Mission to Mars: Food Production and Processing for the Final Frontier

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Abstract

The food systems of the National Aeronautics and Space Administration (NASA) have evolved tremendously since the early manned spaceflights of the 1960s. To date, NASA's mission focus has been limited to exploration of low Earth orbit (LEO), and the agency's prepackaged food systems have been adequate to enable success of their parent programs. With NASA's mission focus increasing to achieve manned space exploration of the Martian surface, the agency is considering a significant departure from the prepackaged food systems of current and past space programs. NASA's Advanced Food Technology (AFT) project is presently investigating the introduction of a bioregenerative food system to support long duration habitat missions to the Martian surface. A bioregenerative food system is expected to impart less of a burden on critical mission resources, such as mass and volume, than a prepackaged, shelf-stable system. This review provides an introduction to past and present spaceflight food systems, and provides a broad examination of the research conducted to date to enable crop production and food processing on the Martian surface.

INTRODUCTION TO NASA SPACE FOOD SYSTEMS

The National Aeronautics and Space Administration's (NASA) food system has evolved significantly throughout the past 50 years to enable the success of government space exploration initiatives. The current system, while adequate to support spaceflight within low Earth orbit (LEO), will undoubtedly continue its evolution as NASA moves toward longer missions to planets such as Mars. This paper provides a brief history of NASA's past food systems, a description of the current food system supporting LEO, and a critical summary of research conducted to date on the establishment of a food system to support future long-duration exploration of Mars.

Summary of Early NASA Food Systems: Mercury, Gemini, Apollo, Skylab

NASA's human space exploration initiatives first became realized during Project Mercury (1961–1963). It was operating under this project that John Glenn, the first U.S. astronaut to eat in space, consumed applesauce directly from an aluminum tube on the third Mercury mission in 1962 (Nanz et al. 1967). "Tube foods," such as this, along with high-energy "cube foods," were the basis of the food system for the Mercury and subsequent Gemini (1965–1966) space programs. Shelf-stable, semisolid, and viscous snack foods were consumed from the tubes, whereas the bite-size cube foods were comprised of a high calorie mixture of protein, high-melting-point fat, sugar, and fruits or nuts. Together, these foods formed a system that was characterized by its caloric density and simplicity, having been extensively engineered to provide an effective interface with the resource-constrained environments of the early manned vehicles (Smith et al. 1971).

The Mercury and Gemini initiatives were also marked by NASA's desire to ensure the maximum safety of its crewmembers. These early programs drove collaborative research between industry and government that eventually allowed for the development of comprehensive specifications and procedures for each individual Gemini food item. This quality assurance process represented the beginnings of the Hazard Analysis and Critical Control Points (HACCP) system, which was developed by a team of representatives from NASA, Pillsbury, and the U.S. Department of Defense, and is now widely used in the food industry (Heidelbaugh 1966).

The heavily engineered foods of the Mercury and Gemini programs indeed met the requirements relevant to enable fulfillment of their respective program goals. However, although the foods began from familiar food ingredients, were lauded for their high efficiency and density, and met the description of acceptability in ground-based tests, consumption in flight was found to be inadequate. A decreased acceptability of these foods during flight was suspected to be a primary factor affecting the weight loss of astronauts in Mercury and Gemini missions (Smith et al. 1971).

Much of the Gemini food system was preserved to support the early missions of the Apollo program. However, as the Apollo program progressed, the food system continued to evolve, with later missions benefitting from technological advances that enabled improved food quality and increased menu variety to encourage food consumption by the crew. In fact, the food system of the later Apollo missions (1968–1972) was markedly improved upon incorporating the use of new processing methods to provide safe, stable, and palatable foods to the crew. Later Apollo missions used retort (thermostabilized) pouches and cans; the former allowed for the use of less aggressive processing parameters and resulted in a higher quality product with less postconsumption waste (Potter & Hotchkiss 1998). The Apollo astronauts were also the first to use irradiated food in space (Bourland et al. 2000). NASA established a special dispensation from the Food and Drug Administration to use these products, which are available through a cooperative agreement with the U.S. Army Soldier Service Center (Natick, MA) to support human spaceflight (Code of Federal Regulations 2011). Another achievement of the Apollo program was technology development that enabled astronauts to eat food, after rehydration with water, using utensils. This was a unique benefit of the "spoonbowl" package developed by NASA during the Apollo program. It allowed astronauts to connect food packages to a water dispenser in flight for rehydration and later remove the top of the package to consume the contents with a knife, fork, or spoon. The use of utensils was embraced by crewmembers, as it provided them with an eating experience that was familiar and reminiscent of Earth.

