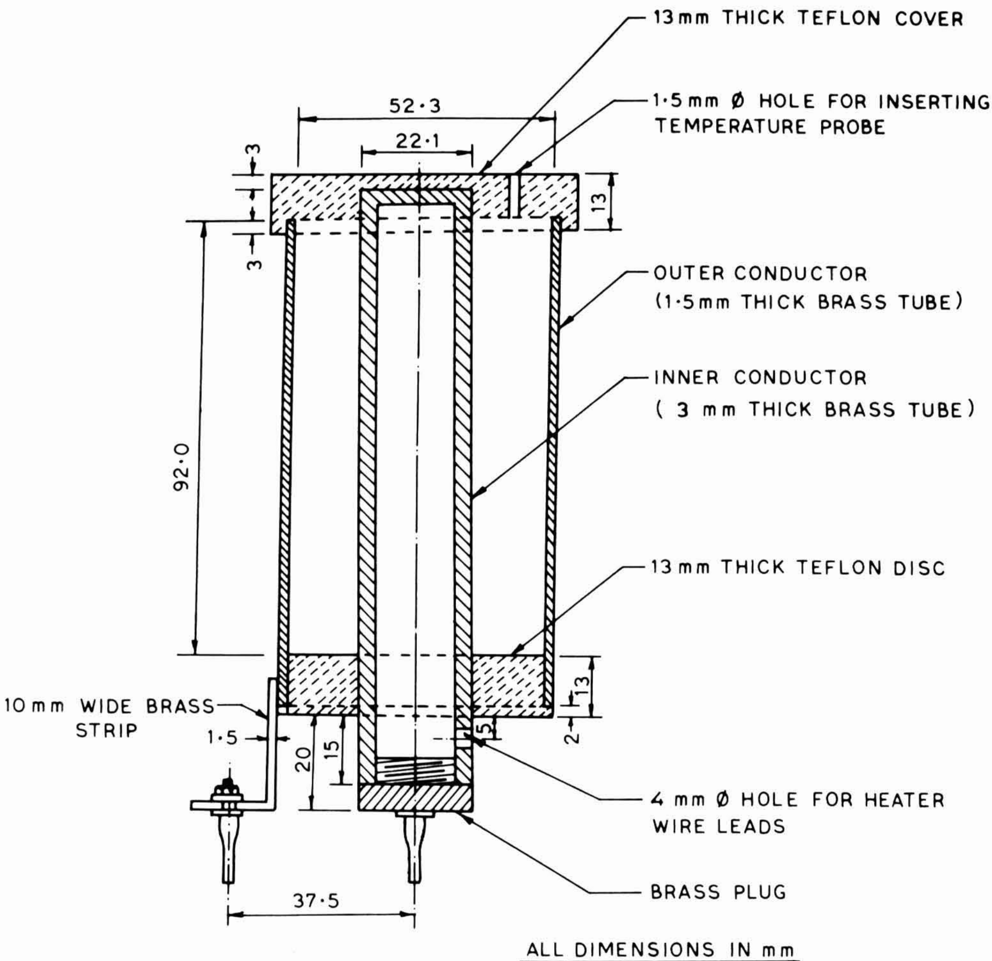

FIG. 1. SECTIONAL VIEW OF THE SAMPLE HOLDER USED WITH Q-METER FOR MEASUREMENTS OF DIELECTRIC PROPERTIES (Heater coils not shown)

The spacing between the conductors was maintained by an annular base plate machined from 13 mm thick Teflon plate to hold the two conductors in coaxial relationship. Teflon provided the required electrical insulation and permitted the use of benzene or other active solvents for calibration purposes. Suitable terminals were provided on the inner and outer conductors for directly connecting the sample holder to the Q-meter. Provision for heating the bran sample was also incorporated in the sample holder by providing heater coils with mica foil insulation at the interior of the inner conductor as well as around the outer conductor of the holder.

The indicating temperature controller was connected to the heater coils with its temperature sensing probe inserted into the sample through the hole provided at the top cover of the holder. This facilitated temperature measurement as well as heating the sample to any desired level for the determination of the properties at higher temperatures.

Calibration of the Meter for Evaluating the Equivalent Parallel Resistance

Instead of using directly the Q-reading obtained from the magnification meter for the calculation of loss tangent, the equivalent parallel resistance for the corresponding fall in the magnification meter deflection was determined using the calibration curve shown in Fig. 2. Standard carbon resistances were used for the calibration measurements. This method was adopted in order to measure the loss tangent values more precisely with the Q-meter used.

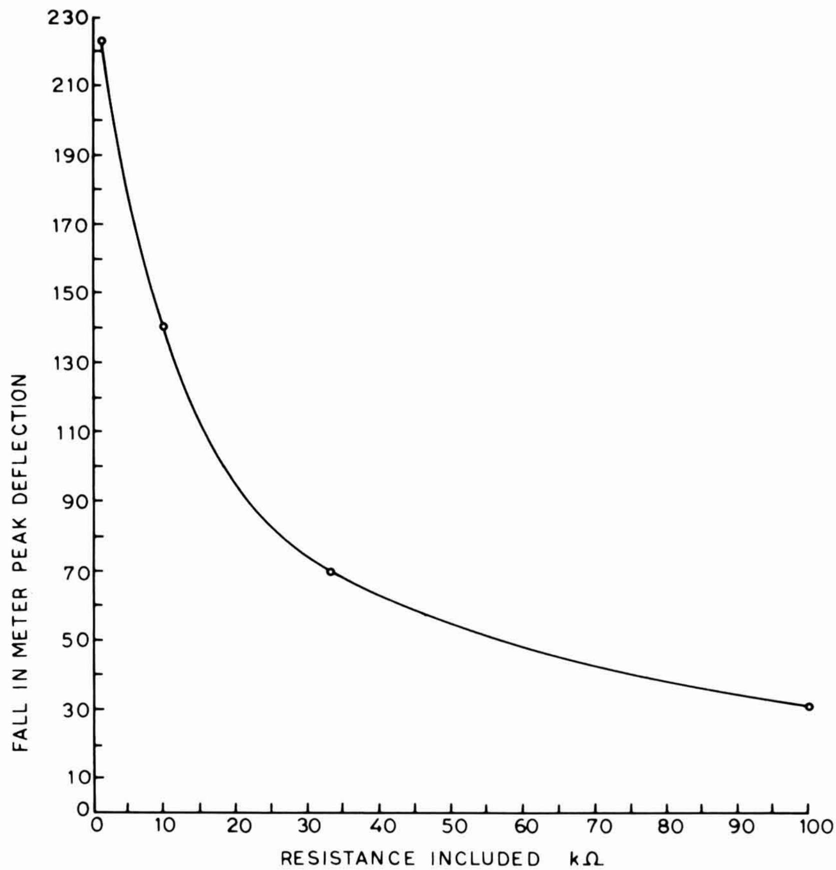

FIG. 2. CALIBRATION CURVE AT 13.56 MHz FOR EVALUATING THE EQUIVALENT PARALLEL RESISTANCE OF THE SAMPLE

Evaluation of Reliability of the Q-meter

Experiments were conducted at a frequency of 13.56 MHz, using benzene as a standard material. The dielectric constant measured was less by 6.09% than the reported value (Gray 1957) and hence suitable corrections in the capacitance measurements were incorporated.

Design of Experiments

In order to study the effects of various factors, namely, the moisture content, temperature and bulk density of rice bran on the dielectric properties, the experiments were designed according to response surface methodology (Cochran and Cox 1957). Experiments were performed in a random order for the various treatment combinations of the factors given in Table 1.

