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RESEARCH NOTE

THE EFFECT OF HEAT TREATMENTS ON DIETARY FIBER AS ASSESSED BY SCANNING ELECTRON MICROSCOPY

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ABSTRACT

Samples of apple fiber, corn fiber, oat bran, and soy fiber were heat processed in the autoclave and by microwave heat to determine the processing effect on the physical structure of the fiber. Scanning electron microscopy was used to evaluate these processing effects. Results showed the two processing methods yielded fiber that had a much greater surface area, as reflected by increased furrowing and cracking on the surface of the heat treated fiber. The increased surface area exposed to enzymes and microorganisms may influence the physiological role of these fibers in animals.

INTRODUCTION

Dietary fiber is derived from various fiber sources; therefore, it is difficult to draw general conclusions about the physiological characteristics of dietary fiber. It is generally accepted by many nutritionists that dietary fiber plays an important role in human physiological responses (Anderson 1985; Behall *et al.* 1984; Chen *et al.* 1981; Lithell *et al.* 1984). These responses include an increase in fecal bulk, lowering of plasma cholesterol and nutrient bioavailability, and reduced occurrence of constipation and diverticular diseases. Physiological studies in humans have shown that the effects of dietary fiber on a number of diseases can be related to the physical and chemical properties of different compounds (Cummings *et al.* 1978; McConnel *et al.* 1974).

Research has been conducted on various functional properties of fiber, including substitution, water-holding capacity, and oil-holding capacity (Babcock

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1987; Childs and Abajian 1976; Collins and Post 1981; Polizzoto *et al.* 1983). Mongeau and Brassard (1982) found the smaller particle size of wheat bran lowered bile salt binding capacity *in vitro*. This indicates that the physical state of the fiber may be related to its physiological role such as water-holding capacity, binding of organic compounds, or ion exchange capacity, which are all associated with the nutritional characteristics of various fiber sources (Schneeman 1986). Related work by Chang and Morris (1990) showed that the ratio of soluble to insoluble dietary fiber and the total dietary fiber content was effected directly by autoclaving and microwave heat treatment. These chemical changes in the dietary fiber fraction appeared to be dependent upon the type of fiber being processed, i.e., the same heat treatment on different fiber sources did not result in the same quantitative effect on the various dietary fiber fractions. Many studies have compared the relationship of the physiological effects to the content and chemical composition of various dietary fibers (Anderson 1985; Anderson *et al.* 1987; Cummings 1987; Mueller *et al.* 1983; Rasper 1979; Selvendran 1984). The objective of this study was to investigate any structural differences on the surface of the fiber as viewed by scanning electron microscopy that could be attributed to processing.

MATERIALS AND METHODS

The following types of fiber were analyzed in this study: apple fiber (Tastee Apple, Inc., Newcomerstown, OH), dry milled corn fiber (Illinois Cereal Mills, Inc., Paris, IL), oat bran (The Quaker Oats Co., Chicago, IL), and soy fiber (Hi-Pro F300, Grain Processing Co., Muscatine, IA). The processing conditions (Table 1) were autoclaving, which simulated general processing conditions (121°C, 15 min) and general cooking conditions (100°C, 30 min), and microwave heating (700 Watts, 2450 MHz) for 5 and 10 min in an open beaker (Schrumpf and Charley, 1975; Varo *et al.* 1984). Preliminary studies indicated that the fiber could not be microwave heated for extended periods of time without severe burning of the fiber. Consequently, the optimum ratio of water to fiber was determined in preliminary studies by adding water and stirring until well mixed before the microwave heat process. The optimum ratios (w/w) were: apple 4.5:1, corn 3:1, oat 3:1, soy 9:1.

A ground homogeneous vacuum dried sample was used for all analyses. After the processing treatment, the samples were dried at 70°C in a vacuum oven (Precision Scientific Co., Chicago, Illinois) overnight (approximately 12 h). Each sample was ground (Wiley Mill, Emerson Electric, St. Louis, Missouri) through a screen of #40 mesh to ensure homogeneity and uniform particle size. Dried samples were mounted on 12.7 mm specimen mounts; 100Å gold-palladium was evaporated onto samples using a vacuum evaporator (Denton Vacuum DV-

TABLE 1.
PROCESSING CONDITIONS OF PRODUCTS

Treatment	Temperature	Time (min.)
Autoclave[a]	121°C	15
Autoclave[a]	100°C	30
Microwave[b]	(2450 MHz)	5
Microwave[b]	(2450 MHz)	10
Unprocessed		

[a]Castle® Steam Sterilizer.

[b]Sanyo microwave oven, 700 Watts.

515). Samples were observed in an ETEC Autoscan Scanning Electron Microscope using 20 KV accelerating voltage. Photographs were taken with Polaroid Type 55 P/N film at the clearest magnification (apple, 8000X; corn, oat, and soy, 4500X).

RESULTS AND DISCUSSION

Scanning electron micrographs were taken to illustrate the processing effect on the surface of the fiber's microstructure. Figure 1 shows scanning electron micrographs of apple fiber before and after processing. After autoclaving or microwave heat treatment of apple fiber, cracks were observed on the surface of the fiber. It is postulated that the cracks in the fiber source may be attributed to the higher pressure of autoclaving, steam, or dehydration during the microwave heat processing. During processing more surface area appears to develop, as exemplified by the increased furrowing appearance on the fiber. Some cracking differences may be due to the different levels of hydration that was required during heat processing. A similar processing effect on the microstructure of the fiber was observed for corn, oat, and soy fiber (Fig. 2–4). Increased processing produced more cracking and furrowing on the surface of the corn fiber as shown in Fig. 2. Processing resulted in a rougher and more irregular surface in oat bran, but no cracking was observed on the surface of the processed oat bran (Fig. 3). Autoclaving produced more of an irregular surface and more furrowing in the soy fiber (Fig. 4); however, microwave heat treatment produced more

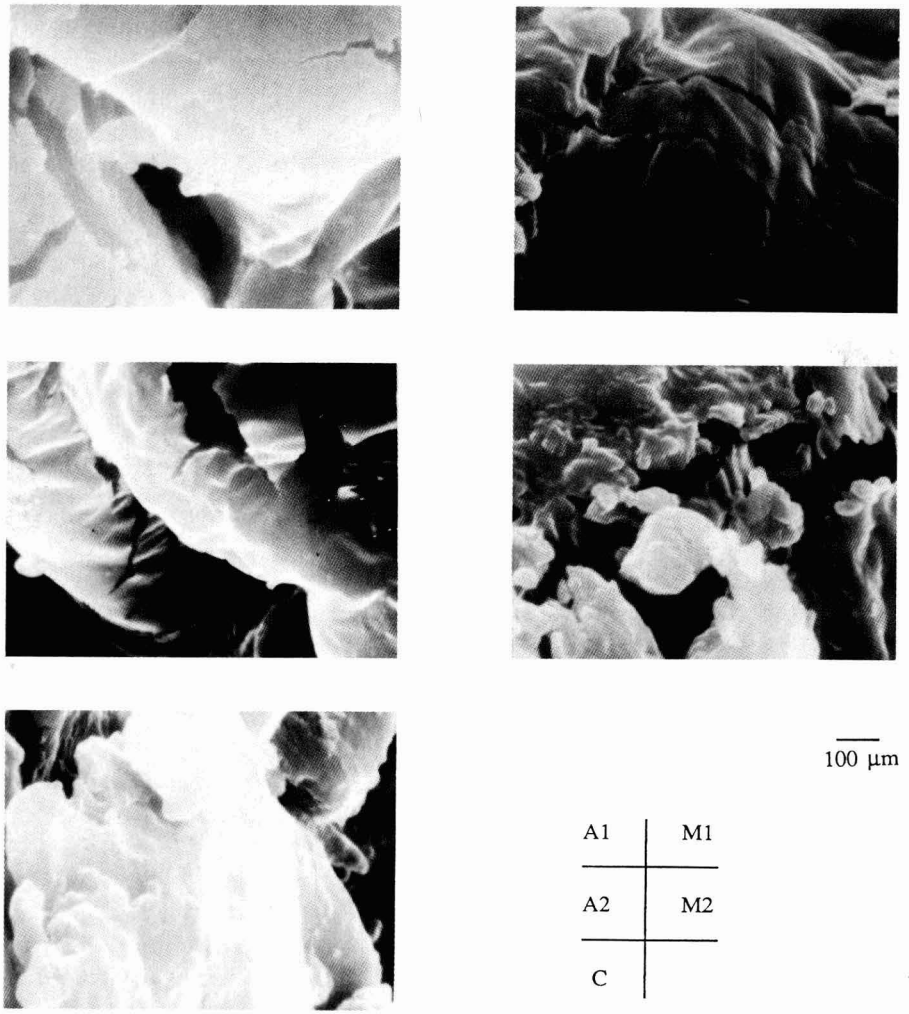

FIG. 1. SCANNING ELECTRON MICROGRAPH OF APPLE FIBER
(8000X) C, control; A1, autoclave 121°C, 15 min; A2, autoclave 100°C, 30 min; M1, microwave 5 min; M2, microwave 10 min.

cracking and irregular surfaces in the soy fiber as viewed in Fig. 4. In general, micrographs of apple, corn, oat, and soy showed increased surface area when the fibers were processed further, as indicated by increased furrowing and more irregular surface. The cracking is macroscopic in nature, while the chemical or physical binding effects are more molecular in nature. The binding, relative to

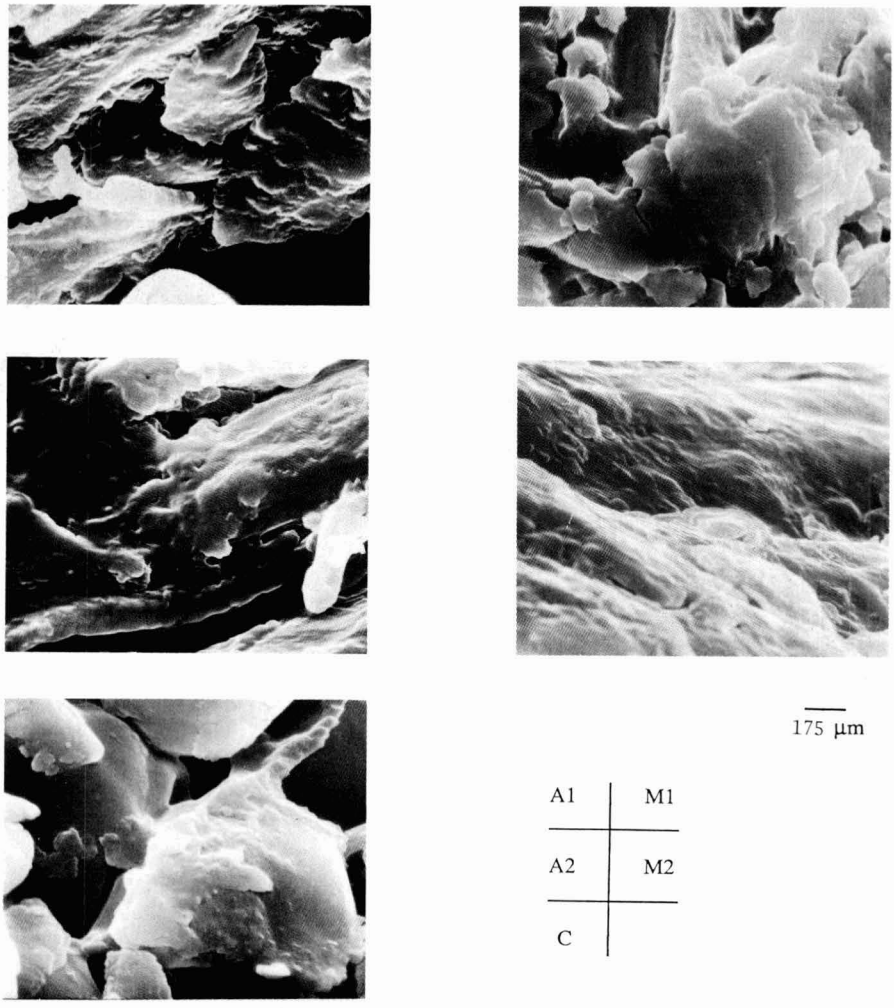

FIG. 2. SCANNING ELECTRON MICROGRAPH OF CORN FIBER
(4500X) C, control; A1, autoclave 121°C, 15 min; A2, autoclave 100°C, 30 min; M1, microwave 5 min; M2, microwave 10 min.

these cracks, depends on the sample porosity and size of pores. Walter and Hoover (1984) demonstrated that upon heat processing sweet potato patties that some cells assumed a wrinkled and crumpled appearance together with cellular separation, but with little cell rupture. These physical changes on the surface of the fiber may have significant physiological implications (i.e., water-holding capacity, bile salt binding, mineral binding, or binding of other organic compounds).

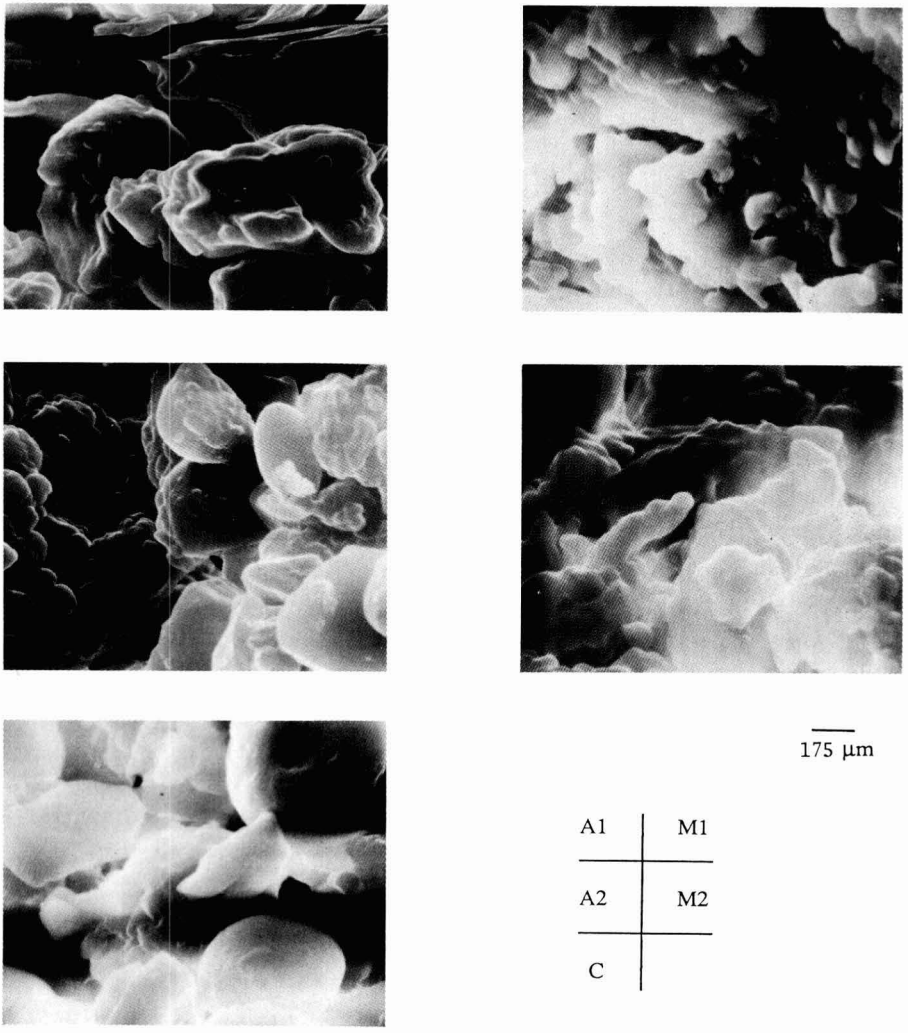

FIG. 3. SCANNING ELECTRON MICROGRAPH OF OAT BRAN (4500X) C, control; A1, autoclave 121°C, 15 min; A2, autoclave 100°C, 30 min; M1, microwave 5 min; M2, microwave 10 min.

CONCLUSIONS

This study was designed to investigate the microstructure of the surface of the fibers in relation to changes during processing by utilizing scanning electron microscopy. The changes in fiber surface structure may be caused by high pressure or dehydration. The processed fibers showed an increase in surface

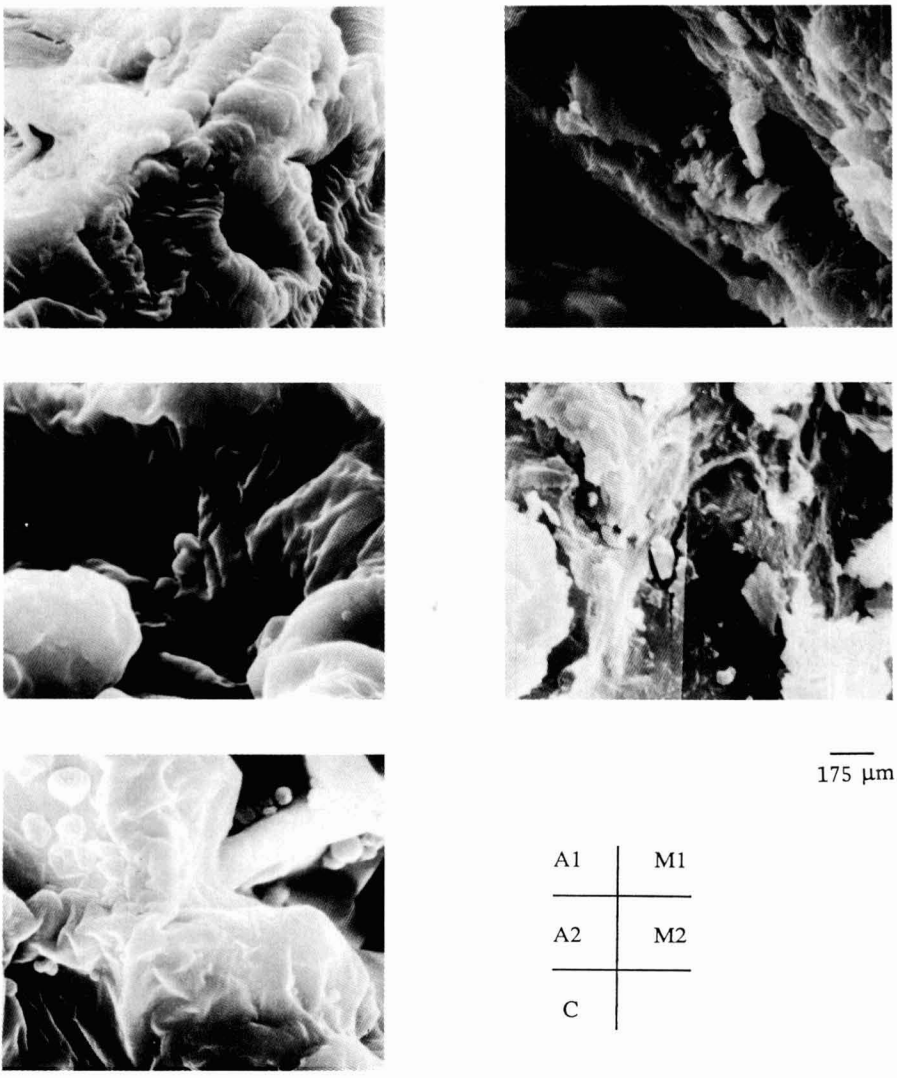

FIG. 4. SCANNING ELECTRON MICROGRAPH OF SOY FIBER
(4500X) C, control; A1, autoclave 121°C, 15 min; A2, autoclave 100°C, 30 min; M1, microwave 5 min; M2, microwave 10 min.

cracking and furrowed appearance, resulting in an increased surface area. It was neither possible to distinguish physical differences between times or temperatures within a specific process nor between the fibers subjected to the microwave heat or autoclave. The greatest morphological differences appear to exist between the nonprocessed fiber and the processed fiber, irrespective of the type or degree of

processing conducted in these trials. Physical and chemical properties are important when those properties are used to predict the physiological effect of fiber. Study of the morphological aspects of the fiber will aid in a better understanding of the complex physico-chemical changes occurring during further processing. The processing of food can change the physical structure of the fiber, and as a result may affect the water-holding capacity, binding of organic compounds, or ion exchange capacity. The change in fiber surface is significant in both autoclaving (mixing without water) and microwave heating (mixing with water). Further physical testing and *in vivo* research is needed to better define the relationship of the physical state of dietary fiber to the physiological effects of processed and unprocessed fibers.

