Developing the NASA Food System for Long-Duration Missions

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Abstract: Even though significant development has transformed the space food system over the last 5 decades to attain more appealing dietary fare for low-orbit space crews, the advances do not meet the need for crews that might travel to Mars and beyond. It is estimated that a food system for a long-duration mission must maintain organoleptic acceptability, nutritional efficacy, and safety for a 3- to 5-y period to be viable. In addition, the current mass and subsequent waste of the food system must decrease significantly to accord with the allowable volume and payload limits of the proposed future space vehicles. Failure to provide the appropriate food or to optimize resource utilization introduces the risk that an inadequate food system will hamper mission success and/or threaten crew performance. Investigators for the National Aeronautics and Space Administration (NASA) Advanced Food Technology (AFT) consider identified concerns and work to mitigate the risks to ensure that any new food system is adequate for the mission. Yet, even with carefully planned research, some technological gaps remain. NASA needs research advances to develop food that is nutrient-dense and long-lasting at ambient conditions, partial gravity cooking processes, methods to deliver prescribed nutrients over time, and food packaging that meets the mass, barrier, and processing requirements of NASA. This article provides a brief review of research in each area, details the past AFT research efforts, and describes the remaining gaps that present barriers to achieving a food system for long exploration missions.

Keywords: food packaging, food safety, Mars, shelf life, space food

Introduction

NASA food system literature and numerous publications have documented the evolution of the space food system (Huber and others 1972; Bourland 1993; Perchonok and Bourland 2002; Perchonok 2007). Several types of food and beverage packaging have been used in NASA space programs, but the storage environment has been virtually constant. With the exception of Skylab, no refrigerator or freezer dedicated to food storage has flown on any U.S. space vehicle. Consequently, the food is provided in a shelf stable form for storage at ambient temperature. To achieve stability, the food undergoes inactivation of the microorganisms during ground processing. Although processing the packaged foods to commercial sterility provides a safe food system, this level of processing can reduce the quality of the food, including nutritional content and acceptability.

The different forms in which food is provided include the following:

(1) Thermostabilized—this process, also known as the retort process, heats food to a temperature that renders it free of pathogens, spoilage microorganisms, and enzyme activity. NASA thermostabilized products include pouched soups, sides, desserts, puddings, and entrees.

(2) Irradiated—irradiation is not typically used to process foods to commercial sterility. However, NASA has received special dispensation from the Food and Drug Administration (FDA) to prepare 9 irradiated meat items to commercial sterility (FDA 2009).

(3) Rehydratable—both commercial and internally processed freeze-dried foods are included in the NASA food provisions and then rehydrated during the mission using the potable water supply. Rehydratable foods are typically side dishes, such as spicy green beans and cornbread dressing, or cereals. Ambient and hot water are available to the crew for rehydration of these items.

(4) Natural form—natural form foods are commercially available, shelf stable foods. The moisture of the foods may range from low moisture (such as almonds and peanuts) to intermediate moisture (such as brownies and dried fruit), but all have reduced water activity, thus inhibiting microbial growth. These foods help to round out the menu by providing very familiar menu options, additional menu variety, and foods requiring no preparation time.

(5) Extended shelf life bread products—items, such as scones, waffles, tortillas, and dinner rolls, can be formulated and packaged to give them a shelf life of up to 18 mo. Like the natural form foods, breads add to menu variety and address crewmembers' desire for familiarity.

(6) Fresh food—foods such as fresh fruits and vegetables, which have a short shelf life, are provided on a limited basis, more for psychological support than as a means to meet dietary requirements.

(7) Beverages—the beverages currently used on the International Space Station (ISS) and the Space Shuttle are either freeze-dried beverage mixes (such as coffee or tea) or

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flavored drinks (such as lemonade or orange drink). The drink mixes are weighed and then vacuum sealed inside a beverage pouch. In the case of coffee or tea, sugar or powdered cream can be added to the pouch before sealing. Empty beverage pouches are also provided for drinking water.

The change in mission duration for trips to asteroids, Mars, and other extended missions beyond low Earth orbit will necessitate an evolution of the food system. The Mars missions, in particular, will require development of technologies to enable the crew to be self-sufficient and less dependent on resupply missions. One proposed mission to Mars designates use of the prepackaged foods, similar to those used on the ISS, for transit but may also include positioning food on Mars before the crew arrives. Under this scenario, prepositioned food may be 3- to 5-y old at the time of consumption. Achieving a 5-y shelf life to make this mission scenario feasible is an ambitious goal given that the current prepackaged foods have a stated shelf life of 18 mo. The determining factors for shelf life—safety, nutrition, and sensory acceptability—must be optimized to maximize the shelf life within the mission scenario. These missions will also require that more attention be paid to utilization of resources including mass, volume, power, crew time, and water.

The challenges are significant but not insurmountable, especially if the key needs are dissected individually. The following 5 items encompass the major technological and development needs for the space food system to successfully supply long exploration missions:

1. Nutrient-dense, shelf stable foods that meet overall sensory acceptability metrics;
2. shelf stable menu items with at least a 5-y shelf life;
3. partial gravity cooking processes with minimization of microbial risk;
4. sustained vitamin delivery in shelf stable foods;
5. a packaging material that meets high-barrier, low-mass, and process-compatibility constraints.

