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JOURNAL OF FOOD PROCESSING AND PRESERVATION

D.B. LUND
EDITOR

FOOD & NUTRITION PRESS, INC.

VOLUME 12, NUMBER 3

1988

JOURNAL OF FOOD PROCESSING AND PRESERVATION

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All subscriptions and inquiries regarding subscriptions should be sent to Food & Nutrition Press, Inc., P.O. Box 374, Trumbull, Connecticut 06611 USA.

One volume of four issues will be published annually. The price for Volume 12 is $90.00 which includes postage to U.S., Canada, and Mexico. Subscriptions to other countries are $104.00 per year via surface mail, and $112.00 per year via airmail.

Subscriptions for individuals for their own personal use are $70.00 for Volume 12 which includes postage to U.S., Canada, and Mexico. Personal subscriptions to other countries are $84.00 per year via surface mail, and $92.00 per year via airmail. Subscriptions for individuals should be sent direct to the publisher and marked for personal use.

The *Journal of Food Processing and Preservation* is listed in *Current Contents/Agriculture, Biology & Environmental Sciences (CC/AB).*

The *Journal of Food Processing and Preservation* (ISSN: 0145-8892) is published quarterly by Food & Nutrition Press, Inc. — Office of Publication is 6527 Main Street, Trumbull, Connecticut 06611 USA. (Current issue is November 1988).

Second class postage paid at Bridgeport, CT 06602.

POSTMASTER: Send address changes to Food & Nutrition Press, Inc., P.O. Box 374, Trumbull, CT 06611.

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Journal of FOOD PROCESSING and PRESERVATION

VOLUME 12
NUMBER 3

Editor: D. B. LUND

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TRUMBULL, CONNECTICUT 06611 USA

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Trumbull, Connecticut 06611 USA

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ISSN 0145-8892

Printed in the United States of America

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RELATIVE SUITABILITY OF PLASTIC FILMS FOR THE FROZEN STORAGE OF MANGO PULP

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Accepted for Publication March 8, 1988

ABSTRACT

Thermally blanched and unblanched mango pulp of three commercial varieties were packed in polyethylene, polypropylene and paper-Al foil-polyethylene laminate pouches, frozen and stored at −12°C for 12 months. Blanched samples were found to be more stable than the corresponding unblanched samples and samples stored in foil laminate pouches were rated superior to all other samples. Retention of total carotenoids in blanched samples ranged between 79.7-95.1% in foil laminate, 56.7-82.5% in polypropylene and 50.9-71.9% in polyethylene pouches while ascorbic acid retention was 56.8-88.4%, 13.4-36.0% and 11.0-19.7%, respectively, in laminate, polypropylene and polyethylene pouches after 12 months storage. Total sugar and acidity did not change appreciably during frozen storage of mango pulp.

INTRODUCTION

In India large quantities of mango pulp are prepared and preserved either by the use of chemical additives or by canning for the manufacture of ready-to-serve beverages, juices, nectars, squashes, ice creams etc. in the off season. Recently there has been considerable concern about the use of chemical additives in foods because of their long term undesirable effects. Freezing is known to retain the original flavor and nutritive value of fruits. Adsule and Roy (1975) have studied the relative suitability of canning, freezing and sulphur dioxide for the preservation of Indian mango pulp. Though frozen pulp was found to be slightly superior to canned and chemically preserved pulp up to six months storage, canned and chemically preserved pulp were rated superior in taste and flavor to frozen samples after 9 months. Ramana *et al.* (1984) also reported that frozen mango (*Totapuri*) pulp developed off flavor after 6 months storage. Since many of the flavor degradation reactions are dependent on the oxygen availability, the nature of packaging employed for frozen storage may

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Journal of Food Processing & Preservation 12 (1988) 171-178. *All Rights Reserved.*
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influence the quality and acceptability of the frozen products. The present study was therefore designed to evaluate the suitability of three indigenously available flexible packaging materials for the frozen storage of mango pulp both with and without blanching.

MATERIALS AND METHODS

Ripe mangoes of three popular varieties (*Totapuri*, *Badami* and *Raspuri*) were purchased from the local market, washed, peeled and flesh was separated from stones with stainless steel knife. The flesh was passed through a stainless steel pulper (Raylon Metal Works, Bombay), fitted with a 2 mm mesh sieve. The pulp of each mango variety was divided into two equal lots. One half was heated and maintained at 90°C for 3 min to inactivate enzymes. Heated samples were cooled to 30°C by keeping in chilled water (5°C) for 15 min and packed in polypropylene (75μ), polyethylene (75μ) and paper (40 GSM)-Al. foil (20μ)-polyethylene (40μ) laminate pouches. The other lot was packed as such without any treatment. In both cases 200 g samples of pulp were packed in 10 x 15 cm pouches and heat sealed. The samples were frozen in a contact plate freezer at −20°C and subsequently stored in a freezing cabinet maintained at −12°C. Initially and after 3, 6, 9 and 12 months storage, two samples from each treatment were analyzed for reducing and total sugars, ascorbic acid and acidity (Ranganna 1986) and total carotenoids (Arya *et al.* 1979). For measuring changes in browning, 10 g pulp was macerated with 20 mL lead acetate (43%) solution, centrifuged and optical density measured at 420 nm (Mannheim and Havkin 1981). All the analyses were performed in duplicate and the results presented are mean of four replicates.

Initially and after 3, 6, 9 and 12 months storage, mango pulps were converted into ready to serve drinks (RTS) of 15° Brix by mixing with sugar syrup in a blender. The proportion of mango pulp in RTS beverage was always maintained at 30%. Stored mango pulp along with RTS drinks prepared from them were given to a panel of 10 judges for sensory evaluation of a nine point hedonic scale with 9 for excellent and 1 for very bad and highly disliked.

RESULTS AND DISCUSSION

The changes in total carotenoids and ascorbic acid which were followed as objective indices of quality deterioration during storage are given in Table 1 and 2, respectively. Heat treatment employed to inactivate enzymes was found to reduce the concentration of total carotenoids and ascorbic acid, the losses being 4.8-10.4% in total carotenoids and 13.5-36.5% in ascorbic acid. Degradation of both carotenoids and ascorbic acid was highest in *Raspuri* pulp and least in *Badami* pulp.

During frozen storage both carotenoids and ascorbic acid decreased considerably.

TABLE 1.
CHANGES IN TOTAL CAROTENOIDS (μg/g) DURING FROZEN STORAGE OF MANGO PULP

Storage period (months)	Packaging material	Badami		Raspuri		Totapuri	
		Blanched	Unblanched	Blanched	Unblanched	Blanched	Unblanched
0	-	128.8±2.4	135.3±1.9	58.7±1.9	65.5±1.5	33.2±0.9	35.7±0.2
3	PFP	127.1±2.1	126.0±2.5	57.9±1.1	60.6±1.5	30.2±1.1	33.2±0.9
	PP	126.2±1.9	119.7±1.8	57.1±1.6	58.8±1.8	29.7±0.8	32.6±0.7
	PE	123.9±2.0	114.8±2.6	54.7±1.3	56.4±1.5	30.1±0.8	32.5±0.9
6	PFP	125.0±2.1	122.1±1.4	55.0±1.2	54.6±1.4	29.8±0.9	32.1±0.9
	PP	123.1±2.6	88.9±2.9	51.3±1.6	38.6±2.1	26.6±1.2	28.0±1.2
	PE	109.1±3.8	80.8±5.2	47.1±2.1	27.8±3.2	25.5±0.9	27.3±1.2
9	PFP	123.1±2.1	120.6±2.6	48.0±1.6	48.6±2.2	29.7±0.8	29.6±0.9
	PP	121.2±1.9	81.7±5.2	35.9±2.1	36.0±3.4	24.9±2.2	27.3±2.1
	PE	98.3±3.9	73.8±5.3	31.2±2.6	21.5±5.1	23.9±1.7	20.1±3.6
12	PFP	122.5±2.9	117.8±2.6	46.6±1.5	44.6±3.3	29.1±1.8	28.0±2.3
	PP	106.3±6.8	39.1±3.8	33.3±2.1	28.6±4.5	23.1±1.5	20.3±3.7
	PE	92.5±6.6	24.5±6.1	29.9±2.1	16.6±4.8	22.0±2.0	16.5±4.1

TABLE 2.
CHANGES IN ASCORBIC ACID (mg/100 g MEAN±STANDARD DEVIATION) DURING FROZEN STORAGE OF MANGO PULP

Storage period (months)	Packaging material	Badami		Raspuri		Totapuri	
		Blanched	Unblanched	Blanched	Unblanched	Blanched	Unblanched
0		21.5±0.3	24.8±0.5	4.0±0.2	6.3±0.2	12.7±0.3	15.2±0.4
3	PFP	19.9±0.4	9.8±0.6	3.8±0.2	2.5±0.3	10.2±0.2	6.8±0.3
	PP	17.3±0.3	3.5±0.6	1.8±0.3	1.6±0.2	6.4±0.3	4.8±0.5
	PE	16.3±0.3	2.9±0.3	1.6±0.3	1.5±0.2	5.9±0.3	3.3±0.3
6	PFP	19.0±0.3	6.7±0.4	3.3±0.3	2.2±0.3	8.9±0.4	5.0±0.4
	PP	8.2±0.4	2.7±0.4	1.7±0.2	1.5±0.2	4.6±0.3	3.8±0.4
	PE	7.8±0.5	2.5±0.3	0.9±0.3	0.9±0.4	4.2±0.3	3.1±0.5
9	PFP	19.0±0.3	6.7±0.5	3.7±0.2	2.2±0.3	8.7±0.2	3.9±0.3
	PP	3.1±0.4	2.0±0.2	1.5±0.3	1.4±0.3	3.1±0.3	1.6±0.2
	PE	2.8±0.3	1.4±0.3	0.7±0.2	0.7±0.3	2.5±0.3	1.6±0.3
12	PFP	18.1±0.2	5.2±0.5	3.5±0.3	2.2±0.3	7.2±0.3	3.4±0.2
	PP	2.9±0.3	1.7±0.3	1.4±0.2	1.3±0.2	3.2±0.3	1.5±0.4
	PE	2.4±0.3	1.1±0.2	0.6±0.2	0.6±0.2	2.5±0.2	1.4±0.3

Losses were considerably higher in enzyme active unblanched mango pulp than in enzyme inactive blanched samples. After 12 months storage, carotenoid retention in unblanched samples ranged between 68.1-87.1% in foil laminate, 28.5-56.8% in polypropylene and 18.1-46.2% in polyethylene pouches as compared to 79.7-95.1%, 56.7-82.5% and 50.9-71.9% respectively, in blanched samples. Ascorbic acid retention was also considerably higher in blanched samples and ranged between 56.8-88.4% in laminate, 13.4-36.0% in polypropylene and 11.0-19.7% in polyethylene pouches as compared to 21.0-35.1%, 7.0-20.8% and 4.5-9.4%, respectively, in unblanched mango pulp indicating the beneficial role of blanching in the preservation of carotenoids and ascorbic acid in frozen mango pulp.

Among the three packaging materials studied, foil laminate pouches were found to provide best protection as is evidenced by higher retention of carotenoids and ascorbic acid in both blanched and unblanched mango pulp samples during the entire 12 months frozen storage. Though no previous study has been published on the relative suitability of various packaging materials for the frozen storage of mango pulp, our results are in conformity with the published results on other oxygen sensitive frozen foods (Powrie 1973). During frozen storage, chemical and enzyme mediated oxidative degradation and associated off flavors are the major causes of spoilage. In packaged foods, the availability of oxygen becomes a limiting factor in determining the rate of these oxidative reactions. The retention of carotenoids and ascorbic acid was highest in foil laminate because of its impermeability to oxygen. Whatever degradation takes place in foil laminate pouches is mostly due to dissolved and head space oxygen present. Slightly higher retention of carotenoids and ascorbic acid in polypropylene as compared to polyethylene is also in conformity with above reasoning because of the slightly lower oxygen permeability of polypropylene (3000 cc $O_2/M^2/24$ h @ atm) than polyethylene (8000 cc $O_2/M^2/24$ h @ atm) film.

Titratable acidity, reducing and total sugar of mango pulp did not change appreciably during frozen storage. Titratable acidity (% citric acid) of *Badami* pulp (0.27±0.03) was lower than *Raspuri* (1.31±0.08) and *Totapuri* (0.45±0.05) pulps. Total sugar (% sucrose) in *Badami, Raspuri* and *Totapuri* pulps were 16.9±0.9, 12.5±0.6 and 15.8±0.7%, respectively.

Browning intensity of stored pulp as measured by optical density at 420 nm of lead acetate clarified extracts of pulp ranged between 0.04-0.10 up to 12 months storage as compared to 0.01-0.02 in fresh samples. Though it tended to increase on storage, the differences among packaging materials and treatments were not large enough to draw inferences.

TABLE 3.
VISUAL COLOR SCORES (MEAN ± STANDARD DEVIATION)
OF FROZEN MANGO PULP

Storage period (months)	Packaging material	Badami		Totapuri	
		Blanched	Unblanched	Blanched	Unblanched
0	-	8.6±0.3	8.7±0.3	7.9±0.4	8.1±0.5
6	PFP	8.0±0.6*	8.0±0.5*	7.3±0.6*	6.8±0.4**
	PP	7.3±0.5**	6.7±0.6**	6.5±0.6**	5.3±0.6**
	PE	7.0±0.6**	6.2±0.4**	6.3±0.7**	5.5±0.7**
12	PFP	7.4±0.5**	6.6±0.6**	6.8±0.4**	6.3±0.6**
	PP	6.4±0.4**	5.8±0.7**	6.0±0.6**	5.2±0.5**
	PE	6.8±0.7**	5.6±0.4**	5.7±0.7**	5.3±0.6**

*, ** significantly different from initial values at 95% and 99% confidence. Interaction between blanched and unblanched samples is significant at 95% confidence while between PFP and PP (or PE) is significant at 99% confidence. Interaction between PP and PE not significant.

However, sensory color scores of frozen mango pulp decreased significantly during storage and the extent of decrease was dependent on the nature of packaging material and blanching treatment (Table 3). After 12 months of storage color scores of blanched samples were higher than unblanched samples and samples stored in laminate pouches were rated superior to those stored in polypropylene and polyethylene pouches. The color scores of samples stored in polyethylene and polypropylene pouches were not significantly different though rate of degradation in carotenoids was higher in polyethylene pouches. Overall acceptability scores of RTS beverage prepared from stored frozen mango pulp followed a similar pattern: laminate samples being rated superior to polyethylene and polypropylene samples (Table 4).

As is evident, during frozen storage, mango pulp behaves typically like other oxygen sensitive food products. Frozen storage is accompanied by decrease in total carotenoids, ascorbic acid and sensory color scores and the extent of degradation was dependent on the packaging material and blanching treatment.

TABLE 4.
OVERALL ACCEPTABILITY SCORE (MEAN ± STANDARD DEVIATION) OF RTS DRINK PREPARED FROM STORED *RASPURI* PULP

Storage period (months)	Blanched			Unblanched		
	PFP	PP	PE	PFP	PP	PE
0	8.0±0.5	-	-	8.0±0.4	-	-
6	7.5±0.6*	6.8±0.5**	6.6±0.6**	6.8±0.5**	6.2±0.6**	6.0±0.7**
12	7.0±0.4**	6.0±0.6**	5.8±0.6**	6.0±0.4**	5.5±0.6**	5.4±0.6**

*, ** significantly different from initial values at 95% and 99% confidence. Interaction between blanched and unblanched samples is significant at 95% confidence while between PFP and PP (or PE) is significant at 99% confidence. Interaction between PP and PE is not significant.

ACKNOWLEDGMENT

We wish to thank Dr. T. R. Sharma, Director, Defence Food Research Laboratory, Mysore for his encouragement during the course of study.

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EVALUATION OF AN INDUSTRIAL PROCESS FOR PRODUCING PROTEIN ENRICHED MESQUITE POD (*PROSOPIS* SPECIES) FLOUR

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Accepted for Publication February 18, 1988

ABSTRACT

*Mesquite pods (*Prosopis *spp) from two species of mesquite trees were industrially processed by toasting, grinding and screening to produce three fractions (large, intermediate and fine). The fine (−100 mesh) flour was enriched in protein and reduced in fiber compared to the other fractions and the starting material. The process was shown to be capable of producing industrial quantities of flour from pods of both* Prosopis *species. Of the processing conditions studied, toasting at 125°C for 40 min was found to result in a maximum yield of fines and maximum protein availability (measured by red flour beetle larva growth). The final product was a fine (−100 mesh) cream colored low cost flour with many potential applications in the food industry.*

INTRODUCTION

Mesquite (*Prosopis* spp) leguminous trees may be a valuable crop for selected ecological niches (Felker 1979) because they are known to tolerate high temperatures and low rainfall and may produce high yields of pods rich in sugar, protein and carbohydrate (Becker and Grosjean 1980).

Previous studies from this laboratory have shown that mesquite pods could be processed to produce an enhanced protein, reduced fiber fraction suitable for use as a food ingredient (Del Valle *et al.* 1986, 1987). The optimum process found (Del Valle *et al.* 1987) involved grinding toasted mesquite pods in an Alpine mill and screening the resulting flour through 45 and 100 mesh screens. The fraction passing through the 100 mesh screen (−100 mesh) was enhanced in protein and reduced in fiber with respect to whole pods as well as the other fractions. Screening of pod

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fractions in both of the above publications, however, was carried out utilizing laboratory screens. Also, only one type of mesquite, that obtained in the area adjoining Chihuahua City, Mexico, was utilized.

The studies reported here were designed to optimize the processing conditions and equipment to produce the maximum quantity of the protein enriched, reduced fiber fraction of optimal protein quality. In addition, processing characteristics of two different species of mesquite pods were compared; those obtained from the area near Chihuahua City, Mexico, and those obtained from the area near Irapuato, Guanajuato, Mexico. Species from the Irapuato area were investigated because this area produces large amounts of pods which could serve as raw material for future industrial exploitation of mesquite.

MATERIALS AND METHODS

Pod collections in the Chihuahua City area were from *Prosopis glandulosa* trees and in the Irapuato area from *P. juliflora*. The whole mesquite pods of both species were processed by toasting followed by milling in an [1]Alpine Pin Mill model A400Cw operated with both discs rotating. The milled material was sieved through an industrial screen equipped with U.S. Standard 45 and 100 mesh sieves so that three fractions were obtained: oversized (retained on the 45 mesh screen); intermediate (passing through the 45 mesh screen but retained on the 100 mesh screen); and fines (passing through the 100 mesh screen).

The toaster consisted of a perforated rotating drum 40 cm in diameter by 70 cm long heated by a butane gas burner (Del Valle *et al.* 1986). The industrial screen was a grain cleaner (scalper) (Harper and Del Valle 1987) to which the 45 and 100 mesh screens were adapted. Toasting temperature-time conditions studied were: 100°C for 40 or 80 min, 125°C for 20 or 40 min, and 150°C for 10 min.

In each industrial screening run, total weight of material fed to the screen and weights of the three resulting fractions were determined. The fractions were analyzed for particle size by laboratory screen analyses (+ 45, + 100, − 100 mesh) and for proximate chemical analyses (moisture, ash, fat, protein, and acid detergent fiber) using AOAC (1970) methods. All determinations were run in triplicate and reported as means that agreed within 5% (Data not shown). The fines fractions resulting from the industrial screening runs were analyzed for protein availability utilizing red flour beetle (*Tribolium castaneum*) larvae according to the method of Vohra *et al.* (1978). Red flour beetle eggs were isolated from an adult colony and grown for 7 days. Larvae were transferred to an adaptation diet for 3 days, then weighed and placed on the test diet for 6 days after which they were again weighed and the weight grain per

[1]Reference to a company and/or product named by the Department is only for purposes of information and does not imply approval or recommendation of the product to the exclusion of others which may also be suitable.

diet recorded. Larvae growth has been shown to correlate well with protein availability especially when similar products are being compared (Vohra *et al.* 1978).