All the experiments were conducted with the bran milled from "Ratna" variety raw paddy. Bran samples of desired higher moisture contents were obtained by adding calculated amounts of distilled water, sealed in polyethylene bags and stored at about 5 °C inside a refrigerator for at least 10 days with frequent agitation to ensure uniform moisture distribution. Lower moisture levels were obtained by drying the samples in an oven at 55 to 60 °C for several hours depending upon the final moisture content required.

Experimental Procedure

The properties were determined by following the resonance method. A known amount of sample of desired moisture content was placed in the sample holder at the required uniform bulk density by gently tapping the holder while filling. The sample holder was then plugged into the Q-meter and the heater coils were energized through the indicating temperature controller to bring the sample to the required temperature. The Q-meter was set to 13.56 MHz and a suitable inductor was connected to the Q-meter. When the temperature of the sample attained the required level, the temperature sensing probe of the indicating temperature controller was removed from the sample and the measurements were made immediately. The Q-meter capacitor was adjusted till the magnification meter of the Q-meter was approximately at resonance. Then fine variations were made with the variable precision condenser till the magnification meter indicated maximum deflection. The capacitance and the corresponding magnification meter deflection were noted. This procedure was repeated with the empty sample holder also. The difference between the two capacitance readings and the fall in the magnification meter peak deflections were noted. The equivalent parallel resistances for the corresponding fall in deflection of the magnification meter readings were obtained from the calibra-

Table 1. Experimental conditions and codings for the determination of dielectric properties of rice bran (2nd order design)

Treatment No.	Natural values of the factors			Coded values of the factors		
	Moisture content (M) per cent (w.b.)	Temperature (T) ^{o}C	Bulk density (ρb) kg/m^3	X_1	X_2	X_3
1	6	32	320	-1	-1	-1
2	12	32	320	+1	-1	-1
3	6	48	320	-1	+1	-1
4	12	48	320	+1	+1	-1
5	6	32	380	-1	-1	+1
6	12	32	380	+1	-1	+1
7	6	48	380	-1	+1	+1
8	12	48	380	+1	+1	+1
9	3.95	40	350	-1.682	0	0
10	14.05	40	350	+1.682	0	0
11	9	26.5	350	0	-1.682	0
12	9	53.5	350	0	+1.682	0
13	9	40	299.5	0	0	-1.682
14	9	40	400.5	0	0	+1.682
15	9	40	350	0	0	0
16	9	40	350	0	0	0
17	9	40	350	0	0	0
18	9	40	350	0	0	0
19	9	40	350	0	0	0
20	9	40	350	0	0	0

Where X_1 = [moisture content (M), per cent (w.b.) − 9]/3
X_2 = [temperature (T), °C − 40]/8
and X_3 = [bulk density (ρ_b), kg/m³ − 350]/30

tion curve given in Fig. 2. The dielectric properties were calculated using the following formula (Corcoran *et al.* 1970; Nelson 1979).

1) Dielectric constant, $\epsilon' = 1 + \dfrac{\Delta C}{C_0}$ (1)

Where, ΔC = difference between the values of the capacitance of the sample holder with and without the sample

and C_0 = Capacitance of the coaxial, cylindrical sample holder with vacuum as the dielectric

$$C_0 = \frac{\pi h}{4 \times 1.411 \ln(b_1/a_1)}$$

Where, h = height of the sample holder, cm
b_1 = inside diameter of the outer conductor of the sample holder, cm
and a_1 = outside diameter of the inner conductor of the sample holder, cm

2) Loss tangent (dissipation factor), $\tan\delta = \dfrac{1}{\omega CR}$ (2)

Where ω = angular frequency
C = Capacitance of the sample
R = equivalent parallel resistance obtained from the calibration curve

3) Dielectric loss factor, $\epsilon'' = \epsilon' \tan\delta$ (3)

4) A.C. conductivity, $\sigma = 0.556\ f\ \epsilon''$ micro mho/cm (4)

Where, f is the frequency in MHz

The dielectic properties determined for the various treatment conditions of the factors shown in Table 1, were subjected to regression analysis and obtained suitable multiple regression models for the various properties.

RESULTS

The following multiple regression models adequately described the relationship between the variables:

$$\epsilon' = 1.1122 - 0.1247M - 1.00 \times 10^{-3}T + 1.597 \times 10^{-3}\ \rho_b + 5.678 \times 10^{-3}M^2 + 1.017 \times 10^{-3}M.T + 2.4 \times 10^{-4}M.\ \rho_b \quad (4)$$

$$\mathrm{Tan}\delta = -0.1589 + 0.0101M + 9.859 \times 10^{-4}T + 3.054 \times 10^{-4}\ \rho_b \quad (5)$$

$$\epsilon'' = -0.2793 - 7.3 \times 10^{-3}M + 2.013 \times 10^{-3}T + 7.467 \times 10^{-4}\ \rho_b + 2.033 \times 10^{-3}M^2 \quad (6)$$

$$\sigma = -2.112 - 0.0543M + 0.0151T + 5.64 \times 10^{-3}\ \rho_b + 0.0153M^2 \quad (7)$$

Table 2. The measured and predicted properties of rice bran

Treatment No.	Moisture content (M) % (w.b.)	Temperature (T) °C	Bulk density (ρ_b) kg/m³	Measured values				Predicted values using Eq. (4) through (7)			
				ϵ'	$\tan\delta$	ϵ''	σ	ϵ'	$\tan\delta$	ϵ''	σ
1	6	32	320	1.705	0.0389	0.0663	0.4999	1.704	0.0310	0.0534	0.4010
2	12	32	320	2.194	0.0871	0.1911	1.4408	2.225	0.0916	0.2292	1.7276
3	6	48	320	1.794	0.0395	0.0709	0.5345	1.785	0.0468	0.0857	0.6426
4	12	48	320	2.382	0.1143	0.2723	2.0530	2.404	0.1074	0.2614	1.9692
5	6	32	380	1.890	0.0419	0.0792	0.5971	1.886	0.0493	0.0983	0.7394
6	12	32	380	2.467	0.1170	0.2886	2.1759	2.493	0.1099	0.2740	2.0660
7	6	48	380	1.979	0.0747	0.1478	1.1143	1.967	0.0651	0.1305	0.9810
8	12	48	380	2.652	0.1195	0.3169	2.3892	2.672	0.1257	0.3062	2.3076
9	3.95	40	350	1.692	0.0391	0.0662	0.4991	1.720	0.0273	0.0654	0.4902
10	14.05	40	350	2.797	0.1292	0.3614	2.7247	2.752	0.1293	0.3613	2.7233
11	9	26.5	350	2.001	0.0773	0.1547	1.1663	1.981	0.0650	0.1344	1.0128
12	9	53.5	350	2.203	0.0801	0.1765	1.3307	2.201	0.0916	0.1887	1.4187
13	9	40	299.5	1.907	0.0714	0.1362	1.0269	1.901	0.0629	0.1238	0.9318
14	9	40	400.5	2.279	0.0792	0.1805	1.3609	2.281	0.0937	0.1992	1.5014

The coefficients of the models, which were found to be significant at the 5% level from a 't' test and analysis of variance were alone included in the Eq. (4) through (7). The predicted properties using Eq. (4) through (7) and the measured properties are presented in Table 2 which shows that the models predicted fairly well the properties. It may be noted that the models developed hold good for predicting the properties only within the ranges of the levels of the factors at which experiments were conducted.

