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Edited by D. R. Heldman, Michigan State University

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QUALITY OF FROZEN FOODS — A REVIEW

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INTRODUCTION

Quality of foods has been defined by Kramer and Twigg (1968) as the composite of characteristics which differentiate individual units and have significance in determining the degree of acceptability of the unit by the user. The overall quality of a food product may be expressed by component characteristics, each of which may be measured, and possibly controlled independently. The nutritive value, flavor, color and texture of the food are preserved by delaying chemical changes, retarding enzyme action and eliminating microbial growth.

Many quality changes during frozen storage of foods are unsolved problems. A major reason is insufficient knowledge of causes of deterioration necessary to predict accurately either character or rate of quality deterioration. The study of methods of retaining quality of frozen foods is an inviting field of research for the food engineer as well as chemist, bacteriologist and food technologist. Several studies in the past have focused on quality changes in frozen foods. The major goal of this paper is to review quality changes in foods important during frozen storage.

CHANGES DURING FROZEN STORAGE OF FOODS

Fundamentally, freezing inhibits the agents responsible for spoilage at room temperatures without causing major alterations in appearance, odor and flavor. It should be recognized that freezing cannot improve the quality of a particular commodity. It cannot even completely

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preserve the quality; some deterioration will inevitably take place even in freezer storage (Luh *et al.* 1975). Among other preservation methods, freezing is one of the better approaches to preserving overall quality in foods. According to Olson and Dietrich (1968, 1969), properly blanched, frozen and packaged vegetables including cauliflower, green beans, peas and spinach can be kept at −29°C for 5 years without measurable change in color, flavor, chemical constituents and physical attributes.

Food materials are never completely frozen during normal commercial storage; thus the food products are not inert during commercial frozen storage. Deteriorative chemical and physical changes occur continually, at a rate governed by the storage temperature and the type of product. Generally, as the storage temperature of the product is lowered the rate of deterioration decreases. At any given storage temperature, large differences are found in the rate at which various products deteriorate (Fennema and Powrie 1964). Recently some published research papers show a reversal phenomenon, indicating an increase in rates of certain reactions with decreasing temperatures. These reactions will be discussed later in this paper.

Biological changes are essentially stopped at −80°C. However, this temperature is not possible or practical in most commercial storage facilities. In addition, such a low temperature would not be necessary for quality maintenance during the normal length of commercial storage. Temperatures of −18°C or below have generally been recommended for storage of frozen foods (Klose *et al.* 1959; Khan *et al.* 1963). Fish, particularly fatty fish, and ice cream, for example, should preferably be kept between −23° to −29°C.

Several physical mechanisms can cause deteriorative effects on the product during freezing and frozen storage. Concentration of food components during slow freezing can result in changes such as denaturation of a protein in certain frozen fish. Nonenzymatic oxidative changes may result in the formation of rancid off-flavor in frozen meats and loss of ascorbic acid in fruits and vegetables. Local dehydration causes deteriorative reactions to occur more rapidly in localized areas of a food product. Hydrolysis may occur in vegetables causing conversion of chlorophyll to pheophytin thus change from bright green to yellow color. Crystallization of sugar in frozen storage of high-sugar spreads causes moldy surface appearance. In ice cream, crystallization causes "sandy" texture. Other important textural changes may occur in frozen storage of fish due to desiccation. To maintain a high-quality product during frozen storage these mechanisms need to be carefully examined.

Physical Changes

The physical changes which occur during freezing and storage of frozen products comprise crystallization of ice with expansion of the volume, and desiccation starting from the surface of the frozen foods (Heen and Karsti 1965). The distribution of ice crystals in frozen tissue and cellular suspensions is important. In general, slow freezing will produce large crystals located exclusively in extracellular areas. This statement applies to both plant and animal tissue (Fennema and Powrie 1964). On the other hand, rapid freezing to a low temperature will generally result in tiny ice crystals, located both extra- and intracellularly. Meryman (1956) has suggested two reasons to explain occurrence of extracellular crystallization in preference to intracellular crystallization during slow freezing:

(1) The freezing point of the extracellular material may be higher than that of the intracellular materials.

(2) The intracellular materials may be deficient in heterogeneous nucleation sites.

An important problem encountered during frozen storage is desiccation. Since refrigeration coils are located inside a cold storage room, poorly protected packages are subject to loss of moisture. Kramer (1966) discussed weight losses in a study of retail size cartons of frozen vegetables packed in paperboard cartons with various degrees of protection. High moisture products stored under frozen conditions for considerable periods of time must be packaged in materials which provide a good barrier to water vapor. Nutting *et al.* (1960) showed a direct correlation between the weight of the waxed paper and the rate of moisture loss, the heavier waxed paper overwrap reducing the rate of moisture loss further.

Fluctuations in storage temperature influence the loss of weight and quality of frozen foods due to desiccation, and contribute to a poor appearance of the product. This phenomenon is sometimes referred to as "freezer burn." In case of frozen fish storage, if the desiccation is pronounced, the fish surface may become dry and fibrous; in some cases the skin may change color. During storage of frozen herring the desiccation may also result in loss of flavor and color and may contribute to more rapid development of rancidity (Heen and Karsti 1965).

Frozen tuna and swordfish may exhibit green and brown discoloration on cooking, which may lead to rejection of the product by consumers. Browning is due to formation of metmyoglobin in the muscle through autoxidation of ferrous myoglobin. Greening is due to pigments resulting from the oxidation of hemochrome that occurs when the meat is unduly exposed to oxidative conditions during and after cooking (Brown and Dolev 1963; Heen and Karsti 1965). Freezing increases toughness of fish muscle, which proceeds progressively during subsequent storage. Love (1958, 1959) and Love and Mackey (1962) devised a method to measure toughness of uncooked cod muscle.

The damage (or "freezing injury") of frozen foods has been attributed to a number of factors, one of which is mechanical stress. Mechanical stress can arise from changes in volume associated with liquid-solid transformation, from the dislocation of water that accompanies slow freezing, from recrystallization, or simply from temperature gradients within the product. Rapid freezing coupled with low final temperatures will nearly always result in severe cracking of food containing large percentages of water. While examining this effect in freezing green beans in liquid nitrogen, Reeve and Brown (1968) suggested that cracking was probably the result of nonuniform contraction following solidification. Love (1966) suggested it is Langham-Mason effect, rupturing of the outer frozen shell when the interior freezes and expands. The actual mechanism of stress cracking may involve both effects. Fennema (1973) suggested that another effect of rapid freezing is to minimize loss of gases from the intercellular spaces of plant tissues. All these postulates need further investigation.

Chemical Changes

Included among the types of chemical changes that can proceed during frozen storage are lipid oxidation, enzymatic browning, flavor deterioration, protein insolubilization and degradation of chlorophyll, other pigments and vitamins (Fennema 1973).

The nutritive values of frozen foods are of concern both to the consumer and the manufacturer. On the whole the nutritive values of foods preserved by freezing are well retained. However, losses of nutrients occur in one or more steps between the time of production and the ultimate use by the consumer (Watt 1968; Van der Berg and Lentz 1974).

The temperature and duration of frozen storage are important factors affecting nutritive values. The ascorbic acid is considered to be protective of other nutrients. Many frozen fruits and vegetables may lose some ascorbic acid unless they are held at temperatures well below −18°C or protected by other means during wholesale, retail storage, distribution, and storage in the home (Watt 1968).

Residual enzyme activity in frozen vegetables may be involved in oxidative reactions (Joslyn 1966; Olson and Dietrich 1968). The fact that oxygen is involved in all these reactions suggests that exclusion of air prior to freezing would be a distinct advantage. The changes associated with the oxidation can be inhibited by the application of additional technical means including modified gaseous atmosphere, vacuum packaging and treatment by antioxidants (Piskarev *et al.* 1976). The application of these means makes it possible to protect the surface of products from oxygen of the air and may not inhibit the quality changes caused by the action of enzymes and other biochemical changes that occur within the product. They also reported that nitrogen packaging of pork, vacuum packaging of beef and ascorbic acid treatment of fish can improve keeping quality at −30°C storage which is suggested to be best of the storage temperatures studied for pork, beef, fish and butter.

The peroxide formation (representing quality degradation) decreases with lowering temperatures for many products (Fig. 1). The use of different packaging methods and antioxidants in addition to refrigeration have a considerable effect on the preservation of quality during storage of frozen products.

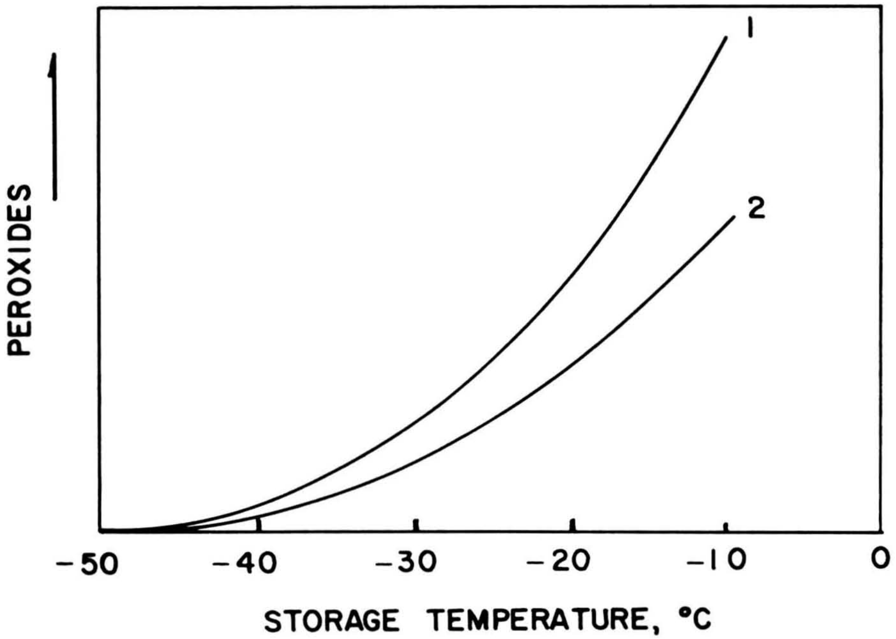

FIG. 1. DEPENDENCE OF PEROXIDE FORMATION ON VARIOUS STORAGE TEMPERATURES: (1) WITHOUT THE USE OF ANTIOXIDANTS AND ADDITIONAL PACKAGING MEANS, AND (2) WITH THE USE OF ANTIOXIDANTS AND ADDITIONAL PACKAGING MEANS

Packaging with carbon dioxide has been suggested by Gibbons (1953) as a means of preventing the development of rancidity in bacon. He reported that bacon stored in air at −10°C was definitely rancid after four months; bacon stored in carbon dioxide was not rancid after seven months and only slightly rancid after 12 months. Arafa and Chen (1976) found vacuum packaging of precooked and prefried chicken to be better than other packaging methods. Tomasyan (1974) and Bogh-Sorensen (1975) studied the effect of various packaging methods on the quality of frozen fish and broilers respectively.

The sensitivity of oils and fats to oxidative deterioration is of particular significance in the preservation of fish by freezing (Lane 1964, 1966). The fundamental deteriorative reaction is generally accepted to be the autoxidation of unsaturated fatty acids, which are abundant in fish lipids. No doubt the highly unsaturated fatty acids are very reactive. Consequently, fatty fish in particular are very susceptible to oxidative changes. Additionally there are enzyme systems in the tissue acting as pro-oxidants which may play an equally important part in oxidation and the resulting rancidity (Heen and Karsti 1965).

Enzymatically accelerated oxidative deterioration is usually controlled by a heat treatment, i.e., blanching in steam or boiling water, prior to freezing. Chemical changes due to oxidation of unblanched food include loss of ascorbic acid, rancidity and allied off-flavors (Van Arsdel *et al.* 1969).

Lee and Labuza (1975) studied the destruction of ascorbic acid as a function of water activity. Pluzhnikov *et al.* (1973) studied the decomposition of ascorbic acid of frozen peppers. They found that ascorbic acid loss showed a high correlation with unfrozen water.

The chemistry of off-flavor formation in frozen fruits and vegetables is a topic that needs further study. Burnette (1977) has extensively reviewed peroxidase and its relationship to food flavor and quality. The most usual kind of off-flavor in meat and fish, namely rancidity, has been studied by Awad *et al.* (1969) and Enser (1974). Awad *et al.* (1969) found the total lipid of whitefish muscle did not change during storage at −10°C for 16 weeks, but the TBA numbers increased when the unsaturated fatty acid was degraded.

RATE OF REACTIONS IN FROZEN FOODS

As long as one limiting reaction exists, the quality stability increases with lowering temperatures in an approximately exponential relationship. Kinetic theory is fundamental to the explanation of many of the changes which occur during common processes. It serves as a basis for describing the rates at which various processes occur during the processing and storage of foods. The rate of a reaction is expressed as the rate of change of concentration with time at a constant temperature:

$$-\frac{dC}{dt} = kC^n \tag{1}$$

where C = concentration of quality index
t = time
k = rate constant
n = order of the reaction

The effect of temperature on the reaction rate is expressed through effect of temperature on the rate constant. If the temperature range is not too large, the dependence of rate constant on temperature can usually be represented by an empirical equation proposed by Arrhenius (Charm 1971).

$$k = Ae^{-Ea/RT} \tag{2}$$

where A = pre-exponential
Ea = activation energy
R = gas constant
T = absolute temperature

The storage temperature has an important effect upon quality stability of frozen foods. Every quality change requires a finite amount of time. The rate of change is controlled by the rate at which the slowest reaction of the complex of food takes place.

Kinetics in Frozen Food Systems

Although storage temperature has effect on the reactions in frozen food systems, different products held at any given temperature differ greatly in their storage behavior. Furthermore, a change in storage temperature affects the storage behavior of some products to a much greater extent than it does others.

To show the influence of temperature on the rate at which ascorbic acid is lost in frozen spinach during storage Charm (1971) used the Arrhenius equation (Equation 2). He plotted the data published by Dietrich *et al.* (1960) on semilogarithmic coordinates as shown in Fig. 2. A distinct change in the kinetics of the reaction apparently occurs

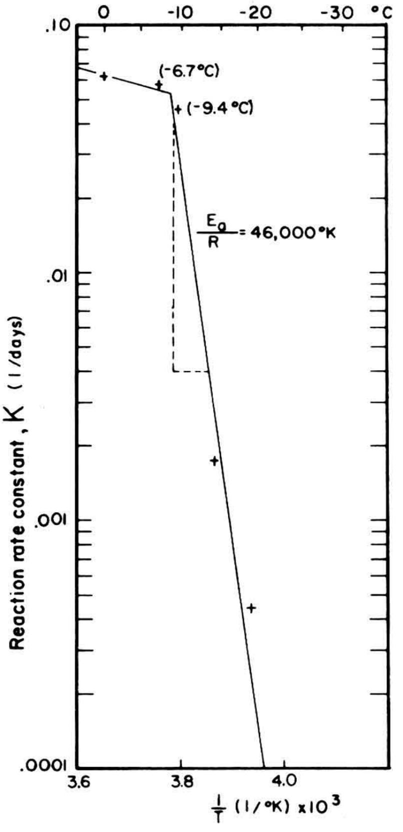

FIG. 2. THE REACTION RATE DEPENDENCE ON TEMPERATURE (adapted from Charm, 1971)

between −6.7°C and −9.4°C. This indicates a lower activation energy above −6.7°C accounting for greater rate of degradation of ascorbic acid from the product. The observed change in kinetics between −6.7°C and −9.4°C suggests that another reaction in the chain may be governing the rate of the reaction at lower temperatures.

Researchers have shown that temperature lowering causes some enzymatic or nonenzymatic reactions to undergo a change in kinetic order. Sizer and Josephson (1942) studied the kinetics of lipase with glycerol present. The change of state in this system occurred at −18.5°C but a sharp break in the relationship of rate to temperature occurred at −1.5°C while the system was still liquid. Lund *et al.* (1969) studied the influence of cooling and freezing on the first-order reaction rate constant for hydrolysis of sucrose catalyzed by invertase. They found similar effects of change in the kinetics of reaction near 0°C.

Dietrich *et al.* (1960) studied the rate and extent of changes in chlorophyll, ascorbic acid, physical properties, and organoleptic quality of commercially processed spinach. They found that significant deterioration occurred above −18°C within periods of handling that may be experienced in commercial practice. They found that measurable rate increased by a multiple of 10 for about each 8°C rise in temperature between −18°C and −4°C.

Negative Effect of Temperature

In recent years it has become evident that certain chemical reactions, enzymatic as well as nonenzymatic, proceed more rapidly at temperatures below freezing. These studies lead to the possibility of reducing stability with decreasing temperatures during frozen storage.

Fennema (1973) has indicated that in certain reactions temperature decrease may result in increased rate of chemical reactions. Lindelov (1976) emphasized that a system can be completely solid only when it is below its eutectic point. It seems best to consider that a "frozen state" exists in the temperature range below the freezing point and above the eutectic, i.e., when the solid is in equilibrium with a liquid phase. The phenomenon is illustrated in Fig. 3 for a system in a state of solid-liquid equilibrium. For certain systems the rate of reaction may increase as the temperature decreases below the freezing point and reaches a maximum near the eutectic point. Below the eutectic point where water bound to the protein remains unfrozen, the rate of reaction would decrease again and approach the rate near the freezing point. It should be emphasized that maximum reaction rates usually do not coincide with final eutectic points in biological systems. In addition, solutes often tend to supersaturate during freezing so that liquid other than that which is bound to proteins (and other solutes) can often exist below the final eutectic point.

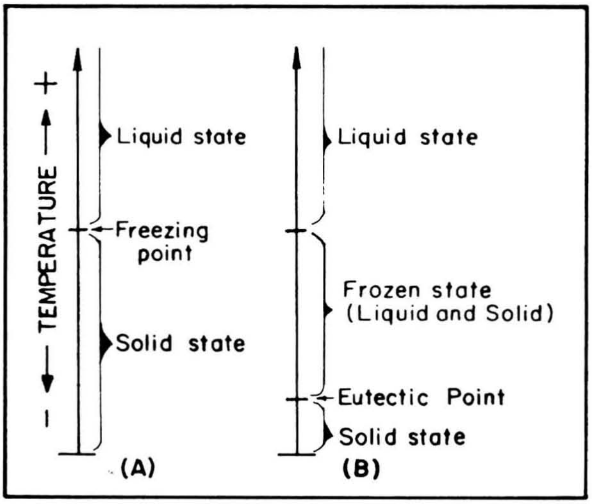

FIG. 3. A: ONE COMPONENT, THE TRANSITION FROM LIQUID TO SOLID PHASE OCCURS SHARPLY. B: TWO OR MORE COMPONENTS (e.g., FOODSTUFF), THE LIQUID TO SOLID PHASE CHANGE OCCURS OVER A RANGE OF TEMPERATURE

The system is assumed in a state of solid-liquid equilibrium.

Anderson and Ravesi (1969) found that the reaction rate of free fatty acids with protein in cod muscle was greater at −29°C than at temperatures a few degrees above 0°C. Pincock and Lin (1973) studied the denaturation of α-chymostrypsin in frozen solutions. The denaturation rate increased as temperature decreased from −5, −10, to −12°C, but was slower at −16°C than at −12°C.

Reactions representing the progress of glycolysis in frozen muscle have been studied for many years. Behnke *et al.* (1973) found that the rate of adenosine triphosphate (ATP) depletion and lactate accumulation in both chicken and beef muscles were significantly faster at −3°C (frozen) than at 10° or 0°C (unfrozen).

The storage of frozen salted meat at incorrect temperatures can lead to severe losses in quality. Gibbons (1953) stated that lowering storage temperatures resulted in greater accumulation of peroxide oxygen in bacon. He reported that microbiological activity influences the quality at lower temperatures. In studying the storage life of sliced bacon packed in 70μ polyethylene bags without vacuum, Poulsen and Lindelov (1975) found sliced bacon had an abnormal temperature profile between 0°C and −40°C. They concluded that −30°C gives a significantly shorter ($p = .05$) shelf-life than −18°C storage for sliced bacon.

Thompson and Fennema (1971) studied the rate of oxidation of L-ascorbic acid in acetate buffer solutions. Samples which were initially dilute and therefore capable of dissolving substantial quantities of oxygen, and those which had pH values of 5.5, exhibited upon freezing either an increased rate of oxidation of ascorbic acid or a smaller than expected decrease in rate. But at higher initial concentrations and a pH value of 4.6, expected decreases in the rate of oxidation of ascorbic acid were observed upon freezing.

Poulsen and Lindelov (1975) studied the rate of reaction between myosin and malonaldehyde (Fig. 4). The reaction rate decreased as the temperature was reduced from 45°C to 0°C. When the mixture is frozen, however, the reaction rate increases once again to the level found at 45°C and the maximum reaction rate for the system is found at −24°C. Brown and Dolev (1963) found similar reversed stability in autoxidation of beef and tuna solutions at temperature range of −5° to −18°C.

Lindelov and Poulsen (1975) studied smoked bacon, liver paste and chopped herring fillets. They found negative effect of temperature in some temperature ranges in these frozen foods. Because some products with added salt show a complex relation between temperature and storage life, lower temperatures do not always result in a better keeping quality (McWeeny 1968).

Other published research papers concerning negative effect of

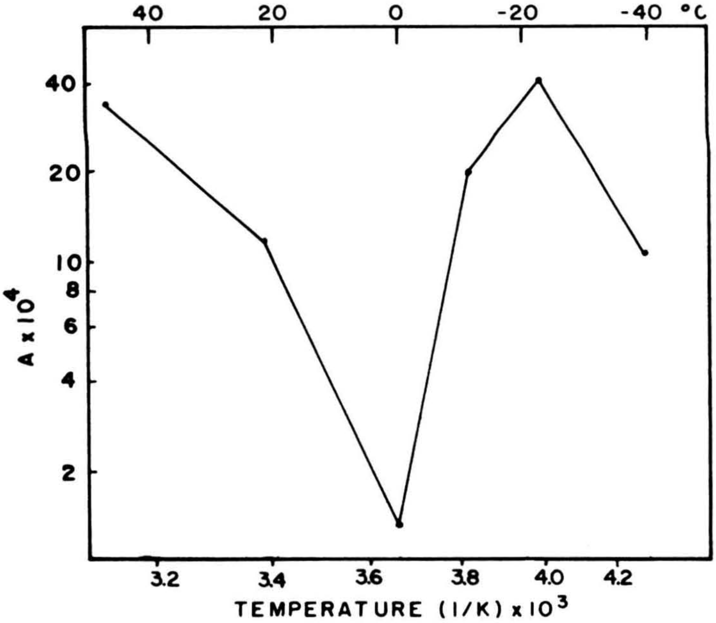

FIG. 4. RATE OF REACTION (REACTION RATE NUMBER A) OF MYOSIN AND MALONALDEHYDE

Reaction at pH 7.0 in 0.026 M phosphate plus 0.45 M KCl (from Poulson and Lindelov 1975).

temperature can be found in various publications (Buttkus 1967; Grant 1966; Grant and Auburn 1967; Fan and Tannenbaum 1973; Lindelov 1976; Mullenax and Lopez 1975; Poulsen *et al.* 1975; Curda *et al.* 1976).

Fennema (1973) has summarized the possible reasons for the negative effect of temperature as one or more of the following factors: freeze concentration effect; catalytic effect of ice crystals; greater mobility of protons in ice than in water; favorable orientation of reactants in the partially frozen state; decrease in dielectric constant; or development of antioxidants at higher temperatures.

EFFECTS OF FLUCTUATING TEMPERATURE

Many investigators have suggested that an ideal temperature condition for retaining the quality of frozen foods is to keep the food at a constant -18°C or lower temperature. It is usually possible to maintain

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the −18°C or lower temperature, but it is impossible to keep the temperature constant. During handling, transporting and storage the temperature of foods may fluctuate.

Information on handling, storage, and distribution of frozen foods has been reviewed by Diehl (1969). It is evident that unduly high temperatures—steady or fluctuating—would produce cumulative adverse effects on frozen-food quality.

The general opinion of research workers is that the fluctuating temperatures would cause excessive desiccation of the stored products, and thereby lower the quality. Woodroof and Shelor (1947) found that fluctuation between −23.3 and −12.2°C caused more damage to quality than storage at the steady mean temperature of −18°C, and was even worse than storing at a steady temperature of −12.2°C, the maximum temperature of the cycle. Hustrulid and Winter (1943) found a fluctuating storage temperature between −18°C to −28.9°C had no significant influence on the quality of properly packaged frozen fruits and vegetables. Many researchers obtained similar results including time-temperature tolerance (T-TT) studies conducted at Western Utilization Research and Development Division, U.S. Department of Agriculture (Hustrulid *et al.* 1949; Gortner *et al.* 1948; Klose *et al.* 1955; Van Arsdel *et al.* 1969; Schober and Munkner 1975).

According to Heen and Karsti (1965) there are two kinds of fluctuations in storage temperature. The first is the regular and unavoidable small fluctuations (1–2°C) resulting from the periodic operations of refrigerating machines. Such fluctuations have negligible effects on storage life of frozen foods. The other fluctuation is related to removal of frozen foods from cold storage to transport and to transfer from vessels to trucks and to retail cabinets. This fluctuation of the order of 10°C may have a definite detrimental effect, as shown by Pottinger (1952), Dyer *et al.* (1957a, b) and Kozima and Nakabayasi (1976).

In somewhat higher temperature ranges, where partial thawing and microbial growth become important factors, additional work is needed to establish the relative importance of temperature fluctuations.

Fennema and Powrie (1964) concluded that fluctuating storage temperatures should generally be avoided. Although the chemical properties of food materials are usually not damaged by fluctuating storage temperatures, the physical properties may be. This is particularly true of products with unstable textures, such as ice cream, gels, and many plant tissues.

McNutt and Lee (1974) studied the influence of freeze-thaw cycles on ready-to-eat prepared frozen foods. Beef stew and chicken a la king seemed to be the most affected with a breakdown of the sauce and softening texture in the vegetables, beginning with the first freeze-thawing cycle. Liquid separation in frozen white sauce, as affected by storage conditions, was studied by Hanson *et al.* (1957). As shown in Fig. 5, a low and uniform temperature is essential for good stability of frozen white sauce.

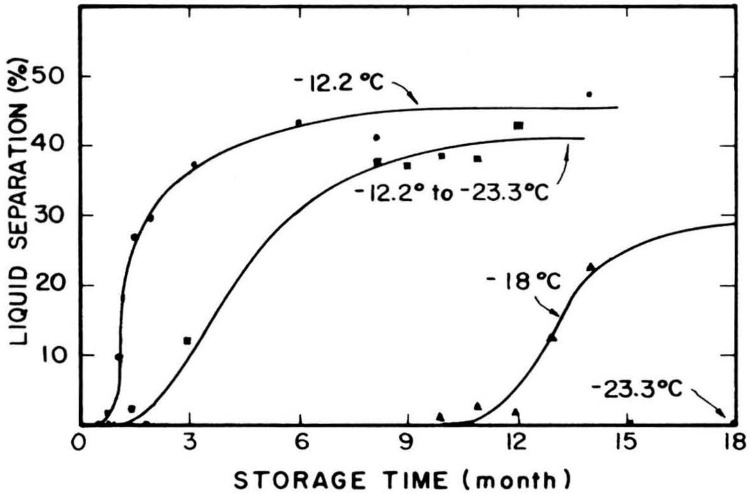

FIG. 5. EFFECT OF CONSTANT AND FLUCTUATING TEMPERATURES ON STORAGE STABILITY OF FROZEN WHITE SAUCE THICKENED WITH WAXY RICE FLOUR (from Hanson *et al.*, 1957)

Kramer *et al.* (1976) studied prepared foods containing protein concentrates, such as texturized vegetable protein. The frozen samples were stored in six freezer chambers. Three of the chambers were maintained at constant temperatures of −10, −20, and −30°C. The other three chambers were maintained at the same temperatures, but with fluctuations of ±5°C. They found fluctuating temperatures generally had detrimental effects on texture and flavor.