Correlating needs, such as temperature controlled storage and a robust bioregenerative food system, are both desired for the food system for long exploration missions and, at times, assumed within mission scenario development but are outside the scope of Advanced Food Technology (AFT). Thus, the focus of AFT is narrowed to this list. For each gap listed here, the discussion defines the gap, details the current research efforts, and ultimately presents potential avenues to gap closure to conclude the section.

Authors' note: Some of the NASA research publications, which are cited in this article, are unrefereed. However, it is important to note that internal and external merit reviews of NASA research plans occur before and during research completion as a condition of funding. To provide the readers with the most comprehensive view of space food system research, the authors have chosen to include all of the available internal data.

Gap 1: Nutrient-dense foods

NASA concerns about mission resource utilization focus on the mass of all crew consumables, but particularly on food provisions because food is such a large percentage of upmass (Bourland and Smith 1991). The mass of the food system depends on the form of foods on the menu and the quantity of food required to meet the crew's caloric requirements.

Historically, the food system began with product design focused on mass and volume restrictions but transitioned to focus on palatability after crew intake became a concern for flight doctors. For instance, in the case of the Gemini Food System, bite-size cubes of meat, fruit, dessert, and bread products were engineered to deliver 21.3 J/g, and the complete food system offered 12100 J, or about 2890 cal, in 0.73 kg of packaged food (Huber and others 1972). However, the in-flight acceptability of cubes quickly waned and many cubes were returned uneaten (Bourland 1993). The introduction of more rehydratable foods increased mass; Smith and others (1975) noted that the mass of the Apollo 7 food system was 0.82 kg of food per person per day. The Apollo 8 crew, in 1968, preferred the newly added thermostabilized foods, referred to as "wetpack foods." By the Apollo 14 mission, the mass of the food averaged 1.1 kg per person per day. According to Smith and others (1975), the crew preference for the thermostabilized product justified the weight increase. Even with the added "wetpack foods," the Apollo food system still contained a significant number of freeze-dried foods, since water from the fuel cells was available for food rehydration.

Current ISS and Shuttle crewmembers receive about 1.8 kg of food plus packaging per person per day. A higher percentage of this food is thermostabilized than on the Apollo missions because the thermostabilized food is still generally preferred in taste tests to freeze-dried items by crew members. Since the ISS utilizes solar panels for a power source and not fuel cells that produce water as a by-product, there is no mass advantage to using freeze-dried foods. Water is now transported to the ISS for rehydration. Furthermore, contributing to the mass increase is an increase in the required caloric delivery. The required calories as stated in the mission guidelines is based on the actual caloric needs of the crewmember, which are based on body weight and height. The result is an average caloric requirement of 3000 kcal (12550 kJ) as opposed to the 2500 kcal (10460 kJ) provided to the Apollo crew. In light of these mass challenges, NASA is considering various avenues of food mass reduction while still providing the crew with adequate calories and an acceptable diet.

In "Packaged Food Mass Reduction Trade Study," Stoklosa found that significant reductions in the space food system mass are possible with further menu development (2009). The aim of the 1st part of the study was to maintain the overall number of calories provided to the crew but to increase the caloric density of menu items by maximizing the percentage of energy from fat (35% of total energy intake per NASA dietary guidelines). With the additional fat, fewer grams of proteins and carbohydrates are necessary for an equivalent amount of energy and the total mass of food is reduced. In addition, sensory results showed that many of the thermostabilized foods could have the moisture levels decreased by 5% to 10% and maintain current taste acceptability. By optimizing the food system to have a 10% decrease in moisture and an increase in energy sourced from fat to 35%, a mass savings of 321 g per crew member per day, or 22%, is possible. The 2nd part of the study, which examined the substitution of standard menu items with one meal replacement bar per crewmember per day, resulted in a mass reduction of 240 g, or 17%. The meal replacement bar was presumed to deliver 1675 kJ at a manufactured weight of 100 g. If the 2 approaches were combined, the mass of the food system could be reduced by as much as 529 g, or 36%. Both the revised menu formulations and the meal replacement bars have yet to undergo the formal sensory evaluation and shelf life evaluation necessary for implementation.

The work by Stoklosa highlighted an opportunity for menu improvement, as did a concurrent AFT menu analysis exercise. The aim of the exercise was to qualitatively determine the efficiency of the current space food system in delivering nutrients and calories to the crew. Based upon the naturally nutrient rich (NNR) score as presented by Drewnowski, a simple (NNR) score was calculated as the average of the percentage daily values (DVs) for 16 nutrients given 2000 kcal, or 8368 kJ, of each particular food item (2005):

$$\mathrm{NNR} = \sum \%\mathrm{DV}_{2000\ \mathrm{kcal}}/16. \tag{1}$$

The 16 nutrients were protein, calcium, iron, vitamin A, vitamin C, thiamin, riboflavin, vitamin B-12, folate, vitamin D, vitamin E, magnesium, potassium, zinc, fiber, and pantothenic acid. The NNR score presented by Drewnowski incorporates monounsaturated fat but those values were not available for the space foods. Magnesium is considered a significant nutrient by the National Cancer Institute and is included within calculations of the calories-for-nutrient (CFN) nutrient density score; thus, it was chosen to replace monounsaturated fat in the calculations. Rather than 14 nutrients, the more recent recommendation to consider 16 nutrients was followed. Finally, to prevent severe skewing of the score by any single nutrient, very high percentage DVs were truncated at 2000%. The results of the exercise are depicted graphically in Figure 1.

