

Aseptically Packaged Orange Juice and Concentrate: A Review of the Influence of Processing and Packaging Conditions on Quality

Thomas R. Graumlich, Joseph E. Marcy, and J. P. Adams*¹

The shelf life of fruit juices and concentrates is limited primarily by microbial, enzymatic, and chemical reactions that adversely affect their nutritional quality, color, and flavor. Pasteurization requirements of freshly extracted citrus juices are based on inactivation of thermally resistant endogenous enzymes whereas requirements for reconstituted juices are based on destruction of microbial populations capable of causing spoilage. Aseptic processing produces a higher quality orange juice than hot filling; however, differences in quality may disappear during storage at ambient temperatures. Oxygen dissolved in the product, in the container headspace or permeating through the container, accelerates the rate of ascorbic acid destruction and nonenzymatic browning and reduces shelf life, although these processes will continue in its absence. The most important factor in determining the shelf life of aseptic orange juice and concentrate is storage temperature.

Orange juice sales, primarily in the form of concentrated orange juice, account for 60% of all fruit juice sales in the U.S. (Florida Department of Citrus, 1983). Often when orange juice is sold as a single-strength ready-to-serve (RTS) product, the juice is concentrated at a processing plant near where the fruit is grown and shipped as a concentrate for reconstitution before retail sale. Sale of RTS orange juice has nearly doubled in volume since 1978 and is the fastest growing segment of the U.S. orange juice market.

Recent interest in aseptic processing and packaging has been spurred by the advantages offered by flexible packaging materials and reduced costs associated with utilization of ambient temperature transportation and storage. Although aseptic processing and packaging has been common throughout the world, these types of products have not been available in significant quantities in the U.S. until the FDA allowed hydrogen peroxide sterilization of the packages in 1981 (U.S. Food and Drug Administration, 1981).

The shelf life of fruit juices and concentrates is limited primarily by microbial, enzymatic, and chemical reactions that adversely affect their nutritional quality, color, and flavor. The objective of aseptic processing is to eliminate microbial and enzymatic activity and to provide a package environment in which extended shelf life can be maintained (von Bockelmann, 1977).

PASTEURIZATION REQUIREMENTS

Enzymes. Pasteurization of fresh citrus juices requires inactivation of pectinesterase to prevent cloud loss in juices or gelation of concentrates. Eagerman and Rouse (1976) noted that about a two log cycle reduction in pectinesterase activity was necessary to achieve commercial stability of citrus juices and concentrates. They investigated the thermal destruction of pectinesterase in Hamlin, Pineapple, and Valencia oranges and Duncan grapefruit. One minute at 90 °C and 1 min at 85.6 °C were reported necessary to achieve a two log cycle reduction in pectinesterase activity in oranges and grapefruit, respectively. Nath and Ranganna (1977) investigated the thermal destruction of mandarin orange pectinesterase. They reported the time

necessary for a one log cycle reduction or decimal reduction time (*D* value) was 0.44 min at 94 °C and pH 4.0 with a *z* value (temperature change necessary for a one log cycle change in *D* value) of 10 °C.

Versteeg et al. (1980) reported that three forms of pectinesterase accounted for 95% of the activity in navel oranges. Although a high molecular weight pectinesterase accounted for only 5% of the total activity in navel oranges, it was considerably more heat stable and was responsible for the cloud loss in chilled juices and gelatin in concentrates produced by the cutback process.

Pasteurization at somewhat lower temperatures, i.e., 74 °C for 16 s or 85 °C for 1 s (Carter, 1981), may be used for reconstituted juices without residual enzyme activity, which are intended for limited shelf life applications. Time and temperature combinations noted for aseptic processing of citrus juices intended for ambient temperature storage are somewhat higher and range from 85 °C for 15 s up to 110 °C for 15 s (Wise, 1979).

