Assessment of the Long-Term Stability of Retort Pouch Foods to Support Extended Duration Spaceflight

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Abstract: To determine the suitability of retort processed foods to support long-duration spaceflight, a series of 36-mo accelerated shelf life studies were performed on 13 representative retort pouch products. Combined sensory evaluations, physical properties assessments, and nutritional analyses were employed to determine shelf life endpoints for these foods, which were either observed during the analysis or extrapolated via mathematical projection. Data obtained through analysis of these 13 products were later used to estimate the shelf life values of all retort-processed spaceflight foods. In general, the major determinants of shelf life appear to be the development of off-flavor and off-color in products over time. These changes were assumed to be the result of Maillard and oxidation reactions, which can be initiated or accelerated as a result of the retort process and product formulation. Meat products and other vegetable entrées are projected to maintain their quality the longest, between 2 and 8 y, without refrigeration. Fruit and dessert products (1.5 to 5 y), dairy products (2.5 to 3.25 y), and starches, vegetable, and soup products (1 to 4 y) follow. Aside from considerable losses in B and C vitamin content, nutritional value of most products was maintained throughout shelf life. Fortification of storage-labile vitamins was proposed as a countermeasure to ensure long-term nutritive value of these products. The use of nonthermal sterilization technologies was also recommended, as a means to improve initial quality of these products and extend their shelf life for use in long-duration missions. Data obtained also emphasize the importance of low temperature storage in maintaining product quality.

Keywords: NASA food system, retort pouch, shelf life, thermal processing

Practical Application: Retort sterilized pouch products are garnering increased commercial acceptance, largely due to their improved convenience and quality over metal-canned products. Assessment of the long-term stability of these products with ambient storage can identify potential areas for improvement, and ultimately increase consumer satisfaction with these technologies.

Introduction

The Advanced Food Technology (AFT) Project of the National Aeronautics and Space Administration (NASA) Human Research Program (HRP) is currently working to design a stable, palatable, and nutritious food supply to support long-duration spaceflight. A large part of this food supply is expected to be positioned, unrefrigerated, at relevant destination sites prior to crew arrival. Therefore, AFT anticipates that the food products used on these missions must maintain acceptable quality for a minimum of 3 to 5 y at ambient conditions. The current spaceflight food system, designed to support short-duration spaceflight, consists of an assortment of retorted foods, intermediate moisture foods, freeze-dried foods, and irradiated foods (Perchonok 2002). Of these, retort-processed pouch products have the highest acceptability, and the greatest potential to maintain this acceptability, in addition to safety and nutritive value, for 3 to 5 y. To this point, however, there has been no quantitative shelf life testing completed on the entirety of NASA's retorted products. Such data are desired by NASA, to aid in assessing the compatibility of the current short-duration menu with future plans for extended-duration spaceflight.

Retort processing has evolved significantly since its incorporation into Dept. of Defense (DoD) and NASA food systems. While the technology still relies on aggressive application and penetration of heat throughout foods, recent advancements in process engineering coupled with evolution of packaging technologies have allowed for an overall improvement of the technology (Lopez 1987; Goddard 1994; Brody 2002; Jun and others 2006). The current state of the art in retort pouch processing has increased commercial value, and can offer to consumers a level of quality, safety, and convenience not realized by other means (Brody 2002). Recent work has also suggested that the unique properties of retort pouches allow for maximum heat penetration, and reduction of nutrient losses associated with standard processing of cans (Chia and others 1983; Lopez 1987). Additionally, as acknowledged by NASA, retort pouch products are efficient in their distribution and have a limited impact on mission-critical resources, such as

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launch mass and stowage volume (Perchonok 2002; Perchonok and Bourland 2002).

Deterioration of foods throughout storage is considered a function of 4 general phenomena: enzymatic, microbial, chemical, and physical processes (Kuntz 1994). The heat processing and hermetic seals employed in retorting eliminate microbial concerns and curb enzymatic processes that would affect products in storage. Still, certain chemical and physical changes can be initiated in retort processing and amplify throughout storage.

Several processing and storage-induced quality changes to retort pouched products are documented in the literature (Chia and others 1983; Branagan and Pruskin 1993; Olivas and others 2002; Rodriguez and others 2003). Additionally, Zwart and others (2009) have recently documented a need to improve the long-term stability of nutrient content in several representative spaceflight food products to improve the adequacy of these foods to support extended duration missions.

Such decline to the quality and nutritive value of food products over time can render the products incompatible with U.S. Standards of Identity, consumer expectations, and, often, nutrient content claims. NASA risk assessment has also identified the importance of food system acceptability and nutrient stability as integral to maintaining successful performance in missions (Perchonok and Bourland 2002). Therefore, the objectives of this study were to furnish data on the chemical and physical stability of NASA's 65 retort processed foods, and to assess the feasibility of using them to support long-duration missions.

The study proceeded first by establishing principle modes of deterioration, corresponding Q10 values, and ambient shelf life values for 13 representative retort pouch products. After consideration of the data obtained in this, estimates were generated to establish shelf life values for the entirety of NASA's retort processed product stock. Finally, an overall assessment was made as to the suitability of these products for use in extended duration missions. Research gaps were identified, and countermeasures were proposed to improve the adequacy of these foods for this purpose.

Materials and Methods

Accelerated shelf life testing of representative products

Sample acquisition. Thirteen retort processed pouched products were evaluated by accelerated shelf life testing (ASLT). A combination of menu items and proposed new products, were carefully chosen for evaluation, in order to be representative of a standard spaceflight menu, as well as to be unique from those considered in previous work (Table 1). All products were obtained from NASA suppliers in series, as availability and flight provisioning needs dictated. Suppliers included Lambert Street Packaging (San Antonio, Tex., U.S.A.), Newtrition Foods (San Antonio), and Sopacko Packaging (Mullins, S.C., U.S.A.). All samples were processed with appropriate time and temperature parameters to achieve commercial sterility. The samples used in analysis of each product came from the same production lot.

Table 1–Food products evaluated by ASLT and their corresponding, designated categories. An asterisk (*) next to product name indicates that the products were developed for stability assessment and were not standard menu items.

