Evidence Report:

Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System

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I. PRD Risk Title: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System (AFT)

Description: Performance is critical for mission success. If the food system is not safe, nutritious, and acceptable, then crew health and performance and the overall mission may be adversely affected. Furthermore, careful attention must be paid to the resources allocated to sustain an adequate food system in order to avoid unduly depriving other systems of essential resources.

II. Executive Summary of Evidence for Risk

NASA is preparing for long duration manned missions beyond low-Earth orbit that will be challenged with long-term exposure to the space environment and very limited resupply. Productive, reliable, and safe human space exploration depends on an adequate food system to provide the crew with safe, nutritious, and acceptable foods for up to 5 years with minimal impact to mission resources.

The food system is the sole source of nutrition to the crew. A significant loss in nutrition, either through loss of nutrients in the food during processing and storage or inadequate food intake due to low acceptability, variety, or usability, may significantly compromise crew health and performance. Recent research has indicated that the current food system will not meet the nutrition, acceptability, or resource requirements of a long duration mission beyond low-Earth orbit. The current shelf life is only 1.5 years and several key nutrients degrade in many foods prior to the targeted 5 year shelf life. Additionally mass, volume, waste, and disposal issues presented by the current packaging must be addressed.

Alternative provisioning strategies, such as inclusion of a bioregenerative system, reduce initial resource use and add fresh foods that may benefit crew health but also increase infrastructure and crew time requirements. A bioregenerative system also introduces the possibility of food borne illness and food scarcity, which may compromise mission success. Current preflight procedures and the use of prepackaged provisions have ensured food safety so far, but there is currently no technology to enable efficient testing of a bioregenerative system in a resource constrained environment.

Current research is investigating strategies to increase the shelf life of a prepackaged food system, decrease use of vehicle resources, and determine the most effective way to balance resource use with provisioning of an adequate food system. The paramount importance of the food system in a long-duration manned exploration mission must not be underestimated. The food system provides not only the nutrients needed for the survival of the crew, but also enhances their psychological well being by being a familiar element in an unfamiliar and hostile environment. This document presents the evidence for the Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System and the gaps that remain.

III. Introduction

The primary goal of the Advanced Food Technology Project (AFT) is to develop requirements and technologies that will enable NASA to provide an adequate food system characterized by the provision of safe, nutritious, and acceptable food to the crew. The requirements of the food system must balance with available vehicle resources such as mass, volume, waste, and crew time during exploration missions. AFT is a project within the Space Human Factors and Habitability (SHFH) Element with the Human Research Program (HRP) objective of developing capabilities and technologies in support of human space exploration, focusing on mitigating the highest risks to crew health and performance. Further details on HRP can be found at http://humanresearch.jsc.nasa.gov/about.asp.

The space program food system must advance in preservation and packaging technologies in order for mission lengths to increase. With the exception of Skylab, there has not been a refrigerator or freezer on board dedicated for food storage. Therefore, the food must be shelf-stable. This requires inactivation of the microorganisms in the food during ground processing before flight. While processing the packaged foods to commercial sterility provides a safe food system, this level of processing can reduce the nutrition and acceptability of the food.

The different forms in which food has been 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. Food items are placed into cans or pouches and then heat processed with steam-overpressure or water-overpressure to remove excess air/oxygen for specified times and temperatures to render the food commercially sterile.

2. Irradiated - Irradiation is not typically used to process foods to commercial sterility. However, NASA has special dispensation from the Food and Drug Administration (FDA) to prepare nine irradiated meat items to commercial sterility (FDA, 2011b). Irradiation involves the use of gamma rays, x rays, or electrons, and uses energy levels that assure negative induction of radioactivity in the irradiated product. It controls naturally occurring processes such as ripening or senescence of raw fruits and vegetables, and is effective for inactivation of spoilage and pathogenic microorganisms.

3. Rehydratable - A number of technologies are available that allow for the drying of foods.
Examples of these technologies are drying with heat, osmotic drying, and freeze drying. These processes reduce the water activity of foods, which results in the inability of microorganisms to thrive.

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). These foods rely on reduced water activity in order to prevent microbial activity.

5. Extended shelf-life bread products - Items such as scones, waffles, and dinner rolls can be
formulated and packaged to give them a shelf life up to 18 months.

6. Fresh Food - Foods such as fresh fruit, vegetables, and tortillas that have a short shelf life

are provided on a limited basis, more for psychological support than as a part of meeting dietary requirements.

7. Beverages - The beverages currently used on the International Space Station (ISS) are either freeze dried beverage mixes (such as coffee or tea) or flavored drinks (such as lemonade or orange drink). The drink mixes are prepared and vacuum sealed inside a beverage pouch. In the case of coffee or tea, sugar or powdered cream can be added. Empty beverage pouches are also provided for drinking water.

A prepackaged food system has been used for each NASA space program, including the current 6-month ISS missions. This food system, with some fresh food supplementation, has been enabled by periodic resupply opportunities that are possible in low Earth orbit. ISS crewmembers have subsisted on this food system, but a nutritional issue is indicated by post-flight vitamin analysis of crew blood, plasma, and urine samples (Smith *et al.*, 2005). The probability that the current food system will be inadequate increases with mission length and distance from Earth, especially without the benefit of fresher foods and produce from resupply. Missions to an asteroid or Mars may be 1-3 years in length and will require technologies to be developed so that the crew is more self-sufficient and less dependent on resupply missions. The complete supply of food will need to be transported for the entire mission duration, which will heavily constrain available upmass.

The high mass and volume of a prepackaged food system may require the food to be shipped separately from the crew. Pre-positioned food may be 3-5 years old at the time of consumption. Currently, NASA's prepackaged foods have a stated shelf life of 1.5 years, far short of the 5 years required for Mars missions. Shelf-life criteria include safety, nutrition, and acceptability, any of which can be the limiting factor. In addition, once out of low Earth orbit space radiation increases, the nutritional content and acceptability of the foods may be reduced. In order to provide an adequate food system, all possible provisioning strategies must be considered, including incorporation of a bioregenerative system and packaging scenarios that protect the food and reduce mass, volume, and waste. The research that AFT conducts focuses on gaps in the ability of the space program to provide an adequate food system for long duration missions. The following are gaps for this risk identified in the HRP Integrated Research Plan:

AFT1: How can the food system deliver the required level of nutrition throughout the mission?

AFT2: How can the nutrition and acceptability of the food system be maintained throughout the mission?

AFT3: How can the acceptability of the food system be maintained throughout the mission?

AFT4: What technologies can be developed that will efficiently balance appropriate vehicle resources such as mass, volume, and crewtime during exploration missions with the safety, nutrition, and acceptability requirements?

This report defines food safety, nutrition, and acceptability criteria, and addresses concerns with vehicle resources. Evidence is presented for the gaps in current food system scenarios that create the Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System. The type of evidence provided is labeled according to HRP's Categories of Evidence:

Evidence Category I: At least one randomized, controlled trial.

Evidence Category II: At least one controlled study without randomization, including cohort, case-control, or subject operating as own control.

Evidence Category III: Non-experimental observations or comparative, correlation, and case or case-series studies.

Evidence Category IV: Expert committee reports or opinions of respected authorities based on clinical experiences, bench research, or "first principles."

IV. Safety

A. Space Food Safety Background

Food safety is defined by the absence of a health risk due to physical, chemical and microbiological contamination. The food system must be designed to ensure that the initial provisions are shelf stable, safe from contamination, and are packaged to remain safe for the mission duration in a range of environmental conditions. Microbiological contamination of food can negatively affect crew health and possibly compromise crew survival.

Microbiological safety is currently ensured through processing with the Hazard Analysis and Critical Control Points (HACCP) system, and Good Manufacturing Practices (GMPs). HACCP is a systematic and preventive approach to food safety that was developed by NASA, the United States Army Laboratory, and the Pillsbury Company in the 1960's. GMPs include employee qualifications and training, sanitation, recordkeeping, process validation, and facilities and equipment maintenance and verification (FDA, 2011a).

The use of thermostabilization, irradiation, and drying (rehydratables) provide shelf stable foods and prevent a health risk from microbial contamination. After processing, the thermostabilized and irradiated food items are tested for pouch integrity and for swelling to determine whether adequate heat was applied to the food to produce commercial sterility (Evidence Category IV). Safe rehydratable foods depend on high quality ingredients and clean surfaces with minimal microorganism contamination at the beginning of the process. However, there still can be viable microorganisms in the food. Therefore, rehydratable foods and natural form foods are tested for viable microorganisms before flight. Food microbiological safety is monitored by the Johnson Space Center's (JSC) Microbiology Laboratory to ensure that preparation and packaging procedures result in products that conform to established microbial standards for flight foods. Table 1 lists the items tested and the associated limits (NASA, 2011).