The minimum values of the dielectric constant, dielectric loss factor and a.c. conductivity within the levels of factors studied were found to be 1.692, 0.0662 and 0.4991 micro mho/cm and these properties increased to a maximum of 2.797, 0.3614 and 2.7247 micro mho/cm, respectively, when the treatment combinations of the factors, namely, moisture content, temperature and bulk density varied from 3.95% (w.b.), 40 °C and 350 kg/m^3 to 14.05%, 40 °C and 350 kg/m^3, respectively. The tan δ increased from 0.0389 to a maximum of 0.1292, when the moisture content, temperature and bulk density of the sample increased from 6% (w.b.), 32 °C and 320 kg/m^3 to 14.05%, 40 °C and 350 kg/m^3, respectively. The dielectric constant, dielectric loss factor and a.c. conductivity had positive and nonlinear relationships with the factors studied, while tan δ had a positive linear relationship with the factors as indicated by Eq. (4) through (7).

The response surfaces for the properties generated at an arbitrary bulk density of 360 kg/m^3 are presented in Fig. 3 and 4.

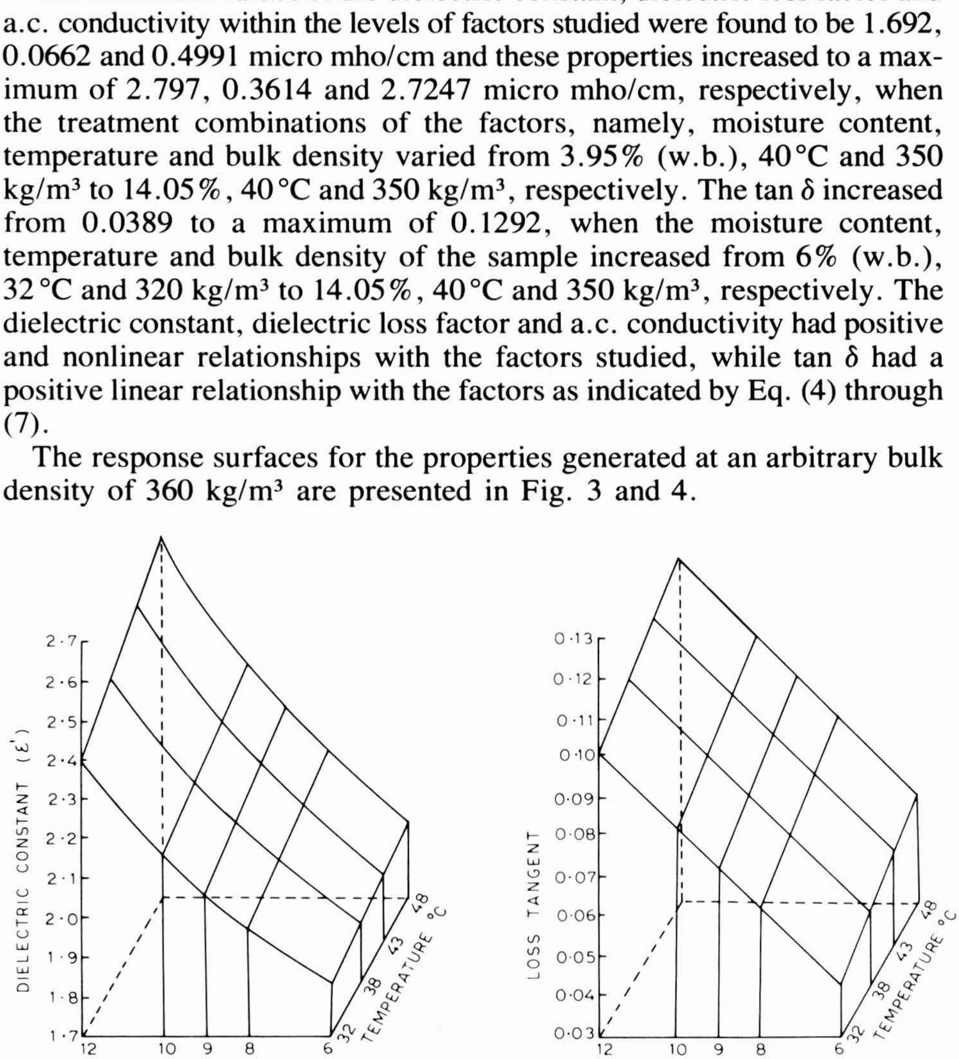

FIG. 3. RESPONSE SURFACES FOR DIELECTRIC CONSTANT AND LOSS TANGENT AT A BULK DENSITY OF 360 kg/m^3

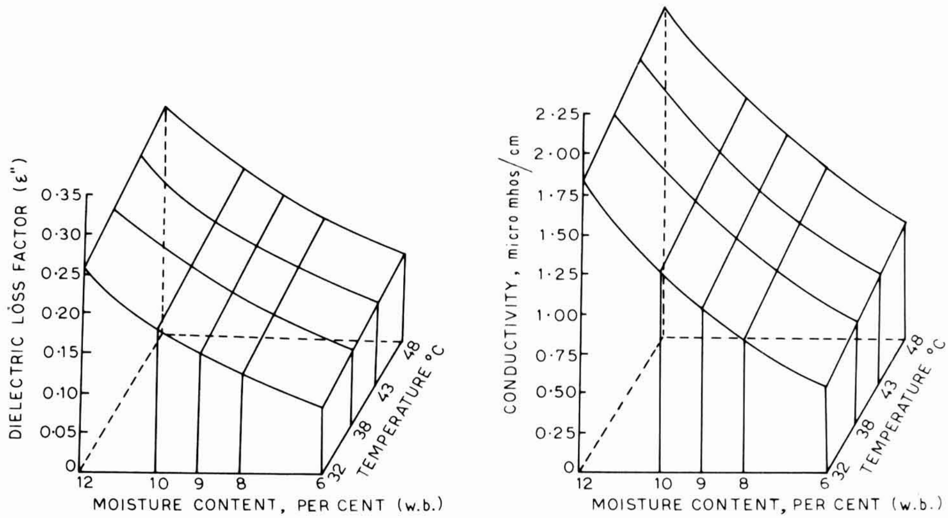

FIG. 4. RESPONSE SURFACES FOR DIELECTRIC LOSS FACTOR AND A.C. CONDUCTIVITY AT A BULK DENSITY OF 360 kg/m^3

DISCUSSION

Generally speaking, the dielectric constant of a solid dielectric consists of four polarizations: electronic, ionic, dipolar and space charge. The space charge polarization plays a major role in the behavior of the dielectric properties of materials and it arises out of movement of free charge carriers and their piling up at interfaces or major defect regions inside the material. Such piling up increases the value of the dielectric constant. Moisture (which will have free charge carriers) in rice bran will provide a leakage path for the electric current and thus the problem, in a way, can be treated as being connected with space charge polarization. In the present study, the larger values of dielectric constant of rice bran with higher concentration of moisture may be ascribed to space charge polarization. The conductivity being due to moisture (leading to space charge polarization) should have larger values at higher moisture contents as obtained in the present study. The effect of moisture content on dielectric properties of rice bran observed in the present investigation is in general agreement with those reported for other biological grains and food materials (Nelson and Stetson 1976; Nelson 1978; Subrahmanyam and Rao 1979).

The increasing trend of dielectric constant with temperature may be due to the fact that in polar materials, the relaxation time decreases as the temperature increases and therefore the dielectric constant will increase with temperature (Nelson 1973). Similar increasing trends of dielectric property values with temperature has been reported also for other biological grains (Knipper 1959).