Category	Food Products
Fruit Products	Rhubarb applesauce, Apricot cobbler
Vegetable Side Dishes	Carrot Coins, Three Bean Salad*, Roasted Vegetables*, Sugar Snap Peas
Desserts	Bread Pudding
Meat Entrées	Grilled Pork Chop, Tuna Noodle Casserole
Starch Side Dishes	Homestyle Potatoes
Egg Products	Broccoli Soufflé*, Vegetable Omelet*
Vegetarian Entrées	Palak Paneer*

Storage and sampling parameters. Shelf life extrapolation was conducted via the standard ASLT procedure, which included analytical quantification of quality, application of Arrhenius kinetics, and mathematical prediction of shelf life for each food product (Labuza 1982; Perchonok 2002). Actual measurement of shelf life was also observed, where possible. Specific procedures of ASLT are described at length by Labuza (1982). Products for this evaluation were stored at refrigerated (40 °F), ambient (72 °F), and high (95 °F) temperature conditions for a maximum of 36 mo. Products were removed from storage for consistent instrumental, nutritional, and sensory analysis, as indicated below. Samples stored at refrigerated (40 °F) conditions were used as reference and control samples where required. Shelf life endpoint was defined in this study in terms of a minimum acceptable sensory quality, as discussed below.

Instrumental quality analysis. Instrumental evaluation of products proceeded at 4-mo intervals for the first 2 y of evaluation, and at 6-mo intervals during the 3rd year. Specific analytical methods were chosen in light of anticipated modes of deterioration for each product, in order to characterize effectively quality loss through storage. These product-specific analyses are summarized in Table 2. Texture analyses were performed on a TA-xT2i texture analyzer, via procedures identified by the manufacturer (Texture Technologies, Scarsdale, N.Y., U.S.A.). Color data were gathered on a Hunter LabScan XE colorimeter, per manufacturer procedure (Hunter Associates Laboratory, Reston, Va., U.S.A.). Water activity was measured with a Decagon CX-2 benchtop water activity meter (Decagon Devices, Inc., Pullman, Wash., U.S.A.). pH was measured on a standard benchtop pH meter (Thermo Scientific Orion, Beverly, Mass., U.S.A.). °Brix was measured with a standard handheld refractometer (MISCO Refractometer, Cleveland, Ohio, U.S.A.). All of these instrumental analyses were conducted in the Space Food Systems Laboratory (SFSL) (Johnson Space Center, Houston, Tex., U.S.A.).

Assessment of product nutritional quality. Nutritional testing was performed by Medallion Laboratories (Minneapolis, Minn., U.S.A.). Tests included a broad assessment of macronutrients, essential vitamins, and minerals in products. Samples were submitted in triplicate for each analysis, and, where possible, analyses were performed by American Organization of Agricultural Chemists (AOAC) approved methods. Products were submitted for baseline nutritional analysis within 3 wk of production. Final evaluation was performed at shelf life endpoint, or after 36 mo of storage, if shelf life exceeded 36 mo.

Analysis of product sensory quality. Sensory evaluation of products proceeded at 4-mo intervals for the first 2 y of evaluation, and at 6-mo intervals during the 3rd year. All sensory analyses were performed in the Sensory Evaluation Center at the SFSL, using untrained employee personnel recruited from the Johnson Space Center. Eligibility of panelists was determined only on the basis of their having reported no relevant allergies and after submission of informed consent paperwork. Panelists were maintained in isolation for the duration of each test, and offered palate cleansers at the start of the test, as well as in between samples and sample sets. Lighting and noise were controlled in the test facility throughout the duration of each test. Approximately 24 h prior to testing, samples were pulled from each storage condition and allowed to equilibrate to room temperature (70 ± 2 °F). If necessary, samples were heated in a 150 °F convection oven for 30 min prior to serving; all other samples were served to panelists at ambient temperature (70 ± 2 °F).

Within 2 wk of receipt into the lab, food products were evaluated by quantitative affective testing for baseline acceptability. These affective tests utilized a 9-point Hedonic scale for all assessments and considered overall acceptability of the items, as well as the preference for broad aspects of key sensory attributes. Attributes considered in both acceptability and difference testing were product specific but generally included assessments of appearance, texture, aroma, flavor, and aftertaste. Between 22 and 38 panelists evaluated products at each baseline test point. Separate paired *t*-tests were conducted to compare acceptability of the 2 treatment samples and control samples ($\alpha = 0.10$).

After baseline acceptability was determined, Difference-from-control testing, based on procedures outlined by Meilgaard and others (1999), was used to quantify differences imparted to products over storage time. The specific Difference-from-control test employed involved the presentation of 3 successive sample pairs to panelists, consisting of a control (40 °F) sample paired with one of the treatment samples (72 °F, 95 °F) or blind control (40 °F), and prompted them to assess the magnitude of the difference between several attributes of the two. Panelists indicated their responses on a 9-point verbal category scale that ranged from "Extremely Different" to "Definitely the Same." Panelists were also prompted at the end of each difference test to provide overall acceptability scores for each sample. Between 13 and 30 panelists participated in each Difference-from-control test session. The mean Difference-from-control score was calculated for each sample and blind control. These data were evaluated by paired *t*-tests to determine significance of the effects of storage temperature on each attribute ($\alpha = 0.10$).

After a significant difference from control was determined for any treatment, products were evaluated at remaining test intervals by quantitative affective testing. The remaining affective testing of products utilized the same questions as those used to determine baseline acceptability. Affective testing continued until the average acceptability had declined to a 6.0, or decreased by at least 20%, if original rating was initially less than 7.5. Separate paired *t*-tests were conducted to compare acceptability of treatment samples and control samples ($\alpha = 0.10$).

Shelf life extrapolation. Analytical data were considered in parallel with sensory data, to determine the principal mode of quality deterioration and corresponding critical quality limits for each food. After identification of these factors, the reaction order for quality loss in each food was gathered from the literature. Depending on reaction order identified through the literature, reaction rate at 95 °F and corresponding Q10 values were determined by appropriate equations, summarized in Labuza (1982). Shelf life endpoints (t_s) at ambient temperature, which were not observed in the 36-mo testing period, were calculated by the following equation:

$$t_s = t_0 e^{-aT},$$

where t_s = shelf life at 72 °F/22.2 °C, t_0 = shelf at 95 °F/35 °C, $a = \ln Q10/10$, $T = 12.8$ °C.