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EFFECT OF RETORT PROCESS TIME ON THE PHYSICAL AND SENSORY QUALITY OF CANNED LOBSTER (*Homarus americanus*) MEAT

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ABSTRACT

Industry has attributed a decline in quality and product sales of canned lobster (Homarus americanus) *meat to a 50% longer retort processing time required by changes in regulations. This study assessed samples of vacuum canned frozen control lobster meat and meat retorted for 28, 35, 40 and 45 min, respectively. Moisture content, expressible moisture (EM) and shear force were determined on claw and tail samples from the various treatments. Concomitantly, samples were evaluated by a trained eight-member quantitative descriptive analysis (QDA) panel for odor, taste, sweetness, saltiness, aftertaste, firmness, chewiness, stringiness, wateriness, springiness, juiciness, inner grey color, inner pink color and overall acceptance. Results show a decrease in moisture content, EM and shear force values with sterilization. In addition, longer operator processing times result in decreased shear force values, increased moisture content and increased EM for both claw and tail muscle. QDA results show increased development of grey color and aftertaste with longer processing time that is congruent with decreased acceptability. These results may reflect microstructural protein damage of the muscle structure and formation of Maillard browning products caused by the excessive cooking at high pressure, temperature, moisture and salt concentration.*

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INTRODUCTION

Preservation of foods to ensure shelf stability requires energy in the form of heat to kill bacteria and inhibit metabolic processes that cause food spoilage, human illness, or death. Crustaceans, such as lobster, are classified as low acid foods (McLay 1982) which require a heat treatment based on pH, can size, absence or presence of can liners, retort temperature, product composition, product pretreatment, can fill, consistency, water activity, heat penetration rate, initial internal temperature and headspace (Dewar and Selfridge 1976; Lopez 1981). Ultimately, the heat treatment is calculated to destruct *Clostridium botulinum* spores in inoculated product for a processing time equivalent to 2.78 min at 250°F or its equivalent at a different temperature. This heat treatment sterilizes the canned product, cooks the food and changes its appearance, texture and chemical nature in a manner that may affect product acceptability (Lund 1975). The current trend to use longer retort processing times for canned lobster (*Homarus americanus*) meat, a product of high commercial value has resulted in a steady decline in product sales (Prince Edward Island Seafood Processing Association 1985; Annual Statistical Review of the Canadian Fisheries 1987; Department of Fisheries and Oceans 1989). The purpose of this study was to assess retort processing parameters to determine the physical and sensory quality of canned lobster muscle as a function of the heat treatment history.

MATERIALS AND METHODS

Heat Penetration Studies

Plants and Retorts. Three lobster processing plants participated in the heat penetration study. Management from these facilities provided a rectangular retort equipped with spreader(s), pressure gauge, mercury thermometer and a temperature chart recorder, an operator and sufficient canned products for the routine operation of the equipment. All operators regularly kept daily process records to monitor the quality and safety of the product.

Can storage and volume within the retort varied with the plant. Plant No. 1 used a large basket to hold the cans in the retort chamber, thereby processing twice as many cans per load compared to Plants No. 2 and 3 which systematically arranged the cans in trays perpendicular to each other on their sides. The parchment lined can size was 307 × 200.25 with a drained weight capacity of 5 oz. lobster meat. Prior to sealing 1–1.5 oz. of brine was added.

Temperature Measurements. Temperature measurements (°F) were made with 3.4 cm needle-type copper-constantan thermocouples (O. F. Ecklund, Inc., Cape Coral, FL) inserted into the cans through a threaded side port so that the tip of the needle was at the geometric center of the can. Output from the ther-

mocouples was recorded on a Westronic (Fort Worth, TX) temperature chart recorder. An average of five thermocouples were used per run with two additional probes monitoring the retort chamber's internal temperature during operation. Cans containing the thermocouples were placed in the center of the large basket (Plant No. 1) or at the geometric center of the retort trays (Plants No. 2 and 3). Measurements were taken at one minute intervals fifteen minutes prior to the introduction of steam into the retort and thereafter continuously until the door of the retort was opened to remove the product. All heat penetration studies on the canned lobster meat were performed in duplicate at the three plant locations.

Heat Penetration Curves and Process Calculations. Heat penetration data from the chart recorder was plotted on inverted three cycle semilogarithmic paper (Lopez 1981). Both time (min) and temperature (°F) at the geometric center of the can was respectively recorded on the x and y-axis. The retort chart recordings and the 'formula' method (Lund 1975; Lopez 1981) were used to calculate the parameter B_B, the time in minutes from the beginning of the process to the end of the heating period. The equations for the calculations were

$$F_i = \log^{-1}\frac{(250 - RT)}{18} \tag{1}$$

$$\log g_{bh} = \log jI - (x_{bh}/f_h) \tag{2}$$

$$f_h/U_{h2} = f_2/(F_oF_i + [r_{bh}(f_2 - f_h)/f_h/U_{bh}]) \tag{3}$$

$$B_B = f_h \log jI + (f_2 - f_h) \log g_{bh} - f_2 \log g_{h2} \tag{4}$$

and

$$P_t = B_B - 0.4\,1 \tag{5}$$

where F_i, RT, g_{bh}, jI, x_{bh}, f_h, U_{h2}, f_2, F_o, r_{bh}, U_{bh}, B_B, and g_{h2} are defined in the Addendum. The processing time after the retort had completely reached steam temperature and appropriate pressure was calculated using Eq. 5.

Physical Analyses

Samples of vacuum canned frozen control lobster meat (cold pack) and meat retorted during regular working hours for either 28, 35, 40 or 45 min (hot pack) were obtained from one plant. Recorder temperature charts were submitted with the sets of samples varying only in the processing time for the treatments. The frozen canned lobster meat used as reference material was processed in a similar fashion but without retorting. Objective measurements of moisture content, EM and Instron shear force values were made to determine processing time and treatment effects on replicate claw and tail samples in comparison with the vacuum canned frozen control lobster meat.

Moisture Content. Moisture content was determined in triplicate on ca. 15 g claw and tail samples placed in aluminum foil dishes (Horowitz 1980). The

samples were dried to constant weight at 110°C in a forced air convection oven, cooled in a desiccator and weighed. The loss in weight was reported as percent moisture.

Expressible Moisture. Expressible moisture was determined using a modification of the procedure of Regenstein and Regenstein (1984). Claw and tail samples were drained for 60 min and 10 g placed between two preweighed 11 cm sheets of Whatman No. 1 filter paper on the test platform of an Instron Universal Testing Machine, Model 1130. The flat compression piston was lowered and adjusted to 17 mm from the platform that held the filter paper containing the lobster meat. Using a 50 kg load cell, the piston was lowered for 30 s to 2.5 mm from the compression plate with the crosshead and chart speed set at 10 cm/min and 20 cm/min, respectively. Samples were carefully removed from the filter paper and the filter paper was weighed. Six replicate analyses of claw and tail muscle were performed and the results were expressed as total filter paper moisture collected divided by the wet weight of the lobster meat as a percent.

Shear Force. Shear force measurements for muscle cohesiveness were determined in replicate on 10 g claw and tail samples using the Instron described in the section on **Expressible Moisture**. The method of Larmond and Petrasovits (1972) was modified to employ a Kramer Shear Compression cell (66 mm × 66 mm) used at diminished capacity (66 mm × 28 mm, 4 blades) by insertion of two aluminum plates as suggested by Bilinski *et al.* (1977) and modified by Gill *et al.* (1979). The Instron was operated with a crosshead speed of 10 cm/min while a recorder speed of 20 cm/min was found convenient. The return gauge was set at 8.35 cm so that the compression cycle terminated just after the blades emerged from the bottom of the test cell. Peak heights were tabulated on the basis of sample weight for ten claw or tail samples of each treatment.

Sensory Analysis

Facilities. Sensory panel screening, selection and training were carried out in the Food Research Laboratory of the Department of Home Economics at Mount Saint Vincent University, Halifax, Nova Scotia. The panel room adjacent to the laboratory had six partitioned booths with pass-throughs and individual lighting. Red lighting was used for all attributes except color and acceptability which were evaluated under Northern daylight white lighting.

Taste Panelist Screening. Sixteen potential panelists were selected from the summer faculty, staff and student population at the university. Panelist selection was based on availability, willingness to evaluate lobster meat for an extended time period and nonallerginicity to the food. Screening sessions followed the procedures of Stone *et al.* (1974) and Szczesniak's (1963) texture evaluation

characteristics for hardness, chewiness, juiciness and moisture. Analysis of the data resulted in selection of 10 panelists consisting of 6 females and 4 males.

Selection of Sensory Attributes. The relevant sensory attributes for the range of lobster claw and tail samples to be analyzed were determined by quantitative descriptive analysis (QDA) (Stone *et al.* 1974). Panelists were provided with three samples of random digit coded vacuum canned frozen control lobster meat and canned lobster meat which had been retorted for 28 and 45 min, respectively. Terms that described the sensory attributes of these samples resulted in 36 parameters that were quantified and clarified by rating them on a scale of 0 to 4 (0 = absent and 4 = extreme). Total scores gave the most characteristic attributes for odor, flavor, texture, color and acceptability to use in the development of the test questionnaire. Panelists were actively involved in the definition of terms and techniques (Szczesniak 1963) to be used in sample evaluation. This information was posted in each panel booth for the duration of the experiment. Panelists gave input into scale design, selection and placement of references (Table 1) on the scale and the choice of an appropriate rinsing agent.

Training of Panelists. Panelists were trained daily during a four week period of time to detect differences in the sensory quality of the canned lobster meat to ensure that (1) they thoroughly understood the terms and procedures to detect the specific sensory attributes; (2) they could accurately quantititate the attributes; and (3) they could replicate analyses. Coded lobster claw or tail samples from several processing times were evaluated in replicate under controlled conditions and results were statistically analyzed to determine panelists' accuracy and reproducibility. Data resulted in the selection of 8 panelists for the experiment.

Sample Preparation and Presentation. The canned retorted samples from the various treatments described in **Physical Analyses** were drained for 30 min and separated into claw, tail and piece meats; only the claw and tail muscle were sensorially evaluated. Sufficient cans were opened from each lot, separated, pooled, thoroughly mixed and served at room temperature in 4 oz. white paper Lily® cups coded with three digit random numbers. Cans of frozen lobster reference meat were defrosted in cold water prior to opening and draining. The eight-member trained sensory panel evaluated the vacuum packed frozen control lobster meat and the canned retorted lobster processed for 28, 35, 40 and 45 min simultaneously with appropriate references (Table 1) for the attributes shown in Table 2. Panelists indicated responses to intensity of the attributes by drawing a vertical line through the horizontal unstructured interval scale (Stone *et al.* 1974) and values were obtained by measuring the distance in cm from the left origin of the scale. A two minute rest was found sufficient for panelist's eyes to adapt to Northern daylight lighting for the determination of inner grey and pink color and overall product acceptability. Both claw and tail lobster meat were evaluated using a randomized balanced block design with replication.

TABLE 1.
ATTRIBUTES, REFERENCES AND DEFINITIONS FOR SENSORY EVALUATION OF LOBSTER (*HOMARUS AMERICANUS*) CLAW AND TAIL MUSCLE

Attribute	Reference	Concentration
Sweet	Sucrose	1.0 % (w/v)
Salty	Sodium chloride (table salt)	0.2 % (w/v)
Sour	Citric acid	0.07 % (w/v)
Bitter	Caffeine	0.03 % (w/v)
Odor	---	---
Taste	---	---
Sweetness	Sucrose	1.5 % (w/v)
Saltiness	Salt	0.3 % (w/v)
Aftertaste	---	---
Firmness	Salami	1 cm^3
Wateriness	Canned potatoes	1 cm^3
Springiness	---	---
Juiciness	Canned potatoes	1 cm^3
Chewiness	All beef hot dog	1 cm^3
Stringiness	Pineapple chunks	Drained for 1 hr, uncut
Inner gray color	Pebble gray card sampler	---
Inner pink color	Shell pink card sampler	---

Attribute	Definition	Scale Range
Hardness	Compress sample between molar teeth and release pressure	Hard candy>carrots>peanuts>cheese
Chewiness	Length of time to prepare sample for swallowing	Toffee>licorice babies>chewy licorice>hot dogs
Juiciness	Increase in free liquids in mouth during mastication	Canned mushrooms>water chestnuts> canned potatoes>raisins>dried apples>shortbread
Moisture	Overall impression of moisture content of sample	Ibid.

TABLE 2.
QDA QUESTIONNAIRE FOR SENSORY EVALUATION OF LOBSTER (*HOMARUS AMERICANUS*) CLAW AND TAIL MUSCLE

Judge # _____ Name_____ Date _____

Instructions: Before you begin, sit down, start clock provided and relax for 2 minutes. This time should allow your eyes to adjust to the red light. Carefully read the instructions on this page and those posted in the panel booth. Please evaluate the samples from left to right in the order presented for the intensity of the labelled attribute. When there is a specified reference for an attribute, please taste the reference sample first, then evaluate the coded sample. Place a vertical line across the horizontal line at the point which best describes the intensity of the attribute in that sample. Please mark the sample code above the vertical line. Thank you. After completing the evaluation of odor, flavor and texture for all samples provided, please switch from red to white light for color evaluation. Allow 2 minutes (use the clock) for your eyes to adjust to the change in color. After you have answered all the questions, return this sheet and the samples.

Sample Codes: _____ _____ _____ _____

ODOR:

Lobster odor — OFF-ODOR — FRESH LOBSTER ODOR

FLAVOR:

Lobster taste — OFF-FLAVOR — FRESH LOBSTER FLAVOR

Sweetness — WEAK — R — STRONG

Saltiness — WEAK — R — STRONG

Aftertaste — WEAK — STRONG

TEXTURE:

Firmness — SOFT — R — HARD

Wateriness — DRY — R — WET

Springiness — SLIGHTLY SPRINGY — VERY SPRINGY

Juiciness — DRY — R — WET

Chewiness — TENDER — R — TOUGH

Stringiness — NON-FIBROUS — R — VERY FIBROUS

Having completed the evaluation of odor, flavor and texture for all four samples, now switch from red to white light for color evaluation. Allow 2 minutes (use the clock) for your eyes to adjust to the change in color.

COLOR:

Inner — WHITE — R — DARK GRAY

Inner — WHITE — R — DEEP PINK

Overall Acceptability — HIGHLY UNACCEPTABLE — HIGHLY ACCEPTABLE

Comments:

Statistical Analyses

The data obtained from the physical and sensory analyses were subjected to appropriate statistical analyses using the Statistical Analysis System (SAS 1985) package on the VAX 11/750 mainframe computer, Mount Saint Vincent University, Halifax, Nova Scotia.

RESULTS AND DISCUSSION

Thermal Processing Time

The derivation of operator processing times is based on the slowest heating point at the geometric center of the parchment lined 307 × 200.25 cans packed with 5 oz. of cooked lobster meat. The mean internal temperature of the cans composed of claw, joint and tail meat ranged between 58.8 to 77.8°F (Table 3). The lowest internal can temperature was below the recommended value of 60°F given in the Department of Fisheries and Oceans guidelines (Dewar and Selfridge 1976). Variations in temperature among the plants, replicates and cans are due to plant operating parameters based on the internal temperature of the lobster meat prior to packaging and the time period from packaging to retort start-up.

A plot of the processing time (B_B), determined using the 'formula' method (Lopez 1981), showed a broken heating curve. Table 3 shows that several cans deviated from the Department of Fisheries and Oceans' accepted process time of 45 min at $F_o = 6$ (Dewar and Selfridge 1976) when values were computed. Mean processing times ranged between 35.6 to 50.3 min at $F_o = 6$ compared with 27.6 to 41.9 min at $F_o = 4$. Operator processing times (P_t) at $F_o = 4$ and $F_o = 6$ respectively, ranged from 24.4 to 45.9 min (Table 3). Linear regression analysis of the data (Table 4) showed a high correlation ($r \geq 0.8$) between the temperature at the center of the can and the length of the processing time. Extrapolated operator processing time data, when corrected for lag time (1), varied inversely with the internal temperature at the geometric center of the can as did processing time in relation to the sterilizing value (F_o). Higher F_o values require a longer processing time. The data suggest that the operator processing time can be reduced from 45 min to 36 min with a lag time of 7–10 min at an acceptable $F_o = 4$ and an initial internal can temperature of 60°F for the coldest can within a production run. Such procedures would still fulfill the Department of Fisheries and Oceans guidelines (Dewar and Selfridge 1976).

Physical Analyses

Lobster Claw and Tail Muscle. The moisture content and EM of the claw muscle (Fig. 1a and 1b) initially decreased with sterilization and then increased with operator processing time whereas Fig. 1c shows shear force decreased with

TABLE 3.
THE COMPUTED PROCESSING AND OPERATOR TIMES FOR THE RETORTED CANNED LOBSTER (*HOMARUS AMERICANUS*) MUSCLE

	Plant No. 1		Plant No. 2		Plant No. 3	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
Initial can temperature (^{o}F)	75.0±1.00	71.7±1.82	76.6±0.39	77.8±1.77	71.3±1.98	58.8±1.00
Processing time (B_B) (min) (F_o=6)	38.0±0.93	39.8±2.05	36.7±4.46	35.6±2.82	40.4±4.61	50.3±0.86
Operator processing time (P_t) (F_o=6)	35.2±0.93	37.0±2.05	33.7±4.64	32.4±2.82	36.4±4.61	45.9±0.86
Processing time (B_B) (min) (F_o=4)	30.0±0.93	29.0±2.05	28.3±4.64	27.6±2.82	32.4±4.61	41.9±0.86
Operator processing time (P_t) (F_o=4)	27.2±0.93	27.8±2.05	25.3±4.64	24.4±2.82	28.4±4.61	37.5±0.86
Number of replicates (n)	3	7	5	5	6	5

TABLE 4.
LINEAR RELATIONSHIP BETWEEN INTERNAL CAN TEMPERATURE AND PROCESSING TIME (n = 31)

$F_o = 6$	$F_o = 4$
$B_B = 92.6 - 0.73 \times Temp^1$	$B_B = 83.5 - 0.72 \times Temp$
$r = 0.83$	$r = 0.83$
$P_t = 83.9 - 0.65 \times Temp$	$P_t = 75.0 - 0.65 \times Temp$
$r = 0.80$	$r = 0.80$

[1]Coldest internal can temperature.

processing time, an indication of increased muscle softening. Similar observations were reported by Chia *et al.* (1983) and Ma *et al.* (1983) for canned shrimp and Warne and Brown (1982) for canned abalone. Nevertheless, there was no difference ($p \leq 0.05$) in moisture content among the five heat processing treatments but the cold pack lobster meat exhibited higher ($p \leq 0.05$) EM and shear force values. The correlation coefficients for the three physical parameters analyzed in relation to length of processing time for the claw muscle (Table 5) show EM and shear force highly correlated ($p \leq 0.001$) with processing time.

Unlike the claw muscle, moisture content of the lobster tail muscle (Fig. 1a) differed ($p \leq 0.05$) among the treatment means. The mean moisture content, EM and shear force values for the cold pack lobster tail muscle are higher ($p \leq 0.05$) than those of the hot pack treatments. The data also show lower ($p \leq 0.05$) EM values for the 28 and 35 min compared to the 40 and 45 min hot pack treatments although the moisture content of the 45 min hot pack lobster tail muscle did not differ ($p \leq 0.05$) from the cold pack treatment. Similar to the claw muscle, EM and shear force values on the tail muscle correlated ($p \leq 0.0001$) with processing time (Table 5). In addition, tail muscle EM correlated ($p \leq 0.05$) with both moisture content and shear force. Figures 1a and 1b show bidirectional curves for moisture content and EM at 28 and 35 min of processing time. Furthermore, as found for the claw muscle, shear force values on the tail muscle continuously decreased as processing time increased.