Microbial Effects. Spoilage by microorganisms is limited to acid-tolerant populations, which are predominantly lactic acid bacteria, yeasts, and molds. Lactic acid bacteria, which are commonly associated with spoilage problems during processing operations at ambient temperatures, were reported to have thermal death times (time necessary to destroy a given microbial population at a stated temperature) or *F* values at 65 °C in the range of 0.1–0.3 min in orange juice with an initial population of 10⁶/mL (Juven, 1976; Murdock et al., 1953). Yeast spoilage is more commonly associated with chilled juices and concentrates. *D* values for vegetative cells in single-strength orange juice are typically less than 1 min at 60 °C (Kopelman and Schyer, 1976). Thermal resistance of yeast ascospores is somewhat higher than that of vegetative cells. Put and De Jong (1982) reported *D* values at 60 °C ranging from 1.5 to 22.5 min for ascospores of several yeasts isolated from spoiled soft drinks and fruit juices. Heat resistance is also higher in concentrates than in single-strength juices (Juven et al., 1976; Murdock et al., 1953). Juven et al. (1978) found increased thermal resistance in concentrated orange juices was related to both sugar and citric acid concentrations, but not to ascorbic acid or pectin levels.

Monitoring of fruit juice concentrates for the presence of heat-resistant molds was advised by Murdock and Hatcher (1976) since pasteurization treatments may not adequately control this type of spoilage. Some heat-resistant mold species are quite capable of surviving pasteurization treatments, although low oxygen levels in

University of Florida, IFAS, Citrus Research and Education Center, Lake Alfred, Florida 33850.

¹To whom correspondence should be addressed at the University of Florida, IFAS, Department of Food Science and Human Nutrition, Gainesville, FL 32611.

packaged products usually prevent mold growth. Spoilage of fruit juices and other fruit products by heat-resistant molds is often caused by *Byssochlamys* and *Penicillium* spp. (Meyrath, 1962; Splittstoesser, 1978). Hatcher et al. (1979) reported thermal death times for 10^4 /mL ascospores of several isolates of *Byssochlamys fulva* ranging from 20 to 50 min at 88 °C with z values ranging from 4 to 8 °C in 12° Brix grape drink. Incubation temperature and sugar concentration also significantly affected recovery of *Byssochlamys* isolates. Visible growth was evident in 15° Brix apple drink base within 48 h at 30 °C but not found after 110 days with 30° Brix apple drink base. Beuchat and Toledo (1977) reported growth and ascospore production of *Byssochlamys nivea* at 30 °C occurred in several fruit juices including orange juice with water activity as low as 0.90. Sucrose protected ascospores against death in fruit products stored at +7 and -30 °C and in grape juice heated at 75 °C. Colony development was retarded in grape juice agar when more than 30 g of sucrose/100 g of media was added.

Van der Spuy et al. (1975) identified spoilage molds *Penicillium vermiculatum* and *Penicillium brefeldianum* from canned apple juice that had been pasteurized at 88 °C. Thermal destruction times for free ascospores from these isolates ranged from 25 to 40 min at 80 °C with z values of 7.2–7.8 °C while intact asci required 30 min or longer at 100 °C with z values of 10.7–11.7 °C.

NONENZYMATIC BROWNING

Nonenzymatic browning of orange concentrates has been reported by many researchers (Kanner et al., 1982; Johnson and Toledo, 1975; Curl, 1949) as a major cause of quality loss in citrus products. Clegg and Morton (1965) suggested sugar-amino acid reactions were unlikely to be in the main contributors to the formation of melanoidin pigments during browning of lemon juice because of the high acidity of the system. Oxidation of ascorbic acid provided the carbonyl compounds that subsequently reacted with amino groups and polymerized to give brown pigments. Although oxygen accelerates rates of ascorbic acid loss, anaerobic degradation of ascorbic acid proceeds in the absence of oxygen and leads to nonenzymatic browning (Kefford et al., 1959; Passey and Mannheim, 1979). Kurata and Sakurai (1967b) postulated pathways and reaction products for aerobic degradation of ascorbic acid that included hydration of dehydroascorbic acid to ketogulonic acid and decarboxylation and dehydration to furfural. Under acid conditions, anaerobic degradation of ascorbic acid also leads to furfural with 3-deoxy-L-pentosone as an intermediate (Kurata and Sakurai, 1967a). The formation of brown melanoidin pigments results from reaction of furfural with amino acids or furfural polymerization. The interactions of nonenzymatic browning and oxidative reactions with juice constituents are very complex, and catalytic behavior of one type of reaction on the other may reduce the predictability of the quality degradation (Adams, 1982).