Where analytical measurements did not reflect sensory assessments of quality, Q10 values were obtained from the literature and used to predict shelf life value at ambient temperature from observed sensory endpoints at 95 °F. This was the case for products whose main mechanism of quality loss was defined in terms of flavor deterioration or deterioration to a specific appearance or texture parameter (that is, moisture migration) that was not assessed in analytical measurement.

Taoukis and others (1997) provide further information on ASLT and a general review of shelf life testing procedures, while Labuza and Schmidl (1985) provide examples.

Estimation of shelf life for all retort processed pouch products. Estimates of shelf life values were made for all NASA standard menu retorted products, based on the data gathered in ASLT of the 13 representative products. These estimates were generated as follows:

Table 2–Analyses performed in the quality assessment of each food product. Nutritional analyses were conducted by Medallion Laboratories. All other analyses were performed at the Space Food Systems Laboratory.

	Instrumental analyses								Sensory evaluation	
Food product	Texture	Color	Nutrition (initial)	Nutrition (final)	pH	°Brix	Aw	Free water	Difference from Control	Acceptability
Vegetable Side Dishes										
Carrot Coins	■	■	■	■					■	■
Three Bean Salad	■	■	■	■					■	■
Roasted Vegetables		■	■	■					■	■
Sugar Snap Peas	■	■	■	■					■	■
Fruit Products										
Rhubarb Applesauce	■	■	■	■	■	■			■	■
Apricot Cobbler	■	■	■	■	■	■	■		■	■
Desserts										
Bread Pudding	■	■	■	■					■	■
Meat Entrées										
Grilled Pork Chop	■	■	■	■				■	■	■
Tuna Noodle Casserole	■	■	■	■					■	■
Starch Side Dishes										
Homestyle Potatoes	■	■	■	■					■	■
Egg Products										
Broccoli Soufflé	■	■	■							
Vegetable Omelet	■	■	■	■						
Vegetarian Entrées										
Palak Paneer	■	■	■	■					■	■

Formulation and processing specification information was obtained for all NASA menu items not considered in this study. This product information was reviewed to identify a maximum of 3 representative products (of the 13 evaluated by ASLT) that were comparable or similar to each menu item. The average of the ASLT estimates for all comparable products identified was computed. This average was accepted as the preliminary estimate of the shelf life for the menu item.

To compute a final estimate of the menu item's shelf life, a list of differences expected to affect longevity were noted between the menu item and the representative product(s). The preliminary estimate of the shelf life for each menu item was then adjusted based on these identified differences. These differences and their corresponding shelf life adjustments were kept consistent and are summarized in Table 3.

Results and Discussion

Shelf life endpoints of representative products

Shelf life endpoints determined for the 13 representative products are summarized in Table 4. Of these, 4 endpoints (Sugar Snap Peas, Broccoli Soufflé, Vegetable Omelet, and Rhubarb Applesauce) were observed during the 36 mo analysis; the shelf life values of the remaining 9 items were determined by extrapolation.

Table 3–Proposed differences and corresponding shelf life adjustments applied in shelf life estimation of NASA retort pouched products.

Identified difference	Shelf life adjustment (mo)
Texture stability and susceptibility to storage-induced change	±3
Retort processing parameters related to acidity of product	±12
Vulnerability to syneresis, moisture migration	±9 (30 mo max)
Presence/absence of browning precursors, likelihood of nonenzymatic degradation	±12
Presence/absence of reactive flavor ingredients, potential for off-flavor development	± 9

Baseline acceptability of representative products. Representative products were found acceptable to panelists immediately after production (average panelist acceptance >6.0), with the exception of one vegetable product (Sugar Snap Peas), and both egg products (Vegetable Omelet and Broccoli Soufflé).

Baseline acceptability of Sugar Snap Peas. Panelists cited tartness, bitterness, and an unacceptable aftertaste as the reasons for the low acceptability of Sugar Snap Peas after production. These off-flavors were attributed to the increase in organic acid content typically present in canned green vegetables (Lin and others 1970, Clydesdale and others 1972). Incorporation of a preliminary blanching step and inclusion of a brine packing solution are conventional means to avoid this off-flavor development. While the blanching of the snap pea ingredients may prove beneficial, the inclusion of a brine solution is not typically appropriate for NASA applications. Pouched vegetables in brine can prove awkward and untidy in microgravity, and also contribute significant nonedible mass, volume, and wet waste to the total food system. Formulation of a sauce component that might simulate the beneficial effects of the brine could be considered for NASA applications to improve initial acceptability and ultimately extend the shelf life of this vegetable product.

Baseline acceptability of egg products. Although retort processed egg products are not currently offered in the NASA food system, 2 candidate egg products were developed for consideration in this study. The Broccoli Soufflé and Vegetable Omelet products were proposed as a means to offer additional menu variety to crew in extended duration missions. Texture was anticipated to be an issue for these products, as the high heat applied the retort process would allow extensive aggregation of egg proteins (Finley 1985). Therefore, considerable effort was made in formulating these products to include egg components at a low level and prevent formation of unacceptable texture. Liquid egg product was included in these formulations at 63% w/w (Vegetable Omelet) and 22.5% w/w (Broccoli Soufflé). Despite this effort, the heat treatment

Table 4–Shelf life of food products evaluated by ASLT and principle mechanisms of quality loss. Ranges have been given for those products whose shelf life endpoint was defined in terms of a 20% quality loss, rather than by a minimum 6.0 quality rating.

Food product	Estimated shelf life w/ ambient storage (72 °F) (mo)	Main mechanisms of quality loss
Vegetable Side Dishes		
Carrot Coins	36–48	Color and flavor change via Maillard degradation
Three Bean Salad	36–50	Flavor change via Maillard degradation
Roasted Vegetables	24	Flavor change via Maillard degradation
Sugar Snap Peas	12–20	Color and flavor change via Maillard degradation
Fruit Products		
Rhubarb Applesauce	24–36	Color change via Maillard browning
Apricot Cobbler	36–65	Color change via Maillard browning; texture change due to moisture migration
Desserts		
Bread Pudding	48	Flavor and color change via Maillard browning; texture change due to moisture migration
Meat Entrées		
Grilled Pork Chop	87	Texture change due to moisture migration
Tuna Noodle Casserole	49	Texture change due to moisture migration; color change via Maillard Browning
Starch Side Dish		
Homestyle Potatoes	48	Flavor change via oxidative and Maillard degradation
Egg Products		
Broccoli Soufflé	0	Inadequate color and texture resulting from the retort heating process
Vegetable Omelet	0	
Vegetarian Entrées		
Palak Paneer	39	Aroma and flavor change via oxidative degradation of spices

applied in the retort process was found to render quality of both products unacceptable to all panelists. Although instrumental analysis of these products continued at scheduled intervals, sensory evaluation was terminated after initial analysis.