Table 6 compares the mean physical data values for claw and tail muscle. Claw muscle was higher ($p \leq 0.05$) than tail muscle both in moisture content and EM whereas the latter exhibited higher ($p \leq 0.05$) shear force due to the striated muscle structure. These observations can be related to the initial differences in the values for the cold pack samples. Stroud and Dalgarno's (1982)

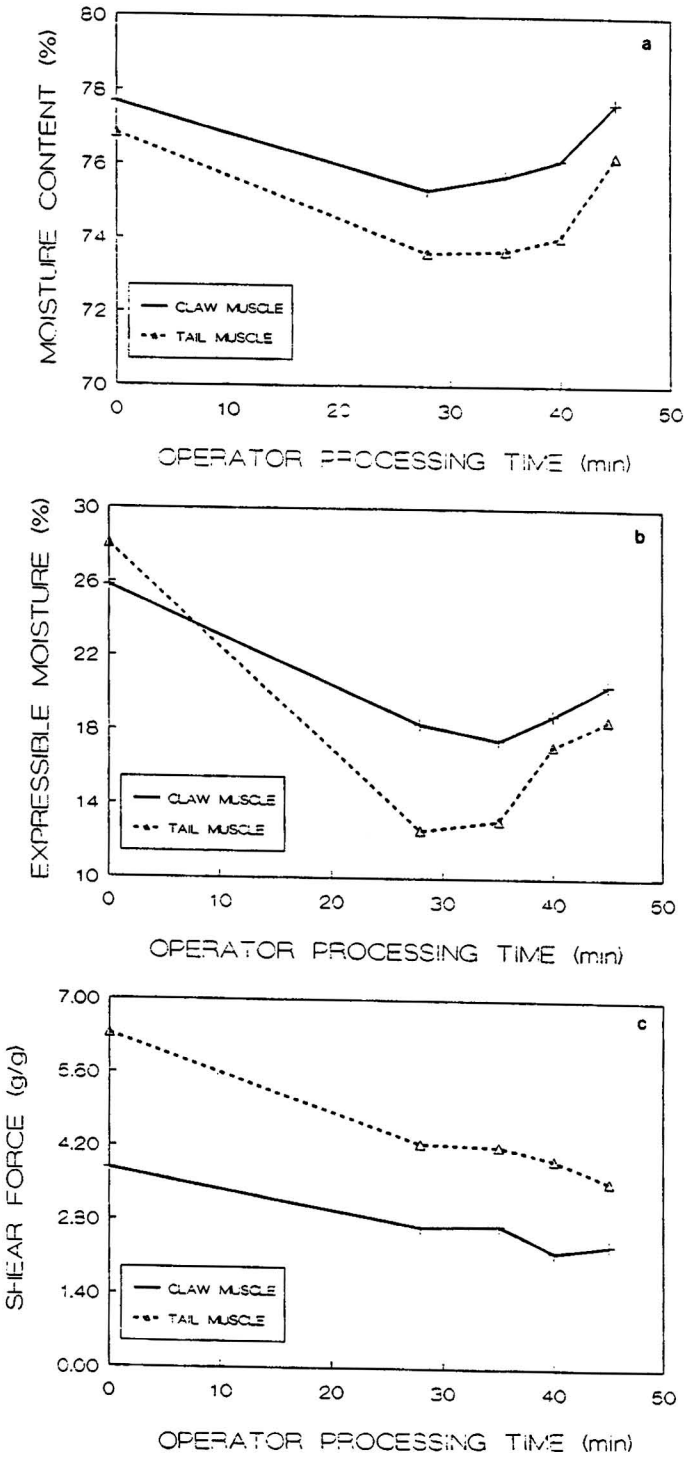

FIG. 1. MOISTURE CONTENT, EXPRESSIBLE MOISTURE AND SHEAR FORCE OF LOBSTER (*HOMARUS AMERICANUS*) CLAW AND TAIL MUSCLE SUBJECTED TO THE VARIOUS PROCESSING TIMES

TABLE 5.
CORRELATION MATRIX FOR PHYSICAL ANALYSES OF LOBSTER (*HOMARUS AMERICANUS*) CLAW AND TAIL MUSCLE [1]

CLAW MUSCLE	Time	Moisture content	Expressible moisture	Shear force
Time	1.000	-0.240 15	-0.611*** 28	-0.722**** 28
Moisture content		1.000	0.490 15	0.377 15
Expressible moisture			1.000	0.317 28
Shear force				1.000

TAIL MUSCLE	Time	Moisture content	Expressible moisture	Shear force
Time	1.000	-0.422 15	-0.680**** 30	-0.759**** 46
Moisture content		1.000	0.607* 15	0.467** 30
Expressible moisture			1.000	0.212 15
Shear force				1.000

[1] * Values significant at $p \leq 0.05$; ** Values significant at $p \leq 0.01$; *** Values significant at $p \leq 0.001$; **** Values significant at $p \leq 0.0001$.

TABLE 6.
MEANS AND STANDARD DEVIATIONS FOR PHYSICAL ANALYSES OF LOBSTER (*HOMARUS AMERICANUS*) CLAW AND TAIL MUSCLE [1]

Variable	Claw muscle	Tail muscle
Moisture content	76.49±1.28a	74.90±1.54b
Expressible moisture	20.03±3.70a	17.91±5.96b
Shear force	2.69±0.68b	4.50±1.33a

[1]Values in the same row with the same letter are not significantly different ($p \leq 0.05$).

findings on both wild and farmed lobster (*Homarus gammarus*) support those presently shown for moisture content of claw and tail muscle. These authors also found that tail muscle contained higher total nitrogen, protein and fat but lower glycogen when compared to claw muscle whereas nonprotein nitrogen content was similar. In addition, claw muscle contains a substantial amount of nonstriated tissue that is higher in lipid (Dyer and Horne 1953) which may contribute to its softening or tenderness. Filament length and cross-sectional density (Hayes *et al.* 1971) may account for the shear force differences observed between claw and tail muscle. Decreases in moisture content, EM and shear force between the cold and hot pack product are caused by the high processing temperature and pressure for sterilization. However, increased operator processing times at high pressure cause resorption of water by diffusion.

It is noteworthy that increased darkening of the pickle was evident with longer operator processing times. Such color changes in the pickle may be due to a decrease in both free glucose and glucose-6-phosphate which reacts nonenzymatically with amino acids to form Maillaird browning products (Taguchi *et al.* 1982a, b; Tanaka *et al.* 1983; Tanaka *et al.* 1985; Tanaka and Taguchi 1985; Tanaka and Kimura 1988).

Sensory Analyses

Lobster Claw and Tail Muscle. The results from the QDA questionnaires for the various sensory attributes were analyzed by two-way analysis of variance with replication. No difference ($p \leq 0.05$) was observed between judges and replicates for the claw muscle samples nor for the sensory attributes of saltiness, aftertaste, chewiness, stringiness and springiness for the five treatments. Figure 2 shows the changes in the various sensory attributes with processing time. Claw muscle odor (Fig. 2a) parallelled the physical changes in shear force as operator processing time increased. Claw muscle taste, sweetness and saltiness (Fig. 2a) initially decreased and may be explained as volatile losses from the muscle to the pickle and decreases of glucose to form Maillard browning byproducts during

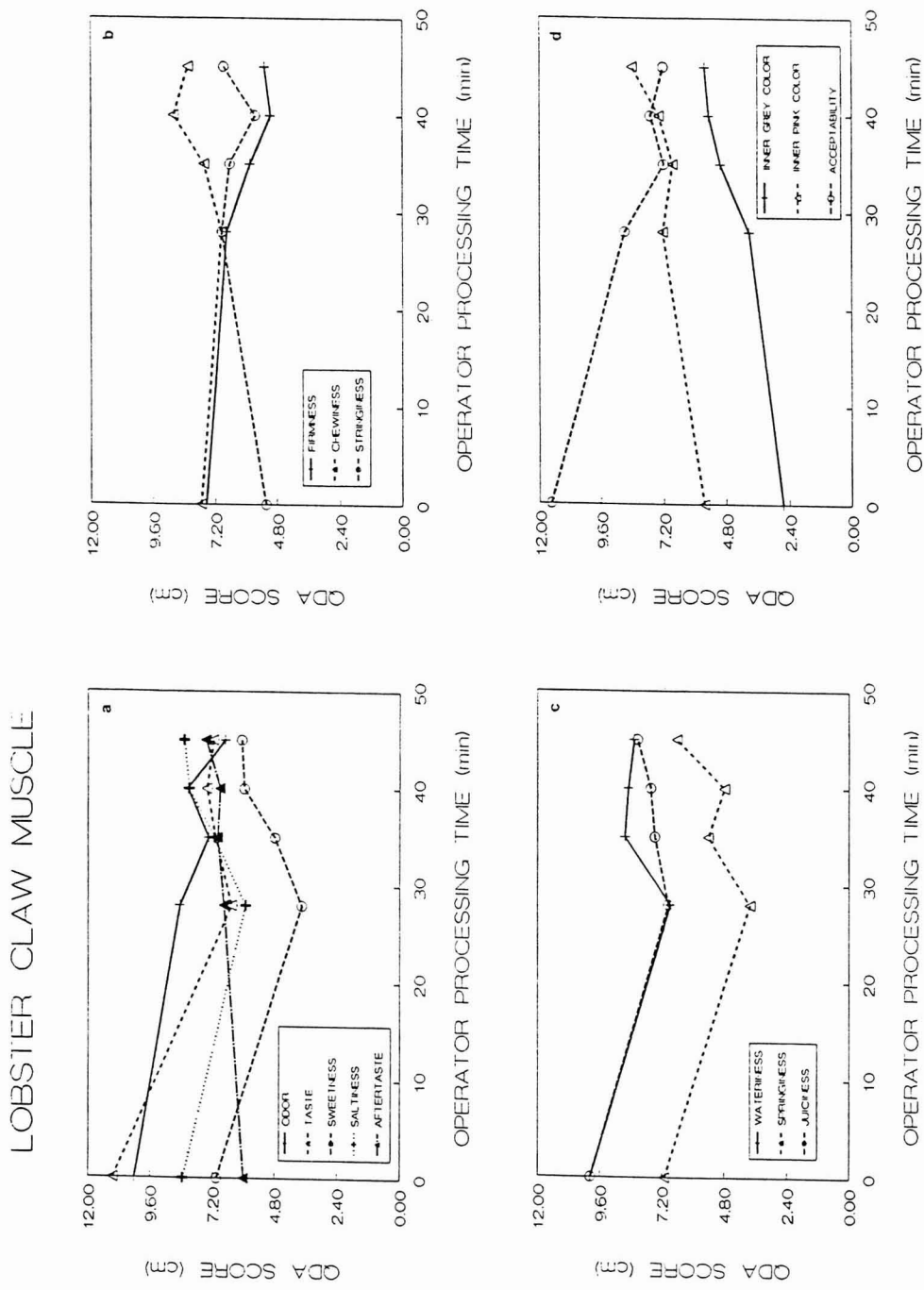

FIG. 2. SENSORY ODOR, TASTE, SWEETNESS, SALTINESS, AFTERTASTE, FIRMNESS, CHEWINESS, STRINGINESS, WATERINESS, SPRINGINESS, JUICINESS, INNER GREY COLOR, INNER PINK COLOR AND ACCEPTABILITY OF LOBSTER (*HOMARUS AMERICANUS*) CLAW MUSCLE SUBJECTED TO THE VARIOUS PROCESSING TIMES

sterilization. This pattern reversed coincident with the physical changes in moisture content and EM (Fig. 1a and 1b). Unlike the other sensory attributes evaluated, aftertaste (Fig. 2a), chewiness and stringiness (Fig. 2b) exhibited increased intensity with longer processing times. Decreased firmness (Fig. 2b) of the claw muscle parallelled shear force (Fig. 1c). As well, the textural attributes of wateriness, springiness and juiciness (Fig. 2c) initially decreased but the pattern of change was congruent with increases in the physical parameters of moisture content and EM for the various operator processing times. Evaluation of the inner pink and inner grey color intensity (Fig. 2d) parallelled the changes in aftertaste. Furthermore, acceptability (Fig. 2d) decreased with longer processing times. Changes in saltiness and springiness may have been caused by protein denaturation concomitant with loss of moisture and salt from the muscle tissue during thermal processing.

It is noteworthy that none of the four retort processing times resulted in a difference ($p \leq 0.05$) among any of the sensory attributes evaluated. However, the attributes of taste, juiciness and acceptability of the cold pack claw muscle were rated higher ($p \leq 0.05$) than those for any of the retorted products and a large difference was apparent between the cold pack and the 28 min samples. The sterilization process results in increased pressure during heating. This can extend the temperature for the deactivation of proteases (Kurth 1986) responsible for adverse flavor and texture changes caused by protein hydrolysis. Other researchers have reported the formation of bitter peptides (Martens *et al.* 1982), loss of glucose and formation of Maillard browning byproducts (Taguchi *et al.* 1982a, b; Tanaka *et al.* 1983; Tanaka *et al.* 1985; Tanaka and Taguchi 1985; Tanaka and Kimura 1988) and changes in flavor nucleotides during thermal processing (Nguyen and Sporns 1985).

Table 7 presents the claw muscle correlation matrix for the sensory attributes evaluated. Length of processing time was negatively correlated ($p \leq 0.05$) with odor, taste, wateriness, juiciness and overall acceptability and positively correlated ($p \leq 0.05$) with inner grey color. Furthermore, acceptability was negatively correlated ($p \leq 0.01$) with inner grey color and positively correlated ($p \leq 0.05$) with odor, taste, sweetness, saltiness, wateriness and juiciness. Odor positively correlated ($p \leq 0.001$) with taste, sweetness, saltiness, wateriness and juiciness but negatively ($p \leq 0.001$) with inner grey color. Taste also showed high correlations ($p \leq 0.0001$) with the attributes of sweetness, saltiness, wateriness and juiciness but lower correlations ($p \leq 0.05$) with chewiness and inner pink color. The negative sensory attribute of aftertaste correlated ($p \leq 0.05$) positively with changes in saltiness, firmness and chewiness.

Similar to the sensory claw muscle results, no difference ($p \leq 0.05$) was found between judges and replicates for the lobster tail muscle samples nor for the sensory attributes of odor, sweetness, aftertaste, chewiness and inner pink color for the five retort treatments. Figure 3 shows the changes in the various

TABLE 7.
CORRELATION MATRIX FOR SENSORY ANALYSES OF LOBSTER (*HOMARUS AMERICANUS*) CLAW MUSCLE, n = 116 [1]

	Time	Odor	Taste	Sweetness	Saltiness	Aftertaste	Firmness	Wateriness	Springiness	Juiciness	Chewiness	Stringiness	Inner gray color	Inner pink color	Overall acceptability
Time	1.000	-0.334 ***	-0.304 **	-0.098	-0.032	0.038	-0.141	-0.354 ***	-0.148	-0.395 ***	-0.023	0.101	0.467 ****	0.100	-0.434 ****
Odor		1.000	0.653 ****	0.483 ****	0.394 ***	0.009	0.190	0.412 ****	0.159	0.434 ****	0.163	-0.053	-0.348 ***	0.152	0.712 ****
Taste			1.000	0.622 ****	0.460 ****	0.128	0.122	0.538 ****	0.158	0.550 ****	0.216 *	-0.160	-0.157	0.239 *	0.805 ****
Sweetness				1.000	0.518 ****	0.091	-0.043	0.340 **	0.212 *	0.288 **	0.105	-0.094	-0.029	0.008	0.620 ****
Saltiness					1.000.	0.280 **	0.139	0.378 ***	0.163	0.404 ****	0.277 **	-0.227 *	-0.150	0.285 **	0.445 ****
Aftertaste						1.000	0.341 ***	-0.019	0.081	0.047	0.220 *	0.079	0.029	0.062	0.167
Firmness							1.000	0.270 *	0.043	0.310 **	0.499 ****	0.155	0.083	0.134	0.132
Wateriness								1.000	0.310 **	0.745 ****	0.380 ***	-0.106	-0.367 ***	0.096	0.495 ****
Springiness									1.000	0.206 *	0.259 *	0.192	-0.183	0.066	0.181
Juiciness										1.000	0.303 **	-0.251 *	-0.353 ***	0.143	0.511 ****
Chewiness											1.000	0.403 ****	0.016	-0.017	0.155
Stringiness												1.000	0.250 *	-0.113	-0.073
Inner gray color													1.000	0.109	-0.330 **
Inner pink color														1.000	0.006
Overall acceptability															1.000

[1] * Values significant at $p \leq 0.05$; ** Values significant at $p \leq 0.01$; *** Values significant at $p \leq 0.001$; **** Values significant at $p \leq 0.0001$.

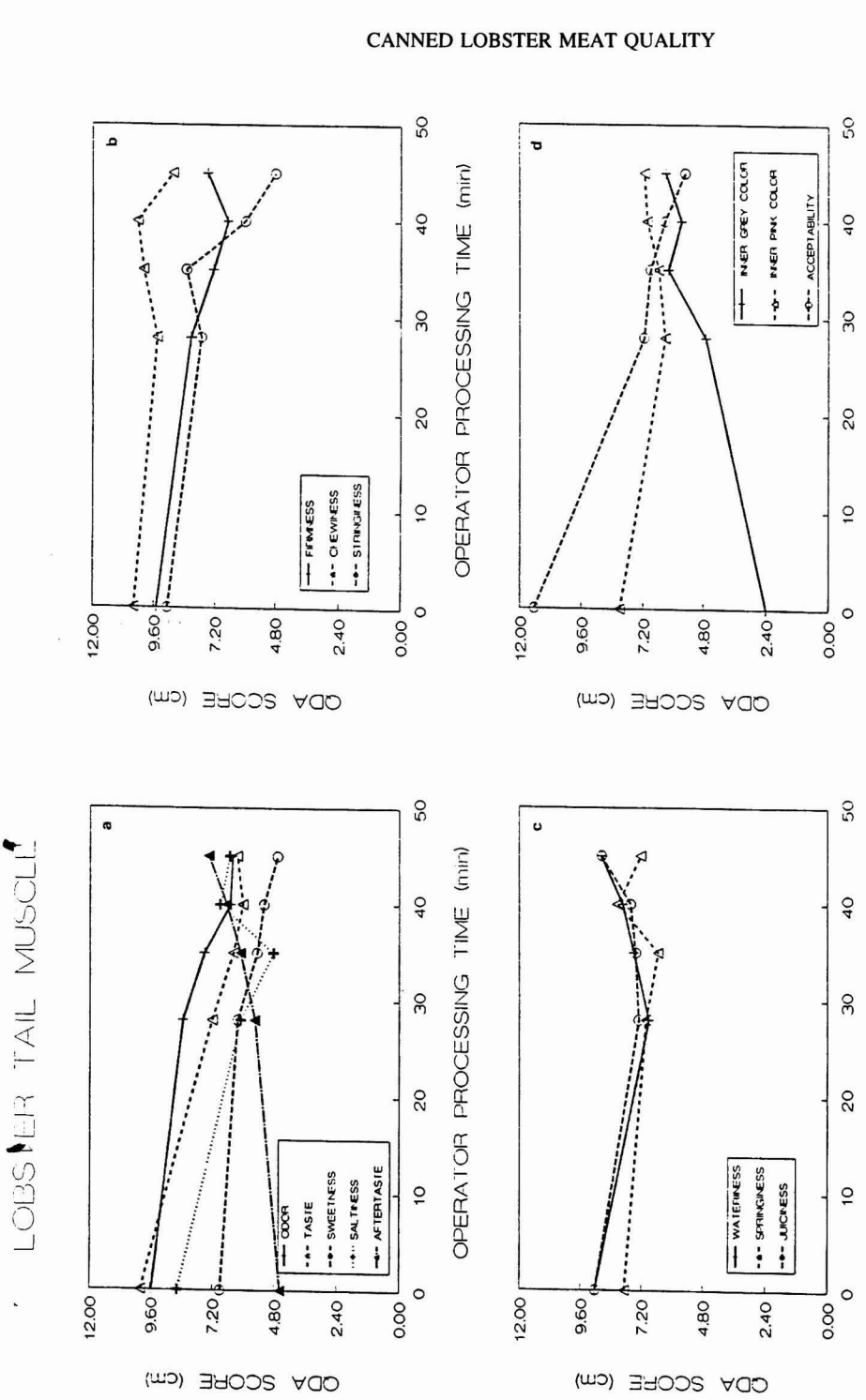

FIG. 3. SENSORY ODOR, TASTE, SWEETNESS, SALTINESS, AFTERTASTE, FIRMNESS, CHEWINESS, STRINGINESS, WATERINESS, SPRINGINESS, JUICINESS, INNER GREY COLOR, INNER PINK COLOR AND ACCEPTABILITY OF LOBSTER (*HOMARUS AMERICANUS*) TAIL MUSCLE SUBJECTED TO THE VARIOUS PROCESSING TIMES

sensory attributes with processing time. Odor, taste and sweetness (Fig. 3a) decreased as operator processing time increased; conversely, aftertaste (Fig. 3a) increased during the same processing time period. Saltiness (Fig. 3a) of the tail muscle decreased up to 35 min of processing and thereafter increased. Firmness and stringiness (Fig. 3b) generally decreased whereas chewiness (Fig. 3b) increased for processing times of 28 and 35 min. Changes in the textural attributes of wateriness, springiness and juiciness (Fig. 3c) parallelled moisture content and EM (Fig. 1a and 1b). Springiness declined slightly during processing but little difference was observed among these three attributes.