Schwimmer Theory

Schwimmer *et al.* (1955) studied the effect of temperature fluctuation on the quality of frozen foods. As temperature fluctuates with time according to some regular periodic wave such as saw-toothed wave, square wave, and sine wave (Fig. 6), they proved that the extent of reaction after a period of time will be the same as it would have been if the material had been held at a certain steady "effective" temperature

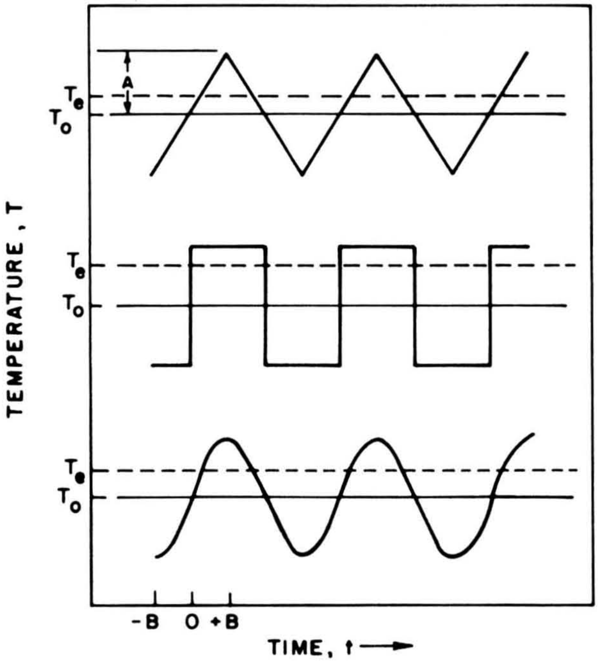

FIG. 6. DEFINITION OF PARAMETERS FOR THREE MODES OF TEMPERATURE FLUCTUATION (Schwimmer *et al.*, 1955)

for the same length of time. For example, if the temperature fluctuates as a sine wave, it can be expressed as:

$$T = T_o + \sin \frac{\pi t}{2B} \tag{3}$$

The average rate of reaction during one cycle is

$$\bar{R} = \frac{R_o}{2B} \int_{-B}^{B} Q_A^{\sin \frac{\pi t}{2B}} dt \tag{4}$$

Schwimmer integrated this equation term-by-term by using the power series. Then the average rate can be written:

$$\bar{R} = R_o Q_A^{\alpha} \tag{5}$$

The relationship between Q_A and α is shown in Fig. 7. It is customary to express the temperature coefficient of a chemical reaction as the quotient, Q_{10}, of the rate at temperature T°C divided by rate at (T − 10°C). The relationship between Q_{10} and Q_A is shown in Fig. 8.

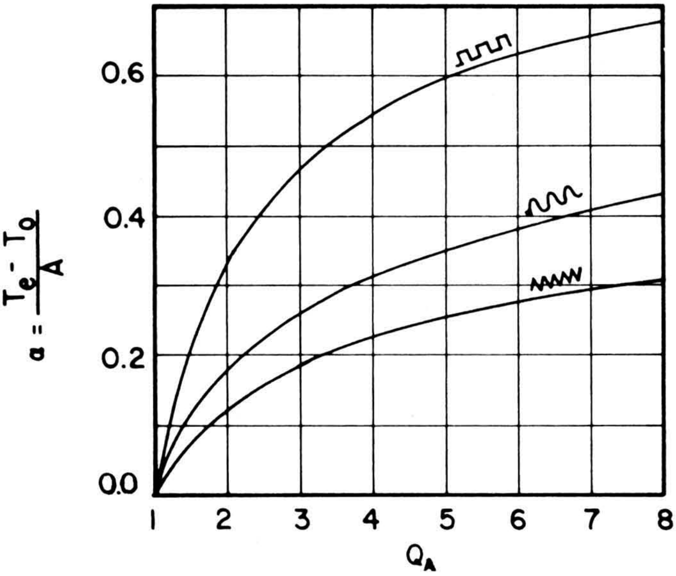

FIG. 7. RELATION BETWEEN A FUNCTION OF EFFECTIVE TEMPERATURE, α, AND AMPLITUDE, A, OF CYCLE (Schwimmer *et al.*, 1955)

The procedure of calculating effective temperature is summarized in the following. It is desired to determine the effective temperature of frozen spinach stored at temperatures with sine wave fluctuations. If the temperature fluctuates between −10° to −20°C, the average temperature quotient, Q_{10} is equal to 9 (Van Arsdel 1969). Since A, half of the amplitude, is equal to 5; from Fig. 8, Q_A is determined to be 3. From Fig. 7, the added fraction of the amplitude α is 0.26, and the effective temperature is 0.26 × 5.0 above the mean temperature, therefore, $T_e = -15°C + 1.3°C = -13.7°C$.

For values of Q_{10} greater than unity, the effective temperature exceeds the mean temperature; the differences are greater for the square wave and smaller for the saw-toothed wave. The amplitude (degree of temperature fluctuation) changes will influence the effective temperature, but changes of period of fluctuating cycles will not influence the effective temperature. In modeling quality changes during frozen storage Singh (1976) obtained similar results.

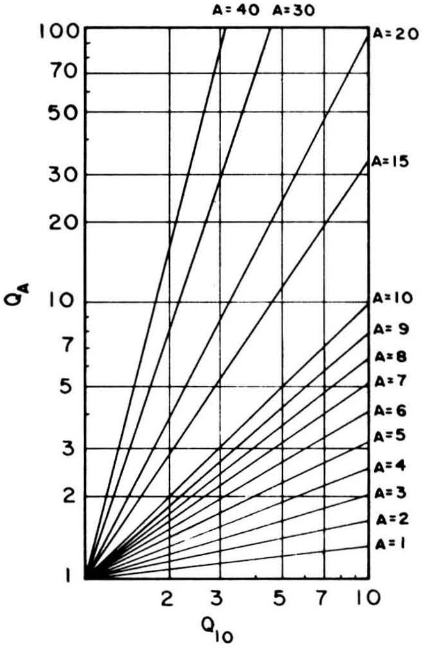

FIG. 8. VARIATION OF Q_{10} AND Q_A FOR VALUES OF A (Schwimmer *et al.*, 1955)

The effective temperature is only a degree or so above the arithmetic mean temperature of fluctuating storage temperatures. This has been confirmed by numerous experiments (Gortner *et al.* 1948; Hustrulid *et al.* 1949; Klose *et al.* 1955; Van Arsdel *et al.* 1969).

There are limitations in the Schwimmer's theory as pointed out by Van Arsdel (1969). Schwimmer assumed a single kind of deteriorative reaction, with a constant temperature quotient. Actually, if two or more reactions with different temperature quotients proceed simultaneously the overall effect will be different.

In a survey conducted by Van der Berg (1966), clumping of the product and surface discoloration (freezer burn) increased with the amount of frost present in the package. About 80% of the packages contained an appreciable amount of frost, and 14% contained an excessive amount of frost within the retail packages of frozen vegetables studied. The effect of temperature fluctuation upon the rate of in-package frost and cavity ice formation has been found by Gortner *et al.* (1948) and Klose *et al.* (1955). The conclusions of their studies were that frost formation increased with temperature, and for the −23.3°C to −12.2°C fluctuation frost formation was considerably greater than for the highest, −12.2°C, constant temperature.

Time-Temperature Tolerance (T-TT) Method

The fluctuating temperature during frozen storage and transportation is not a regular saw-toothed, square wave, or sine wave. Thus Schwimmer's theory lacked practical application since its publication in 1955. Van Arsdel and Guadagni (1959) published a method for the estimation of the accumulated quality change in a product which has experienced an irregular but known temperature history. This method was named Time-Temperature Tolerance (T-TT) method. The method involves determination of the area beneath the corresponding irregular time-temperature curve plotted on a transformed coordinate system derived from, and depending on, the observed relation between relative rate of change and temperature. The area beneath the curve is proportional to the total amount of change in the measured quality. This is equivalent to graphical integration over the temperature history. Using this procedure, good agreement was obtained between calculated and actual experimental values of color and ascorbic acid changes at various points in an irregular time-temperature pattern. This is in agreement with results from regularly fluctuating temperatures in Guadagni and Nimmo (1958) and shows that temperature variation has no special effect.

Using T-TT method, Van Arsdel and Guadagni (1959) compared the experimental data and calculated data on quality changes in frozen strawberries, sliced peaches, and raspberries.

Jul (1963) used T-TT method quite extensively in combination with data obtained by Munter *et al.* (1953). Van Arsdel (1969) reviewed the method for estimating quality change of frozen food. As an example, he estimated quality changes in frozen chickens. Based on data for minimum storage life of frozen chicken, he plotted the reciprocals of storage times, (month^{-1}), against temperature, as shown in Fig. 9. The assumed temperature history is plotted in Fig. 10. From these data, Van Arsdel found the equivalent duration of storage at steady temperature of —18°C. He calculated the length of time at which these frozen chicken could be held at the final temperature of —21°C before it reached the end of its expected minimum storage life. The temperature history was plotted on a special coordinate system, as shown in Fig. 11. The temperature ordinate is spaced proportionally to the corresponding ordinate in Fig. 9; for example, it is spaced 0.442 units from the baseline for —9.4°C and 0.105 units for —18°C. After plotting the temperature history on this special coordinate grid, planimeter was used to measure the area under the curve, which for the above example is 0.61. Thus 61% of the minimum storage life is deteriorated and only 39% remains. Because the rate of change at —18°C is 0.105 (month)$^{-1}$, product stored at steady temperature of —18°C for 5.8 months (.61/.105) would have the same extent of change. The rate of change at —21°C is 0.063 (month)$^{-1}$, thus for additional 6.2 months the remaining 39% of product life would be deteriorated.

In studying time-temperature tolerance of frozen foods, Bengtsson *et al.* (1972) pointed out that T-TT relationships are not mathematical functions but empirical data subject to large variability, particularly because of variations in product, processing methods and packaging. They emphasized that to evaluate the quality of frozen foods it is

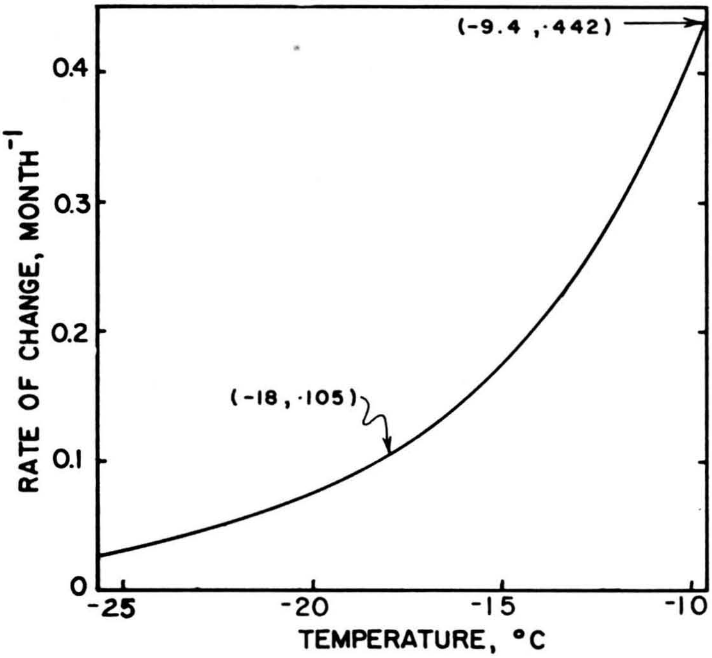

FIG. 9. RATE OF CHANGE OF ACCEPTABILITY IN FROZEN CHICKEN (adapted from Van Arsdel 1969)

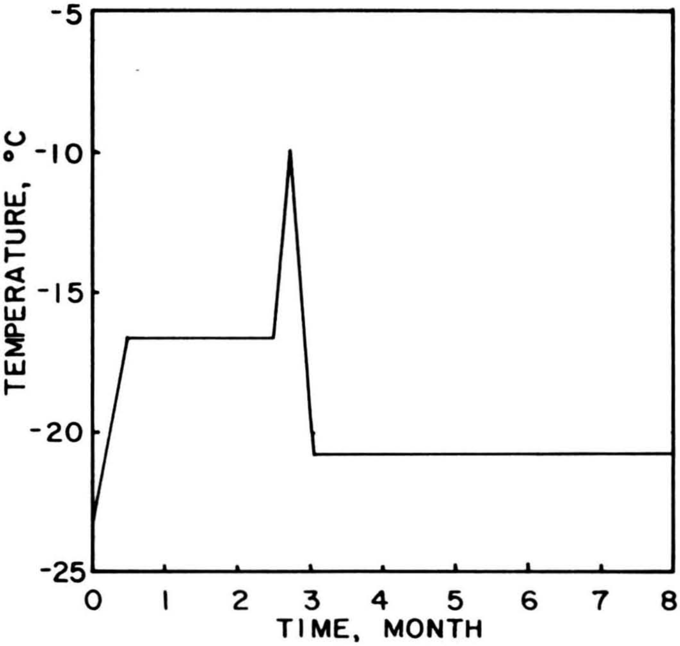

FIG. 10. TEMPERATURE HISTORY ASSUMED FOR EXAMPLE IN TEXT (adapted from Van Arsdel 1969)

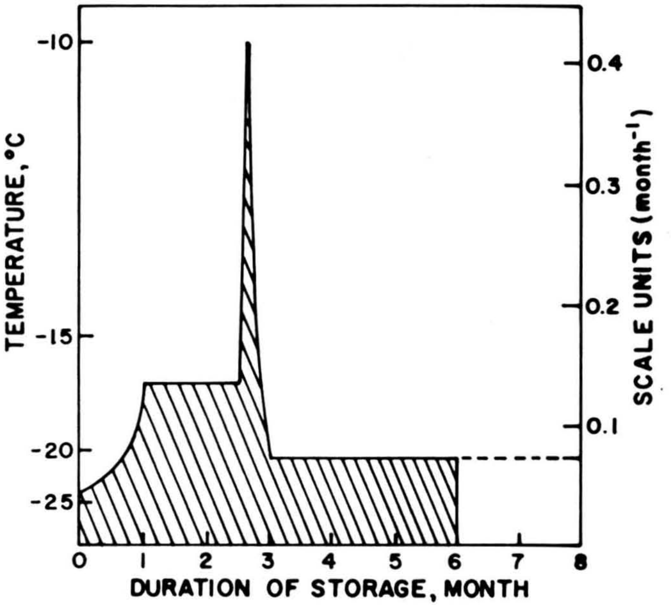

FIG. 11. TRANSFORMED COORDINATE GRID WITH THE SPECIFIED TEMPERATURE HISTORY
(from Van Arsdel *et al.*, 1969)

necessary to study the product processing and packaging factors in addition to T-TT relationships.

Computer-Aided Simulation

The above two methods cannot be easily used in computer-aided simulation of storage life for frozen foods. Schwimmer's theory is only suitable for three special regular temperature fluctuation patterns. T-TT method must use graphic integration to find required value. Singh (1976) used a mathematical interpolating formula to find the quality change during frozen storage using computer-aided simulation. The method is illustrated in the following.

Brown and Dolev (1963) published experimental data on rates of oxidation of purified beef oxymyoglobin at various storage temperatures. From their study, the computed first-order rate constants at various temperatures at 0.1 M phosphate buffer are presented in Fig. 12. It is obvious from the figure that the rate of reaction is the lowest at —5°C storage temperature. The reaction rate increases as storage temperature is either lowered below or increased above —5°C.

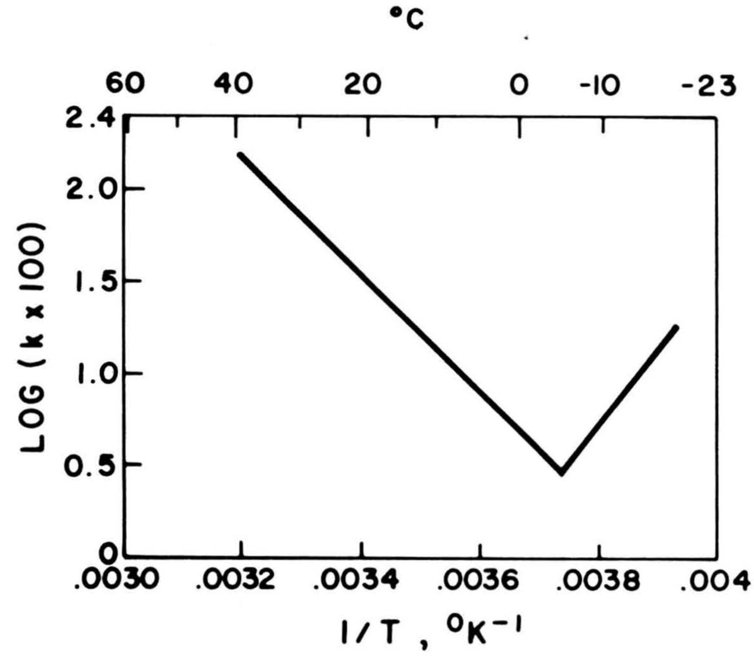

FIG. 12. RATES OF OXIDATION OF OXYMYOGLOBIN IN BEEF AT VARIOUS TEMPERATURES (Brown and Dolev 1963)

From regression analysis, the following two equations were computed to describe the variation of reaction rate with temperature.

$$\log k = -17.0076 + 4136.61 \times \frac{1}{T} \text{ where } (255K < T < 268K) \quad (6)$$

$$\log k = -10.2856 - 3162.36 \times \frac{1}{T} \text{ where } (268K < T < 313K) \quad (7)$$

The preceding two equations were used in the computer program to compute rate constants by interpolation at any storage temperature. The computed rate constants were used to calculate the concentration. It was assumed that the initial concentration of oxymyoglobin is 6 mg/g beef.

The storage temperature was allowed to vary as a sinusoidal function. It must be noted that any other types of functions can be easily incorporated into the program.

The reduction in oxymyoglobin content at three constant storage temperatures, −5°C, −10°C, and −15°C is presented in Fig. 13. The results indicate that oxidation is minimal at −5°C, this result is expected since the rate constant at −5°C is lower than at any other temperature. The curves can be used to predict oxymyoglobin concentration history at any pre-selected storage temperature.

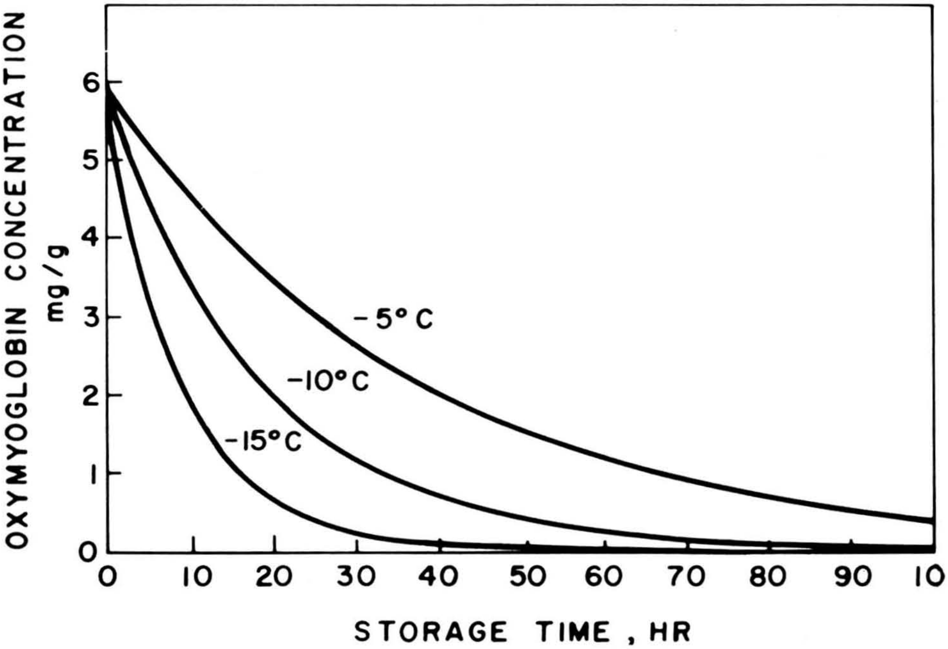

FIG. 13. OXYMYOGLOBIN CONCENTRATION HISTORY DURING CONSTANT TEMPERATURE STORAGE

Next, it was assumed that the temperature fluctuations can be expressed by a sinusoidal function on a 24-hour cycle basis. The influence of temperature range of ±10°C, for average temperatures of −5°C on oxymyoglobin content is compared with constant temperature storage at −5°C. The results are shown in Fig. 14. The oxidation was rapid when the temperature was allowed to fluctuate, since the rates of reaction were higher for longer times.

The influence of varying cyclic period on oxidation of oxymyoglobin is presented in Fig. 15. Three cycles, 8-hr, 12-hr, and 24-hr are examined for storage temperature range of −5 ± 5°C. There is no evident difference between the three cyclic periods. This is expected

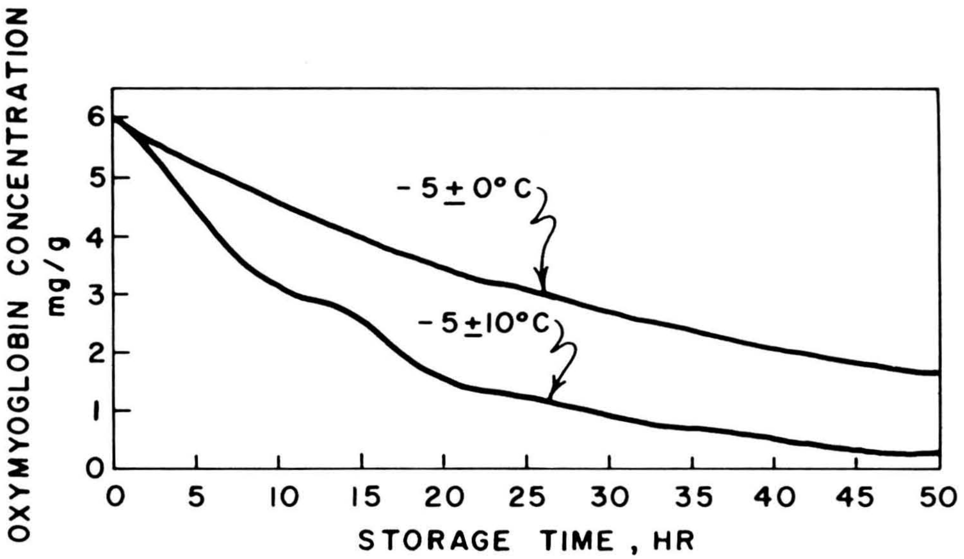

FIG. 14. INFLUENCE OF STORAGE TEMPERATURE VARIATIONS ON OXYMYOGLOBIN CONCENTRATION HISTORY IN BEEF

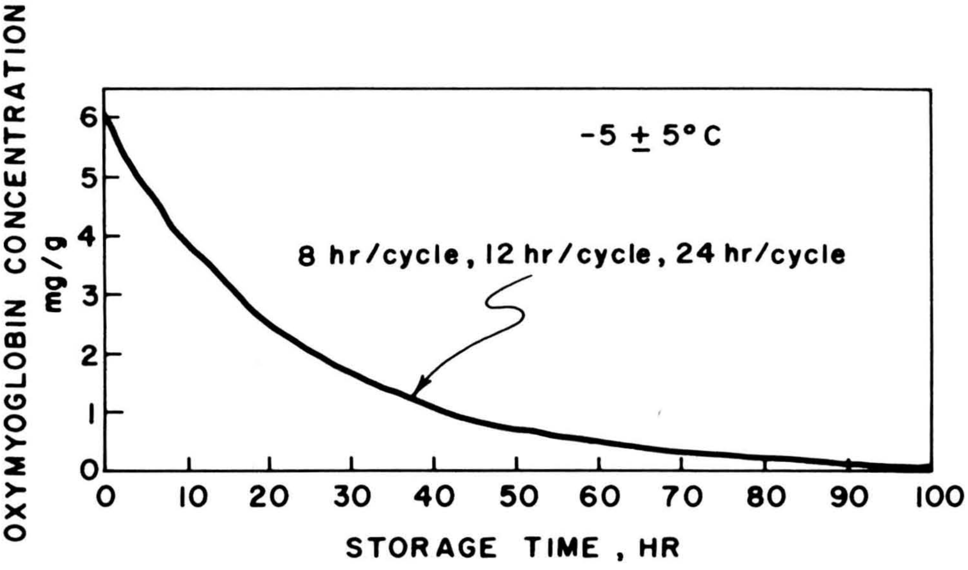

FIG. 15. OXYMYOGLOBIN CONCENTRATION IN BEEF STORED AT —5 ± 5°C WITH THREE CYCLIC VARIATIONS IN STORAGE TEMPERATURE

since the rate constant does not change appreciably with −5 ± 5°C temperature range. Next, lower storage temperatures were used to observe the influence. For a temperature range of −15°C ± 10°C the loss was considerably more for an 8-hr cycle than for a 24-hr cycle (Fig. 16). This result emphasizes the need to maintain smaller cyclic variations in temperature during storage.

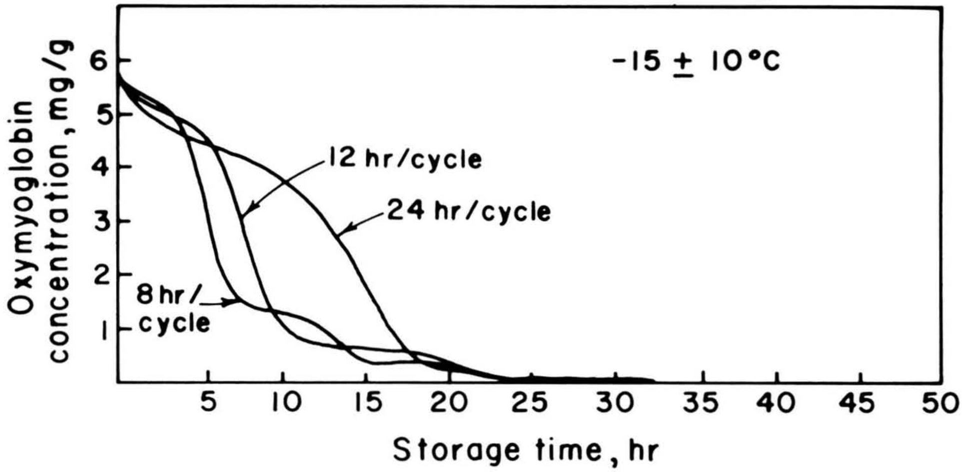

FIG. 16. OXYMYOGLOBIN CONCENTRATION IN BEEF STORED AT −15 ± 10°C WITH THREE CYCLIC VARIATIONS IN STORAGE TEMPERATURE

In actual use of the computer-aided simulation, the kinetic information on critical quality change in a food product is necessary. The quality change data can be obtained from objective measurements, consensus of opinions, or measured noticeable differences as indicated in T-TT studies (Van Arsdel *et al.* 1959).