The nature of the effect of bulk density on the dielectric properties of rice bran is in line with the reported data for tobacco leaves (Henson and Hassler 1965); wheat straw (Ko and Zoerb 1970) and other biological grains (Nelson 1981).

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MOISTURE TRANSFER PROPERTIES OF WILD RICE

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ABSTRACT

Working isotherms for processed wild rice and desorption isotherms for unprocessed wild rice were determined at temperatures ranging from 10 to 43.5°C. The constants for the Guggenheim-Anderson-DeBoer (GAB), Day and Nelson, Chen and Clayton and modified Halsey equations were determined by using a nonlinear optimization technique. The GAB equation showed extremely good fit to the experimental data (less than 5% error). The diffusion coefficients for moisture transport in both broken and whole processed wild rice and for unprocessed wild rice samples were determined at room temperature. The processed broken wild rice kernels had an effective diffusion coefficient of 2.66 × 10^{-9} m²/h, whereas the effective diffusion coefficient was 7.08 × 10^{-10} m²/h for the processed whole wild rice kernels. Unprocessed wild rice had moderate effective diffusivity (1.4 × 10^{-9} m²/h). These results predicted quite well the equilibrium water activities and time to equilibrium of wild rice-white rice mixtures using both analytical methods and the finite element method. The transfer of moisture to or from packaged wild rice was also illustrated for different distribution systems.

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INTRODUCTION

Wild rice (*Zizania aquatica*) is a native crop of North America. It is an aquatic grass which grows in man-made paddies as well as in natural stands such as shallow lakes, streams and marshes. It is now popular due to its unique toasted flavor and high nutritional value. The nutritional value of wild rice has been reviewed by Anderson (1976). Wild rice is an excellent source of high quality protein. Except for lysine, its content of essential amino acids exceeds or equals the FAO pattern (Watts and Dronzek 1981). Wild rice is also a good source of the essential fatty acids, linoleic and linolenic acid. With the exception of calcium, it has more of the common minerals than white rice. Although it contains no vitamin A or C, the thiamine, riboflavin and niacin content of wild rice exceeds that of other cereals (Anderson 1976). Because of its high price, many processors are mixing both whole and broken processeed wild rice (damaged in handling) with white rice which could result in a shortened shelf-life. Normal processing yields about 40% broken kernels which have less economic value.

Most of the prior research studies on wild rice have been concerned with wild rice production and marketing. However, information on shelf-life stability and packaging requirements are not available, including the storage requirements for unprocessed wild rice prior to drying. The information to fill this gap can be obtained if the working moisture sorption isotherm and the moisture diffusivity (D_{eff}) are available (Labuza 1985).

The specific objectives of this study were: (1) To develop working isotherms for processed wild rice and desorption isotherms for unprocessed wild rice. (2) To determine the effective diffusion coefficient (D_{eff}) for broken and whole kernels of wild rice. (3) To determine the equilibrium moisture contents and water activities of white rice-wild rice mixtures as well as the time to equilibrium. (4) To use moisture sorption data to predict the moisture transfer to or from packaged wild rice under different storage conditions.

MATERIALS AND METHODS

Processed wild rice and white rice samples were purchased from a local supermarket. Processed broken wild rice and unprocessed wild rice samples (whole) were obtained from the Department of Agricultural Engineering, University of Minnesota. Unprocessed rice samples were stored at −20 °C for two months prior to the experiments. The air oven drying method (72 h at 130 ± 1 °C) was used for moisture content determinations.

Water Sorption Isotherms

Prior to initial moisture determinations and sampling, frozen, unprocessed (wet) wild rice samples were equilibrated at 25 °C for 4 h. Plastic petri dishes (15 mm × 60 mm) containing approximately 2 g samples were suspended on a platform in one-quart wide-mouth Mason jars over saturated salt solutions of constant relative humidity (a_w 0.0 to 0.84). The solutions were prepared as explained by Labuza (1984). Isotherms were determined for the processed wild rice (store-bought) and the processed broken wild rice (University of Minnesota, Department of Agricultural Engineering). The jars for each a_w (in duplicate) were held at 10, 24.5, 38 and 43.5 °C for the processed broken and purchased wild rice samples, and at 10 °C. and 43.5 °C for the unprocessed whole wild rice. The weight changes of the samples were recorded every three to four days to ±0.1 mg. Equilibrium was assumed to be reached when the change in the moisture content was less than 0.5% dry basis in three consecutive samples taken at one week intervals. This criterion was found to be adequate to determine equilibrium weight by Lomauro *et al.* (1985a). To confirm the equilibrium, the weighings were repeated one month after the equilibrium was believed to have been reached. The processed rice showed both gain and loss of moisture over the whole range of a_w (working isotherm) while the unprocessed wild rice lost only moisture (desorption isotherm).

Isotherm Equations

A nonlinear optimization technique called "SEARCH" (Bakshi and Chhinnan 1984) was used to calculate the values of parameters in Equations (1), (2), (3) and (4). This technique uses the steepest descent method to calculate the parameter values. The isotherm equations used in this study are given below.

GAB equation (Van den Berg and Bruin 1981):

$$\frac{M}{M_0} = \frac{Cka_w}{(1 - ka_w)(1 - ka_w + Cka_w)} \tag{1}$$

Day and Nelson equation (1965):

$$1 - a_w = \exp\left[-P(1)T^{P(2)} \bullet M^{P(3)T^{P(4)}}\right] \tag{2}$$

Chen and Clayton equation (1971):

$$a_w = \exp[-P(1)T^{P(2)}] \bullet [\exp(-P(3)T^{P(4)}) \bullet M] \tag{3}$$

Halsey's modified equation (Iglesias and Chirife 1976):

$$a_w = \exp[-P(1)T + P(2)] \cdot M^{-P(3)} \tag{4}$$

To evaluate the accuracy of the fit for each equation, the mean deviation modulus (P) was used as the criterion as shown in Eq. (5). The P value shows the average percent difference between the predicted and experimental data points.

$$P = \frac{100}{n} \sum_{i=1}^{n} \frac{|M_a - M_p|}{M_a} \tag{5}$$

where M_a is actual moisture content at each a_w and M_p is the predicted moisture content.

Lomauro *et al.* (1985a) showed that a P value of less than 5 (95% confidence limit) corresponds to extremely good fit, a P value of between 5 and 10 (< 90% confidence) shows a reasonably good fit, and a P value above 10 (90% confidence) is considered a poor fit.

Determination of Effective Diffusion Coefficients

To determine the change in moisture content with time, triplicate samples (1 g each) were placed on a wire mesh which was suspended in 10 gallon glass fish tanks containing a layer of saturated NaBr solution (58% RH) at room temperature. The sample weights were recorded to 1 mg without removing the samples from the controlled environment. Average dimensions for wild rice kernels were determined by measuring 30 kernels before and after the experiments. Equation (6) (Crank 1975) was solved for D_{eff} by using a nonlinear optimization technique.

$$\Gamma = \frac{M - M_e}{M_0 - M_e} = \frac{1}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{b_n^2} \exp - (D_{eff}\, b_n^2 \theta) \tag{6}$$

where b_n = roots of $J_0(b_n \cdot a) = 0$; $J_0(b_n \cdot a)$ = Bessel function of first kind of order zero; a = radius of the cylinder; Γ = moisture ratio for semi-infinite cylinder. Lomauro *et al.* (1985a) showed this to be a good method and model for determination of diffusivities related to packaging systems. Over the a_w range considered, the radius of the rice (assumed to be an infinite cylinder) does not change.