In addition to texture, unacceptable appearance and odor of egg products were cited by panelists as reasons for failure at 0 mo. The unacceptable odor was likely due to formation of sulfurous gases produced during cooking of eggs, and subsequent containment of that gas within the retort pouch. The observed, greenish gray color is likely due to the formation of ferrous sulfide that is often observed with extended heating of liquid eggs at high temperatures (Gossett and Baker 1981). Odor could be curbed by decreasing the egg product fraction of the formulation, and appearance may be improved either by acidifying the formulations with salts or through the addition of various chelating agents.

Increased springiness and cohesiveness in egg white gel networks have been observed previously as a function of the heating time and temperature (Woodward and Cotterill 1986, Luechapattanaporn and others 2005). The phenomenon has been attributed to the denaturation of egg albumin proteins with the continued application of heat, and reassembly into an extensive fiber-like network (Finley 1985, Woodward and Cotterill 1986). Although increased cohesiveness was not indicated by panelist comments on the representative egg products studied, unacceptable hardness, springiness, and rubbery quality were observed. Instrumental texture analysis of these products was carried out for the duration of the storage analysis and showed that hardness of Broccoli Soufflé decreased gradually over time ($P < 0.05$). No such decline was observed for Vegetable Omelet, presumably because of its higher protein content. Even with reformulation and in spite of texture softening over time, retorted egg products are not likely to be acceptable for extended duration missions. Emerging processing technologies (microwave/radio frequency and pressure-assisted sterilization) should be considered for this purpose, as they appear to provide acceptability and storage stability that are more appropriate to NASA's needs (Luechapattanaporn and others 2005; Juliano and others 2006).

Quality loss to representative products throughout storage. Overall, changes to the color and flavor of representative products over time were found to have the greatest impact on product quality. For the most part, these changes were slowed significantly with product storage at low temperatures. Changes to product texture and nutritive value during storage were also observed for several of the representative products.

Color loss in representative products. Critical color limits observed in representative products over time are summarized in Table 5.

Table 5–Critical limits of color loss in representative products. Limits were only determined for those products whose shelf life was determined by product color change.

Food product	Critical limit of color loss
Vegetable Side Dishes	
Carrot Coins	Hunter $b^* = 41.9 \pm 1.37$
Sugar Snap Peas	Hunter $L^* = 32.4 \pm 1.48$
Fruit Products	
Rhubarb Applesauce	Hunter $L^* = 25.8 \pm 0.91$
Apricot Cobbler	Hunter $L^* = 35.2 \pm 0.92$
Desserts	
Bread Pudding	Hunter $L^* = 57.2 \pm 0.81$
Meat Entrées	
Tuna Noodle Casserole	Hunter $L^* = 66.9 \pm 0.47$

Significant color loss was generally limited to fruits, vegetables, and products containing high proportions of dairy ingredients. Analytical color differences were generally supported by panelist ratings of product appearance, as well as by general panelist comments on product color intensity.

Color changes previously reported in long-term storage of canned goods have been defined in terms of color fading in green vegetable products, high carotenoid products, and uncured meats; and color darkening in bakery products, starch products, fruits, and cured meats (Feaster 1949; Cecil and Woodruff 1963; Goddard 1994). Although both fading and darkening were observed in the present study, the latter was the most significant color change influencing product quality. The most substantial declines in color were observed for fruit and vegetable products. On average, the critical color limits of fruit and vegetable products represented a decline of 20% in the value of initial color parameters.

Generally, observation of color fading was limited and had minimal bearing on sensory acceptance of most products. The most substantial fading of color was observed in green color of Sugar Snap Peas, where the Hunter a-value had increased from 1.75 to 2.92 after 20 mo of storage at 72 °F. However, decreases in the Hunter L-value during this time, indicating darkening of the product, were found to have a greater effect on overall product quality.

Additionally, some color fading was measured in the Grilled Pork Chop product, but was not found to have a significant effect on the overall panelist acceptability over time. Color fading in Grilled Pork Chop was characterized in terms of a hue shift from orange to yellow-green. This shift appeared to coincide with decreased reporting by panelists that the product appeared red or pink over storage. The shift was not significant for the product stored at the low temperature (40 °F) conditions.

Color darkening was found to have a greater effect than color fading on acceptability of Apricot Cobbler and Carrot Coins products. Although instrumental assessment showed gradual change of all color parameters over time for ambient and high temperature storage of these products, panelist perception of color change was limited to discernment of relative product darkness. The lack of significance of color fading in these products is likely due to their formulations: Carrot Coins contains butter at 1.61% w/w; Apricot Cobbler contains pie crust and sugar at 8.37% and 21.22%, respectively. Both of these products contain reasonable levels of reactive browning precursors, which would therefore account for their darkening over time. Cecil and Woodruff (1963) assessed storage stability of retorted Apricot Jam at 70 and 100 °F, and have noted similar product observations to those of the present study.

Color changes in the Bread Pudding and Tuna Noodle Casserole products were characterized only by product darkening. The critical limits of color decline in these products were more moderate than in fruits and vegetables. Color darkening in Bread Pudding represented a decrease in 12.4% of initial parameter value. It was accompanied by the generation of Maillard-type flavors that were found desirable by panelists until approximately 16 mo of storage at 95 °F.