Several methods may be utilized to quantitate the development of browning in citrus juices. Kanner et al. (1982) reported browning of orange juice concentrate as the negative change in L as measured with a tristimulus colorimeter. The Hunter value L is the amount of light reflected from the sample; therefore, a more negative value indicates an increase in absorbance. Browning of citrus juices and concentrates may also be determined by the procedure of Meydav et al. (1977), which measures only brown melanoidin pigments after alcoholic extraction of the pigments from samples. Robertson and Reeves (1981) reported that tristimulus color values of high-tempera-

ture-abused orange juice were highly correlated with a browning index described by Meydav et al. (1977).

Saguy et al. (1978a) investigated the kinetics of ascorbic acid loss in grapefruit juice during thermal and concentration processes. They found an apparent first-order anaerobic reaction that was dependent on temperature and product concentration, but not on initial ascorbic acid concentration. Browning in grapefruit juices during thermal and concentration processes was also studied (Saguy et al., 1978b). The reaction was found to be initially slow (lag period) and later relatively rapid (postlag period), represented by an exponential and a linear time function, respectively.

TEMPERATURE ABUSE

Nagy and Randall (1973) reported furfural was not the component responsible for flavor changes in storage temperature abused orange juice; however, furfural levels have been reported to closely parallel the extent of flavor differences in orange juices (Nagy and Randall, 1973) and grapefruit juices (Nagy et al., 1972; Maraulja et al., 1973).

Herrmann and Partassidou (1979) reported furfural formation in orange juices and concentrates at temperatures ranging from 36 to 100 °C followed the pattern of a sequential reaction. After an induction period, the reaction curve was found to be linear corresponding to a zero-order reaction. The reaction rate constants in Arrhenius equations yielded the same energy of activation for all the orange juice concentrations investigated. Furfural formation was determined to result from specific acid catalysis, because the reaction rate was directly proportional to the hydronium ion concentration.

However, Kanner et al. (1981) reported furfural accumulated in single-strength orange juice more rapidly than in concentrates during storage of orange juice and concentrates ranging from 12–58° Brix at temperatures from -18 to +37 °C. In deaerated concentrates, furfural accumulation increased gradually during storage at a rate dependent on temperature and inversely related to solids content. The reaction between furfural and other compounds was believed to occur at a higher rate with increasing solids concentration. Thus, less furfural accumulated in concentrates, and thus less furfural accumulated in concentrates than in juice.

PROCESSING AND STORAGE CONDITIONS

Processing and storage temperatures are major factors determining stability and quality of citrus juices and concentrates. Mannheim and Havkin (1981) compared quality of an aseptic bottled juice to a hot-filled orange juice during storage. Immediately after filling the aseptically filled juice was judged slightly better; however, differences between the juices disappeared rapidly during storage. Storage temperature was the major factor limiting shelf life in both products. Lafuente et al. (1979) also evaluated the storage stability of hot- and cold-filled orange juice at temperatures between 0 and 22 °C. Orange juice aseptically cold filled in glass bottles had a higher level of sensorial acceptance than hot-filled bottles or cans during the first 4 weeks of storage at 0–2 °C. Acceptance of both juices was similar after that point. A significant loss in acceptance was detected after 2 weeks of storage at room temperature for aseptically cold-filled orange juice that had been reconstituted from frozen concentrate.

The effect of storage temperature (-17.7 to +4.4 °C) and time (0–12 months) on quality of 66° Brix orange concentrate was determined by Marcy et al. (1984). Nonenzymatic browning increased, and taste panel scores significantly decreased with increasing storage temperature and time.

Oxygen also influences quality and stability of fruit juices and concentrates. Oxygen may be dissolved or entrained in the product or in the container headspace or may permeate through the container. Kefford et al. (1959) reported the presence of oxygen in frozen orange juices stored at -18°C permitted slow oxidative loss of ascorbic acid throughout the storage period; however, in pasteurized juices stored in cans at 30°C free oxygen disappeared rapidly. Oxidative destruction of ascorbic acid occurred during the first few days of storage when oxygen was present; subsequent losses of ascorbic acid during storage occurred at a rate about one-tenth of that in the early period. Ohta et al. (1983) investigated the influences of headspace volume, pasteurization temperature, pasteurization time, and storage temperature on the quality of Satsuma mandarin juice. Headspace volume and storage temperature were found to have a much greater influence on juice quality than pasteurization temperature and time. With increased headspace volume and storage temperature, ascorbic acid and sensory scores decreased rapidly while browning and (hydroxymethyl)furfural gradually increased.