FREEZER STORAGE PRACTICES AND FOOD QUALITY

The following storage time-temperature studies and recommendations are summarized from various research studies as reviewed by Van Arsdel *et al.* (1969). These recommendations are presented here to provide information on predicting product quality at a given storage temperature.

Meats

Since freezer burns caused by surface desiccation may seriously affect the quality of frozen meats, a water-vapor proof package tightly fitted on the product is recommended. In addition, any air pockets inside the package can be avoided by covering the meat with a film of antioxidant containing lard, glycerol or some breading process.

If the product is well packaged and surface desiccation is avoided, fluctuating storage temperatures do not cause serious quality defects. The traditionally accepted maximum practical storage life for meats at −18°C is presented in Table 1.

Table 1. Maximum practical storage life for meats stored at −18°C

Product	Traditional Practical Storage Life (days)	Practical Storage Life for Well-packed Well-formulated Products (days)
Beef	240	Over 700
Beef, chopped	a	Over 700
Beef, cooked with gravy	a	Over 700
Pork	135	Over 610
Pork, ground	a	Over 645
Pork, cooked with gravy	a	Over 700
Lamb	170	a
Pork sausage	60	Approx. 600
Goulash	a	Over 1200

[a] Not available
Adapted from Van Arsdel *et al.* (1969)

For poultry meat, studies show that storage life at −18°C or below provide extended storage life. The storage life at −18°C was at least six months in poorly packaged poultry and about 2 years in well-packaged meat (Klose *et al.* 1959).

Seafoods

Seafoods loose significant weight when stored at low relative humidities. Therefore high humidities in the frozen storage room should be maintained.

Regular and small fluctuations (1–2°C) in storage temperature do not affect the quality of stored seafoods. Larger fluctuations in storage temperature seriously affect the quality. Studies indicate that temperature fluctuations between −18°C and −10°C cause more deteriorative effect due to melting of larger amounts of water than fluctuations in the interval −15°C and −20°C.

The storage life of various seafoods is given in Table 2. The product is still of good acceptability when slight but detectable changes in quality occur. However, it is of low acceptability when significant changes in quality occur at longer storage durations. The storage times vary with the quality of fish prior to freezing. Additional technical means such as vacuum packaging will help in extending the shelf life more than that indicated in the table.

Table 2. Storage life for packaged or glazed whole or filleted fish and shellfish

Product		Storage Time in Days at −18°C	
		Slight but Detectable Changes	Significant Changes in Quality
Fatty fish[1]	Mackerel Salmon Sea herring Smelt Sprat Trout	60–90	120–180
Lean and medium fatty fish[1]	Cod Haddock Flounder Ocean perch Plaice Pollock Sole	90–120	210–300
Shellfish	Shrimp Scallop	90–120	180–240
	Clam Lobster (cooked) Oyster	60–180	120–180

[1] Values for fish up to 3 days in ice prior to freezing

Adapted from Van Arsdel *et al.* (1969)

Vegetables

Perceptible losses in quality of many frozen vegetables occur in less than a year's storage at −18°C. The quality deteriorative effects of temperature fluctuations caused by rise in temperature during delivery, failure to reduce temperature rapidly after delivery, carelessness in holding low temperature during marketing and consumer mishandling are all additive. Attempts should be made to avoid temperature fluctuations if the product is intended for long-term storage.

The storage life of vegetables at various temperatures is presented in Table 3. A storage temperature of −18°C for vegetables is acceptable as long as quick delivery and rapid turnover in retail markets is maintained. The storage life at various temperatures is presented in Table 3.

Table 3. Storage life (in days) at various temperatures required to bring about a perceptible change in quality

		Beans		Peas		Cauliflower		Spinach	
°C	(°F)	Color	Flavor	Color	Flavor	Color	Flavor	Color	Flavor
−18	(0)	101	296	202	305	58	291	350	150
−12.2	(10)	28	94	48	90	18	61	70	60
− 9.4	(15)	15	53	23	49	10	28	35	30
− 6.7	(20)	8	30	11	27	6	13	20	20
− 3.9	(25)	4	17	5	14	3	6	7	8

Adapted from Van Arsdel *et al.* (1969)

Fruits

The influence of storage temperature conditions on the quality (flavor changes) of frozen fruit is shown in Table 4. These studies by Tressler and Evers (1957) indicate that most frozen fruits are stable for at least one year at −18°C except for blueberry pie filling.

Selection of Storage Temperatures

The preceding discussion emphasizes the need of careful selection and maintenance of storage conditions to minimize quality losses in frozen foods.

The recommendations of the T-TT type studies and other research investigations indicate that frozen foods should be kept at −18°C (0°F) or lower. Fish, particularly fatty fish, and ice cream should preferably be kept at −23 to −29°C.

The Frozen Food Coordinating Committee endorsed by several U.S. food related trade associations, recommends the industry's goal to maintain reasonable uniform frozen food product temperature of −18°C (0°F) or lower (Anon. 1974).

Table 4. Stability of frozen fruits and fruit products held at various temperatures

Product	Type of Pack	Stability[1], Days −18°C	−12°C	−7°C
Apples	Pie filling	360	250	60
Boysenberries	Pie filling	375	210	45
	Bulk, no sugar	405	125	45
	Retail, sirup	650	160	35
Blueberries	Pie filling	175	77	18
Cherries	Pie filling	490	260	60
Peaches	Pie filling	490	280	56
	Retail, sirup	360	45	6
Blackberries	Bulk, no sugar	630	280	50
Raspberries	Bulk, no sugar	720	315	70
	Retail, sirup	720	110	18
Strawberries	Bulk, dry sugar	630	90	18
	Retail	360	60	10

[1] Stability based on flavor changes, except for retail pack peaches, for which it is based on color changes

Adapted from Van Arsdel *et al.* (1969)

SUMMARY

In this paper research findings on quality changes in frozen storage of food products are reviewed. The emphasis has been to identify important physical and chemical changes occurring in storage of frozen foods. The reaction kinetics are useful in developing computer-aided quality prediction models. The negative effect of temperature in certain food products emphasizes the need to carefully evaluate the reaction kinetics of individual quality parameters. For most frozen foods a reasonably uniform storage temperature of −18°C will maintain quality for commercial storage.

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EFFECT OF TEMPERATURE AND WATER CONCENTRATION DURING PROCESSING ON FOOD QUALITY

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ABSTRACT

Water content and temperature during food processing have a pronounced influence on the rates of those changes in food properties which are the object of the process such as reduction in water content or sterilization. However, they also strongly influence adverse side effects such as browning, loss of nutrients or shrinking. When the effects of temperature and water concentration on the process rates of the desired and adverse processes are known, the processes can be optimized. An example of the optimization procedure is given for the spray drying of heat-labile aroma containing liquid foods. Both temperature and moisture content of the droplets change with time in spray-drying. In a second example a new and simple calculation method is introduced for the optimization of quality retention in the sterilization of packed foods.

INTRODUCTION

Food processing has five basic objectives: improvement of nutritional value, improvement of sensory acceptability, improvement of convenience for the consumer, increase in shelf-life and cost reduction.

The first four of these basic objectives can be translated into various sub-objectives which can be grouped into:

(1) Removal of foreign contaminants, such as dirt, pesticides, insects and microorganisms.
(2) Isolation or removal of component(s), such as extraction of fat or sugar, removal of toxins.
(3) Destruction of microorganisms, enzymes, toxins, eggs of insects.
(4) Protection of the product from e.g. dirt, microorganisms, insects, oxygen and light.
(5) Prevention of losses of product or of losses from the product.

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Table 1. Matrix of physical operations and of objectives

Physical Operation	Objective of the Processes										
	Removal of Foreign Contaminants	Isolation or Removal of Components	Destruction of Microorganisms	Protection of Product	Loss Prevention	Reversible Changes			Irreversible Changes		
						cooling	freezing	concentration	drying	physical	chemical
1. Physical-mechanical											
sedimentation,	x	x						x			
filtration, washing	x	x									
2. Phase Mixing											
mixing, dispersing										x	
whipping, kneading										x	
emulsification,										x	
agglomeration										x	
3. Nonmembrane Mass Transfer Operations											
extraction, washing,	x	x						x			
leaching	x	x									
evaporation	x	x				x	x	x			
dehydration		x			x				x		
distillation		x						x			
crystallization		x			x		x	x		x	
4. Membrane Mass Transfer Operations											
direct osmosis		x						x			
reverse osmosis		x						x			
ultrafiltration		x						x			
electro dialysis		x									
ion exchange		x									
5. Heat Transfer											
heating			x								x
cooling					x	x	x				
6. Irradiation			x								
7. Coating, Encapsulation				x	x						

(6) Accomplishment of reversible changes in product properties, including cooling, freezing, concentration, drying.

(7) Accomplishment of deliberate, permanent changes in the product.
  a. Without chemical reaction, such as converting from liquid to crystal state, from liquid to foam or emulsion, size enlargement or reduction.
  b. By chemical reactions, such as maceration, tenderization, denaturation and flavor development, such as in baking and roasting.

The physical operations that can be used to meet the various objectives are presented in matrix form in Table 1.

Every operation, however, has side effects which adversely influence product properties, albeit to a varying extent. This is the case because during every operation many processes may take place simultaneously, such as mechanical processes, physical processes, chemical- and biochemical processes and microbial processes.

The adverse effects can be classified as follows:

(1) Material losses:
e.g. losses of particulates (fines, dust etc.); losses of dissolved solids (leaching losses, drip losses); losses of volatiles (aroma losses).

(2) Deteriorative physical changes:
e.g. changes in structure, density, color, permeability etc.; changes in state of aggregation, such as melting, dissolution, crystallization.

(3) Physico-chemical destruction of cell-membranes, which may result in turgor losses and drip losses.

(4) Quality degrading chemical reactions:
e.g. enzymatic and nonenzymatic browning reactions, vitamin destruction, destruction of amino acids, destruction of pigments, development of undesirable flavors by reaction products.

Virtually all processes taking place during food processing are dependent on the water concentration-temperature-time relationship. Process kinetics, physical properties and physical and chemical equilibria are all influenced by temperature and water content. Nevertheless every operation could in principle be optimized if the effects of temperature and water concentration on the desired product changes and/or the accompanying adverse side effects were known quantitatively and the temperature-water concentration-time relationship during the process could be measured or calculated.

EFFECT OF PROCESS CONDITIONS ON PROCESS RATES

In food processing a change has to be brought about in a property or properties of the food, whether it is a change in concentration of one or more of the constituents, a change in e.g. tenderness or a change in temperature per se. The rate of change of a property P_i is indicated by r_i. For chemical reactions including simple equilibrium reactions and the complicated thermal inactivations of enzymes and microorganisms the reaction rate r_i is only dependent on temperature, water content and the concentration of the components which participate in the reaction. The reaction rate is not dependent on the way in which these conditions are obtained. For physical rate processes such as evaporation, crystallization, extraction, however, r_i is moreover a function of the specific surface area, the degree of mixing in the phases etc.

The dependence of r_i on the value of its corresponding property P_i is indicated by:

$$r_i = k_i \, P_i^{\,n} \tag{1}$$

in which k_i is the reaction or process rate coefficient.

For physical processes, the value of n, which indicates the order of the process in the property i, generally is between 0 and 1. During the regular regime the desorption and absorption rates, such as in drying or extraction, are first order or higher in the concentration of the component to be desorbed or absorbed. But during the constant rate regime the concentration dependence is of zero order. For chemical reactions in foods, including degrading reactions and the destruction of enzymes and microorganisms, a first order dependence is assumed in general. If the property subject to a change can be expressed in a concentration it follows:

for n = 0
$$r_i = \frac{-dC_i}{dt} = k_i \tag{2}$$

after integration
$$C_{i,o} - C_{i,t} = \int_0^t k_i \, dt \tag{3}$$

for n = 1
$$r_i = \frac{-dC_i}{dt} = k_i \, C \tag{4}$$

consequently
$$\frac{d \ln C_i}{dt} = -k_i \tag{5}$$

after integration
$$\frac{C_{i,t}}{C_{i,o}} = \exp\left(\int_o^t k_i \, dt\right) \tag{6}$$

For a constant value of k_i and a small change in the concentration C_i the value of C_i is almost proportional with time. In case of degrading chemical reactions the effect of time on quality can be quite complicated. This because the conversion of a food constituent A into a component B can be followed by consecutive reactions:

$$A \xrightarrow{k_a} B \xrightarrow{k_b} C$$

Undesirable flavors for example are often caused by reaction products of consecutive reactions. A certain threshold concentration of the undesirable flavor compound has to be surpassed before the effect becomes sensorically detectable.

Effect of Temperature on Process Rates

The temperature dependence of r and consequently also of k can usually be represented by an exponential function. For the inactivation of enzymes and microorganisms Equation (7) holds in general

$$k_i = k_{i,o} \exp(a_i T) \tag{7}$$

in which T is the absolute temperature in degrees Kelvin, the constant a_i represents the dependence of k on temperature and $k_{i,o}$ is the value of k_i at $T = 0$

and slightly modified
$$k_i = k_{i,\,T_r} \exp(a_i (T - T_r)) \tag{7a}$$

in which k_{T_r} is the value of k at the reference temperature T_r.

Microbiologists use the value z to indicate the temperature dependence and the decimal reduction time D instead of k. D is the time required to reduce the concentration of the reactant, or the number of spores, by one order of magnitude. z is the required increase in temperature expressed in degrees Fahrenheit to reduce the value of D by one order of magnitude. It can be derived from the definitions that:

$$D_i = \frac{2.303}{k_i} \tag{8}$$

and

$$z_i = \frac{4.145}{a_i} \tag{9}$$

For most *chemical* reactions and *physical* processes the temperature effect is better described by the Arrhenius equation:

$$k_i = A_i \exp\left(- E_i/RT\right) \tag{10}$$

in which E is the activation energy, R the gas-law constant and A is the frequency factor. Equation (10) reads with respect to a reference temperature T_r

$$k = k_{T_r} \exp\left(-\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right) \tag{10a}$$

For the relationship between a_i and E it can be derived that

$$E_i = a_i\, T.T_r.R \tag{11}$$

If the temperature range of relevance to the process is not too large, the difference between Equations (7) and (10) is small. Table 2 presents the kinetic parameters of the principal physical properties, chemical and biochemical reactions, and of the destruction of nutrients, enzymes and microorganisms.

Effect of Water Concentration

Most physical properties, including vapor pressure, viscosity, thermal conductivity, diffusivity, and relative volatility of aroma compounds, are greatly dependent on water concentration. It follows that the rate processes, such as rate of drying and rate of aroma loss, are also dependent on water concentration. Enzymatic processes, chemical processes and the destruction of enzymes and microorganisms are likewise greatly affected by the water concentration. For chemical and biochemical processes it is customary to use the water activity a_w rather than the water concentration itself. This because the water

Table 2. Activation energies and k values at high water activities of physical properties, rates of physical processes and rates of various groups of reactions

Property or Process	$k_{250^\circ F}$ s^{-1}	$D_{250^\circ F}$ s	E k J/mol	z °F
Physical Properties	na[1]	na	2—40	
water vapor pressure	na	na	40	
water diffusion coeff.	na	na	8—40	
heat transfer coeff.	na	na	2—30	
viscosity water, 20°C	na	na	0.01	
viscosity glucose, 25°C	na	na	(200)	
Physical Process Rates	wv[2]	wv	17—60	
drying rate				
crystallization rate				
extraction rate etc.				
Enzymatic Reactions			17—60	
Chemical Reactions			60—210	
hydrolysis	10^{-1}		60—110	
thiamine destruction	10^{-4}—10^{-3}		110	
chlorophyll destruction	10^{-4}—10^{-3}		30—80	
Maillard browning	10^{-4}—10^{-1}		100—200	
(protein denaturation)			(350—500)	
Destruction Microorganisms			200—700	
yeasts		6 (55°C)		—
molds (ascospores)	10^{1}—10^{2}	10^{-2}—10^{-1}		10—23
vegetative bacteria	10^{6}—10^{13}	10^{-13}—10^{-6}		7—25
spores	10^{-2}—10^{0}	6—600		12—18

[1] Not of application
[2] Widely varying, very dependent on process conditions

activity expresses the availability of water for the reaction.

$$a_w = P_w{}^{*}/P_w{}^{o} \qquad (12)$$

where $P_w{}^{*}$ is the equilibrium water vapor pressure of the food and $P_w{}^{o}$ is the vapor pressure of pure water.

Sorption isotherms, representing the relationship between a_w and water concentration have been reviewed by Labuza (1968) and by Loncin *et al.* (1968). With the exception of Maillard reactions, which exhibit an optimum of the browning rate at an intermediate water activity between 0.5 and 0.7, and lipid oxidations, which have a minimum reaction rate at an intermediate level of water activity, all process rates decrease with decreasing water activity. The process rates relative to the rates at a water activity of one are given for some chemical processes, the inactivation of spores or bacteria and the rate of drying in Fig. 1.

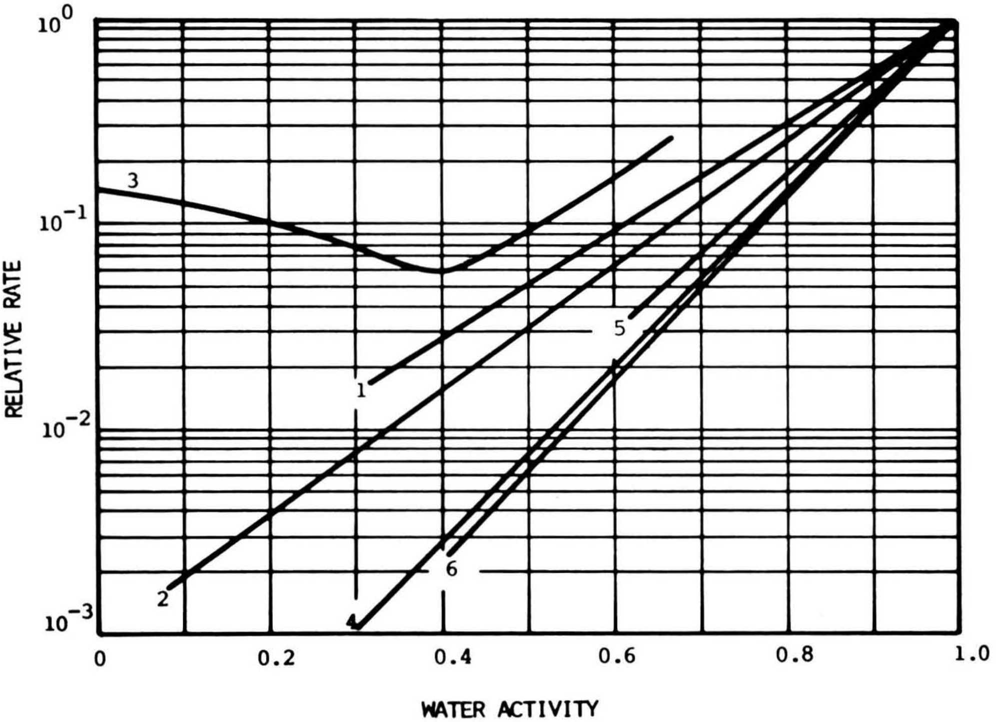

FIG. 1. DEPENDENCE OF THE RELATIVE RATES OF VARIOUS PROCESSES ON WATER ACTIVITY AT CONSTANT TEMPERATURE

Curve 1: relative destruction rate of chlorophyll in spinach at 37°C (La Jollo *et al.* 1971); curve 2: relative decay rate of abscorbic acid (Labuza 1972); curve 3: relative oxidation rate of potato chips stored at 37°C (Karel 1975); curve 4: relative rate of inactivation of phosphatase in skim milk (Verhey 1973); curve 5: relative rate of inactivation of *C. botulinum* (Karel 1975); curve 6: drying rate of a slab of glucose at 30°C slab temperature (Schoeber and Thijssen 1975).

OPTIMIZATION OF PROCESS CONDITIONS

Optimization of Process Temperature

It is obvious that, when the various processes taking place during food processing, including the desired process such as drying and the quality degrading side processes, all have different activation energies, the temperature of the product during processing will influence the quality. When the E-value of the property to be changed is higher or lower than the E-values of the quality degrading processes and when there are no local temperature differences in the product, the quality will be fully preserved at extremely high or extremely low temperatures. The degree to which this can be achieved in practice depends on technical and economic limitations. When the E-value of the property which needs to be changed has an intermediate value, there is an optimum in the process temperature. In this case the overall quality degrading effect should be minimized. Because physical rate processes have in general considerably lower E-values than chemical processes, see Table 2, the quality of the product will be most effectively preserved at the lowest possible temperature. An example is the concentration or drying of heat-labile foods. The E-value of the drying rate is 60 k J/mol or lower, whereas the E-values of the degrading chemical reactions are somewhere between 60 and 200. The increase in drying time that will be the consequence of a lower temperature is fully offset by much lower rates of the chemical reactions. In sterilization the reverse is true, the E-values of the destruction processes of microorganisms are considerably higher than those of physical and chemical degrading processes and reactions. For products which can be heated more or less homogeneously this has resulted in the development of the high temperature short time (HTST) and more extremely the ultra high temperature ultra short time (UHT) sterilization processes.

Optimization of Water Content

In processes in which one is free to select the water content the food quality is best preserved at that water concentration at which the process rate of the desired change in the food property is highest compared with the r-values of the quality degrading processes and reactions. Consequently if $dr_i/d\,a_w$ of the desired process is higher or lower than those of the degrading processes, the quality will be preserved most effectively at the highest or lowest possible water activity. Again if $dr_i/d\,a_w$ of the desired process has an intermediate value, the optimum will be at an intermediate moisture level. When the water concentration varies during the process, such as in drying when water removal is the objective of the process, moisture ranges which are favorable for adverse processes should be passed as quickly as possible.

CALCULATION OF THE TEMPERATURE-WATER CONCENTRATION-TIME RELATIONSHIP DURING PROCESSING

Changes are generally brought about by contacting a food with a second phase with a different composition, pressure and/or temperature. This contact can be direct, semi-direct, or indirect. In indirect contact the food is separated from the second phase by means of a barrier which is impermeable for mass transfer. An example is the heating of canned foods with steam or water. In semi-direct contact the barrier is permeable for only part of the components. In direct contact processes the food or food constituents may be present in one phase only or distributed over both phases. The distribution of food constituents over both phases can be the objective of the process such as in leaching or extraction processes or can be an undesired effect which has to be reduced to a minimum, such as aroma losses in concentration or drying processes.

The process, including the water concentration-temperature-time relationship in one or both phases can be calculated quite easily if the following conditions are satisfied:

(1) constant values of the heat and mass diffusion coefficients in the disperse phase and constant values of the heat and mass transfer coefficient in the continuous phase;
(2) simple conditions of the phase flows such as co-current flow, counter-current flow, cross flow and a constant specific surface area between the phases;
(3) homogeneity of the flows, no channeling or by-passing. Dispersion or mixing within each phase in the direction of flow can easily be accounted for.

The process in general can be calculated analytically if the partition coefficient of water between the phases is also constant or is a simple function of the water concentration.

The calculation-procedure is of ultimate simplicity if the process is stationary, the phases are in—or close to—equilibrium and the phase containing the food constituents is an ideally mixed liquid. In that case the residence time is exactly known and the water concentration and temperature are constant. An example of such a process is a forced circulation evaporator. The temperature is controlled by the pressure and the concentration in the evaporator is equal to that of the product leaving the evaporator.

If the conditions of constant partition coefficients are not satisfied, the process can still be calculated relatively easily, either graphically or numerically. Calculation-procedures are given in various chemical engineering handbooks such as Perry and Chilton (1963), Rohsenow and Hartnett (1973), Eckert and Drake (1972), and King (1971).

When heat and/or mass transfer coefficients in the continuous phase and/or mass and thermal diffusion coefficients in the disperse phase are not constant, numerical computer calculations are the only possibility. An example of this situation is the drying of foods. In drying the diffusion coefficient of water decreases by several orders. The numerical solutions to these problems, however, are in general very complicated and can hardly be used for process optimization in engineering practice, even if the dependences of the transfer coefficient and/or diffusion coefficient on temperature and water-concentration were known, which is usually not the case. Consequently one has to resort to short cut methods. Recently Schoeber (1975, 1976) introduced a short cut method for drying calculations. In this paper a short cut method for the calculation of the optimum sterilization conditions of packed foods will be touched on briefly.

EXAMPLES OF PROCESS OPTIMIZATION WITH RESPECT TO TEMPERATURE AND MOISTURE CONTENT HISTORY DURING PROCESSING

There are innumerable processes in which moisture, temperature or both affect the quality of the product. By way of illustration one example will be given in the field of drying during which both temperature and water concentration vary with time and one example in the field of in-package sterilization during which only the temperature varies with time and place.

Quality Preservation During Spray-drying

When heat-labile, aroma containing liquid foods such as coffee extract are spray-dried, the volatile aromas should be retained as fully as possible and the heat-labile constituents should suffer minimum thermal damage. The shorter the time required to lower the water content at the surface of the droplet to an activity smaller than 0.9, the higher will be the aroma retention.

At a surface water activity below 0.9, which corresponds with the end of the constant rate period the surface of the droplets becomes selectively permeable for water and starts to retain the larger aroma molecules. Consequently it is only during the drying time elapsing between the release of the droplets at the nozzle and the moment that the surface water activity of the droplets reaches the critical value of

0.9 that the droplets will lose aromas through their surface. This period of aroma loss decreases with increasing initial dissolved solids content in the feed to the spray-drier and with increasing air temperature. It has been shown (Thijssen 1972; Kerkhof *et al.* 1975) that even the very volatile aromas can be retained for almost 100%. However, optimum process conditions for aroma retention may result in severe thermal degradation of the product. At high initial dissolved solids concentration and high inlet air temperatures of the dryer the period of constant rate evaporation is very short indeed. This means that before a significant fraction of the water has been evaporated, the water activity at the surface of the droplet starts to decrease and the droplet temperature starts to rise rapidly from the wet bulb temperature to the temperature of the air in the dryer. In other words, the droplet temperature rises to values well above 100°C while the water content in most of the droplet is still high. Because most heat-labile compounds are very sensitive to heat at high water activities this causes severe decomposition of these compounds. The effect of the length of the constant rate period upon the retention of aroma and the retention of the heat-labile compounds is presented schematically in Fig. 2. It is obvious that there will be an optimum in the process conditions assuming that both the heat-labile compounds and the volatile aromas contribute to the quality of the product.

Short Cut Method for the Calculation of the Sterilization Conditions for Packed Foods Yielding Optimum Quality Retention

Introduction. It is well-known that the HTST or UHT methods cannot be applied to canned foods. Very high temperatures will have caused severe thermal degradation of the food near the container wall, long before the food at the center of the container has risen in temperature. A relatively low retort temperature, however, will also cause great losses of quality by adverse chemical reactions because of the very long time it will take to attain sterility.