These findings are consistent with those of Lyon and Klose (1981) who reported differences ($p \leq 0.05$) in the sensory parameters of tenderness and off-flavor of cooked control and canned fowl meat whereas cohesiveness showed no significance. Literature findings on textural changes during thermal processing show that physically determined hardness of canned sardines decreased with longer processing times (Tanaka and Taguchi 1985) but firmness of canned mackerel increased at equal lethality (Tanaka *et al.* 1985). The present changes in texture of the tail muscle may be attributed to thermal denaturation of the myofibrillar proteins which leads to degradation of myosin and collagen. This may contribute to decreased fiber cohesiveness exhibited as muscle softness. Martens *et al.* (1982) also found that actin denaturation resulted in increased juiciness. Furthermore, nonspecific degradation of peptide bonds that break the protein into smaller units (Kokuryo and Seki 1980; Tanaka and Kimura 1988) may also contribute to the softening process.

Inner grey color increased during sterilization whereas inner pink color (Fig. 3d) initially decreased and then increased with processing time; moreover, acceptability decreased as these color changes became more apparent. As well, the inner grey color of the frozen cold pack tail muscle increased and overall acceptability decreased ($p \leq 0.05$) when compared to the other four hot pack canning treatments. As well, taste, firmness, inner gray color and acceptability of the cold pack tail muscle differed ($p \leq 0.05$) from the 45 min hot pack. Results also show that the 28 min hot pack differed ($p \leq 0.05$) from the 45 min hot pack for the sensory attributes of saltiness, wateriness and stringiness. Trained sensory panelists were able to distinguish between the 35 min and 45 min hot pack tail muscle for the attributes of saltiness and stringiness and among all treatment conditions for the attribute of juiciness.

Table 8 presents the correlation matrix for the sensory attributes measured on the tail muscle. With the exception of sweetness and springiness, processing time correlated ($p \leq 0.05$) with all other attributes analyzed. Acceptability correlated ($p \leq 0.05$) with all parameters except aftertaste, springiness and stringiness. Similar to the results for the claw muscle, odor of the tail muscle correlated ($p \leq 0.0001$) with taste, sweetness, saltiness, and firmness and to a

TABLE 8.
CORRELATION MATRIX FOR SENSORY ANALYSES OF LOBSTER (*HOMARUS AMERICANUS*) TAIL MUSCLE, n = 116 [1]

	Time	Odor	Taste	Sweetness	Saltiness	Aftertaste	Firmness	Wateriness	Springiness	Juiciness	Chewiness	Stringiness	Inner gray color	Inner pink color	Overall acceptability
Time	1.000	-0.168 *	-0.202 *	-0.144	-0.318 **	-0.232 *	-0.384 ****	-0.217 *	-0.116	-0.345 ***	-0.191 *	-0.268 **	0.510 ****	-0.245 **	-0.351 ***
Odor		1.000	0.763 ****	0.634 ****	0.529 ****	0.149	0.402 ****	0.337 ***	0.211 *	0.309 **	0.285 **	-0.080	-0.065	0.071	0.598 ****
Taste			1.000	0.630 ****	0.460 ****	0.052	0.412 ****	0.369 ***	0.204 *	0.408 ****	0.159	-0.015	-0.087	0.233 *	0.751 ****
Sweetness				1.000	0.508 ****	-0.083	0.195 *	0.269 **	0.078	0.273 **	0.048	-0.020	0.020	0.088	0.627 ****
Saltiness					1.000	0.268 **	0.482 ****	0.337 ***	0.331 ***	0.396 ***	0.313 **	0.127	0.031	0.004	0.406 ****
Aftertaste						1.000	0.265 **	0.248 *	0.198 *	0.233 *	0.180	-0.073	0.335 ***	0.070	-0.034
Firmness							1.000	0.483 ****	0.140	0.501 ****	0.445 ****	0.215 *	-0.103	0.210 *	0.392 ****
Wateriness								1.000	0.166	0.724 ****	0.302 **	0.066	-0.049	0.404 ****	0.362 ***
Springiness									1.000	0.104	0.150	0.020	0.103	0.145	0.013
Juiciness										1.000	0.240 *	-0.009	-0.187	0.283 **	0.404 ****
Chewiness											1.000	0.268 **	-0.040	0.142 *	0.142 *
Stringiness												1.000	0.087	0.026	0.077
Inner gray color													1.000	-0.037	-0.196 *
Inner pink color														1.000	0.195 *
Overall acceptability															1.000

[1] * Values significant at $p \leq 0.05$; ** Values significant at $p \leq 0.01$; *** Values significant at $p \leq 0.001$; **** Values significant at $p \leq 0.0001$.

lesser extent with wateriness, springiness, juiciness and chewiness. Taste also highly correlated ($p \leq 0.001$) with odor, sweetness, saltiness, firmness, wateriness and juiciness. The negative sensory attribute of aftertaste for the tail muscle correlated ($p \leq 0.05$) with length of processing time, saltiness, inner grey color and the texture attributes of firmness, wateriness, springiness and juiciness.

Table 9 presents a comparison of the mean sensory attributes of claw and tail muscle. Differences ($p \leq 0.05$) were observed in taste, firmness, chewiness, springiness, wateriness, stringiness, juiciness and inner grey color of the nonstriated and striated muscle types. Claw muscle values for taste, wateriness and juiciness were higher ($p \leq 0.05$) than those found for tail muscle. The physical measurements of moisture content and expressible moisture presented in Table 6 support these findings. The shear force values (Table 6) coincide with the mean values for the textural attributes of firmness, chewiness, stringiness, and springiness that were higher ($p \leq 0.05$) in the tail muscle than the claw muscle. There is a paucity of data on changes in lobster claw and tail muscle particularly during thermal processing. Power *et al.* (1967) analyzed claw and tail meat stored on ice after irradiation. These researchers also found that changes in texture were more prevalent in striated tail meat than nonstriated claw meat. In addition, little information can be found comparing conventional cooking changes to those seen in a closed thermal canning system. The latter process shows no moisture loss to the ambient environment during the heating process. Sensorially, a trained panel could only detect differences ($p \leq 0.05$) in striated tail muscle related to differences in retort processing times. These findings are supported by those of Casales *et al.* (1988) who found no sensorial difference ($p \leq 0.01$)

TABLE 9.
MEANS AND STANDARD DEVIATIONS FOR SENSORY ATTRIBUTES OF LOBSTER (*HOMARUS AMERICANUS*) CLAW AND TAIL MUSCLE [1]

Variable	Claw muscle	Tail muscle
Odor	8.34±1.28a	8.09±1.31a
Taste	8.02±1.35a	6.98±1.55b
Sweetness	5.64±1.20a	5.44±1.30a
Saltiness	7.00±0.90a	7.28±0.86a
Aftertaste	6.66±1.11a	6.97±1.39a
Firmness	6.47±0.92b	8.18±0.92a
Chewiness	7.51±1.06b	9.29±1.03a
Stringiness	6.74±1.07b	7.51±1.10a
Wateriness	8.53±0.72a	8.17±0.64b
Springiness	5.39±1.23b	6.83±1.35a
Juiciness	8.44±0.78a	7.98±0.74b
Inner grey color	5.01±0.97b	5.76±1.48a
Inner pink color	6.92±1.20a	7.12±1.10a
Overall acceptability	7.65±1.62a	7.40±1.66a

[1]Values in the same row with the same letter are not significantly different ($p \leq 0.05$).

in odor, flavor, texture, color and appearance of nonstriated mussel tissue thermally processed at different temperatures.

CONCLUSIONS

Care must be taken at all times to ensure that the initial temperature at the geometric centre of the coldest can is at least 60°F because this temperature dictates the length of the processing time, B_B. Data collected at the three lobster processing plants show a high regression correlation coefficient ($r \geq 0.8$) between temperature and length of processing time. Extrapolation of can temperature using the formula method (Lopez 1981) equations demonstrates that the operator processing time at a sterilizing value of $F_o = 4$ could be reduced from 45 min to 36 min with a lag time of 7–10 min. Results from this study support a regulatory change provided that a minimum initial internal can temperature of 60°F is used for the coldest can prior to the retort process.

Physical analyses show that claw and tail muscle differed ($p \leq 0.05$) in moisture content, EM and shear force. Moreover, QDA sensory data on firmness, chewiness, stringiness, springiness, wateriness, juiciness and inner gray color support the physical findings and parallel the negative changes which occurred with length of processing time for both the lobster claw and tail muscle. Tail muscle samples processed for 40 or 45 min differ ($p \leq 0.05$) in saltiness and stringiness from the samples processed for 28 and 35 min. A decrease in retort processing time from 45 to 36 min, if permitted, would improve the product's physical and sensory quality, reduce processing costs and lower energy use.

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Addendum. Definition of terms and symbols used in text.

Term	Symbol	Definition
Retort temperature	RT	The temperature in ^{o}F of the medium in which the container is processed.

Can temperature	CT	The temperature of the can contents at the slowest heating point.
Initial temperature	IT	The value of CT at the beginning of the process.
	jI	The number of degrees below RT where the extended straight line of the heating curve crosses the corrected 0 of the process.
Process time	B_B	The time in minutes from the beginning of the process to the end of the heating period.
Heat penetration Curve slope, or Heating curve slope	f_h	The number of minutes required for the straight line portion of the heating curve plotted on semilogarithmic paper to pass through one log cycle.
Sterilizing value	F_o time is	The equivalent value of the process in terms of minutes at 250°F when no involved in heating to 250°F or cooling to sublethal temperatures.
	f_h/U	Factor related to the g value in accordance with an appropriate table.
	F_i	Factor related to RT.
	g_{bh}	The number of degrees below retort temperature at which the heating curve exhibits a change of slope.
	x_{bh}	Number of minutes from the corrected beginning of the process to the point of break in the heating curve.
	g_{h2}	The number of degrees below retort temperature on a broken heating curve at the end of the heating period.
Second slope of heating curve	f_2	The number of minutes required for the second heating curve portion of the curve to pass through one log cycle.
	f_h/U_{bh}	Factor related to g_{bh} in accordance with an appropriate table.
	r_{bh}	Factor related to g_{bh} in accordance with an appropriate table.
	f_h/U_{b2}	Factor related to g_{bh} in accordance with an appropriate table.
	P_t	Processor's time in minutes.
	l	Lag time in minutes for heating the retort.

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RESEARCH NOTE

THE USE OF PROPYLENE GLYCOL AND/OR LACTIC ACID IN CHILL WATER FOR REDUCING SALMONELLAE ON BROILERS[1]

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ABSTRACT

A study was conducted to determine the effects of propylene glycol (PG) and lactic acid (LA) alone, or in combination, on levels of salmonellae on broiler carcasses. Chicks were inoculated with salmonellae via the drinking water on days 2, 7, 14, and 21. At 49 days, birds were processed and the carcasses were subjected to chemical treatment in the chill water. Two treatments were effective in completely eliminating salmonellae from the carcass (0.25% LA + 20% PG or 0.50% LA + 20% PG). However, both levels of LA resulted in discoloration of the skin, and all levels of PG that were evaluated (5, 10, or 20%) produced carcasses that exhibited a sickeningly sweet odor. Color and odor problems did not diminish with time.

INTRODUCTION

Propylene glycol (PG) (1,2-propanediol) is used as a nontoxic antifreeze in breweries and milk processing plants. PG is used in confectionary products, chocolates, ice cream, shredded coconut, beverages, baked goods, toppings, icings, and meat products (Winter 1984). Taken internally, PG is harmless, probably because its oxidation yields pyruvic and acetic acids (Merck Index 1976). PG is approved for use in dairy feeds as an aid in the prevention of acetonemia (Anonymous 1988). Low levels (2.5 to 5%) have been used effec-

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tively as an energy source in the diet of broiler chicks (Persons *et al.* 1968; Waldroup and Bowen 1968).

Airoldi and Zottola (1989) reported that at 37°C, 5% or more PG in solution inhibited the growth of *Salmonella typhimurium*. At concentrations greater than 20% PG, no recovery was possible after 4 h at 37°C. At 1°C, a slow decline in the population of *S. typhimurium* was seen regardless of PG concentration. The rate of decline was proportional to the concentration of PG. Aeration of the system resulted in a more rapid decrease in the number of *S. typhimurium*.

Broiler carcasses are normally chilled in an agitated ice bath at or near 0°C for approximately 1 h. Previous reports from this laboratory (Izat *et al.* 1989) have examined the use of various compounds in the chiller water for the reduction of salmonellae on broiler carcasses. The addition of lactic acid (LA) at 0.5% has been effective in significantly reducing levels of salmonellae but has caused some skin discoloration of the carcasses. The objective of this study was to examine the effects of various levels of PG in combination with different levels of LA on levels of salmonellae on broiler carcasses. It was hypothesized that a combination of PG and LA may be more effective than LA alone, perhaps allowing for the use of lower concentrations of LA that might not result in the skin discoloration problems that have been previously noted.

MATERIALS AND METHODS

One hundred and fifty day-old Cobb 500 male broilers were obtained from a local hatchery and randomly assigned to two pens of 75 chicks each. The pens were 5.2 m^2 and contained two hanging feeders and an automatic water fount. Previously used wood shavings were used over concrete floors. Brooding and rearing temperatures followed normal industry guidelines. Broilers were inoculated with 10^7 to 10^8 cfu/mL *Salmonella typhimurium* ATCC 14028 (American Type Culture Collection, Rockwell, MD) via water fountains on days 2, 7, 14, and 21. Diets used in the study were considered to be nutritionally adequate, meeting suggested nutrient standards (National Research Council, 1984). Salinomycin (Bio-Cox, Agri-Bio Corp., Gainesville, GA) at 66 mg/kg was used as an anticoccidial.

At 49 days of age, 120 of the broilers were processed in a pilot poultry processing plant. The birds were stunned with an electric knife (''The Stunner'', Model G, Cervin Automated Systems Inc., Minneapolis, MN), killed and allowed to bleed for 2 min, scalded for 2 min in clean hot water at 60°C, picked in a rotary drum picker (Pickwick Co., Cedar Rapids, IA), and manually eviscerated.

After evisceration, 96 of the prechill carcasses were randomly assigned to one of 12 chill water treatments for a total of eight carcasses per treatment. The treatments were a factorial arrangement of four levels of PG (0, 5, 10, and 20%) and three levels of LA (0, 0.25, and 0.50%) in all possible combinations. All treatments were applied on a vol/vol basis, potable water was used, and all chill water supplies were at 0 to 1°C prior to the addition of any PG and/or LA. The PG and LA were held at 0 to 1°C 24 h prior to addition to the chill water. Carcasses were held in the individual nonagitated chill water treatments for 1 h. Carcasses were removed from the chill water treatments, dipped into a clean ice water solution to rinse the carcass (control carcasses were also dipped in a clean ice water rinse) and subjected to a whole carcass rinse as described by Cox *et al.* (1983). The temperature of the dip solutions, and the pH of each solution was determined using a pH meter (Accumet pH Meter 910, Fisher Scientific, Fair Lawn, NJ). Color of the breast skin was evaluated after chill water treatment using a Flavomycin poultry skin color guide (1 to 7 scale, 1 lightest) (American Hoechst Corp., Somerville, NJ). Levels of salmonellae were determined using a three-tube most probable number (MPN) procedure (Oblinger and Koburger 1984).

All samples were preenriched (37°C for 24 h) in Lactose Broth (Difco, Detroit, MI) prior to performing the MPN procedure in accordance with FDA (1984) procedures for salmonellae that have been subjected to physical stress. The MPN procedure was performed in Selenite Cystine (Difco, Detroit, MI). MPN bottles and tubes were incubated at 37°C for 24 h. After incubation, a loopful of sample from each bottle and tube was streaked onto Hektoen Enteric and Xylose Lysine Desoxycholate agar plates (Difco, Detroit, MI). Plates were incubated at 37°C for 24 h. After incubation, suspect colonies from each plate were streaked and stabbed into Triple Sugar Iron and Lysine Iron agar slants (Difco, Detroit, MI). Slants were incubated at 37°C for 24 h. Slants exhibiting typical salmonellae reactions were confirmed serologically (FDA 1984). No attempt was made to determine specific serotypes isolated.

Data from this experiment were statistically analyzed using the General Linear Model procedure of SAS (1982). Means were separated using least squares means. Individual carcasses were the experimental unit. The model included level of LA, level of PG, and the interaction of these two main effects. Residual effects were used for the error term. Data were analyzed on a $\log_{10}$ basis, but reported as MPN salmonellae/mL. Samples from which salmonellae could not be isolated were statistically analyzed using half of the lower detection level for the organism (0.02 MPN salmonellae/mL). This was done to allow for statistical analysis, and to keep from reporting a value of "zero" when there is a lower detection level for the salmonellae assay.

RESULTS AND DISCUSSION

There was a significant LA effect on salmonellae levels due to a significant interaction (P = 0.002) between level of PG and level of LA. This was due to the increase in MPN salmonellae/mL from 5 to 10% PG in combination with 0.25% LA compared to the decrease in MPN salmonellae/mL from 5 to 10% PG in combination with 0.50% LA (Table 1). Two of the 12 treatments (0.25% LA + 20% PG or 0.50% LA + 20% PG) were effective in completely elim-

TABLE 1.

EFFECTS OF PROPYLENE GLYCOL AND/OR LACTIC ACID IN CHILL WATER ON MICROBIOLOGICAL AND COLOR CHARACTERISTICS OF BROILERS

Treatment[1]	pH of chill water (n=1)	Temp C of chill water (n=1)	Color Score[2] (n=8)	# Sal pos. carcasses/ #sampled (n=8)	MPN salmonellae/mL rinse fluid
Control	7.96	0.6	1.0	6/8	0.16^{bcd}
5% PG	5.42	3.9	1.0	6/8	0.15^{bcd}
10% PG	4.90	3.9	1.0	4/8	0.08^{cde}
20% PG	4.70	7.2	1.0	7/8	1.29^{a}
0.25% LA	2.73	0.0	2.0	6/8	0.11^{bcde}
0.25% LA + 5% PG	2.79	3.3	2.0	7/8	0.26^{abc}
0.25% LA + 10% PG	2.80	5.6	2.0	7/8	0.75^{ab}
0.25% LA + 20% PG	2.88	7.2	2.0	0/8	$< 0.02^{e}$
0.5% LA	2.55	0.6	2.0	5/8	0.06^{cde}
0.5% LA + 5% PG	2.58	3.9	2.0	6/8	0.06^{cde}
0.5% LA + 10% PG	2.59	5.0	2.0	1/8	0.03^{de}
0.5% LA + 20% PG	2.62	7.2	2.0	0/8	$< 0.02^{e}$

(SEM for MPN salmonellae = 0.31).