However, the influence of headspace composition on the quality of concentrated citrus juices during storage was reported to be considerably less. Passey and Mannheim (1979) compared the effects of vacuum deaeration, hot filling, and nitrogen sparging on concentrated grapefruit juice quality. They concluded that there was not a difference in quality parameters and shelf life due to the different deaeration treatments. Gasque et al. (1981) reported that headspace volumes of 20% had no effect on the quality of 60° Brix orange concentrate during 10 months storage at $0-2^{\circ}\text{C}$. For higher headspace volumes, it was recommended to keep the juice under nitrogen atmosphere to improve the ascorbic acid and flavor retention.

PACKAGING OF ORANGE JUICES AND CONCENTRATES

The environment provided by the package itself can significantly affect storage stability. In order to provide an adequate shelf life and protect product quality the package must meet a number of requirements including (1) barrier to light, (2) impermeability to gases and vapors, (3) resistance to absorption of moisture, (4) resistance to flavor or taint interaction with the product, (5) composition of materials not toxic or harmful to health, (6) unalteration by chemical and/or heat treatment, (7) hermetic sealability, (8) stability for appropriate storage periods, and (9) resistance to handling abuse.

Yoshida et al. (1983) examined the influence of various container types of Satsuma mandarin juice during storage. Juice quality in oriented nylon/aluminum foil/polyethylene standing pouches and paper cups laminated with aluminum foil/polyethylene was the same as that in glass bottles or metal cans. Standing pouches made of vinylidene chloride/oriented nylon/polyethylene and oriented nylon/polyethylene, which were permeable to oxygen, gave lower ascorbic acid retention, higher browning, and reduced sensory scores.

Durr et al. (1981) investigated the aroma quality of orange juice after filling and storage in soft packages and glass bottles. A distinct loss of limonene into the polyethylene layer of the package was reported; however, the reduction in limonene was considered to be an advantage due to limonene acting as a precursor of off-flavor components. Other flavor volatiles were not significantly absorbed by the soft package. But industry experiences have noted a reduction in flavor intensities. Solutions to this problem have included increased oil addition or utilization

of alternative flavor such as aqueous essence.

CONCLUSIONS

From the preceding discussion a number of conclusions may be drawn regarding aseptic processing and storage stability of aseptically packaged citrus juices. Aseptic processing initially produces a higher quality orange juice than hot filling; however, differences in quality may disappear during storage at ambient temperatures. Although nonenzymatic browning and ascorbic acid destruction will continue in its absence, oxygen dissolved in the product or in the container headspace or permeating through the container accelerates these processes and reduces shelf life. The most important factor in determining the shelf life of aseptic orange juice and concentrate is storage temperature.