Table 1. Microbiological Testing for Flight Food Production

Area/Item	**Microorganism Tolerances**	
Food Production Area	Samples Collected*	Limits

Surfaces	3 surfaces sampled per day	3 CFU/cm^2 (Total aerobic count)
Packaging Film	Before use	
Food Processing Equipment	2 pieces sampled per day	
Air	1 sample of 320 liters	113 CFU/320 liters (Total aerobic count)
Food Product	**Factor**	**Limits**
Non-thermostabilized**	Total aerobic count	20,000 CFU/g for any single sample (or if any two samples from a lot exceed 10,000 CFU/g)
	Coliform	100 CFU/g for any single sample (or if any two samples from a lot exceed10 CFU/g)
	Coagulase positive Staphylococci	100 CFU/g for any single sample (or if any two samples from a lot exceed10 CFU/g)
	Salmonella	0 CFU/g for any single sample
	Yeasts and molds	1000 CFU/g for any single sample (or if any two samples from a lot exceed 100 CFU/g or if any two samples from a lot exceed 10 CFU/g Aspergillis flavus)
Commercially Sterile Products (thermostabilized and irradiated)	No sample submitted for microbiological analysis	100% inspection for package integrity

*Samples collected only on days that food facility is in operation
** Food samples that are considered "finished" product that require no additional repackaging are only tested for total aerobic counts

B. Evidence for Inadequate Food Safety During Spaceflight and from Ground-based Testing

Incidences of gastrointestinal distress have been recorded by crewmembers during missions, but none of these cases have been attributed to a food borne illness (Crucian *et al.*, 2009; Hawkins and Zieglschmid, 1975). Instances of spoiled food packages on orbit have been recorded once a year on average and have not been documented to result in food borne illness (Evidence Category III). The crew is trained to identify bloated packages or spoiled foods and they are instructed to discard them. Passage of this inspection does not ensure that the food is safe.

There have been instances where rehydratable foods did not pass microbiological specifications due to contamination from mold, yeast, or bacterial pathogens detected during preflight testing. Dr. C. Mark Ott from the JSC Microbiology Laboratory reported that 51 out of 7221 products failed to meet the microbiological specifications (Table 1) between 2007 to 2011 and hence were not approved for Shuttle and ISS flights. Though only a small number of the samples failed, even one contaminated food lot can result in crew illness and possibly death during a mission (Evidence Category I). The use of HACCP, good manufacturing practices, standard operating procedures, and finished product testing of processed and prepackaged foods should prevent food borne illness events during space missions, but the rare occurrence of spoiled food on ISS suggests that there is always a small risk of food borne illness during flight.

C. Inadequate Food Safety in Context of Exploration Missions

Safety issues may become more important for prepackaged foods during long-duration exploration missions. If prepackaged foods are prepositioned on the Mars surface, then the food packages may be compromised prior to the crews' arrival. The possibility of food borne illness will also increase with the implementation of a bioregenerative food system on an extraterrestrial surface. Fresh food, bulk ingredients, processing and meal preparation will provide the crew with more variety and the potential for increased quality and nutrition, but food safety and availability will no longer be ensured as it is through ground-based processing, packaging, and safety testing (Evidence Category IV). It is necessary to reach a certain temperature/time combination to ensure safety. Heat and mass transfer are affected by partial gravity and reduced atmospheric pressure. Consideration must be given to the changes in environment and the processing equipment and procedures that will be required to ensure safe food processing on an extraterrestrial surface.

If fresh fruits and vegetables are consumed without a heating (cooking) step, there is potential for microbial contamination, food borne illness, and death, as demonstrated by the commercial produce-related *Escherichia coli* outbreaks in recent years (Aruscavage *et al.*, 2006; Bielaszewska *et al.*, 2011) (Evidence Category III). The possibility of produce contamination followed by illness in a closed environment with carefully controlled procedures has not yet been evaluated. It is essential to identify sources of contamination during food production, processing, and preparation in a controlled closed loop system, and determine safety procedures and testing methods to prevent possible food borne illness. Mission loss or major impact to crew health would likely occur if this risk is not quantified and reduced.

Recent evidence indicates that consumption of probiotic bacteria promotes human health (Azcarate-Peril *et al.*, 2011; Clancy *et al.*, 2006; Leyer *et al.*, 2009; Ohland and Macnaughton, 2010) (Evidence Category I). Investigations into the effects of probiotic strains on human immunity during spaceflight might lead to incorporation of some strains into the space food system. If probiotics are incorporated, protocols will be required to ensure pure bacteria cultures are safely added and meet shelf life requirements (Cooper *et al.*, 2011b).

V. Nutrition

A. Space Food Nutrition Background

Adequate nutrition has two components – 1) necessary nutrients and 2) caloric energy (protein, carbohydrate, and fat). It is possible to consume sufficient calories without adequate nutritional intake, resulting in deficiency diseases that diminish health, impact performance and in extreme cases lead to loss of life. Therefore, it is essential that the crewmembers are provided with the required level of each nutrient throughout their missions. Table 2 summarizes the nutritional requirements (NASA, 2011).

Table 2. Nutrition Composition Breakdown

Nutrients	**Daily Dietary Intake**
Protein	0.8 g/kg And ≤ 35% of the total daily energy intake And 2/3 of the amount in the form of animal protein and 1/3 in the form of vegetable protein
Carbohydrate	50-55% of the total daily energy intake
Fat	25-35% of the total daily energy intake
Ω-6 Fatty Acids	14 g
Ω-3 Fatty Acids	1.1 - 1.6 g
Saturated fat	<7% of total calories
Trans fatty acids	<1% of total calories
Cholesterol	< 300 mg/day
Fiber	10-14 grams/4187 kJ
Fluid	≥ 2000 mL
Vitamin A	700-900 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 µmol Men: 1.2 µmol
Riboflavin	1.3 mg
Folate	400 µg
Niacin	16 mg NE
Biotin	30 µg
Pantothenic Acid	30 mg
Calcium	1200 - 2000 mg
Phosphorus	700 mg And ≤ 1.5 x calcium intake
Magnesium	Women: 320 mg Men: 420 mg And ≤ 350 mg from supplements only
Sodium	1500 - 2300 mg
Potassium	4.7 g
Iron	8 - 10 mg
Copper	0.5 - 9 mg

Nutrients	Daily Dietary Intake
Manganese	Women: 1.8 mg Men: 2.3 mg
Fluoride	Women: 3 mg Men: 4 mg
Zinc	11 mg
Selenium	55 - 400 µg
Iodine	150 µg
Chromium	35 µg

B. Evidence of Inadequate Nutritional Content of Food and Intake During Spaceflight

The importance of nutrition in the adaptation of astronauts to weightlessness has been recognized since the Gemini program (Rambaut *et al.*, 1975). Nutritional data from past missions indicate the health risk of inadequate caloric and nutrient intake, especially as mission length increases. Crewmembers often experienced reduced appetite, possibly due to a combination of effects such as fluid shifts, pressure changes, nausea, and work load (Rambaut, Smith *et al*., 1975; Smith, Zwart *et al.*, 2005). Throughout Mercury, Gemini, and the Apollo missions, weight losses were noticed with few exceptions (Smith *et al.*, 1975). Caloric intake during these missions was consistently below quantities necessary to maintain body weight. Although the National Academy of Sciences National Research Council Recommended Daily Dietary Allowance (RDA) is 2,870 kcal/day, the mean energy intake during these missions was only 1,880 +/- 415 kcal/day. The inadequacy of specific nutrients in the Apollo diet compounded the issues from insufficient caloric intake. Apollo food provided only marginal amounts of nicotinate, pantothenate, thiamine, and folic acid (Rambaut, Smith *et al.*, 1975). The occurrence of arrhythmias in Apollo 15 astronauts was attributed to a potassium deficiency in the space food system (Smith, Heidelbaugh *et al.*, 1975). The potassium deficiency in this short-term mission was mitigated in later missions through potassium supplementation. (Evidence Category III)