All results were statistically analyzed utilizing Analysis of Varience and Student's t-Test techniques (Spiegel 1975).

RESULTS AND DISCUSSION

TABLE 1.
PROXIMATE CHEMICAL ANALYSES OF WHOLE CHIHUAHUA AND IRAPUATO MESQUITE PODS

Proximate Analyses, %	Chihuahua Mesquite Pods	Irapuato Mesquite Pods
Moisture*	0.79	4.12
Ash**	3.0	4.09
Fat***	1.63	1.84
Protein*** (N x 6.25)	11.33	10.76
Acid Detergent Fiber**	28.30	30.95

*Differences between the two mesquite types significant at $P < 0.01$ level (t test).

**Differences between the two mesquite types significant at $P < 0.05$ level (t test).

***No significant differences between the two types of mesquite (t test).

The proximate chemical compositions of the pods from Chihuahua and Irapuato are shown in Table 1. The Irapuato pods contained significantly more ash and acid detergent fiber ($p < 0.05$, t test) than Chihuahua pods. Fat and protein contents were not significantly different (t test). The pod moisture content is affected by ambient humidities, so these differences are not critical. These results are consistent with analyses of pods from similar *Prosopis* species (Becker and Grosjean 1980; Meyer *et al.* 1986).

The yields and compositions of the different process fractions are shown in Tables 2 and 3. The higher toasting temperatures tested resulted in generally higher yields of −100 mesh material, the desired product, and correspondingly lower yields of +45 and +100 mesh material. The material lost during processing was primarily from the +45 and +100 mesh fractions.

Laboratory screen analyses of the industrially produced fraction demonstrated that the process successfully produced a fine fraction with only small amounts of larger pieces. The +45 and +100 mesh fractions contained some −100 mesh material which could probably be recovered. Toasting at 125°C for 40 min or 150°C for 10 min gave both the highest yield of −100 mesh material and fewer large (+45 and +100) contaminants in the fine fraction.

TABLE 2.
CHARACTERISTICS OF FRACTIONS DERIVED FROM PODS HARVESTED NEAR CHIHUAHUA CITY, MEXICO

Toasting Conditions	Yield			Net	Screen Analyses[a]			Proximate Composition (%)				
	+45	+100	-100	Loss	+45	+100	-100	H_2O	Protein[b]	Ash	Fat	ADF[c]
100°C/40 min.	23.5	-	-	7.9	92.5	0.4	6.7	2.9	9.1	4.1	2.1	49.1
		24.1	-		59.7	36.1	3.9	3.3	9.5	3.9	2.4	37.3
	-	-	45.0		2.0	7.2	90.7	4.3	15.2	4.3	4.0	23.2
100°C/80 min.	42.0	-	-	6.7	90.9	1.5	7.2	3.5	9.6	4.1	2.8	43.6
	-	12.3	-		40.4	54.5	4.8	3.9	9.8	3.5	3.0	36.7
	-	-	39.0		3.7	9.0	87.2	3.5	15.6	4.0	4.3	21.2
125°C/20 min	19.0	-	-	17.4	57.2	2.0	38.7	1.5	9.6	4.0	2.6	44.4
	-	13.6	-		54.3	29.5	15.4	2.7	7.4	3.7	2.6	47.2
	-	-	50.0		2.0	6.7	90.3	3.1	14.5	4.0	3.4	29.2
125°C/40 min.	19.4	-	-	7.3	69.7	1.7	27.6	3.0	10.4	3.7	2.4	48.9
	-	19.4	-		57.9	29.1	12.6	3.7	9.2	3.5	3.9	48.9
	-	-	53.9		0.9	3.2	95.7	3.8	19.1	4.4	6.3	21.0
150°C/10 min.	16.1	-	-	16.2	67.7	1.9	29.7	3.8	11.9	3.8	3.9	46.2
	-	14.0	-		79.0	9.8	11.0	2.6	13.6	4.3	3.8	33.0
	-	-	53.7		3.0	4.1	93.3	6.0	13.8	3.6	4.6	24.9

a. U.S. Standard Mesh, Laboratory Analyses

b. N X 6.25

c. Acid Detergent Fiber

TABLE 3.
CHARACTERISTICS OF FRACTIONS DERIVED FROM PODS HARVESTED NEAR IRAPUATO, MEXICO

Toasting Conditions	Yield			Net	Screen Analyses[a]			Proximate Composition (%)				
	+45	+100	-100	Loss	+45	+100	-100	H_2O	Protein[b]	Ash	Fat	ADF[c]
100°C/40 min.	18.7	-	-	3.3	95.1	0.2	4.7	2.6	6.2	2.0	1.5	50.4
	-	31.6	-		62.6	35.6	1.8	2.8	8.7	3.3	1.5	33.5
	-	-	46.9		10.1	22.9	67.3	3.6	15.2	4.3	2.4	23.6
100°C/80 min.	26.2	-	-	10.4	89.5	1.4	9.1	3.3	7.7	2.7	1.5	51.8
	-	32.4	-		48.5	50.6	1.2	4.0	8.3	3.0	1.8	39.0
	-	-	31.8		6.6	28.0	66.1	4.8	14.0	4.0	2.9	25.5
125°C/20 min.	12.5	-	-	6.2	86.7	0.2	13.1	1.7	7.4	2.0	0.8	54.0
	-	31.3	-		58.5	30.3	11.2	3.1	8.0	3.5	1.9	40.5
	-	-	50.0		2.3	6.3	91.2	3.3	10.7	4.0	2.6	24.2
125°C/40 min.	12.9	-	-	2.9	88.7	0.4	10.9	2.0	6.5	2.2	0.9	55.6
	-	29.6	-		68.6	19.7	11.7	3.4	7.1	3.1	1.9	46.2
	-	-	55.1		4.1	7.3	88.6	3.6	11.6	4.3	2.4	28.4
150°C/10 min.	8.8	-	-	8.8	90.3	0.3	9.4	2.8	5.9	2.3	1.6	57.4
	-	24.0	-		71.7	14.2	14.1	3.9	12.4	3.5	2.9	35..9
	-	-	58.4		4.9	7.1	88.0	2.9	14.4	1.9	1.4	20.3

a. U.S. Standard Mesh, Laboratory Analyses
b. N X 6.25
c. Acid Detergent Fiber

Toasting at 125°C for 40 min resulted in fines with higher levels of protein, ash and fat and lower ADF. Lower toasting temperatures (100°C for 40 or 80 min) resulted in higher protein levels but reduced yields. Comparison of the pods from Chihuahua and Irapuato showed little difference in yields of the different fractions (Tables 2 and 3).

As with the pods from Chihuahua, toasting the pods from Irapuato at lower temperatures resulted in higher protein levels but lower yields. The Irapuato pods toasted at 125°C/40 min had a lower yield and protein content than pods toasted at higher temperatures, but had a preferred appearance and flavor. Chihuahua and Irapuato flours toasted at 125°C/40 min contained 73 and 68% respectively, of the total seed protein. Toasting at 150°C for 10 min gave high protein and high yield but created off flavors.

TABLE 4.
PROTEIN QUALITY OF DIFFERENT CHIHUAHUA MESQUITE SAMPLES, DETERMINED BY WEIGHT GAIN OF RED FLOUR BEETLE (*TRIBOLIUM CASTANEUM*) LARVAE

Toasting Conditions	Mean Weight Gain Per Larva ± Std. Deviation
CONTROL SAMPLE, Whole wheat flour[a]	2.96 ± 0.6
100°C/40 min*	1.18 ± 0.12
100°C/80 min.*	1.24 ± 0.01
125°C/20 min.**	1.24 ± 0.05
125°C/40 min.**	1.71 ± 0.13
150°C/10 min.***	0.97 ± 0.11
150°C/20 min.***	1.31 ± 0.09

cF-value between type of process (5/12 degrees of freedom) = 14.99, significant, $p < 0.01$ level.

*Difference in weight gain due to change in toasting time at 100°C not significant (t test).

**Difference in weight gain due to change in toasting time at 125°C significant at $p < 0.05$ level (t test).

***Difference in weight gain due to change in toasting time at 150°C significant at $p < 0.01$ level (t test).

Growth of red flour beetle larvae indicated that toasting at 125°C for 40 min optimized protein availability (Table 4). Larvae had lower weight gains when grown on flours toasted at higher and lower temperatures and at 125°C for shorter times.

Organoleptic evaluation by a taste panel (data not shown) indicated a strong panel preference for the sample toasted at 125°C for 40 min. Because of the agreement between the panel and the insect assay, the preferred toasting conditions were judged to be 125°C for 40 min. The panel found mesquite flour to be a very acceptable sweetener with a unique flavor useful in baked goods, breakfast cereals and beverages. Product development studies are in progress.

The above observations support the following conclusions: *Prosopis* species pods from different sources and of different varieties can be successfully processed on an industrial scale by toasting at 125°C for 40 min, pin milling with both discs rotating, and sieving through 45 and 100 mesh screens. Three fractions are produced; the fibrous material is concentrated in the + 45 and + 100 mesh fractions; the fine (– 100 mesh) fraction is higher in protein and minerals, contains reduced amounts of fiber, has maximal protein availability, and is preferred by a taste panel. This process appears to be highly economical and produces a flour with many possible applications in the food industry.

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FERMENTATION OF SOYMILK WITH COMMERCIAL FREEZE-DRIED STARTER LACTIC CULTURES

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Accepted for Publication February 18, 1988

ABSTRACT

Fresh soymilk was prepared with 9:1 and 7:1, water:dry soybeans ratio, and fermented with commercial freeze-dried starter cultures comprising three lactics, L. acidophilus, S. thermophilus, *and* L. bulgaricus. *pH and titratable acidity reached their lowest and highest values, respectively, after 8 h of incubation at 43°C. Addition of sucrose did not influence pH or titratable acidity, and utilization of carbohydrate was 0.4%, (expressed as sucrose), irrespective of the initial sucrose level in the soymilk. Taste testing indicated that soy yogurt (4% sucrose, 8 h of incubation), with a final pH of 4.5 and titratable acidity of ≤ 0.5%, expressed as lactic acid, was the most acceptable product. Its storage stability at 5°C exceeded 3 weeks.*

INTRODUCTION

Yogurt processed from cow's milk has been gaining considerable acceptance by the American consumer in recent years. In the process, the milk is inoculated with a balanced culture of two or three species of homofermentative lactic acid bacteria which grow well at 45°C. During incubation the lactose undergoes lactic acid fermentation and the casein precipitates and is partially digested by the action of bacterial proteases. Soymilk yogurt, a less familiar product, is presently being developed by the soyfoods industry, and rapid increase in its acceptability is foreseen: by 1990, nondairy yogurt-type products are projected to reach 5% of the total yogurt market (Anon. 1987). While there are several similarities between cow's milk and soymilk, the fermentable carbohydrates in soymilk are the low molecular weight oligosaccharides sucrose, raffinose and stachyose, lactose is absent, and the proteins are chiefly globulins and albumins. Hence, acid production and gel formation in soymilk may differ from those produced in cow's milk when commercially available mixed bacterial starter cultures are utilized.

Journal of Food Processing & Preservation 12 (1988) 187-195. *All Rights Reserved.*
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The suitability of soymilk as a medium for growth of lactic acid bacteria has been studied by a number of investigators (Angeles and Marth 1971; Mital and Steinkraus 1974, 1975, 1979; Wang *et al.* 1974; Kothari 1975; Pinthong *et al.* 1980; Patel and Gupta 1982; Shehata *et al.* 1984). Several microorganisms were employed and acid content, pH, incubation time and temperature, as well as other parameters, were measured. While fermentation was frequently reported to suppress the soymilk beany flavor, the use of additives such as sucrose, lactose, citric acid, yeast extract, or a variety of flavoring agents in the products has been noted.

The objectives of the present study were to examine fermentation of soymilk with commercially available starter cultures used in the dairy industry and the effect of sucrose supplementation on acid production and flavor.

MATERIALS AND METHODS

Soy Milk

Soybeans (*Glycine max*, Corsoy variety, 300 g) were soaked overnight, combined with distilled water (9:1 or 7:1, water:bean ratio), and blended. The slurry was heat processed for 1 min at 15 psi, immediately cooled, and pressed. The milk was pasteurized in a microwave oven (72°C, 15 s, Amana model RR-6W), and cooled to 45°C before inoculation. A commercially available pasteurized soymilk (Michigan Soy Products Co., Royal Oak, MI), which consisted of water and soybeans, was also used in the study. It was pasteurized and cooled before inoculation as described above.

Analysis of Soymilk. Samples of the soymilk were analyzed for moisture, protein content (macro Kjeldahl), lipids (Roese-Gottlieb method, AOAC, 1984), carbohydrates (phenol sulfuric acid method), using sucrose solutions (0 to 50 ppm) as a standard (Meloan and Pomeranz 1980), and ash. Calcium, sodium, potassium, magnesium, iron and zinc contents in the milk were analyzed by atomic absorption (Perkin Elmer model 5000 spectrophotometer). For the analysis, a 1 g sample of soymilk was ashed overnight in a muffle furnace at 600°C. The ash was treated with ca 3 mL nitric acid (trace element free), dried to evaporate the acid, dissolved in ca 3 mL HCl (trace element free) and diluted 10X for Zn analysis and 500X for Mg analysis. Ca, K, Na, and Fe were analyzed directly in soymilk after appropriate dilutions: 500X for Ca, with addition of 0.5% $LaCl_2$ to suppress phosphate interference; 5000X for Na and K, with addition of 1000 ppm KCl or NaCl, respectively, to suppress ionization (Anon. 1982).

Bacterial Strains and Culture Methods:

Freeze dried starter cultures consisted of *Lactobacillus bulgaricus, Streptococcus thermophilus* and *L. acidophilus* (Chr. Hansen's Laboratory, Milwaukee, WI, and

Yogourmet, Lachute, Quebec, Canada). In addition, single strains of each of these organisms (Chr. Hansen's) were studied alone or in combination.

Milk samples were inoculated with the test cultures in the recommended levels and incubated at 43°C. Samples were removed for testing at various time intervals during a 24-h incubation period; pH was measured by direct immersion of the glass electrode into the product and titratable acidity (TA) was determined with 0.1N NaOH, using duplicate 10-mL samples, and titrating to end point pH of 8.1. L-lactic acid values were confirmed by the lactate dehydrogenase (LDH) assay (Boehringer Mannheim, GmbH), using 0.1 mL of a 1:50 dilution of the yogurt.

Addition of Sucrose. Sucrose (0-5%, W/V) was added to soymilk prior to pasteurization and inoculation, samples were incubated at 43°C and total carbohydrate content was determined after 0, 2, 4, 6, and 8 h of incubation. In addition, pH and titratable acidity, were measured in samples incubated for 24 h.

Carbohydrate Utilization By the Culture

To examine the ability of each of the organisms in the starter culture to utilize the three major soluble carbohydrates in soymilk, sterile nutrient broth (NB) samples (5 mL) containing 1% (w/v) of sucrose, stachyose or raffinose (Sigma Chem., St. Louis, MO) were inoculated with pure cultures of *L. acidophilus, L. bulgaricus* or *S. thermophilus*, or their mixtures. For the inoculum, each of the organisms was grown for 24 h at 37°C in NB containing 1% glucose, the media were centrifuged, the cells collected, washed twice in NB alone, and suspended in sterile NB. This suspension was used to inoculate the carbohydrate-containing media. Optical density at 600 nm was measured after 2, 4, 6, 8 and 24 h of incubation at 37°C.

Sensory Procedures. Sensory evaluations were conducted on samples after 24 h refrigeration using a descriptive flavor profile analysis (IFT 1981). Evaluations were made by a 10-member panel of graduate students of food and nutrition who consume cow's milk yogurt. Coded yogurt samples containing 0-5% sucrose were presented simultaneously to the individual panel members. Sensory characteristics scored were aroma, flavor and aftertaste (rating scale from threshold to 3). Panelists recorded also their impression on appearance, consistency, and overall rating. An open discussion followed the independent examination of the product.

With the exception of carbohydrate content determination, three replications of each determination were conducted and mean values calculated. For the former, data represent means of six replicates.

RESULTS

TABLE 1.
PROXIMATE COMPOSITION OF SOYMILK AND COW'S MILK

Value (%, w/w)	Soymilk		Cow's Milk[c] (2%)
	Prepared[a]	Commercial[b]	
Moisture	92.6	94.4	89.2
Protein	3.3[d]	1.9[d]	3.3[e]
Lipid	1.8	1.2	1.9
Carbohydrate	1.0[f]	1.2[f]	4.8
Ash	1.0	*	0.7
Ca	0.02	0.02	0.12
K	0.12	0.13	0.15
Na	0.05	0.06	0.05
Mg	0.0146	0.0141	0.014
Zn	0.0003	0.0002	0.00039
Fe	0.00004	*	0.00005

[a]Water:soybeans ratio of 7:1
[b]Michigan Soy Products Co., Inc., Royal Oak, MI
[c]USDA Agriculture Handbook 8-1, 1976
[d]N x 6.25
[e]N x 6.38
[f]Expressed as sucrose
*Not determined

The proximate compositions of the prepared and commercial soymilk are shown in Table 1. For comparison, the composition of cow's milk (2% fat) was included in the Table. The differences between the two soymilks are attributed to the water:soybeans ratio used in the process. The soymilk prepared with a water:beans ratio of 7:1 was comparable in composition to cow's milk, except for the carbohydrate and calcium content, which were significantly higher in the latter.

Soymilk inoculated with the mixture of the three lactics showed little change in pH or TA during the first 4 h of incubation, followed by a sharp drop in pH and increase in acidity. After 8 h the acidity level reached a maximum of 0.51% and the pH a minimum of 4.6 (Table 2, left column). A soft gel generally formed after 6 h, and a firm gel showed after 8 h of incubation. Samples incubated for 24 h showed a slight increae (<0.1%) in TA, but no change in pH values.

TABLE 2.
EFFECT OF ADDED SUCROSE ON pH AND TITRATABLE ACIDITY OF SOY YOGURT[a,b]

TIME AT 43C (HR)	ADDED SUCROSE LEVEL (%)					
	0		3		5	
	pH	T.A.(%)	pH	T.A.(%)	pH	T.A.(%)
0	6.6	0.14	6.4	0.14	6.5	0.14
4	6.4	0.16	6.4	0.16	6.4	0.16
6	5.1	0.38	4.9	0.43	5.0	0.44
8	4.6	0.51	4.5	0.64	4.6	0.63

[a]Soymilk was prepared with a water:soybeans ratio of 7:1 and inoculated with a mixture of three lactics (*L. acidophilus*, *S. thermophilus*, and *L. bulgaricus*).
[b]All values are means of 3 determinations.

Since soymilk contains primarily sucrose as a fermentable carbohydrate, and small amounts of the tri- and tetrasaccharide raffinose and stachyose, the ability of each of the three lactics, as well as their combination, to utilize these carbohydrates was tested in NB. Rapid increases in absorbancy (600 nm) were observed between 4 and 8 h of incubation in NB containing sucrose after inoculation with pure cultures of *L. acidophilus, L. bulgaricus, S. thermophilus* or their mixture. Poor growth of the lactics was observed in NB alone or in NB containing raffinose or stachyose (data not shown), indicating their inability to utilize these carbohydrates.

When soymilk was inoculated with the individual organisms or their combinations, pH declined in all samples and TA increased. Values of pH ranged from 4.23 to 5.57, and titratable acidity from 0.18 to 0.41% as lactic acid after incubation for 8 h at 43°C (Table 3). Values determined by the lactate dehydrogenase (LDH) assay agreed well with values obtained by titration, suggesting that lactic acid was the major acid produced. There was no evidence of synergistic effects of culture combination. Gel formed in all samples after 8 h of incubation. Subsequent refrigeration of the samples for 24 h effected very slight changes in pH or in acidity.