Dry Food Mixing — Moisture Equilibrium Predictions

The processed white rice samples purchased from the local supermarket were equilibrated to an a_w of 0.75 for three days. Unprocessed wild rice samples were dried in an air oven (52 ± 1 °C, 72 h). The white rice and wild rice samples were then mixed to a 50:50 ratio and placed in glass jars at 25 °C for 24 h. Next, duplicate samples of white rice-whole wild rice and white rice-broken wild rice mixtures were transferred in plastic cups which were then sealed with wax to prevent moisture exchange with the environment. The sample cups were stored at 25 ± 1 °C. Moisture content determinations for the individual components were carried out weekly, except the first week during which the moisture contents were determined at one or two day intervals. Wild rice was considered to be broken when the kernel length was less than ¼ in. The equilibrium water activity of the mixture was predicted by using Eq. (7) (Salwin and Slawson 1959) and the additive isotherm technique (Iglesias *et al.* 1979). The Salwin equation is:

$$a_{eq} = \frac{(W_{s_i} b_i a_i) + (W_{s_j} b_j a_j)}{(W_{s_i} b_i) + (W_{s_j} b_j)} \tag{7}$$

In the additive isotherm method the moisture content of the mixture at a given a_w is:

$$M_M = \frac{W_{s_j} M_j + W_{s_i} M_i}{W_{s_j} + W_{s_i}} \tag{8}$$

However, in the additive isotherm technique, the GAB model was used for the isotherm at each a_w instead of the BET model as suggested by Iglesias *et al.* (1979). The white rice isotherm at 24.5 °C was constructed using the 20 °C and 30 °C isotherm data from Benado and Rizvi (1985). In both equations i and j designate components 1 and 2. The additive isotherm method predicts the moisture content of the mixture at any given a_w, thus if one knows the moisture of each component in any mixture, the equilibrium a_w is determined by plugging the calculated moisture content of the mixture (M_M) into the GAB equation for the constructed isotherm. In the Salwin equation the equilibrium a_w is calculated assuming the isotherm is linear.

The water activities at each time period were calculated from the GAB equation using the measured moistures of each separated component. The water activities of the individual components at the end of equilibrium were measured using the Kaymont device (Stamp *et al.* 1984).

A finite element mathematical model (Hong *et al.* 1986) was used to predict the change in moisture with time for a well mixed wild and white rice system. When the moisture difference of the slowest adsorbing component did not differ from the previous value by more than 2%, equilibrium was assumed. A time difference of 13 days was used. The equation is as follows:

$$\Delta = \frac{|M_t - M_{t+13}|}{M_t} \times 100\% \leqslant 2\% \quad (9)$$

The details of the method and theory are described by Lomauro and Bakshi (1985), and Hong *et al.* (1986). A modification of the boundary condition, adopted from Hsu (1983), was used to describe the surface moisture content change with time as follows:

$$M = M_{eq}(1 - e^{-\beta t}) + M_i\, e^{-\beta t} \quad (10)$$

where β is the rate constant.

The rate-limiting component was assumed to be the component with the smallest D_{eff}/L_0^2 value. The value of L_0 is the characteristic half thickness. The wild rice in our study has the smallest value. A 36 4-node element model and a 28 4-node element model were used to describe the quadrant cross-sections for the whole and broken wild rice, respectively. Preliminary work showed that an adequate time step increase was six hours and an adequate β value was 0.005.

Storage Simulation

To predict the change in moisture content of packaged wild rice under different distribution conditions, the following assumptions typical of normal handling were made: (1) Wild rice is harvested and processed in Minnesota (the major growing area) in the late fall. (2) Processed wild rice is sealed in one pound packages. (3) Polyethylene (0.00125 in. thick) is used as the packaging material typical of the industry. (4) Wild rice packages were assumed to be shipped to New York, Miami, Dallas and San Francisco, and also stored in Minnesota at 21 °C, thus giving different environmental conditions. (5) Storage period starts on January 1 and ends on December 31. The starting point will affect the final value. (6) Wild rice loses or gains moisture from all sides of the package, which has been found to be a good assumption. (7) Storage temperature was assumed to be 21 °C (it actually may vary).

The indoor relative humidities at 21 °C for each month were determined from the monthly average outdoor dry bulb temperature and outdoor relative humidities (Ruffner 1978) by using a psychrometric chart. Film permeability values (k/x) for each month were calculated by using the linear regression equation from the values reported by Labuza and Contreras-Medellin (1981) for different relative humidities. Then Eq. (11) and (12) were solved for moisture content as a function of time (Labuza 1982).

Moisture gain:

$$\ell n \frac{M_e - M_i}{M_e - M} = \frac{k}{x} \frac{A}{W_s} \frac{P_0}{b} \theta \tag{11}$$

Moisture loss:

$$\ell n \frac{M_i - M_e}{M - M_e} = \frac{k}{x} \frac{A}{W_s} \frac{P_0}{b} \theta \tag{12}$$

RESULTS AND DISCUSSION

Wild Rice Isotherms

Equlibrium moisture content data as a function of a_w for processed and unprocessed wild rice are presented in Fig. 1 and 2. The average values at each a_w are shown. Both of these isotherms showed a sigmoid shape (Type II) as expected for food materials.

Parameters or constants and P values for the GAB, Day and Nelson, Chen and Clayton, and modified Halsey equations are given in Table 1-4. The GAB model shows extremely good fit to the experimental data as is also illustrated in Fig. 1 and 2. In all cases the P value was less than 5 for the GAB, making it the best isotherm equation, as found by Lomauro *et al.* (1985b).

The constants for the Day and Nelson, Chen and Clayton, and modified Halsey equations were calculated by using the combined data from all temperatures for both processed and unprocessed wild rice, in addition to the constants at each temperature. Except for the Chen and Clayton equation, the other two equations showed reasonably good fit ($5 < P < 10$) to the experimental data (Tables 2-4). However, for individual

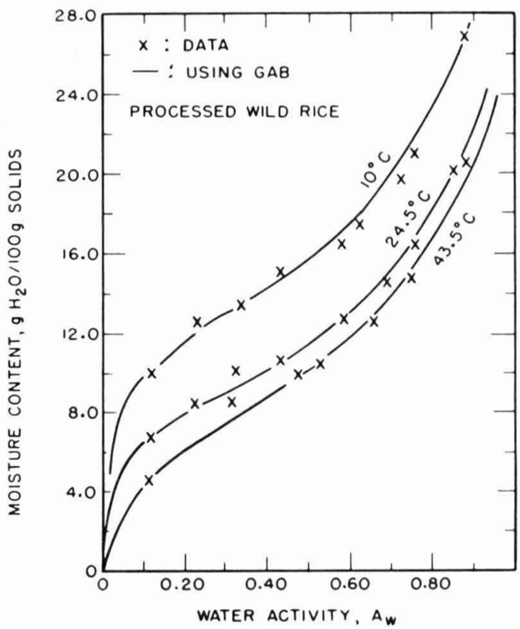

FIG. 1. WORKING ISOTHERMS FOR COMMERCIALLY WHOLE WILD RICE (average of duplicate samples)

Table 1. Isotherm constants and goodness of fit for the GAB equation determined from moisture sorption isotherms of wild rice