Longer term effects of space travel on nutritional profiles of astronauts have been documented through physiological changes during the 3 to 6-month long Mir and ISS Expeditions (Smith *et al.*, 1999; Smith, Zwart *et al.*, 2005). Body mass and nutrient contents in urine, blood, plasma, and serum were measured post-flight in some ISS crew members and statistically compared to preflight baselines. Of particular concern were the decreased levels of several vitamins and minerals in the urine, blood, plasma, and serum. For example, Vitamin D levels, antioxidant capacity, γ-tocopherol levels, and folate levels were all significantly lower post-flight, creating malnutrition concerns during ISS Expeditions. The reduced caloric intake on ISS Expeditions (around 80% of recommended intake during space flight), as documented in 2005, led to an average weight decrease of 5%, potentially explaining some of the measured nutrient decreases (Smith, Zwart *et al.*, 2005). Body mass losses in some ISS and Mir crewmembers have been measured as high as 10-15% (Lane *et al.*, 2007; Smith, Wastney *et al.*, 1999; Smith *et al.*, 2009). (Evidence Category II)

The recorded body mass losses are particularly concerning considering that a study on hunger strikers estimated that body mass losses around 30% resulted in death (Leiter and Marliss, 1982). It has been suggested that the inadequate nutritional profiles of astronauts in most space missions confound all other medical data interpretation (Smith, Zwart *et al.*, 2009). The Skylab crews, who were required to eat enough to meet their caloric needs, preserved body mass (Thornton and Ord, 1975). More information on inadequate nutrition can be found in the Evidence Report for the Risk Factor of Inadequate Nutrition (Smith, Zwart *et al.*, 2009).

C. Inadequate Nutritional Content of Food and Intake in Context of Exploration Missions

Crews on long duration missions may only have access to foods that have been stored for 5 years by the end of their mission. Preliminary results indicate that current space food technology is not adequate to maintain the nutritional content of the food for 5 years. Inadequate delivery of a single nutrient or insufficient caloric intake may result in reduced cognitive function and physical capability (Friedl and Hoyt, 1997), limiting crew ability to complete mission critical tasks. Extended periods of malnutrition could result in crew illness and possibly death. Inadequate nutritional content of the food could delay a long duration mission beyond low-Earth orbit even if all other mission elements are ready.

D. Evidence of Inadequate Nutritional Content of Food and Intake for Exploration Missions – Ground and Spaceflight Research

Food loses nutrients through processing and during storage, and may not have the expected nutritional content when consumed. Changes in vitamin content of certain processed foods stored at various temperatures for 2 years demonstrates the potential for significant degradation (Kamman *et al.*, 1981; Kim *et al.*, 2000; Kramer, 1974; Lund, 1975; Pachapurkar and Bell, 2005). Canned fruits and vegetables stored for 2 years at 80°C showed losses in ascorbic acid, riboflavin, and thiamin as high as 58%, while the same products held at 50°F only showed maximum losses of 38% (Cameron *et al.*, 1955) (Evidence Category I). Currently, the commercial food industry does not require foods with shelf lives of more than 2 years (Evidence Category III), so little research exists past this point.

Nutrient changes during processing and throughout the shelf life of processed foods include isomerization of vitamins or vitamin precursors, changes in bioavailability of amino acids and vitamins as the food structure is broken down, and nutrient degradation, including oxidation of several vitamins and amino acids (Chen *et al.*, 1995; Dewanto *et al.*, 2002; Graziani *et al.*, 2003; Gregory, 1996; Rock *et al.*, 1998; Seybold *et al.*, 2004). Bioavailability of vitamins may be more important than overall quantity in a food, as other components in the diet and the form of the vitamin may influence absorption and function. Bioavailability of vitamins in individual foods may vary, making the knowledge of nutrient availability as critical as overall quantity (Gregory, 1996) (Evidence Category I).

The ability of the food to meet the nutritional requirements and its potential for use during long duration missions can only be determined when the nutritional profile of the entire space food system is known at the time when the food is consumed. Until recently, there was limited empirical nutritional data for flight foods. Macronutrients and some minerals were determined chemically at the JSC Water and Food Analytical Laboratory (WAFAL) but many micronutrients were only calculated with a computerized nutrient database (Genesis R&D) developed by the USDA and the food industry. The level of processing required for shelf stable food safety, followed by storage at ambient temperature can reduce the nutritional quality of the food. Additionally, environmental conditions, such as the higher radiation levels expected during planetary missions, may contribute to nutrient losses. While lower storage temperatures would increase nutritional stability, exploration vehicles will not likely have the available mass or power to provide cold storage for food (Perchonok and Bourland, 2002) (Evidence Category I and IV). In the absence of empirical nutrient data specific to the space food system it is unknown whether the processing, storage, and environmental effects are accurately reflected in the computerized nutrient database, or whether these processed foods would be nutritionally adequate if consumed after 5 years of storage.

It is critical to accurately measure the degradation rate of nutrients in each flight food over the required shelf life, identify foods where degradation is a concern, and determine mitigation strategies in order to prevent deficiencies on these missions. All foods provided in the flight food system must be nutritionally stable through the end of long duration missions to prevent nutrient deficiencies associated with individual crewmember food choice. Nutrient degradation due to deep space radiation must also be determined in order to accurately resolve nutritional inadequacies.

Extensive extravehicular activities (EVA) and emergency contingency for extended crew time in pressurized suits (over 100 hours) will increase the risk of inadequate nutrition. EVAs will require no less than an additional 200 kilocalories above nominal metabolic intake, similar in nutrient composition to the rest of the diet, per EVA hour (NASA, 2011) (Evidence Category II). Currently, there is no effective delivery method for providing nutrition to the crew during extended time in a pressurized suit. This would be especially concerning over a multiple day event in which crewmembers are expected to be cognitively functioning and physically capable of performing tasks required for safe return. The insufficient nutritional delivery capabilities and lack of accurate nutrient data create one of the gaps for this risk.

AFT1: How can the food system deliver the required level of nutrition throughout the mission?

Several recent projects have analyzed the adequacy of the nutritional availability in some spaceflight foods (Cooper *et al.*, 2011a). Currently, 24 vitamins and minerals are being measured in each NASA food item one month, one year, and three years post-processing (Evidence Category I). The foods in this study are processed according to current space readiness protocol and then stored at 72°F for up to three years. Results one month after processing demonstrate that computer generated nutrient estimates are not always accurate predictions of post-processing nutrient profiles (Figure 1) (unpublished data) (Cooper, 2012a).

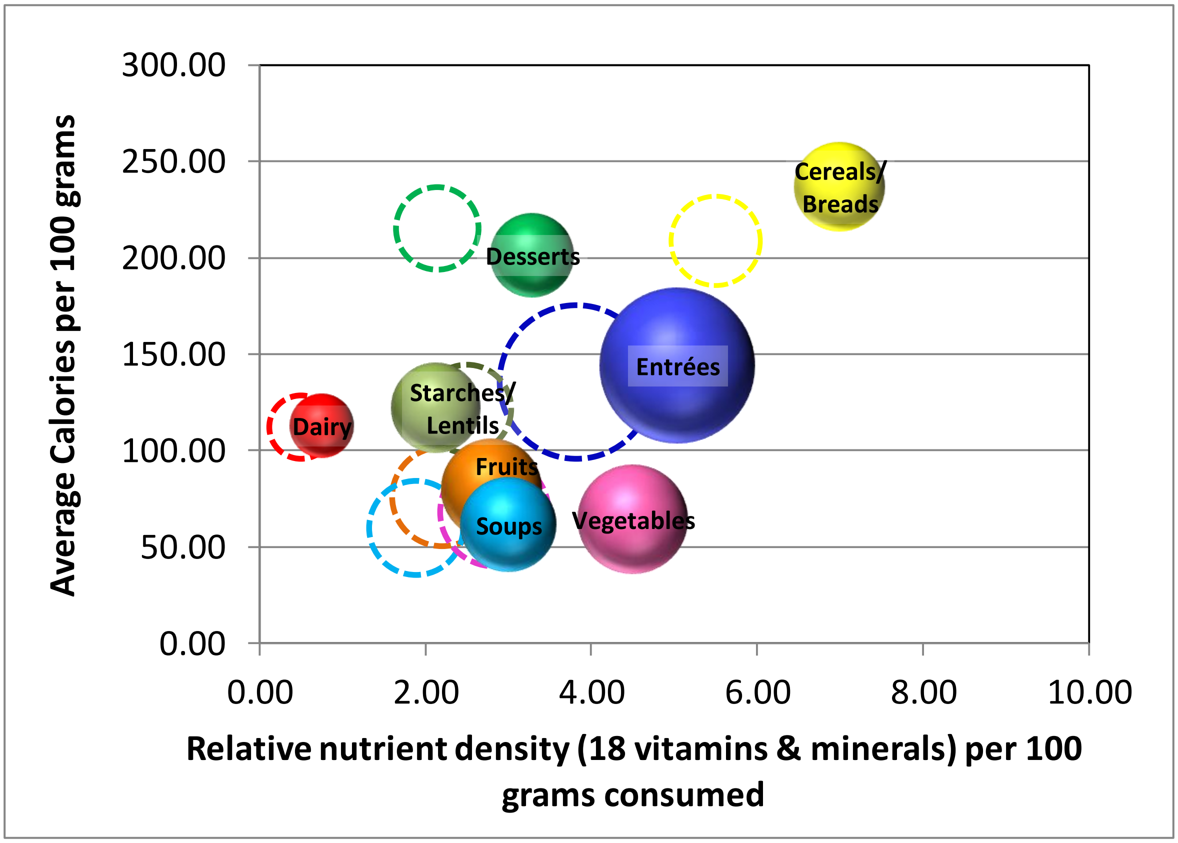

Figure 1. Analytical nutritional profile (solid circles) compared to estimated nutritional profile (dotted circles) of 87 NASA space food items. Nutritional profiles were generally underestimated by the Genesis R&D computer software.