Although yogurt produced after 8 h of incubation had an acceptable odor, and its consistency and appearance were similar to those of cow's milk yogurt, the mean flavor scores were low, when judged by the 10-member panel of graduate students: 80% of the taste panel members indicated a strong dislike to its flavor, and only 20% judged it to be acceptable. An improvement was sought by sucrose addition

TABLE 3.
CHANGES IN pH AND TITRATABLE ACIDITY (TA) OF SOYMILK INOCULATED WITH LACTIC ACID BACTERIA[a]

	ORGANISM			
	L. acidophilus	*L. bulgaricus*	*S. thermophilus*	Combination of the three
8 hr at 43°c				
pH	4.78	5.57	4.28	4.40
TA, %	0.30	0.18	0.41	0.40
After additional 24 hr at 5°c				
pH	4.96	5.69	4.45	4.50
TA, %	0.35	0.21	0.50	0.49

[a]Data are means of 3 determinations.

to the soymilk. Results indicated that the gel was firmer in yogurt containing 3-5% added sucrose than in sucrose-free yogurt, and the flavor of the sweetened product was preferred and judged acceptable.

The effects of sucrose additions (3 and 5%) on pH and titratable acidity of soy yogurt are summarized in Table 2, providing comparison to values in sucrose-free yogurt. Additions of sucrose did not influence the pH, although TA values were slightly higher in the sucrose containing samples. Measurements after additional storage for 24 h at 5°C showed, as before, that TA increased slightly after storage (a mean of 0.07%), while pH remained essentially unchanged.

TABLE 4.
CARBOHYDRATE CONTENT IN SOY YOGURTS BEFORE AND AFTER 8 H OF INCUBATION AT 43°C[a,b]

Added Sucrose %	Total Carbohydrate, % Incubation time at 43°C (hr) 0	8
0	1.11 ± .30	.75 ± .25
3	4.08 ± .67	3.64 ± .28
5	5.68 ± 1.01	5.29 ± 1.04

[a]Expressed as sucrose.
[b]Each value is mean ± standard deviation of 6 determinations.

Analysis of the carbohydrate content in soy yogurt containing 0, 3 and 5% added sucrose was performed during the 8-h incubation period. Values, expressed as sucrose, before and after 8 h of incubation are summarized in Table 4. Mean levels of carbohydrates utilized during this period were 0.36, 0.44 and 0.39% for yogurts with 0, 3, and 5% added sucrose, respectively. Samples were examined once a week during prolonged refrigerated storage. No changes in pH, TA, and overall quality of the products were discerned during a period exceeding three weeks.

DISCUSSION

Soymilk prepared with 7 parts of water per one part of dry beans, rather than the typical 9 or 10 parts, had protein and fat levels similar to those in 2% cow's milk. Inoculation of this high solid milk with commercially available mixed cultures consisting of *S. thermophilus, L. bulgaricus* and *L. acidophilus* and incubation for 8 h at 43°C produced a stable yogurt with a firm consistency. Its titratable acidity (expressed as lactic acid) and pH were approximately 0.50% and 4.5, respectively. Products prepared with mixed cultures from either Chr. Hansen's Laboratory or Yogourmet had similar final TA and pH values.

In the preparation of cow's milk yogurt, cultures are selected on the basis of flavor, acidity, consistency, texture and homogeneity. Although gel formed when each of the individual strains was added to soymilk, the acidity after 8 h of incubation was low when *L. bulgaricus* or *L. acidophilus* were used (0.18 and 0.30, respectively) (Table 3), and the fast rate of acid production by *S. thermophilus* resulted in whey separation. Moreover, the flavor of fermented products prepared with single strains was inferior to the one obtained with the mixed culture.

The final lactic acid content in the soy yogurt (ca 0.5%) was lower than that seen in cow's milk yogurt (0.74%), but in agreement with values reported for soy yogurt by most other investigators. No increase in acidity was seen after additional incubation time, and these results are in agreement with observations reported by Angeles and Marth (1971) in a study with 13 species of lactics. Studies by Mital and Steinkraus (1974) appear to further support the present findings: these authors reported three to four-fold higher population of *S. thermophilus* in cow's milk than in soy milk. They observed that the population in the former increased throughout an incubation period of 16 h, while in the latter it remained stationary after 8 h. A mixed culture of *S. thermophilus* and *L. bulgaricus* exhibited a similar growth behavior, and maximum populations were nearly one log cycle lower in soymilk than in cow's milk.

The present study showed that mixed starter cultures of *S. thermophilus, L. bulgaricus* and *L. acidophilus*, which are employed in the production of yogurt from cow's milk, are suitable for the preparation of a mildly fermented yogurt from soymilk. The product can be prepared from soymilk with the traditional 9:1 water:bean ratio, but a 7:1 ratio produced a superior and more nutritious product. Although less acid was produced in soymilk than in cow's milk, the final pH values

were comparable, and fermentation proceeded without the need for supplementation of carbohydrates or stabilizers. Acidity change appeared to be a more sensitive method to follow fermentation, as wider differences in acidity could be seen in the data than among pH values, which fell within a narrower range. Carbohydrate utilization data indicated that added sucrose did not affect the fermentation. The phenol sulfuric acid method used to determine utilization has several drawbacks. In particular, the use of sucrose as a standard does not measure accurately soluble polysaccharides and oligosaccharides in soymilk, or their hydrolysis products during the incubation period. Hence, although the values may not have been accurate, they could be used for comparative purposes. These data indicated that total utilization of carbohydrates during incubation was ca 0.4%, irrespective of the initial sucrose level. The addition of 4% sucrose did not enhance acid production but improved the flavor of the product. Soy yogurt remained stable at refrigerator temperature for periods exceeding three weeks, showing no changes in texture, acidity or microbial stability.

Fermentation of soymilk reduced the beany flavor of soymilk, and addition of sucrose to soy yogurt improved the flavor scores. Members of the taste panel in this study were familiar with the taste of cow's milk yogurt, but were more accustomed to the flavored types, which contain approximately 10% added sugar, rather than to the unflavored yogurt. Hence, the low flavor scores for the unsweetened soy yogurt were attributed not only to the residual beany flavor in the fermented soymilk, but also to the general preference for sweetened flavored yogurts. In recent trials in our laboratory, additions of flavors such as vanilla or lemon before inoculation of the soymilk, in combination with sucrose, indicated further improvement of flavor scores by masking the soybean flavor.

ACKNOWLEDGMENT

We thank Chr. Hansen's Laboratory for their gift of bacterial cultures.

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A FLOUR FROM FERMENTED COWPEAS: PROPERTIES, COMPOSITION AND ACCEPTABILITY

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Accepted for Publication February 26, 1988

ABSTRACT

A fermented cowpea flour was prepared by fermenting dehulled beans in three volumes of water at 38°C for 48 h. After fermentation the beans were washed, dried then ground it into flour.

The flour was acidic, and slightly greenish white in color. The composition was 21% protein, 2.5% oil, 1.6% ash and 66.6% carbohydrate. It also contained 35 I.U. beta-carotene, 1.28 mg ascorbic acid, 1.03 mg thiamin and 0.64 mg pyridoxine. Nitrogen solubility index, water absorption, and viscosity became greater after fermentation. Two products; bread and chips, were prepared using unfermented and fermented cowpea flour as an ingredient. The products containing unfermented cowpea flour were scored higher than the ones containing unfermented cowpea flour. African panelists gave higher scores than American panelists.

INTRODUCTION

Cowpeas (*Vigna unguiculate*), a good source of plant protein, is regarded as a very important crop in West Africa (McWatters 1983). Fermentation, one of the oldest methods of food preservation, is often employed to develop desirable characters such as flavor and texture (Sathe and Salunkhe 1981). The nutritive values of legumes generally improves on fermentation (Zamora and Field 1979a). Information concerning the fermentation of cowpeas is limited (Shaffner and Beuchat 1986). Reduction in trypsin inhibitor activity in fermented cowpeas (Zamora and Field 1979b) and decrease in oligosaccharides in germinated cowpeas (Nnanna and Phillips 1987) were reported. The traditional way of preparing cowpea foods in West Africa is laborous and time consuming. It involves dehulling of beans after first soaking in water, followed by grinding them into paste, then steaming or frying to serve (Akpapnum and Markakis 1981). The availability of ready to use flour would greatly

Journal of Food Processing & Preservation 12 (1988) 197-206. *All Rights Reserved.*
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enhance the use of this legume. In the present study, cowpeas were fermented at 37°C for 48 h. A flour was prepared from the fermented beans and its properties, composition and acceptability investigated.

MATERIALS AND METHODS

Cowpea flours

Cowpeas (*Vigna unguiculata*) were purchased from a seed store in Tuskegee, Alabama. Two types of flours, fermented and unfermented, were prepared.

Cowpeas were fermented in the following way. Ten pounds of beans were soaked in water at room temperature for 10 min. The beans were dehulled by hand rubbing gently in water, washed, drained and placed in a container filled with 3 volumes of water and fermented naturally by endogenous microflora at 37°C for 48 h. The beans were washed thoroughly with cold water, drained and dried overnight at 60°C. The dry beans were ground into powder by a motor driven grinder, then passed thru sieves to collect uniform particle sizes of 40-60 mesh. The flour was packaged in a plastic pouch and stored at 4-6°C until use.

For unfermented flour, 10 pounds of cowpeas were treated the same way as the fermented cowpeas except for the fermentation step.

Nutrient Composition. Moisture, ash, fat and protein (AOAC 1985), beta carotene, thiamin and ascorbic acid (Strohecker and Heinz 1965) were determined. Pyridoxine content was determined by the microbiological method employing Saccharomyces carlsbergensis (Difco's Technical Information 1971).

Bacterial Count. One mL of soaking solution was diluted 10^4 to 10^6 times. One mL of diluted sample solution was pipetted into petri dish and mixed with Lactobacillus agar AOAC (Difco). The plates were incubated at 37°C for 48 h. The number of colonies were counted by a Quebec colony counter. The analysis was done in triplicates.

Functional Properties. Water binding, oil binding (Beuchat 1977), soluble nitrogen (Albrechty *et al.* 1966) were determined. An Oswald viscometer was employed to determine relative viscosity of 4% cowpea flour solution at 20°C. Color was determined visually and also by a Spectronic 20 spectrophotometer equipped with a color reflectance attachment. The color values were expressed as L, a and b values.

Cowpea Products. Two products, cowpea chips and breads, were prepared. To prepare cowpea chips, 100 g fermented or unfermented flour was mixed with 100 g corn starch, 2 tablespoons of dehydrated onion, 35 g sugar, 3.5 g corn oil, 11 g salt and 200 mL of water to make a thick batter. The batter was spread thinly on a teflon coated plate then steamed for 20 min at 100°C. The gel sheet thus formed was cut into a triangle shape with a knife, peeled off from the plate, dried in an oven for 30 min at 50-60°C. The dry chips were deep fat fried in a corn oil bath at 170°C for 7-10 s. The excess oil was drained over a paper towel. The fried cowpea chips were packaged in a plastic pouch and stored for analysis.

The formula of bread was the same as the one reported by Klein *et al.* (1980). For experimental breads, 20% of wheat flour were replaced with fermented or unfermented cowpea flour. A few pieces of cowpea chips and a slice of bread were served with a cup of water to panelists for evaluation. A 9-point hedonic scale was employed to determine acceptability (ASTM 1968), with 9 being the highest score and 1 being the lowest score. Cowpea chips were evaluated by 54 subjects. Among them 29 were Americans. Breads were evaluated by 50 subjects. Twenty of them were Africans. The difference in mean scores was computed statistically (Steel and Torie 1980).

RESULTS AND DISCUSSION

One of the important criteria in food preparation is pH because it affects taste and acceptability. The pH of the soaking solution was 6.3 at the beginning but it dropped to 4.0 after 48 h at 37°C. The number of bacteria increased from the initial count of 4.2×10^3/mL to 10.6×10^7/mL at the end of the fermentation. Microscopic examination of the colonies on the plates showed that a large number of bacteria were long rod shaped and appeared like Lactobacillus. No attempt was made to identify those bacteria in this study. According to Zamora *et al.* (1979b), they isolated and identified the following bacteria from fermented cowpeas: *Lactobacillus casei, L. leichmanii, L. plantarum* and *Pediococcus pentosaceus.*

TABLE 1.
NUTRIENT COMPOSITION[a] OF COWPEA FLOURS

	Unfermented	Fermented
Moisture	7.48 ± 0.71	7.84 ± 0.31
Protein	20.02 ± 2.13	21.74 ± 1.54
Fat %	1.56 ± 0.21*	2.52 ± 0.32*
Ash	3.12 ± 0.18*	1.65 ± 0.19*
Carbohydrate	67.42	66.65
beta-Carotene (I.U.)	25.2 ± 0.34*	35.0 ± 2.4*
Ascorbic acid	1.11 ± 0.34	1.28 ± 0.15
Thiamin (mg)	0.71 ± 0.17	1.03 ± 0.09
Pyridoxine	0.72 ± 0.21	0.64 ± 0.46

[a]mean + S. D. of six determinations
[b]determined by difference
*significantly different at the 5% level

Nutrient composition of fermented and unfermented flours is shown in Table 1. There was no difference in moisture, protein, thiamin, ascorbic acid and B_6 ($p > 0.05$) but fat and beta-carotene content were greater and ash content smaller for the fermented than the unfermented flour ($p > 0.05$). The small ash content was probably caused by the low pH of the soaking solution. Minerals such as sodium and potassium might have leached out into the solution. Slightly greater oil and beta-carotene content of fermented flour might reflect the fact that depletion of some minerals and fermentable carbohydrate have occurred during fermentation, therefore concentrations of these nutrients appeared greater than those in unfermented flour. It was reported (Nnanna and Phillips 1987) that starch and protein of cowpeas remained unchanged but soluble carbohydrate decreased after germination. According to Zamora and Fields (1979a) B-vitamins did not increase significantly in fermented cowpeas except riboflavin.

TABLE 2.
FUNCTIONAL PROPERTIES OF COWPEA FLOUR

Functional Properties		Unfermented	Fermented
Nitrogen Soluble Index		29 ± 2.0*	38 ± 4.0*
Water Absorption (g/g)		1.80 ± 0.80*	3.00 ± 0.20*
Oil Absorption		1.73 ± 0.12	2.00 ± 1.00
Relative Vicosity (4% solution)		1.30 ± 0.3	1.38 ± 0.2
Color	L	73.9	75.5
	a	-1.1	-.5
	b	9.3	7.9
Visual Perception		Light greenish white	Greenish white

*Significantly different at the 5% level

It is important to evaluate how new food ingredients will perform in foods before use. Ingredients that contain substantial levels of protein receive much attention since proteins can greatly influence functionality in many food systems. Functional properties may change with fermentation. As shown in Table 2, percent nitrogen solubility and water absorption were greater for fermented cowpea than for unfermented cowpea flour ($P < 0.05$).

Development of acidity and possibly partial degradation of cowpea proteins as a result of fermentation might be contributed to apparent high water absorption of fermented cowpea flour. Fermented cowpea flour also had slightly greater oil absorption and viscosity than nonfermented flour. These changes in functional properties may be desirable. Fermented cowpea flour may be able to mix well with meat, retain more moisture and provide more viscosity when added in soup. The color of the fermented flour was slightly lighter than the unfermented one as observed visually and also determined colorimetrically (Table 2). Low pH may be a contributing factor to the light color of fermented cowpea flour. It was reported that acidification of canned peas with citric acid resulted in lighter color than non-acidified canned peas (Flora 1980).

The composition of two products, cowpea chips and breads is shown in Tables 3 and 4, respectively. No difference was observed between the fermented and unfermented cowpea chips ($P > 0.05$). The result, however, showed that cowpea chips were low in fat and calories and high in protein when compared with commercial potato and corn chips. The low fat content in cowpea chips could be due to its high protein content. One explanation to this phenomenon is that heat denaturation of proteins during deep fat frying may involve the formation of a fat resistant barrier at the surface of food (Wolfe and Cowan 1971). Composition of wheat bread and cowpea flour fortified breads is shown in Table 4. Moisture, fat and ash content was greater for the breads but the protein content was greater for the breads supplemented either with fermented or unfermented cowpea flour. Visual comparison of bread showed that there was no appreciable difference in loaf volume between the control and cowpea flour added breads. However, the color was slightly darker for cowpea flour added breads than the control.

The results of sensory evaluation are shown in Table 5. The mean scores of cowpea chips were 7.24 for the unfermented and 7.13 for the fermented, indicating that these products are well accepted. These scores were not significantly different ($P > 0.05$). When mean scores of two groups were compared, the result showed that Americans gave lower scores than Africans. The reason was that the cowpea chips made from fermented flour tasted slightly sour. African panelists on the other hand did not seem to discriminate against sour taste probably because they were accustomed to sour taste for some fermented products i.e., kenkey and gari (International Labor Org. 1984) in their countries.

The sensory evaluation of breads showed that the control bread was preferred to the experimental breads added either with fermented or unfermented cowpea flour especially the latter ($P < 0.05$). When mean scores of two groups were compared, the result showed that Africans gave 7.17 for unfermented and 7.9 for fermented which are higher than Americans. Tougher texture and some beany odor were cited as the reason for low score by Americans. The African panelists on the other hand credited the cowpea fortified bread for their bulkiness and a mouthful feeling reflecting the fact that food acceptance varies with cultural background. It was noteworthy that both panels scored the bread fortified with fermented cowpea flour higher

TABLE 3.
PROXIMATE COMPOSITION OF COWPEA CHIPS[a] AND COMMERCIAL CHIPS[b]

	Food Energy Calories (100g)	Moisture %	Ash %	Protein %	Fat %	Carbohy-drate %
COWPEA CHIPS						
Unfermented	485.0	4.22 ± 0.59	3.98 ± 0.55	6.53 ± 0.77	18.67 ± 0.74	66.60
Fermented	493.8	5.13 ± 0.53	3.53 ± 0.58	7.07 ± 0.77	20.51 ± 0.17	63.76
COMMERCIAL CHIPS						
Potato	605.6	2.1	4.0	5.0	42.8	50.10
Corn	551.2	3.7	2.4	1.7	33.2	61.40

[a]Mean + SD of three determinations
[b]Values reported by Sheppard *et al.* 1978.

TABLE 4.
PROXIMATE COMPOSITION OF CONTROL AND EXPERIMENTAL BREADS

	Food Energy Calories (100g)	Moisture %	Ash %	Protein %	Fat %	Carbohy-drate %
Control	300.6	34.46 ± 0.62	1.05 ± 0.56	10.75 ± 0.21	3.50 ± 1.41	50.24
Unfermented[a]	302.7	34.02 ± 0.02	1.50 ± 0.66	13.21 ± 0.30	3.50 ± 1.83	47.77
Fermented[b]	303.1	31.84 ± 0.71	1.49 ± 0.71	14.21 ± 0.70	3.91 ± 0.18	48.56

[a]Bread supplemented with unfermented cowpea flour
[b]Bread supplemented with fermented cowpea flour

TABLE 5.
SENSORY EVALUATION OF COWPEA CHIPS AND BREADS

		No. of Judges	Unfermented Cowpea Flour	Fermented Cowpea Flour	Wheat
Cowpea Chips	All Judges	53	7.24a	7.13^{a}	---
	Africans	29	7.41a	7.44^{a}	---
	Americans	24	7.04a	6.76^{a}	---
Bread	All Judges	50	6.46^{b}	6.98^{ab}	7.58^{a}
	Africans	20	7.17^{b}	7.9a	8.0a
	Americans	30	6.0^{c}	6.37^{b}	7.33a

Means within rows followed by the same letter are not significantly different at the 5% level.

than the one with unfermented flour indicating that fermented cowpea flour was favored over the unfermented one. Although further improvement is needed, fermented cowpea flour could be used as a potential ingredient to improve nutrient content of various foods. Cowpea is an important crop in Africa. Fortification of foods with cowpea flour may alleviate protein deficiency problems, the disease prevalent among people in many developing countries.

ACKNOWLEDGMENTS

This study was supported in part by the George Washington Carver Agricultural Experiment Station, Tuskegee University, Alabama 36088.