	T($\pm$1°C)	m_0*	k	C	Goodness of fit (P)
Unprocessed (d)	10.0	0.11665	0.64049	32.48119	1.45
Unprocessed (d)	43.5	0.07657	0.74749	25.89481	4.17
Processed (w)	10.0	0.10317	0.69529	412.68153	2.86
Processed (w)	24.5	0.07377	0.74905	68.60153	2.80
Processed (w)	38.0	0.07046	0.73580	37.16071	1.88
Processed (w)	43.5	0.06946	0.75102	17.74351	3.40

d = desorption isotherm
w = working isotherm
*m_0 = monolayer value in g water g solids

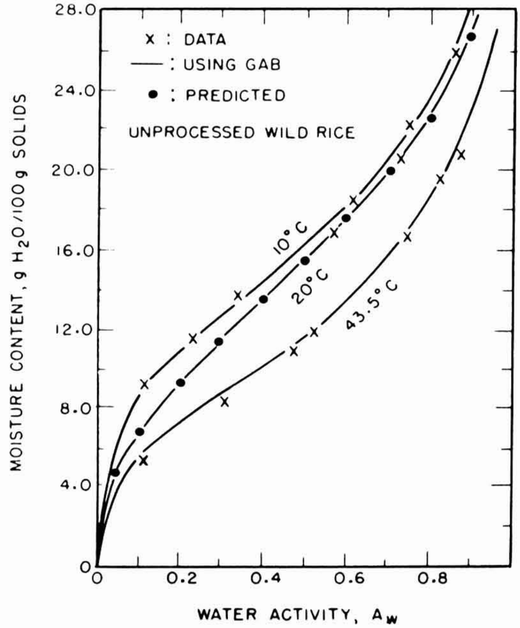

FIG. 2. DESORPTION ISOTHERMS FOR UNPROCESSED WILD RICE
(average of duplicate samples)

The 20 °C isotherm was calculated by the Day and Nelson equation with constants derived from the 10 °C and 43.5 °C data.

Table 2. Isotherm constants and goodness of fit for the Day and Nelson equation applied to the moisture sorption isotherms of wild rice

		T($\pm$1°C)	P(1)	P(2)	P(3)	P(4)	Goodness of fit (P)
Unprocessed	(d)	10.0	5.2603E-9	3.7385	42.8407	-0.4520	3.43
Unprocessed	(d)	43.5	2.0603E-8	3.3660	39.7531	-0.4800	4.70
Unprocessed Combined Data	(d)	--	7.8953E-9	3.5832	34.4755	-0.4397	5.75
Processed	(w)	10.0	7.0982E-9	3.8538	65.3582	-0.4856	6.50
Processed	(w)	24.5	6.8898E-9	3.7029	52.0653	-0.4951	6.45
Processed	(w)	38.0	6.9329E-9	3.6777	52.4267	-0.4999	5.90
Processed	(w)	43.5	5.9791E-9	3.5736	50.5725	-0.5231	6.08
Processed Combined Data	(w)	--	7.3240E-9	3.6557	59.3795	-0.5185	7.97

d = desorption isotherm
w = working isotherm

Table 3. Isotherm constants and goodness of fit for the Chen and Clayton equation applied to the moisture sorption isotherms of wild rice

		T(±1°C)	P(1)	P(2)	P(3)	P(4)	Goodness of fit (P)
Unprocessed	(d)	10.0	0.0784	0.7665	11.3005E-4	1.5336	4.16
Unprocessed	(d)	43.5	0.0513	0.7160	11.1457E-4	1.5149	6.40
Unprocessed Combined Data	(d)	--	0.0850	0.6727	12.9463E-4	1.4914	17.33
Processed	(w)	10.0	0.1050	0.9042	11.0063E-4	1.5997	5.99
Processed	(w)	24.5	0.0524	0.8261	11.2918E-4	1.5666	5.94
Processed	(w)	38.0	0.0519	0.7841	11.7772E-4	1.5527	5.87
Processed	(w)	43.5	0.0523	0.7486	12.1275E-4	1.5357	4.96
Processed Combined Data	(w)	--	0.0586	0.7594	11.2556E-4	1.5424	22.76

d = desorption isotherm
w = working isotherm

Table 4. Isotherm constants and goodness of fit for the modified Halsey equation applied to the moisture sorption isotherms of wild rice

		T(±1°C)	P(1)	P(2)	P(3)	Goodness of fit (P)
Unprocessed	(d)	10.0	-0.0309	-5.1054	2.6825	4.70
Unprocessed	(d)	43.5	-0.0271	-4.3901	2.3631	8.87
Unprocessed Combined Data	(w)	--	-0.0250	-5.1043	2.6629	7.13
Processed	(w)	10.0	-0.0152	-3.6906	3.7680	3.79
Processed	(w)	24.5	-0.0369	-4.8164	2.4714	2.13
Processed	(w)	38.0	-0.0322	-4.1617	2.2007	2.30
Processed	(w)	43.5	-0.0319	-4.2257	2.2695	5.73
Processed Combined Data	(w)	--	-0.0289	-4.9981	2.5613	6.67

d = desorption isotherm
w = working isotherm

isotherms, all three equations showed reasonably good fit to the experimental data. The constants obtained from the Day and Nelson and Chen and Clayton equations are comparable to the ones reported for white rice (Chen and Clayton 1971).

The values of the constants for the equations are not a strong function of temperature. Isotherms of processed wild rice were predicted by using the constants from the 24.5 °C temperature data as a check on the equations. Table 5 shows the P values for the predictions. The differences between experimental and predicted data points range from 5.31% to 19.76%.

Table 5. Goodness of fit (P value) of processed wild rice isotherms using the constants from 24.5 °C to predict for other temperatures

Temperature	P Value		
	Modified Halsey	Day & Nelson	Chen & Clayton
10.0°C	8.45	15.82	19.76
43.5°C	16.40	5.31	11.16

It should be noted that Iglesias and Chirife (1976), who used a modified Halsey equation to predict isotherms at other temperatures, found no difference in the isotherm constants as a function of temperature. Although the GAB model best represents the moisture isotherms for both processed and unprocessed wild rice, to predict wild rice isotherms for any other temperature between 10 and 43.5, the Day and Nelson or modified Halsey equations could be used with constants obtained from combined data, rather than the constants from a single temperature. This improves the accuracy of the prediction.

The values of the monolayer moisture content as calculated by the GAB and standard BET models are presented in Table 6. The monolayer moisture content decreases with increasing temperature. In general, the values obtained by the BET equation are about 15-20% lower than the ones obtained by the GAB equation. This is in agreement with the findings of Labuza *et al.* (1985) who observed a difference of 2-15% for fish flour and cornmeal monolayer calculations.

The moisture diffusion coefficients of whole and broken wild rice are shown in Table 7. Broken kernels had a diffusion coefficient four times larger than that of whole wild rice. The diffusion coefficient values are similar to the value reported for raisins (1.5E $-$ 9m^2/h) which are also a dense product (Lomauro *et al.* 1985a), suggesting that the rice is also dense internally. This information along with isotherm data can be used to predict the time to reach equilibrium in a packaged food mixture which contains wild rice.