Ball and Olson (1957), Teixeira *et al.* (1969), Hayakawa (1969), and Jen *et al.* (1971) have presented methods of estimating nutrient degradation in canned food during thermal processing. The method of Ball and Olson requires major computational efforts. The finite difference method of Teixeira also requires complex computerization in application. The method of Jen is in this respect a significant step forwards. All the same the method is still rather time-consuming and requires tedious interpolations of the Stumbo tables (Stumbo 1973). The method introduced by the authors (Thijssen and Kerkhof 1977) can be used without consulting any tables. The calculation procedure quickly

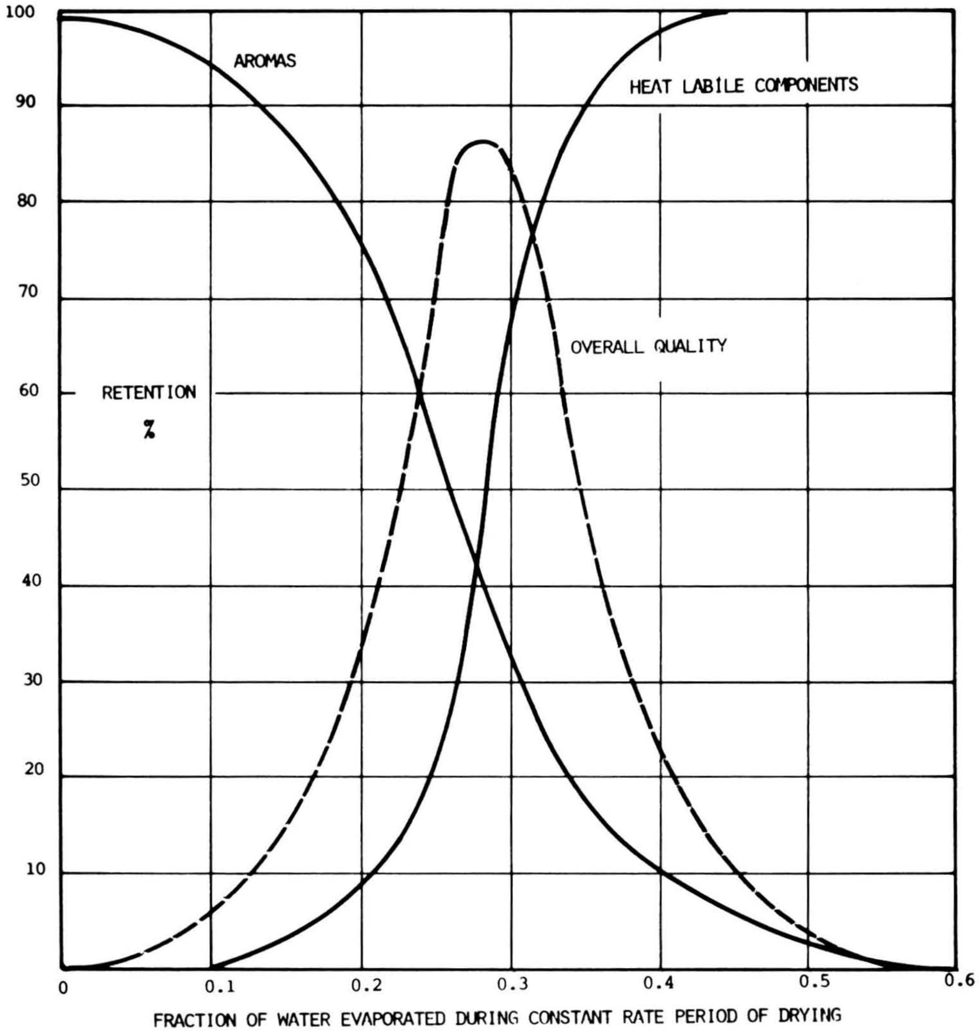

FIG. 2. EFFECT OF FRACTION OF WATER EVAPORATED DURING THE CONSTANT RATE PERIOD OF DRYING ON THE RETENTION OF VOLATILE AROMAS, ON THE RETENTION OF HEAT-LABILE NONVOLATILES AND ON THE OVERALL QUALITY OF THE PRODUCT AFTER DRYING

produces the process conditions that give the desired degree of sterilization at maximum retention of the quality.

Basic Programme. The temperature distribution in a can as a function of time is calculated analytically. Subsequently the conversion of heat-labile compounds, including the inactivation of microorganisms, is calculated numerically and integrated over the total can volume.

This integrated value of the reduction of the heat-labile constituents is a function of four key variables:

$$\ln \frac{\overline{C}_i}{\overline{C}_{i,o}} = f\,(\mathrm{Foh}, N_{i,1}, N_{i,2}, \beta) \tag{13}$$

in which

$$\mathrm{Foh} = \frac{D' t_h}{R^2} \text{ and } \mathrm{Fo} = \frac{D' t}{R^2} \tag{13a}$$

$$N_{i,1} = \frac{R^2 k_{i,T_c}}{D^1} \tag{13b}$$

$$N_{i,2} = a_i\,(T_h - T_c) \tag{13c}$$

$$\beta = \frac{T_o - T_c}{T_h - T_c} \tag{13d}$$

$\overline{C}_i$ = mean concentration of compound i in the pack after a dimensionless heating time Foh and cooling to temperature T_c

$\overline{C}_{i,o}$ = mean concentration of component i at Fo = 0

D' = effective thermal diffusivity of the food in the pack (in case of pure conductive heating $D' = \lambda/\rho cp$; for fluids the effective diffusivity is considerably higher)

t_h = time elapsed between the onset of the heating of the pack and the onset of cooling

R = characteristic radius of the pack

T_h = temperature of heating medium

T_o = temperature of food before heating

T_c = temperature of the cooling medium

Results. From the computer solutions it has been concluded that for $\beta = 0$, the condition that the initial temperature of the product in the pack is equal to the temperature of the cooling medium, the quality is optimally retained if the desired sterilization effect is obtained with Foh = 0.5. This holds closely if the activation energy or a_i value of the quality degrading reactions is a factor 3 or more smaller than the corresponding value of the inactivation of the microorganisms. This condition is satisfied in general.

Figure 3 shows the numerically calculated relationship between $N_{i,2}$

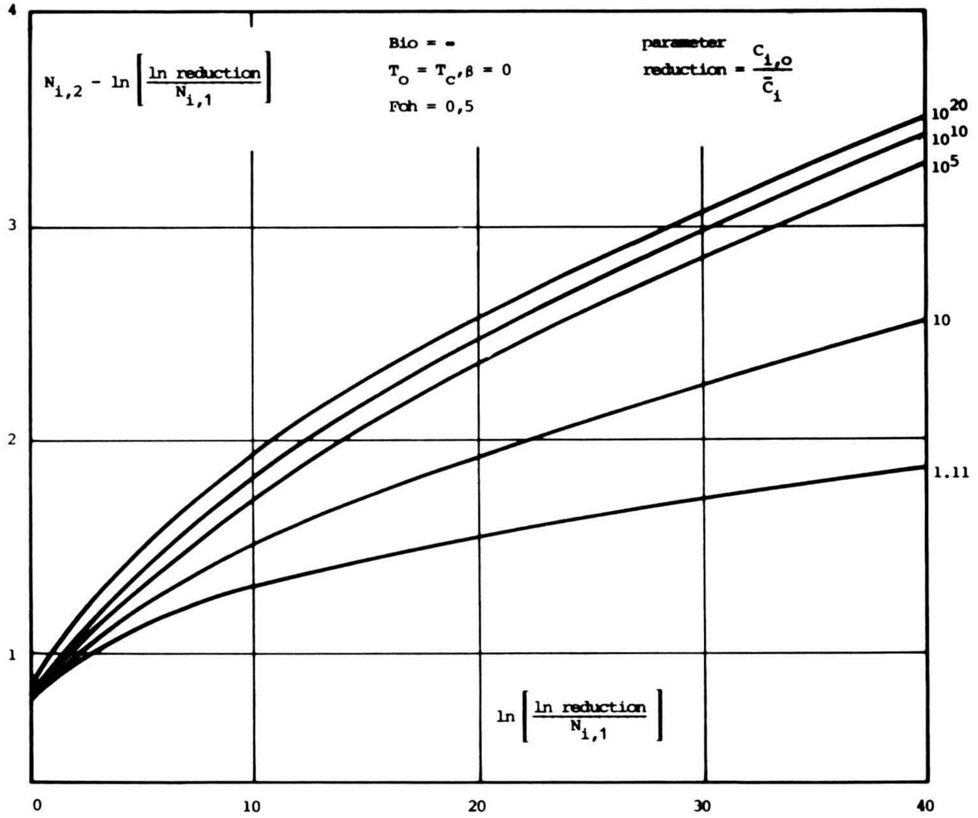

FIG. 3. RELATIONSHIP BETWEEN REDUCTION OF HEAT LABILE CONSTITUENTS, $N_{i,1}$ AND $N_{i,2}$ FOR $\beta = 0$, Bio $= \infty$ AND Foh $= 0.5$

and ln reduction/$N_{i,1}$ with the reduction as parameter for both microorganisms and other thermally unstable components such as nutrients and other quality factors.

The value of the characteristic radius R of the pack can be calculated from the dimensions and geometry, of the pack, see Equations (14a), (14b) and (14c).

sphere with diameter d

$$\frac{1}{R^2} = \frac{5.84}{d^2} \qquad \text{for Foh} = 0.5 \tag{14a}$$

cylinder with diameter d and height h

$$\frac{1}{R^2} = \frac{1.20}{h^2} + \frac{2.80}{d^2} \tag{14b}$$

rectangular body of dimensions b, h and l

$$\frac{1}{R^2} = \frac{1.20}{b^2} + \frac{1.20}{h^2} + \frac{1.20}{l^2} \tag{14c}$$

Figure 3 is also valid for the condition that $\beta \neq 0$ or $T_o \neq T_c$. The only difference is that if $\beta \neq 0$ the corresponding Foh value becomes smaller than 0.5. The correct value of Foh can be obtained from Table 3. In the table Fo* is defined by

$$Fo^* = \frac{\ln \text{reduction}}{N_{i,1} \exp N_{i,2}} \quad \text{at Foh} = 0.5 \text{ and } \beta = 0$$

Table 3. Value of Foh required for optimal quality retention if initial temperature of the food and cooling temperature are not equal

β	Foh
0	0.5
0.1	0.49 + 0.01 Fo*
0.2	0.47 + 0.02 Fo*
0.3	0.45 + 0.04 Fo*
0.4	0.43 + 0.06 Fo*
0.5	0.41 + 0.09 Fo*
0.6	0.38 + 0.12 Fo*
0.7	0.35 + 0.15 Fo*
0.8	0.29 + 0.20 Fo*
0.9	0.24 + 0.22 Fo*
1.0	Fo* − 0.06/$N_{i,2}$

Combination of the value of $N_{i,1}$, the value of $N_{i,2}$ obtained from Fig. 3 and the value of Foh calculated from Table 3 gives the desired reduction of microorganisms at optimum quality retention.

Calculation Procedures. The successive steps will be given of the calculation of the process conditions that result in the required reduction of the number of microorganisms at minimum quality loss.

step 1: Calculate the value of k_{i,T_c} at cooling water temperature T_c and the value of a_i from the values z and D_{250} with Equations 8, 9 and 10a.

step 2: Calculate the characteristic radius R for the geometry of the pack and the pack dimensions with the aid of Equations 14a, 14b or 14c.

step 3: Calculate the value of $N_{i,1}$ for the microorganisms with definition (13b). The value of the thermal diffusion coefficient can be calculated from the food composition or be determined experimentally.

step 4: From Fig. 3 read the corresponding value of $N_{i,2}$ for the required reduction of the number of microorganisms at $T_o = T_c$ or $\beta = 0$.

From $N_{i,2}$ the value of $T_h - T_c$ and consequently the required temperature of the heating medium can be obtained.

step 5: Calculate the required time t_h between onset of heating and onset of cooling from the Foh value, see definition (13a). Foh is calculated from Table 3. β is defined by (13d).

The calculation procedure for nutrient retention is as follows.

step 6: Calculate from the z and D value of the nutrient or any other quality factor the corresponding values of a_i and k_{i,T_c}.

step 7: Calculate $N_{i,1}$ for the nutrient and calculate the value of $N_{i,2}$ for the nutrient from the value of $T_h - T_c$ obtained in step 4. Calculate the reduction of nutrient with these values in first approximation by assuming for the nutrient that reduction = exp (Foh $N_{i,1}$ exp $N_{i,2}$).

Subsequently this approximated value of the reduction is used to calculate the abscissa value in Fig. 3. For that abscissa value the accurate value of the reduction is obtained from the corresponding ordinate value, again using the first approximation of the reduction as parameter.

The whole calculation requires about 5 min on a pocket calculator. For routine calculations the procedure can conveniently be programmed.

Table 4. Calculated effect of the thermal diffusivity D′ and the characteristic radius R of the package on sterilization temperature T_h, sterilization time t_h and retention of thiamine for a spore reduction of 10^{10}

$\frac{R^2}{D'}$ (sec)	R (D′ = 1.5 × 10^{-3} cm²/sec (cm)	T_h (°C)	t (hours)	Thiamine Retention (%)
1.50 × 10^5	15	114.0	20.8	19.3
6.66 × 10^4	10	117.2	9.3	38.5
1.66 × 10^4	5	122.6	2.3	68.0
6.02 × 10^3	3	126.6	0.83	82.6
1.33 × 10^3	1.4	132.4	0.18	93.5
1.66 × 10^2	0.5	140.5	0.02	98.3
0	0		0	100.0

Reduction spores *Clostridium botulinum* by a factor 10^{10}
Cl. botulinum $a_i = 0.27\,°C^{-1}$, $k_{i,\,20°C} = 2.0 \times 10^{-14}\ sec^{-1}$
Thiamine $a_i = 0.082\,°C^{-1}$, $k_{i,\,20°C} = 1.9 \times 10^{-8}\ sec^{-1}$

Example. Table 4 shows for a spore reduction of 10^{10} the effect of the ratio of the square of the characteristic radius R of the package to the thermal diffusion coefficient D′ on sterilization temperature, sterilization time t_h and retention of the nutrient thiamine. The table clearly demonstrates the negative effect of an increase in package size or decrease in thermal diffusivity on quality retention.

As the table has been derived from Fig. 3, the given combinations of temperature and time are the optimum combinations for quality retention.

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ENERGY CONSUMPTION FOR REFRIGERATED, CANNED, AND FROZEN PEAS

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ABSTRACT

The energy inputs at different stages in the total food cycle of peas were estimated for the market modes: refrigerated, frozen, and canned. The energy accounting showed for refrigerated 3,368; for canned 3,637; and for frozen 3,281 Btu/2.8-oz serving. Because the energy consumption for each market mode is of the same order of magnitude, there is little reason for the consumer to select on bases other than availability, taste preference, and convenience. It was also found that energy for packaging, marketing, shopping, and in the home can be high depending on the market mode. Measures to reduce energy consumption are discussed for several sectors.

INTRODUCTION

This study was undertaken with the aim of obtaining reliable estimates on energy consumption at the various postharvest stages of the food cycle for refrigerated, canned, and frozen peas. The results will provide guidelines for energy reducing strategies. Dehydrated peas are not of significant commercial importance (Luh and Woodroof 1975), and peas once harvested must be maintained at about 32° F in order to be of an acceptable quality (Ryall and Lipton 1972). For these reasons, the present study excludes dehydrated peas, and includes refrigerated peas in place of fresh peas.

Estimates of the annual energy consumption by the U.S. food system vary between 13% (USDA 1974) and 17% (Slater 1976) of the total energy utilized in the U.S. The discrepancy in the estimates is primarily due to the complexity of the food system. Discrepancies are also encountered in the literature on estimates of energy required for protein from crop and animal sources; Henig and Schoen (1976b) showed that

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omission of energy input into processing, packaging, distribution, storage, and preparation led to erroneous conclusions by Heichel (1975).

It is emphasized here that a consumer might select a market mode for a variety of reasons other than energy consumption such as personal preference, price, availability, sensory attributes, and retained nutrients.

Previous studies on energy consumption for foods include those on production (Pimentel *et al.* 1973, 1975; Gunkel *et al.* 1974), and gross estimates of energy for processing (Unger 1975), distribution, storage, packaging, and preparation of food (Hirst 1974; Steinhart and Steinhart 1974; USDA 1974; Booz *et al.* 1976). A few studies have been published recently detailing energy consumption in the total food cycle of corn (Brown and Batty 1976; Henig and Schoen 1976a), a meat analog (Henig and Schoen 1976b), peas (Londahl 1976), and mashed potatoes (Olabode *et al.* 1977). These studies emphasized the differences in energy consumption in the various marketing forms of a commodity.

The study of Londahl (1976) was based on data from the Swedish food industry. Further, the energy data were expressed in kwh of electricity, while the interest in the U.S. is with regard to fossil fuels. In part for these reasons, a comparative study of energy consumption for peas in the U.S. is necessary.

In this report, all energy data are reported in British Thermal Units (Btu's) of fossil fuel. Electrical energy, a secondary energy source, was converted to Btu's of fossil fuel taking into account the efficiency of production as 29.4% (Summers 1971), i.e., 1 kwh = 11,600 Btu. This practice is consistent with that of a number of earlier studies (Henig and Schoen 1976a, b; Newman and Day 1975; Olabode *et al.* 1977; Booz, Allen, and Hamilton 1976), and the chief reason is that hydro and nuclear power contribute only about 7.1% to the electric utility sector (Stanford Research Institute 1972).

MATERIALS AND METHODS

To facilitate an equitable comparison between the three market modes, energy consumption was computed for a serving (2.8 oz) (Sweeney *et al.* 1962) of boiled peas. An effort was made to use data that would be representative for the nation as a whole. For example, in computing the transportation by truck and rail, data published by the U.S. Department of Transportation (1974) were utilized. Likewise, the data of USDA (Matthews and Garrison 1975) were used to estimate the number of servings of peas that can be obtained from a pound of frozen, canned, and refrigerated peas as 5.314, 3.310, and 2.063, respectively.

The sequence of steps in the food cycle of refrigerated, canned, and frozen peas are shown in Fig. 1. For frozen and canned peas, sources of energy required for all the operations within the rectangle in Fig. 1 are accounted in the fuel and power inventories at the processing plants. A complete study of energy inputs in the total food cycle must include the energy expended to produce the machinery used at each stage of the cycle (Steinhart and Steinhart 1974; Brown and Batty 1976). Such a task is extremely difficult and hence was not undertaken in the present study.

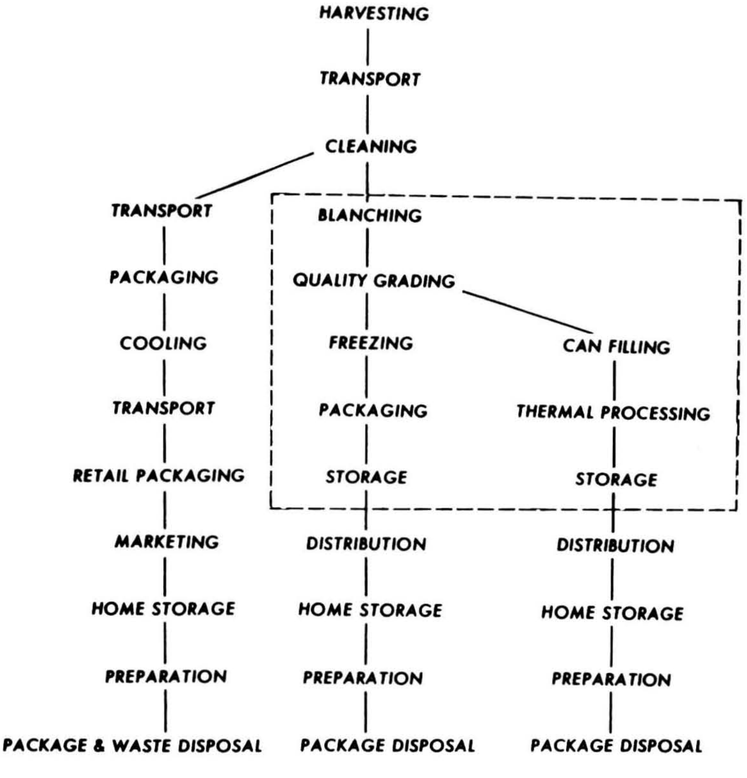

FIG. 1.

Energy for Transportation

The energy for transportation can be estimated in two parts: (1) the energy required for a vehicle to travel a given distance, and (2) the energy required to maintain the inside of the vehicle at the desired environment. For estimating the former it was assumed for each market mode that: (1) the round trip distance between a farm and a plant is 50 miles, and motor truck is the mode of transportation, (2) the distance between a processing plant and a retail warehouse is 1,130 miles, and 60% of the transportation is by rail and 40% by truck, and (3) the round trip distance between retail warehouse and store is 70 miles, and motor truck is the mode of transport.

The various distances were assumed because reliable data for each market mode were not encountered. Also, while it may be possible to compute distances for minimum energy consumption, it is unlikely that an average of the actual distances traversed can be computed in a free market.

From data published by the Department of Transportation (U.S. Department of Transportation 1974), the energy intensiveness for intercity truck transport in 1972 was estimated to be 2,540 Btu/ton-mile. This figure is in close agreement with the estimate for 1970 of Hirst (1973), and that of Brown and Batty (1976). Also from the data of the Department of Transportation, the energy intensiveness for trains was estimated to be 721 Btu/ton-mile; this figure is also in good agreement with the estimate of Hirst (1973) for 1970.

In computing the energy per serving for transportation between farm and plant, the solid waste generated at the freezing and canning plants was taken into consideration using data of Katsuyama *et al.* (1973).

Energy requirements for maintaining the desired environment in railroad cars were obtained from industry sources (Burlington Northern, Inc. 1976); these were: 2.8×10^5 Btu/hr for frozen and refrigerated foods, and 6.3×10^4 Btu/hr for canned and dehydrated foods for a carload of 100,000 lbs. The reason for heating railroad cars and motor trucks carrying canned and dehydrated foods is to prevent condensation that can occur at temperatures below about 55°F. Travel time by rail was determined from the same industry source to be 45.5 mph.

For trucks, the energy requirement for maintaining low temperatures for frozen foods in motor trucks was obtained from an industry source (Fruit Growers Express Co. 1976) as 1.12×10^5 Btu/hr per 45,000 lb load; this figure is in good agreement with data of USDA (Kuenzli 1962) for a truck with 40,000 lb load. It was also learned from the industry source that the same rate of energy consumption is valid for heating trucks. Travel time by truck was determined assuming an average speed of 55 mph for highways and 30 mph in urban areas (between retail warehouse and retail store).

A truck or a raidroad car is brought to the desired temperature before it is loaded with the food product. The time necessary for obtaining the desired temperature for refrigerated and frozen foods was estimated from data presented by Kuenzli (1962). Published data are not available for preheating trucks in cold weather, and for preheating or precooling railroad cars. It was assumed that for trucks the time requirements would be the same for heating as for cooling for similar temperature differentials. Finally, for railroad cars, the cooling and heating times were assumed to be equal to the corresponding truck times.

Refrigerated peas require top ice in addition to a temperature of 32°F during transport (Redit 1969; Ashby 1970). Top ice requirements were computed on the basis of 2 tons of ice per 40,000 lb load of green peas.

Energy Consumption in Processing Plants

In estimating energy consumption for processing, it is preferable to use in-plant data. However, because of economies of scale, care should be used in selecting in-plant data. For example, our earlier studies on canning plants (Rao *et al.* 1976a, b) show that energy consumption per can or pound of product will be low for plants that have a high rate of production and that are in operation most of the year. Further, because peas are processed between June and September, there is no need to heat the plant facilities during the processing season; use of fuel and electricity data for the pea processing season alone will indicate low energy consumption per pound. In reality, a processing plant needs to be heated during the cold weather, whether it is being used or not.

In view of the above arguments, for frozen and canned peas, data from plants with large production rates and that were in operation beyond the pea season were used. In the case of refrigerated peas, a hypothetical plant that is kept heated in winter is the basis for data on processing; a real plant producing refrigerated peas could not be located.

For frozen and canned peas, the energy for processing was estimated from the magnitudes of all the fuels and electricity consumed in the processing plants. Calorific values for the fuels were taken from Gatts *et al.* (1974). The data given in Table 1 were derived from one plant for frozen peas and two plants for canned peas.

Energy for Packaging

Previous studies (Henig and Schoen 1976a; Olabode *et al.* 1977) have shown that packaging is highly energy intensive. Also, a wide range of

Table 1. Energy inputs for refrigerated, canned, and frozen peas (Btu/serving)

	Energy Input, Btu/Serving			
Operation or Segment	Refrigerated	Canned	Frozen	Sources of Data
Peas in pod to plant	31	NA[1]	NA	50 miles round trip by truck; energy data from U.S. Dept. of Transpn. (1974)
Shelled peas from farm to plant	NA	14	14	
Processing and in-plant storage	264	892	747	Processing plant data for canned and frozen; hypothetical plant for refrigerated
Packaging				
Bushel basket, plastic film, and backing	568	NA	NA	Derived from Hoddinott (1975), Berry and Makino (1974), Payne (1975), Breakiron and Nicholas (1967)
Can, label, and glue	NA	1,586	NA	
Carton and paper	NA	NA	322	
Box and carton	NA	141	70	
Distribution				
Plant to retail warehouse	399	247	157	1,130 miles, 60% by rail and 40% by truck; data from U.S. Dept. of Transpn. (1974), Kuenzli (1962), and industry sources
Environment control in transit	72	10	12	
Retail warehouse to supermarket	43	27	17	
Environment control in transit	3	1	1	
Commercial warehouse, 6 mos.	NA	9	79	Data of Henig and Schoen (1975) for frozen foods, and from Rao *et al.* (1976b) for canned peas
Retail warehouse, 2 mos.	NA	3	26	
Marketing				
Freezer, 1 week	NA	NA	606	Data from refrigeration industry, Beatty (1975), and Super Market News' Distribution Study (1976)
Refrigeration, 3 days; packages are 4 deep	471	NA	NA	
Heating, lighting, and air conditioning	69	174	136	
Store packaging (paper bag)[2]	—	—	—	

(continued)

Table 1. Energy inputs for refrigerated, canned, and frozen peas (Btu/serving) (continued)

	Energy Input, Btu/Serving			
	Refrigerated	Canned	Frozen	
Shopping				
Travel by car[2]	—	—	—	
Home Storage				
Freezer, 2 weeks	NA	NA	394	Data from Newton (1976), Newman and Day (1975)
Refrigerator, 3 days	187	NA	NA	
Home preparation				
Gas and electric ranges	833	421	594	Data from Sweeney *et al.* (1962), Newman and Day (1975)
Waste and package disposal				
Electric waste disposer	9	NA	NA	Data from Newman and Day (1975), Midwest Research Institute (1974), Berry and Makino (1974), Watt and Merrill (1963)
Package disposal	4	9	3	
Dishwasher	103	103	103	
Wastewater treatment	312	—	—	
Total	3,368	3,637	3,281	

[1] NA means not applicable

[2] Energy for this item is also important, but an equitable method of apportioning is not available at the present time.

energy values per unit weight of a packaging material are available.