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RESPONSE CHARACTERISTICS OF FULL-HISTORY TIME-TEMPERATURE INDICATORS SUITABLE FOR PERISHABLE FOOD HANDLING

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Accepted for Publication March 8, 1988

ABSTRACT

Time-temperature indicators manufactured by LifeLines Technologies (models 21, 34, and 57) and I-POINT Biotechnologies (models 2140, 2180, and 2220) were stored at 0°, 5°, 10°, 15°, 20°, 25°, and 37°C. The response of the LifeLines model 57 and I-POINT model 2180 indicators were compared to the manufacturers data and found to be in good agreement. Indicator responses were documented for the constant temperature exposures, and modeled with a first-order kinetic equation. The effect of temperature on indicator response was described according to the Arrhenius relationship, and the activation energies for the LifeLines indicators were found to range from 17.8 to 21.3 kcal/g-mole, and from 14.0 to 14.3 kcal/g-mole for the I-POINT indicators.

INTRODUCTION

Time-temperature indicators exhibit a change in a physical characteristic (i.e. color) in response to the cumulative effect of time and temperature. These temperature history indicators do not provide a precise record of temperature as it changes with time, as do time-temperature recorders or digital data acquisition systems, but respond in relation to the combination of time and temperature. There exist a wide variety of devices which could be called time-temperature indicators. For example, an ice cube could be used as a simple time-temperature indicator, as the rate at which ice melts is directly related to time and temperature exposure. Similarly, a time-temperature indicator could be made from a temperature sensitive chemical (or biological) reaction, where the products of the reaction could be monitored to gauge the time and temperature history.

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Journal of Food Processing & Preservation 12 (1988) 207-218. *All Rights Reserved.*
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Review articles by Schoen and Byrne (1972) and Kramer and Farquhar (1976) provided information on patented and commercially developed indicators that monitor changes in temperature with time. The indicators reported utilize a variety of concepts to indicate time-temperature change, including: the use of bacteria or enzymes which interact with a substrate to change the solution chemistry; chemical substances which polymerize to form new substances with different physical properties; capsules which rupture upon freezing thereby releasing liquid dyes when thawed; oils which diffuse along a paper or fabric wick in proportion to time and temperature; and devices that mechanically deform as temperature fluctuates.

Time-temperature indicators may be classified according to the manner in which each device responds to a temperature vs. time function. The indicators which respond continuous in time for all temperature conditions are said to be "full-history" indicators, whereas the devices which respond only for the period of time during which a temperature threshold has been exceeded are called "partial-history" indicators (Wells and Singh 1985). The classification denotes whether an indicator can monitor the complete range, or only a partial range, of temperatures to which it is exposed.

Time-temperature indicators have been promoted by their manufacturers as a means to monitor temperature related quality changes in perishable foods. Recent investigations have demonstrated that full-history time-temperature indicators can monitor food quality changes during storage (Mistry and Kosikowski 1983; Campbell *et al.* 1985; Singh and Wells 1985; Singh *et al.* 1984 and 1986). These researchers presented evidence that the response of full-history indicators is highly correlated with changes in specific quality attributes of frozen and refrigerated foods. The use of time-temperature indicators as food quality monitors has a potentially important application in the area of perishable inventory management (Wells and Singh 1988a, 1988b). The design of an inventory management system would require knowledge of the response characteristic of commercially available full-history indicators. Thus, the objective of this paper is to document the response characteristics of selected models of the LifeLines Freshness Monitor™ and the I-POINT® Time/Temperature Monitor.

MATERIALS AND METHODS

Time-Temperature Indicators

LifeLines™ Freshness Monitor. The LifeLines™ Freshness Monitor (LifeLines Technologies, Morristown, NJ 07960) has been previously described by Fields and Prusik (1983). The indicator uses the polymerization of an actylenic molecule to record a visual response of the time and temperature history. The polymerization changes the optical density of the actylenic material which results in a darkening of the indicator. Since the polymerization is irreversible and the reaction rate is temperature dependent, the LifeLines indicator effectively integrates the time-temperature function to which it is exposed. Indicator response is monitored with

a hand-held microcomputer and optical light wand which records the reflectance, 0 to 100%, of the polymer. In addition, the hand-held unit can read a bar-code containing an identification number printed on each indicator. The identification number and indicator response can be downloaded to a personal computer and linked via a computerized database to product information such as lot number and manufacture date.

I-POINT® Time/Temperature Monitor. The I-POINT® Time/Temperature Monitor (I-POINT Biotechnologies A.B., Reston, VA 22091) has been previously described by Blixt and Tiru (1976) and Wells and Singh (1985). The I-POINT time-temperature indicator uses a simple biochemical reaction to monitor temperature history. The indicator has two compartments (initially separate); one containing a pH indicator dye and enzyme solution, and the other a lipid substrate in fluid suspension. When the contents of the two compartments are mixed enzymatic hydrolysis of the substrate follows initiating an irreversible change in solution pH. The extent of the pH change is reflected as a color change caused by the pH indicator dye. The hydrolysis reaction, and thus the indicator color change, is continuous in time once the indicator has been activated, and proceeds at a rate proportional to temperature. The color change is seen to proceed from green, to yellow, to brown-red, to red; and is visually compared to a printed color scale and scored as 0, 1, 2, or 3. The I-POINT TTM currently lacks an electronic monitoring system to detect and record indicator response.

Experimental Procedures and Data Analysis

The indicator response data reported in this paper was collected in conjunction with the perishable food storage study conducted by Singh *et al.* (1986). Three models of the LifeLines Freshness Monitor (models 21, 34, and 57), and three models the I-POINT Time/Temperature Monitor (models 2140, 2180, and 2220) were examined. Ten indicators of each model were placed in storage rooms maintained at 0°, 5°, 10°, 15°, 20°, 25°, and 37°C. The temperature variation within each storage room was held to less than ±1.5°C for the duration of the investigation. Each indicator was inspected within their respective storage room at intervals of 3 days to 2 weeks depending upon indicator model.

Individual indicator responses were recorded at each inspection interval, and the mean values of the individual responses were used for presentation and calculation. The response of the LifeLines indicator was described with a classic first-order kinetic model (Singh and Wells 1987). The response of the I-POINT indicator was also described as a first-order model, after the data had been transformed with a Gaussian type equation (Taoukis and Labuza 1987). The effect of temperature on response rate of both indicators was described with the Arrhenius relationship. The activation energy term of the relationshp was determined from a plot of the natural logarithm of indicator rate constant as a function of the reciprocal of absolute temperature. The microcomputer statistical software StatView 512 + (BrainPower, Calabasas, CA) was used to conduct the linear regression analysis to determine isothermal response rates and activation energy.

RESULTS AND DISCUSSION

Observed Performance and Response Characteristics

Several models of both the LifeLines and I-POINT time-temperature indicators are available from their respective manufacturers. The different indicator models allow a variety of different response rates and temperature sensitivities. One indicator model might expire (achieve its full scale response and no longer function) in a few days at a given temperature, while another model would expire only after several months of storage at the same temperature. For example, the I-POINT indicator model 2140 will reach a full-scale response in approximately 5 days at 15°C, while the LifeLines indicator model 21 will achieve only a fraction of its full-scale response after several months at the same temperature. The different response characteristics are useful in selecting time-temperature indicators to monitor quality changes in a variety of perishable foods.

According to the manufacturer, the LifeLines indicators model 21 and 34 were designed to be used in conjunction with items which require long term storage, thus these models were observed to respond more slowly than the model 57 indicator. The LifeLines models 21 and 34 did not yield a significant response at 0°, 5°, or 10°C during the 16 weeks of storage, and the model 57 reached a near full scale response at 20°, 25°, and 37°C within one week. The LifeLines model 57, however, was suitable for the cooler temperatures, but expired too rapidly at temperatures above 20°C to be used in extended storage.

The I-POINT indicator model series 2000 was designed for long-term storage at frozen temperature conditions. Indicators in the 2000 model series, however, had been used successfully by previous investigators to monitor refrigerated temperatures (Singh *et al.* 1986). Currently, the manufacturer suggests indicators in a new series (model series 4000) for use in refrigerated conditions. During the investigation, the I-POINT model 2140 responded more quickly to all treatment conditions compared to models 2180 and 2220. At temperatures of 20°C and above, all I-POINT models examined expired rapidly (yielded a response of 3 or red), in some cases in less than three days.

The response of the LifeLines model 57 observed during this investigation compares favorably with the data provided by the manufacturer, while the I-POINT model 2180 was observed to respond slightly more rapidly than anticipated from the manufacturer's data. The differences in response of the I-POINT indicator can be attributed in part to discrepancies in the perception of the observer who examined the indicators. That is the ambient lighting conditions under which the I-POINT indicators are inspected, and the visual acuity of the observer will influence the subjective judgement of color change given by the indicator. Discrepancies between manufacturer data and experimental finding for the I-POINT indicator was also observed by Dolan *et al.* (1985). Development of an electronic color detector, and the definition of the I-POINT response scale in terms of the detector signal, could eliminate discrepancies in visual judgements (Witt *et al.* 1987).

Inspection of the LifeLines indicator was conducted with the hand held microcomputer and optical wand previously described. The indicator lacks a means to be inspected without the aid of the optical scanner, and while inspection with the scanner is not tied to the visual acuity to the observer, conditions such as insufficient charge in the microcomputer batteries, fouling of the optical portal, and angle of incidence at which the wand is held affects the recorded indicator response. To account for minor differences between individual scan inspections, the manufacturer suggests that a series of five scans be taken on a single indicator during one inspection. The average of the five successive observations would be the recorded indicator response used in further analysis.

A small percentage of the individual scan observation on the LifeLines indicators (approximately 1 in 300) were recorded as "null scans." The null scans reported a value of 0% reflectance (i.e., no reflectance because the indication band was completely blackened) even though repeated scans and visual observation would verify a much higher reflectance value. The manufacturer claims to have corrected this situation with the addition of new ROM programming within the microcomputer.

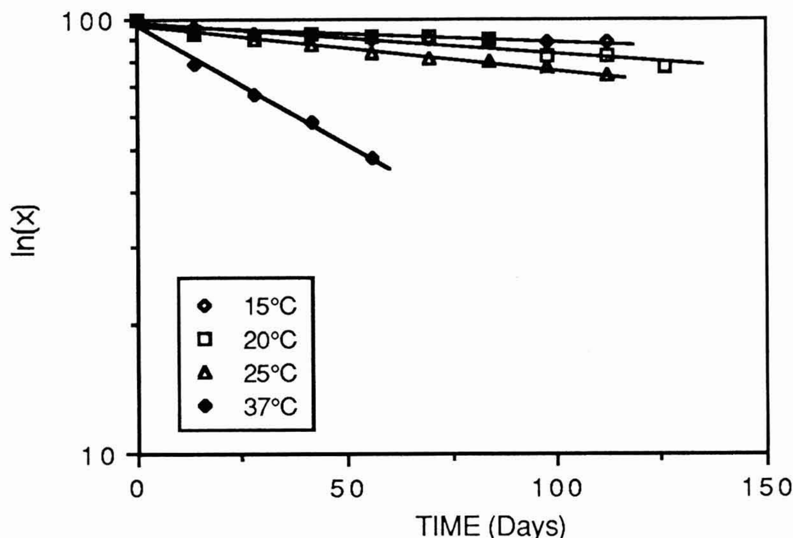

FIG. 1. SEMI-LOG PLOT OF THE RESPONSE OF THE LIFELINES FRESHNESS MONITOR MODEL 21 TO ISOTHERMAL STORAGE

Temperature Influence on Indicator Response

The mean responses of the LifeLines indicator models 21 and 57 held at constant temperature storage are shown in Fig. 1 and 2, respectively. The semi-log plot of mean response as a function of storage time was used to find the reaction rate constant at each isothermal condition (first-order kinetic model), and the best fit regression line for the response data are shown. For the LifeLines indicators some deviation

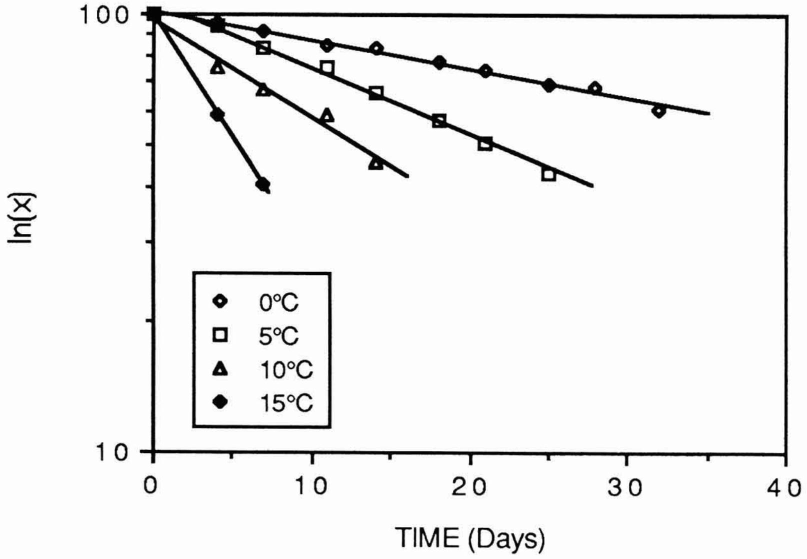

FIG. 2. SEMI-LOG PLOT OF THE RESPONSE OF THE LIFELINES FRESHNESS MONITOR MODEL 57 TO ISOTHERMAL STORAGE

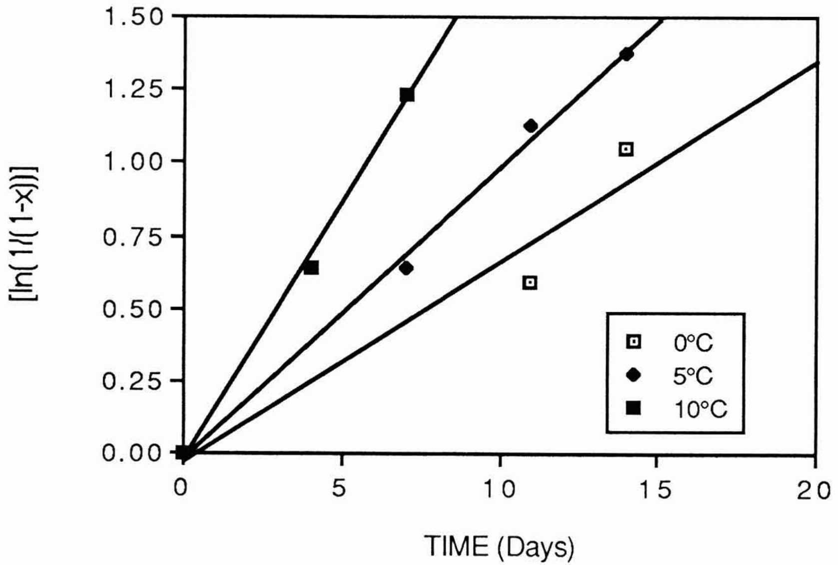

FIG. 3. PLOT OF THE GAUSSIAN TRANSFORMATION OF THE RESPONSE OF THE I-POINT TIME/TEMPERATURE MONITOR MODEL 2180 TO ISOTHERMAL STORAGE

from a first-order kinetic model was seen at longer storage times. The first-order model predicted a more rapid response than observed, indicating that a higher order model might more appropriately describe the entire range of indicator response. Additionally, in higher temperature storage the response of LifeLines model 57 was observed to plateau at an absolute reflectance reading of approximately 10%, perhaps indicating an intrinsic resolution threshold for the indicator monitoring equipment. To account for these observations, indicator response below 40% reflectance were not included in the modeling analysis. Based on the limitations discussed above, the first-order model accurately described the reflectance change at all temperature conditions to 50% reflectance.

The mean responses of the I-POINT indicators models 2180 and 2220, expressed in the linearized form of the Gaussian type equation, are shown in Fig. 3 and 4. The best fit regression lines for a first-order reaction are shown and appear to suitably describe the transformation. This finding would support modeling analysis conducted by Taoukis and Labuza (1987).

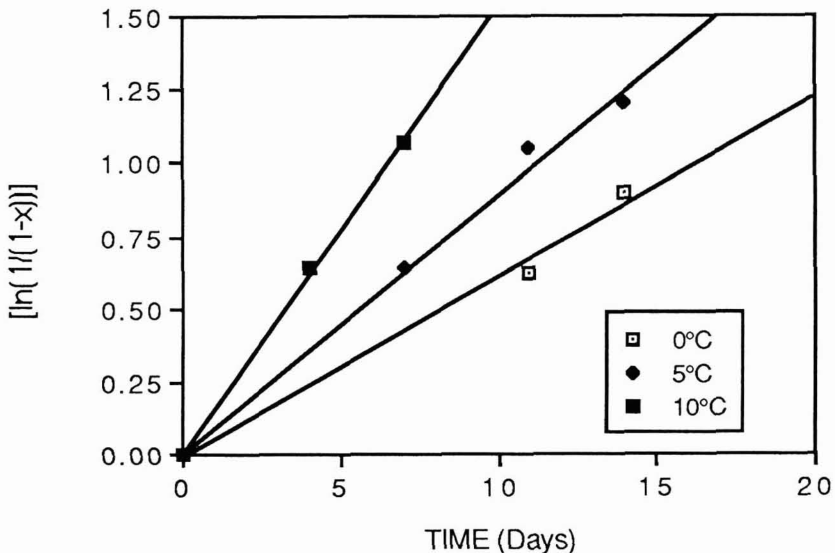

FIG. 4. PLOT OF THE GAUSSIAN TRANSFORMATION OF THE RESPONSE OF THE I-POINT TIME/TEMPERATURE MONITOR MODEL 2220 TO ISOTHERMAL STORAGE

TABLE 1.
ESTIMATED FIRST-ORDER REACTION RATE CONSTANTS AND COEFFICIENT OF VARIATION OF THE RATE CONSTANT ESTIMATE FOR THE RESPONSE OF THE LIFELINES AND I-POINT TIME-TEMPERATURE INDICATORS STORED AT ISOTHERMAL CONDITIONS

Indicator	Indicator Response Rate Constant (day $^{-1}$)						
Model	0°C	5°C	10°C	15°C	20°C	25°C	37°C
LifeLines 21	–[a]	–	–	0.00091[b]	0.00160	0.00241	0.01262
				15.9[c]	14.4	5.7	4.6
LifeLines 34	–	–	–	0.00047	0.00073	0.00130	0.00415
				7.7	15.1	5.5	5.7
LifeLines 57	0.01526	0.03427	0.05127	0.1290	–	–	–
	3.8	4.2	9.3	2.0			
I-POINT 2180	0.06930	0.09995	0.1758	–	–	–	–
	24.3	4.3	6.5				
I-POINT 2220	0.06176	0.08857	0.1535	–	–	–	–
	10.3	5.9	2.6				

[a] The response of the LifeLines model 21 at 0°, 5°, and 10°C; model 57 at 20°, 25°, and 37°C; I-POINT model 2140; and the response at 20°, 25°, and 37°C for models 2180 and 2220 were excluded from the analysis because of excessively slow or rapid responses.

[b] Estimated mean value of the reaction rate constant.

[c] Coefficient of variation of the rate constant ($\sigma/\mu \times 100\%$)

The estimates of the reaction rate constants, and the coefficient of variation of each estimated, for the indicators examined are given in Table 1. Large variations were observed in the response rate constants for both the I-POINT and LifeLines indicators. The variations in the response of the I-POINT indicators were primarily due to the discrete color judgements enforced during visual inspection. It is believed that if a continuous color change monitor was developed for indicator inspection, a more precise estimate of the response rate constants could be determined.

The effect of temperature on the indicator response was described with the Arrhenius relationship. Figure 5 shows a graphical presentation of the Arrhenius relationship with a plot of indicator response rate in semi-log coordinates as a function of the reciprocal of absolute temperature. If the Arrhenius relationship appropriately describes the influence of temperature on indicator response the result of the plot will be a straight line, and the slope of the line is equal to the ratio of the activation energy divided by the ideal gas constant. A summary of the activation energies and selected response characteristics for the LifeLines and I-POINT indicators examined are given in Table 2. The activation energies of the indicator response were determined from linear regression, and in all cases the coefficient of determination (R^2) for the regression line was significant at $p<5\%$.