LITERATURE CITED

- Adams, J. P. Proceedings of the 22nd Annual IFT Short Course on the Food Industry, University of Florida, Gainesville, FL, 1982; pp 245-257.
- Beuchat, L. R.; Toledo, R. T. *Trans. Br. Mycol. Soc.* **1977**, *68*, 65-71.
- Carter, R. D. "Reconstituted Florida Orange Juice. Production/Packaging Distribution. Technical Manual"; Florida Department of Citrus: Lakeland, FL, 1981.
- Clegg, K. M.; Morton, A. D. *J. Sci. Food Agric.* **1965**, *16*, 191-198.
- Curl, A. L. *Food Res.* **1949**, *14*, 9-14.
- Durr, P.; Schobinger, U.; Waldvogel, R. *Alimenta* **1981**, *20*, 91-93.
- Eagerman, B. A.; Rouse, A. H. *J. Food Sci.* **1976**, *41*, 1396-1397.
- Florida Department of Citrus Market Research Report, Annual Summary; Florida Department of Citrus: Lakeland, FL, 1983.
- Gasque, F.; Perez, R.; Lafuente, B.; Navarro, J. L. *Rev. Agroquim. Technol. Aliment.* **1981**, *21*, 131-136.
- Hatcher, W. S.; Weihe, J. L.; Murdock, D. I.; Folinazzo, J. F.; Hill, E. C.; Albrigo, L. G. *J. Food Sci.* **1979**, *44*, 118-122.
- Herrmann, J.; Partassidou, V. *Nahrung* **1979**, *23*, 143-150.
- Johnson, R. L.; Toledo, R. T. *J. Food Sci.* **1975**, *40*, 433-434.
- Juven, B. J. *J. Milk Food Technol.* **1976**, *39*, 819-822.
- Juven, B. J.; Kanner, J.; Weisslowicz, J. *J. Food Sci.* **1978**, *43*, 1074-1076, 1080.
- Kanner, J.; Fishbein, J.; Shalom, P.; Harel, S.; Ben-Gara, I. *J. Food Sci.* **1982**, *47*, 429-431, 436.
- Kanner, J.; Harel, S.; Fishbein, Y.; Shalom, P. *J. Agric. Food Chem.* **1981**, *29*, 948-949.
- Kefford, J. F.; McKenzie, H. A.; Thompson, P. C. O. *J. Sci. Food Agric.* **1959**, *10*, 51-63.
- Kopelman, I. J.; Schyer, M. *Lebensm.-Wiss. Technol.* **1976**, *9*, 91-92.
- Kurata, T.; Sakurai, Y. *Agric. Biol. Chem.* **1967a**, *31*, 170-176.
- Kurata, T.; Sakurai, Y. *Agric. Biol. Chem.* **1967b**, *31*, 177-184.
- Lafuente, B.; Gasque, F.; Nieto, P.; Izquierdo, L. *Rev. Agroquim. Technol. Aliment.* **1979**, *9*, 82-88.
- Mannheim, C. H.; Havkin, M. *J. Food Proc. Pres.* **1981**, *5*, 1-6.
- Maraulja, M. D.; Blair, J. S.; Olsen, R. W.; Wenzel, F. W. *Proc. Fla. State Hortic. Soc.* **1973**, *86*, 270-275.
- Marcy, J. E.; Graumlich, T. R.; Crandall, P. G.; Marshall, M. R. *J. Food Sci.* **1984**, *49*, 1628-1629.
- Meydav, S.; Saguy, I.; Kopelman, I. J. *J. Agric. Food Chem.* **1977**, *25*, 602.
- Meyrath, J. *Rec. Adv. Food Sci.* **1962**, *2*, 117-127.
- Murdock, D. I.; Hatcher, W. S., Jr. *Proc. Fla. State Hortic. Soc.* **1976**, *89*, 202-204.
- Murdock, D. I.; Troy, V. S.; Folinazzo, J. F. *Food Res.* **1953**, *18*, 85-89.
- Nagy, S.; Randall, V. *J. Agric. Food Chem.* **1973**, *21*, 272-275.
- Nagy, S.; Randall, S. V.; Dinsmore, H. L. *Proc. Fla. State Hortic. Soc.* **1972**, *85*, 222-225.
- Nath, N.; Ranganna, S. *J. Food Technol.* **1977**, *12*, 411-419.
- Ohta, H.; Yoshida, K.; Hyakudome, K.; Aoyagi, H.; Okabe, M.; Susukida, W. *J. Food Sci. Technol.* **1983**, *30*, 200-208.
- Passey, N.; Mannheim, C. H. In "Tropical Foods: Chemistry and Nutrition"; Inglet, G. E., Charalambous, G., Eds.; Academic Press: New York, 1979; Vol. 1, pp 141-153.
- Put, H. M. C.; De Jong, J. *J. Appl. Bacteriol.* **1982**, *52*, 235-243.

- Robertson, G. L.; Reeves, M. J. *J. Food Technol.* 1981, 18, 535-541.
- Saguy, I.; Kopelman, I. J.; Mizrahi, S. *J. Food Proc. Eng.* 1978a, 2, 213-225.
- Saguy, I.; Kopelman, I. J.; Mizrahi, S. *J. Food Proc. Pres.* 1978b, 2, 175-184.
- Splittstoesser, D. F. In "Food and Beverage Mycology"; Beuchat, L. R., Ed.; AVI Publishing Co.: Westport, CT, pp 83-109.
- U.S. Food and Drug Administration *Fed. Reg.* 1981, 46.
- Van der Spuy, J. E.; Mathee, F. N.; Crafford, D. J. A. *Phyto-phyllactica* 1975, 7, 105-108.
- Versteeg, C.; Rombouts, F. M.; Spaanssen, C. H.; Pilnick, W. J. *Food Sci.* 1980, 45, 969, 974, 998.
- von Bockelmann, B. *Proc. Int. Soc. Citric.* 1977, 3, 820-822.
- Wise, D. J. Proceedings of the 19th Annual IFT Short Course on the Food Industry, Gainesville, FL, 1979; pp 93-102.
- Yoshida, K.; Ohta, H.; Hayakudome, K.; Aoyagi, H.; Okabe, M.; Susukida, W. *J. Food Sci. Technol.* 1983, 30, 467-475.