While energy density is a key consideration in the definition of healthy diets for industrialized nations, a crucial factor for the space program is the mass of the food required to deliver the energy and the micronutrients. In this analysis, the energy-dilute foods, such as beverages and vegetables, have the highest NNR score. However, the energy density of these categories is quite low. Substantially more beverage and vegetable mass would be required if these categories were heavily used to provision the crew. Hence, low energy density foods conflict with the goal to minimize required upmass. In contrast, nuts are the most efficient offering currently, having relatively high energy, and significant nutrients in a compact food matrix. Significant white space exists for higher density, more nutritious foods in the space food system. Directional shifts of the food supply to the upper left portion of Figure 1 would ultimately allow a smaller mass of food to meet the required macronutrient and micronutrient needs of the crew. Care must be taken during any future menu planning to ensure that nutritionally void items are not selected solely for their the caloric contribution and that the bioavailability of the nutrients within the foods are considered.

Supplying food provisions, which have higher nutrient density, is an appropriate goal given that plausible and substantial mass reductions can be accomplished with potential product reformulations and the incorporation of food bars. Also, the current foods have relatively low nutrient density when compared to power foods like nuts. The challenge facing AFT is to source or formulate new nutrient-dense products that are shelf stable and maintain overall organoleptic and appearance acceptability. Commercial food bars that meet the nutritional requirements for meal replacement sometimes lack pleasant mouthfeel or present an unacceptable aftertaste. Increasing the fat content of foods often affects the shelf stability of the product over time. Artificial fortification of foods can lead to compromised nutrient delivery over extended storage time as well as create unpleasant tastes. These identified hurdles and those yet to be identified must be overcome to deliver the mass-reduced provisions required for viability of deep space missions.

Gap 2: Extended shelf life products

Commercial shelf stable food products are generally accepted as having sufficient shelf life, if the product is still consumer-accepted 1 y after manufacturing. NASA assigns an 18- to 24-mo shelf life to most space food provisions, but even this span is inadequate for future deep space missions. Food quality is predicted to have a pronounced role in crew psychological well-being due to the isolation and confined space associated with extended missions (Evert and others 1992). Hence, ensuring the quality of the food up to the point of consumption is paramount.

A main consideration in the quality of the food is how the food is perceived by the crew. The complexity of food acceptability prevents definitive quantitative assessment. Currently, flight foods are evaluated using sensory analysis for acceptability on the ground by a panel of 30 or more consumers. The products are rated

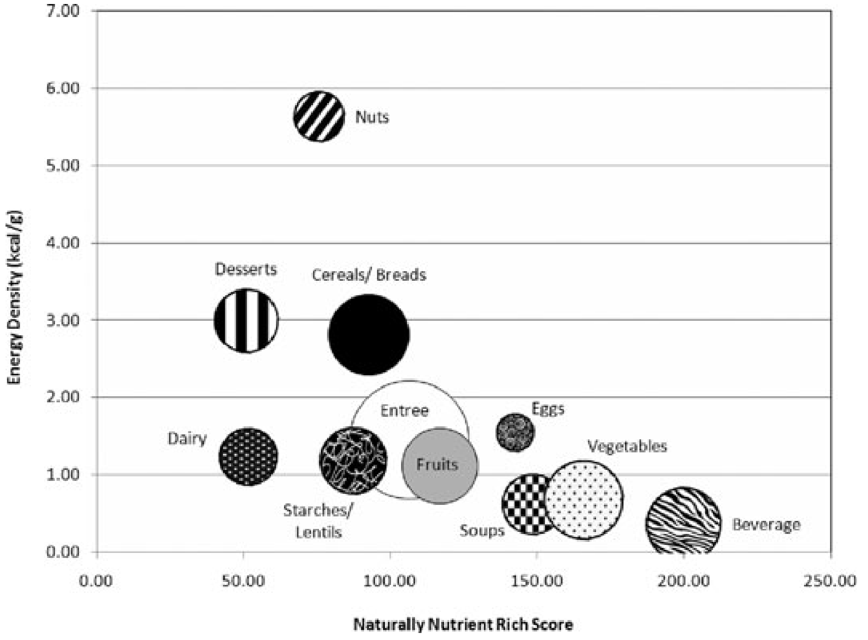

Figure 1–Relation between average energy density and average NNR score for space food.

on the basis of appearance, flavor, texture, and aroma using a 9-point Hedonic Scale. However, product acceptability can also be affected by factors such as product age, storage conditions, and the environment where the food is consumed. Menu variety and usability of the food system also contribute to food acceptability. A large variety of food items are recommended to provide the crew with choices and to avoid menu fatigue. If the food is difficult to prepare or eat, then the overall acceptability of the food is reduced (Vickers 1999). Finally, food acceptability can be affected by the social context and timing of meals. Food and mealtimes offer crews significant psychological-social benefit, such as reducing the stress and boredom of prolonged space missions or promoting unity by having dinner together.