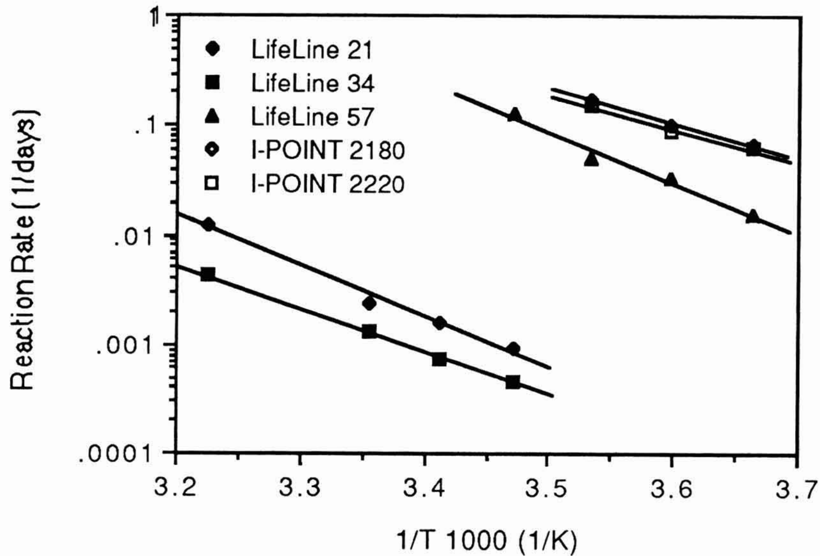

FIG. 5. EFFECT OF STORAGE TEMPERATURE ON THE RESPONSE RATE OF THE LIFELINES AND I-POINT TIME-TEMPERATURE INDICATORS EXPRESSED IN TERMS OF THE ARRHENIUS RELATIONSHIP

TABLE 2.
ACTIVATION ENERGY AND SELECTED RESPONSE CHARACTERISTICS FOR THE LIFELINES AND I-POINT TIME-TEMPERATURE INDICATORS

Indicator	Model	E_{AR} (kcal/mole)	Temp. (°C)	time (days)	Response[a]
LifeLine	21	21.3	15	20	95%
	34	17.8	15	20	99%
	57	21.3	15	20	18%
I-POINT	2180	14.3	10	6	Color 2
	2220	14.0	10	12	Color 2

[a] Response of LifeLine indicators is given in percent reflectance of LifeLine scale; response of the I-POINT indicators are given in the units of the I-POINT color scale.

Indicator Selection for Food Quality Monitoring

Much research has been undertaken to mathematically describe the quality deterioration of perishable food products. Generally, time and temperature dependent quality changes in foods are modeled with kinetic analysis and the Arrhenius relationship. Labuza (1982) and Singh and Heldman (1983) presented a summarized listing of the activation energy for many refrigerated and frozen food products. Because of the similarities in modeling indicator response and changes in food quality, kinetic data can be used to select specific indicator models for use in conjunction with particular foods.

Selection of an appropriate indicator model for a specific application in food quality monitoring requires the activation energy and a reference rate constant to be approximately matched to that of the food product. Both conditions are important as it would be of little value to select an indicator with the appropriate activation energy for an observed quality change, if the indicator would not yield a response within the time period considered to be the shelf-life of the product. For example, pasteurized milk has a shelf-life of 14-21 days at 2°C, and an activation energy for microbial and sensory changes that varies from 15-24 kcal/g-mole depending on raw product quality, processing technique, and quality analysis method (Labuza 1982). Based on the data in Table 2, the activation energies of all of the LifeLines indicators examined fall within the range of values given for milk. However, only the LifeLines model 57 would yield a response which is rapid enough for use with pasteurized milk. Grisius *et al.* (1987) verified that the response of the LifeLines model 57 was highly correlated to total microbial growth in pasteurized milk. Similarly, it is expected that the selection of indicators with activation energy and response times which correspond to the activation energy and shelf-life observed for other foods, would also result in indicator responses highly correlated with quality changes in that food.

With increasing demands on food processors to sustain and increase the supply of high quality foodstuffs, continued attention must be given to current distirbution and handling procedures for perishable food. Better quality control procedures, and inventory management schemes will be among the foremost concerns of manufacturer, wholesalers, and retailer of frozen and refrigerated foods. Time-temperature indicators can be a tool in quality assurance programs during product storage and distribution. Documentation of the response characteristics of full-history time-temperature indicators is considered to be an important step in the design of procedures to improve the maintenance of perishable food quality.

ACKNOWLEDGMENT

This research was supported by U.S. Department of Army Contract No. DAAK60-84-C-0076. The authors wish to acknowledge the assistance of Mr. Jianliang Zhao and Mr. Hongda Chen. Also, the authors appreciate the comments of Bob Rose (I-POINT Biotechnologies) and Ted Prusik (LifeLines Technologies) in response to an early draft of this manuscript.

Reference to manufacturer names of indicator models given in this presentation does not constitute an endorsement by the authors.

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ON THE THERMAL MODELING OF FOODS IN ELECTROMAGNETIC FIELDS

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Accepted for Publication April 8, 1988

INTRODUCTION

The use of RF and microwaves for heating and/or processing of biological materials is increasing. In the food industry, international competition and changing consumer demands and preferences have created the need for not only increased microwave processing of food materials and microwaveable meals, but also combination (microwave-convection) processing systems. Two of the major problems usually encountered in the microwave processing of food materials are the lack of good color formation and the absence of crust formation. These are both very important parameters because they represent visual attributes of prepared foods that are synonymous with the perception that the food has been properly cooked. This presents opportunities for combination processing systems which take advantage of the speed afforded by microwave and RF energy, in addition to providing the desirable visual indicators generally associated with cooked food.

Food processes that are generally considered suitable for RF and microwave applications include dehydration, freeze-drying, blanching, baking, thawing, pasteurization, sterilization and curing. In spite of the fact that RF and microwave technologies have been available for food processing for several decades, there are few established applications at the industrial level. The lack of reliable heat and mass transport models for the analysis of food materials in electromagnetic fields accounts, in large part, for this anomaly.

The primary effect of exposing a biological material to microwave or RF radiation is a volumetric heat generation that induces a temperature rise in the material. This volumetric heat generation is generally non-uniform, even in homogeneous materials (Kritikos and Schwan 1975). In the last decade, a considerable amount of progress has been made in the modeling of the human dosimetry. This advancement of knowledge has occurred primarily because microwave and RF radiation

Journal of Food Processing & Preservation 12 (1988) 219-241. *All Rights Reserved.*
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have been studied as possible treatments for certain types of cancer. The resulting research has focused on heat deposition patterns in biological tissue, with important contributions being made by Chen (1981); Shapiro *et al.* (1971); Johnson and Guy (1972); Kritikos and Schwan (1975); Kritikos *et al.* (1981); Jaeger (1952) and Shitzer (1975), among others.

There is, however, a clear difference between the effects of microwave absorption in highly self-regulated or homeostatic living bodies and those in foods during processing. At medium to high process temperatures, the generation of heat in food materials is also accompanied by significant moisture migration. This moisture migration, in turn, affects the energy absorption characteristics of the food, thus creating a coupling of heat and mass transport that complicates mathematical analysis.

The literature on RF and microwave processing of food materials reveals an obvious need for models that account for this coupled interaction of heat and mass transport, particularly models that provide energy deposition patterns that may be used for modeling foods and other biological products which require medium to high process temperatures. Several important food-related studies have been undertaken, dealing primarily with the study of complex permittivities (Akyel *et al.* 1983) and dielectric properties (Nelson 1981; Pour-el *et al.* 1981; and Mudgett 1974, to name a few). The information generated by these studies needs to be incorporated, even if only by analogy, to a comprehensive study of the thermal modeling of foods.

The objectives of this study are (1) To review some current approaches to heat and mass transfer analysis of materials in a microwave environment; and (2) To discuss the role of the electric field strength in the modeling of the thermal environment, and present an approach to its determination and mapping for a given microwave cavity.

REVIEW OF SOME ENERGY ABSORPTION MODELS

Three approaches have generally been used in the study of energy deposition in biological tissue exposed to RF or microwave radiation: analysis of the heating potential, analysis of the power absorbed, and solution of the general energy equation. Each of these approaches is briefly discussed below, with some comments on their positive and negative aspects, in relation to thermal modeling of foods.

Modeling by Analysis of Heating Potential

This approach characterizes the mechanism of heating a biological tissue in electromagnetic waves by an analysis of the heating potential (Johnson and Guy 1972; Kritikos and Schwan 1972, 1975; Johnson *et al.* 1975). The heating potential is defined as the rate at which heat is generated in the tissue and is determined by the product of the electrical conductivity of the material and the scalar product of the electric field vector. The resulting equation is represented as

$$\psi = \frac{1}{2}\sigma |E|^2 \tag{1}$$

where variables used in this and all equations are defined in the nomenclature.

The apparent difficulty of using Eq. (1) for food systems is that it only gives an indication of the heating potential, not the amount of energy actually transferred to the biological material. It, therefore, does not provide a direct means of determining the temperature profile in the material. However, if it is known that the electric field is uniformly distributed in the material or if the electric field strength can be mapped, then Eq. (1) can be used to obtain some indication of a limiting mass-averaged temperature of the irradiated body.

Modeling by Measuring Power Absorbed

This approach attempts to calculate the temperature rise of the material by measuring the absorbed power. Walker *et al.* (1976), working on a system for the controlled heating and thawing of small samples, represented the heating rate by the equation

$$\frac{dT}{dt} = \frac{P_a}{m_s C_s + m_c C_c} \tag{2}$$

The authors assumed constant specific heats in the derivation of Eq. (2).

There are two problems encountered in the utilization of Eq. (2) for food systems. By its formulation, the equation assumes that the container and the sample experience the same temperature rise. Since most containers used for microwave heating are designed to absorb as little microwave energy as possible, this assumption is unrealistic, especially in the case of small biological samples.

The second problem is that for most situations, the absorbed power, P_a, cannot be accurately measured. However, when it can be measured, the expression can be used to estimate the change in the mass-averaged temperature.

Checcucci *et al.* (1983) represented the change in temperature experienced by the material as

$$\Delta T = \frac{P_{tr} t}{\rho C V} \tag{3}$$

This equation is, essentially, an integrated form of Eq. (2), if it is assumed that the container absorbs negligible energy. Thus, it is subject to the same limitation in relation to power measurement as the previous model.

Modeling by Solution of the Energy Equation

This approach has provided the most generally applicable models. Ang *et al.* (1977) analyzed the two-dimensional freeze-drying of food products by microwave energy. They found that mass transfer resistance, temperature of the specimen and the absorption of microwave energy were interdependent, thus providing a hint of the coupling of heat and mass transfer phenomena. The equations for heat and mass transfer for the dried layer were

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial T^2}{\partial y^2} + \left(\frac{\partial k_x}{\partial x} - C_p G_x\right)\frac{\partial T}{\partial x} + \left(\frac{\partial k_y}{\partial y} - C_p G_y\right)\frac{\partial T}{\partial y} = \rho C_p \frac{\partial T}{\partial t} - Q_{em} \tag{4}$$

and

$$D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + \frac{\partial D_x}{\partial x}\frac{\partial c}{\partial x} + \frac{\partial D_y}{\partial x}\frac{\partial c}{\partial x} = \phi \frac{\partial c}{\partial t} \tag{5}$$

The heat transfer equation used for the frozen layer was

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + \frac{\partial k_x}{\partial x}\frac{\partial T}{\partial x} + \frac{\partial k_y}{\partial y}\frac{\partial T}{\partial y} += \rho C_p \frac{\partial T}{\partial t} - \frac{P_a}{V} \tag{6}$$

It was assumed that no mass transfer takes place in the frozen layer, since sublimation can be accounted for in the boundary condition. The above approach is, perhaps, the most comprehensive model available in the literature. It is also the only study that specifically incorporates an analysis of mass transfer. The only drawback of the heat transfer model is that it assumes a uniform deposition of microwave energy in the material.

Kritikos and Schwan (1979) analyzed the differential temperature rise in a spherical region simulating a potential hot spot. The heat transfer equation included heat conduction as well as heat convection due to blood flow, and was represented as

$$\rho C \frac{\partial T}{\partial t} = k\nabla^2 T - Q_b + Q_{em} \tag{7}$$

This model assumes an isotropic material with constant density, specific heat and thermal conductivity, and is more limited than the one presented before.

Kritikos *et al.* (1981) used a steady state version of Eq. (7), except that Q_{em} was replaced by $Q_{em}(r)$, thus acknowledging the dependence of microwave energy deposition on the spatial variable.

Bardata (1981), in his analysis of the temperature distribution inside simulated living tissues exposed to time-varying EM radiation and surface cooling, used the equation of conduction in a homogeneous volume:

$$k\nabla^2 T - \rho C \frac{\partial T}{\partial t} - B(T(\bar{x},t) - T_b(\bar{x})) = -Q_m(\bar{x}) - Q_{em}(\bar{x},t) \tag{8}$$

This equation is a special case of the general energy equation. It is arrived at by assuming that the material is isotropic.

THEORETICAL DEVELOPMENT

Heat Transfer

Analysis of a process involving heat and mass transport in biological materials processed at RF and microwave frequencies requires knowledge of the volume heat generation within the biomaterial. The transient energy equation for a stationary biological body, in the absence of a cooling fluid, is

$$\rho C_p \frac{\partial T}{\partial t} + Q_c = \nabla(k\nabla T) + Q_m + Q_{em} \tag{9}$$

Note that each of the above parameters may be a function of space, time and/or temperature. For practically all food processes, the metabolic heat generation, Q_m, is negligible.

For materials in an electromagnetic field, Eq. (9) may be subject to a boundary condition of the fifth kind,

$$k_i \nabla T \quad + \quad h_i T \quad + \quad \rho C_p L_c \frac{\partial T}{\partial t} \quad = \quad f_i(\bar{x},t) \tag{10}$$

and an initial temperature distribution of the form

$$T(\bar{x},t) \quad = \quad F(\bar{x}) \tag{11}$$

The volume heat generation due to electromagnetic sources has a complex functional relationship that may be represented as

$$Q_{em} \quad = \quad Q_{em}(f,E,\kappa'',\mu,T,\bar{x},M) \tag{12}$$

The study of the volume heat generation in food materials due to EM sources has been a difficult undertaking, due primarily to the unavailability (until recently) of instrumentation immune to electromagnetic interference (EMI) and appropriate for medium to high-temperature RF and microwave processing of biological materials (Ofoli 1986).

Mass Transport

The moisture transfer in a generalized biological body may be described by

$$\frac{\partial c}{\partial t} \quad = \quad \nabla(D \nabla c) \tag{13}$$

Representation of the Temperature Profile

During food processing at microwave frequencies, heat generation by metabolic processes is virtually absent, and heat transfer by thermal conduction may be considered negligible in comparison to heat transfer by radiation. Thus Eq. (9) reduces to

$$\rho C_p \frac{\partial T}{\partial t} \quad = \quad Q_{em} \quad - \quad Q_c \tag{14}$$

In the absence of a cooling fluid, the temperature profile in a body subjected to a given rate of microwave energy input may be characterized by

$$\frac{\partial T}{\partial t} = \frac{f_p P_a}{\rho C_p f_w V} \tag{15}$$

In the above expression, P_a is the power absorbed at power level 10, f_p is the fraction of maximum microwave power used, and is computed as the ratio of the power level used to 10. The factor f_w is the water fraction of the material being heated, and ρ and C_p are the density and the specific heat, respectively, of the sample.

Role of the electric field strength in thermal modeling

The power absorbed per unit volume is related to the microwave frequency, dielectric constant of free space, the square of the electric field strength or intensity, and the dielectric loss factor by (Mudgett 1974)

$$\frac{P_a}{V} = f \varepsilon_o E^2 \kappa'' \tag{16}$$

where the usual factor, 2π has been incorporated into the value of the dielectric constant of free space (see nomenclature).

The dielectric loss, the density and the specific heat are generally known to be functions of temperature. Incorporating Eq. (16) into Eq. (15),

$$\frac{\partial T}{\partial t} = \frac{f_p f \varepsilon_o E^2 \kappa''(T)}{f_w \rho(T)\, C_p(T)} \tag{17}$$

As is clear from Eq. (17) the electric field strength is a key parameter in thermal modeling of microwave systems. If it is known, and the variation of ρ, C_p and κ'' with temperature is known, Eq. (17) may be used to obtain an expression for the temperature-time history for the exposed material.

Determination of the Electric Field Strength

In most commercial cavities and in virtually all residential cavities, the electric field strengh is nonuniform, and highly localized. However, in a given cavity at a given power level, repeated experimental runs have shown a fair amount of location consistency as observed through temperature-time history. Since no direct measurement techniques were available to map the field strength, an experimental procedure was set up to obtain the necessary information.

First, Eq. (17) was solved for E^2, obtaining

$$E^2 = \frac{f_w \rho C_p}{f_p f \varepsilon_o \kappa''} \frac{\partial T}{\partial t} \tag{18}$$

Equation (18) provides a means for calculating the electric field strength, given appropriate temperature-time data. The field intensity can be determined by using a material for which the functional expressions for ρ, C_p and κ'' are known.

In this study, water was used because its physical and thermal properties are well-established. The dielectric loss factor, κ'', was modeled on the basis of the data of Von Hippel (1954), over the temperature range $20°C \leq T \leq 100°C$. Even though all experimental runs were made at a frequency of 2.45 GHz in this study, it was felt that this data at 3.0 GHz would provide acceptable results at the lower frequency. The regression equation obtained for the dielectric loss factor, based on this data, is

$$\kappa'' = 20.95\, e^{-0.0225\,T} \tag{19}$$

The correlation coefficient (R^2) for the above equation was determined as 0.99. The plot of the fit is shown in Fig. 1.

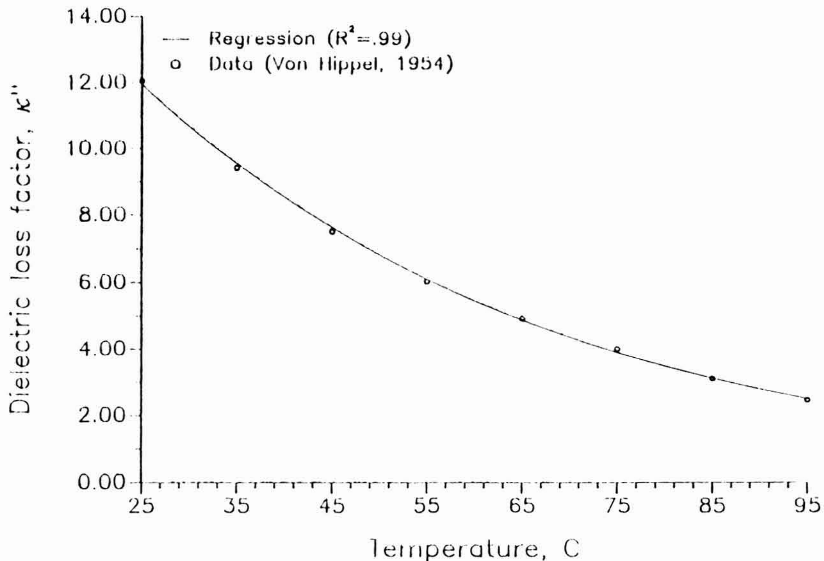

FIG. 1. DIELECTRIC LOSS FACTOR OF WATER AT 3 GHz

The density and specific heat of water as a function of temperature was based on information from Holman (1986). Over the temperature range of concern ($24 \leq T \leq 100°C$), the product of the density of water and the specific heat was

relatively insensitive to temperature: 4164 kJ m^{-3} C^{-1} at 24°C and 4145 kJ m^{-3} C^{-1} at 100°C. An average value of 4154 was used, resulting in a maximum error of 0.24% on the product of those two parameters.