The food subsets that have currently been tested one month post-processing indicate that empirically measured nutritional profiles are often superior to predicted profiles, likely due to the use of high quality ingredients in spaceflight foods. However, degradation of Vitamins A and C, and folic acid is significant in several products, with losses as high as 100% (Cooper, 2012a).

Specific food matrices and some forms of vitamins used for fortification seem to offer protection against losses during heat processing and subsequent oxidation during storage (Cooper, 2012a) (Evidence Category III). Vitamin A concentrations decreased significantly in food matrices susceptible to oxidation, such as split French-style green beans, but increased in other products, such as carrot coins. Vitamin A stability was attributed to oxidation protection provided in specific food matrices, coupled with vacuum packaging. The elevated Vitamin A concentrations measured in some products is likely due to increased extractability of carotenoids as the products age (Rickman *et al.*, 2007). Vitamin C is especially susceptible to oxidation, and was unstable in many food items. Vitamin C was shown to be stable in fortified products when added in a form compatible with processing, and in foods with matrices similar to those that provided Vitamin A stability.

Thiamin appears to be present and relatively stable at low levels in several foods, but most of these foods are not a good thiamin source. Bread products are a good source of thiamin even after one year of storage. Folate stability was product specific, with some fortified foods exhibiting greater stability than natural sources with similar matrices. Alternatively, riboflavin was less stable in fortified products compared to foods where it was present naturally. Riboflavin and niacin degradation did not appear to be a concern in most products after one year of storage. Other vitamins demonstrated sufficient stability across the food system and deficiency is not likely after one year as long as a variety of foods are consumed (Cooper, 2012a).

After one year of storage fortified beverage powders demonstrated superior stability in many nutrients including Vitamins A and C, thiamin, and folate. The stability of the fortified nutrients can be attributed to 1) their addition after the drying step, 2) the inhibition of chemical reactions due to the low a_w and, 3) the packaging of dried powders in high barrier foil pouches under vacuum (Cooper, 2012a).

Vitamin D is not present consistently in the space food system, even one-month post-processing. The deficit of Vitamin D, due largely to lack of exposure to sunlight, has always been mitigated with a supplement on ISS.

Currently, only a small subset of foods has been analyzed at the three year time point. For most products, nutrient stability or degradation continued in a similar pattern to what was observed after one year (Cooper, 2012a), although further nutrient degradation kinetic measurements are required to confirm a pattern. This indicates that many foods consumed three years post-processing do not provide the expected nutritional content. The promising preliminary evidence of nutrient stability of several fortified products and the indication that specific food matrices offer protection from oxidation suggest that further studies with food formulation, matrices, and process improvement may enable a prepackaged food system to provide adequate nutrients over a long duration mission.

Ground-based studies have provided the bulk of nutrient degradation data for spaceflight foods, but it is critical to understand how the space environment will impact nutrition over storage. Cost and mass constraints have limited the available food nutritional data after exposure to spaceflight. Currently, nutritional profiles have only been measured for five food items exposed to low Earth orbit (Evidence Category I). These foods received a cumulative radiation dose of 74.53 mGy over 880 days on ISS, which did not cause a significant decrease in the 30 nutrients measured. However, folic acid, thiamin, and Vitamins K and C decreased and lipid peroxidation increased over the 880 days in orbit similarly to samples stored on Earth (Zwart *et al.*, 2009), providing further evidence for the loss of nutrients from the space food system over long duration storage.

While radiation in low Earth orbit did not compromise the nutrition in this limited test sample, the effects of continual exposure to mixed types of radiation in deep space are unknown (Zwart, Kloeris *et al.*, 2009). Mitigation strategies, which may include the addition of antioxidants to the food, may help prevent the formation of free radicals that contribute to food spoilage (Gandolph *et al.*, 2007; Wilson *et al.*, 2007). In the case of a bioregenerative food system, radiation may affect the plants' ability to germinate and grow or affect resulting functionality in the absence of sufficient protection (Wilson, Perchonok *et al.*, 2007).

Further research and innovative technologies might enable shelf stable food to provide nutrition for long duration missions, but the ability to deliver this nutrition during contingency operations requiring a pressurized spacesuit in a hypobaric, microgravity environment is currently not possible. The importance of effective in-suit nutrition delivery in an emergency event, such as depressurization of the crew vehicle, becomes critical depending on the length of time.

Preliminary concept and hardware analysis addressing in-suit nutrition delivery supports the use of a liquid product capable of meeting the kinematic and dynamic viscosity range compatible with potential delivery interfaces (unpublished data, Evidence Category IV) (Catauro and Glass, 2011). A product must be identified or developed that meets nutritional, sensory, and suit waste requirements. Currently, no commercial product has been identified that meets all spaceflight requirements. In fact some options would supply toxic levels of several nutrients if enough of the product were provided to be the only source of nutrition.

Preliminary glove box tests utilizing a liquid product were unsuccessful due to challenges with food behavior in the absence of pressure and under differential pressure during entry of a spacesuit (unpublished data) (Catauro and Glass, 2011). Issues with powder solubility, trapped air leading to vapor pressure buildup, ineffective dispensing of liquid through the pressure differential created by the pressurized suit, and potential microbial concerns must be resolved. Although several mechanical designs were proposed to enable liquid to be dispensed into the suit, funding for the project was terminated due to changes in agency direction (Catauro and Glass, 2011). Further development of a dispensing system and identification or development of a nutritional, acceptable liquid product is critical to prevent malnutrition during suited contingency operations.

VI. Acceptability

A. Space Flight Acceptability Background

Food acceptability can be defined and determined in several ways. First is in terms of sensory acceptability, including appearance, flavor, texture, aroma, and serving temperature. Currently, flight foods are evaluated for sensory acceptability by a panel of 30 or more consumers. The sensory attributes of the products are rated using a 9.0-point Hedonic Scale, where 9 is the highest acceptability score (Chambers and Wolf, 1996). Food products must receive an overall score of 6.0 or higher to be included in the space food system. Similarly, prior to their mission, crewmembers evaluate the foods, and those scored 6.0 or higher are included in their personal preference containers. Second, food system variety and usability are factors in defining acceptability. A large variety of food is recommended to provide the crew choices and to avoid menu fatigue. If the food is difficult to prepare or eat, then the overall acceptability of the food is reduced (Smith, Heidelbaugh *et al.*, 1975). Finally, food acceptability can be affected by the social context and timing of meals. Food and mealtimes can play a primary role in psychological-social benefits by promoting unity and reducing the stress and boredom of prolonged space missions.

B. Evidence of Inadequate Acceptability During Spaceflight

The acceptability of the food system has been linked to caloric intake and associated nutritional benefits. If the food is not acceptable to the crew, then the crew will not eat an adequate amount and will be compromised nutritionally. Large improvements and advances in the space food system were achieved during the Apollo food program with the addition of thermostabilized and irradiated foods (Perchonok and Bourland, 2002). Nevertheless, the majority of Apollo astronauts did not consume sufficient nutrients and experienced loss of body weight, fluids, and electrolytes with few exceptions (Smith, Heidelbaugh *et al.*, 1975).