Received for review December 28, 1984. Accepted June 10, 1985.

Postprocessing Changes in Aseptically Packed Beverages

Romeo T. Toledo

Aseptic packaging has been a commercial success in other parts of the world. In the U.S. however, commercial success has been limited to fruit juices and beverages. The kinetics of nutrient degradation and microbial inactivation during food sterilization favor the use of high-temperature short-time treatments and aseptic packaging to minimize nutrient degradation and off-flavor development. However, in fruit juice pasteurization, the flavor quality difference between aseptically packaged products and rapidly cooled hot-filled products is small and may not be readily perceived by a consumer. Flavor and color also change during ambient temperature storage, and these changes can negate the advantages of aseptic packaging. Reduced storage temperature, reduction of oxygen in a package by proper product deaeration, use of minimal headspace, and use of oxygen-impermeable containers are needed to reduce rate of postprocessing changes and maintain flavor and color quality of aseptically packaged beverages.

The commercial viability of aseptic packaging, demonstrated with the successful operation of the Dole system, did not result in extensive commercial activity in the U.S. until 1982 when systems utilizing non-metal containers were introduced. Extensive research on the use of chemical sterilants for aseptic packaging conducted since 1972 (Toledo et al., 1973) resulted in the Food and Drug Administration's (FDA) approval of the use of hydrogen peroxide for sterilizing polyethylene that directly contact foods (Federal Register, 1981). Approval was later extended to include all polyolefins (Code of Federal Regulations, 1984a), and aseptic packaging became a commercially attractive alternative to conventional canning.

The U.S. market for aseptically packaged products consists primarily of juices, milk, and flavored milk. Although the juice market is doing very well (Smith, 1984), acceptance of aseptically packaged unflavored milk has been very poor. On the other hand, there is increasing confidence within the food industry on the economic viability of aseptic packaging technology, as evidenced by the announcement of a commitment by a major processor of canned soups (Campbell Soup, 1984) to replace metal soup cans with plastic before 1990. Plastic was preferred over cans because of its lower cost and its suitability for heating in microwave ovens.

Currently, the most dominant aseptic packaging system in the U.S. produces brick-shaped, laminated fiberboard/aluminum foil/polyethylene packages. The system that was designed originally for packaging milk has been accepted as a convenient means of distributing nonrefrigerated milk in Europe for almost 20 years. Ultrahigh temperature (UHT) sterilized milk is also well accepted in South America and Asia where the quality of available

pasteurized refrigerated milk is often unreliable. Aseptically packaged products enjoyed early acceptance in these markets because consumer purchasing habits permitted rapid product turnover in retail establishments, minimizing the time for undesirable quality changes to develop. Consumers also minimize home storage of food products. The U.S. food market however differs from that which exists in other countries because a product stays in the retail distribution chain and in-home storage for longer periods, increasing the extent of product degradation prior to consumption.

This prolonged storage raises some concern over quality changes prior to consumption. While a number of reports are available on nutrient degradation during heating (Wilkinson et al., 1981; Rao et al., 1981; Feliciotti and Esselen, 1957), very little information now exists on changes that occur in aseptically packaged products during storage. This paper summarizes data on postprocess quality and changes that occur in aseptically packaged products during storage.

Kinetics of Product Quality Degradation. It is generally recognized that nutrient degradation and the appearance of undesirable reaction products that impair flavor and color of processed foods proceed following either zero-order or first order reaction kinetics (Saguy and Karel, 1980). Equation 1 shows the change in nutrient concen-

$$\ln (C/C_0) = -kt \quad (1)$$

tration when a product is heated at constant temperature. C and C_0 represents the concentration of undegraded nutrients at any time and at the start of the process, respectively, and k is the first-order rate constant.

The equation for microbial inactivation (eq 2) is also first order, and the reaction rate constant has traditionally been expressed in terms of the D value, defined as the time required to inactivate 90% of the organism at a constant temperature. N and N_0 are viable microorganisms at any

Food Science Department, University of Georgia, Athens, Georgia 30606.