Table 6. Comparisons of GAB and BET monolayer moisture content predictions

Wild rice	M_o = g H_2O/100 g solids GAB	BET
Unprocessed		
@ 10.0°C	11.67	9.85
@ 43.5°C	7.66	5.86
Processed		
@ 10.0°C	10.32	8.27
@ 24.5°C	7.38	6.22
@ 38.0°C	7.05	5.48
@ 43.5°C	6.95	5.70

Table 7. Diffusion coefficients for moisture in wild rice

Wild Rice	Temp. (±1°C)	%RH	Initial Moisture (%d.b.)	Equilibrium Moisture (%d.b.)	Thickness (mm)	D_{eff} (m^2/hr)	S.D. (m^2/hr)*
Whole	20.0	59.0	5.097	14.048	1.525	7.079×10^{-10}	7.67×10^{-11}
Broken	25.0	57.0	6.458	11.951	1.477	2.66×10^{-9}	1.026×10^{-11}
Unprocessed	20.0	59.0	45.446	16.590	1.580	1.420×10^{-9}	1.39×10^{-10}

*Standard deviation

Application of Sorption Data

The final predicted equilibrium moisture contents and water activities of both white rice-whole wild rice and white rice-broken wild rice mixtures, by using Eq. (7) and (8), are given in Table 8. The actual moisture change versus time for each component and finite element model predictions are seen in Fig. 3 and 5. The final equilibrium moisture contents obtained with Eq. (7) and (8) for both components of the mixtures are less than 10% different from the experimental determinations. The water activities, versus time, determined with the GAB isotherm, are shown in

Table 8. Equilibrium moisture predictions for white rice-wild rice mixtures

	Final moisture content g H_2O/100 g solids			Final water activity		
	Experimental	Additive Isotherm Pred.	Salwin/ Slawson Pred.	Experimental	Additive Isotherm Pred.	Salwin/ Slawson Pred.
White rice	9.24	8.70	9.20	0.230	0.199	0.224
Whole wild rice	5.49	5.49	5.95	0.200	0.199	0.224
Mixture (50/50)	7.22	6.95	—	—	0.199	0.224
White rice	9.10	9.85	9.80	0.223	0.262	0.259
Broken wild rice	6.86	6.65	6.60	0.274	0.262	0.259
Mixture (50/50)	7.92	8.06	—	—	0.262	0.259

Fig. 4 and 6. Using these analytical methods, the final predicted a_ws differed by about 0.04 from the actual a_w, which is generally acceptable in the lower a_w range.

The finite element predictions of moisture and of a_w versus time are given by the solid lines in Fig. 3-6. As can be seen, there is a good agreement between the predicted values and the experimental result. The mean error was 0.74% for white rice-whole wild rice mixture and 0.72% for white rice-broken wild rice mixture. Given the 2% moisture difference error, the finite element model predicted 28 days to equilibrium for the broken wild-white rice mixture and 38 days for the whole wild-white rice mixture.

The change in moisture content and water activity of packaged wild rice under different simulated storage conditions using Eq. (11) and (12) are presented in Fig. 7 and 8 for the distribution conditions presented earlier. For storage in Minneapolis, New York, and San Francisco, the change in moisture content would be less than 1% under these conditions. However, for the Dallas and Miami distribution, the moisture content would increase up to 15% and 17%, respectively, from an assumed initial moisture content of 9.9%. These moisture contents correspond to 0.65 a_w for the packages stored in Dallas and to 0.81 a_w for the ones stored in Miami. Considering extended storage periods, it is likely that microbial spoilage, especially from yeasts and molds, would result.

In conclusion, moisture isotherms and diffusion coefficients for processed and unprocessed wild rice were determined experimentally. The applica-

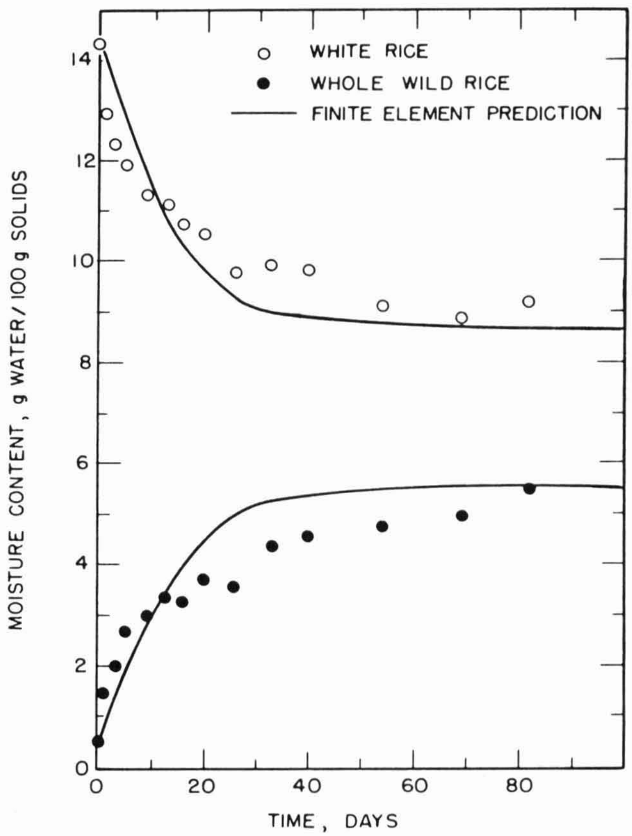

FIG. 3. ACTUAL MEASURED MOISTURE CONTENTS VERSUS TIME FOR THE COMPONENTS OF A WHITE RICE-WHOLE RICE MIXTURE COMPARED TO THE FINITE ELEMENT PREDICTION

tion of this sorption data to predict packaging and storage behavior of wild rice was demonstrated. The information obtained in this study can be used in the design of packaging for safe and extended storage of wild rice as well as other foods.

NOMENCLATURE

A	area of the package (m^2)
a_{eq}	equilibrium water activity calculated in Eq. (8)
a_i, a_j	initial water activity of component i, j in Eq. (8)
a_w	water activity
b_i, b_j	isotherm slope of component i, j in Eq. (8)

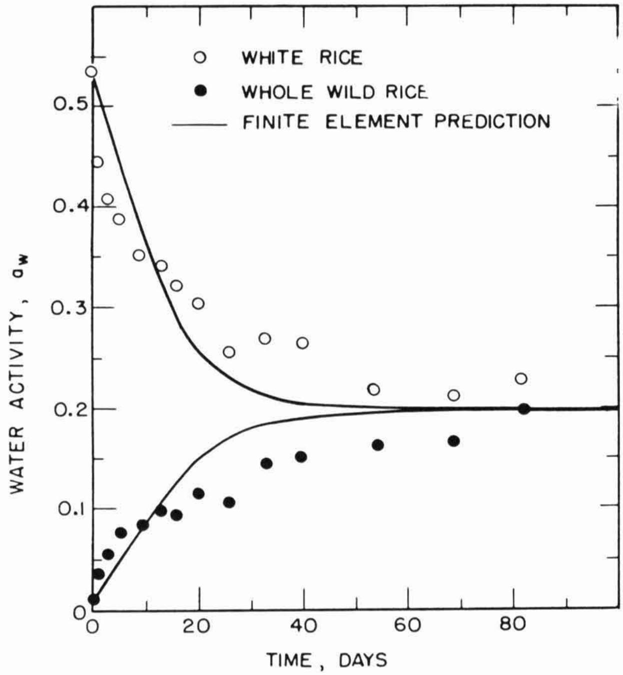

FIG. 4. CHANGE IN WATER ACTIVITY
(as determined from the GAB isotherm)
FOR THE COMPONENTS OF A WHITE RICE-WHOLE RICE MIXTURE (from Fig. 3)
AS A FUNCTION OF TIME COMPARED TO THE FINITE ELEMENT PREDICTION