[1]Treatment applied on a vol/vol basis in the chill water.

[2]Color of the breast skin scored using the Flavomycin poultry skin color guide (1 to 7, lightest to darkest) (American Hoechst Corp., Somerville, NJ).

[abcd]MPN salmonellae treatment means with different superscripts differ significantly ($P \leq 0.10$).

inating salmonellae from the post-chill carcass. Six of the eight control carcasses were positive for the organism, and the level of salmonellae on these carcasses was 0.16 MPN salmonellae/mL of recovered rinse fluid. No effort was made to determine whether the salmonellae recovered from any of the carcasses were the serotype inoculated or indigenous species.

As the level of propylene glycol increased from 10% to 20% (without the addition of LA) the level of salmonellae recovered from the rinse fluid increased significantly. Airoldi and Zottola (1989) reported that *Salmonella typhimurium* could be recovered from 0.1% nonfat dry milk solutions containing as much as 20% PG for more than 3 wk at −1.0°C. In their study a 5 log cycle reduction was noted in 1 day when 40% PG was added to the milk solution. The authors also reported that at 37°C, 5% or more PG inhibited the growth of *Salmonella typhimurium* in vitro. The difference in results between the studies of Airoldi and Zottola (1989) and those obtained in the present study may be due to the nature of poultry skin in comparison to in vitro evaluation of chemical agents, or to temperature of treatment application.

A change in skin color was noted when LA was used at 0.25 or 0.50% alone or in the presence of PG. This darkening of the skin has been noted in other studies where lactic acid has been utilized (Snijders *et al.* 1979; Woothuis and Smulders 1985; Izat *et al.* 1989). Even when the pH of the chill water was extremely low (2.55 with 0.5% LA), low levels of salmonellae could still be recovered from the surface of some of the carcasses. Ayres (1966) reported that pH's below 2.3 to 2.5 were necessary for complete destruction of the organism. Using 0.50% LA alone, the decrease in level of salmonellae compared to the control level was 60%.

Unfortunately, the two treatments that were effective in eliminating salmonellae not only caused the change in skin color but also resulted in carcasses that possessed a sickeningly sweet odor that did not diminish with time. In fact all carcasses that were exposed to any of the treatments containing PG exhibited the same odor. Therefore, it is advised that propylene glycol not be used at high concentrations (>5.0%) in poultry chiller water for any reason.

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EVALUATION OF DRYING CHARACTERISTICS OF PINEAPPLE IN THE PRODUCTION OF PINEAPPLE POWDER

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ABSTRACT

The drying behaviour of osmosed and fresh pineapple, and the development of pineapple powder for use as dry food ingredient were investigated in this study. It was found that by osmotic dehydration alone 30 to 40% of the water content of pineapples could be removed in a day. The effects of temperature and sample thickness were evaluated when drying was carried out with air under controlled conditions. A mass transfer model, based on Fick's law of diffusion as applied to thin slab, was used to determine the effective diffusivity by using the experimental data where the shrinkage in sample thickness due to loss of water was taken into account. A power law equation was used to correlate the shrinkage in thickness with the moisture content of the sample. The effective diffusivity was found to be in the order of 10^{-10} m^2/S. *The activation energy for pineapple, which was estimated by using Arrhenius equation, was found to be 35.5 kJ/mol.*

For the production of pineapple powder, hygroscopicity and caking are considered to be the main problems. Chemical treatment with magnesium stearate was found useful at a concentration of 1% by weight.

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INTRODUCTION

In some countries, where pineapple is grown in large quantities, the fruit is wasted during the peak season of harvest, especially at the production points, due to nonavailability of sufficient storage, transportation and processing facilities. The most common method for pineapple preservation is canning of slice and juice, which is an expensive process. Development of a simple and inexpensive process is always desirable. Dehydration may be considered as an alternative low cost preservation process. The lower storage and transportation costs associated with the reduction of weight and volume due to removal of water may provide additional economic incentives for widespread use of this process. Some works on pineapple dehydration are published by Mehta *et al.* (1982) and Cheema and Ribeiro (1978).

In osmotic dehydration, water is removed from porous materials using concentrated sugar or salt solutions. Osmotic dehydration process for fruits may be considered as a prestep to other conventional drying process in order to make them more economic by reducing the water load (Ponting *et al.* 1966; Farkas and Lazar 1969). Nanjundaswamy *et al.* (1978) reported some work on osmotic dehydration of pineapple.

Osmotic dehydration alone cannot give a product of moisture content low enough to be shelf-stable. The product must be dried further by other means to provide reasonable shelf-life. Products having moisture contents corresponding to water activities below 0.7 are considered as dehydrated products (Beuchat 1981).

In this study, the potential of preservation of pineapple by means of osmosis and air drying processes have been investigated.

ANALYTICAL MODEL

In most cases of drying of food materials, the constant rate period is absent. The experimental data on drying in the falling rate period may be analyzed by a diffusion model. Fick's second law of diffusion has been used by several workers (Fish 1958; Chen and Johnson 1969; Vaccarezza *et al.* 1974) to study diffusion of water through the material to the surface from which water then evaporates. Assuming a constant diffusion coefficient, the equation may be written as,

$$\frac{\partial w}{\partial t} = D \frac{\partial^2 w}{\partial x^2} \tag{1}$$

On the basis of uniform initial moisture distribution and in absence of any external resistances, Fick's law may be solved for an infinite slab being dried from two major faces, as

$$\frac{w - w_e}{w_o - w_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[- (2n+1)^2 \frac{D\pi^2 t}{L} \right] \quad (2)$$

Boundary conditions:

$$t = 0 ; 0 \leq x \leq L ; w = w_o$$

$$t > 0 ; x = 0, L ; w = w_e$$

In Eq. (2) it is assumed that the sample temperature and thickness are constant during drying. Several experimental works (Chirife 1971, Saravocos and Charm 1962, Vaccareza *et al.* 1974, van der Lijn 1976) indicate that the internal temperature gradients within foods during drying are close to zero and thus heat transfer effects in drying analysis may be neglected. Sample shrinkage is incorporated in the equation by relating sample thickness to the moisture content in calculating the diffusivity.

For long drying time and for moisture ratio $[(w-w_e)/(w_o-w_e)]$ less than 0.6, generally only the first term of the equation is used (Rao and Rizvi 1986). For low value of equilibrium moisture content (w_e) the expression is simplified to a straight-line equation,

$$\ell n\ (w/w_o) = \ell n\ (8/\pi^2) - \pi^2 D\ t/L^2 \quad (3)$$

For the present system the assumption to neglect w_e is justified in the results and discussion section.

In drying of porous food material the moisture movement is caused by various transport mechanisms such as liquid diffusion, vapor diffusion, thermal diffusion, internal evaporation and condensation, surface diffusion or most frequently a combination of these mechanisms. Since the knowledge of the exact mechanisms in food dehydration is still limited and due to the complexity of the drying process a lumped value of diffusivity, called effective diffusivity, is generally used in design calculations of food dryers. In this study the experimental drying data are used to calculate the effective diffusivity.

When experimental data are plotted as $\ell n\ (w/w_o)$ versus (t/L^2), the effective diffusion coefficient may be calculated from the slope of the straight line.

MATERIALS AND METHODS

Experimental procedure was divided into three sections: osmotic dehydration, air drying and powder production.

Fresh pineapples were peeled and after removing the core cut into rectangular pieces of approximately 50 mm × 20 mm size of different thickness. Initial weights of the fresh samples varied between 5.5 to 22.0 g for different thickness (5, 10, 20 mm). For osmotic dehydration, the samples of known thickness were

immersed into sugar solutions of different concentrations. The experiments were conducted at 25°C. In order to avoid any significant dilution effect on the sugar solution, a 5:1 solution to fruit ratio was used (Islam and Flink 1982). Fresh solution was used in each experiment. At different times, samples were withdrawn from the solution and weighed after they were quickly rinsed and gently blotted to remove the surface moisture. Some preliminary experiments showed that sugar solution of concentration below 40% by weight was not very effective for osmotic dehydration. Therefore, all the experiments were carried out at 40%, 50% and 60% sugar solutions.

For air drying experiments, an electrically heated and thermostatically controlled oven with air circulation was used. Air velocity in the oven was 0.02 m/s. The average relative humidity of the ambient air of temperature 28–30 °C during the experiments was about 60%. Three either fresh or osmosed samples were placed in single layer on a wire mesh tray so that the drying might take place from both surfaces. Sample weights and the thickness were measured during drying process initially at 10 min interval and after 1.5 h every 30 min. For bone dry weight, the samples were left in the oven at 105°C for at least 12 h. Different drying temperatures (50°C, 60°C, 70°C, 80°C) and sample thicknesses (5mm, 10mm, 20mm) were used in the experiments.

For pineapples powder production, the fresh samples were dried up to a moisture content of about 12% (dry basis). Dried samples were then cooled in a desiccator where a further reduction in moisture content might have occurred. Magnesium stearate was added to the dried sample before grinding. After grinding for 3 min in an electrically powered high speed mechanical blender, the ground powder was graded by ASTM E-11 sieve (Number: 35, Aperture: 0.5 mm) screen. Different amounts of magnesium stearate (0.1% to 2.0% by weight) were tried out. The powder characteristics were evaluated by flow assessment and agglomeration index (Peleg 1977, Peleg and Hollenbach 1984, Shukur 1980). The angle of repose is the criterion to evaluate 'ease of flow'. The powder was poured through a funnel on to a horizontal sheet of graph paper until the tip of the heap so formed reached the stem of the funnel. By reading the diameter of the base, the angle of slope of the cone was calculated. The agglomeration index relates unpassed fraction weight of a treated sample to that of untreated sample through the funnel.

RESULTS AND DISCUSSION

For fresh pineapple having high moisture content (600–800% dry basis), large quantity of water has to be removed in order to achieve a shelf-stable product. In the present investigation, osmotic and air drying processes are studied. Diffusivity is considered an important physical transport property, useful in the

analysis of drying processes, and experimental data are necessary for the prediction of drying time. Besides production of dried product, emphasis has been given to obtain diffusivity data at different drying conditions. The results obtained are discussed in the following sections.

Osmotic Dehydration

It was intended to study the effectiveness of osmotic dehydration on pineapple. Some preliminary experiments showed that solutions with less than 40% sugar content are not very effective for osmosis. Experiments were conducted with 40%, 50% and 60% sugar solutions for three different sample thicknesses, 5mm, 10mm and 20mm. The more concentrated the sugar solution and thinner the sample,

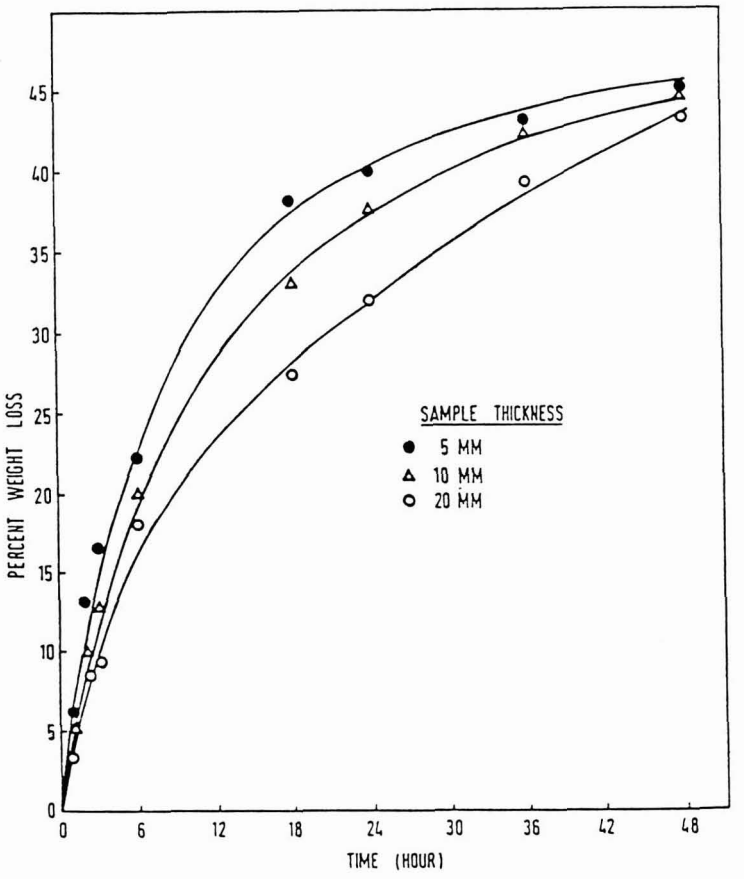

FIG. 1. PERCENT WEIGHT LOSS VERSUS IMMERSION TIME FOR OSMOTIC DEHYDRATION IN 60% (w/w) SUGAR SOLUTION AT 22°C

higher was the percentage of water losses. Influence of immersion time on osmotic dehydration for 5mm, 10mm and 20mm thick samples are shown in Fig. 1. The detailed investigation to obtain optimum time and osmotic conditions was not the objective of the present study. It may be concluded from the conditions considered in this study that significant amount of water (30–40%) may be removed from pineapple by osmotic dehydration alone in about 24 h. For thinner samples, up to 60% water loss is possible with longer immersion time. For air drying experiments osmosed samples were prepared using 60% sugar solution and at least 24 h immersion time.

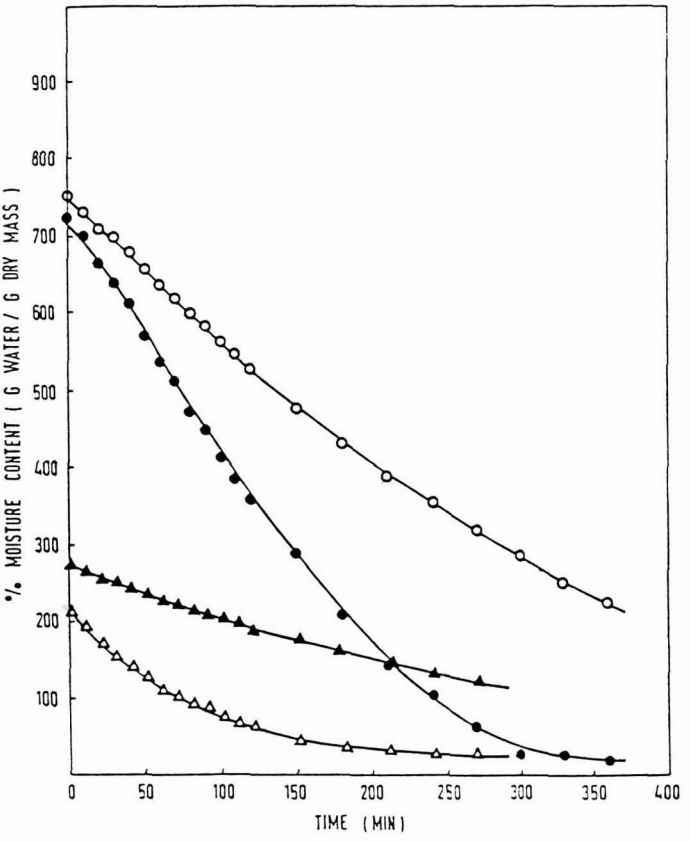

FIG. 2. VARIATION OF MOISTURE CONTENT IN PINEAPPLE DURING AIR DRYING AT 80°C
● 5 mm (Fresh), ○ 20 mm (Fresh), △ 5 mm (Osmosed), ▲ 20 mm (Osmosed).

Air Drying

In air drying of fresh and osmosed pineapple samples, process variables such as drying temperature (50, 60, 70, 80°C) and sample thicknesses (5, 10, 20mm) were investigated. Figures 2 and 3 show some typical plots of moisture content against drying time for both osmosed and fresh samples. For fresh sample dried at 80°C the equilibrium moisture content (w_e) was found to be 0.026. With this value, when w_e is neglected in Eq. (3) the error is calculated to be about 3% at 50% sample moisture content or about 12% at 20% moisture content.

It was considered that the internal structure and the moisture content of the fresh pineapple were uniform throughout. During any experiment few samples were used to average out any variation in sample moisture content at any particular time of drying. Assuming that there was no evaporation from the edges

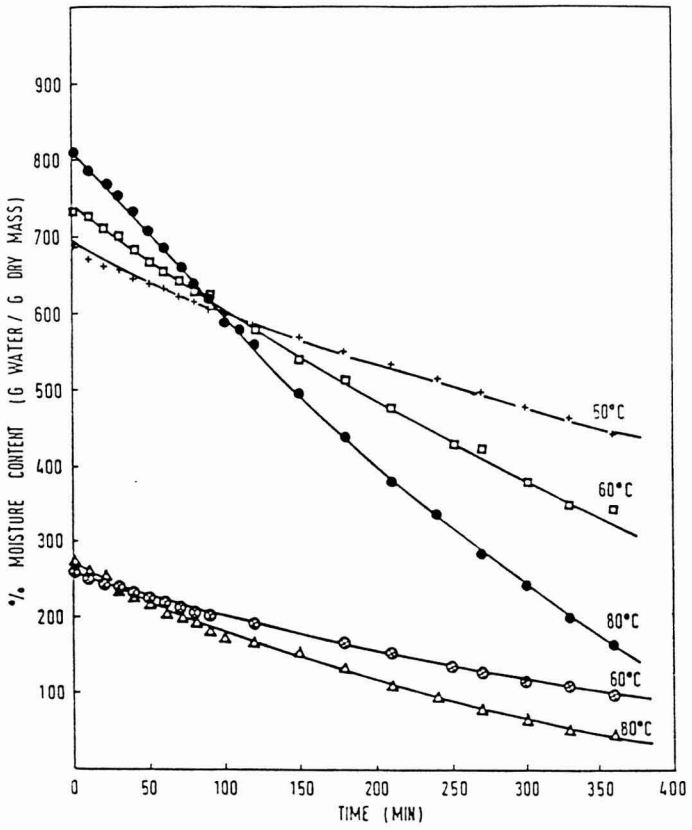

FIG. 3. VARIATION OF MOISTURE CONTENT OF PINEAPPLE DURING AIR DRYING AT DIFFERENT TEMPERATURES
Sample thickness 10 mm. + □ ● Fresh sample, ⊗ △ Osmosed sample.

of the sample, the drying rate was calculated using initial surface area. No constant drying rate period was observed at any of the conditions studied. Figures 4 and 5 show the drying rates at 70°C as functions of moisture content and drying time for a sample thickness of 10mm.

As it is found that there is no constant drying rate period for pineapple drying, experimental data could be analyzed by Eq. (3). Assuming a constant value of effective diffusivity, a linear plot of $\ell n\ (w/w_o)$ versus (t/L^2) is expected. When the experimental data are plotted using constant initial sample thickness, deviations from linearity are observed. This occurs mainly at higher values of t/L^2 and higher drying temperatures, as shown in Fig. 6. This is particularly found in case of fresh pineapple samples.