A historical database reviewing the Apollo experience was generated based on 14 surviving Apollo astronauts' responses to 285 questions (Scheuring *et al.*, 2007). The identification of medical issues during Apollo 7 through 17 provided evidence to modify medical requirements for future exploration missions (Scheuring, Jones *et al.*, 2007). The astronauts answered 28 questions in 11 categories relating to food and nutrition, providing 76 responses and 8 recommendations. It was reported that reduced food consumption may be partially attributed to a combination of physiological effects such as fluid shifts, pressure changes, nausea, issues preparing food, issues with the water system, and work load, but acceptability and familiarity of the food were also critical to consumption (Rambaut, Smith *et al.*, 1975; Scheuring, Jones *et al.*, 2007). Changes in the sensory perception of the food were noted between ground-based taste tests and Apollo and Shuttle missions, making it important to understand the effect of pressure and fluid shifts on sensory perception. Apollo crewmembers have also stated that the cabin temperature was cold and having hot water for hot drinks was important, and provided a psychological boost (for example, having coffee in the morning) (Scheuring, Jones *et al.*, 2007). (Evidence Category III)

Consistently during ISS crew debriefs, the crews have stated that their food preferences change from preflight to flight (documents not published due to confidentiality). Similar to Apollo and Shuttle, the crews have also noted that their tastes for certain foods change in microgravity and they may crave different foods on orbit compared to on Earth. (Evidence Category III)

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 months. When the menu cycle repeated after only 8 days (as opposed to the current 16-day 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 of some items may decrease.

Currently, food resupply on ISS is dependent on allotment of cargo space and crew size predictions. Food stowage is not allotted on every resupply vehicle so food may be sent into orbit months in advance of a crew's arrival. Sudden reductions in crew size result in extra food on orbit that must be consumed. This results in consumption of some foods after three years of storage, which decreases acceptability and intake. ISS crews have recently consumed some foods three years post-processing, necessitated by resupply schedules and changes in crew size. Crewmembers have reported that these foods have decreased in acceptability, some to the point where they are no longer consumed (Evidence Category III).

C. **Inadequate Acceptability of Food in Context of Exploration Missions**

Crews on long duration missions may only have access to foods that have been stored for 5 years towards the end of their mission. Current space food technology is not adequate to maintain food acceptability for 5 year missions. Inadequate food acceptability decreases food consumption, and may affect crew nutrition and psychosocial health, limiting crew ability to complete mission critical tasks (Friedl and Hoyt, 1997). Inadequate acceptability of the food could delay a long duration mission beyond low-Earth orbit even if all other mission elements are ready.

D. Evidence of Inadequate Acceptability of Food for Exploration Missions – Ground and Spaceflight Research

Sensory acceptability can be affected by factors such as serving temperature, product age and formulation, storage environment, variety, and place of consumption. Food acceptability may also indicate nutritional degradation. Food quality (color, texture, etc.) may provide a general indication of nutritional loss of the food (Lund, 1988). There are two acceptability gaps contributing to this risk. One gap (AFT2) combines tasks that simultaneously address nutrition and food quality through processing, packaging, and storage environment. A second gap (AFT3) addresses the physiological and psychological aspect of food acceptability. AFT has conducted several HRP studies to address these gaps over the past few years.

AFT 2: How can the nutrition and acceptability of the food system be maintained throughout the mission?

Changes in food, whether nutritional or quality, occur through chemical reactions. All chemical reactions in food adhere to the simple general rate equation of

$$-\frac{d[A]}{dT} = k[A]^n$$

where A is the quality attribute being measured, T is the time, k is the rate constant, and n is the reaction order (Labuza and Schmidl, 1985). After testing confirms which chemical reaction in a food will determine the ultimate shelf life endpoint, reactions rates are calculated. These reactions can serve as models to theoretically determine shelf life in similar foods.

Most quality reactions in food are zero or first order. Zero order reactions have a constant change in quality over time. Typical zero order reactions ($n = 0$) are enzymatic browning, non-enzymatic browning, and lipid oxidation. Typical first order reactions ($n = 1$) are protein and most vitamin deterioration, and microbial growth. Although not many reactions in food are second order ($n = 2$), it has been reported that in limited oxygen, the degradation of Vitamin C is second order (Labuza, 1982).

The Q_{10} is a measure of how the rate changes for every 10°C change in temperature. Q_{10} is defined as

$$Q_{10} = \frac{\text{Shelf life at temperature T°C}}{\text{Shelf life at temperature (T°C + 10)}}$$

If a reaction that changes the product color happens in half the time at 10°C higher temperature, then the $Q_{10} = 2$ (Perchonok, 2002).

Since food is not a model system, it is not simple to estimate Q_{10}; however, typical Q_{10} values are shown in Table 3. Table 3 shows that there is no definitive Q_{10} for a given category of food and that each type must be tested to determine its own Q_{10}. A food may have several Q_{10} values, each contributed by different reactions, such as lipid oxidation and Maillard browning (Perchonok, 2002).

With Q_{10} values calculated, product shelf life can be projected using the formula:

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

where:

t_s = shelf life desired

t_0 = shelf at a reference temperature

a = slope of the line equal to $\ln Q10/10$

T = temperature difference between temperature at which the shelf life, t_s, is desired and the reference temperature

Table 3. Q_{10} values for various food preservation methods

Food Preservation Method	**Q_{10}**
Thermally Processed	1 – 4
Dehydrated	2 – 10
Frozen	3 – 40

Shelf life information may be collected at a faster rate using accelerated shelf-life testing (ASLT) and the Q_{10} value. ASLT requires three storage temperatures 1) a control temperature where no changes are expected to occur through shelf life, 2) the expected storage temperature, and 3) an elevated temperature to accelerate reactions rates. The reaction rates and resulting shelf life at the elevated temperature can be used to determine the shelf life at the current temperature using the Q_{10} value (Perchonok, 2002). However, the elevated temperature may cause changes that would not normally occur in foods at regular storage temperature, such as melting, protein denaturation, and increased water activity (Labuza and Schmidl, 1985). These changes must be considered when analyzing shelf-life data.

The complexities of food structure and variety of components make food a dynamic system, which increases the difficulty in quantifying changes with kinetic models. The loss of vitamins to leaching, whether the vitamins are consumed in the leach liquid, the loss of nutrients during thermal processing, and the potential for increases in nutrient bioavailability as the food matrix is broken down during processing create an ambiguous picture of the actual nutritional content of processed foods. While the literature attempts to quantify the changes in nutritional content, the answers are not always obvious.

Kinetic data have previously been determined for the loss of several nutrients under pre-determined processing and storage conditions, but the rate constants provided are specific to the food and the testing parameters (Evans *et al.*, 1981; Feliciotti and Esselen, 1957; Kamman, Labuza *et al.*, 1981; Kirk *et al.*, 1977; Lathrop and Leung, 1980; Mulley *et al.*, 1975; Rao *et al.*, 1981) (Evidence Category I). Use of these models would only provide a rough estimate of remaining nutrition if kinetic models were prepared using this data.

A recent study evaluated changes in thirteen representative thermostabilized spaceflight foods using ASLT to assess the potential of the current food system for use during long duration missions. The sensory, quality, and nutrition of each product was determined at regular intervals over three years of storage at 40°F (control), 72°F (storage temperature of actual flight food), and 95°F (accelerated temperature) (Catauro and Perchonok, 2011) (Evidence Category I). Egg products did not respond adequately to the thermostabilization process, and were found unsuitable immediately after production. There were considerable losses in folic acid and B and C vitamins, often correlating with unacceptable changes in flavor or color. Other vitamins appeared to be maintained throughout shelf life. Low temperature storage (40°F) maintained product quality throughout the study. The changes in quality and nutrition were used to determine the shelf life of each item (Catauro and Perchonok, 2011).

The shelf life values were extrapolated to NASA's 65 thermostabilized items (Figure 2). Meat products and other entrées were projected to maintain sensory quality the longest, over 3 years, without refrigeration. Fruit products and dessert products followed with 1.5-5 years, then starches and vegetable side dishes with 1-4 years. Approximately 10% of the 65 thermostabilized items are estimated to have a shelf life of 5 years or more and 45% of the products are estimated to have a shelf life of more than 3 years. In general, the major determinants of shelf life appear to be the development of off-flavor and off-color over time. Analysis of these 13 thermostabilized products suggests that new processing and storage technologies must be investigated in order to improve initial quality and extend shelf life of food products for use in long-duration missions (Catauro and Perchonok, 2011).