One can approach the exercise of mapping the electric field strength by making three assumptions that appear, on the surface, to be relatively reasonable:

(1) the electric field strength, E, is independent of the temperature of the material being heated;
(2) E is independent of the duration of exposure; and
(3) E is independent of type of material being heated.

The combination of the first two assumptions above and the forms of Eq. (18) and (19) dictate that the temperature gradient must satisfy the equation

$$\frac{dT}{dt} = kT \tag{20}$$

the solution of which is an Arrhenius type relationship

$$T = A\,e^{kt} \tag{21}$$

It is obvious that Eq. (21) does not follow the temperature profile normally observed in materials being heated, therefore the first two assumptions above cannot be true. It is questionable whether assumption 3 holds.

EXPERIMENTAL PROCEDURE

The mapping of the electric field was done for a residential cavity donated by Tappan Corp. All food and other materials exposed to microwave radiation in our laboratory are placed in crystallization dishes, each 10 cm in diameter. To provide for consistency, Luxtron 750 fluoroptic probes were inserted into the crystallization dishes through any specified four of thirteen predrilled holes in a plastic "probe-guide" (Fig. 2), and the plastic guide aligned so as to be in the same position for each experimental run. This experimental procedure was set up to enable the electric field strength to be mapped over the cross-sectional area of the crystallization dishes. A schematic of the total experimental set-up is shown in Fig. 3.

To determine the electric field strength for each of these probe locations, 1 mL of water was heated in a 5 mL test tube (approximately 1cm in diameter) situated at each of the thirteen spots, and the temperature-time history was recorded during microwave exposure with the Luxtron Sensing system.

For each location, the time-temperature data was used to develop a regression equation for T(t). The derivative of the resulting equation was then substituted, along with Eq. (19), into Eq. (18) to obtain the electric field intensity for that location.

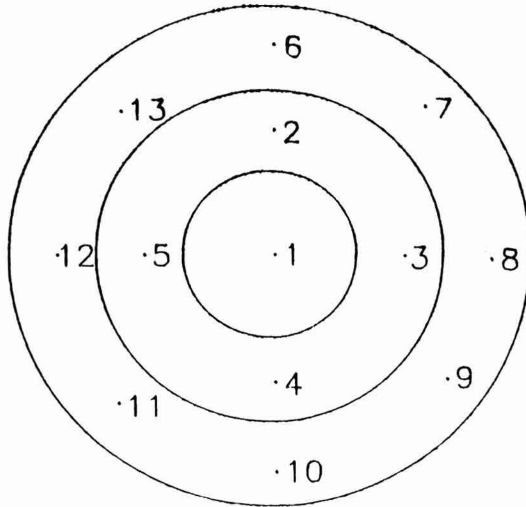

FIG. 2. TOP VIEW OF PLASTIC LID USED TO GUIDE TEMPERATURE PROBES INTO PRE-DETERMINED LOCATIONS.

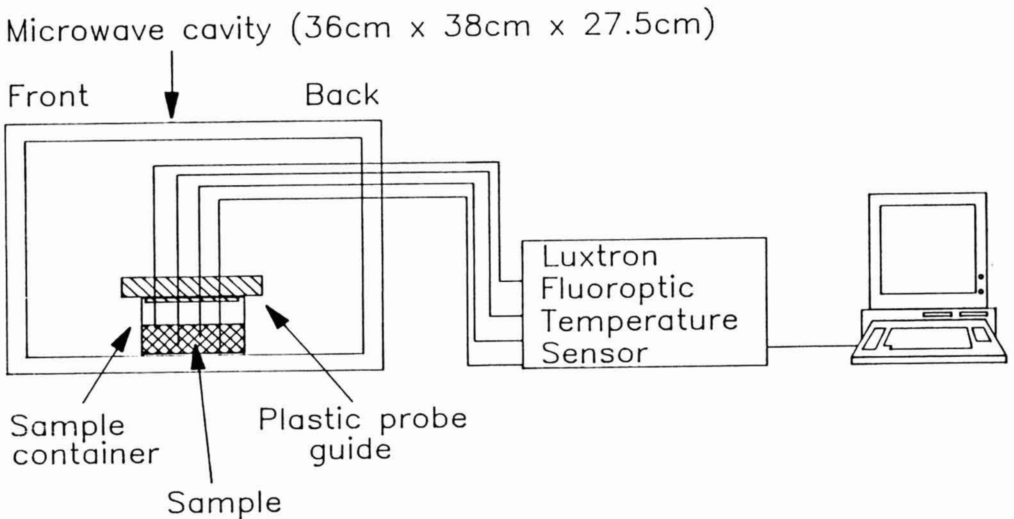

FIG. 3. SCHEMATIC OF EXPERIMENTAL SET-UP

RESULTS AND DISCUSSION

The observed time-temperature history at each of the thirteen locations was regressed according to the general formula:

$$T = T_i + a\,t^b \tag{22}$$

In addition, the average of all the collected data was regressed; the result is given by the following equation

$$T = 25.6 + 5.7\,t^{0.515} \tag{23}$$

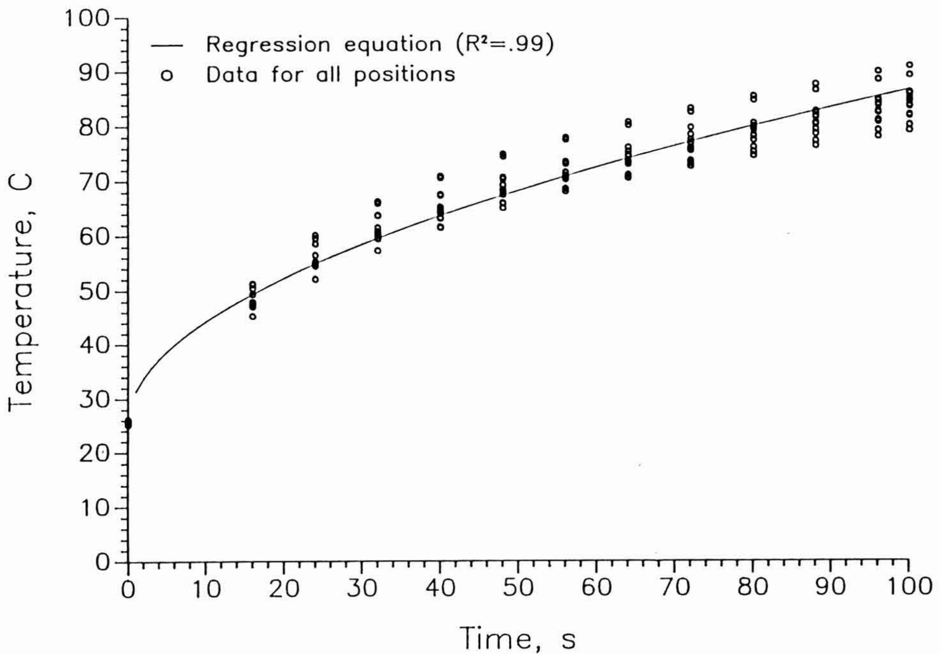

FIG. 4. EQUATION OF AVERAGE TEMPERATURE PROFILE VS. ALL DATA

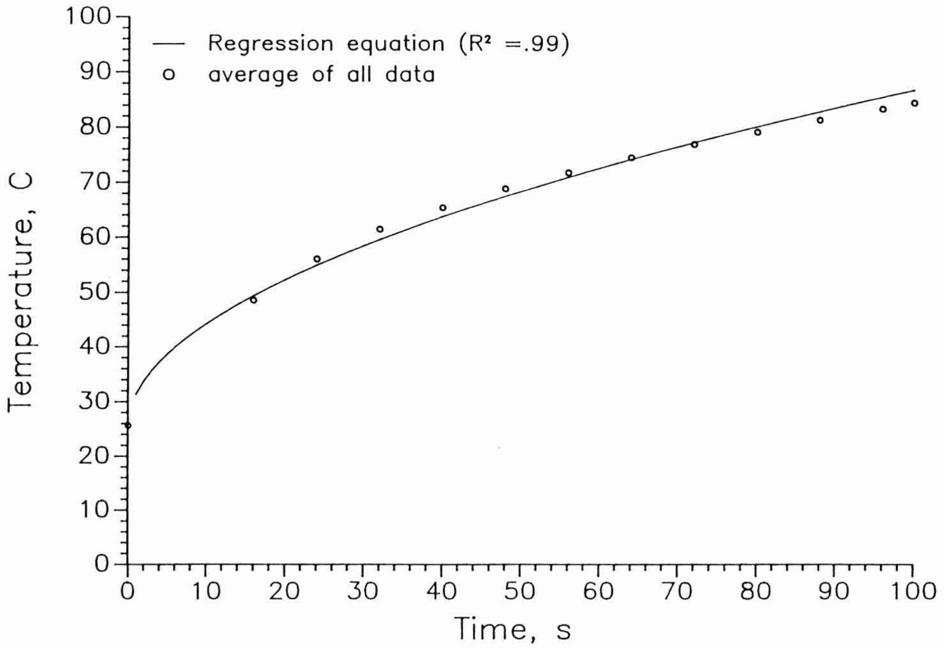

FIG. 5. EQUATION OF AVERAGE TEMPERATURE PROFILE VS. AVERAGE OF ALL DATA

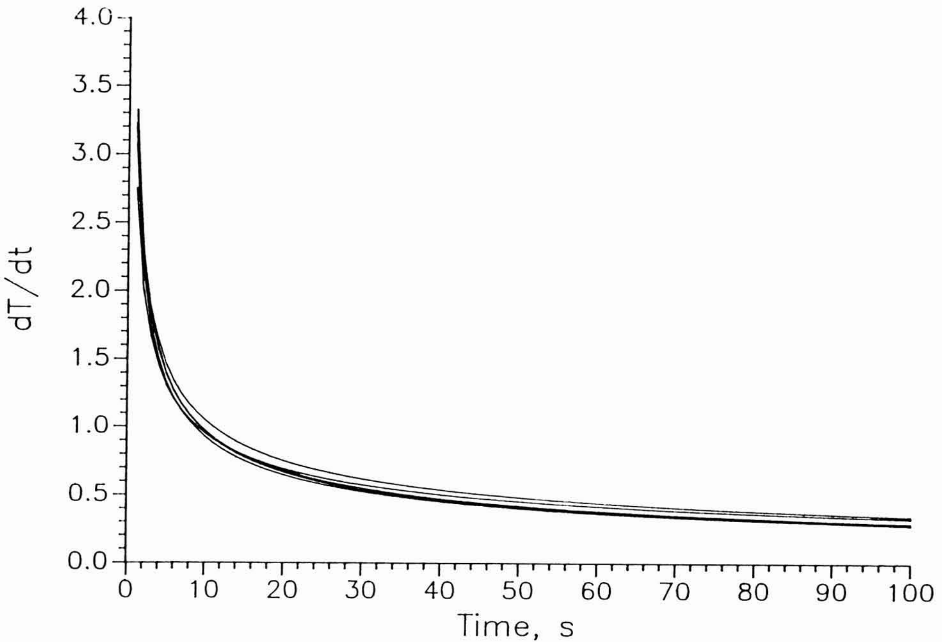

FIG. 6. TIME DERIVATIVES OF THE TEMPERATURE PROFILES AT LOCATIONS 1 THROUGH 5.

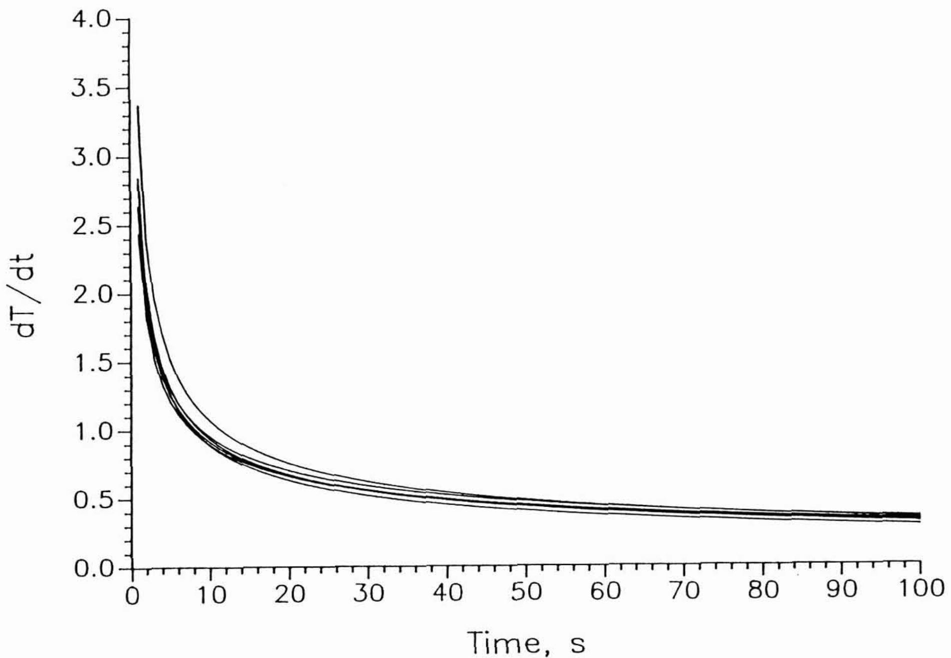

FIG. 7. TIME DERIVATIVES OF THE TEMPERATURE PROFILES AT LOCATIONS 6 THROUGH 12.

When Eq. (23) was plotted against all the collected data, it showed significant scatter (Fig. 4); however, the equation correlates very well with the average data (Fig. 5). In addition, while Fig. 4 shows considerable variation, it must be remembered that the electric field strength depends on the time derivative of the temperature, and not on the temperature itself. When the time derivative of the temperature for each location is plotted against the time derivative of the average temperature profile, there is little significant variation (Fig. 6 and 7). Thus, the equation of the average temperature was used to determine the electric field strength. The final expression for the electric field intensity is

$$E^2 = \frac{f_w \rho C_p}{7.14 f_p f \varepsilon_o} t^{-0.485} e^{0.0225\,T} \tag{24}$$

This expression shows clearly that the field intensity is a function of both temperature and time, confirming the observation made by Lorrain and Corson (1970).

Since T = T(t), E^2 can be reduced to a function of one variable, giving

$$E^2 = \frac{f_w \rho C_p}{7.14 f_p f \varepsilon_o} t^{-0.485} e^{0.0225\left(T_i + at^b\right)} \tag{25}$$

where T_i, a_i and b correspond to Eq. (22).

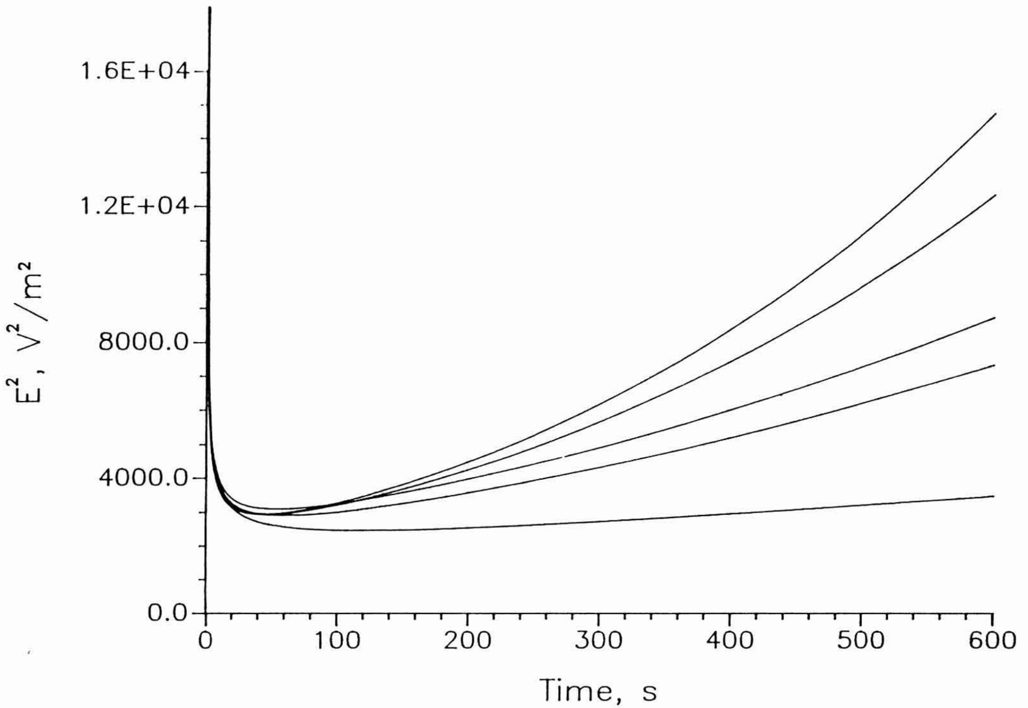

FIG. 8. SQUARE OF THE ELECTRIC FIELD INTENSITY AT VARIOUS LOCATIONS

The plot of Eq. (25) for various locations is shown in Fig. 8. The plot shows clearly that there is substantial spatial variation in the square of the field strength (note the scale on the ordinate).

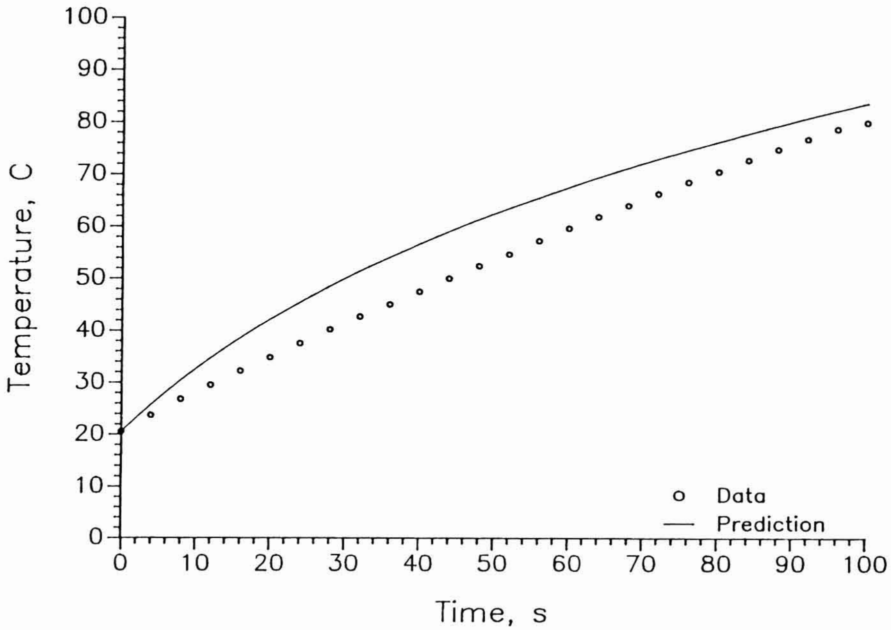

FIG. 9. TIME-TEMPERATURE HISTORY PREDICTION BASED ON EQ. 25 FOR THE ELECTRIC FIELD INTENSITY.

When Eq. (25) (with the parameters of the average temperature) was incorporated into Eq. (17), along with Eq. (19) and the resulting expression used to predict the mass-averaged temperature profile of 200 mL of water exposed to 100 s of microwave radiation, the prediction showed significant variation from the experimental data (Fig. 9), confirming the fact that the electric field intensity is a function of the load.