Due to high moisture content in pineapple, shrinkage in thickness was observed in drying. During the experiment, sample thickness was measured at different drying time along with the sample weight. The data are correlated to the sample moisture content (Fig. 7) in a power law equation:

$$(L/L_o) = (w/w_o)^{0.20} \tag{4}$$

The deviation from linearity of the Eq. (3) as discussed earlier is believed to be due to the shrinkage in sample thickness. Instead of using a constant initial

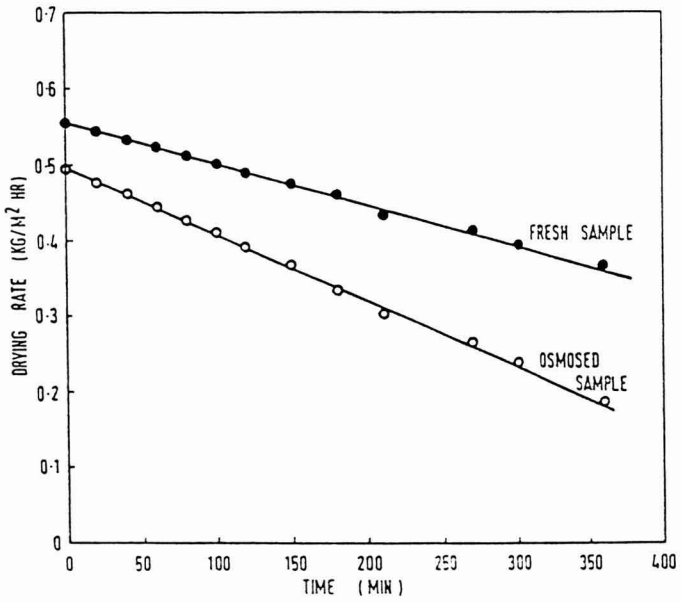

FIG. 4. VARIATION OF DRYING RATE OF PINEAPPLE WITH DRYING TIME AT 70°C, 10 mm THICK SAMPLE

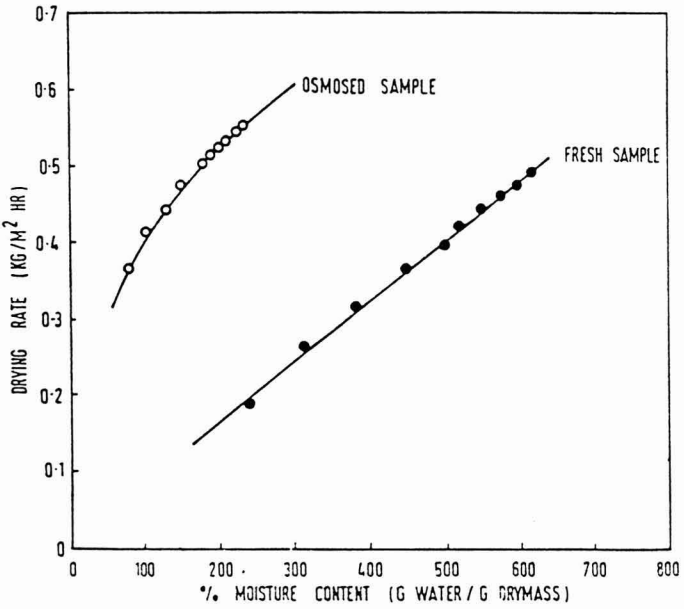

FIG. 5. VARIATION OF DRYING RATE OF PINEAPPLE WITH MOISTURE CONTENT

thickness in Eq. (3), the power law Eq. (4) is used to take into account the shrinkage effect. A much better fit to the experimental data is obtained, as shown in Fig. 8. From the slopes of the plot, the water diffusion coefficients are calculated for both osmosed and fresh samples. These are presented in Table 1. It is found that the diffusion coefficients increase with sample thickness, but according to the diffusion equation it should be independent of sample thickness. It is believed that for thicker samples different internal structures are developed during drying, possibly due to less shrinkage which allowed faster moisture transport than thin samples. Similar phenomena might have occurred during drying of osmosed samples where in general, slightly higher diffusion coefficients compared to those of fresh samples are found. During osmosis some sugar molecules diffuse into the pore structure, resulting in less degree of shrinkage in osmosed samples in drying. Diffusivities obtained for other food materials, as reported in literature are quite similar in order of magnitude as compared to the present values, 3.6×10^{-9} m^2/s for apple at 76°C (Roman *et al.* 1979), 3.3×10^{-10} m^2/s for avocado at 56°C (Alzamora *et al.* 1980). The temperature dependency of effective diffusivity may be used to calculate the activation energy for drying. Arrhenius equation is used for this purpose,

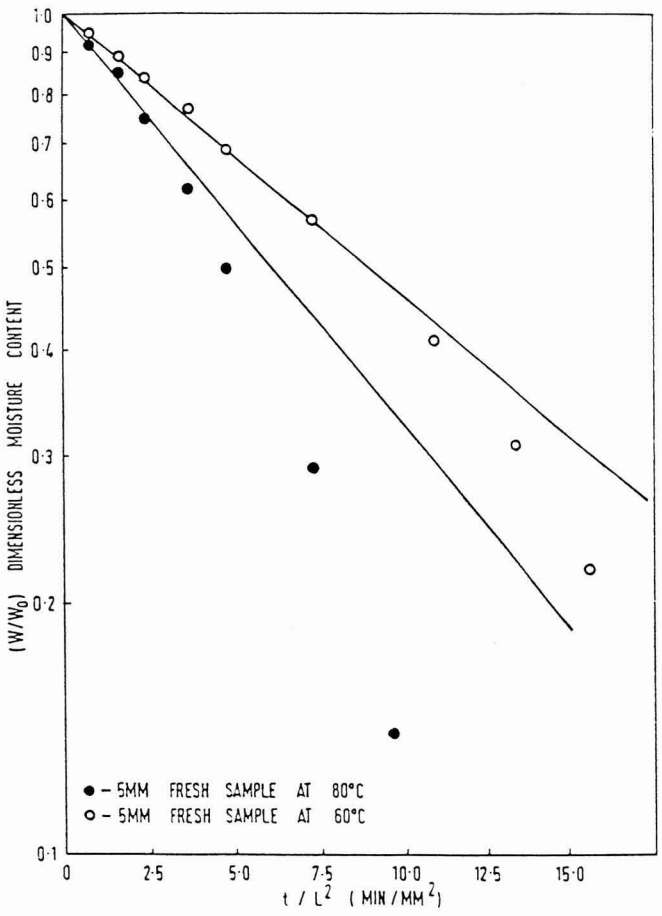

FIG. 6. PLOT OF ℓn (w/w$_o$) VERSUS (t/L$_o^2$) Eq. (3).

$$D_{eff} = D_o \exp(-E_a/RT) \tag{5}$$

A plot of ℓn D_{eff} against (1/T) should yield a straight line and from the slope activation energy E_a may be calculated. For pineapple, the data are plotted in Fig. 9 and the activation energy is found to be 35.5 kJ/mol. This value is comparable to that found by Alzamora (1980) for avocado, 39.8 kJ/mol.

From the plot of Eq. (3) as ℓn (w/w$_o$) versus t, the drying rate constant ($\pi^2 D_{eff}/L^n$) could be calculated from the slope. The dependency of drying rate constant on initial sample thickness may be used to conclude whether the internal or the external mass transfer resistance is controlling the drying process. For total internal resistance controlled drying, the value of the power (n) of thickness (L) should be 2, as shown in Fick's diffusion equation. For completely external

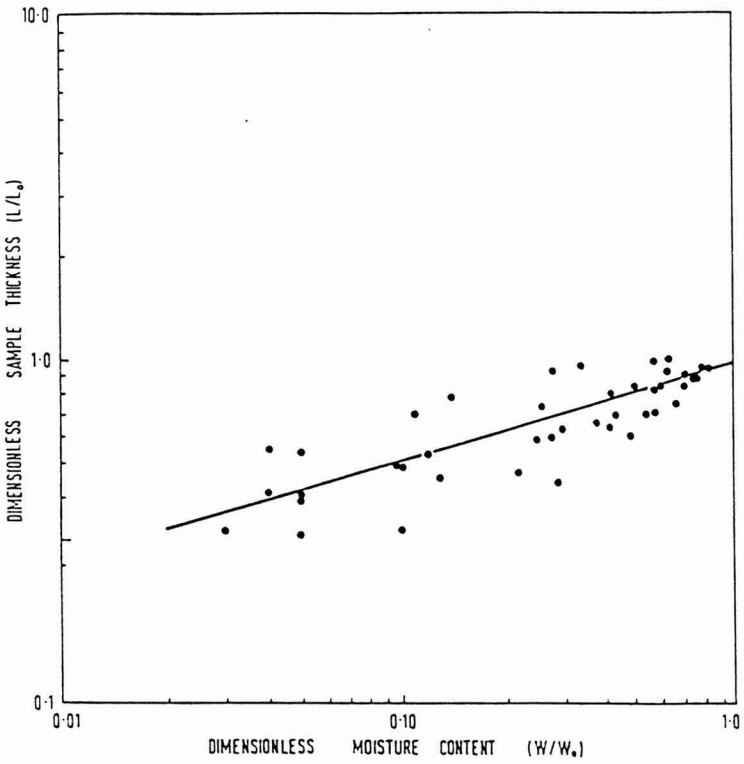

FIG. 7. SHRINKAGE IN PINEAPPLE THICKNESS AS FUNCTION OF MOISTURE CONTENT

resistance controlled drying, n is expected to be unity (King 1968). Experimental results reported for air drying of food materials usually show values of n between 1.41 and 1.85 (Vaccarezza and Chirife 1975). In the present case of pineapple drying, the value of n is found to be 1.32, as shown in Fig. 10. This lower value of n indicates that the drying experiments were conducted under conditions of some external resistances, which may be due to the low air flow rate.

Pineapple Powder

The hygroscopicity and caking are the main problems for the production of pineapple powder. Use of magnesium stearate as anti-caking agent improved the powder characteristics. Magnesium stearate is one of the most widely used dry additive (Peleg and Hollenbach 1984, Shukur 1980). The stearate is adsorbed on the powder surface and gives good restriction to the moisture absorption. Fig. 11 shows the agglomeration index and the angle of repose for different

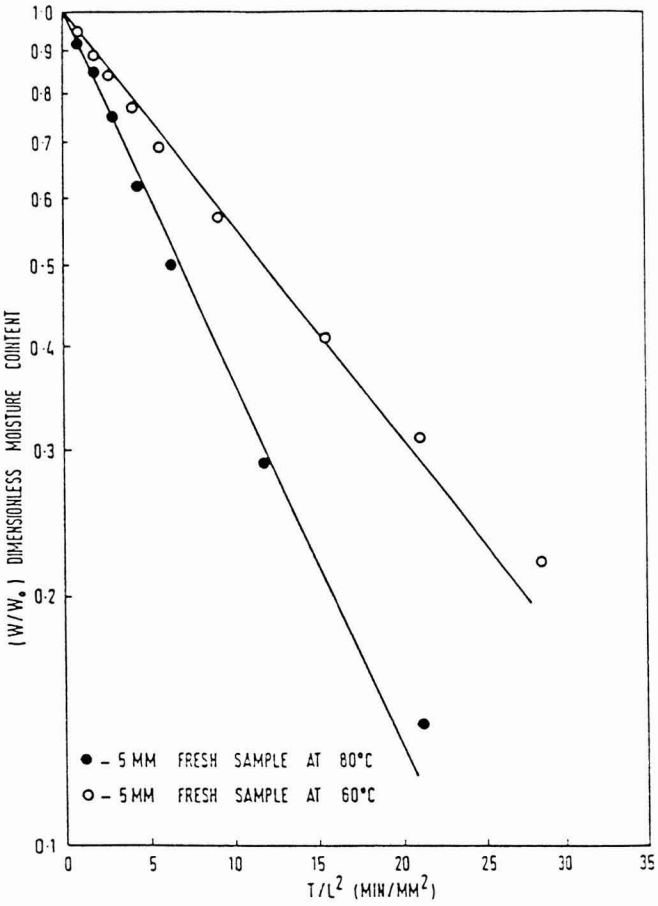

FIG. 8. PLOT OF $\ell n\ (w/w_o)$ VERSUS (t/L^2) (SHRINKAGE CORRECTED)

level of magnesium stearate concentration. A minimum agglomeration index occurred at 1% concentration of magnesium stearate, whereas an immediate clogging of the powder at the funnel tip was observed at concentration level of 0.1%. The angle of repose was found to be the same for both 1% and 2% concentrations of the additive.

The powder was light yellow in colour and flavour retention was good. Both the colour and flavour were found to be much dependent upon the drying temperature.

The study indicates that a good quality dehydrated pineapple product, either in slice or powder form, may be developed. Sliced product may either be re-hydrated or used as snack without further processing. The product in the powder form may be used in preparation of drink and food.

TABLE 1.
EFFECTIVE DIFFUSION COEFFICIENTS FOR FRESH AND OSMOSED PINEAPPLE IN AIR DRYING

Temperature (°C)	Pineapple sample	Diffusivity x 10^{10} (m^2/s)		
		Sample thickness		
		5 mm	10 mm	20 mm
50	Fresh	0.32	1.01	3.50
"	Osmosed	0.39	1.24	3.79
60	Fresh	0.86	2.69	8.37
"	Osmosed	0.94	2.89	8.57
70	Fresh	0.99	3.00	9.98
"	Osmosed	1.47	3.27	9.72
80	Fresh	1.29	4.01	10.90
"	Osmosed	1.61	4.22	10.50

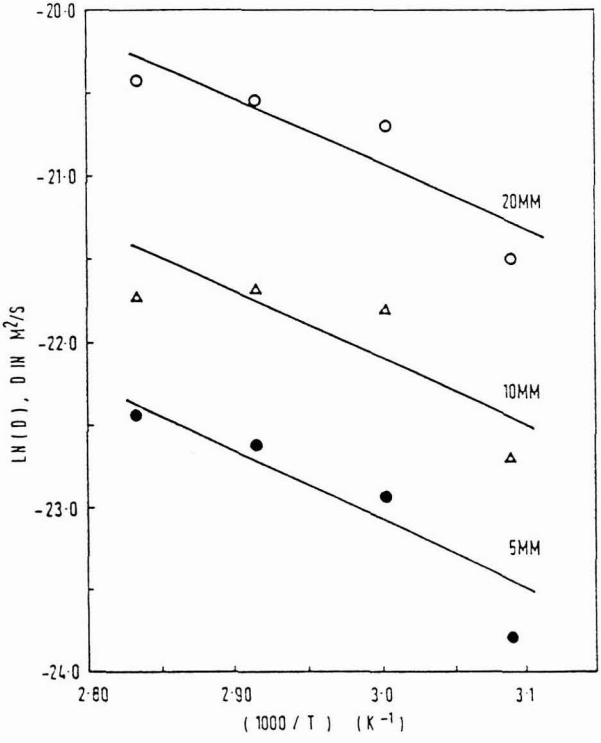

FIG. 9. PLOT OF ARRHENIUS EQUATION FOR AIR DRYING OF PINEAPPLE

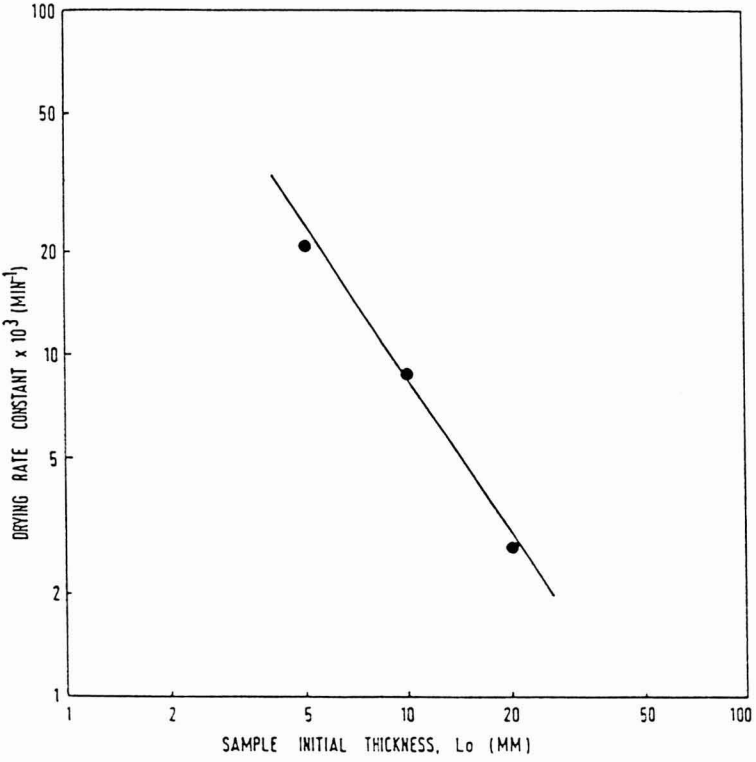

FIG. 10. CHANGE OF DRYING RATE CONSTANT WITH SAMPLE THICKNESS AT 80°C

CONCLUSIONS

The results of the present study on drying of pineapple lead to the following conclusions:

Osmosis alone can reduce 30 to 40% of the moisture content in fresh pineapple in about 24 h.

Air drying of pineapple does not show any constant drying rate period.

Shrinkage in pineapple sample is correlated to its moisture content in a power law equation with the exponent value of 0.2.

A thin slab mass transfer model based on Fick's law of diffusion is successfully used to analyze the drying data, which takes into account the shrinkage in sample thickness. The calculated values of the effective diffusion coefficients are found to vary between $(0.32 - 10.9) \times 10^{-10}$ m^2/s over the experimental range of drying temperature and sample thickness.

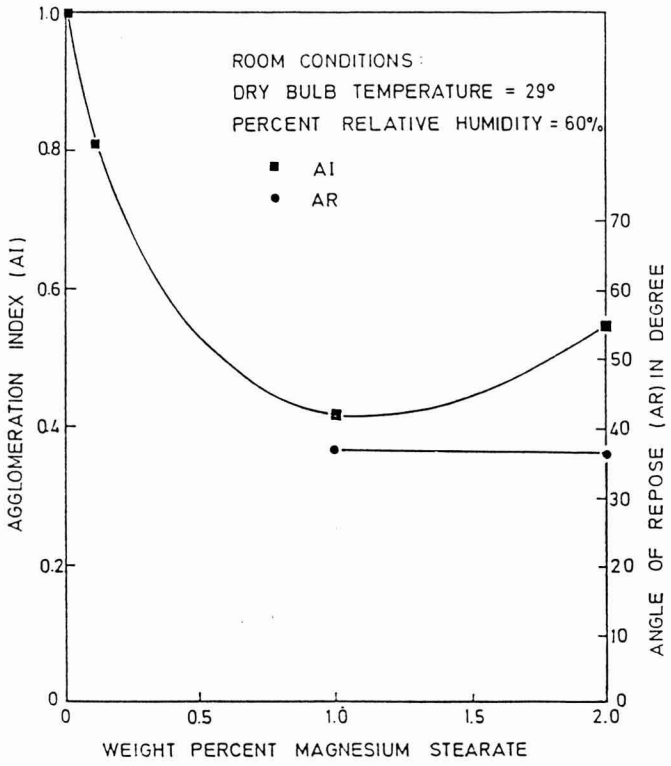

FIG. 11. AGGLOMERATION INDEX AND REPOSE ANGLE OF MAGNESIUM TREATED PINEAPPLE POWDERS AT ATMOSPHERIC CONDITION

The temperature dependency of the diffusivity is evaluated with Arrhenius equation and the activation energy for pineapple is found to be 35.5 kJ/mol.

The relationship between the drying rate constant and the sample thickness in the form of a power equation indicates that in the present experimental condition some external resistance was present and the heat transfer effect on drying may not be neglected in case of pineapple.

Hygroscopicity and caking are major problems in pineapple powder production. Chemical treatment with magnesium stearate has been found useful at an optimum concentration of 1 wt%.

ACKNOWLEDGMENT

The authors would like to thank Miss Sharimah Mohd Shariff for doing some of the experiments presented in this paper.