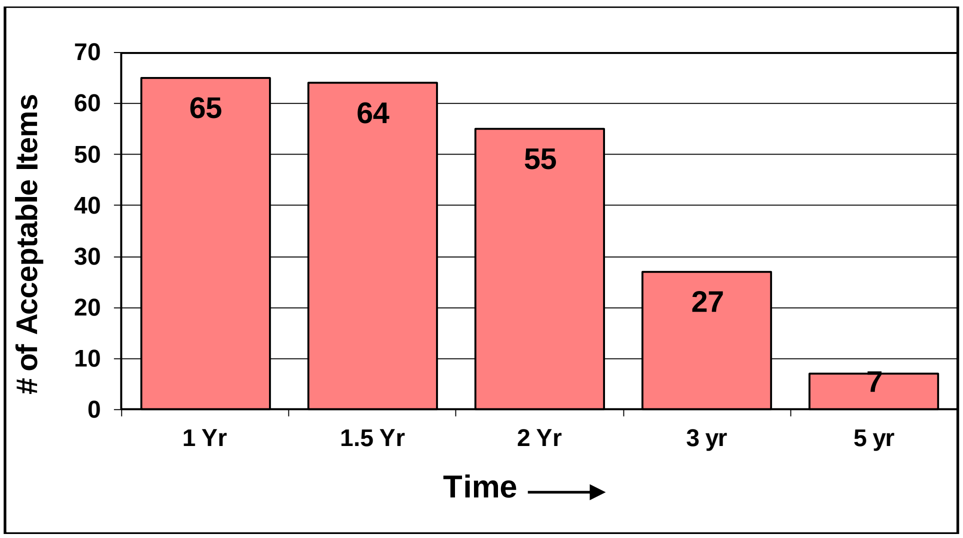

Figure 2: Number of acceptable thermostabilized space foods decreases by 90% over 5 year shelf life.

Besides processing and storage, food packaging significantly contributes to product shelf life. The effect of relative humidity and oxygen on dry and high lipid products varies significantly in different types of packaging under various storage conditions (Catauro and Oziomek, 2011b). The superior barrier properties offered by aluminum foil containing laminates prevent oxidation and water activity increases that may be destructive to vitamins, alter texture, flavor, and aroma profiles, and in the worst cases enable the growth of microorganisms. The data suggests that at high relative humidity (50-75%) products packaged without an aluminum layer equilibrated with the storage conditions, resulting in unacceptable levels of oxidation and increases in water activity (unpublished data, Evidence Category I) (Catauro and Oziomek, 2011b). Unfortunately, the foil layer presents several challenges that are considered under Section VII, Resource Utilization, requiring further research into product packaging to find alternatives with superior barrier qualities.

The residual oxygen in the final package of dry foods causes oxidation, leading to off-flavors. The methods used to remove oxygen from the food packages by flushing with nitrogen were inefficient and sealed in a significant amount of oxygen. An improved method of vacuum hold and longer flush cycles was developed to decrease the amount of oxygen entrapped in the food package (unpublished data, Evidence Category II) (Oziomek and Cooper, 2010).

These shelf life findings, preliminary NASA food nutritional degradation results, and the comparative packaging study indicate that in order to achieve a food system with a 3-5 year shelf life, a combination of factors will be required. These studies determined that nutritional content, flavor, color, and texture are affected by the high heat treatments used for processing, the residual oxygen and ingress of oxygen and moisture into food packages, and the storage conditions (temperature, relative humidity).

The integration of optimized processes, storage environment, packaging, and products to increase food quality and nutrition and ultimately extend shelf life is currently being investigated (Cooper and Glass, 2012). There are some emerging processing technologies that have demonstrated potential to provide higher quality commercially sterile products. It is expected that these higher quality products will have extended nutritional stability. The two technologies with most promise are High Pressure Processing (HPP) and Microwave Sterilization.

Microwave sterilization is a high-temperature, short-time process that shortens the thermal treatment to 10 minutes at 265°F (Release, 2004). HPP is a nonthermal pasteurization process in which food is subjected to elevated pressures (up to 135,000 psi, which is approximately 900 MPa or 9,000 atm), to inactivate vegetative cells and enzymes. The pressure causes only small product temperature increases around 3-9°C/100 MPa (Patterson, 2005). Pressure-assisted thermal sterilization (PATS) is a variation of HPP combining pressure with a reduced sterilization temperature to inactivate spores and produce commercially sterile products (Wimalaratne and Farid, 2008). PATS processing is currently being compared to thermostabilization for initial production of higher quality NASA foods with extended shelf life (Cooper and Glass, 2012).

Low temperature storage options are currently being identified as part of the integration approach to maintain food quality. Mass, volume, and power constraints reduce the possibility of refrigeration on the vehicle. Therefore, the possibility of storing food in the ultra-cold conditions beneath the Martian surface, protected from the planet's extreme temperature shifts, is being evaluated (Cooper and Glass, 2012). The quality of NASA food items stored for up to a year at ultra-cold temperatures (-80°C) compared to items stored at -4°C, 21°C, and 30°C will be determined. The integrity of current packages and seals during ultra-cold storage will be assessed. The integration approach will also investigate alternative high-barrier packaging, moisture scavengers, and the use of blast freezing in an effort to increase shelf life for long duration missions (Cooper and Glass, 2012).

The effect of space radiation on nutrition and acceptability is another concern for long duration missions. Although radiation has not been shown to reduce nutritional content in low Earth orbit (Zwart, Kloeris *et al.*, 2009), the ability of galactic cosmic rays and solar flares to initiate unacceptable changes to food quality and reduce nutritional content in deep space is unknown. Galactic cosmic rays doses are expected to be at cGy levels, with solar flares adding unknown amounts over long duration missions (Hu *et al.*, 2009; Townsend *et al.*, 2011). This may not seem concerning considering that some foods are irradiated with gamma photons or electrons to provide commercial sterility or decrease bacterial content. However, the effect that particulate radiation present in galactic cosmic rays and solar particle events will have on food is unknown (Hu, Kim *et al.*, 2009), and must be quantified to ensure development of a nutritious and acceptable food system. Additionally, individual foods react differently to radiation, and studies with soybeans have demonstrated that doses as low as 1 Gy can lead to oxidized flavors and reduce production yields (Wilson, Perchonok *et al.*, 2007).

AFT3: How can the acceptability of the food system be maintained throughout the mission?

Current data suggests that in addition to meeting physical requirements, a familiar and acceptable food system will be important to psychological well-being during long duration missions. The food quality, variety, environment, and social setting surrounding eating experiences were all shown to influence unity and morale in extraterrestrial analog Antarctic expeditions (Hunter *et al.*, 2003; Leon *et al.*, 2000). Shared food preparation and food familiarity have been found to be important to relieve anxiety and promote bonding (Locher *et al.*, 2005). Studies conducted by the armed forces in the 1950's showed that most foods decreased in acceptability when repeatedly consumed. The degree of loss of acceptability depended on the specific food (Vickers, 1999). (Evidence Category III)

Food acceptability and psychological importance is not currently included in calculations used to assess different food systems for next generation NASA and commercial space vehicle concepts. These vehicles are considerably smaller than the Shuttle and ISS and resource constraints have eliminated provisioning of a food warmer or hot water on some planned missions. A study conducted at JSC's Space Food Systems Laboratory in 2006 measured the acceptability of ambient temperature food that would normally be consumed hot. The study showed that the food lost about 20% of its acceptability when consumed at room temperature and about 17% of the food items were determined to be unacceptable (unpublished data, Evidence Category I). Previous studies have shown that decreased acceptability reduces consumption and leads to weight loss and deterioration of health (Friedl and Hoyt, 1997).

Reducing overall initial sensory acceptability is particularly concerning in spaceflight due to individualized alterations in sensory perception of foods experienced by many astronauts and cosmonauts in microgravity (Evidence Category III). The contradictory results obtained from in-flight and analog studies investigating flavor alterations were likely complicated by unknown contributions from physiological and psychological stresses experienced during spaceflight, including nasal congestion, bodily fluid redistribution, space sickness, and isolation (Olabi *et al.*, 2002). Insufficient food acceptability contributed to inadequate caloric and nutritional intake in past missions, and will be more detrimental as mission length and distance from Earth increases.

The effects that changes in sensory perception, menu fatigue, and personal control have on appetite, acceptability, and crew mood, are currently being investigated (Hunter *et al.*, 2011). Restricted olfactory acuity and its affect on aroma identification and appetite will be analyzed using bed rest subjects, with measurements taken over time to incorporate effects of menu fatigue. Additional subjects will be provided with prepackaged food and ingredients for food preparation to determine the influence that choice and personalized menu preparation has on acceptability, mood, and menu fatigue. Insight into the factors contributing to reduced sensory acceptability and food consumption will enable effective countermeasures to be implemented. Resource cost comparisons using Equivalent Systems Mass (ESM; explained in Section VII) will quantify the resource use of both prepackaged and bulk supply systems.