Even if the food is acceptable to the crew on day one of the mission, the acceptability is not guaranteed to the end of the 5th y, particularly because the food quality degrades. A shelf life study conducted at Johnson Space Center (JSC) from 2003 to 2008 highlighted the quality changes of the thermostabilized space foods over a 3-y period (Perchonok and others 2003; Perchonok 2005a; Perchonok and Antonini 2008). The shelf life study began with 13 thermostabilized items stored at 4.4 °C (control), 22 °C (storage temperature of actual flight food), and 35 °C (accelerated temperature) and 50% relative humidity. The shelf life tests were terminated at the point when the product became unacceptable or at 3 y. The study was conducted on an assortment of products (vegetable sides and starch dishes, fruits, desserts, meats, and other entrées) that were chosen to be representative of the entire inventory of thermostabilized food products. Of these, meat products and other entrées were projected to maintain product quality the longest, over 3 y, without refrigeration. Fruit products and dessert products followed, as they were projected to maintain their quality from 1.5 to 5 y without refrigeration. Starches and vegetable side dishes should maintain their quality from 1 to 4 y without refrigeration. Egg products did not respond adequately to the thermostabilization process and were found unsuitable immediately after production. In general, the major determinants of shelf life within this test were the degradation of flavor acceptability as evaluated by sensory panelists and the progression of chemical reactions as detected in Hunter colorimeter readings over time. Lund determined that food quality (color, texture, and so on) may provide a general indication of nutritional loss of the food (1988). Losses in excess of 40% for naturally occurring vitamin C, folic acid, and pantothenic acid were noted in most of the 13 products at ambient conditions, but other nutrients seemed to be maintained throughout shelf life.

In part 2 of the study, shelf life values were estimated for the 65 NASA thermostabilized items. Figure 2 shows the decline in the number of acceptable products over a 5-y period as determined by the study. A paltry amount of food remains acceptable after the 2-y time frame. Similar decreases are predicted with rehydratable foods, natural form foods, and extended life breads based on supplier data, anecdotal accounts, and in-house food evaluations. The overall results suggest that new processing technologies and storage conditions should be investigated to improve initial quality and extend shelf life of food products for use in long-duration missions.

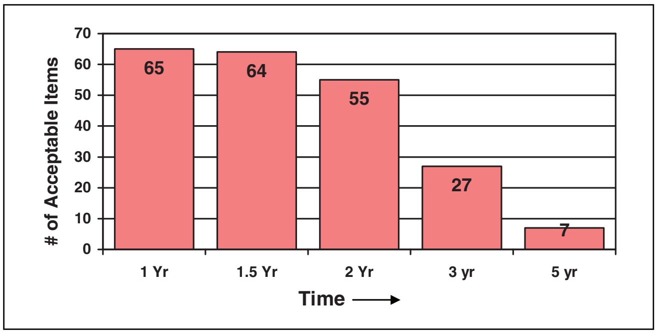

Figure 2–Number of thermostabilized space foods as shelf life extends to 5 y.

Analyses of the NASA food system using a total systems approach produced evidence that shelf life of the dry products could be improved by reducing the amount of oxygen in the final package (Oziomek 2010). Current oxygen purge methods, namely nitrogen flushing, used in NASA packaging are inefficient and seal in a significant amount of oxygen. An improved method of vacuum hold combined with longer flush cycles was developed to decrease the amount of oxygen entrapped in the food package.

One alternative for deep space provisioning is to develop a food system around the existing foods that have the required shelf life. Undoubtedly, restricting the menu to fewer items would be detrimental to overall acceptability of the menu. ISS crews have noted in crew debriefs that they would prefer more food variety for the length of the missions and they tire of certain foods over 6 mo. When the menu cycle repeated after only 8 d (as opposed to the current 16-d menu cycle for ISS missions), the crews noted that there was not enough variety in the menu (document not available externally due to confidentiality). Since the diets of the crewmembers during a mission are limited to just those items available, the long-term acceptability may decrease for some of the menu items. Vickers (1999) reported that studies conducted by the armed forces in the 1950s showed that most foods decreased in acceptability when they were consumed repeatedly. The degree of loss of acceptability depended on the specific food.

Another oft mentioned alternative for deep space provisioning is to utilize the space environment essentially as an outdoor freezer for the food supply. The cold temperatures would predictably halt any degradation of the food and provide a ready food supply to the crew. Because an actual mission destination has yet to be determined, there is little way to predict the radiation exposure and define the temperature ranges to which the food supply would be subjected. Work will begin in 2010 to assess the impact of temperatures within the −80 to −40 °C on the space food packaging and current food quality. The other issue is the appropriate crew interface to the storage as food has never been stored external to the crew habitat. Engineering technologies would still be required to ensure safe, repeated retrieval of the food by the crew. A food supply, which is stable within the crew habitat, is adaptable to most mission scenarios and provides the predictability for AFT to ensure food quality throughout the mission.