C	Guggenheim constant depending on the temperature
k	factor correcting properties of the multilayer molecules with respect to the bulk liquid
$\frac{k}{x}$	water vapor permeability of the packaging film (g/day m^2 mm Hg)
L_0	characteristic half thickness
M	moisture content at any time
M_a	actual moisture content
M_e	equilibrium moisture content on dry basis
M_i, M_j	initial moisture content of component i or j on dry basis
M_M	moisture by mixture model
M_o	monolayer value
M_p	prediced moisture content
M_t	moisture content at any time
n	numerical value
P_0	vapor pressure of pure water at storage temperature (mm Hg)

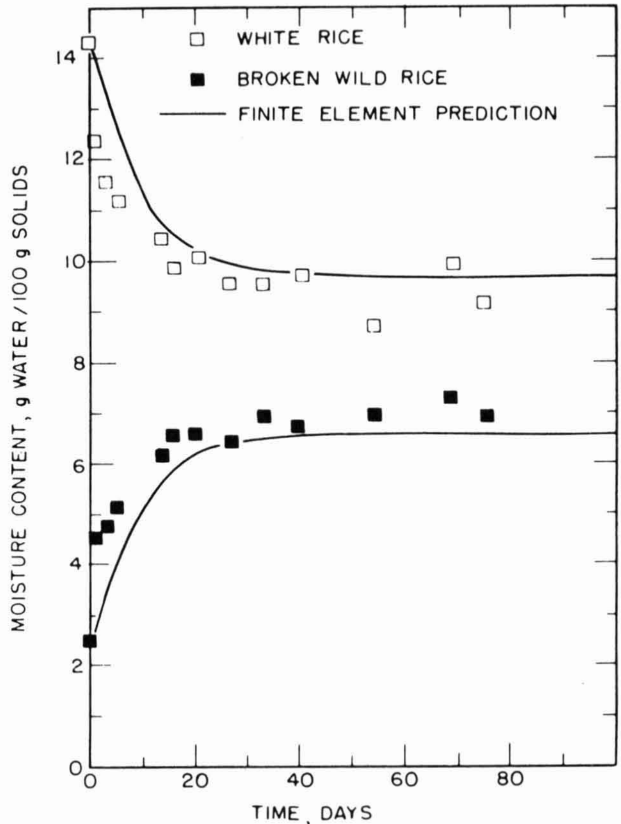

FIG. 5. ACTUAL MEASURED MOISTURE CONTENT VERSUS TIME FOR THE COMPONENTS OF A WHITE RICE-BROKEN WILD RICE MIXTURE COMPARED TO THE FINITE ELEMENT MODEL

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NOMENCLATURE (continued)

P(1), P(2), P(3) and P(4)	are empirical constants fitted to the individual equations
T	temperature, °C or °K
W_{s_i}, W_{s_j}	weight of solids of component i, j in Eq. (8)
θ	time, hour
β	surface rate constant boundary condition

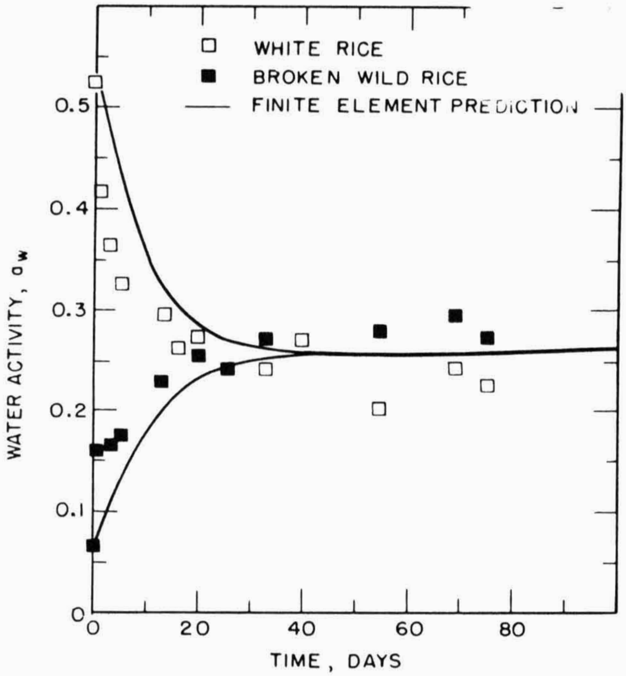

FIG. 6. CHANGE IN WATER ACTIVITY
(as evaluated from the GAB isotherm)
FOR A WHITE RICE-BROKEN WILD RICE MIXTURE (from Fig. 5)
AS A FUNCTION OF TIME COMPARED TO THE FINITE ELEMENT PREDICTION

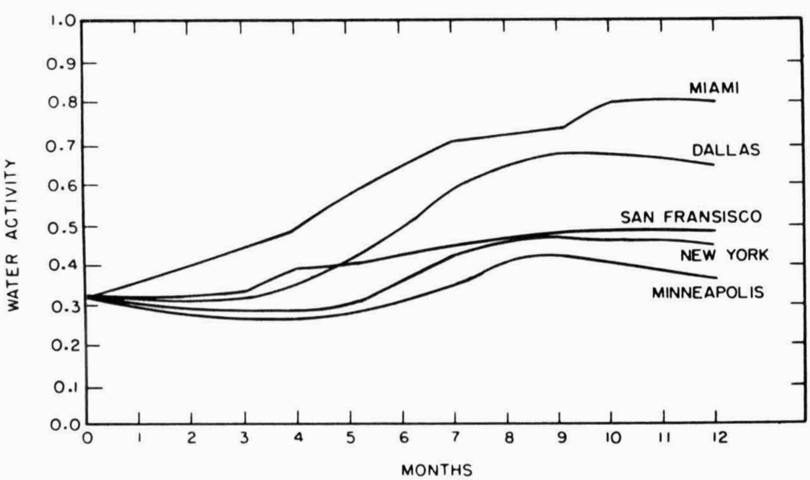

FIG. 7. PREDICTED THEORETICAL CHANGE IN MOISTURE CONTENT
OF PACKAGED WILD RICE UNDER DIFFERENT STORAGE CONDITIONS

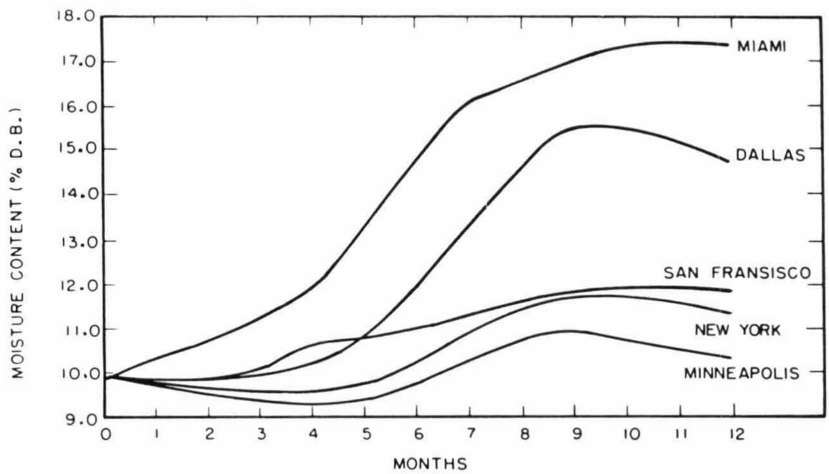

FIG. 8. PREDICTED THEORETICAL CHANGE IN WATER ACTIVITY OF PACKAGED WILD RICE UNDER DIFFERENT STORAGE CONDITIONS

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HASSON, E.P. and LATIES, G.G. 1976. Separation and characterization of potato lipid acylhydrolases. Plant Physiol. *57,*142–147.

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