Darkening of Tuna Noodle Casserole occurred gradually throughout storage at ambient and high temperatures, and only represented 8.4% reduction in initial parameter value. These gradual changes were likely the result of nonenzymatic browning reactions, as they occurred most considerably at high temperatures, were accompanied by product darkening, and because the

S: Sensory & Food Quality

casserole sauce contains dairy and other browning precursors. However, although the color changes were minor, they were still reflected in panelist ratings of appearance for this product. This was likely due to simultaneous progression of other quality changes that affect appearance, such as moisture migration between sauce and noodle components. Rodriguez and others (2003) have reported similar findings in their analysis of retorted burrito combat rations. Specifically, their work has suggested that extended storage of multicomponent pouched foods with high starch contents has detrimental effects to the appearance, texture, and flavor of the food. The most significant effects to these quality parameters in their retorted burrito products were found to result from storage of the products at high temperatures. Observations of Tuna Noodle Casserole, the only discrete, multicomponent food considered in this study, were found to align with this suggestion.

Darkening of Rhubarb Applesauce was observed over time at ambient and high temperature storage conditions, while those samples in low temperature storage remained almost unchanged, even after 36 mo of storage ($P < 0.05$). Color change was assumed in large part to be the result of nonenzymatic browning reactions, as it was characterized largely by a decrease in Hunter L-values, was accompanied by a flavor change, and was most pronounced for those products stored at high temperatures. Similar characteristics were observed for the darkening of Roasted Vegetables, but the color aspects were overcome by off-flavor development, presumably because of the relative mildness of the initial product flavor.

Flavor changes in representative products. Although not characterized over time by analytical measurement, flavor deterioration was observed and documented by panelists over time for nearly all products. Flavor loss was observed in terms of loss of characteristic product flavors and formation of unacceptable flavor, with the latter contributing most significantly to overall acceptability.

For most products, flavor change was accompanied by a change in color, which was often observed before panelist perception of flavor differences. For those products found acceptable at baseline, flavor did not appear to drive overall sensory acceptability until after a minimum of 16 mo of storage at ambient conditions.

Panelist acceptability of the flavor of all representative vegetable products (Carrot Coins, Three Bean Salad, Roasted Vegetables, Sugar Snap Peas) was found to decline over time, especially at ambient and high temperatures. Similarly, a decreased acceptability of aroma and aftertastes were observed in vegetable products stored at high temperatures over time ($P < 0.05$). As these changes tended to coincide with product darkening, and because of the nature of the products, flavor changes in these vegetable products were assumed to be resultant from Maillard browning reactions.

Maillard reactions were also implicated in the flavor and color change observed in the Bread Pudding representative dessert product. Association of color and flavor changes has previously been observed in a canned fruit cake product by Cecil and Woodruff (1963). Their research noted increasing perception of "bitter" and "burned flavor" with darkening of color. As these changes were accompanied by hydrolysis of 50% of the product disaccharides, the study attributed them to nonenzymatic or Maillard browning reactions. NASA dessert products are formulated with adequate dairy, egg, and sugar ingredients to allow formation of characteristic flavors and colors in dessert products by Maillard reactions during processing. At ambient and high temperatures, however, the reactions were allowed to proceed throughout storage to a point where they began to impart negative effects on product quality. This was observed after only 16 mo of storage at 95 °F. Sensory analysis suggested that browning reactions in the retort processed dessert can be correlated with increased panelist preference to this point. After this point, however, color quality appears to become unacceptable, and flavor intermediates too overbearing. As most dessert products are formulated similarly and are potentially subject to these reactions, they should conceivably benefit from a moderate amount (<16 mo) of high temperature storage. However, the specific storage conditions should be optimized on a product specific basis to minimize disadvantageous effects and maximize product quality.

Although not affecting quality over time, sensory panelists also noted an off-flavor in the Grilled Pork Chops meat entrée, shortly after production. The panelists consistently mentioned that they perceived a fish-like taste in the product, which suggests that the retort processing of meat entrées had introduced off-flavors reminiscent of fish into the product. Panelists who evaluated the Tuna Noodle Casserole product did not comment on such an off-flavor, but indeed a fish-like taste would not have been peculiar for that product. The extensive heat applied in retort processing typically results in an overprocessing of meat products, to ensure sterility throughout the entire product (Potter and Hotchkiss 1998). Perhaps with the implementation of nonthermal processing methods, off-flavor development in these types of meat products could be avoided, and initial panelist acceptance of the products might be improved. This could ultimately serve to increase the shelf life of the meat entrée products.

Texture changes in representative products. Texture changes affecting quality of representative products in storage were limited to moisture migration, starch gelatinization, and syneresis. These changes were most considerable for those products with discrete components (Tuna Noodle Casserole), and in products with high starch (Homestyle Potatoes) or protein contents (Grilled Pork Chop). Changes in consistency of fruit over time and a low panelist acceptability of texture in vegetable products were also observed.

Although analytical texture data on the Homestyle Potatoes product were inconclusive, sensory data suggested that product texture immediately after production was unacceptable. Comments on product texture were consistent throughout the study, and assumed to be the result of potato tissue softening imparted by the retort process. Despite this perception of soft texture, panelist acceptance of initial flavor, aroma, and other quality factors was satisfactory and allowed maintenance of product quality throughout shelf life. Declines in flavor and aroma attributes, therefore, were determined to be the primary mechanisms of quality loss for Homestyle Potatoes. Schmidt and Ahmed (1971) also reported decreased hardness of thermally processed potatoes relative to unprocessed control samples after retorting. They attributed this difference to solubilization of intracellular pectic substances, absorption of water, and gelatinization of starch granules. Prolonged storage of their processed potato samples indicated some hardness decrease due to a reduction of starch granule water holding capacity over time.

Another high starch product considered in the present study was the Three Bean Salad vegetable product. Texture of this product was found to be quite stable over time, but was greatly degraded by storage at low temperatures. Storage at 40 °F was found to result in gelatinization of filling aid starches, which shortened the shelf life of the product considerably to 12 m. With extended storage of the retorted product, and especially with exposure to freeze thaw cycling, cooked starches within retort product filling solutions can be prone to retrogradation (Goddard 1994). The retrogradation of the starch molecules that occurred in this product was initially observed through a slight thickening of the product sauce after 4 mo of storage at 40 °F. After 12 mo of low temperature storage, retrogradation had proceeded to a level that rendered the product unacceptable to panelists. No significant texture differences were observed for this product throughout storage at ambient and high temperatures. Replacement of the starch used in this formulation and avoidance of low temperature storage of this product are proposed as countermeasures to realize the greatest shelf life for this product.