NOMENCLATURE

D	water diffusivity (m^2/s)
D_{eff}	effective diffusivity (m^2/s)
D_o	constant in equation (5)
E_a	activation energy (kJ/mol)
L	sample thickness (mm)
R	gas law constant (kJ/mol K)
T	temperature (K)
t	drying time (min)
w	sample moisture content (g water/g dry mass)
Subscripts:	
o	initial value
e	equilibrium value

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EFFECTS OF ELECTRICITY ON MICROORGANISMS: A REVIEW[1]

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ABSTRACT

Although the idea of electrical treatment of foods for microbial control is not new, the data available on nonthermal effects of electricity are limited and inconclusive. An understanding of such effects would be useful in developing new methods for microbial inactivation. The present review discusses a number of different methods of electrical treatment and their nonthermal *effects on microorganisms. Subjects discussed include electric pasteurization of milk, electrohydraulic shock, electroporation, and electroconductive heating. Information relating to mechanisms contributing to microbial death is summarized and discussed.*

INTRODUCTION

Recent industry interest in rapid methods of heating and nonthermal microbial inactivation in foods has resulted in revived attention towards technologies utilizing electrical energy or electromagnetic waves. Relevant technologies in this connection include ohmic and microwave heating (ionizing radiation is excluded from the present discussion). Both methods can cause rapid heating in

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interior locations of foods and consequently hold promise of microbial inactivation through purely thermal means.

One of the items of interest in this connection is the nature of the interaction of microorganisms with electric fields. While it is tempting to speculate that the biological organism is subject to certain nonthermal effects which could act in synergy with thermal treatment, resulting in a reduced overall inactivation requirement, the evidence to date remains inconclusive. Consequently, the position of regulatory officials has rightly been that any microbicidal effects from electrical/microwave treatment cannot be separated from the purely thermal effects arising from such treatment. In connection with microwave energy, the Scientific Status Summary by the IFT's Expert Panel on Food Safety and Nutrition (IFT 1989) also indicates that the effect appears to be purely thermal.

The present review is an attempt to examine critically the various studies on the effects of electrical treatment on microorganisms, with a view to separate thermal effects from consideration. The primary motivation for this study is scientific curiosity, rather than any desire to reopen the books on the subject. It is hoped that an improved understanding of the mechanisms of interaction of microbes with electricity will result in ideas for future development and investigation.

Since a wide variety of electrical/electromagnetic treatments have been attempted over the years, there is some diversity (although not much quantity) in the literature on microbial interactions. Thus the following review is organized into sections, dealing with the literature on (1) electric pasteurization of milk, (2) electrohydraulic shock, (3) electroporation, (4) bipolar electric fields in air, (5) low-voltage alternating current, (6) electroconductive heating, (7) electrical stimulation of meat, (8) microwave and dielectric heating, and (9) effects of electricity on microbial growth rates. Finally, the literature findings are discussed according to the suspected mechanisms of microbial death, mechanical, thermal or chemical.

Electric Pasteurization of Milk

Among the earliest applications of electricity in food processing was in milk pasteurization. This section is considered separately from others on electroconductive heating because of the once-widespread acceptance of the method. It was reported by Anderson and Finkelstein (1919), Prescott (1927), Fetterman (1928), Gelpi and Devereux (1930), Getchell (1935), and Moses (1938) that milk could be pasteurized using alternating current. This electrical method of processing milk, called the "Electropure Process", was introduced in the United States from Europe (Moses 1938) in the early nineteen twenties. The process involved the application of electric current directly through milk resulting in the generation of heat, which was reported as responsible for bacterial death.

The method of electric pasteurization of milk was explained by Getchell (1935) and Moses (1938). The milk was pumped through a regenerative (heat exchange) coil, an electrical heating chamber, and then a surface heat exchanger in the system for cooling. The electrical chamber consisted of a vertical rectangular tube, the two opposite walls of which were carbon electrodes, and the other two walls were of heavy glass insulators. A 220 V alternating current supply with a constant power input of 15 kW was applied to the carbon electrodes. The milk passing through the heating chamber provided a conducting medium for the flow of current, and its resistance to this flow generated heat within the milk itself. The process temperature and the residential time were controlled by varying the flow rate and/or voltage supplied to the electrode.

Fetterman (1928) reported other studies (without providing citations), stating that the "Electropure Process" destroyed tubercle bacilli, *Escherichia coli* and other organisms in milk which cause acute infectious diseases. Gelpi Jr. and Devereux (1930) reported a 99.5% bacterial spore destruction in milk by the "Electropure Process" compared to 2.7% by a batch heating and holding method. Since the electric pasteurization was at 71°C for 15 seconds in a continuous flow-system, and the conventional heat-hold treatment was in a batch system at 62.8°C for 30 min, the comparison cannot be considered truly valid. In addition, the apparent lack of consideration of the time-temperature history and the residence time distribution tends to detract from the credibility of this study. Horral (1935) mentioned that it was possible to reduce the temperature required to kill *E. coli* and *M. tuberculosis* when electric current was used. Getchell (1935) stated that electric pasteurization not only destroyed all the harmful bacteria commonly found in milk, but was also an effective safeguard against certain varieties of bacteria on which other methods of pasteurization had little or no effect. However, no data or citations were presented to substantiate these findings. Indeed, none of the early studies on electric pasteurization of milk appears to have separated the electrical effects (if any) and thermal effects on bactericidal action.

Examinations of the electropure process were conducted by various state health departments, and this method was accepted as a safe pasteurization technology in six states: New York, Pennsylvania, Illinois, Michigan, CT and Maryland (Moses 1938). As a result, by 1938 there were about 50 milk pasteurizers in the nation serving 50,000 consumers. Fetterman (1928) stated that a company in Pittsburgh alone processed 30,000 gal of milk per day using this method. A common electric conduction unit handling 100 gal/h was generally used by dealers selling 1200 qt/day. Electric conduction pasteurizers were manufactured by Trumbell Manufacturing Company (Getchell 1935). However, the method fell into disfavor; Hall and Trout (1968) reported that these units were not in existence in any dairy industry by the 1960's. It is not clear why processors stopped using electric pasteurizers, since no literature could be found on the subject since the 1940's. Hall and Trout (1968) stated that some studies had concluded that there was no

additional effect due to electricity on the bacterial kill other than the effect of heat generated by electric current.

Electrohydraulic Shock

Electrohydraulic shock refers to a rapid discharge of high voltage electricity across an electrode gap below the surface of aqueous suspensions of microorganisms. The submerged high voltages result in the formation of tremendously high transient pressure pulses producing shock waves (Fruengel 1960). Several physical and chemical effects occur, and the microorganisms present in the discharge liquid are killed (Edebo and Selin 1968). The present discussion includes the treatment using a.c. and d.c. sources of power, despite the extremely short time duration of the pulses that would normally tend to render the distinction meaningless. The rationale is that while the polarity of the a.c. pulses could be reversed from pulse to pulse, those of the d.c. pulses would remain the same; thus the reactions and microbial microenvironment in the vicinity of the electrodes could be different in each case.

Fedorov and Rogov (1960) observed a reduction of microorganisms due to high voltage d.c. impulses. They used voltages upto 30 kV at a rate of 120 discharges (pulse length <20 μs) per minute to inactivate *E. coli*. The bactericidal effect was attributed to cavitation and wave impact. Gossling (1960), who conducted similar studies with *E. coli*, claimed that if the power density was high enough, microorganisms may have had mutations induced and been destroyed. Sale and Hamilton (1967a) quoted Ingram and Page (1953) saying that direct current pulses of 2 kV/cm had no lethal effect on microorganisms. They also mentioned that there was literature both for and against the existence of bactericidal effects of electric current.

Sytnik and Sytnik (1976) quoted Brandt *et al.* (1962) as reporting that a 90% reduction in bacteria was obtained when using 40 discharges of 32 kV d.c., under water. They stated that the effectiveness of the killing of intestinal bacilli was directly proportional to the voltage of the submerged electrical discharge. A number of other bacterial species like *Pseudomonas aeruginosa, Serratia marcescens, Staphylococcus aureus, Streptococcus faecalis,* and *Bacillus subtilis* were also inactivated by this process. They also reported an increased lethality due to increased clearance between electrodes, and decreased lethal effect with greater initial concentration of microorganisms. The bacterial death was considered to be due possibly to formation of free chemical radicals and ions, which may be affected by the concentration of microorganisms, total volume of the medium used, and distribution of chemical radicals.

Bactericidal action was obtained when microorganisms were suspended in a dielectric liquid (Brandt *et al.* 1962). However, a reduced bacterial kill was

observed in solutions like 0.85% solution of sodium chloride. Interestingly, the liquid medium subjected to the electrohydraulic shock was found to be lethal when microorganisms were added after the treatment. This may have been due to chemical action and not due to thermal effects, as there was no significant temperature rise during the treatment. The sooner the bacterial suspension was added to the ionized liquid, the stronger the lethal effect, although the bactericidal activity was still observed two hours after the discharges. It is not possible to critically evaluate this work since details of electrode material and methodology were not specified.

Allen and Soike (1966) conducted experiments with different bacterial species and indicated that the total energy requirement for complete sterilization could differ depending on the type of bacteria and the initial concentration of bacterial cells. Intestinal bacilli were reported as the least resistant and yeast as the most resistant to electrohydraulic treatment. They used a capacitance range of 5–95 μF and d.c. voltages between 5–14 kV. The rate of kill varied with changes in voltage and capacitance, the greatest effect being at the lowest voltage. No morphological changes in were observed when bacterial cells were examined after the treatment using light microscopy.

Allen and Soike (1967) studied the factors affecting bactericidal action and reported that the effectiveness was greatest at a capacitance of 6 μF and a voltage of 5 kV. For the same total energy input (obtained by varying the number of discharges), greater kill was achieved at lower capacitance and lower voltage. The electrode material and the electrode gap were not presented in the report. Distilled water was used in these experiments to suspend microorganisms. The researchers concluded that the electrohydraulic treatment was an extremely effective, quick, and inexpensive method for sterilizing water and sewage without raising temperature or adding chemicals.

Sale and Hamilton (1967a) demonstrated a lethal effect of high voltages upto 25 kV/cm, applied as direct current pulses, on *E. coli, S. aureus, M. lysodeikticus, Bacillus subtilis, B. cereus, B. megaterium, C. perfringens* and *Saccharomyces cerevisiae*. The conductivity of the medium varied from 0.8–3.2 mmho/cm. The temperature rise was minimized by applying very short pulses (<20 μs) with long intervals (1s) between pulses. Carbon electrodes and polythene spacers were used, and the temperature was controlled by water circulation through the brass blocks that supported the carbon electrodes.

A neutral solution of sodium chloride was used as the suspending medium, and *E. coli* was used as the test organism to study the parameters influencing bacterial kill. They obtained microbial kill by suspending the organisms in a gel that was impermeable to electrolytic products, and therefore concluded that the lethal effect was not due to the products of electrolysis. As the temperature rise in most of the experiments was less than 5°C, it was concluded that temperature was not responsible for the lethal effect. The degree of kill was proportional to

the pulse length, number of pulses and the voltage applied. The various microbial species differed in their sensitivity to this treatment.

Sale and Hamilton (1967b) explained that the bacterial kill during high voltage discharges was not due to heating or electrolysis, but was due to an irreversible loss of membrane function as a semipermeable barrier between the bacterial cell and its environment. Membrane damage was demonstrated by the lysis of protoplasts, the leakage of intracellular contents, the loss of ability of *E. coli* to plasmolyze in a hypertonic medium and the release of galactosidase activity in a permease, negative mutant of *E. coli*. They concluded that cell death was due to membrane damage, since the number of cells of *Staphylococcus aureus* killed by high voltage discharges correlated with the number that could not be converted to spheroplasts.

Gilliland and Speck (1967a) found electrohydraulic treatment effective in destroying at least 95% of the vegetative cells of *E. coli, Streptococcus faecalis, M. radiodurans, Bacillus subtilis* and its spores within ten discharges. The outer shell of the electrode was made of aluminum alloy and the core was made of copper alloy. The electrode gap varied from 0.16 to 0.64 cm, voltages in all experiments did not exceed 15 kV and the capacitance was 24 μF. The nature of power source (a.c. or d.c.) was not reported. The bacterial cells were suspended in 1 L of sterile water for treatment. The ionization time varied from zero (instantaneous ionization) to 300 μs. High voltage electrical impulses were discharged at a rate of 1/s. *S. faecalis* and *E. coli* were least resistant, and *M. radiodurans* and *B. subtilis* were most resistant to electrohydraulic shock.

The specific resistances of the bacterial suspensions were found to be in the range of 10^4 to 5.3×10^4 ohm-cm. In all the experiments the bacterial suspensions were at room temperature at the start and the temperature measured before and after the treatment never differed by more than 0.5°C. However, temperatures were not measured during the treatment, and the technique used for measuring temperature was not specified. Increased rates of bacterial death were obtained with increased voltage and capacitance. Although the metabolic injury decreased with the number of discharges, the bacterial death rate increased. Water subjected to electrohydraulic treatment was found to retain a certain amount of toxicity only when copper-core electrodes were used. No residual effect was observed in water treated with either iron or aluminum core electrodes. Gilliland and Speck (1967a) explained this residual toxicity as being due to the formation of copper ions, in agreement with the residual bactericidal action reported by Brandt *et al.* (1962). They also confirmed the findings of Allen and Soike (1966) by stating that there was no mechanical disruption of bacterial cells.

Gilliland and Speck (1967b) used a double tank system to separate the effect of mechanical shock waves from chemical, thermal or any other effects. The high voltage discharge occurred in the lower chamber and was separated from the bacterial suspension in the upper chamber by a rubber diaphragm. Both

chambers were completely filled to obtain full effect of pressure pulses. No significant kill or metabolic injury was observed, indicating that mechanical action alone was not responsible for the bactericidal action. No significant amount of cell breakage was observed by phase microscopy and cell wall stain preparations. The possibility of thermal effect was ruled out, since the increase in temperature was only 0.5°C, and more than 90% of the population was killed within 10 discharges.

Gilliland and Speck (1967b) extensively studied the chemical effects of electrohydraulic shock using only aluminum electrodes. The presence of oxidation reactions (which serve to inactivate compounds important for cellular metabolism) were shown by a decrease in optical density at 340 mμ after the treatment. This result was confirmed by the conversion of ferrous sulfate to ferric sulfate and the reduction of free sulfhydryl groups. They explained that the oxidation reactions obtained by electrohydraulic treatment were mediated by the free radicals (OH, and HO_2) and H_2O_2 produced by electric discharges under water. They concluded that the oxidation reactions inactivated certain compounds important for cellular metabolism, since intracellular materials of *E. coli* lost the ability to absorb at 260 mμ after electrohydraulic shock.

Gilliland and Speck (1967b) also demonstrated enzyme inactivation due to electrohydraulic treatment, and the enzymes used in their study were lactic dehydrogenase, trypsin, and proteinase of *Bacillus subtilis*. The enzyme inactivation was also attributed to oxidation reactions mediated by free radicals and atomic oxygen. Although the destruction of enzymes would not necessarily lead to loss of viability of bacterial cells *per se*, the authors considered it to indicate the possibility of bacterial death via enzyme inactivation. They considered enzymes which contained or required free sulfhydryl groups as being probably most susceptible to electrohydraulic inactivation.

Edebo and Selin (1968) applied high voltage discharges up to 50 kV to suspensions of *E. coli* in distilled water, by means of a.c. pulses. The electrode gap was varied between 10 and 24 mm, and the pulse length between 20 and 105 μs at a rate of 1/s. They reported bacterial kill when voltages above a certain threshold value were discharged and the killing effect increased with voltage until a plateau was reached. The separation of pressure shock waves from other activities, by screening the discharge gap with a thin steel sheet, showed no decrease in the bacterial count. So, they concluded that the pressure shock waves alone had no bactericidal effect. No morphological changes in the bacterial cell structure were observed due to this treatment.

Edebo (1968) used a discharge voltage of 45 kV, capacitance of 0.6 μF, inductance of 43 μH, electrode gap of 11 mm, and *E. coli* suspended in 0.001 M KCl and tap water of conductivity 354–413 μmho/cm, to study the effect of photon radiation in the microbicidal effect. The electrode materials were copper and tungsten, and the volume in the discharge vessel was 1200 mL. They reported

a bactericidal effect, attributed it to photon emissions from arc plasma. The kinetics of the inactivation by discharges were similar to those of UV-irradiation, under certain conditions. A decreased bactericidal effect with increased distance from the spark was also reported. They explained this by stating that the bacteria close to the spark might be hit by photons so heavily that they could not be photoreactivated. Edebo (1969) explained a reduction in bactericidal effect by a reduction in photon emissions.

Edebo *et al.* (1968) showed that the bactericidal effect of water treated by the electrohydraulic method depends on the material of the electrodes. They used the same experimental design as above, but the material of the electrodes was varied in different experiments. Great bactericidal effect was obtained using copper-containing electrodes. Unstable cuprous ions and other chemical substances with strong oxidizing qualities were responsible for a rapid reduction of *E. coli* during the first few minutes while the stable microbicidal activity was due to cupric ions released from the electrodes. Addition of ascorbic acid was found to increase copper ions and increase the bactericidal effect of water treated by the electrohydraulic method, whereas inorganic salts neutralized copper ions and decreased the bacterial kill. However, the bactericidal effect was also observed when using iron, steel and aluminum electrodes.

The addition of inorganic salts to the discharge liquid increased the electrical conductivity (>5 mmho/cm) and reduced the bactericidal effect (Edebo *et al.* 1969). In the opinion of the researchers, this was related to the chemical neutralization of the microbicidal substances formed during electrical discharges. The reduction in the lethal effect was also attributed to a decrease in force of the impulse discharge and a decrease in the yield of photons from the electric arcs. It was found that at high concentration of salts, the microbicidal effect was completely extinguished. Therefore, the electrohydraulic method could have a bactericidal effect only in a relatively clean water medium with a minimal mineral content.

Sytnik and Sytnik (1976) studied the effect of electrohydraulic method using high voltage d.c. on the food yeasts *Candida utilis, C. guilliermondii* and *Saccharomyces cerevisiae*. They obtained the greatest lethal effect on yeast cells at 40 kV (electrode gap unspecified) after 50 electrical discharges, which was accompanied by significant changes in cell morphology. Open zones in the cytoplasm, particularly in the central portion of the cell, were observed in many cells after the treatment. Large concentrations of detrimental mass, consisting of grains and remnants of destroyed yeast cells, were also observed. The destruction increased in proportion to the number of electrical discharges, and after 200 impulses, all fields of view were filled with amorphous formations without clear contours or normal internal structures of yeast cells.

An analogous study with a culture of *Staphylococcus pyogenes* showed a death of 93.4% at 30 kV after 20 shocks, and close to complete sterilization after 50

shocks. They have reported that the effect of electrohydraulic treatment depends on the voltage and the number of electrical discharges, but only up to a particular level.

From the summary of previous works on electrohydraulic treatment by Sytnik and Sytnik (1976), it appears that the major contribution to bacterial kill was due to chemical reactions, and the thermal effect is insignificant as the temperature rise reported by many researchers was only a few degrees. They have also cited some materials (Wesley and Williams 1968; Thomas *et al.* 1969; and Peshkov *et al.* 1972) which reported bacterial cell disintegration due to electrohydraulic treatment.

Electroporation

The relatively new technique of electroporation is used for genetic transformation of bacterial cells, and the mechanism may yield insight into microbial death under electrical treatment. The technique involves the discharge of high-voltage electric pulses through cell suspensions, causing temporary disruption of the cell membranes. Under these conditions, the membranes become permeable to extracellular substances, and interchange of macromolecules including DNA could result. Research on the uses of electroporation on eucaryotic cells has been in existence for some time; however, its use with bacterial cells is comparatively recent (Shivarova *et al.* 1983). Since that time, literature on the technique is increasing rapidly (MacNeil 1987, Fiedler and Wirth 1988; McIntyre and Harlander 1989, to name but a few). The technique is still being refined, but the principal parameters influencing bacterial transformation have been identified by Mercenier and Chassy (1988) as being the field strength and pulse duration, the optimum combination of which would depend on the bacterial strain. McIntyre and Harlander (1989) indicated that the shape of the pulse may be a critical factor as well. These studies may be useful in interpreting the earlier literature on electrohydraulic shock, as will be done later under Bactericidal Mechanisms.