The ability of food and surrounding experiences to influence stress, mood, and resultant health will be further investigated in order to develop optimal eating experiences for long duration space missions (Vickers *et al.*, 2011). It is expected that moods will improve, stress will decrease, and more food will be consumed by subjects with some control over meal details and preparation and who are able to eat in groups.

These studies will indicate the psychological benefits derived from systems involving some bioregenerative and bulk supply foods as opposed to purely prepackaged foods. The data will suggest the appropriate balance generated by the cost of crew time usage and the benefits of decreased stress and improved food acceptability, mood, and crew unity.

VII. Resource Utilization

A. Spaceflight Food System Resource Utilization Background

During the development of a space flight food system, several resources have to be considered including mass, volume, power, crew time, water use, and waste disposal capacity. Ineffective use of vehicle resources will decrease the possibility of mission success. Resource constraints on each space vehicle drove several food system requirements and modifications as mission lengths increased. The lack of refrigeration required foods to be shelf stable. The production of byproduct water from fuel cells on the Shuttle drove the development of freeze-dried foods, reducing initial launch mass and volume. The hard plastic spoon bowls designed for freeze-dried and low moisture foods during the Apollo era were reduced to a clear, flexible plastic laminate. Instead of rigid cans, a flexible laminate with an aluminum foil layer was used for thermostabilized foods. The flexibility of these packages reduced mass and volume requirements during stowage (Perchonok and Bourland, 2002).

Food packaging is a major contributor to mass, volume, and waste allocations for NASA missions. Packaging is integral to maintaining the safety, nutritional adequacy, and acceptability of food, protecting it from foreign material, microorganisms, oxygen, light, moisture, and other modes of degradation. Higher packaging barrier properties equate to greater food protection from oxygen and water ingress. 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 increased enzymatic and microbiological activity.

Currently, a clear, flexible, plastic laminate is used for freeze-dried and natural form foods, enabling visual product inspection. Additionally, the clear plastic is able to be thermoformed and thermosealed without flex cracks that are common with foil laminates. However, the clear packaging does not have adequate oxygen and moisture barrier properties to allow for an 18-month shelf life for ISS. Foods are overwrapped with a second opaque foil-containing package that has higher barrier properties. The packaging materials used for the thermostabilized, irradiated, and beverage items contain a foil layer that protects the food from oxygen and moisture beyond the required 18-month shelf life.

Tables 4 and 5 list the oxygen and water vapor permeability of the current NASA food packaging materials.

Table 4. Oxygen Permeability of Packaging Materials (CC/100IN2/DAY)

	73.4ºF@100% Relative Humidity
Overwrap	0.0065
Thermostabilized and Irradiated pouch	<0.0003

Rehydratable Lid and Natural Form	5.405
Rehydratable bottom (heat formed)	0.053

Table 5. Water Vapor Permeability of Packaging Materials (G/100IN$_2$/DAY)

	100ºF@100% Relative Humidity
Overwrap	<0.0003
Thermostabilized and Irradiated pouch	0.0004
Rehydratable Lid and Natural Form	0.352
Rehydratable bottom (heat formed)	0.1784

B. Resource Use During Spaceflight

A significant resource concern lies with the mass of the system. The mass of the food is dependent on the type of food and the quantity required per crewmember. The Apollo 7 food system provided 0.82 kg of food per person per day (Smith, Heidelbaugh *et al.*, 1975). Starting in 1968 thermostabilized foods were included in the food system and were preferred to freeze-dried options, justifying the weight increase. By Apollo 14, the mass of the food averaged 1.1 kg per person per day (Smith, Heidelbaugh *et al.*, 1975). The Apollo food system still contained a significant number of freeze-dried foods since water from the fuel cells was available for food rehydration (Evidence Category III).

Current ISS crewmembers receive about 1.8 kg of food plus packaging per person per day. Compared to the Apollo missions a higher percentage of the food is thermostabilized, as a result of crew preference, contributing to the weight increase. Since ISS uses solar panels for a power source, and not fuel cells that produce water as a by-product, there is little mass advantage to using freeze-dried foods. Furthermore, the average number of calories is now based on the actual caloric needs of each crewmember according to body weight and height. This results in an average caloric requirement of 3,000 kcal as opposed to the 2,500 kcal provided to the Apollo crews, and a corresponding food weight increase (Evidence Category III).

Food packaging produces a significant amount of waste. In confidential crew debriefs, the NASA Mir crewmembers stated that the overwrapped foods created a trash management problem since there were two food packages per food item for the rehydratables and natural form foods. Even though the foods were not overwrapped on Shuttle missions, the trash was still significant. Around 60% of the waste mass on STS-99 was generated from the food system (including food, drinks, and packaging). The food system generated 86% of the waste mass on STS-101 (Lee, 2000). An analysis of the food waste on STS-51D showed a total trash mass of 23 kg that included 12.2 kg of uneaten food and 10.8 kg of food packaging. Eighty–five percent of the trash by volume on STS-29 and STS-30 was food packaging and 7% was food (Wydeven and Golub, 1991). (Evidence Category III)

C. Constraining Food System Resource Use in Context of Exploration Missions

The provisioning of a safe, nutritious, and acceptable food system must be balanced with available resources on each specific mission. For two-day missions between Earth and ISS it may be decided that food acceptability must be compromised to accommodate the small vehicle volume, eliminating hot water and a food warmer. While the decrease in food acceptability may be tolerated for short two-day missions, the balance between resources and food will need to be reassessed with each mission length increase to prevent inadequate caloric intake and nutritional deficiency.

There is a risk that the food system mass and volume will be too constraining as mission lengths extend to 3-5 years. In the event of a bioregenerative system, there is a risk that acceptable food may not grow as expected due to radiation, reduced gravity, or different atmospheric pressures. Infrastructure required to grow crops extraterrestrially will increase mass and volume constraints (Perchonok *et al.*, 2011). There is the potential risk of equipment not working or water quantities being inadequate for food hydration, processing, or preparation. There is also the risk that the bioregenerative food system could require too much crew time.

Resource constraints on the system could delay a Mars mission even if all other elements of the mission were ready. The risks increase with the increased length of the Mars mission, longer term effects of radiation, especially during transit, and the lack of resupply during the mission.

D. Evidence of Constraining Food System Resource Use for Exploration Missions – Ground and Spaceflight Research

Recent research has demonstrated that the mass of the current food system can be reduced by taking advantage of new packaging techniques and adjusting product formulations (unpublished data, Evidence Category IV) (Catauro and Perchonok, 2011). However, even without packaging it is estimated that the mass of food required to be launched for six crewmembers on a three year mission will be nearly 11,000 kg. Based on this constraining resource use, and the inadequate nutrition and acceptability of the current prepackaged food system, mass reduction options and alternative food systems for long duration missions must be considered. The tasks in the final AFT gap address technologies that may decrease resource use while enabling provisioning of a safe, nutritious, and acceptable food system.

AFT4: What technologies can be developed that will efficiently balance appropriate vehicle resources such as mass, volume, and crewtime during exploration missions with the safety, nutrition, and acceptability requirements?

Packaging is about 15-17% of the mass of the total food system. The bulk overwrap currently used to protect freeze-dried and low moisture foods from oxygen and moisture is a significant contributor to food system mass and waste. It was determined that around 3% of prepackaged foods would be left in the package if an attempt was made to eat everything (Duffield, 2008). It would therefore be expected that, at a minimum, 18% of the rehydrated food system would become waste (Levri *et al.*, 2001). (Evidence Category I)

Researchers recently evaluated the use of a single, large overwrap to contain and preserve one ship container of food items within a high barrier, flexible material (unpublished data, Evidence Category II) (Catauro and Oziomek, 2011a). These ship containers have recently been implemented into the ISS food system, replacing the rigid collapsible food containers and saving the International Space Station around 15-17% in upmass.

Another path to reduce packaging waste could be the use of an alternative packaging material. Alternative packaging would ideally provide moisture and oxygen protection similar to the current packaging without a foil layer. While the current foil packaging provides an excellent barrier, the tendency for flex cracks limit its use with thermoforming equipment and it is not compatible with some emerging technologies that may be used to produce higher quality commercially sterile foods. In addition, foil packaging complicates plans to incinerate trash at an extraterrestrial base, as it will not incinerate completely and will leave some ash (Wydeven and Golub, 1991). Food system wet waste materials must be properly disposed of to limit microbial contamination to the crew.