Refrigerated peas are packaged in bushel baskets, cooled with water at 32° F, and transported to retail markets. The peas are later packaged into retail units made up of a paper board backing and covered with PVC film. The required data for the packaging material were obtained from Berry and Makino (1974). The bushel baskets were assumed to have a 4-time recycle capability (Breakiron and Nicholas 1967).

Energy data for cans were presented in a number of studies (e.g., Payne 1975; Hoddinott 1974; Berry and Makino 1974), and the magnitudes vary between about 4,000 (Berry and Makino) and 7,600 (Hoddinott 1974) for a size 303 can. In this study, a value of 5,490 derived from data presented by American Can Company (Payne 1975) was used.

For frozen peas the packaging necessary was assumed to be a carton and paper wrapping (Henig and Schoen 1976a); the energy data was obtained from Hoddinott (1974).

Cans and frozen packages are in turn cased in cardboard boxes. The energy per cardboard box was obtained from the weight of a box and energy data of Berry and Makino (1974). Again, the energy input was computed on the basis of a serving of peas.

Energy for Storage in Warehouses

One of the essential steps in the distribution of frozen and canned peas is storage in commercial and retail warehouses. Based on the earlier study by Henig and Schoen (1976a), storage times in the commercial and retail warehouses were assumed to be six and two months, respectively.

Energy consumption in refrigerated warehouses can vary over a wide range depending on the product throughput and location. For example, Merchants Refrigeration Co. operates warehouses whose energy consumption varies from 17 to 100 kwh/ft^2 /yr. It would have been preferable to have throughput and energy usage data of a number of warehouses so that an average could be computed and used; such data were not available. For this reason, the energy consumption figure of 836 Btu/lb-yr used by Henig and Schoen (1976a) was taken as being reasonable. For illustrative purposes, we note that the energy consumption in a large warehouse that handled about 239 million pounds per year was found to be 472 Btu/lb-yr.

Canned foods also need warehouses in the distribution sector of food cycle. Energy for heating and lighting a warehouse of a large canning plant was deduced from data collected in an earlier study (Rao *et al.* 1976b) as 61 Btu/yr for a size 303 can. This figure was used for estimating the energy for storage of canned foods. The cans were assumed to have the same residence time requirements as the frozen foods.

Refrigerated peas have a maximum life about 3 weeks after harvest. For this reason, it was assumed that there was no warehouse storage for refrigerated peas.

Energy Inputs in Marketing of Peas

The marketing segment energy inputs are essentially those in a supermarket. Refrigerated and frozen peas need low temperature storage in a supermarket. Further, all the three market modes must share in the energy used for lighting, heating, air-conditioning, and other comfort conditioning employed in the supermarket.

Frozen foods are stored at or below 0°F in supermarkets in a variety of freezers. According to Hussmann Refrigeration Co. a five shelf multideck freezer, which is widely used, consumes 1.28 kwh/day/ft^3. This figure includes energy for both the refrigeration unit and the lights of the freezer. Energy consumption per serving was computed assuming a storage time of one week and from the volume of a 1 lb package of frozen peas.

Based on data provided by Hussmann Refrigeration Co., a single deck produce shelf was assumed for the marketing of refrigerated peas; such a shelf has cold air coming in at 33°F, an area of 35 ft^2, and consumes 0.583 kwh/ft^2/day.

The energy consumption for refrigerated peas was computed by first assuming a package 6 in × 4.6 in × 3 in. for 1 lb of peas, and that packages four deep are placed on the produce shelf. The size of the package was determined from the bulk density of peas in pod (21.0 lb/ft^3).

Considerable energy is expended in supermarkets for heating, lighting, and comfort conditioning (HLC). The apportioning of energy was based on the dollar value of a retail unit and the energy consumed for HLC per sales dollar. This procedure was used earlier by Brown and Batty (1976), however, recently published data were used in the present study.

The energy consumed for HLC per sales dollar was estimated for a typical supermarket with a sales area of 15,125 ft^2 and total electricity consumption of 25.05 kwh/100 ft^2/day (Gerke 1976). It is also known that in a supermarket on the average 51.2% of the electricity is consumed for lighting and comfort conditioning (Beatty 1975), and that the average annual heating energy requirements is 37,663 Btu per 100 ft^2 of selling area (Gerke 1976).

Super Market News' Distribution Study (1976) showed that the sales in 1974 for a typical store were \$5.09/week/ft^2 of store area. This figure was corrected to base 1976 by means of the Consumer Price Index (Wall Street Journal, October 22, 1976) and combined with the energy data; the energy consumed for HLC per sales dollar was found to be 1,569 Btu. This figure was used together with the price of retail units of refrigerated, canned, and frozen peas to obtain their portion of energy for HLC. The prices of retail units of canned and frozen peas were determined in local supermarkets, while the price of refrigerated peas in pod was assumed.

It would have been of interest to determine the energy requirements for HLC based on another criterion such as the volume or area occupied by each market mode in a supermarket, however, reliable data for such an effort could not be located.

Energy for Shopping

Energy for shopping depends on the distance between home and supermarket, energy consumed by the car, and other factors. Two methods have been reported in the literature for estimating the energy consumption for shopping. Olabode *et al.* (1977) apportioned energy on a per item basis after obtaining the number of items per average grocery shopping trip from a market basket survey. Unfortunately, the results of the survey are not available; also, it is unlikely that the survey would be representative for the nation as a whole. Brown and Batty (1976) utilized data on the average distance and number of trips between home and supermarket, average sales per customer transaction, and the price of a retail unit to compute the energy for shopping for a can of corn.

Neither of these methods can be considered to be satisfactory. Furthermore, it appears that until more reliable data on shopping habits of consumers are available, an equitable method of apportioning energy for shopping of each market mode is not possible. For these reasons, apportioning of energy for each market mode was not undertaken in this study. However, it must be emphasized that considerable energy is expended for grocery shopping. For illustrative purposes we note that using the method of Brown and Batty (1976), the recent data of Super Market News' Distribution Study (1976), and the energy intensiveness data of Hirst (1973), the energy for shopping was calculated to be 5,650 Btu per purchase dollar.

Energy is expended to produce the paper from which grocery bags are made. Based on the energy data of Berry and Makino (1974) for packaging paper and the weight of a typical shopping bag, the energy per paper bag was estimated to be 2,624 Btu. However, as in the case of energy for shopping, an equitable method of apportioning the energy for each market mode is not available at the present time. For this reason, the energy for packaging paper was not apportioned for each market mode.

Energy for Home Storage

Energy consumption figures for home storage of frozen and refrigerated peas were computed based on data by Newton (1976) and Newman and Day (1975). Newton (1976) found that a 15 ft^3 top-freezer refrigerator is very popular in the USA. The study of Newman and Day (1975) established that 51% of households have frost-free refrigerators and 49% have "must defrost" refrigerators. The study of Newman and Day (1975) also shows that while nearly all households have refrigerators, only 34% have freezers.

From the energy consumption data of Newton (1976) and Newman and Day (1975), it was determined that the frost-free 4 ft^3 freezer consumes 724 kwh/yr and the 11 ft^3 refrigerator consumes 1,116 kwh/yr. The corresponding figures for a "must defrost" type are 480 and 738 kwh/yr, respectively.

The above data together with the bulk densities were used to compute energy for home storage of frozen peas for 2 weeks and refrigerated peas for 3 days.

Energy for Preparation of Peas at Home

Energy consumption for preparation of boiled peas at home was estimated from the preparation time data of Sweeney *et al.* (1962), energy consumption data for gas and electric stoves by McCracken and Beveridge (1955), and data on distribution of gas and electric stoves by Newman and Day (1975).

From the description of the procedure used by Sweeney *et al.* (1962), the theoretical energy required for the preparation of boiled peas from a size 303 can was first estimated. This magnitude was used to estimate the energy expenditure with an electric range assuming 75% efficiency for the conversion of electricity to heat (Stanford Research Institute 1972), and a further efficiency of 66% for the transmission of heat to the food. The energy expenditure with a gas stove was computed assuming an overall efficiency of 25%. The ratio of computed gas range to electric range Btu values was 0.58; the same ratio can be deduced from the data of McCracken and Beveridge (1955).

Because there are approximately 53% gas stoves and 47% electric stoves (Newman and Day 1975), the average energy required can be obtained by apportioning the gas and electric range energy requirements in the same ratio. The preparation times and the number of servings per retail unit data reported by Sweeney *et al.* (1962), were utilized together with the computed energy requirements for the canned mode to arrive at the energy requirements when fresh and frozen peas were used to prepare boiled peas.

Waste and Package Disposal

Energy is expended for waste and package material disposal, as well as for operating a dishwasher; the energy expenditure per serving of peas is discussed in this section.

Waste (mainly pods) is generated when refrigerated peas are used and these could be disposed by an electric waste disposer. Newman and Day (1975) report that the average energy consumption for a waste disposer is 30 kwh/yr. This figure can be combined with the assumption that 2,190 meals are eaten at home per year by a family of three (Midwest Research Institute 1974) to obtain energy consumption by the waste disposer per meal as 140 Btu/meal. To obtain the energy consumption per serving of peas, we assumed that it is proportional to the number of food calories in peas and that an average meal has 1,000 food calories; the number of food calories in peas were obtained from Watt and Merrill (1963).

Energy for package disposal was computed from the weight of the package and the data of Berry and Makino (1974), which showed that 155 Btu are needed to dispose 1 lb of solid waste.

Energy consumption by the dishwasher per serving of peas were computed in a manner similar to energy for waste disposal, with the exception of using 4×10^6 Btu/yr as energy consumption by a dishwasher (Newman and Day 1975).

In the case of refrigerated peas, the disposed pods contribute to the biochemical oxygen demand (BOD) of the municipal wastewater treatment plant (MWTP). This energy requirement was estimated from the data of Fair *et al.* (1968) and the BOD for ground pods. The average annual operating cost of a MWTP in the U.S. varied from $9.20 to $0.88 in 1965; the higher cost being for a population of 100 and the lower for one million. It is also known that the average water usage per capita per day in the U.S. is 100 gallons, the BOD of municipal waste is about 300 mg/liter, and the average cost of electricity is $0.02 per kwh.

For an assumed municipality of 100,000 people and the known annual operating cost of $1.20 per capita, as well as the above data, it can be shown that the energy required to provide 1 g of BOD is 1.496

$\times 10^{-3}$ kwh. Pea pods contain 12% carbohydrate and if glucose is assumed to be the carbohydrate, the required BOD is 1.067 g per g of glucose. Because 140.5 g of pods are generated per serving of peas, it follows that 312 Btu are required per serving of peas.

RESULTS AND DISCUSSION

The results of this study are in general agreement with those of earlier studies (Henig and Schoen 1976a; Olabode *et al.* 1977; Brown and Batty 1976) in that at the present time considerable energy is expended at the various stages of the total food cycle of processed foods.

Some comparisons are possible with previous studies. For processing energy, Henig and Schoen (1976a) used 2,242 and 3,000 Btu/lb for canned and frozen corn, respectively; the figure for corn was the average for all canned vegetables produced in the U.S. In the present study, the corresponding figures based on in-plant data are 2,952 and 3,970 Btu/lb. Brown and Batty (1976) assumed 2,600 Btu/lb for canned corn. While no simple explanation can be offered for these differences, it is noted that the figures used in this study for both market modes are 32% higher than those of Henig and Schoen (1976a).

Energy for packaging is very high for refrigerated and canned peas; it is higher than the processing energy requirements. Payne (1975) noted that by using less metal and municipal recycling, energy for steel cans can be reduced by 36%. Similarly, energy savings can be achieved by recycling paper board for cartons.

In the distribution sector, energy for transportation is the major component for all the market modes. For the purpose of comparison we note that the distance of 1,180 miles assumed in this study compares favorably with 1,400 miles used by Brown and Batty (1976) for canned corn. For refrigerated peas, top ice required to maintain high humidity in transit contributes to the high energy consumption for environment control. Energy for warehouse storage of frozen peas is more than that for canned peas; however, it is less than that for transportation. Berry and Makino (1974) also pointed out that energy for warehouse storage of frozen foods is a small fraction of the total energy requirements; the large throughput rates of modern warehouses was given as the reason.

Food stores use large quantities of energy, particularly electricity. Recently initiated energy studies show that measures such as heat reclamation from compressors, better insulation of walls, lowering store humidity to 35–40%, etc., result in substantial savings (Beatty 1975). The energy magnitudes that can be conserved are not yet available.

Energy consumption in the home sector is extremely large; it is the major portion for frozen and refrigerated peas being 33% of the total, while for canned peas it amounts to 15% of the total. Some energy can be saved by decreasing the residence time of peas in the freezer and minimizing the use of dishwashers for all market modes. Additional savings are possible when energy efficient appliances are available. For example, Newton (1976) suggests six changes in the design of a typical refrigerator which would reduce energy consumption by 53.8% and the U.S. Department of Commerce is proposing energy reduction targets for all appliances. Because of rapidly dwindling supplies of natural gas, electricity can be expected to be the chief source of energy for meal preparation. In this respect, the energy consumption by microwave and conventional electric ovens needs to be investigated. Finally, for refrigerated peas, disposing the pods as solid waste would eliminate the energy for waste disposer and wastewater treatment; the net energy savings would be 273 Btu per serving.

SUMMARY AND CONCLUSIONS

For the total food cycle, at the present time and as per the assumptions in this study, the energy per serving for frozen peas is less than that for refrigerated and canned peas. The energy per serving for frozen peas is less than that for canned peas, partly because of the higher number of servings possible per retail unit of comparable size. It is of interest to note that a similar conclusion can be reached from the energy per lb of corn data of Henig and Schoen (1976a) and the yield data of Matthews *et al.* (1975); it is noted that one serving of corn is 2.9 oz (Sweeney *et al.* 1962). However, as discussed above, reducing the energy content of the can alone would lead to lower energy consumption for canned peas. These comments are based on the assumption that the energy for shopping and store bags would be equal for each market mode.

The major finding of this study is that refrigerated peas require energy of the same order of magnitude as the canned and frozen peas. However, refrigerated peas are not available beyond two or three weeks after the end of a short growing season. Therefore, in the case of peas the two preservation methods: canning and freezing are necessary and of great value from the point of view of energy consumption, availability, and convenience.

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MOISTURE ADSORPTION INFLUENCES ON RICE

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ABSTRACT

Rice is a hygroscopic grain which adsorbs or desorbs moisture depending on its ambient environment. Moisture desorption is associated with rice drying. Much research has been conducted to determine those drying procedures which produce the highest head rice yield. Moisture adsorption is associated with water reentering the rice grain. This occurs when the vapor pressure within the grain is lower than the vapor pressure in the surrounding air. Rapid moisture readsorption causes the rice grain to fissure. Fissured grains usually break during subsequent hulling and milling operations. This paper reviews the literature related to moisture adsorption and fissuring of the rice grain, and discusses those preharvest and postharvest conditions where rice grains are subjected to moisture-adsorbing environments which have the potential to fissure the grain and subsequently reduce head rice yield.

INTRODUCTION

Rice is among the oldest of cultivated crops. Today nearly one-half of the world's arable land is used for the production of cereals and about one-fifth of this is for the production of rice. About one-fourth of the world's population depends on rice as a major staple food.

The ultimate goal of the rice industry is to produce a maximum amount of whole-grain rice (head rice) from each hundredweight of product milled. Research indicates that much breakage in rice occurs because the rice kernels have previously been weakened by stress cracks (fissures) caused by rapid moisture adsorption or desorption. Rice drying procedures have been studied by numerous researchers for many years. The moisture adsorption phenomenon has been observed from time to time but little effort has been made to synthesize and integrate this information into current rice harvesting, handling and processing procedures. This paper is concerned with the moisture adsorption-

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fissuring aspect of the rice grain and discusses those preharvest and postharvest conditions where rice grains are subjected to moisture-adsorbing environments which have the potential to fissure the grain and subsequently reduce head rice yield.

REVIEW OF LITERATURE

Rice, like other grains, is hygroscopic in nature. It gains or loses moisture when the vapor pressure of water in the space surrounding the grain is greater or less than the vapor pressure exerted by the moisture within the grain, Hogan and Karon (1955). Samples of rice brought to a single moisture content by drying in one case and by moistening in another are in equilibrium with atmospheres of different relative humidities, Houston (1952). This indicates that the moisture content at hygroscopic equilibrium of rice is dependent on how the grain approaches this equilibrium condition. The difference between adsorption and desorption equilibrium moisture contents is not large and exceeds 1.5% only from 50 to 70% rh at 25°C. A difference of over 1% is maintained throughout the range from 20 to 80% rh at the same temperature (Breese 1955).

Karon and Adams (1949) found that the rate of moisture diffusion from the kernel interior to its surface was relatively slow. They worked with the rice kernel and its components and found that rough rice and polished head rice did not attain hygroscopic equilibrium as rapidly as did rice bran or hulls. They suggested that rapid drying of the surface along with slow drying of the interior would set up strains within the grain that would produce cracks and checks which would subsequently cause many broken kernels during milling. Houston and Kester (1954) found that there is relatively little difference between the equilibrium moistures of brown and white rice.

Coleman and Fellows (1925) stated that 6 to 8 days were required for rice grains to reach equilibrium moisture content in a new environment. Karon and Adams (1949) showed that naturally dried rough rice reached equilibrium in about 15 days while 20 days were required for artificially dried rice to reach this same state. Breese (1955) found that equilibrium by adsorption was extremely rapid when rice grains at 3.3% moisture wet basis (wb) were subjected to relative humidities above 50%. More than 96% of the eventual water uptake took place within the first 4 days. Kunze and Hall (1967) reported that rice kernels with higher moisture content adsorbed moisture much faster than lower moisture grains when both groups were subjected to essentially the same increases in ambient vapor pressure. This is a significant observation with practical implications for rice which is maturing in the field.

The foregoing references have through the years established the hygroscopic nature of rice and its fractions. Now, what are its consequences?

The most studied consequence is that of rice drying. High moisture grains which contain elevated vapor pressures are subjected to ambient or heated circulating air with a low vapor pressure. The water vapors flow from the high vapor pressure areas within the kernel to the low vapor pressure in the circulating air with a consequent drying effect on the grain. Rough rice drying is discussed in detail by Wasserman and Calderwood (1972). In addition they cite 68 drying-related references. Hence, no further effort is made to discuss or summarize drying procedures in this paper.

A less studied consequence of the rice grain's hygroscopicity is that it readsorbs moisture whenever ambient conditions are appropriate. Numerous scientists throughout the world have observed this phenomenon and reported its consequences. The rice grain not only readsorbs moisture; but if it does this rapidly enough, the grain will develop internal fissures perpendicular to its long axis. Stresses that develop within the grain are undoubtedly three-dimensional but the principal stresses appear to be parallel to the long axis of the grain.

Kondo and Okamura (1930) initially reported that moisture readsorption by the kernel after it was dried was much more responsible for fissuring of the grain than the drying process itself. When well dried rice was subjected to a high relative humidity environment, a large number of fissured grains developed very rapidly. One of their experiments shows the result of rough rice being exposed to the ambient environment for a period of 24 hours. The initial moisture content of the grains was 12.6% at 8:00 am. This then dropped to 9.5% by 4:00 pm with no fissured grains. At 6:00 pm the grain moisture had increased to 10.8% with 4% fissured kernels. At 8:00 am the following morning, 72% of the test kernels were fissured and the moisture content was back up to 12.4%. A similar experiment on the same day with brown rice showed that 100% of these kernels had fissured by midnight. Results of these experiments are the consequence of a somewhat routine ambient relative humidity variation within a 24-hour period.

Approximately 5 years later, Stahel (1935) made similar observations in Surinam. He concluded that if dry paddy is remoistened, sun cracks develop and these always cause more breakage of the grains in milling. He further observed that the term 'sun-crack' was a misnomer since the cracks were not due to rapid drying in the sun but to a rise in moisture content. His experiments showed that rice with a moisture content of 15% or more could be remoistened without a deleterious effect. The lower the moisture content below 15% before remoistening, the greater were the number of broken grains which resulted. For example, rice at 9% moisture content showed on the average 14% whole grains remaining after remoistening and shelling with a Smith sheller.

The citations which follow are only a partial literature review. They attempt to trace in a somewhat chronological order the unravelling of the moisture adsorption-grain fissuring concept. The findings of Kondo and Okamura (1930) and those of Stahel (1935) received little attention because the communication of knowledge across continental barriers was limited at that time.

Wheat is a grain that is somewhat similar to rice. Swanson (1943), while working with wheat, observed that the weight of nonweathered wheat samples was on the average 4 pounds higher than for weathered wheat samples. The swelling of the grain from moisture adsorption disturbed the internal compact condition and after the water escaped, vacuoles were left that decreased the specific gravity and hence the test weight. The difference in test weights was a definite indication that a change had occurred in the weathered grain, but the nature of the change could not be clearly described or defined.

Kik (1951) conducted nutritive studies of rice and reconfirmed the findings of Kondo and Okamura (1930) and that of Stahel (1935). He observed cracks in nonstained kernels by placing them on the stage of a stereoscopic microscope and shining a light through them. Observations of the number of cracks were made before staining, because additional cracks developed in stained kernels as a result of moistening and drying in the staining process.

Smith and McCrea (1951) studied kernel breakage in rice milling operations. They reported that some breakage always occurs. This was because many kernels were broken or cracked in the hull before the milling was started. When the hull was removed, the pieces of the kernel fell apart. They stated that if rice remains uncut in the field too long, the kernels crack or 'sun-check.' Sun-checking itself was not discussed.

Milner and Shellenberger (1953) published an article entitled "Physical Properties of Weathered Wheat in Relation to Internal Fissuring Detected Radiographically." Fissures appeared when moisture-swollen grain was dried in a manner that produced stresses within the wheat kernels. The authors state that their discovery, utilizing x-ray techniques, afforded for the first time visual proof of the existence of internal spaces in weathered wheat as was postulated by Swanson (1943). The indication is that Milner and Shellenberger (1953) were of the opinion that the grains had to be rewetted and then redried before the fissures developed.

Breese (1955) then published his work on the hysteresis in the hygroscopic equilibria of rough rice at 25°C. He reiterated Stahel's (1935) statements that moisture adsorption in rice below 14% moisture content would cause rice grains to crack and to subsequently break during milling.

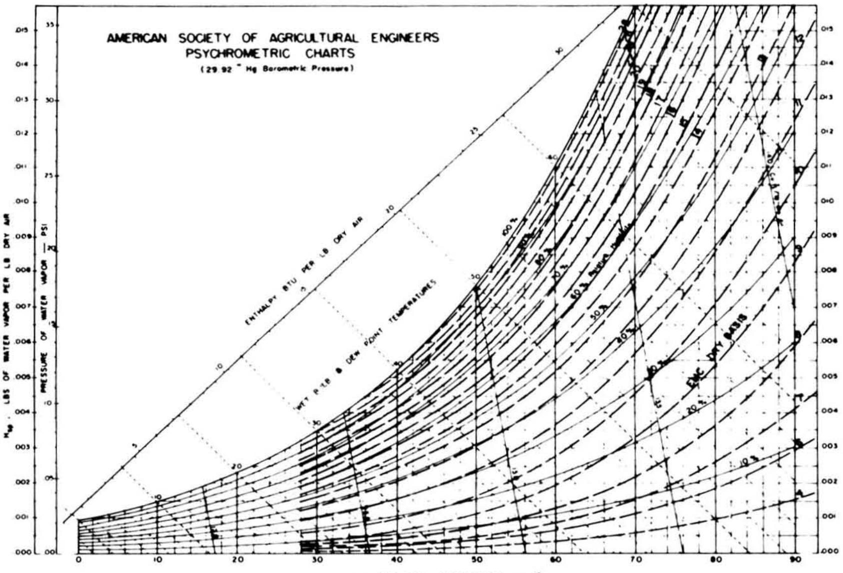
Russian scientists, Burmistrova *et al.* (1956), were also pursuing the phenomenon of grain fissuring. They found that rice with cracked grains is not only found after machine threshing, but already in plants in windrows, and even in standing crops. — — Over a four-day period of windrow drying, cracking in the lower part of windrows increased from 11 to 78% and in their upper part from 14.3 to 83.6%.

Grosh and Milner (1959) published an article entitled "Water Penetration and Internal Cracking in Tempered Wheat Grains." Their x-ray study revealed that cracks, radial and transverse to the crease, occurred in the hard vitreous endosperm in *advance* of water movement through the kernels. No cracks could be observed in kernels prior to wetting, but transverse and radial cracks could be noted within 30 min after wetting. They reported that "Although other workers have noted cracking when endosperm is dried, direct evidence that cracks form in wheat as a result of wetting of endosperm alone has not been offered previously. While it would be reasonable to assume that some fine cracking may exist in sound grain, these results indicated a pronounced increase in cracks, both as to number and dimension, as a result of *wetting*."

Researchers in India (Desikachar and Subrahmanyan 1961) studied the formation of cracks in rice during wetting and its effect on the cooking characteristics of the cereal. It took a longer time for cracks to develop in parboiled rice than in raw rice. Formation of cracks was accelerated by temperatures in the case of parboiled rice; whereas a retarding effect was observed above 70°C in raw rice. The development of cracks in grains immersed in water seemed to be a direct effect of hydration.

Nagato *et al.* (1964) studied the formation of cracks in rice kernels during wetting and drying of paddies. When paddies were soaked in water, cracks occurred increasingly with the progress of soaking time until the moisture content of the kernel reached about 20%. Moist kernels, above about 20%, did not crack from wetting because they were too flexible. Stresses set up in the endosperm caused cracks which were parallel with the short axis of the kernel. The authors did additional work relating hardness of the grain to its moisture content and concluded that hardness of any specified point within the endosperm increases or decreases linearly according to the decrease or increase of its moisture content.

Kunze and Hall (1965) worked with six varieties and two ages of brown rice at environmental temperatures of 38, 68 and 92°F. Rice grains were equilibrated at one relative humidity before they were moved into a higher relative humidity environment which caused the grains to adsorb moisture. Fissuring of the grains was observed and recorded. The grains were permitted to equilibrate in the second environment before they were dehydrated to dry-matter content. The two previous equilibrium moisture contents were calculated and the resulting data were used to superimpose equilibrium moisture content lines on a standard psychrometric chart, Fig. 1, Kunze (1964), Kunze and Hall (1965), and Kunze (1975).



KUNZE and HALL, 1965
Transactions of ASAE 8(3):397

FIG. 1. EQUILIBRIUM MOISTURE CONTENT LINES FOR BROWN RICE SUPERIMPOSED ON A STANDARD PSYCHROMETRIC CHART

Factors influencing 'suncracking' in rice and their effects on the milling quality of the grain were studied by McDonald (1967). Moisture content was found to be the most important single factor controlling the development of 'suncracking' in Caloro II rice. Grains having moisture contents above 21% did not crack but below this level they may or may not have cracked depending on the stress to which they were exposed. He found high temperatures to be more influential in cracking grains than relative humidity changes.

The tensile strength of rice in a moisture adsorbing environment was studied by Kunze and Choudhury (1972). Polished rice adsorbed moisture about twice as fast as brown rice. The decreasing strength of grains in a moisture-adsorbing environment is illustrated in Fig. 2. The quadratic curve is the most likely fit of the actual strength conditions. The mean response time for all polished rice grains to fissure and consequently have zero tensile strength was experimentally determined to be 41.8 min for the indicated environmental change. The quadratic equation predicted zero strength to be reached about 45.2 min after exposure.