So, despite shelf life challenges, the acceptability of the food system must be ensured for 5 y, with enough variety and ease of use that the crew consumes adequate quantities throughout this period. New food products may be required if this standard is to be reached. Some emerging technologies that are less destructive to the food matrix may be approved by the FDA as pathways for food manufacturers to achieve commercial sterility. The 2 technologies with the most promise are high-pressure processing (HPP) and microwave sterilization. HPP is a method of food processing in which food is subjected to elevated pressures (up to 600 MPa or approximately 6000 atmospheres), with or without the addition of heat, to achieve microbial inactivation, or to alter the food attributes to achieve qualities desired by consumers. Pressure inactivates most vegetative bacteria at pressures above 415 MPa. HPP retains food quality, maintains natural freshness, and extends microbiological shelf life (Ramaswamy and others 2010). Microwave sterilization is a high-temperature, short time process in which the packaged food is cooked at 129 °C for 10 min (Natick 2004). The current thermostabilized NASA food products are cooked to about 121 °C, but for a much longer time. Preliminary studies suggest that the quality of the foods is much higher when these promising technologies are used. More substantive work is needed with these foods to determine the long-term impact of the processing methods on degradation of quality.

Gap 3: Safe cooking in partial gravity

Microbiological contamination of food can negatively affect crew health and possibly compromise crew survival. Most food items are monitored by the JSC Microbiology Laboratory per established space food requirements to ensure that preparation and packaging procedures result in products that conform to established microbial standards for flight foods. First, the cleanliness of the environment is verified. Samples from the food production area are collected only on the day that the food facility is in production. The table surfaces, packaging film, food processing equipment, and air are evaluated for their total aerobic count. The food products themselves are also tested. Table 1 divides the foods based on whether thermostabilization has been applied and provides the subsequent limits on the presence of microorganisms.

To ensure safety, NASA adheres to the Hazard Analysis and Critical Control Points (HACCP) system, a systematic and preventive approach to food safety that was developed by NASA, the U.S. Army Laboratory, and the Pillsbury Company in the 1960s. Both the Centers for Disease Control and Prevention (CDC) and the U.S. Dept. of Agriculture (USDA) cite the implementation of the HACCP system of inspection as a principal reason why the incidence of foodborne illness seems to be declining (Kvenberg and others 2000; CDC 2004). The use of HACCP, including the strict use of good manufacturing practices, standard operating procedures, and testing of processed foods, is associated with the prevention of foodborne illness events during space missions.

Evidence shows that the current system is working. Good manufacturing practices and the microbiological testing of food products before flight—part of NASA HAACP—have likely prevented foodborne illness. For example, freeze-drying hampers foodborne illness by eliminating the water necessary for microorganisms to grow. However, viable microorganisms can still exist in the food, if ingredients or processing surfaces are compromised. Therefore, these foods are tested for microorganism load before flight. Dr. C. Mark Ott, a researcher with the JSC Microbiology Laboratory, reported at the 2006 Spring Meeting of the American Society for Microbiology Texas Regional Branch, Wimberley, Texas that 14 items over several years, including chicken salad and shrimp, failed to meet the microbiological specifications and hence were not approved for Shuttle and ISS flights. Though this is a small number compared to the number of samples that were tested in the JSC Microbiology Laboratory, even one contaminated food lot can result in several crewmembers becoming sick during a mission and, consequently, risk mission success.

Although the risk of foodborne illness from prepackaged food is successfully mitigated with the current safety procedures, the foray into other food sources changes the risk landscape significantly. Specifically, once NASA builds extraterrestrial habitats, food may not be limited to only prepackaged food. Crewmembers may be required to harvest hydroponically grown produce, store and repackage ingredients in the foreign environment, and cook with equipment engineered for a partial gravity surface. The potential contamination points of the food supply will increase unless an equally stringent HACCP plan is applied to the new system.

Hydroponically grown produce is a viable path to reducing food system mass and adding variety to the menu. Previous AFT projects, such as the Bulk Ingredient-Based Menu Development, assumed that fresh fruit and vegetables would be grown as a portion of the food supply (Perchonok 2006). The consumption of nonsterile food items introduces new, albeit manageable safety risks to the crew. If the fresh fruits and vegetables are consumed without adequate heat or cleaning step, there is a potential for microbial food contamination and, hence, foodborne illness. The risk has yet to be quantified for a closed environment, but from 1991 to 2002, several produce-related *Escherichia coli* O157:H7 outbreaks were reported for field-grown produce (Aruscavage and others 2006). Work began in 2005 under Michele Perchonok at NASA to examine hydrogen peroxide solutions as a potential cleaning agent for produce, but experimentation on actual hydroponic produce was not conducted due to crop availability (Perchonok 2005b). In addition, microorganisms have exhibited rather robust behavior in space, suggesting that disinfection procedures on Earth may not be as effective in space (Horneck and others 2010). A proven sanitation method for the space produce is desired to minimize the risk to the crew.

The other consideration for safety is the cooking process. Some food processing is proposed to convert bulk ingredients into menu

Table 1–Microbiological testing for flight food production.