To correct this situation, the temperature-time data plotted in Fig. 9 was regressed ($R^2 = 0.99$) to obtain

$$T \;=\; 20.5 \;+\; 1.05\, t^{0.88} \tag{26}$$

The above expression was then used to determine a new relationship for the electric field. The resulting equation is

$$E^2 \;=\; \frac{f_w \rho C_p}{22.67 f_p f \varepsilon_o} t^{-0.12}\, e^{0.0225\left(20.5 + 1.05 t^{0.88}\right)} \tag{27}$$

The above equation and Eq. (19) were substituted into Eq. (17) to obtain an expression for the temperature gradient. Because of the form of the relationship for E^2,

the resulting expression, however, requires numerical integration. Since it was considered desirable to obtain an analytical expression for the temperature profile, the data generated by Eq. (27) for E^2 was first regressed to obtain the simpler relationship

$$E^2 = 2000\, t^{-.009} e^{0.01t} \tag{28}$$

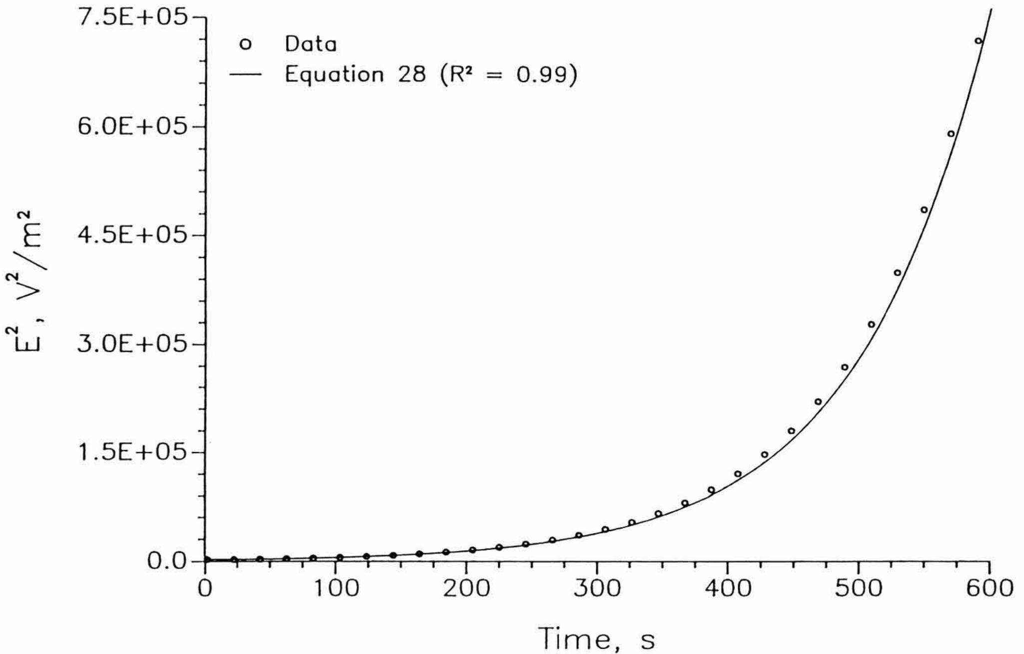

FIG. 10. PROFILE OF THE ELECTRIC FIELD STRENGTH.

This new equation provides an excellent fit (Fig. 10) with a regression coefficient (R^2) of 0.99.

One critical observation can be made about the behavior of the electric field strength in Fig. 10. It is a very strong function of time (and, therefore, temperature) and only relatively constant ($2000 \leq E^2 \leq 5000$) during the first 100 s of microwave exposure. This behavior is also evident in Fig. 8, and is a direct result of the fact that the field strength was obtained from temperature-time history data: as the material gains energy, it requires more work to achieve additional changes of equal magnitude in product temperature.

Combining Eqs. (28) and (19) with Eq. (17) and simplifying, the following is obtained

$$\frac{\partial T}{\partial t} = \frac{4.19 \times 10^4 f_p f \varepsilon_o}{f_w \rho C_p} t^{-0.009} e^{0.01t} e^{-0.0225T} \tag{29}$$

which, upon integration, yields the following expression for the mass-averaged temperature

$$T = 44.4 \ln\left(e^{0.0225T_i} + \frac{942.8 f_p f \varepsilon_o}{f_w \rho C_p} (1.01 t^{0.99} e^{0.01t} - e^{0.01t}(t - 100) - 100) \right) \tag{30}$$

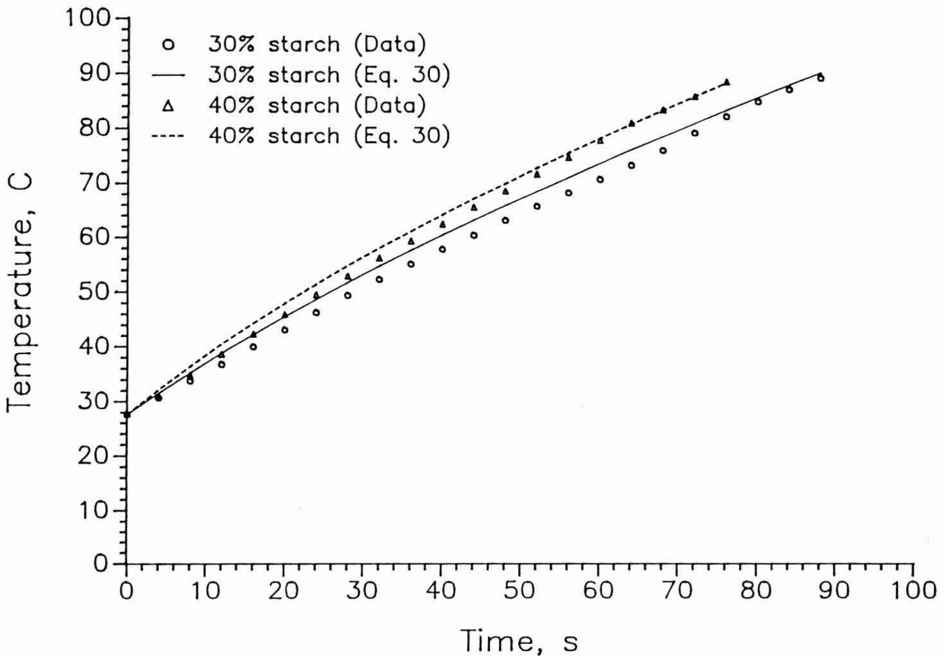

FIG. 11. MASS-AVERAGED TIME-TEMPERATURE PROFILES FOR CORN STARCH AT f_p = 1.0

Eq. (30) was used to model the mass-averaged temperature-time history of several concentrations of corn starch and 20% rice starch solutions at power levels of 5, 8 and 10 (Fig. 11 through 14). The agreement between Eq. (30) and the experimental data was reasonably good at power level 10 for both concentrations (30 and 40%) of corn starch heated (Fig. 11). The agreement between prediction and observation is also very good at power level 8 at concentrations of 20 and 30%, and acceptable at 40% (Fig. 12).

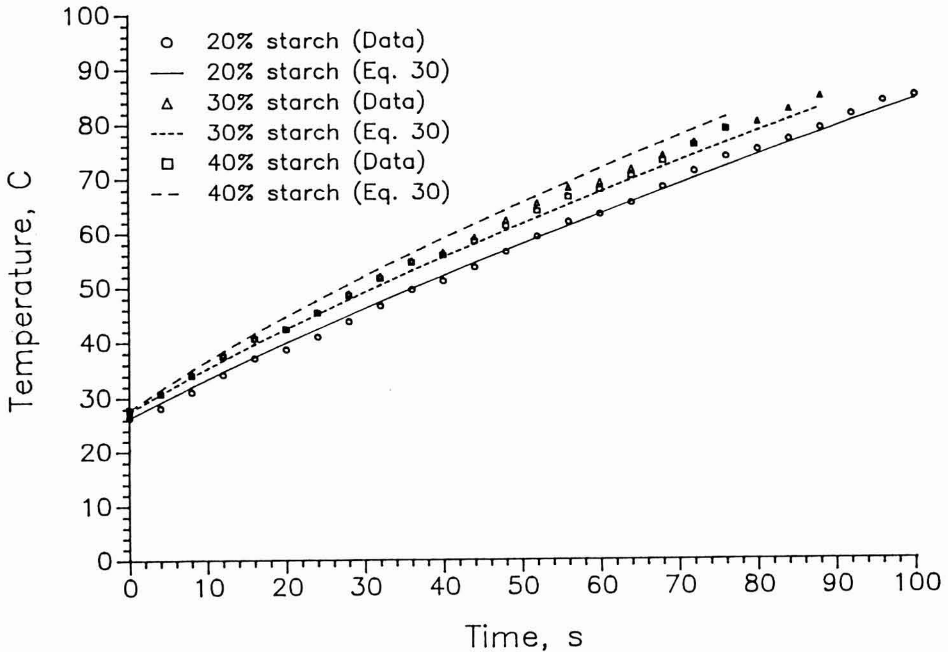

FIG. 12. MASS-AVERAGED TIME-TEMPERATURE PROFILES FOR CORN STARCH AT $f_p = 0.8$

There appears to be a noticeable deviation between the prediction and the experimental data at power level 5 (Fig. 13). However, much of this difference is due to the manner in which microwave radiation is applied at power levels other than full power (level 10). At reduced power levels, instead of radiating the material continuously at a percentage of full power, the energy is deposited at full power for a percentage of the time. For example, at power level 5, the energy deposition is on 50% of the time and off 50% of the time. This leads to the data assuming a "step-wise" temperature-time profile. The pattern is barely discernible at power level 8 (Fig. 12), but quite apparent at power level 5 (Fig. 13).

The model, as is, assumes that a reduced power level is constantly applied to the sample. One can represent f_p by a step function correlated to the "power on, power off" format at each power level to enable the model to mirror the step-wise profiles observed at power levels other than 10; however, it is debatable if this will provide any more meaningful information than what is currently given. The model prediction still has good agreement to the measured profiles. Thus, it is still a useful tool for simulation of the thermal process.

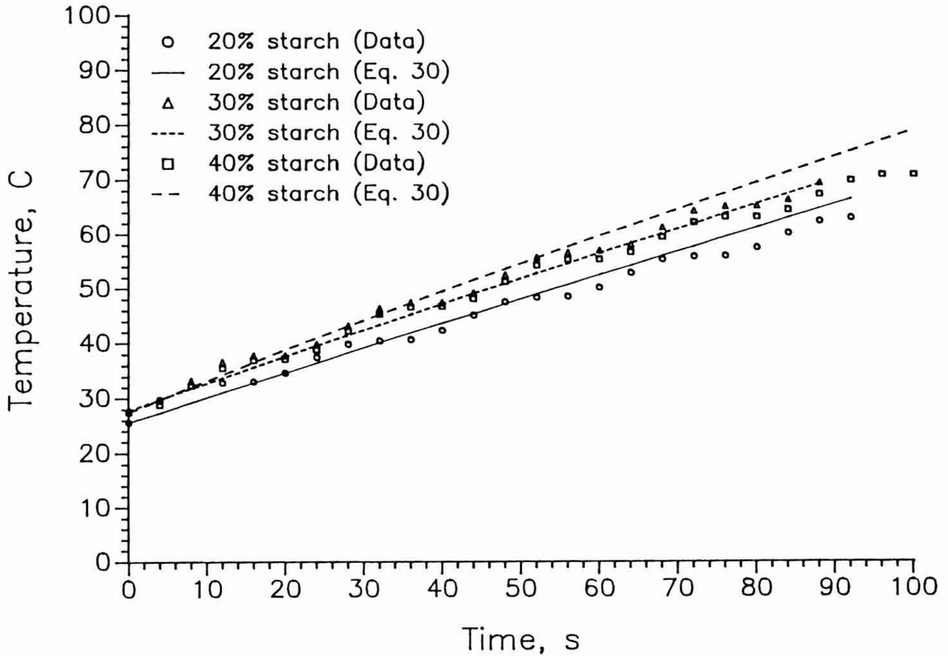

FIG. 13. MASS-AVERAGED TIME-TEMPERATURE PROFILES FOR CORN STARCH AT $f_p = 0.5$

Since the model assumes a continuous energy transfer at 50% of full power, the performance of Eq. (30) at power level 5 for 20 and 30% corn starch concentrations is quite good, although there is a noticeable difference between the prediction and the experimental data at a concentration of 40%. This slight over-prediction was also observed at power level 8 for 40% corn starch (Fig. 12), although not at power level 10 (Fig. 11). In spite of the accuracy at power level 10, however, there is enough evidence to suggest that the model becomes less accurate as dough behavior is approached. This is to be expected since Eq. (30), in its current form, uses the physical, thermal and electromagnetic properties of water.

The model was also used to predict the temperature-time history of a 20% rice starch solution at power levels 5, 8 and 10. The overall performance was good at power level 5, excellent at power level 8, and fair at power level 10, although the prediction got better with duration of heating at this power level (Fig. 14).

Eq. (30) is currently being modified to make it more suitable for modeling low moisture systems, to enable its use for the thermal analysis of doughs.

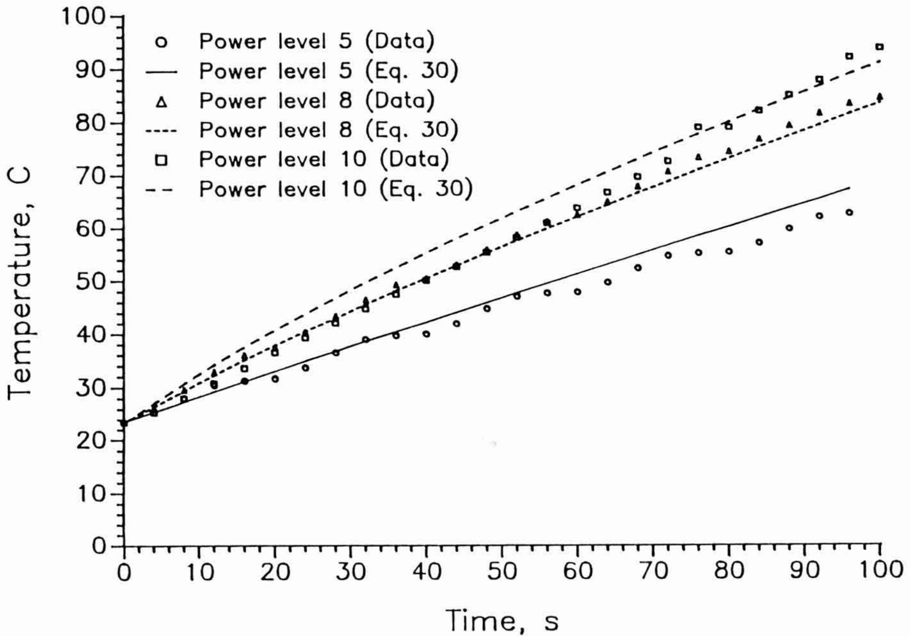

FIG. 14. MASS-AVERAGED TIME-TEMPERATURE PROFILES OF 20% RICE FLOUR AT VARIOUS POWER LEVELS

CONCLUSIONS

A review of several modeling approaches used in the thermal analysis of materials exposed to microwave radiation have been presented, with discussions on their strengths and weaknesses. The importance of the electric field strength or intensity in the thermal modeling of microwave systems has been discussed, and one procedure for its mapping outlined.

An equation to predict the mass-averaged temperature-time history of several concentrations of corn and rice starch solutions exposed to microwave radiation at three power levels (5, 8 and 10) has been derived. The expression shows excellent agreement with experimental data obtained in a Tappan microwave cavity at power levels 5, 8 and 10. The model, however, provides a slightly poorer fit at lower concentrations of moisture. The model is being modified to make it suitable for use in low as well as high moisture systems.

Because of the large number of parameters involved, a purely analytical procedure as presented here is not always practical for modeling microwave systems. An alternate procedure is to use dimensional analysis to establish several practical and physically meaningful dimensionless parameters that can be used for thermal

analysis. The feasibility of using the dimensional analysis procedure in thermal modeling of materials exposed to microwave radiation is explored in a follow-up paper.

Due to the relatively short microwave exposure times, the validity of the derived equation for predicting temperature-time history profiles in situations where there is significant moisture loss from the material, as is typical with most food processes, was not determined. It is necessary to do this in other or follow-up studies to obtain an understanding of the mechanisms associated with the mass transfer. The information obtained from this exercise is necessary for the development of models that would enable *a priori* prediction of required processing times in relation to the thermal and kinetic behavior of food materials. It will also open up avenues for the study of interphase and interfacial phenomena in heterogeneous and composite food systems (pizza, for example), and provide a boost to process engineering, design and control.

NOMENCLATURE

c	mass concentration, kg m^{-3}
C	specific heat, J kg^{-1} C^{-1}
D	mass diffusivity, m^2 s^{-1}
E	electric field strength, V m^{-1}
f	frequency, s^{-1}
f_p	power factor (fraction of max. microwave power), dimensionless
f_w	water fraction, dimensionless
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} C^{-1}
k	thermal conductivity, W $m^{-1}C^{-1}$
K_1	proportionality constant, m^{-1}
L_c	characteristic dimension, m
m	mass, kg
M	moisture content, wet basis, %
P	power, W
Q_b	volumetric heat transport by blood flow, W m^{-3}
Q_c	volumetric heat removal by convected mass, W m^{-3}
Q_{em}	volumetric heat generation from EM sources, W m^{-3}
Q_m	volumetric metabolic heat generation, W m^{-3}
$\bar{r}$	generalized position vector, m
t	time, s
T	temperature, C
V	volume, m^3
x	coordinate orientation, dimensionless
$\bar{x}$	generalized position vector, m
y	coordinate orientation, dimensionless

GREEK LETTERS

α thermal diffusivity, $m^2\ s^{-1}$
ε_0 dielectric constant of free space (5.563×10^{-11}), $F\ m^{-1}$
$\varkappa''$ generalized dielectric loss factor, dimensionless
μ relative permeability, dimensionless
ρ material density, $kg\ m^{-3}$
σ electrical conductivity, $mho\ m^{-1}$
ϕ porosity of the material, dimensionless
ψ heating potential, $W\ m^{-3}$
∇ nabla or del operator

SUBSCRIPTS

a absorbed
b blood
c container
d dry phase
em relating to electromagnetic sources
f frozen phase
i relating to a given species or sample
m relating to metabolic processes
s sample

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FLOW PARAMETERS FOR NON-NEWTONIAN FOODS USING A CO-AXIAL CYLINDER VISCOMETER[1]

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Accepted for Publication June 21, 1988

INTRODUCTION

The measurement of viscosity and flow parameters of fluid foods are an important aspect of the study of the physical properties of such foods (Wood 1968). Many researchers and industry personnel routinely work on viscometric measurements of foods using a concentric cylinder viscometer (Mizrahi and Berk 1972; Charm 1963). An algorithm was developed in this work to facilitate the determination of flow parameters of non-Newtonian foods and to estimate the apparent viscosity from both apparent and true shear rates. The algorithm developed was based on the work of Rao *et al.* (1975) and is suitable for use with microcomputers.

THEORETICAL CONSIDERATIONS

The most common equation in describing the flow of non-Newtonian foods is the power law equation. The equation is:

$$\tau = \tau_o + k \ \dot{\gamma}^{\ n} \qquad [1]$$

where τ is the shear stress, τ_0 is the yield stress, $\dot{\gamma}$ is the rate of shear, k is the coefficient of shear rate and n is the flow behavior index. For a concentric cylinder viscometer the shear stress (τ) is readily obtained from the moment reading (M) as:

$$\tau = M \ / \ 2\pi r^2 h \qquad [2]$$

where r is the radius and h is the height of the bob. Since the fluid is non-Newtonian, the shear rates are not readily evaluated in terms of the known angular velocity, Ω (Krieger and Maron 1954) unless the gap between the cup and bob is very small.

[1]The use of trade names in this publication does not imply endorsement of the products by the authors or the University of Georgia nor criticism of similar ones not mentioned.

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Journal of Food Processing & Preservation 12 (1988) 243-249.

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This has been achieved in very few commercial instruments (Van Wazer *et al.* 1963). One such instrument is the Merrill Brookfield viscometer which has a gap less than 1% of the cup radius. Such an instrument, however, will not handle even moderately coarse suspensions which are common in many foods.