Changes to the textural quality of representative fruit products (Apricot Cobbler and Rhubarb Applesauce) were reflected in sensory ratings of each product's texture, and were also presumed to have affected panelist ratings of appearance. Both fruit products were noted by panelists to have lost firmness and become thinner over time, with such effects being most pronounced at higher temperatures. This was assumed to be the result of moisture release from fruit tissues and a subsequent increase in free water in the products over time. An increase in free water of Rhubarb Applesauce was reflected in product thinning, as noted by an increase in Bostwick flow consistency over time. Free water release within the Apricot Cobbler product was less pronounced, likely because of the presence of ingredients that were able to capture the released water. An informal sensory analysis of the product at 48 mo indicated that tapioca pearls (present at <2% w/w in the product) were noticeably swollen, as they appeared to have absorbed much of the water released from the apricot fraction of the product. This evaluation also indicated that free water released from the apricots may also have been incorporated into the pie crust. This incorporation had resulted in softening, and even dissolving, of a considerable amount of the crust component by the end of the product's shelf life.

Immediately after processing, panelists noted that the textures of 3 vegetable products (Carrot Coins, Sugar Snap Peas, and Roasted Vegetables) were not desirable. Panelist comments indicated that they found the products to lack freshness, citing that the vegetable components were "too soft," and "too moist." Similar comments were observed throughout storage testing, but could not be correlated to any data from instrumental textural analyses. It is likely that the comments addressed textural changes imparted to these vegetables by the retorting process itself, irrespective of storage time and temperature.

Entrées (both meat and vegetarian) were among the most durable products considered. Texture loss in the representative entrées (Grilled Pork Chop, Tuna Noodle Casserole, Palak Paneer) appeared to occur gradually, and was characterized primarily by sensory evaluation. Changes to the Grilled Pork Chop product were limited to an increasing hardness and dryness of the meat and thinning of the sauce over time. The observations were likely due to decreased water holding capacity of the meat proteins over time and gradual release and incorporation of water into the sauce. However, no conclusive analytical data were available to assess the rate of this deterioration. Texture data and free liquid measurements were very inconsistent. This is likely due to the addition of varying levels of sauce to the products, as sauce addition occurs as required to maintain acceptable pouch fill weights. Therefore, shelf life projections were accomplished primarily through consideration of sensory data. As sensory data are varied by their nature, shelf life calculations were performed conservatively to account for the lack of analytical data.

A hardening of cheese cubes in the Palak Paneer vegetarian entrée was also observed over time. Instrumental analysis of texture indicated a gradual hardening and decrease in cohesiveness over time for cheese cube samples over time. These changes were reflected in sensory texture scores, and were significantly more

Table 6–Nutrient retention of representative products after storage at ambient temperatures. Values are given in terms of percent of the initial value retained at shelf life endpoint or 36 mo. Dashes indicate limited data and/or absence of considerable initial levels of nutrient.

	Nutrient retention (% of initial level retained at shelf life endpoint)												
	Vegetable Products				Fruits		Starches	Meat Entrées		Veg. Entrées	Egg Products		Desserts
Nutrient	**Three Bean Salad**	**Sugar Snap Peas**	**Carrot Coins**	**Roasted Vegetables**	**Rhubarb Applesauce**	**Apricot Cobbler**	**Homestyle Potatoes**	**Grilled Pork Chop**	**Tuna Noodle Casserole**	**Palak Paneer**	**Broccoli Soufflé**	**Vegetale Omelet**	**Bread Pudding**
A	–	–	300	–	–	–	–	–	–	–	–	8	–
B1	–	88	–	–	–	100	–	7	92	–	–	83	–
B2	50	–	50	–	50	8	–	3	6	92	–	–	98
Niacin	–	–	37	–	69	65	–	–	–	–	–	72	–
B6	88	–	–	–	–	–	65	44	80	78	–	78	100
Pantothenic acid	3	42	22	–	–	–	4	4	83	65	–	–	58
Biotin	0.9	–	73	0.8	90	87	–	60	–	–	–	–	97
Folic acid	45	68	63	–	0.4	–	43	–	48	–	–	54	–
C	–	50	–	–	86	3	–	–	–	–	–	–	–
K	53	90	–	62	–	50	–	–	–	92	–	–	–

pronounced with high (95 °F) temperature storage. As with other entrée items, these changes are suspected to be the result of a decrease in water holding capacity of the proteins in the cheese cubes, and subsequent moisture release. Maintenance of refrigerated and ambient storage of this product appeared to slow this texture change. Rao and Patil (2006) have observed hardness decreases throughout storage of retorted paneer curry, but have acknowledged prior research that has characterized increase in hardness similar to the present study. Both studies observed most extensive texture decline with storage at higher temperatures.

Nutrient degradation in representative products. Nutrient losses in representative products were generally limited to reductions in those nutrients with previously established storage lability (Gregory 1996). Table 6 summarizes the levels of several storage labile nutrients observed in representative products after long-term storage at 72 °F. Decline in vitamin C was the most significant loss observed for fruit products over time. These losses were varied, yet were consistently more pronounced for products stored at ambient high (95 °F) temperatures. Vitamin B losses were most significant for vegetable products, and showed no temperature dependence.