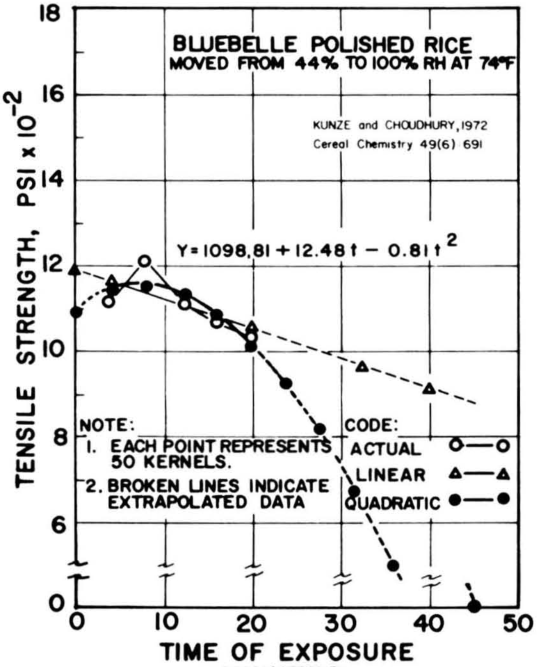


FIG. 2. INFLUENCE OF EXPOSURE TIME ON THE TENSILE STRENGTH OF POLISHED RICE EQUILIBRATED AT 44% RH BEFORE BEING EXPOSED TO 100% RH AT 74°F

DISCUSSION

Moisture adsorption by rice and other cereal grains has been studied by scientists throughout the world. With few exceptions, most of these have authored only a single article on the subject. Therefore the lack of synthesis of available information is perhaps not surprising. We are still lacking knowledge of research conducted in much of Asia during the past two decades. Titles of articles are available in English but translations are difficult to obtain.

Results reported in the literature about the causes of fissured grains are not necessarily in agreement. Some authors feel that temperatures during the maturation period of the grain are important while others feel that relative humidity is the most influential factor. Still others mention both temperature and relative humidity as the causative agents. This lack of agreement is not disturbing because temperature and relative humidity are usually dependent on each other. Scientists who propose that high temperatures cause fissured grains are usually implying the existence of low relative humidity environments. Kondo and Okamura (1930) reported temperatures of 25°C and 36% rh at 12 noon which then changed to −1°C and 100% rh by 2:00 am the following morning. The daylight environment was excellent for drying while the night environment was equally good for moisture readsorption. Within the 24-hour period, both brown and rough rice showed moisture variations of 3.1%. Higher ambient temperatures and lower relative humidities may cause even greater moisture variations. Stahel (1935) shows data where Rexora rice had 20.9% moisture at 8:00 am and this was reduced to 15.2% at 4:00 pm on a day with 97% sunshine. Therefore, a large variation of either temperature or relative humidity will usually cause large variations in both.

During ambient air drying the thermal gradients within a grain probably remain rather small. During the period of maximum ambient temperature and low relative humidity the grain dries the fastest and is thus subjected to evaporative cooling at its surface. The resulting temperature gradient between the center and the surface of the grain should be of a small magnitude. The moisture gradient within a grain may be subject to a relatively large variation. The grain surface must lose moisture before a drying front is established. Continued loss of moisture then causes the drying front to move inward. The moisture gradient in the kernel could conceivably be maximum when the drying front reaches the kernel center. If the average moisture in a kernel varies as much as 5% within an 8-hour period (Stahel 1935), it appears that the moisture gradient from the center to the surface of the kernel could possibly have an even greater magnitude.

Earle and Ceaglske (1949) investigated factors causing the checking of macaroni, which is a cereal product. They measured moisture gradients which were present during drying. The relative magnitude of the stresses due to temperature and relative humidity changes showed clearly that it is the moisture content of the air and not the temperature that is responsible for the checking of macaroni products. Their conclusions were that thermal stresses are small compared to moisture stresses.

Preharvest Moisture Readsorption

After flowering, the rice caryopsis attains full length in 4 days, maximum width in 14 days, maximum thickness in 21 days and optimum weight in 28 days. Tropical rice varieties may be harvested 30 days after flowering. In cooler climates, 60 days may be required for rice to ripen, Juliano (1972). According to Nagato *et al.* (1964), changes of moisture content in the rice kernel during maturation are divided into three periods. In the first period, moisture decreases physiologically with the increase of dry weight until the kernel reaches about 28% moisture. At this time dry weight becomes maximum. In the second period, the moisture content of approximately 28% lasts for about 10 days with no appreciable change. In the third period, moisture content decreases physically under the influence of weather and cracked grains may occur in the field. McDonald (1967) determined moisture contents of individual grains on a panicle and showed that these had variations of 10% or more. He found that many of the kernels removed from panicles were cracked or fissured. The highest moisture content which he observed in a fissured grain was 21%. If the moisture contents in grains on a panicle have a normal distribution, then a panicle with an average grain moisture of 25% may have some grains with 20% moisture while other grains have a moisture content of 30%. The low moisture grains on such a panicle have already reached that critical moisture content at which they are subject to fissure due to ambient changes in the environment. Nagato *et al.* report that kernels above 20% in moisture content do not crack by wetting.

Other researchers (Kondo and Okamura 1930; Stahel 1935; Kunze and Hall 1965) indicate that rice with more than 15 or 16% moisture (wb) will not fissure when exposed to a moisture adsorbing environment. Different rice varieties grown under different climates and levels of fertilization may have different moisture thresholds at which fissuring commences. Also the nature and length of a drying environment which precedes a rapid increase of relative humidity having several hours duration will influence fissuring responses of rice grains in the field.

Rice is not necessarily a uniformly maturing crop. The rice plant continues to produce tillers for some time and it is not uncommon to find panicles with mature grains in the field while there may be others that are still flowering. The plant population and rice variety have some influence on the number of late tillers that develop. With grain moisture content variations of 10% or more within a panicle (McDonald 1967), the moisture variations among panicles is subject to be much greater.

Kunze and Prasad (1976) collected what appeared to be the most mature grains from a breeding plot. A section of the same plot was harvested to obtain grain (5 kilograms) for a drying test and moisture determination. The moisture content was determined to be 29.4% (wb). Of 60 grains selected from the most mature and driest panicles, 14 kernels were fissured. This indicates that the most mature grains in a field may reach the critical moisture level at which fissures can develop while the average moisture of all grains may still be so high that the crop would normally not be harvested.

The field condition is a dynamic one where the number of mature grains, which reach the critical moisture level for fissures to develop, increases as the crop matures. Early in the season more kernels per day may actually be maturing into harvestable high moisture grains than reach the critical moisture stage. At this time head rice yields may increase. However, when more kernels per day reach the critical moisture level than mature into harvestable grains, then the head rice yield has passed its peak and commences on an increasingly rapid decline. The longer the harvest is delayed the lower the head rice yield will be.

Postharvest Moisture Readsorption

At harvest when rice is combined at 22 to 25% moisture, what are the moisture contents of the wettest and the driest grains? Rice kernels fissure individually and they need to be observed individually to determine when these fissures occur. The foregoing discussion indicates that individual grain moisture contents will vary from below the critical moisture level at which fissures can develop from moisture readsorption all the way up to the dough or milk stage. Rice grains at 80° F and 24% moisture (wb) will create an interstice relative humidity of 98.4%, Wasserman and Calderwood (1972).

Kunze and Prasad (1976) simulated field conditions where both high and low moisture kernels would be present at harvest time. Such grains would be combined and then held together in the combine hopper, transport cart, truck or holding bin before the rice would be artificially dried. The high moisture grains would desorb moisture to the interstice air while the low moisture grains would adsorb moisture from it. Basically the high moisture grains were being used to produce a high relative humidity instead of the ambient environment. The percentage of low moisture grains in the mixture was small and probably was a good simulation of field harvesting conditions.

Whole kernels of rough, brown and milled rice were equilibrated at 26.7°C and at relative humidities of 33, 43, 53 and 64%. Other rough rice was equilibrated at 26.7°C and 95% rh. Small quantities of the low moisture rices were then mixed with the high moisture rough rice. The mixture was placed into a quart jar and sealed for 48 hours. Thereafter, the jar was opened and the test grains were retrieved and inspected for fissures. Figures 3 and 4 show the type of results obtained. The low moisture milled rice fissured most readily in the mixture and was followed by brown and rough rice, respectively. Fissured grains in nearly all rice categories could still be produced in reduced numbers when grains equilibrated at 64% rh were mixed with the high moisture rough rice.

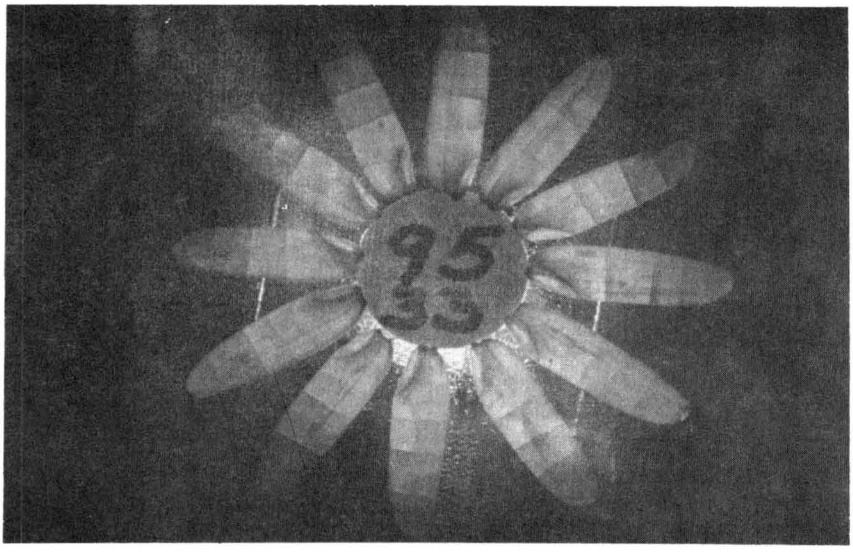


FIG. 3. WHOLE KERNELS OF BROWN RICE OF THE DAWN VARIETY WERE EQUILIBRATED AT 33% RH AND 26.7°C BEFORE BEING MIXED WITH ROUGH RICE EQUILIBRATED AT 95% RH AT THE SAME TEMPERATURE

Mixture of kernels was then sealed in a jar. Fissures as shown above were observed in the brown rice when test kernels were removed after 48 hours.

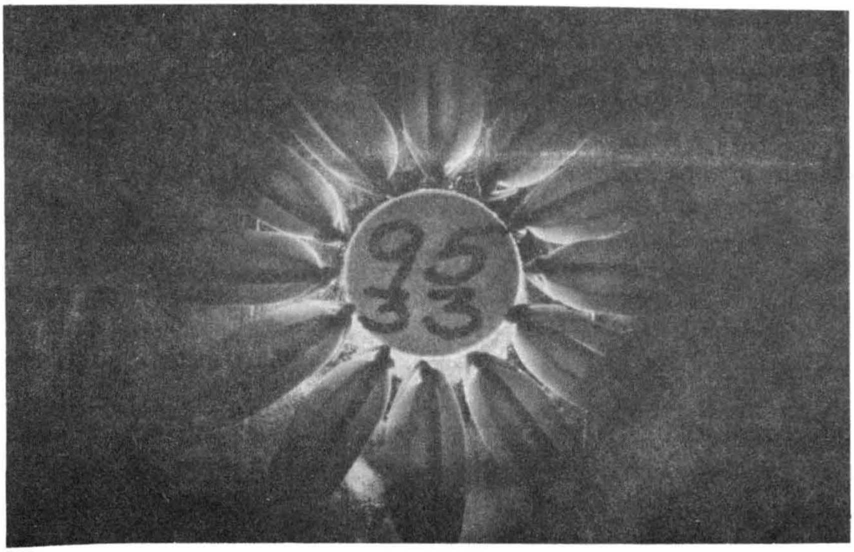


FIG. 4. WHOLE KERNELS OF ROUGH RICE OF THE NATO VARIETY WERE EQUILIBRATED AT 33% RH AND 26.7°C BEFORE BEING MIXED WITH ROUGH RICE EQUILIBRATED AT 95% RH AT THE SAME TEMPERATURE

Mixture of kernels was then sealed in a jar. Fissures as shown above were observed in the rough rice when the test kernels were removed after 48 hours.

In another experiment, Kunze and Prasad (1976) simulated conditions which may occur at the drier when a mixture of high and low moisture grains is to be dried. Kernels of brown and rough rice with a moisture content between 10 and 12% (wb) were placed into screen envelopes before being placed on top of a column of higher moisture rough rice that was to be dried. Depth of the column ranged from 30.5 to 40.6 cm (12 to 16 in.). Air at 60°C was used for drying and the process was continued until the exhausting air reached 37.8°C. Thereafter the test kernels were removed. Fissured grains were counted in the brown rice. The rough rice was shelled by hand before these grains were inspected for fissures.

In this case the drying process was used to create a high relative humidity environment from which low moisture grains ahead of the drying front could adsorb moisture. A 14.5% rice (wb) produced a sufficiently high relative humidity exhaust air for a sufficient length of time to cause some of the grains to fissure. When higher moisture rices were dried, the test grains fissured quite readily.

These results indicate that a mixture of high and low moisture rice placed into a drier could cause many of the lower moisture grains to readsorb moisture and fissure before the drying front reaches them. The information also indicates that mixing type driers may be more efficient in producing higher head rice yields than nonmixing column, batch or deep-bed driers. In the mixing type driers, the lower moisture grains would be alternately exposed to hot-dry and warm-humid environments. These results also give insight into multipass drying and why it has been somewhat more effective in producing higher head rice yields than other drying systems.

SUMMARY AND CONCLUSIONS

The moisture adsorption-grain fissuring phenomenon in rice has been observed periodically for the last half century. The data developed by any one of the studies have not bridged the gap between the researcher's goal and the producer's needs. The subject in itself has not been one that would capture the interest of the grower or processor because their interest has been in drying the rice and not in wetting it. The body of knowledge in the moisture adsorption-grain fissuring area is now reaching the critical mass where it is sufficiently comprehensive to suggest more and more practical applications. In many cases moisture adsorption is inherent with moisture desorption. The drying process itself is a matter of moisture being adsorbed by the surface layers of the grain while it is being desorbed from the center. Effects on the grain are the consequence of both. Temperature gradients may be an additional consideration.

Both adsorption and desorption occur while rice is maturing in the field. Fast drying followed by rapid moisture adsorption may cause the rice kernel to fissure before it is harvested.

High moisture rice as normally harvested in the field is not of a uniform moisture content. The harvested mass has an average moisture content but also contains kernels with moisture contents above and below the average. Depending somewhat on their proportions and moisture contents, the high moisture grains in the harvested mass can cause the low moisture grains to fissure.

In artificial drying, the hot drying air is changed to humid warm air as it passes through the drying front in the grain mass. Low moisture grains ahead of the drying front will readsorb moisture and possibly fissure before the drying front reaches them. After drying, the grains readsorb moisture whenever they are exposed to an ambient environment that will permit them to do so.

This paper and the research that it has reviewed do not propose that the rice grain cannot be damaged in the actual drying process. The paper does suggest that the current technology relating to rice breakage should be re-evaluated in order that the causes of fissured grains can be viewed in their proper perspective.

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PREDICTION OF FREEZING TIMES FOR FOODS AS INFLUENCED BY PRODUCT PROPERTIES

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ABSTRACT

This investigation utilizes a computer simulation technique to predict the freezing times and temperature history curves for food products. The input information consists of the product properties for temperatures above the initial freezing point, freezing medium conditions and the initial product temperature.

It has been established that food products with lower initial freezing points, higher initial water contents and higher initial product densities will have longer freezing times. The prediction of freezing time is most sensitive to the accuracy of the measurement of the product density and the initial freezing point if the freezing point is above −0.5°*C. The influence of the accuracy of unfrozen product thermal conductivity data on the freezing time is not important in the range of* 0.45 *to* 0.55 *W/m°K investigated. The combined influence of inaccuracy in measuring these product properties on the freezing time prediction will be significant even if the influence of an individual product property is small.*

INTRODUCTION

Food freezing is characterized by the continuous changing of product properties during the process. The lack of accuracy in measurement of the freezing properties and rates for food products has emphasized the need for computer simulation models to describe the process. In order to solve heat transfer problems which involve continuous changes in product properties during freezing, numerical techniques and digital computers were utilized by Lescano and Heldman (1973), Heldman and Gorby (1974) and Gorby (1974). These prediction models were based

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on the available product properties data above the initial freezing point and the assumption of an ideal solution being present in the food system. Mathematical calculations of thermal properties based on phase theories of physical chemistry, the freezing point depression equation, some empirical equations (such as Kopelman's (1966) equations and Dickerson's (1969) equation) and the basic equations to describe transient heat conduction problems have been utilized successfully in the prediction of food freezing processes by Heldman (1974). The predicted results based on the above formulations were compared with Charm's (1972), Lescano's (1973) and modified Plank's results.

The objectives of this investigation were:

1. To utilize the computer techniques which predict the product properties at temperatures below the initial freezing point with the prediction models developed by Gorby (1974) in predicting freezing time and temperature history for isotropic products.
2. To compare simulated freezing times, temperature history curves and product properties during freezing processes for several different food products.
3. To investigate the independent effect of different product properties on freezing time.
4. To explain the differences between freezing time and temperature history curves for different food products.

After the relationships between product properties and freezing time have been established, the freezing time of other food products with similar shapes and freezing conditions can be predicted. Furthermore, the relative significance of the accuracy in experimental determination of product properties will be more evident.

THEORETICAL CONSIDERATION

Food freezing rate changes not only with the freezing conditions but also with the food product properties. Changes in product properties during freezing are due to the continuous depression of the freezing point and therefore the continuous changing of the unfrozen water content.

An ideal binary solution was assumed for a food product to establish the relationship between the product temperature (T) and the mole fraction of liquid water (X_a) in the system. This relationship can be described by the following equation:

$$\ln X_a = \frac{\Delta H_f}{R}\left[\frac{1}{T_{ao}} - \frac{1}{T}\right]$$

where ΔH_f is the heat of fusion per mole for pure water, R is the gas constant and T_{ao} is the freezing point of pure water. The relationship between water content and temperature provides the basis of predicting new product properties as affected by temperature during the freezing processes.

Kopelman's (1966) isotropic model was utilized to predict the thermal conductivity of the food product. For a two-component system:

$$k = k_c \left[\frac{1 - Q}{1 - Q(1 - M)} \right]$$

where:

$$Q = M^2 \left[1 - \frac{k_d}{k_c} \right]$$

M^3 = volume fraction of the discontinuous phase

k_c = thermal conductivity of the continuous phase

k_d = thermal conductivity of the discontinuous phase

This model has been modified by Heldman and Gorby (1974) for a three-component system (water, ice and product solids) and has been used successfully in predicting the thermal conductivity of frozen sweet cherries by Gorby (1974).

The density of a food product during freezing is predicted by accounting for the volume expansion due to ice crystal formation which has a lower density than water.

The total heat content of a food product during freezing as proposed by Lescano and Heldman (1973) was expressed by considering zero enthalpy at −40°C.

$$H = m_s C_{ps} (T + 40) + m_i C_{pi} (T + 40) + m_w C_{pw} (T + 40) + m_w L - M_w (\text{at} - 40°\text{C}) L$$

Where the subscripts s, w and i stand for solids, water and ice portion respectively. L is the heat of fusion per gram of water. The apparent specific heat of a food product can then be calculated by $C_{pa} = \Delta H / \Delta T$.

The one-dimensional transient heat conduction within a spherical product with temperature dependent properties, can be described by the following differential equation:

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left[\alpha (T) r^2 \frac{\partial T}{\partial r} \right] = \frac{\partial T}{\partial t}$$

where $\alpha(T)$ is the thermal diffusivity of the food product. The above equation applies if the direction of heat flow is assumed to be in the radial direction only.

EXPERIMENTAL METHODS

Asparagus, carrots, cherries, peas, plums, and strawberries were chosen for the freezing time comparisons. The reasons for selection of these products were as follow:

1. The products are available in frozen form and the individual-quick-freezing (IQF) process is used on a commercial scale to assure freshness and quality of these products.
2. The product properties of these food products are typical of fruits and vegetables.
3. They are isotropic or can be approximated by isotropic conditions.
4. They are of comparable sizes or can be reduced into comparable sizes for use in comparing the effects of product properties on the freezing time.

A computer program to simulate the freezing processes of spherical products was developed by Gorby (1974). The program generated the predicted product properties as a function of temperature and the predicted temperature history for a set of initial conditions. The input information consists of three major parts:

1. Initial product conditions: initial product temperature, initial freezing point, initial water content, unfreezable water content, density, heat capacity, thermal conductivity and diameter. Values of physical properties of these food products are listed in Table 1.
2. Freezing medium conditions: freezing medium temperature and convective heat transfer coefficient.
3. Operating conditions: computing time increment, print time increment, freezing termination criterion and the number of shells into which the product will be divided.

The termination criterion for the freezing simulation was established as mass average enthalpy for the product at −25°C.

The following parameters were chosen to evaluate:

1. Product diameters of 1 cm for asparagus[1] and peas, 2 cm for carrots[1], cherries, plums and strawberries.

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[1] The dimensions of asparagus and carrots are referred to as the diameter and length of the reduced pieces which can be approximated as a spherical product.

Table 1. Values of physical properties of several food products utilized in the simulation

Properties	Units	Asparagus	Carrots	Cherries	Peas	Plums	Strawberries
Initial Freezing Point (TF)	°C	−0.67	−1.11	−1.44	−1.83	−2.28	−0.89
Initial Water Content (IWC)	g-H_2O/g-product	0.926	0.88	0.867	0.758	0.76	0.893
Unfreezable Water Content (UFWC)	g-H_2O/g-product	0	0	0	0	0	0
Initial Product Density (IPD)	g/cm^3	1.03	1.06	1.07	1.01	1.05	1.04
Initial Specific Heat (ICP)	J/g °K	3.97	3.89	3.79	3.56	3.64	3.93
Initial Thermal Conductivity (IK)	W/m °K	0.53	0.50	0.52	0.47	0.51	0.54

From Reidy (1968), Dickerson (1969) and Bedford (1976)

2. Initial product temperature: 10°C.
3. Convective heat transfer coefficients: 25, 70, 170, and 340 W/m^2 °K.

Times for the products to reach a mass average enthalpy at −25°C were predicted.

The output information included:

1. Predicted apparent specific heat, thermal conductivity, product density, unfrozen water content and enthalpy of food products as a function of temperature.
2. Predicted temperature history of the entire freezing processes.
3. Predicted freezing time for the product to reach the freezing termination criterion.

RESULTS AND DISCUSSION

The results in Fig. 1 illustrate the predicted values of unfrozen water content as a function of temperature for the various products. The sudden decrease in unfrozen water content near the initial freezing point of each product is due to ice crystal formation. As more ice is formed, the water solution becomes more concentrated and the freezing point is further depressed.

The results in Fig. 2 illustrate the predicted thermal conductivity changes during the freezing process. The significant increase at temperatures below the initial freezing point is related to the presence of ice which has a higher thermal conductivity than that of water.

The influence of temperature on the product density is evident in Fig. 3. The decrease in product density during freezing is caused by the ice formation; ice has a lower density than water.

By comparing the values of product properties at the initial temperature and at temperatures well below the initial freezing point, it is evident that the value of thermal conductivity increases nearly 4 times, whereas the product density decreases about 10%.

Removal of latent heat contributed most to the reduction in heat content at temperatures just below the initial freezing point where the temperature decrease is very small. The significant decrease in enthalpy of the product in that region results in very high values of the apparent specific heat as illustrated in Fig. 4.