Area/item	Microorganism tolerances	
Food product	**Factor**	**Limits**
Nonthermostabilized*	Total aerobic count	20000 CFU**/g for any single sample (or if any 2 of 5 samples from a lot exceed 10000 CFU/g)
	Coliform	100 CFU/g for any single sample (or if any 2 of 5 samples from a lot exceed10 CFU/g)
	Coagulase-positive staphylococci	100 CFU/g for any single sample (or if any 2 of 5 samples from a lot exceed 10 CFU/g)
	Salmonella	0 CFU/g for any single sample
	Yeasts and molds	1000 CFU/g for any single sample (or if any 2 of 5 samples from a lot exceed 100 CFU/g or if any 2 of 5 samples from a lot exceed 10 CFU/g *Aspergillus flavus*)
Commercially sterile products (thermostabilized and irradiated)	No sample submitted for microbiological analysis	100% of packages pass package integrity inspection

*Food samples that are considered “finished” products and that require no additional.
Repackaging is tested only for total aerobic counts.
** CFU is the abbreviation for colony-forming units.

items, such as soybeans into tofu and wheat into wheat flour for bread production. Dry beans contain antiphysiological factors, such as trypsin inhibitors and hemagglutinins, unless properly deactivated (Fernández and others 1982). During ingredient processing and subsequent preparation of meals during long-duration exploratory missions, it will be necessary to reach a certain temperature-time combination to ensure safety and certain functionality. Past proposals assumed that the lunar habitat will maintain an atmospheric pressure of 55 kPa. Heat and mass transfer are affected by partial gravity and reduced atmospheric pressure. At that pressure, the boiling temperature for water is 82.8 °C. Understanding the physical changes in the environment and the impact to food preparation and processing is critical to estimate the microbial load throughout the cook, quantify the risk of foodborne illness, and reduce the risk to acceptable levels. A viable microbial risk could delay a long lunar mission even if all other elements of the mission were ready. Mission loss or major impact to postmission crew health would likely occur if this risk is not quantified and reduced.

Gap 4: Vitamin delivery

Without adequate nutrition, human performance and sustainment are endangered. Adequate nutrition has 2 components—required nutrients and supplied energy in the form of calories. Distinct health issues stem from inadequate calories and from inadequate micronutrient intake; for example, vitamin C deficiency leads to scurvy, and a deficiency in niacin may result in pellagra. It is important that the crewmembers are provided with the required level of nutrition throughout their missions to prevent disease. Table 2 summarizes the nutritional requirements as stated in the NASA Constellation Program (C×P) document 70024, "Human-Systems Integration Requirements," section 3.5.1.3.1 (not publicly available).

The ability of the food system to meet the nutritional requirements can be determined only when the nutritional profile of the entire space food system is known for the time at which the food is consumed. Historically, only limited measurement of the nutritional content of the flight food items has been conducted. Macronutrients and some minerals are determined analytically at the JSC Water and Food Analytical Laboratory. Other nutrients, such as vitamins, are systematically calculated with a computerized nutrient database developed by the USDA and the food industry.

Whereas establishing the requirements is a relatively straightforward baseline activity, ensuring nutrient delivery is never an easy task in the space program. Crewmembers during Apollo missions often experienced reduced appetite, possibly due to a combination of effects such as fluid shifts, pressure changes, nausea, and workload.. Smith and others (1975) noted that throughout the Mercury, Gemini, and Apollo missions, crewmembers lost weight, with few exceptions. Consistently, food intake during these missions was below quantities necessary to maintain body weight. Although the recommended energy intake from the Food and Nutrition Board, Inst. of Medicine, Natl. Academies, is about 12000 kJ/d, the mean energy intake during these missions was only 7866 ± 1736 kcal/d (Rambaut and others 1975). Rambaut and others (1975) also stated that Apollo nutrition provided only marginal amounts of nicotinate, pantothenate, thiamine, and folic acid. The occurrence of arrhythmias in Apollo 15 astronauts was attributed to a potassium deficiency due to inadequate nutrition in the space food system (Smith and others 1975). The potassium deficiency in this short-term mission was mitigated in later missions through potassium supplementation. The experience highlighted how an unexpected deficiency of one or more nutrients in a long-term space mission may significantly affect mission success.

The food stabilization processing done by NASA can reduce the quality of the food, including nutritional content and acceptability (Feliciotti and Esselen 1957; Kirk and others 1977; Lathrop and Leung 1980; Evans and others 1981; Kamman and others 1981). If the food loses nutrients through processing or storage, then the crewmember will not have adequate nutritional intake despite the quantity of food ingested. Available data on the vitamin content of certain processed foods at various temperatures over 2 y of storage demonstrate the potential for significant vitamin loss (Cameron and others 1955; Lund 1975; Kim and others 2000; Pachapurkar and Bell 2005). Cameron and others (1955) compiled data on the loss of ascorbic acid, riboflavin, and thiamine over 2 y in several canned fruits and vegetables, showing vitamin losses as great as 58% in some canned products held at 26.7 °C, while the same products held at 10 °C only showed maximum losses of 38%.

Table 2–Nutrition requirements for long-duration missions.