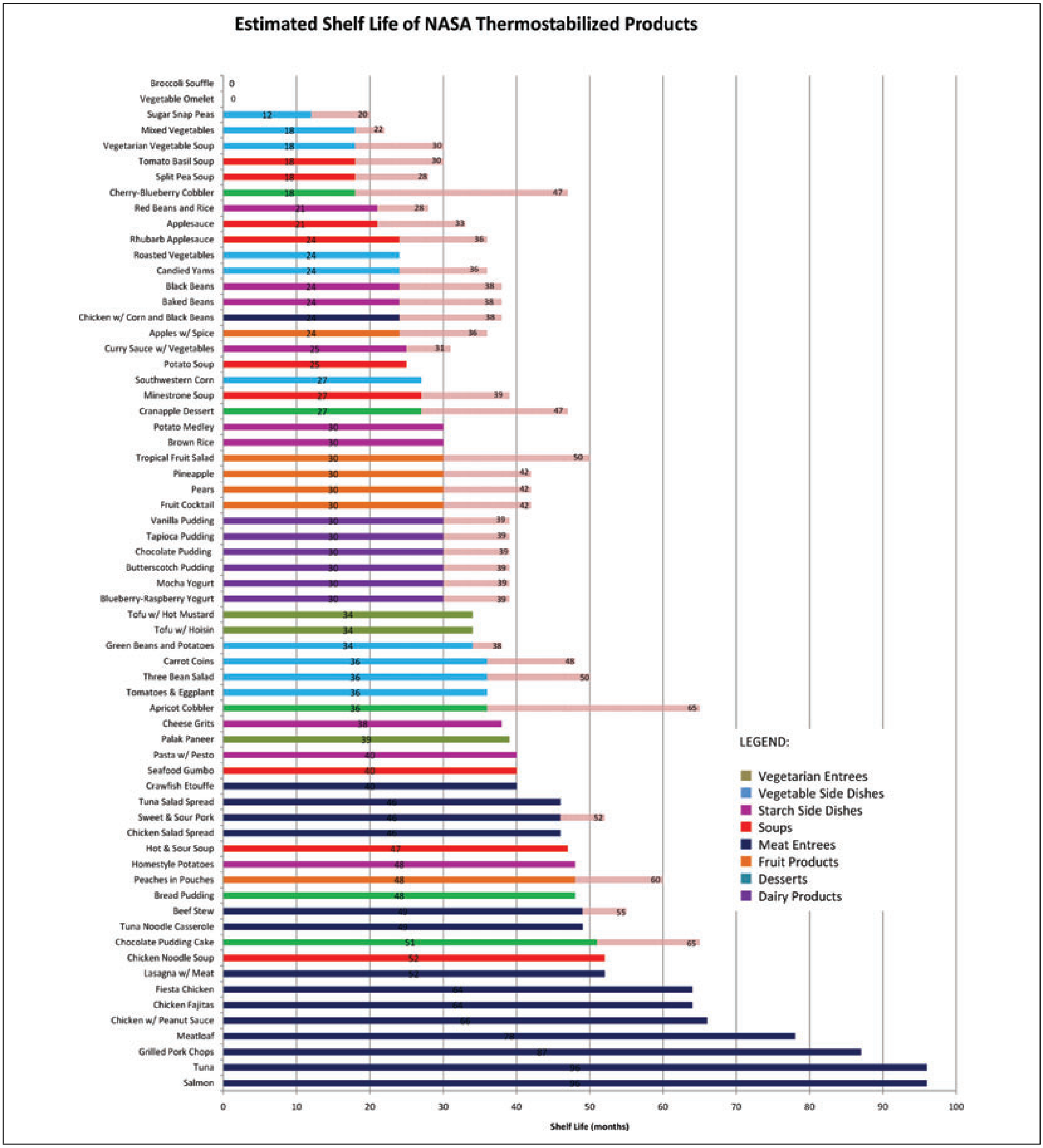

Figure 1–Shelf life estimations of NASA's stock of retort processed pouch products.

Increases in carotenoid content were observed for Carrot Coins products stored at ambient and high temperatures. Vitamin B content of meat and vegetarian entrees showed considerable declines over time, with greatest losses occurring for products stored at ambient and high temperatures. Vitamin K was found to decline in Palak Paneer stored at ambient and high temperatures. Vitamin A levels in the Vegetable Quiche egg product appeared to decrease by 90% after 36 mo of storage at all temperatures. The dessert product showed reasonable vitamin stability over time, with substantial losses only observed in pantothenic acid and the contents of several minerals. An extensive analysis is currently underway to further assess the nutrient stability of NASA's retort pouch products.

Shelf Life Estimations for All NASA Retort Pouched Products

Shelf life estimations of NASA's current stock of retorted products are summarized in Figure 1. Fruit and dessert products were estimated to have a minimum shelf life between 1.5 and 5 y; vegetable side dishes were estimated to have a minimum shelf life between 1 and 4 y; soups and starch side dishes were estimated to