In order to investigate the independent influence of product properties on the freezing time, a series of freezing simulations were conducted by fixing all the properties at a constant value except the one

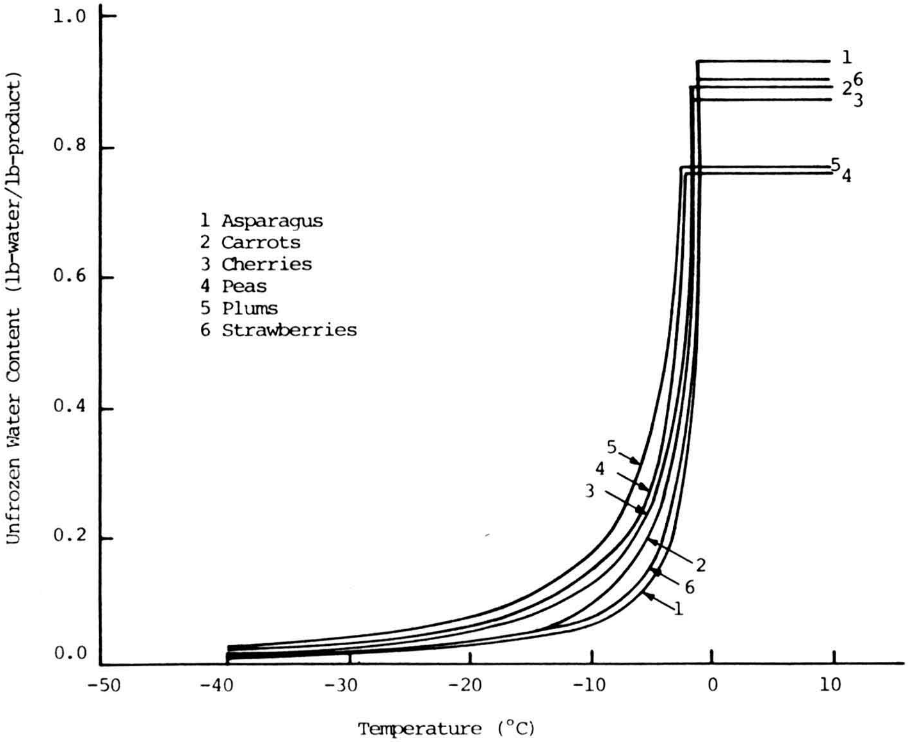

FIG. 1. PREDICTED UNFROZEN WATER CONTENT FOR DIFFERENT FOOD PRODUCTS

under investigation. The results indicate that a food product with a higher initial freezing point, a lower initial water content, higher unfreezable water content (existing in some fibrous food products, e.g. meat) and a lower product density will have a shorter freezing time. The values of the initial thermal conductivity have almost no influence on the predicted freezing time in the range of 0.45 to 0.55 $W/m^2 {}^\circ K$. Based on the results from the above independent analysis, the maximum allowable deviations in product property values which result in tolerable percentage errors in the prediction of freezing time are listed in Table 2. The results are based on arbitrarily chosen conditions: (a) initial product temperature of 10°C, (b) freezing medium temperature of −75°C, (c) surface heat transfer coefficient of $70 W/m^2 {}^\circ K$ and (d) product diameter of 2 cm. The product with a higher initial freezing point (above −0.5°C) requires a more accurate measurement of the initial freezing point. The results in Table 2 also indicate that the prediction of freezing time is very sensitive to the accuracy of the product

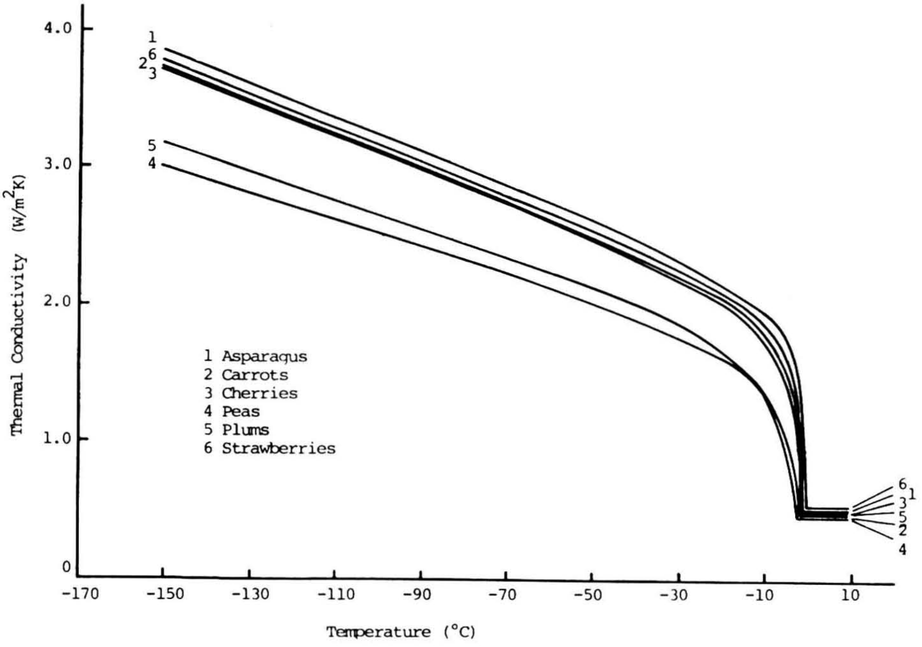

FIG. 2. PREDICTED THERMAL CONDUCTIVITY FOR DIFFERENT FOOD PRODUCTS

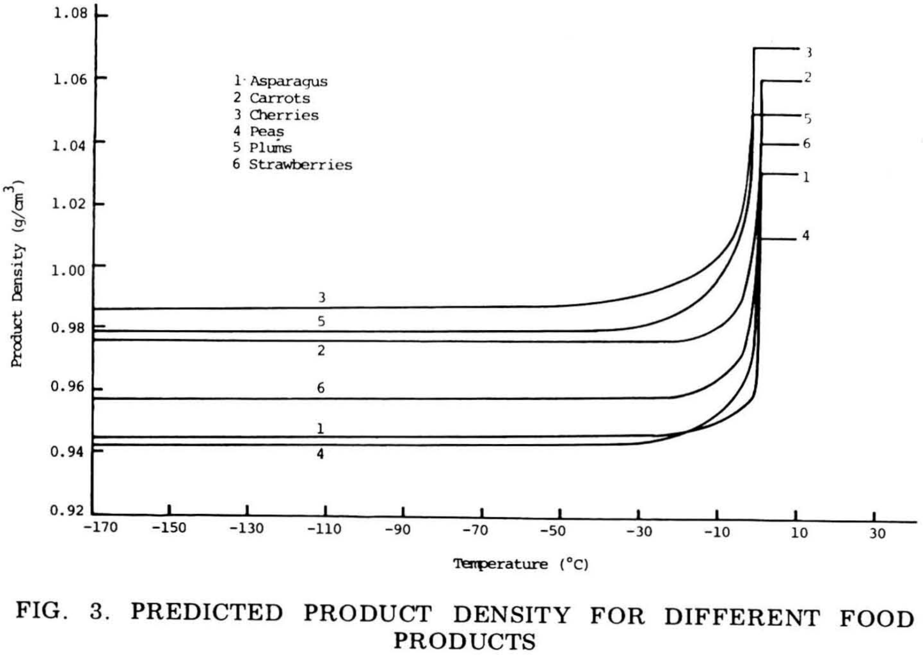

FIG. 3. PREDICTED PRODUCT DENSITY FOR DIFFERENT FOOD PRODUCTS

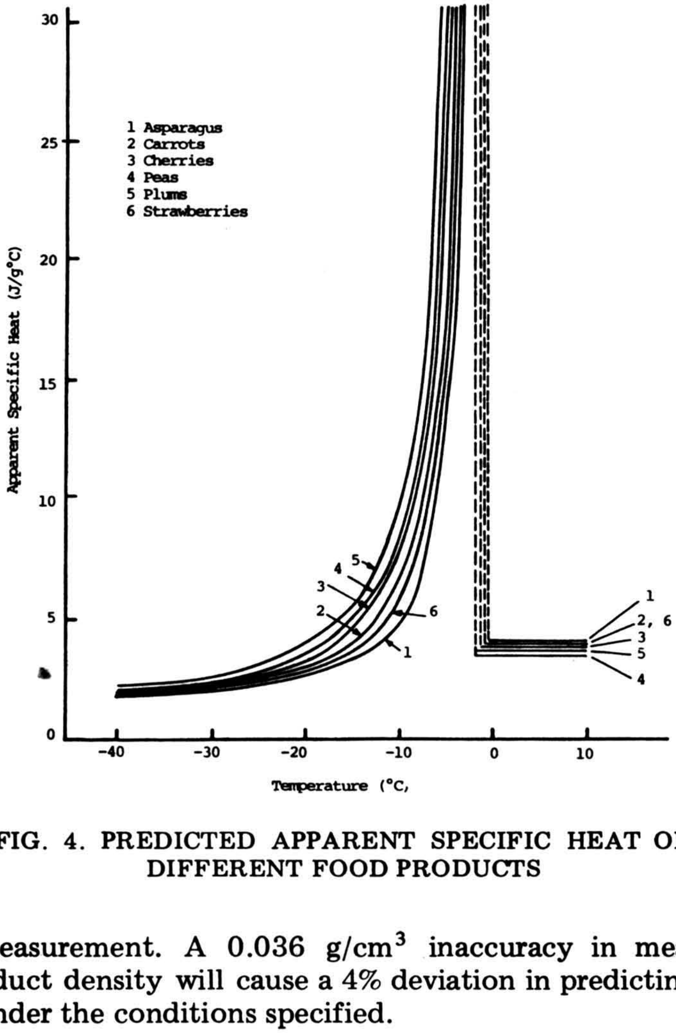

FIG. 4. PREDICTED APPARENT SPECIFIC HEAT OF DIFFERENT FOOD PRODUCTS

density measurement. A 0.036 g/cm^3 inaccuracy in measuring the initial product density will cause a 4% deviation in predicting the freezing time under the conditions specified.

Additional factors which influence the freezing time are the product diameter and the freezing conditions. It was found that an increase in product diameter will increase the freezing time. The results in Fig. 5 and 6 illustrate the influence of freezing conditions on the freezing time. At freezing medium temperatures below —200°C, reduction in the freezing medium temperature has a slight influence on the freezing time. At freezing medium temperatures above —100°C, the appropriate selection of the freezing medium will reduce the freezing time significantly as shown in Fig. 5. With surface heat transfer coefficients lower than 100 W/m^2 °K, Fig. 6 demonstrates that a significant reduction in the freezing time can be achieved with a small increase of the surface heat transfer coefficient.

Table 2. Maximum allowable deviations in measuring product properties from the actual values for the stated variations in the prediction of freezing time. Based on carrots with initial product temperature of 10°C, the freezing medium temperature of −75°C, the surface heat transfer coefficient of $70 W/m^2 \, ^\circ K$ and the product diameter of 2 cm

			Variations of Freezing Time			
Product Properties	Range	Units	±1%	±2%	±3%	±4%
Initial Freezing Point	−0.1 to −0.5	deg C	±0.013	±0.025	±0.038	±0.05
Initial Freezing Point	−0.5 to −1	deg C	±0.04	±0.08	±0.12	±0.16
Initial Freezing Point	−1 to −2	deg C	±0.02	±0.4	±0.6	±0.8
Initial Freezing Point	−2 to −3	deg C	±0.3	±0.6	±0.9	±1.2
Initial Water Content	0.75 to 0.90	g-water/g-product	±0.03	±0.06	±0.10	±0.13
Unfreezable Water Content	0 to 0.1	g-water/g-product	±0.04	±0.07	±0.10	±0.14
Initial Product Density	1.0 to 1.1	g/cm^3	±0.009	±0.018	±0.027	±0.036
Initial Thermal Conductivity	0.45 to 0.55	W/m °K	—	—	—	—

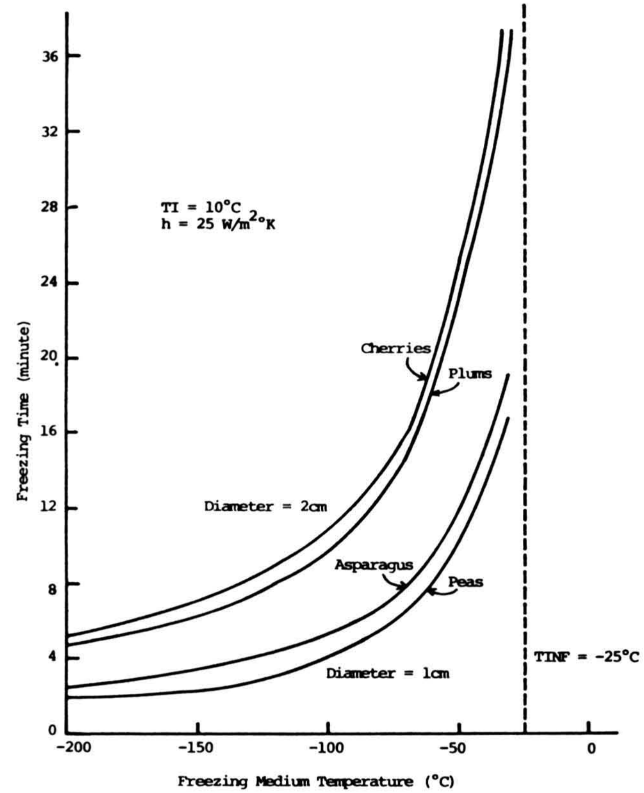

FIG. 5. PREDICTED FREEZING TIME VERSUS FREEZING MEDIUM TEMPERATURE FOR VARIOUS FOOD PRODUCTS OF DIFFERENT PRODUCT DIAMETERS

Two plots of freezing history are presented in Fig. 7 and 8. Temperature history in Fig. 7 compares asparagus, cherries and peas which have different initial water contents (asparagus = 0.926, cherries = 0.867, and peas = 0.758). The center temperature of asparagus stays very close to the initial freezing point for a longer period compared to the other two products, therefore, a longer freezing time was expected for asparagus. The results in Fig. 8 illustrate the influence of the surface heat transfer coefficient on the temperature history of strawberries. At a lower value of the surface heat transfer coefficient, the product center temperature stayed at the initial freezing temperature for a longer period.

The influence of product properties on the freezing time for the actual food product is complex due to the combined effect of product

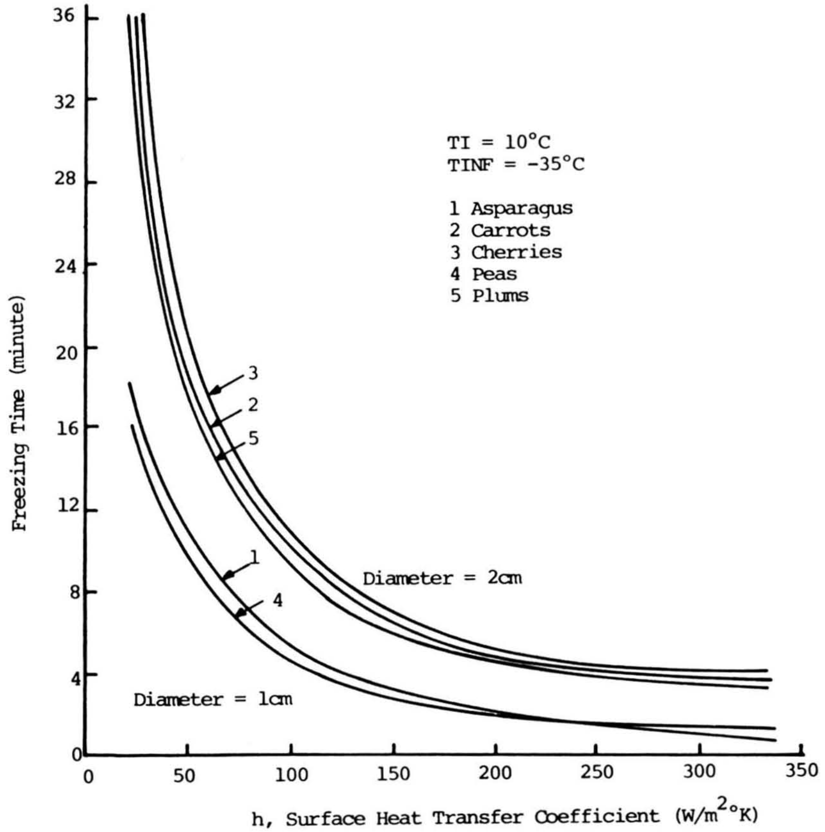

FIG. 6. PREDICTED FREEZING TIME VERSUS SURFACE HEAT TRANSFER COEFFICIENT FOR VARIOUS FOOD PRODUCTS WITH DIFFERENT PRODUCT DIAMETERS

properties. The results indicate that these influences are consistent with the trends predicted by the usage of *independent* product property variation. Inaccuracies in measurement of product properties may have a very significant influence on accurate prediction of the freezing time for the product.

CONCLUSIONS

1. A food product with a lower initial freezing point, a higher initial water content and a higher initial product density has a longer freezing time.
2. At freezing medium temperatures below —200°C, reduction in the

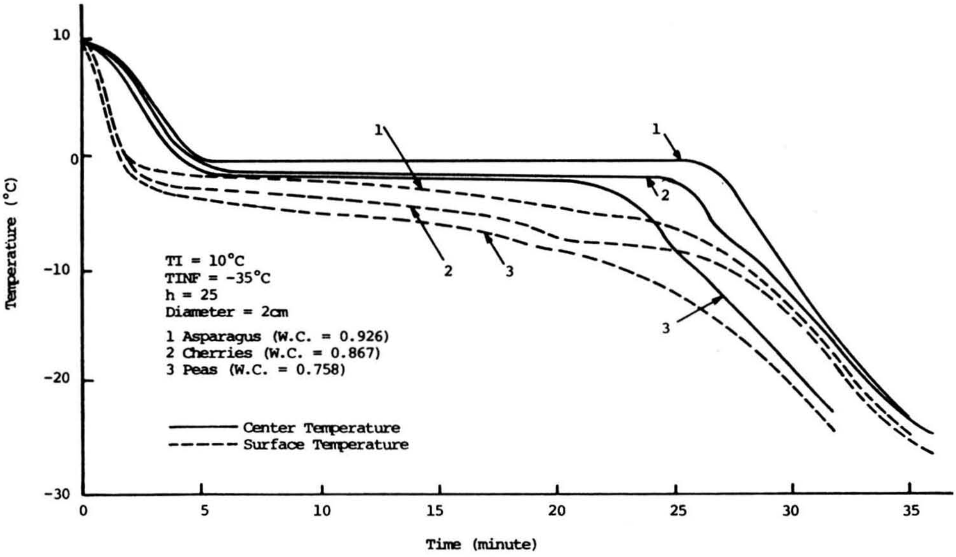

FIG. 7. PREDICTED TEMPERATURE HISTORY FOR DIFFERENT FOOD PRODUCTS

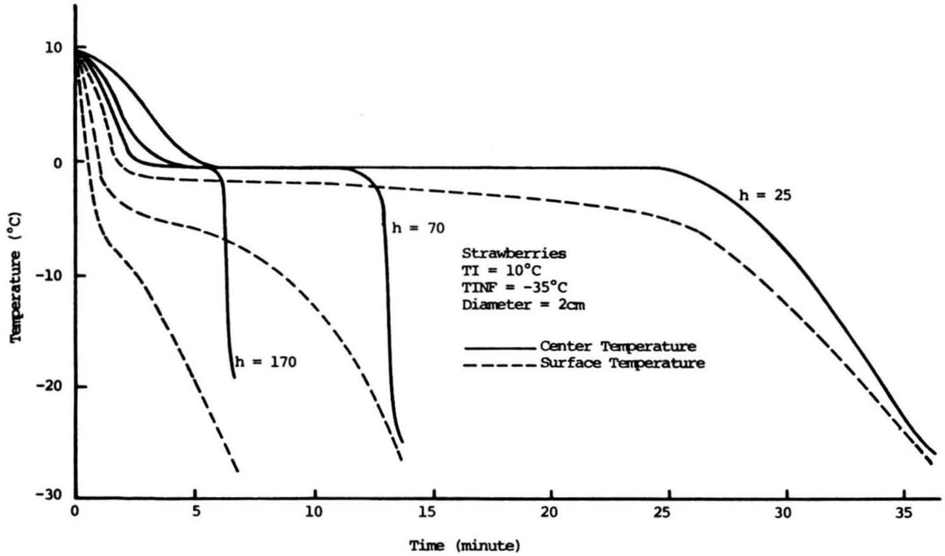

FIG. 8. PREDICTED TEMPERATURE HISTORY OF STRAWBERRIES FREEZING AT DIFFERENT VALUES OF SURFACE HEAT TRANSFER COEFFICIENT

freezing medium temperature has a small influence on the freezing time. With a convective heat transfer coefficient greater than 200 W/m^2 °K, further increase in the convective heat transfer coefficient has a smaller influence on the freezing time.

3. The prediction of the freezing time is most sensitive to the accuracy of the initial product density and to the accuracy of the initial freezing point when the initial freezing point of the food product is above -0.5°C. The accuracy of the initial thermal conductivity does not influence the predicted freezing time for fruit and vegetable products significantly.
4. The combined effect of uncertainties in measuring product property values may have a very significant influence on prediction of the exact freezing time.

NOMENCLATURE

C_p — Specific heat, J/g°K
C_{pa} — Apparent specific heat, J/g°K
h — Convective heat transfer coefficient, W/m^2 °K
k — Thermal conductivity, W/m°K
M — Cubic root of the volume fraction of the discontinuous phase
m — Mass, g
Q — Parameter used in Kopelman's equation
R — Gas constant, 8.314 J/mole °K
r — Radial direction of a sphere
T — Product temperature, °K
T_{ao} — Freezing point of pure water, °K
TI — Initial product temperature, °C
TINF — Freezing medium temperature, °C
t — Time
X_a — Mole fraction of liquid water
ΔH_f — Heat of fusion per mole of water, J/mole
α — Thermal diffusivity, m^2 /hr

Subscripts

c — the continuous phase
d — the discontinuous phase
i — ice
s — solid
w — water

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LITERATURE ABSTRACTS

ABSTRACTS FROM ASHRAE TRANSACTIONS

Each of the following abstracts has been reprinted with permission from the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ESTIMATING HEATS OF MIXING. C. C. Li, ASHRAE Trans. *82*(1), 283–288 (1976).

Heats of mixing are of fundamental importance in chemical separation processes and the related industrial applications. Furthermore, it is an essential property for the evaluation of molecular interactions among unlike species. This paper presents a simple, but fairly accurate method of estimating this property.

FREEZING PROCESS BETWEEN TWO CONCENTRIC PIPES WITH A CONSTANT HEATING TEMPERATURE AT THE INNER WALL. S. Lin, ASHRAE Trans. *82*(1), 256–268 (1976).

Freezing processes which take place in a fluid with laminar flow contained in the space between two concentric cylindrical pipes are considered. Heat is supplied at the inner wall and removed at the outer wall of the annular space. The heat supplied to the inner wall is expressed as a constant wall temperature. The heat removal is a result of heat convection in a cold medium surrounding the outer pipe, which has a temperature lower than the solidification temperature of the fluid in the space between the pipes. An analytical method is developed for solving the rate of propagation of the phase boundary between the solid and liquid phases. The system described can be used for storage of thermal energy by solid-liquid phase change. The equilibrium condition of energy storage and extraction is also discussed.

HEAT PIPE HEAT EXCHANGERS AS ENERGY RECOVERING DEVICES. M. A. Ruch, ASHRAE Trans. *82*(1), 1008–1014 (1976).

Counterflow heat exchangers comprised of a bundle of heat pipes with secondary finned surfaces attached offer attractive advantages as energy recovery units. With no moving parts and wide design flexibility, these heat pipe heat exchangers are finding ever increasing usage in air-to-air heat recovery. Three general classes of applications can be identified (1) using energy recovery from process exhaust to regenerate the process; (2) using energy from process exhaust to heat comfort make-up air during the winter months; and (3) using comfort exhaust to preheat comfort make-up air during the winter months and/or precool comfort make-up air during the summer months. Illustrations of each class are presented.

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TRNSYS — A TRANSIENT SIMULATION PROGRAM. S. A. Klein, W. A. Beckman and J. A. Duffie, ASHRAE Trans. *82*(1), 623–633 (1976).

A solar energy system can be regarded as a collection of interconnected components, which normally operate in transient modes. To facilitate the simulation of such systems, a computer program called TRNSYS has been developed to interconnect components in any desired manner and solve the simultaneous algebraic and differential equation describing the system. With this program, the essential problem of transient system simulation reduces to one of formulating mathematical models for each of the components in the system. General mathematical models of many components common in solar energy systems have been studied for energy conservation. Energy savings modifications were analyzed for this building. Savings estimated for the modifications were a 39.9% reduction in gas and electric costs. Actual savings for the first quarter of 1975, based on meter readings compared to the same quarter of 1972, were a 63% reduction in cost.

HEAT, MASS AND MOMENTUM TRANSFER IN A PARALLEL PLATE DEHUMIDIFYING EXCHANGER. F. C. McQuiston, ASHRAE Trans. *82*(2), 87–106 (1976).

The process of combined heat, mass, and momentum transfer in a mixture of water vapor and air flowing over a cold surface where the velocity, temperature, and vapor concentration profiles all under simultaneous development was investigated.

When condensation occurs, droplets or a film of condensate collects on the surface. The presence of the water on the surface does affect the transfer phenomena, and the rate at which water is deposited may be a factor. The j-factor analogy is not always reliable when applied to predict wet surface heat and mass transfer coefficients (or j-factors) from dry surface heat transfer coefficients (or j-factors).

The basic objective was to discover as much as possible about the basic mechanism of combined heat and mass transfer. A simple parallel plate surface was used so that some variables could be eliminated.

The results of the study indicate that the quantity of water on the surface is important; however, free stream turbulence intensity does not appear to be an important factor. Results of the visualization study showed that the condensation was dropwise on aluminum, constantan, and copper over a Reynolds number range of 600 to 4000. The droplets seemed to be under the influence of gravity and surface tension only.

DESIGN AND OPTIMIZATION OF AN EVAPORATIVE AIR COOLER. N. Ravichandian and V. Kambi, ASHRAE Trans. *82*(2), 66–75 (1976).

A drip-type evaporative air cooler has been designed, fabricated and experimented upon to determine the effects of variations in fan speed, pad density, water recirculation rate and outdoor air conditions on the mass flow rate of air delivered by the cooler, the power consumed by the fan, magnitude of cooling, net unit sensible heat conversion and the saturation efficiency of the cooler. The data thus obtained are used to derive curve-fit expressions by regression analysis, for the dependent quantities in terms of the independent variables. Further, a nonlinear programming problem has been structured to determine the optimum values of the design variables for specific outdoor air conditions. The power input to the fan divided by the net sensible heat conversion rate (a parameter that reflects the economy of the cooler), forms the objective function to be minimized subject to a set of geometric and behavioral constraints. An illustrative example indicates that the optimal design saves power and enhances the cooling effect significantly.

A NEW CORRELATION FOR HEAT TRANSFER DURING BOILING FLOW THROUGH PIPES. M. M. Shah, ASHRAE Trans. *82*(2), 66–75 (1976).

A new correlation, called the CHART, is presented for prediction of heat transfer coefficients during saturated boiling of Newtonian fluids inside pipes. This correlation has been compared with 780 data points from 18 independent experimental studies and correlates 90% of these data within ±30%, the mean deviation for all data being 14%. The data analysed include common refrigerants, water, and cyclohexane, pipe diameters ¼ to 1 in., reduced pressures 0.004 to 0.8, heat fluxes 500 to 250,000 Btu/hr ft^2, mass fluxes 10^3 to 10^6 lb/hr ft^2, and vapor qualities 0 to 100%. Horizontal and vertical orientations, circular and annular test sections, as well as most common pipe materials are included. Freon evaporator data include temperatures from −110 to +130 F, while boiling water data are over a pressure range 15 to 2500 psia. The extensive data analysis shows the CHART to be a reliable, generally applicable predictive technique. Other correlations are also discussed and recommendations are made for the practical design of ammonia and freon evaporators.

A COMPUTER PROGRAM TO SIMULATE THE FLOW RATES, TEMPERATURES AND PRESSURES OF A CENTRAL CHILLED WATER SYSTEM. W. F. Stoecker, S. R. Richter, G. E. Higges and A. R. Baker, ASHRAE Trans. *82*(1), 539–547 (1976).

The designer of the distribution network in a central chilled water system is often faced with the need of analyzing various combinations of thermal loads in order to determine whether the system can adequately meet all demands. The purpose of this computer program is to allow the designer to provide physical and performance descriptions of the elements of the system as well as the thermal loads at all cooling coils. The program then simulates the temperatures, flow rates and pressures of the chilled water and determines whether any coils are short of capacity under the load combination. The program can accommodate any arrangement of piping, any location of pumps, and combinations of two-way or three-way control valves on the coils along with wild coils.

EXPERIMENTAL HEAT AND MASS TRANSFER DATA FOR CONDENSING FLOW IN A PARALLEL PLATE HEAT EXCHANGER. D. R. Tree and W. A. Helmer, ASHRAE Trans. *82*(1), 289–299 (1976).

The increased pressure to conserve our natural resources continues to require that all heat exchanges be optimized. Numerical techniques have been devised to optimize the exchangers with respect to many parameters which influence their behavior. In optimization programs for condensing flow heat exchangers, a knowledge of the local heat and mass transfer coefficient and the local friction factor are usually required. Unfortunately, the amount of heat transfer, mass transfer and friction factor data published in the open literature for a given configuration is very limited and the data available for condensing of water on the air side for a specific heat exchanger is almost nonexistent. The purpose of the present work is to investigate the influence of the condensing water on the friction factor, heat transfer coefficient and the mass transfer coefficient during condensing flow in a heat exchanger. In this investigation a very simple heat exchanger configuration was examined, i.e., a parallel plate heat exchanger involving only two plates. This paper presents the experimental results of this work. Experimental measurements were made to determine both average and local values of the friction factor and heat transfer coefficient. Both are presented in this paper. Due to several conditions, the local data has a large scatter and the uncertainty may be as much as 100%. Since the uncertainty calculation is based on the worst possible case, the error in the actual data should be less than this. Nevertheless, because of lack of this type data in the open literature it is presented.

ABSTRACTS FROM JOURNAL OF FOOD SCIENCE

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LETHAL EFFECT OF FOOD TEMPERATURE ON LINEAR PORTION OF A HEATING OR COOLING CURVE. C. M. F. Flambert, J. Deltour, R. W. Dickerson and K. Hayakawa, *J. Food Sci. 42*, 545–546 (1977).