A recent study compared the effectiveness of a flexible aluminum-oxide coated laminate (Tolas®) against the current primary clear laminate (Combitherm®) and a material similar to the current aluminum foil and plastic laminate overwrap (Technipaq®). Analysis of barrier properties indicated that the Combitherm® material does not provide a sufficient barrier and requires overwrap, while the Technipaq® and Tolas® materials each appear to maintain adequate barriers independently (unpublished data, Evidence Category I) (Catauro and Oziomek, 2011b). Successful performance of the Tolas® material might allow optimization of the current ISS packaging system by reducing it to a single package.

The identification of a capable packaging material lends itself to other packaging reductions. A gusseted pouch design for rehydratable foods would be easier to produce and would minimize mass, volume, and waste compared to the current thermoformed rehydratable package (unpublished data, Evidence Category II) (Oziomek and Cooper, 2010). The gusseted pouch reduces the production process from three pieces of packaging equipment to one and the packaging from two pouches to one, decreasing the total amount of packaging mass by approximately 66%.

Significant reductions in food system mass are also possible with further menu development. In one analysis overall calories were maintained but the caloric density of menu items were increased by adding more fat and reducing moisture. The increase in caloric density reduced system mass by 321 g per crew member per day, or 22% (unpublished data) (Stoklosa, 2009). In another analysis, the substitution of standard menu items with meal replacement bars at a frequency of one bar per crew member per day resulted in a mass reduction of 240 g, or 17% (Stoklosa, 2009). If both approaches were combined, the mass of the food system can be reduced by as much as 529 g, or 36% (Evidence Category I). Work is ongoing to develop high caloric density meal replacement bars and drinks that meet long duration space food system requirements (unpublished data) (Cooper, 2012b).

Hydroponically grown produce is a viable path to reducing food system mass and adding variety to the menu. Several studies have been conducted to determine the effect of a bioregenerative food system on an extraterrestrial mission, with an attempt to balance mass, volume, crew time, and power requirements with nutrition and acceptability. In one trade study five menus were evaluated (Table 6) using Equivalent System Mass (ESM) (Levri, Ewert *et al.*, 2001). ESM converts mass, volume, power, cooling, and sometimes crew time requirements, into one mass value. The volume, power, cooling, and crew time requirements are converted to mass using equivalency factors. These equivalency factors are based on mission length and location.

Table 6. Food System Options (Levri, Ewert *et al.*, 2001)

Case	Food System	Packaging Approach	Crop Growth
1	ISS Assembly Complete	Individual Servings	Salad

	(some frozen food)		
2	Shuttle Training Menu	Individual & Multiple Servings	Salad
3	Shuttle Training Menu	Individual Servings	Salad & White Potato
4	Shuttle Training Menu	Individual Servings	Salad
5	Shuttle Training Menu w/reduced water content	Individual Servings	Salad

The Shuttle Training menu was a menu similar to the Shuttle and ISS food system. The various cases supplemented the Shuttle Training menu with frozen foods, bulk packaged snack foods and/or salad and/or potatoes. The salad and potatoes would be grown on the Mars surface. If only ESM was considered in choosing a menu, either case 2, case 4, or case 5 would have been chosen (Table 7). However, non-quantifiable aspects (with respect to ESM), such as food palatability and psychological benefits of plant-crew interaction were not able to be included and would need to be considered when evaluating food systems (Levri, Ewert *et al.*, 2001) (Evidence Category I).

Table 7. Non-crew time ESM , Crew time ESM and Total ESM (Levri et al., 2001)

ESM	**1(frozen)**	**2(multiple serving)**	**3(potato)**	**4 (indiv)**	**5 (reduced water content)**
ESM_{NCT}*	27,587	23,246	27,198	23,324	23,351
ESM_{CT}**	4,398	3,635	4,848	3,650	3,654
ESM_{TOTAL}	31,984	26,881	32,047	26,974	27,005

* non-crew time
** crew time

During the Lunar Mars Life Support Test Project simulation in a closed chamber, a four-person crew tested a 10-day vegetarian diet based on crops expected to be grown during long duration missions. The crops were processed into ready-to-use ingredients outside of the chamber, leaving general cooking activities and cleanup to the crew. The general preparation and cleaning activities required 4.6 crew hours total per day. The amount of waste, mostly from leftovers, ranged between 20-80%. This experience demonstrated a need for automated processes, a diverse menu, and improvements in recipe scaling based on crew size (Kloeris *et al.*, 1998) (Evidence Category II).

Preliminary studies determined that food preparation would require about 3 active hours and 6 passive hours of crew time per day for a crew of six (unpublished data, Evidence Category II) (Perchonok, 2006). Passive time was defined as the preparation time that did not require a crewmember to constantly watch over the process, such as baking. Currently, only 30 minutes is set aside for crew to prepare a meal on ISS missions.

Additional limitations and benefits of a bioregenerative system are being determined compared to a prepackaged system for a three year mission, where resupply is defined as ingredients that are either prepositioned or shipped with the crew at the start of the mission (Cooper and Catauro, 2012). The study is evaluating five food systems for a crew of six, with each scenario incorporating different levels of a bioregenerative system (Table 8). Fresh fruits and vegetables (farm edible), such as spinach, lettuce, tomatoes, carrots, bell peppers, onions, potatoes, and strawberries could be grown hydroponically in environmentally-controlled chambers. In addition, baseline crops such as wheat, rice, peanuts, and dried beans could be grown on the surface or launched in bulk from Earth. These crops would be processed into edible ingredients and used in preparing meals in a galley. Mass assumptions for each food system do not include packaging due to continuing packaging development that will likely change mass numbers over time.

Table 8. Food and equipment mass for five different food system scenarios. Shipping masses include small scale processing equipment when required (unpublished data).

	Food System	Edible Crop (kg)	Ship (kg)
1	Farm edible, grow wheat/rice/beans/peanuts	12058.2	2041.3
2	Farm edible, ship wheat flour/rice/beans/peanut oil	7651.3	4854.4
3	Farm with prepackaged food and resupply	9650.5	3103.0
4	Farm, bulk, prepackaged, and resupply	6266.0	5271.5
5	Prepackaged food only	0	10765

While food items prepared from ingredients included in the bioregenerative system received an average acceptance score of a 7.45 on a 9.0 Hedonic scale, almost two hours of active crew time is required per meal (unpublished data, Evidence Category II) (Cooper and Catauro, 2012). The crew time and mass requirements are constraining the available resources on long duration missions. Additionally, dependence on the processing and preparation of bioregenerative and bulk commodity foods presents unique risks for these missions, including the risk of food scarcity from failed crop production.

Providing ease of use (preparation difficulty and time) and a constant supply of food with respect to crew scheduling will be necessary to prevent inadequate caloric intake and associated nutritional and psychological issues. Excess food preparation time also impacts the time available for scientific and maintenance endeavors (Evidence Category III). However, current studies are determining the benefits that a fresh food system and the food preparation experience will provide the crew on long duration missions (Hunter, Halpern *et al.*, 2011). Aspects of a bioregenerative system may provide enough benefit to balance out crew time and mass costs when crewmembers must live and work in an extreme extraterrestrial environment for several years. A food metric value assessment will enable inclusion of factors such as nutrition, palatability, variety, and psychological benefit in the ESM comparison to ensure provisioning of an adequate food system for long duration missions (Cooper and Catauro, 2012; Cruthirds *et al.*, 2002).

VIII. Conclusion

The current space food system is inadequate for long duration missions beyond low Earth orbit. Without extensive research and development to increase the adequacy of the food system, the crew’s health and performance will be compromised during these missions. It is clear that in developing future NASA food systems, 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. Nutrition, acceptability, and resource utilization may take on different priorities based on mission duration and distance from earth. Incorporation of fresh foods, and/or food processing and food preparation during long-duration missions may increase the probability of safety and resource utilization issues, but may provide a psychosocial boost and decrease the possibility of inadequate nutrition and acceptability issues.

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XI. List of Acronyms

AFT	Advanced Food Technology
ESM	Equivalent System Mass
GMP	Good Manufacturing Practice
HACCP	Hazard Analysis Critical Control Point
HPP	High Pressure Processing
HRP	Human Research Program
ISS	International Space Station
JSC	Johnson Space Center
PATS	Pressure Assisted Thermal Sterilization
SHFH	Space Human Factors and Habitability