The method employed here for calculating shear rates was a modified form of the equation developed by Krieger and Elrod (1953). The equation for shear rate as derived by Rao *et al.* (1975) can be expressed as:

$$\dot{\gamma} = f(\tau_b - \tau_o) = \frac{\Omega}{\ln s}\left[1 + \ln s \frac{d \ln \Omega}{d \ln (\tau_b - \tau_o)}\right] \quad [3]$$

where s is the ratio of the cup to bob diameter. If $\ln(\tau_b - \tau_0)$ and $\ln \Omega$ are linearly related (which is true for fluids obeying Eq. [1]), a method is presented here to obtain τ_0, k and n without having to find the shear rates. This method should be very useful for non-Newtonian flow problems. There are other direct methods for nonlinear least square fit, but the method presented here is simple and does not involve derivatives or Taylor's series expansions. If $\ln(\tau_b - \tau_0)$ and n are linearly related (which can be verified in this method), Eq. (3) can be written as:

$$\dot{\gamma} = f(\tau) = \lambda\Omega, \quad [4]$$

where

$$\lambda = \left[1 + \ln s \frac{d \ln \Omega}{d \ln(\tau_b - \tau_o)}\right] / \ln s. \quad [5]$$

Hence, Eq. [1] becomes:

$$\tau = \tau_o + k(\lambda \Omega)^n = \tau_o + \beta \Omega^n, \text{ and } \beta = k \lambda^n. \quad [6]$$

Writing Eq. [6] in logarithmic form gives:

$$\ln(\tau - \tau_o) = \ln \beta + n \ln\Omega. \quad [7]$$

Logarithmic transformation of these expressions has been examined by Reiner (1960). The minimum deviation of the sum of squares of logarithms is not necessarily that of the actual relationship (Wylie 1966). However, in the present study this has been considered in evaluating the sum of squares of deviations.

Starting with an initial value of $\tau_0 = 0$

$$\ln\tau = \ln\beta_1 + n_1 \ln\Omega.$$

There exist unique values of β_1 and n_1 which require the deviation sum of squares to be minimum. Having determined β_1 and n_1, the sum of squares of deviations in the original equation can be calculated as:

$$S_1 = \Sigma\ (\tau - \beta_1\Omega^{n_1})^2.$$

The value of τ_0 can be increased (according to the desired accuracy) by X such that:

$$\ln(\tau + X) = \ln\beta_2 + n_2 \ln\Omega.$$

Then,

$$S_2 = \Sigma\ (\tau - X - \beta_2\Omega^{n_2})^2.$$

If $S_2 < S_1$, X is increased again such that:

$$\ln(\tau + 2X) = \ln\beta_3 + n_3 \ln\Omega,$$

and

$$S_3 = \Sigma\ (\tau - 2X - \beta_3\Omega^{n_3})^2.$$

This procedure should go on until $S_{m+1} > S_m$. Hence, the least sum of squares will have been obtained and the parameters β_m and n_m along with $\tau_0 = (m-1)$ X will best fit the equation:

$$\tau = \tau_o + \beta\ \Omega^n.$$

The statistical correlation coefficient and R^2 (% explained variation) can be calculated and used to ascertain the linearity of $\ln(\tau_b - \tau_0)$ vs $\ln(\Omega)$.

The value of k is easily determined from:

$$k = \frac{\beta}{\lambda^n}$$

and, therefore, all the parameters (τ_0, k and n) in Eq. [1] are completely determined. If shear rates are desired, they can be calculated using Eq. [4].

COMPUTER ALGORITHM

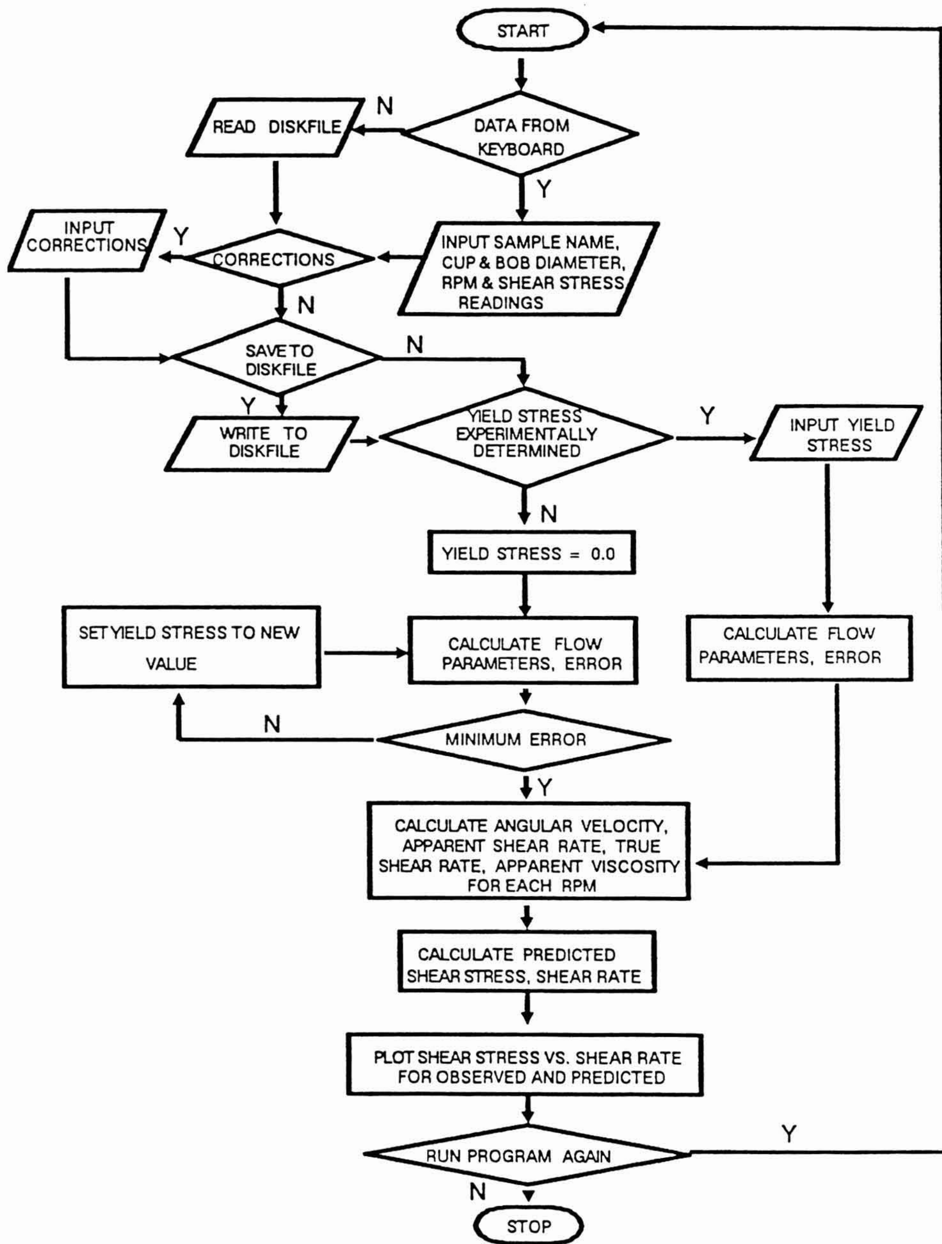

FIG. 1. FLOW CHART FOR THE ALGORITHM FOR DETERMINING FLOW PARAMETERS

Sample: ORANGE-JUICE-CN-2

Yield Stress	Coefficient Beta	PWR N	Res Sum of Sq	R - Square
0.0000	3.5068	0.4252	0.5880	0.9917
1.0000	1.6738	0.9522	46.7916	0.3390
0.1000	3.3757	0.4417	0.4267	0.9940
0.2000	3.2417	0.4600	0.2761	0.9961
0.3000	3.1040	0.4807	0.1489	0.9979
0.4000	2.9618	0.5042	0.0685	0.9990
0.5000	2.8137	0.5316	0.0794	0.9989

Yield Stress	K	N	Res. SS	R-Square
0.4000	0.9903	0.5042	0.0685	0.9990

Press any key to continue ...

FIG. 2. AN EXAMPLE OF THE OUTPUT GENERATED BY THE PROGRAM SHOWING THE ITERATIONS FOR DETERMINING YIELD STRESS

Sample: ORANGE-JUICE-CN-2

RPM	Angular Velocity	Apparent Shear Rate	True Shear Rate	Shear Stress	Apparent Viscosity
0.50	0.0524	0.4163	0.4599	1.0204	2.4515
1.00	0.1047	0.8325	0.9198	1.4300	1.7177
2.50	0.2618	2.0813	2.2994	1.9229	0.9239
5.00	0.5236	4.1626	4.5988	2.5824	0.6204
10.00	1.0472	8.3252	9.1975	3.3737	0.4052
20.00	2.0944	16.6503	18.3950	4.6649	0.2802
50.00	5.2360	41.6259	45.9876	7.0530	0.1694
100.00	10.4720	83.2517	91.9752	10.2324	0.1229

Press any key to view graph ......

FIG. 3. PROGRAM OUTPUT SHOWING TRUE SHEAR RATES AND APPARENT VISCOSITY AT EACH RPM

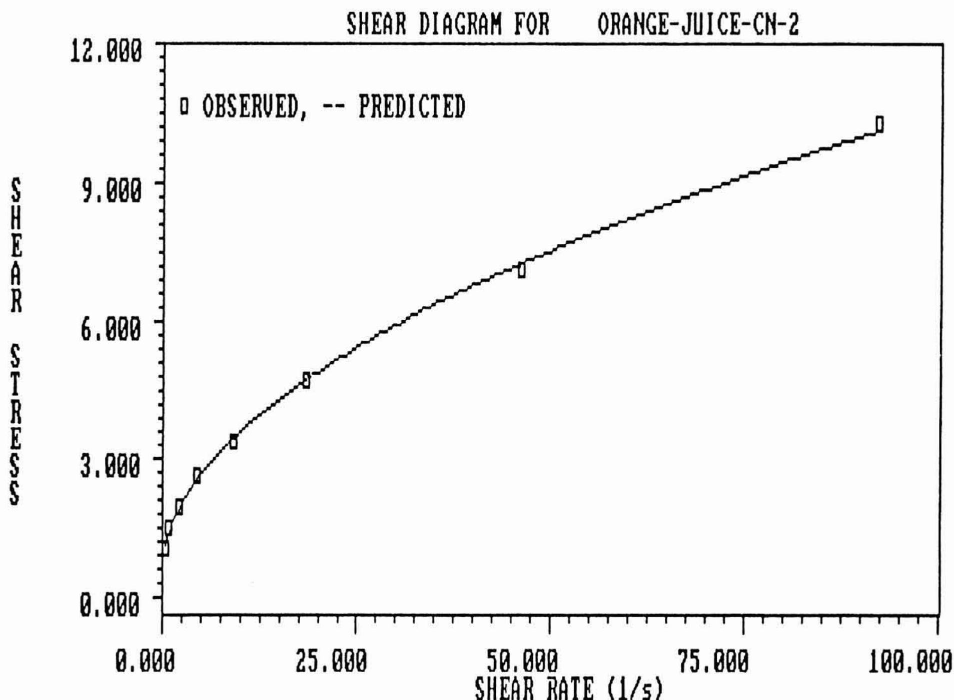

FIG. 4. A COMPUTER GENERATED SHEAR DIAGRAM FOR ORANGE JUICE CONCENTRATE

COMPUTER ALGORITHM

The computer algorithm developed in this work was coded in Turbo Pascal and compiled to machine language code on an IBM personal computer. The program can be accessed directly from the DOS prompt by typing the name of the program. A flow chart illustrating the algorithm is shown in Fig. 1. The program first accepts input of the data for RPM and shear stress, whether from keyboard or diskfile. The user is allowed to review the data, make corrections and save the data to diskfile. The program prompts the user for the yield stress if experimentally determined. If the yield stress was experimentally determined the input value for yield stress is used to calculate the flow parameters. If the yield stress was not experimentally determined the program sets the initial yield stress to 0.0 and asks for the desired accuracy (e) of the yield stress. Using 0.0 as the starting value for yield stress, the program calculates the flow parameters and the associated R^2 for those parameters. The program then recalculates the yield stress value and flow parameters until the best value for yield stress has been obtained, using the R^2 as a criteria. The final adjustments in the recalculation of the yield stress are made in increments of the desired accuracy (e). The best yield stress, k, n, residual sum of squares and R^2

values are shown on the screen along with the previously attempted yield stresses and associated flow parameters. A sample of this output is shown in Fig. 2. Once the flow parameters have been determined the program calculates and displays on the screen the angular velocity, apparent shear rate, true shear rate and apparent viscosity for each RPM (Fig. 3). A prompt is displayed for the user to "Press any key to view graph…", whereupon the program calculates the predicted points for shear stress vs. shear rate. A graph is drawn on the screen which plots both the observed points and the predicted points for shear stress vs shear rate (Fig. 4). The final prompt allows the user to execute the program again if desired.

CONCLUSIONS

The computer program developed in this work has been useful for estimating power law parameters for foods that are non-Newtonian. The program has been successfully tested on several microcomputers including IBM PC/XT, AT and Zenith PC at several universities and research centers. The program and a user manual are available from the authors at the University of Georgia.

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BOOK REVIEW

POSTHARVEST PHYSIOLOGY OF VEGETABLES. (Food Science and Technology Series/24). Edited by J. Weichmann. Marcel Dekker, Inc., 270 Madison Avenue, New York, NY 10016. 1987. 616 pages. $150.00 (U.S. and Canada); $180.00 (All other countries).

As stated in the preface, the book was written to cover the void of information dealing with postharvest physiology of vegetables. The book focuses primarily on physiology rather than postharvest technologies of horticultural crops which have been described elsewhere. The editor has assembled an array of thirty-two international authors to review this diverse field.

The book is organized into six sections which encompasses some thirty-one chapters. The first section has an introductory chapter which describes vegetable classification and definition of the physiological state. The second chapter offers an interesting discussion of biochemical and physiological changes during the time after harvest but prior to postharvest storage.

The next section deals with basic postharvest physiology. Four chapters are devoted to the fundamental areas of respiration and gas exchange, hormonal alterations, membrane changes and transpiration. Although the individual chapters are well organized, the overall section could have been strengthened with additional topics. For example, the fundamental theories of fruit ripening, senescence, maturation, and synthetic and degradative enzymes should have been addressed in this portion rather than in a few brief paragraphs throughout the text.

Part three examines the influences of external factors on postharvest metabolism (eight chapters). The classical environmental factors—temperature, water vapor, oxygen, carbon dioxide and ethylene are discussed. In addition, this section contains two informative chapters on the effects of adding carbon monoxide to controlled atmospheres and of air movements in storage. A chapter on chemical dips (e.g. calcium infiltration) which has received considerable attention in improving vegetable quality would have complemented this section.

The fourth section has six chapters dealing with postharvest diseases and injuries. The topics of chilling injury, frost/freezing injury, host-parasite relationships, bacterial and fungi diseases, and mycotoxins and phytoalexins are presented.

Section five is devoted to postharvest quality changes. Five chapters cover the areas of sensory quality, vitamins, carbohydrates, amino acids and nitrogenous compounds, and minerals. This section would be even stronger if other important quality factors such as softening, lignification, and color changes had been included.

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The last portion consisting of six chapters discusses applied aspects of vegetable postharvest physiology. One chapter is devoted to a brief overview of market preparation methods and shelf-life of vegetables. The remaining chapters cover the storage, general physiology, and storage disorders of pertinent commodities from the Brassica crops, fruit vegetables, root vegetables, and lastly bulbs and tubers. This section should be useful to applied physiologists, horticulturists, and food technologists in integrating physiological principles to extend vegetable quality.

Although the book was designed to provide "comprehensive and complete" information on postharvest physiology of vegetables, the book falls short of this goal. As previously mentioned, some vital areas of postharvest physiology are not presented in depth. As with most books with many contributors, style and quality varies greatly. Despite some of its shortcomings, this book is a welcome addition to the field. This book should prove to be a useful reference for graduate students and researchers in postharvest and food science disciplines.

DAVID JAY FROST

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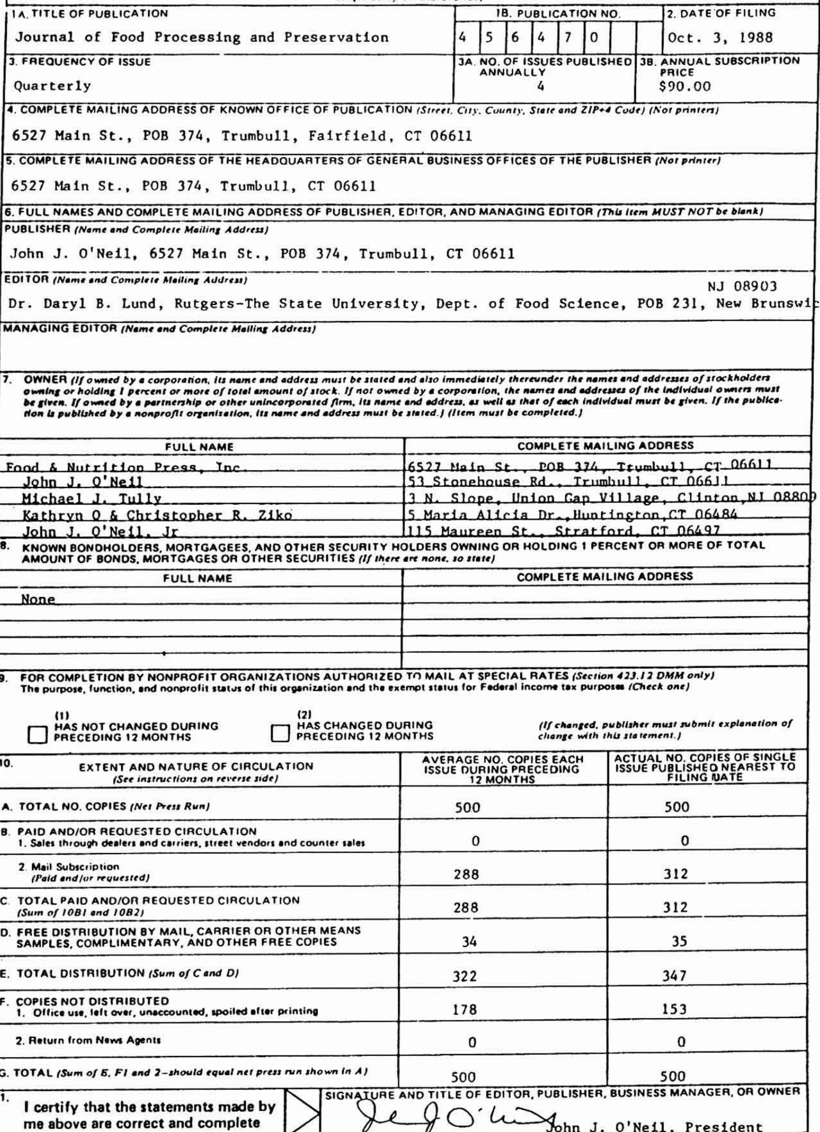

U.S. Postal Service
STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION
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1A. TITLE OF PUBLICATION	1B. PUBLICATION NO.	2. DATE OF FILING
Journal of Food Processing and Preservation	4 5 6 4 7 0	Oct. 3, 1988

3. FREQUENCY OF ISSUE	3A. NO. OF ISSUES PUBLISHED ANNUALLY	3B. ANNUAL SUBSCRIPTION PRICE
Quarterly	4	$90.00

4. COMPLETE MAILING ADDRESS OF KNOWN OFFICE OF PUBLICATION *(Street, City, County, State and ZIP+4 Code) (Not printers)*

6527 Main St., POB 374, Trumbull, Fairfield, CT 06611

5. COMPLETE MAILING ADDRESS OF THE HEADQUARTERS OF GENERAL BUSINESS OFFICES OF THE PUBLISHER *(Not printer)*

6527 Main St., POB 374, Trumbull, CT 06611

6. FULL NAMES AND COMPLETE MAILING ADDRESS OF PUBLISHER, EDITOR, AND MANAGING EDITOR *(This item MUST NOT be blank)*

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JOURNAL OF FOOD PROCESSING AND PRESERVATION VOL. 12, NO. 3

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