Nutrients	Daily dietary intake
Protein	• 0.8 g/kg *and* • ≤35% of the total daily energy intake *and* • 2 of 3 of the amount in the form of animal protein and 1 of 3 in the form of vegetable protein
Carbohydrate	50% to 55% of the total daily energy intake
Fat	25% to 35% of the total daily energy intake
Ω-6 fatty acids	14 g
Ω-3 fatty acids	1.1 to 1.6 g
Saturated fat	<7% of total calories
Trans fatty acids	<1% of total calories
Cholesterol	<300 mg/d
Fiber	10 to 14 g/4187 kJ
Fluid	• 1 to 1.5 mL/4187 kJ *and* • ≥2000 mL
Vitamin A	700 to 900 μg
Vitamin D	25 μg
Vitamin K	Women: 90 μg Men: 120 μg
Vitamin E	15 mg
Vitamin C	90 mg
Vitamin B12	2.4 μg
Vitamin B6	1.7 mg
Thiamin	Women: 1.1 mg Men: 1.2 mg
Riboflavin	1.3 mg
Folate	400 μg
Niacin	16 mg niacin equivalent
Biotin	30 μg
Pantothenic acid	30 mg
Calcium	1200 to 2000 mg
Phosphorus	• 700 mg *and* · ≤1.5 × calcium intake
Magnesium	• Women: 320 mg Men: 420 mg *and* • ≤350 mg from supplements only
Sodium	1500 to 2300 mg
Potassium	4.7 g
Iron	8 to 10 mg
Copper	0.5 to 9 mg
Manganese	Women: 1.8 mg Men: 2.3 mg
Fluoride	Women: 3 mg Men: 4 mg
Zinc	11 mg
Selenium	55 to 400 μg
Iodine	150 μg
Chromium	35 μg

Zwart and others (2009) studied vitamin degradation during storage, noting significant decreases in folic acid, thiamin, vitamin A, vitamin C, and vitamin K in various space food products. Though the study ran 880 d, significant differences in intact vitamin concentrations were noted after 596 d—about 1.5 y—in tortillas, salmon, and broccoli au gratin. The multivitamin tablet also underwent chemical degradation evidenced by decreases of 10% to 35% in riboflavin, vitamin A, and vitamin C by the end of the study. Space radiation did not affect the nutrient level of any of the foods.

Cooper presented initial results on space food nutrition sustainability in the 2009 Human Research Program Annual Report on the Effect of Processing and Subsequent Storage on Nutrition (2010). The foods in this study were processed according to current space readiness protocol and then stored at 22 °C for up to 5 y. At given time intervals after processing (namely, 1 mo, 1 y, 3 y, and 5 y), the foods were analyzed for the current concentrations of 24 vitamins and minerals. Preliminary, conclusions of the study were that the thermal stabilization of the foods induced degradation of vitamins A and C, thiamin, and folic acid, and subsequent oxidation drove further vitamin degradation in storage. Vitamin A continued to diminish in the package for most products during the 1st y of storage. Likewise, most folic acid and thiamin levels decreased, and vitamin C levels in all products declined from original levels by 37% to 100%. Therefore, nutritional loss at 3 to 5 y is predicted to be significant and would likely result in inadequate nutrition in the food system.

Supplying adequate nutrients over a 5-y span will necessitate additional advancement of the food system such that nutrient density, stability, and bioavailability are adequate to meet crew and mission needs. For long-duration missions, the risk of inadequate nutrition stems from intake as well as the nutritional quality of the food eaten. The prepackaged food must maintain sufficient nutrient density to supply the necessary micronutrients for 5 y. Any prepositioning of the food or delay in the consumption of the food will potentially decrease the nutritional content of the food. In addition, the packaging will have to maintain its physical and chemical barrier properties to protect the food. Encapsulated vitamin fortification or new methods of vitamin stabilization may be required to achieve nutrient-rich foods with limited degradation potential. Additional consideration will have to be given to the bioavailability of nutrients provided through the provisions to verify the adequacy of the nutrient concentrations in the proposed food system.

The use of bulk ingredients and fresh fruits and vegetables at an extraterrestrial base camp can provide the crew with a variety of fresh foods and associated nutrients. These fresh foods should provide at least some of the vitamins that may be lost over time in the processed foods, enhancing the nutritional intake of the crew and their subsequent health, and thereby reducing the risk of inadequate diet. However, any failure in the growth, processing, and preparation of the foods could increase the risk of loss of nutrition. The overall risk of this type of food system has not been quantified. Consequently, complete dependence on the fresh food supply for adequate nutrition is not favored.

Gap 5: Optimized food packaging for space

During the development of an extraterrestrial food system, mission resources, including mass, volume, power, crew time, and waste disposal capacity, must be considered. Misuse of these resources could limit mission success. Consistently, the balance of resources with other necessary mission factors—food quality or crew hygiene—is at the forefront of planning and design. The conundrum of long exploratory missions is that these missions are both resource constrained and of long duration, requiring strict adherence to nutritional guidelines. Even though food and resource utilization may be at odds, both are vital to mission success.

Food packaging is a major contributor to mass, volume, and waste allocations for NASA missions. Yet, packaging is integral to maintaining the safety, nutritional adequacy, and acceptability of food, as it protects the food from foreign material, microorganisms, oxygen, light, moisture, and other modes of degradation. The higher the barrier provided by the packaging, the more the packaging can protect the food from oxygen and water ingress from the outside environment. Oxygen ingress can result in oxidation of the food and loss of quality or nutrition. Water ingress can result in quality changes such as difficulty in rehydrating the freeze-dried foods and in increased microbial activity.

One major drawback of the current packaging system with regard to mass and volume is that 2 different packages are actually being used jointly to pack a number of the products. The primary packaging material for the freeze-dried foods and natural form foods is not adequate as an oxygen and moisture barrier to allow an 18-mo shelf life (required for the ISS flight food system). However, the packaging material does allow tray molding for freeze-dried foods and visual inspection of the natural form foods. To provide the necessary protection and achieve an 18-mo shelf life, those foods are then overwrapped with a second foil-containing package that has more restrictive barrier properties. Table 3 presents the oxygen and water vapor transmission rates of the current NASA food packaging materials as provided by Mocon, Inc. (Minneapolis, Minn., U.S.A.).