Bipolar Electric Field in Air

Stersky *et al.* (1970) conducted an investigation to reduce or eliminate airborne contamination in food plants. An electrode of 4 in × 4 in × 32 in size, which produced a bipolar oriented electric field, was suspended from the ceiling of a chamber. A constant temperature of 21°C and relative humidity of 70% were maintained in the chamber. Bacterial species of *S. marcescens, P. fragi, Candida lipolytica,* and *Penicillium roqueforti* were continuously aerosolized separately in different experiments. With field voltages of 6,000, 10,000, 14,000 and 20,000 measured at 1m from the electrode, the reduction in aerosol population was largest at 14,000 volts, and there was no additional effect at 20,000 volts.

Stersky *et al.* (1970) also pointed out that the distance of microorganisms from the electrode has an effect on reduction of the aerosol population. This might be due to the variation in field strength with the distance from the electrode. This factor has a bearing on the amount of electrode surface required per cubic foot of space, and has a direct effect on the installation and operating costs. The mechanisms of the reduction, and the practicability of the principle for commercial application in food plants were not discussed in their study.

Low Voltage Alternating Current

Tracy (1932) inoculated grape juice with yeast cells and subjected the suspension to 120V, 60 Hz alternating current in a chamber with carbon electrodes. The surface areas of the electrodes used were 0.95, 1.17 and 4.9 cm^2, and the electrode gap was 5 to 7 mm. The chamber was externally cooled by a rapid stream of cold water. The highest temperatures attained were recorded by a thermocouple and a potentiometer. A set of lethal temperature and time combinations to obtain complete sterilization was determined, and the minimum lethal temperature reported was 46°C. The initial concentration of yeast cells used were 1.5×10^6 /mL, and the temperature of solution varied from 30°–48°C with an average of 44°C.

A killing effect was obtained at all current levels used, and this was reported as being due purely to the passage of alternating current through the sample. An increased percentage kill was reported with increased amperage and increased exposure time. The killing effect at different current levels were compared without keeping the diameter of the chamber constant; thus the current density was not constant for all studies. The authors suggested that the microbicidal action of alternating current depended upon a definite quantity of electricity applied at or above a certain minimum current density. The maximum reduction in yeast cells was only two to three log cycles, and this was explained by the consideration that there might have been an increase in resistance to killing action of alternating current when the cells decreased in number. Chemical analysis showed no toxic gases to have evolved after the treatment, but it was speculated that the formation of temporary toxic substances like free chlorine might be the reason for the death of yeast cells. Since the temperature in these studies was not controlled, even a few seconds at the lethal temperatures (>46°C) might have caused microbial death resulting in an experimental artifact.

Rosenberg *et al.* (1965) reported an inhibition of cell division during an electrical treatment with 2 A at 1000 Hz frequency. They used *E. coli* B and K-12 cells with platinum electrodes in their study. The temperature of the sample chamber was maintained at 37 ± 0.1°C. Microscopic examination showed that the cells ceased dividing within 1–2 h after the treatment, and began to elongate. They concluded that this inhibition effect on cell division was due to the presence

of certain group VIIIb transition metal compounds in concentrations of about 1–10 ppm.

Pareilleux and Sicard (1970) studied the effects of low voltage alternating current (50 Hz), ranging from 10 to 200 mA, on the viability of *E. coli* grown in a liquid nutrient broth medium. Stainless steel electrodes were used, and the temperature measured after the treatment was below 40°C in all experiments. The total time of exposure never exceeded 10 s. It was reported that the minimum current required to obtain bacterial kill was 25 mA. There was no decrease in the number of viable cells immediately after the treatment, but the number decreased with the holding time. The toxicity might be due to labile compounds whose effect can be inhibited by the addition of cysteine or protein in the medium. They concluded that the bactericidal effect depended on the current passing through the suspension, presence of chloride containing compounds, and the time during which the cells were left standing in the medium after the treatment. They also mentioned that the loss of viability was not high when untreated cells were added to a medium through which the current was just passed. These results seem to indicate that the mechanisms influencing bacterial death are extremely complex, involving a number of interactions between the organisms, medium and electrode material.

Shimada and Shimahara (1977) subjected *E. coli* strain B cells to an alternating current ranging from 0 to 110 mA, using a power supply source of 100V and 50 Hz. They used a glass chamber and two carbon electrodes with an electrode gap of 7.5 cm. A mixture of 0.5 mL of the suspension and 8 mL of the liquid agar medium was incubated in the glass chamber, which was submerged in a water bath to maintain the temperature below 40°C. The temperature of the culture was measured by a chromel-alumel thermocouple, but the location and time of measurement of temperature was not stated. The area of electrodes contacting the culture varied from 0–1.5 cm^2 because of shaking of the chamber at 60 or 120 strokes/min with an amplitude about 3 cm during the treatment. The electrical conductivity of the culture before and after the treatment was 8.1 and 7.8 mmho/cm at 25°C, respectively. Lag time with increased current density, and the effect of current on lag time decreased with increased concentration of inoculum. They concluded that there was no stimulative effect of electric current on the growth of *E. coli* B.

Shimada and Shimahara (1981, 1982) conducted experiments with *E. coli* B cells suspended in a phosphate buffer solution. A cell suspension of 8.5 mL (10^5 cells/mL) was exposed to a.c. of 0–300 mA/cm^2 using the same experimental setup and procedures as in their earlier studies. They also used another glass chamber with diaphragms to prevent direct contact of cell suspension with carbon electrodes. Although the method of temperature measurement was not presented, it was reported that the temperature was kept at 29 ± 3°C during the treatment. They reported the following results.

With an increase in current density or exposure time, the surviving fractions of a.c. exposed cells were found decreased. The inactivation of cells was attributed to the toxicity of hydrogen peroxide produced during the treatment, and it was confirmed that at a definite current density, the amount of hydrogen peroxide produced increased with increasing exposure time under aerobic conditions. The suspension between diaphragms had lower concentration of H_2O_2 ($<10^{-2}$ mM at 200 mA/cm^2 and 2.5 h) and higher surviving fraction (0.92) than suspension between diaphragm and electrode (0.5 mM and 2.7×10^{-3}). They indicated that H_2O_2 was also produced in the case of phosphate buffer solution without cells, and it was concluded that H_2O_2 was formed on the surface of carbon electrodes by electrolytic reduction of dissolved O_2.

The bactericidal effect was decreased when the initial concentration was increased. This was explained by the reduction in concentration of hydrogen peroxide which resulted due to the decomposition of peroxides by catalase contained in the cells. Under anaerobic conditions, surviving fractions were large compared to aerobic conditions. This was due to the unavailability of dissolved O_2 and thus H_2O_2 to cause lethal effect. Holding the treated cells in suspensions after a.c. exposure further reduced surviving fractions, and this may be because of increased reaction time of cells with hydrogen peroxide. A rise in holding temperature (after the treatment) was also reported to have an effect due to increased rate of chemical reaction.

Shimada and Shimahara (1983) reported that *E. coli* cells exposed to alternating current were injured sublethally, (measured as the inability of surviving cells to grow on a minimal medium) and inferred that the injury was caused by H_2O_2 formed on a.c. exposure. The injury developed was repaired effectively when the treated cells were incubated on a nutritionally rich medium at 37°C. It has also been reported (Shimada and Shimahara 1985a) that *E. coli* cells anaerobically exposed to a.c. (600 mA/cm^2 and 34 $\pm$ 3°C) had higher electrophoretic mobility and higher negative charge on their surface. The respiratory rate of exposed cells decreased with increasing exposure time, which may be due to increased surface charges. They suggested that the permeability of the cell membrane was modified since the stainability of a.c. exposed cells with crystal violet was low.

Shimada and Shimahara (1985b) presented results showing higher concentration of UV-absorbing materials in the supernatant fractions of the cell suspension exposed to a current density of 600 $\pm$ 60 mA/cm^2 and temperature of 34 $\pm$ 3°C. Based on an increased absorbance of 260 nm with increased exposure time, they suggested that the intracellular materials (including DNA) were released from the cells during a.c. exposure. Electron micrographs of thin sections showed more disorganized materials in the central areas within exposed (5h) cells than in unexposed (only shaken for 5h) or fresh (untreated) cells. They concluded that a.c. exposure enhanced the aggregation of DNA related materials and within cells following the leakage of cellular contents from the cells.

Electroconductive Heating

Experiments were conducted by Mizrahi *et al.* (1975) to inactivate enzymes by electroconductive heating of corn on the cob immersed in an isoelectrical conductivity aqueous system. A bath having two 6 × 14 cm aluminum plate electrodes spaced 7 cm apart was used as an electroconductive cell. When 380 V alternating current was applied to the electrodes, a 2–3°C/s temperature rise at the geometric center was observed. They have reported a complete peroxidase inactivation by this method in less than 3 min as compared to 17 min in the case of boiling water blanching. They attributed the enzyme inactivation only to heat and no other mechanism was considered in their study.

On a commercial scale, some devices (Vigerstrom 1976; Simpson 1983 and Remik 1988) accomplish heating when electric current is passed through the food, without involving any heat transfer surface. Ohmic heating involves the flow of current in a continuously flowing electrically conducting food product (Biss *et al.* 1987). Rapid and uniform heating of the food product to lethal temperatures has been reported (Skudder 1988). The contributions of electrical treatments in bactericidal action have not been reported in the literature, but no claims have been made by the manufacturers of any lethal effects other than those by heating.

It is notable that while most studies on electrical effects have been conducted at low temperatures to eliminate thermal effects, to our knowledge no studies exist that report the effect of the combination of heat and electricity in *thermally lethal* environments. This remains a topic worthy of investigation.

Electrical Stimulation of Meat

Electrical stimulation of meat is a process in which a voltage gradient of 5–10 V/cm is applied as AC pulses to the sample through the electrodes fixed at the opposite ends of the long axis of the muscle (Lawrie 1985). The information available about the effects of electrical stimulation on meat microbiology is inconsistent, but a number of researchers have shown a significant reduction in the bacterial population. Ockerman and Szczawinski (1983, 1984) observed a decrease in bacterial count when inoculated meat samples were stimulated in sterile petri dishes with 21 mA current (60 Hz a.c.) and 2 s duration shocks for 4 min. They have also shown a reduction in thermal resistance of bacteria after electrical stimulation. In these studies, the temperature of the meat samples was not measured during the treatment.

There are several hypotheses on the mechanisms by which electrical stimulation of meat can affect microorganisms, including the following.

(1) A reduction in the muscle pH value retards the microbial growth (Kotula 1981)

(2) Electrical stimulation impairs the metabolism of bacterial cells (Raccach and Hendrickson 1980)
(3) Electrical stimulation initiates the release of some proteolytic enzymes from the meat tissue which causes the bacterial death (Dutson *et al.* 1980)
(4) Changes in meat E_h (the oxidation-reduction potential) or generation of free radicals during electrical stimulation causes bacterial reduction (Mrigadat *et al.* 1980)

Since the voltages used in these studies are several orders of magnitude lower than those used in electrohydraulic shock treatments, the reasons for lethal effects appear to be different from those for the latter case. Further investigation would appear to be needed.

Microwave and Dielectric Heating

Researchers who studied microbial inactivation by microwave energy in the 1960's concluded that microbial death was caused solely by thermal mechanisms mechanisms (IFT 1989). Dreyfuss and Chipley (1980) conducted experiments with cultures of *Staphylococcus aureus* to characterize some of the effects of sublethal microwave radiation. The results indicated differences in specific enzyme activity which cannot be explained solely by thermal effects. However, the results cannot be compared due to lack of thermal control during both conventional and microwave heating. Recent studies of Khalil and Villota (1988) on microwave and conventionally heated *S. aureus* cells at a sublethal temperature of 50°C indicated a greater reduction (approximately 1 log cycle) by microwave. The temperature history of the sample during microwave and conventional heating were not presented. Greater membrane damage and slower rate of regaining enterotoxin synthesis ability were reported for microwave-heated cells. The authors also mentioned some of the reported causes of the adverse effects like breakage of hydrogen bonds and secondary linkages, release of bound water, electron tunneling and pair chain formation.

In connection with dielectric heating, some early literature (Hasché and Leumig 1935; Fleming 1944) indicated that microorganisms could be killed without the apparent aid of heat. However, the evidence was not conclusive with regard to heat resistant spores of food significance. Results of Fleming (1944) showed that one minute at 28 MHz and 10 watts was sufficient to inactivate *E. Coli* in a salt-free medium; however the addition of a few hundredths of one percent of sodium chloride reduced the degree of kill considerably. Benjamin and Ecklund (1946) indicated that 10 min exposure to a 10 MHz frequency field caused no reduction of thermophilic flat sour spores in neutral phosphate solution.

The effects of microwave and dielectric heating are clearly fields in which the knowledge gap is vast, and much further investigation is needed.

Effects of Electricity on Microbial Growth Rates

A limited amount of information exists, primarily in the medical literature, relative to the effects of electrical fields on growth of microorganisms. One of the earliest reported studies is that of Stone (1909), (cited by Rowley 1972), in which many genera of bacteria were placed in electrolytic growth media between dissimilar metallic plates. It was reported that the current generated through electrochemical reactions *stimulated* the growth of bacteria, resulting in bacterial counts 100 fold greater than for controls.

More recent literature on *in vivo* studies of electrical current effects on wound healing (Carey and Lepley 1962; Wolcott *et al.* 1969) have shown inhibition of infection when using mild electrical currents (1 to 3 mA) on wounds. Rowley (1972) reported that alternating currents of upto 30 mA at 60 Hz had little or no effect on the growth rate of *E. Coli,* while the general effect of direct current (upto 140 mA) was to increase generation time of the same microorganism. Studies using filters to reduce microbial contact with electrolytic products resulted in increased growth rates in comparison to samples without filters. The author concluded that electrolytic products therefore played a significant role in inhibition. Effects due to changing pH were ruled out, since there was no change in the pH in the vicinity of microorganisms. The difference between these results and those of Stone (1909) remain unclear, although the conditions of experiment were different in both cases.

Microbicidal Mechanisms

Although different explanations have been offered for the bactericidal property of electric current, substantiating data is not available for all the claims. Microbicidal mechanisms can be categorized into 3 major groups:

(1) Mechanical effects
(2) Chemical effects
(3) Thermal effects

(1) Mechanical Effects. There is no shock-wave formation when using low voltage alternating current; although membrane damage causing permeability modification and leakage of cellular contents was reported by Shimada and Shimahara (1985). When using high voltage impulses, the resistance of the dielectric medium leads to high instantaneous pressure pulses resulting in the formation of shock waves. Fruengal (1960) attributed the bacterial death mostly to shock waves. But, Gilliland and Speck (1967b), and Edebo and Selin (1968) tried to separate the effect of shock waves, and observed no microbicidal effect due only to mechanical action. Allen and Soike (1966), Gilliland and Speck (1967b), and Edebo and Selin (1968) did not find any morphological change due to electrohydraulic treatment using a.c. sources.

In contrast to the above findings Sale and Hamilton (1967b) reported membrane damage and its functional loss. Wesley and Williams (1968); Thomas *et al.* (1969); Peshkov *et al.* (1972); and Sytnik and Sytnik (1976) also have reported a change in morphology of bacterial cells due to high voltage discharges. The effect of electrohydraulic shock increased with voltage and number of discharges up to a particular level; whereas a reduction in capacitance reduced the volume of shock waves produced and limited the role of shock waves in the microbicidal action (Sytnik and Sytnik 1976). It is notable that many of the cases involving significant disruption of bacterial cells, d.c. pulses were used, indicating that pulse shape may have a significant effect. Unfortunately, in many cases, it is not possible to draw any definitive conclusions from relevant papers due to lack of experimental details with regard to spark gaps, field strengths, electrode materials and composition of media.

The apparent contradictions in the above findings may be at least partially understood in light of the available literature on electroporation. Under low field strengths, microbial death may be caused by entry of toxic substances through the temporarily disrupted cell membrane, leaving no evidence of mechanical disruption. It is possible that under much stronger field strengths, permanent membrane disruption occurs, resulting in death due partially to mechanical causes. In such cases, mechanical damage **would** be observed. Unfortunately, the studies showing positive evidence of mechanical damage (Sytnik and Sytnik 1976) do not contain sufficient details to permit any significant hypothesizing to such an effect.

(2) Chemical Effects. Chemical actions were considered to be the major factor for bacterial death during high voltage discharges. Formation of free oxygen and hydrogen, and hydroxyl and hydroperoxyl radicals, in addition to metal ions from the electrodes, were found to cause bacterial death (Martin 1960; Brandt *et al.* 1962; Gilliland and Speck 1967b; and Edebo *et al.* 1968). Brandt *et al.* (1962) and Edebo *et al.* (1968) also reported the residual bactericidal quality of the liquid medium subjected to electrohydraulic treatment. Gilliland and Speck (1967b) and Edebo *et al.* (1968) showed that this residual effect depends on the material of the electrodes. Lethal effect might also be due to oxidation reactions or enzyme inactivation.

The bacterial death due to chemical actions during low voltage electric treatment might be due to the presence of chloride containing compounds (Parellieux and Sicard 1970) or due to the production of hydrogen peroxide which causes a mutation of nutritional deficiency (Shimada and Shimahara 1981). Bactericidal effect during electrical stimulation may necessitate other explanations.

Bacterial death during high voltage pulses was also explained by mutations induced (Gossling 1960), lysis of protoplasts (Sale and Hamilton 1967b) and photon emissions from arc plasma (Edebo 1968). Sytnik and Sytnik (1976) has reported that the formation of a low temperature plasma, which contains the

energy of ionization, excitation, and dissociation, caused lethal effect. Bactericidal action during low voltage treatment might also be due to a reduction in pH (Kotula 1981) and release of proteolytic enzymes (Dutson 1980).

Thus, chemical action during high voltage pulses depends on the type of microorganism, initial concentration of cells, volume of the medium used, distribution of chemical radicals, and electrode material. The findings in the literature indicate that the interactions of these variables are extremely complex, and studies must be conducted with a high degree of control and care to ensure reproducibility of results. In relation to electrical impulses, as indicated in the preceding section, reversible membrane disruption could permit entry of potentially toxic materials.

(3) Thermal Effects. The thermal effect seems to have no role in bacterial kill during high voltage pulses, since the temperature rise reported by many researchers was only a few degrees. However, the flow of low voltage alternating current in an electrically conducting medium was found to generate heat which causes bacterial death (Biss *et al.* 1987 and Skudder 1988). Enzyme inactivation by low voltage treatment was reported by Mizrahi *et al.* (1975). A rapid heating of the medium to high temperatures was observed by many researchers.

In cases of thermally lethal treatment, it has generally not been possible to separate thermal and nonthermal effects. Experimental difficulties are quite considerable because it becomes necessary to expose a control sample to the same thermal history as an electrically heated sample in order to conduct meaningful comparisons. Thus, the effect of electricity under thermally lethal conditions remains to be studied.

CONCLUSIONS AND FUTURE NEEDS

Shock waves and chemical actions are important factors for bactericidal action when using high voltage impulses. Cell destruction or membrane damage was observed by several recent researchers. This could be either due to mechanical or chemical actions. Formation of chemical radicals and metal ions from the electrodes where found to cause bacterial death. The bactericidal action is tremendously increased due to the forced penetration of chemical compounds through the cell walls of microorganisms, under the action of great shock wave pressure. Thermal effect has a limited role when using high voltage pulses, whereas it is the major factor for bacterial death when using low voltage alternating current or continuous flow through the medium. The effects of combinations of electrical and heat treatments needs to be further characterized.

The literature relevant to electric current and microbial death has been summarized and reviewed critically in this report. In several cases, independent researchers have obtained different results, but experimental details are insuf-

ficient to permit meaningful comparisons. Experimental conditions have varied widely and several results are apparently contradictory. The mechanisms involved in bacterial death are not yet clearly determined and not fully understood. The same applies to the influence of electricity on microbial growth. Further research must be conducted to differentiate between thermal, electrical (if there is any), and combination (thermal and others) effects and their interrelationships.

Finally, it may be helpful to quote Benjamin Franklin, who upon being electrically shocked during an experiment, is reported to have said: "If no other use is discovered for electricity, it will always serve to make a vain man humble."

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

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