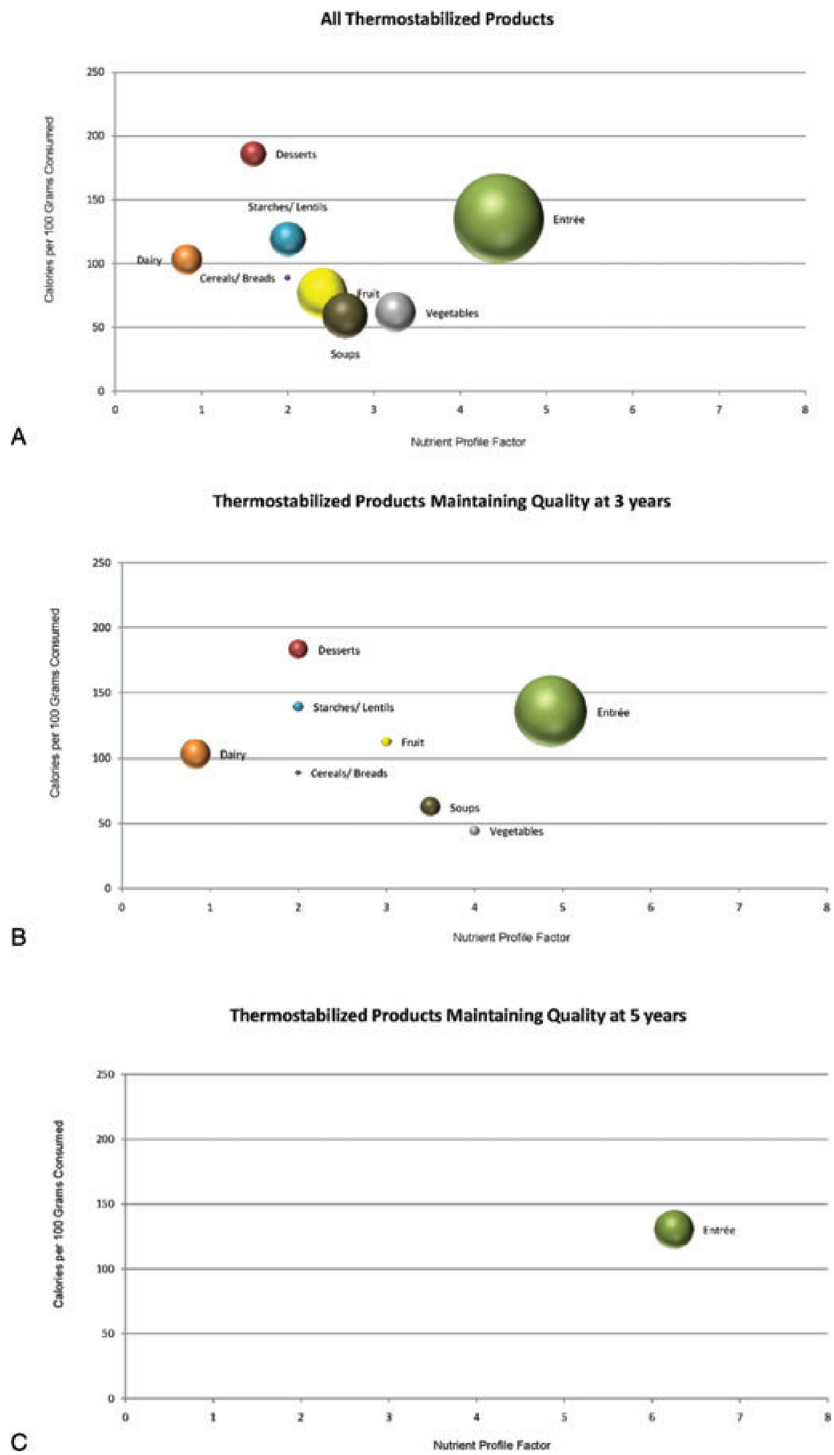

Figure 2–Menu landscapes of retort processed products maintaining quality immediately after production (A), at 3 y (B), and at 5 y (C). Nutrient density in these figures is expressed in terms of a measure of % RDI of 18 NASA required nutrients provided per 100 g of each product. Bubble size in the figures indicates the number of products available per each food category.

S: Sensory & Food Quality

have a shelf life between 1.75 and 4 y; and dairy products and vegetarian entrees are estimated to have a shelf life between 2.5 and 3.25 y. Meat products were found to be the most durable products, as they were all estimated to maintain quality for a minimum of 2 y, with an expected shelf life maximum of 8 y.

Of the 65 products, only 27 are estimated to have a shelf life of greater than 3 y, and would therefore fall within the minimum range required by AFT to support extended duration spaceflight. Additionally, there are likely to be mission scenarios requiring up to a 5 y shelf life for food. Supporting such a scenario with the current food system would allow only the provision of a limited number of entrée products with shelf life estimates that extend beyond 5 y.

The bubble chart plots in Figure 2 are provided to represent the caloric and nutrient provisions that would be possible in various mission scenarios, based on the shelf life estimates of this study. Figure 2A represents a full landscape of foods in NASA's thermostabilized product stock, with respect to each food's caloric content and calculated nutrient density parameter. The size of the bubbles in these charts is defined with respect to the number of foods that exist in a given category. Calories are considered per 100 g of the food product. The nutrient density parameter for each food was defined internally, using NASA requirements for food system nutrition (Smith 2005). The following 18 nutrients were considered in the definition of this parameter: vitamins A, C, D, E, K, B1, B2, B3, B6, B12, folate, biotin, pantothenic acid, calcium, magnesium, potassium, iron, and zinc. The level of each nutrient that was present per 100 g of food was compared against the corresponding NASA requirement, and points were awarded as follows: the presence of 10% to 49% of the NASA RDI of a given nutrient contributed 1 unit to the nutrient density, the presence of 49% to 99% of the NASA RDI of a given nutrient contributed 2 units to the nutrient density of the food, and a nutrient present in excess of 100% of the NASA RDI contributed 4 units to the nutrient density. The sum of the nutrient density units awarded to each product per its nutritional profile is represented in the nutrient density parameters plotted in menu landscapes of Figure 2. While Figure 2A represents the menu landscape of the full product stock of thermostabilized foods, Figure 2B represents a menu landscape comprised of only the food provisions that would be possible with a 3-y shelf life requirement for NASA missions. Furthermore, Figure 2C depicts the even more limited landscape of options that would be available to support a 5-y shelf life requirement. As is apparent from the progression of the charts in this figure, the menu landscape available to support a NASA mission becomes quite limited with increasing requirements for the shelf life of the food system.

In fact, supporting a 5-y scenario with the current food system would allow the provision of a very limited number of meat entrée products. Therefore, modification to the current food system will be required to ensure provision of an adequate food system in extended duration mission scenarios. Modification may be accomplished in terms of individual product reformulations, application of emerging nonthermal processing technologies, and development of low temperature options for food stowage volumes.

Reformulation of retorted pouch products should include changes that will improve the initial acceptability of products, as well as those that may improve product stability over time. Several means of reformulation have been proposed for representative products herein. These should be considered on a product-specific basis as appropriate for the entire stock of NASA's retorted items. Additionally, Branagan and Pruskin (1993) have reported that fortification of thermally stabilized cheese spread products can allow the maintenance of adequate levels of several nutrients, even after exposure to adverse storage conditions. Fortification of NASA's retorted foods is likely to have a similar benefit and should be considered to improve the nutrient value of the products after storage.

Incorporation of emerging and nonthermal preservation technologies are currently being investigated by NASA through a collaboration with the U.S. DoD. These are being considered for their potential to improve the initial quality and as a means to extend the longevity of the food system for use in extended duration spaceflight.

Finally, as the present study dictates, the most significant changes to the quality of NASA's retorted products occurred at ambient and high temperature storage conditions. Consequently, NASA should consider incorporating low temperature storage volumes for support of extended duration missions, to further prolong food system shelf life. These efforts would likely require significant integration between the AFT program and relevant vehicle design teams. Provision of low temperature storage volumes would allow shelf life for a majority of products to extend into the minimum range defined by AFT.

Conclusion

Shelf life endpoints were established for all of NASA's retorted pouch products. At ambient storage conditions, shelf life endpoints of the products range from 0 to 96 mo, depending on the product formulation. Therefore, use of these products to support extended duration missions will not be feasible without modification. Modification may be accomplished in terms of individual product reformulations, application of emerging nonthermal processing technologies, and development of low temperature options for food stowage volumes.

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