In 2009, AFT researchers tackled the practice of using a secondary overwrap pouch to further protect freeze-dried and natural form food items (Oziomek and Catauro 2009, 2010). Instead of individual overwraps, a single, large overwrap was proposed to contain and preserve one container equivalent of food items within a high-barrier, flexible material. A switch to bulk overwrap could save the ISS program nearly 50 kg/y in upmass. It also reduces volume nearly 20% and reduces the time required to package the food by about 50%.

The aforementioned bulk overwrap is one way to reduce packaging waste in space. Another way could be the use of an alternative packaging material. Hence, another packaging study is being performed to evaluate the effectiveness of clear, aluminum oxide-coated plastic laminate material against the current primary packaging material, a clear, quad-plastic laminate, and a material similar to the current overwrap (aluminum foil, plastic laminate) (Catauro 2009). Two food products (dry oat cereal and peanuts)

Table 3–Oxygen and water vapor permeability of NASA food packaging materials.

	Oxygen permeability at 73.4 °F, 100% RH (cc/100in^{2}/d) (ASTM F-1927)	**Water vapor permeability at 100 °F, 100% RH (g/100in^{2}/d) (ASTM F-1249)**
Overwrap	0.0065	<0.0003
Thermostabilized and irradiated pouch	<0.0003	0.0004
Rehydratable lid and natural form pouch	5.405	0.352
Rehydratable bottom (heat formed)	0.053	0.1784

RH = relative humidity.

and one ingredient (cottonseed oil), which are extremely susceptible to the effects of oxygen and moisture, have been packaged in each material. The packaged products have been stored at distinct relative humidity levels (25%, 50%, 75%) to simulate conditions that might be encountered on the vehicle. As the study approaches 24 m, results indicate that the clear, quad-plastic laminate material does not provide a sufficient barrier and would require an overwrap system, while each of the plastic laminates with aluminum materials appears to maintain adequate barriers on its own. Successful performance of the clear, aluminum oxide-coated plastic laminate material might allow optimization of the current ISS packaging system by reducing it to a single package. However, the barrier properties of this material are not adequate for a Mars mission.

The 2nd shortfall of the current space food packaging is the amount of trash generated by the system. The food system generates both wet and dry waste. Dry waste includes the dry food packaging like overwrap material. Potential wet waste includes cleaning materials and wet food packaging. Because food substances left on cleaning materials and in packaging can spoil, food system wet waste materials must be properly disposed of to limit exposure of the crew to microbial contamination. Minimization of the overall trash quantity and the associated complications is desired to limit their impact on resources.

Levri and others, in Food System Trade Study for an Early Mars Mission (2001), evaluated 5 potential menus for use during a Mars mission. During that study, it was determined that for prepackaged foods, generally 3% of the food would be left in the package if an attempt was made to eat everything. Since packaging is about 9.5% of the mass of the total food system, it would therefore be expected that, at a minimum, 12.5% of the rehydrated food system on the shuttle would become waste.

The packaging materials used for the thermostabilized, irradiated, and beverage items contain a foil layer to maintain product quality beyond the required 18-m shelf life. Although the foil layer provides the desired protection, the material is not compatible with some emerging technologies that produce high-quality, commercially sterile foods. This incompatibility will require NASA to either continue using the foil packaging and forego the new technologies or to acquire new packaging compatible with those technologies. In addition, foil packaging complicates plans to incinerate trash in the future. Incineration is postulated as a possible solution to trash accumulation at an extraterrestrial base. However, the foil layer within the food package will not incinerate completely and will leave some ash from the foil (Wydeven and Golub 1991). Finally, as previously mentioned, metalized films generally do not provide the transparency necessary for the human inspection of products after packaging.

The identification of a capable packaging material lends itself to other packaging reductions. As a part of the AFT study Total Systems Approach, a gusseted pouch design was compared to the current thermoformed rehydratable package (Oziomek 2010). The gusseted pouch design yielded very good results by making the rehydratable packages easier to produce, while minimizing mass, volume, and waste. It reduced the equipment required in the production process from 3 pieces of packaging equipment to one. It reduced the packaging from 2 pouches to one and decreased the total amount of packaging mass by about 66%.

In summary, NASA is seeking a low-mass, high-barrier packaging material that is compatible with incineration and processing procedures to optimize the resource utilization in future missions. The ideal material would provide extended protection against oxygen and moisture ingress at ambient conditions but still have the flexibility and sealing capability to fit with large and small pouch production.

Conclusion

Without an adequate food system, it is possible that space crewmembers' health and performance would be compromised. It is clear that in developing adequate NASA food systems for future missions, a balance must be maintained between use of resources (such as power, mass, and crew time), and the safety, nutrition, and acceptability of the food system. In short, the food must provide the nutrients to sustain crew health and performance, must be acceptable throughout the course of the mission, must be safe even after cooking and processing, and must be formulated and packaged in such a way that the mass and volume are not restrictive to mission viability. It is this delicate balance that frames the food system needs for our next mission and charts the work for NASA Advanced Food Technology.

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