The purpose of this note is to clarify the ambiguity in the presentation in a heat processing text re using an exponential integral function to estimate analytically a sterilizing value of a linear portion of a heating or cooling curve.

EFFECT OF MILLING CONDITIONS ON YIELDS, MILLING TIME AND ENERGY REQUIREMENTS IN A PILOT SCALE ENGELBERG RICE MILL. R. L. Roberts and T. Wasserman, *J. Food Sci. 42*, 802–803 (1977).

The current energy shortage and the desire for high yields of total and head rice are very important economic factors in the production of milled white rice for direct food use. The favorable yields obtained from this work indicate that reduction in energy requirements and increased yields could be achieved by proper mill adjustments and the use of various additives. The pilot scale results reported need to be evaluated further under commercial milling conditions to select the best combinations of mill settings and additives to obtain the greatest economic advantage, as well as energy savings.

KINETICS AND COMPUTER SIMULATION OF ASCORBIC ACID STABILITY OF TOMATO JUICE AS FUNCTIONS OF TEMPERATURE, pH AND METAL CATALYST. Y. C. Lee, J. R. Kirk, C. L. Bedford and D. R. Heldman, *J. Food Sci. 42*, 640–644 (1977).

The rates of ascorbic acid destruction in tomato juice were determined as functions of storage temperature, pH and copper concentration. Ascorbic acid destruction under anaerobic conditions was confirmed to be a first-order reaction with respect to ascorbic acid concentration. The effect of storage temperature on the rate of ascorbic acid destruction was accounted for by the Arrhenius equation. The activation energy of anaerobic destruction of ascorbic acid was 3.3 kcal/mol at pH 4.06, and was shown to change with changes in pH. The rate of ascorbic acid destruction was influenced by pH, reaching a maximum near the pKa of ascorbic acid. The rate of copper-catalysed destruction of ascorbic acid increased as copper concentration in tomato juice increased, and was affected by pH. A mathematical model, which described the rate of ascorbic acid destruction as functions of storage temperature, pH and copper, was developed based on the experimentally derived equations. A computer simulation program was developed using the mathematical model to predict ascorbic acid stability in tomato juice. The computer-aided predictions of ascorbic acid stability in tomato juice was in good agreement with the results obtained from the shelf-life tests.

VISCOELASTIC AND HISTOLOGICAL PROPERTIES OF GRAPE SKINS. B. Hankinson, V. N. M. Rao and C. J. B. Smit, *J. Food Sci. 42*, 632–635 (1977).

Comparisons were made between the viscoelastic properties and the histology of the skins of two varieties of Muscadine grapes (*Vitis rotundifolia*) and of Thompson Seedless grapes (*Vitis vinifera*). Uniaxial tensile tests and puncture tests were performed using the Universal Testing Machine (Instron Model 1130) at three different, constant deformation rates. The grapes were prepared for sectioning by embedding in the low viscosity epoxy resin, Spurr. 1–2μ thick sections were taken and the average area of the cells of the skins calculated. The failure stress in puncture tests correlated well with average cell area ($r = 0.99$). The thickness of the skin was positively correlated with relaxation time determined from uniaxial tensile tests ($r = 0.97$).

EFFECT OF THERMOCOUPLE WIRE SIZE ON THE COOKING TIMES OF MEAT SAMPLES. R. L. Hostetler and T. R. Dutson, *J. Food Sci. 42*, 845–846 (1977).

The study was designed to determine if two types of thermocouples give the same readings when placed in the same steak and if not, which thermocouple actually gives the more accurate temperature measurement. The larger thermocouple was made of 23 gauge (0.048 cm diam) copper/constantan wire; the smaller, 40 gauge (0.008 cm diam). Results indicate cooking times will be shorter in small steaks if the larger thermocouples are used. There is evidence the larger thermocouples conduct heat into small steaks whereas the smaller thermocouples do not; the smaller thermocouples give a better indication of the internal temperature of the meat than do the larger thermocouples.

TOTAL ENERGY TO PRODUCE FOOD SERVINGS AS A FUNCTION OF PROCESSING AND MARKETING MODES. H. A. Olabode, C. N. Standing and P. A. Chapman, *J. Food Sci. 42*, 768–774 (1977).

Major food processing and marketing modes were examined in terms of their relative energy intensiveness in order to quantify the differences which exist among them. Detailed energy accounting was executed from point of harvest to point of consumption, using available industry data, direct experimentation, and theoretical engineering analysis for ten potato product models: fresh, flake-dried, microwave-dried, granulated, spray-dried, freeze-dried, canned, retort-pouched, refrigerated, and frozen. Total energy for a finished 4-oz serving of mashed potatoes was found to range from a low of about 1950 Btu for fresh to a high of 6950 Btu for frozen, with dehydrated models ranging from 2200 Btu for flaked to 5860 Btu for freeze dried. The broad differences between modes suggest a need for inclusion of energy accounting in decision making for food product development, processing, marketing and preparation.

EFFECT OF TEMPERATURE DEVIATION ON PROCESS STERILIZATION VALUE WITH CONTINUOUS AGITATING RETORTS. R. Houtzer and R. Hill, *J. Food Sci. 42*, 775–777 (1977).

Little information is available for canned foods specifying the extent and duration of a drop in retort temperature during thermal processing which could cause a public health hazard. Count reduction and heat penetration studies were performed using either a continuous agitating retort or a laboratory simulator to determine process lethality during temperature deviations (involving temperature drops of 20°F). In these tests, the can conveying reel was stopped as soon as the sterilizer temperature dropped, and was restarted when the retort temperature returned to that of the scheduled process. The results show that in the products tested, the process lethality during the temperature deviation was greater than that of the normal process.

EFFICACIES OF THREE SANITIZERS UNDER SIX CONDITIONS OF APPLICATION TO SURFACES OF BEEF. M. E. Anderson, R. T. Marshall, W. C. Stringer and H. D. Naumann, *J. Food Sci. 42*, 326–329 (1977).

Efficacies and optimum application conditions of three sanitizers (chlorine, 200–250 ppm; acetic acid, 4.0%; and quaternary ammonium, 3.78 g/liter) were determined. Variables were three rates of flow of sanitizer (1.7, 3.4 and 6.8 liters/min), washed and unwashed meat, warm (38°C) and cold meat (3.3°C), and two pressures of sanitizer application (3.5 and 14.0 kg/cm^2). Results were averaged over other variables providing the following data for individual variables. Acetic acid gave a high initial average decrease in counts (−1.47 log), and counts decreased (−1.79 log) up to 48 hr after sanitization. Chlorinated solution caused an initial mean difference of −0.31 log and a difference after 48 hr of 0.53. The quaternary ammonium compound produced differences of −0.79 and −0.03 log in immediate and 48-hr counts. Acetic acid and hypochlorite were nonselective, but the quaternary sanitizer allowed more oxidase positive, nonfermentative bacteria to survive.

A THERMAL CONTROLLER FOR THE SHORT COD DETERMINATION. P. G. Crandall, C. C. Niementowski and P. E. Nelson, *J. Food Sci. 42*, 839–842 (1977).

An instrument, the Short COD Thermal Controller, was developed to make the short COD test faster, safer and more precise through automatic control of heating and agitation. The instrument was used to analyze a glucose solution, simulated tomato wastes and corn processing wastes. Glucose solutions were found to have a coefficient of variation of 1.4%, compared to the 20% reported for the BOD and the 8% for the long COD. The coefficient of variation for the tomato waste was 2.7%, and on the corn processing waste the instrument was able to give more reproducible results than the inherent variability found in preparing the replicate waste samples. The new instrument reduced both the time required to analyze a large number of samples and the hazards to technicians.

BEAN PROTEIN SEPARATIONS USING LABORATORY AND CONTINUOUS DECANTER CENTRIFUGES. J. C. Miers, A. C. Olson and G. M. Gray, *J. Food Sci. 42*, 367–369 (1977).

California Small White bean meal was given three acidic extractions at low pH followed by three at high pH by laboratory and pilot plant procedures under similar conditions. Extracts and residues were neutralized to pH 6.5 and lyophilized. Acid extracted bean solids were 31% of the original bean meal by both laboratory and pilot plant procedures. The basic extracted solids were 6% by the two procedures. The protein content in the acid extract was 14% of the original meal by each procedure while the protein in the basic extract was 3% by the two procedures. The decanter-centrifuge was effective for the separation if the ground bean was not too fine.

TEMPERATURE DEPENDENCE OF THE COOLING RATE OF DRY LEGUMES. D. G. Quast and S. D. da Silva, *J. Food Sci. 42*, 370–374 (1977).

It is well known that high temperatures reduce the cooking time of dry beans and peas. However, little quantitative information on the temperature dependence of the cooking time can be found in the literature. The temperature dependence of the cooking rate was obtained by cooking samples of dry legumes for various times at 98, 116, and 127°C and measuring the maximum force on a Kramer TP-1 shear press with a CS-1 cell containing 100g samples. The time-temperature combinations which gave the same texture were plotted to obtain z-values for softening of the beans. The following z-values for softening due to cooking were found: Black beans: 19°C; brown beans: 18°C; soybeans: 16°C; and Alaska dried peas: 16°C. The results reported can be used for more adequate design of cooking processes of beans with special regards to energy savings since beans are frequently cooked for 5 hr at 100°C.

ENZYME INACTIVATION BY AN IMMOBILIZED PROTEASE IN A PLUG FLOW REACTOR. F. M. Bliss and H. O. Hultin, *J. Food Sci. 42*, 425–428 (1977).

Streptomyces griseus protease was immobilized to porous glass and characterized kinetically. The immobilized protease was then used in a plug flow reactor to inactivate enzymes in solution at low concentrations. The glass-bound protease was effective against fungal glucose oxidase and partially effective against soluble *S. griseus* protease. Some enzymes were more efficiently inactivated by plain or silanized glass without enzyme, presumably due to adsorption. Less tomato pectin methylesterase was inactivated by glass-bound protease than by plain glass. This is most likely due to masking of adsorption sites by the immobilized protease.

SOME VISCOELASTIC AND MACRONUTRIENT CHARACTERISTICS OF PEANUTS. R. C. Clark, V. N. M. Rao and C. T. Young, *J. Food Sci. 42*, 479–481 (1977).

Some of the viscoelastic properties of four peanut varieties were investigated by a series of uniaxial compression tests. The uniaxial tests were performed with a universal testing machine at temperatures of 5, 20 and 30°C, all at 55% relative humidity. Individual amino acid contents of the peanuts were determined by ion exchange chromatography. A proximate analysis was run to determine Kjeldahl nitrogen and oil. The results of the mechanical tests were analyzed to obtain uniaxial modulus of elasticity at various times and a decay constant. A correlation analysis of viscoelastic properties with chemical composition yielded significant correlations between modulus of elasticity and some individual amino acids, protein and oil. The amino acids and protein were positively correlated while oil exhibited a negative correlation to the viscoelastic properties.

RHEOLOGICAL PROPERTIES OF CRANBERRY CELL WALL MATERIAL. A. B. Holmes, S. L. Gilbert and C. K. Rha, *J. Food Sci. 42*, 29–31 (1977).

Rheological properties of cell wall material suspensions recovered from pressed cranberries were studied with rotational viscometers at 25°C. The general power law equation was found to be an adequate model, the flow behavior index decreasing, and the consistency coefficient and yield stress increasing, as concentration increased. Time dependency and pseudoplastic or mixed-type flow behavior were observed. Large yield stresses at low concentrations suggested potential use of cell wall material as a food thickener.

HYDRATION AND RHEOLOGY OF SOY-FORTIFIED PREGELLED CORN FLOURS. G. S. Ayernor and M. P. Steinberg, *J. Food Sci. 42*, 65–69 (1977).

The objective of this work was to prepare a soy-fortified corn dough having the same rheological properties as the unfortified material. Water sorption isotherms and hydration kinetics of pregelled corn-flour, corn-soy and starch powder systems were investigated. The effect of adding processed full-fat soy flour on hydration, reconstitution and rheological properties of dough systems were studied with Brabender Farinograph and Extensograph instruments. Soy flour imparted an undesirable plasticizing effect on pregelled corn doughs. Rheological properties of model dough systems were studied to solve this problem. Results indicated this effect could be reversed by the addition of pregelled tapioca starch as an elasticizing agent. A corn flour:soy flour:tapioca starch::60:30:10 mixture produced a dough with rheological properties similar to those of a corn flour dough.

STATISTICAL ANALYSIS OF a_w MEASUREMENTS OBTAINED WITH THE SINA-SCOPE. J. A. Troller, *J. Food Sci 42*, 86–90 (1977).

A calibration procedure for the Sina-scope hygrometer is described. Four saturated salt solutions, covering a range from 0.755–0.967 a_w, and two foods, with a_w levels in the intermediate moisture food range, were tested to determine the accuracy and precision of the Sina instrument. Accuracy, relative to averaged published a_w levels for the four standard salts, was evaluated. Most measured values were slightly less than the averaged standards. The greatest difference noted was −1.06% of the standard. Estimates of instrument precision showed that the coefficient of variation decreased with measurement of successively higher a_w standard solutions and did not exceed 1%. Instrument readings to two decimal places possessed standard deviations slightly lower than corresponding readings estimated to three decimal places. Standard deviations (20 replicates at each a_w) ranged from 0–0.004. Estimates of pooled, between-sensor standard deviation showed that there were no significant differences between the two sensors used in those studies. Equilibration periods of 45 or 60 min were almost equally precise. The number of replicates required to produce a given level of data confidence are calculated and presented. Similar results relative to estimates of precision were obtained with the two foods tested.

PREDICTION OF SENSORY RESPONSE TO TEXTURAL PARAMETERS OF BREADED SHRIMP SHAPES USING INSTRON TEXTURE PROFILE ANALYSIS. H-M. Soo and E. H. Sander, *J. Food Sci. 42*, 163–167 (1977).

A method for objective measurement of textural parameters of fabricated comminuted shrimp-binding matrix agent mixtures using the universal testing machine (Instron) has been developed. An abbreviated Instron texture profile analysis (TPA) of fabricated cooked shrimp patties was used to predict sensory textural scores on subsequent mechanically extruded shrimp shapes. The technique eliminates expensive and time consuming pilot plant operation of equipment to produce a sufficient quantity of shrimp shapes required to measure single formula and process parameters.

A STUDY OF FACTORS AFFECTING MEMBRANE PERFORMANCE DURING PROCESSING OF COTTONSEED PROTEIN EXTRACTS BY ULTRAFILTRATION. D. W. Hensley, J. T. Lawhon, C. M. Cater and K. F. Mattil, *J. Food Sci. 42*, 812–815 (1977).

Commercial membrane processing is an emerging new field. Consequently, there is still much to be learned about the process in general and about particular applications. Except for the dairy industry, little work has been reported in the literature relative to food processing. The purpose of the work reported was to determine which factors influence membrane performance when processing cottonseed protein extracts by ultrafiltration. Interest was centered on those factors affecting membrane flux and ways to improve and maintain the flux during processing. Maintenance of membrane flux is imperative for the process to be economically feasible on a commercial scale. Protein extracts were prepared at the Food Protein Research and Development Center (FPRDC) pilot plant from glandless cottonseed flour using a selective extraction procedure. Extracts were pasteurized and processed directly or frozen until used. The effects of pressure, feed velocity, temperature and feed composition on permeate flux were investigated using different membranes and membrane systems. It was found that permeate flux could be estimated as a function of Reynolds number. Viscosity, an important variable in Reynolds number, was found to be a function of total Kjeldahl nitrogen in the membrane feed solution and the relation was of the form $\nu = aB^{N}$ where ν is kinematic viscosity and N is feed nitrogen content, and a and B are constants which are functions of temperature. The viscosity did not correlate as strongly with total organics (total solids minus ash) or carbohydrates as with total nitrogen.

A SIMPLIFIED METHOD FOR AGITATION PROCESSING OF CANNED FOODS. P. Parchomchuk, *J. Food Sci. 42*, 265–268 (1977).

A simple method of agitating cans to cause rapid heat penetration during thermal processing in retorts has been developed. Cans are oscillated in a circular path in such a way that can orientation remains fixed. The effectiveness of this method was tested with bentonite mixtures in 603 × 700 cans with different oscillating radii, headspaces, viscosities and can orientations. Heating time of 5% bentonite mixture was reduced from 360 min to less than 10 min. Although comparable heating rates were achieved with end-over-end rotation, circular oscillation required only a ½–¾ in. radius and caused lower inertia forces. These features make this method readily adaptable to conventional retort systems.

CO- AND COUNTERCURRENT MULTISTAGE AQUEOUS AND AQUEOUS ETHANOL EXTRACTION OF TEXTURED VEGETABLE PROTEIN FLOURS: PRODUCT YIELDS AND PROCESS DATA. G. F. Cegla, W. W. Meinke and K. F. Mattil, *J. Food Sci. 42*, 816–820 (1977).

Co- and countercurrent multistage water and ethanol: water extraction of textured vegetable flours (soy and glandless cottonseed) have produced extracted TVPs with protein contents of 79–81% (moisture free basis). Extracted soy TVP samples are characterized by carbohydrate contents (NFE) of 14–15% and less than 3% ash. The extracted cottonseed flour TVP assayed around 7% ash and 8% NFE. Such results are achieved by both co-current and countercurrent extractions at 65°C with a ratio of extraction medium to original TVP of 6 to 1. Both a drain-press and a centrifugal approach were used to separate liquid extract from solids between extraction stages. The drain-press technique tends to favor higher protein content due to possible loss of insoluble carbohydrates and fiber to the extract. TVP solids losses to the extract ranged from essentially 30% for the cottonseed TVP to around 40% for the soy TVP. A countercurrent extraction is favored because a more concentrated extract is available for the recovery of solids. Dried extracted solids range from 21–36% protein, 9–13% ash and 57–69% NFE.

ANALYSIS OF THE PLASTOMETER AND CORRELATION OF BOSTWICK CONSISTOMETER DATA. M. A. Rao and M. C. Bourne, *J. Food Sci. 42*, 261–264 (1977).

The rheological parameter measured by the Plastometer is shown to be the difference in apparent viscosities at two shear rates. Flow property data obtained on various pseudoplastic pureed foods were utilized to show that the difference in apparent viscosities at 50 and 400 s^{-1}, and data with a Bostwick Consistometer are correlated nonlinearly. For the range of Bostwick reading between 3.5–12.0 cm/10s, an equation is presented to estimate the magnitude of the difference in apparent viscosities. Yield stress was found not to correlate as well as the difference in apparent viscosities. The Bostwick Consistometer was found to be not suitable for pseudoplastic nonpureed foods; adhesion of the nonpureed foods to the gate of the Bostwick Consistometer was identified as the reason.

PRODUCTION OF PROTEIN ISOLATES AND CONCENTRATES FROM OILSEED FLOUR EXTRACTS USING INDUSTRIAL ULTRAFILTRATION AND REVERSE OSMOSIS SYSTEMS. J. T. Lawhon, D. Mulsow, C. M. Cater and K. F. Mattil, *J. Food Sci. 42*, 389–394 (1977).

The consumption of protein isolates from oilseed flours is expected to continue its upward trend as meat analogs from vegetable proteins are more widely marketed. However, conventional protein isolation procedures are lengthy and somewhat expensive. These processes also result in whey-like liquid by-products which constitute a water pollution threat unless properly processed. Preparation of protein isolates and concentrates from glandless cottonseed and soy flours by extracting the protein and ultrafiltering the solubilized protein directly from the liquid extract was investigated. In the process devised, proteins normally precipitated to produce isolates were recovered together with the conventional whey protein by ultrafiltration (UF). The UF permeate was further processed with a reverse osmosis (RO) membrane. Different industrial UF and RO systems were utilized in 22–60 lb extractions. UF membranes were found which gave desirably high permeation rates and satisfactory constituent separations, especially with cottonseed storage protein (SP) extract. With SP extract, initial UF permeate flux achieved was in excess of 150 gal of permeate per square foot of membrane area per day (gfd). The flux declined to 96 gfd over a period of 8 hr while the volume of original extract in the feed solution was being reduced by a ratio of 12.5 to 1 in the final UF concentrate. As expected, nonstorage protein (NSP) and SP extracts from cottonseed were found to require membranes having different molecular weight cutoff points. Noncellulose-based membranes performed better for this application because of their broader pH and temperature operating ranges.

ABSTRACTS FROM JOURNAL OF TEXTURE STUDIES

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THE FLOW PROPERTIES OF SKIM MILK CONCENTRATES OBTAINED BY ULTRAFILTRATION. H. Randhahn, *J. Texture Studies* 7, 205–217 (1976).

The flow properties of skim milk concentrates were measured at temperatures ranging between 5 and 60°C. The concentrates obtained by ultrafiltration showed, in the studied range of shear rate $5 \leqslant D \leqslant 1000\ s^{-1}$, pseudoplastic behaviour depending on solids content and temperature. This behaviour is well described by the power law. For both the parameter ψ and n of this law there is a clear dependence on solids content and temperature. The viscosity parameter ψ increases highly from a certain solid content. As there exists a relation between the viscosity and the coefficient of diffusion, which is an essential factor of influence on the process of ultrafiltration, these well defined results of objective rheological measurements have consequences about the practicability of this process of separation for the enrichment of protein in skim milk.

THERMAL CONTRACTION OF MEAT DURING COOKING AND ITS POSSIBLE INFLUENCE ON TENDERNESS. P. E. Bouton, P. V. Harris and W. R. Shorthose, *J. Texture Studies* 7, 193–203 (1976).

Samples of beef muscles with different states of myofibrillar contraction were cooked at 80° C, both restrained and unrestrained from thermal shortening. Samples restrained from thermal shortening lost similar amounts of moisture to the unrestrained samples and had significantly ($P < 0.001$) larger decreases in the cross-sectional area. The effects of restraint on structural strength were assessed using adhesion, tensile and shear testing. Restraint decreased adhesion between the fibers and increased tensile, initial yield and peak force values in the control and stretched samples where, without the restraint, thermal contraction would normally have been large. Shear force values of the cooked meat showed the increase normally associated with cold shortening whether or not thermal shortening occurred.

TENSILE PROPERTIES OF BEEF SEMITENDINOSUS MUSCLE AS AFFECTED BY HEATING RATE AND END POINT TEMPERATURE. M. P. Penfield, C. L. Barker and B. H. Meyer, *J. Texture Studies* 7, 77–85 (1976).

The effects of heating rate and end point temperature on tensile properties of beef semitendinosus muscle were studied. Samples of meat heated in glass tubes in a water bath to simulate oven roasting at 93° C had lower ($P < 0.01$) shear values than those heated to simulate oven roasting at 149° C. Samples heated to 60 and 70° C had lower ($P < 0.001$) shear values than samples heated to 50° C.

Instron breaking strength values varied ($P < 0.001$) with end point temperature, but were not significantly affected by the rate of heating. Significant ($P < 0.001$) interactions between the end point temperature and heating rate, as well as between the end point temperature and fiber direction suggested that Instron breaking strength measurements may be more sensitive to changes in tenderness than Warner Bratzler shear measurements.

DIMENSIONAL CHANGES IN MEAT DURING COOKING. P. E. Bouton, P. V. Harris and W. R. Shorthose, *J. Texture Studies* 7, 179–192 (1976).

Continuous measurements of changes in meat fiber length with increasing temperature during cooking showed three zones where rates of length change are significantly different. The first (>40° C) is attributed to myofibrillar change. The second (>55° C) is thought to be related to connective tissue shrinkage and shows differences with myofibrillar contraction state attributable to changes in spatial orientation of collagen fibers. The third zone (>70° C) is believed to be due to the interaction between myofibrillar and connective tissue contraction.

Measurements of changes in cooking loss, length and cross-sectional area of samples of contracted and stretched muscle showed that cooking losses and the decrease in the cross-sectional area were greater in contracted samples, whilst length changes were greater in stretched samples. This has been attributed to differences in spatial orientation of connective tissue.

DEFINITION AND MEASUREMENT OF MEAT TEXTURE IN MILITARY DEVELOPMENT AND PROCUREMENT. J. M. Tuomy, *J. Texture Studies* 7, 5–9 (1976).

The need for improved texture evaluation methods in meat product development and procurement is discussed with emphasis on problems facing the Armed Forces. It is pointed out that inexpensive, reproducible, simple methods are needed similar to, for example, the rapid moisture analysis equipment now being used in chemical evaluation of foods.

MEETINGS

OCTOBER 1977

Oct. 11–12: **THIRD ANNUAL CONFERENCE ON NEW ADVANCES IN SEPARATION TECHNOLOGY.** Cherry Hill Hyatt House, Cherry Hill, NJ. W. F. Heneghan, Conference Chairman, 289 Greenwich Ave., Greenwich, CT 06850.

Oct. 22–27: **SYMPOSIUM ON FOOD RHEOLOGY.** Madison, WI. Nuri Mohsenin, 229 Agricultural Engineering Building, Pennsylvania State Univ., University Park PA 16802.

Oct. 23–28: **CONFERENCE ON STORAGE FOR SOLAR ENERGY AND TRANSPORTATION APPLICATIONS.** Sea Palms Club, St. Simmons Island, GA. Engineering Foundation, 345 E. 47th St., New York, NY 10017.

Oct. 24–28: **INTERNATIONAL CONFERENCE ON ENERGY USE MANAGEMENT.** Marriott Hotel and Community Center, 180 W. Broadway, Tucson, AZ 85701. Craig B. Smith, General Chairman, Energy Use Management Conference, Box 64369, Los Angeles, CA 90064.

NOVEMBER

Nov. 5–8: **72nd ANNUAL MEETING AND CONVENTION, AMERICAN MEAT INSTITUTE.** McCormack Place and Palmer House, Chicago, IL.

Nov. 28–Dec. 1: **N.F.S.A. 23rd ANNUAL CONVENTION AND CHEMICAL EQUIPMENT EXPOSITION.** Dallas Convention Center, Dallas, TX.

DECEMBER

Dec. 5–8: **36th EXPOSITION OF CHEMICAL INDUSTRIES, INTERNATIONAL EXPOSITION CO.** McCormack Place, Chicago, IL.

Dec. 13–16: **AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS.** Annual Winter Meeting, Palmer House, Chicago, IL.

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In some cases it might be desirable to combine results and discussion sections.

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DEWALD, B., DULANEY, J. T. and TOUSTER, O. 1974. Solubilization and polyacrylamide gel electrophoresis of membrane enzymes with detergents. In *Methods in Enzymology*, Vol. xxxii, (S. Fleischer and L. Packer, eds.) pp. 82–91, Academic Press, New York.

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

ZABORSKY, O. 1973. *Immobilized Enzymes*, pp. 28–46, CRC Press, Cleveland, Ohio.

Journal abbreviations should follow those used in *Chemical Abstracts*. Responsibility for the accuracy of citations rests entirely with the author(s). References to papers in press should indicate the name of the journal and should only be used for papers that have been accepted for publication. Submitted papers should be referred to by such terms as "unpublished observations" or "private communication." However, these last should be used only when absolutely necessary.

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Standard nomenclature as used in the engineering literature should be followed. Avoid laboratory jargon. If abbreviations or trade names are used, define the material or compound the first time that it is mentioned.

EDITORIAL OFFICE: Prof. D. R. Heldman, Editor, Journal of Food Process Engineering, Michigan State University, Department of Agricultural Engineering, East Lansing, Michigan 48824

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