Despite the improvements realized in the later Apollo food systems over those used on earlier flights, the majority of the Apollo astronauts were not observed to consume sufficient nutrients. It became apparent through crewmember feedback that adequate nutrient intake required an even greater focus on presenting appropriate food to the crew in a form that was familiar to them (Smith et al. 1975).

The Skylab food system (1973–1974) was characterized by increased palatability and menu variety beyond that in Apollo. NASA provided Skylab crewmembers with a stock of 72 food options that made up a six-day menu cycle. All of the food identified for the Skylab program was launched with the first mission, which meant that it would be more than two years old when the program's final crew was able to consume it. Therefore, many of the foods were packaged in aluminum cans to exceed the two-year shelf life minimum (Klicka & Smith 1982). Skylab was also the first U.S. space program to have on-board freezers, refrigerators, and food warmers. The freezers provided foods such as ice cream, filet mignon, and lobster, and the refrigerator offered chilled beverages and desserts. Crews were also provided with scissors to supplement their utensil kit and allow easier opening of plastic seals (Turner & Sanford 1974). The use of these four utensils was found effective by crew and is preserved in the spaceflight food systems of today.

Summary of the Current NASA Food System: Space Shuttle, International Space Station

STS-135, the final Shuttle mission, flew in July 2011, ending a 30-year program (1981–2011). The food system on board the Shuttle was similar to the current food system on the International Space Station (ISS) (2000–present). Unlike Skylab, refrigerators or freezers are not available to enable long-term storage of food. Therefore, all the food supporting these programs is processed to achieve shelf stability. These processed foods are designed to provide crewmembers with a variety of menu options that are ready to eat or that require only minimal preparation, such as adding water to or reheating foods. Given that the fuel cells used on a Shuttle provide water as a byproduct of fuel consumption, approximately 50 percent of the Shuttle food is shipped in a dried form (Bourland 1993). The dried food—which includes beverages, and freeze-dried and other rehydrated foods, such as breakfast cereals with nonfat dry milk—is vacuum packaged. Before consumption, these items are connected to a water dispenser and hydrated through a septum assembly, which includes a one-way valve to prevent migration of the liquid out of the food package after disconnecting the food from the water dispenser. Additional foods supporting the Shuttle and ISS programs include thermostabilized (retorted) and irradiated food items, which are processed to commercial sterility; foods classified as natural form foods, such as nuts, granola bars, and cookies; and dried fruits, which are classified as intermediate moisture foods. The natural form and intermediate moisture foods are ready to eat and are vacuum packaged in individual servings. The surface tension of the water in the foods with higher moisture contents prevents the food from leaving the package or the spoon during eating in microgravity.

Condiments are also an important part of the current food system. Condiments provided to the crewmembers include individual commercially packaged pouches of ketchup, mustard, mayonnaise, taco sauce, and hot pepper sauce. Bulk supplies of liquid pepper and liquid salt are provided to crewmembers in small dropper bottles. The pepper is suspended in oil and the salt is dissolved in water (Perchonok & Bourland 2002). This broad assortment of condiments offers flexibility, allowing customized menu items to suit individual preference.

The ISS is inhabited continually with up to six international crewmembers. The length of each crew's stay is generally around 180 days, and is referred to as an expedition. During a given expedition, approximately three crewmembers are from the United States, Europe, Japan, and Canada, with the remaining crewmembers from Russia. The United States, with help from Japan and Europe, supplies approximately 50 percent of the food; Russia supplies the remaining 50 percent of the food. Russian and U.S. foods together create a unique variety in orbit (Lane et al. 2007). In light of the importance of variety to the crew, NASA food scientists have worked to develop more than 60 new food items in the past decade, which has allowed for the current 16-day menu cycle on the ISS, composed of more than 180 different U.S. food items. The ISS food is stowed pantry style, or by category (e.g., soups, beverages, fruits), to allow crewmembers more liberty in customizing their meals to suit their preferences. Additional variety in the crew diet is achieved by allowing crews to supplement their standard menu diet with personal preference items from the U.S. food stock and even bonus or commercial items beyond those available in the U.S. food stock.

In light of the ISS expedition length and the fact that the food is prepositioned, the required shelf life of the individual food items is 18 months. The packaging material used for the rehydrated and natural form foods allows for efficient visual inspection to identify an unacceptable degree of broken pieces, which are difficult to eat on-orbit in microgravity. However, this material does not have adequate oxygen and moisture-barrier properties to ensure shelf life beyond 9 to 12 months. For that reason, these items are overwrapped with an opaque multilayer foil-containing material. However, as NASA begins to consider manned missions beyond LEO, the challenges in developing a food system for an extended duration mission increase significantly. The duration of a mission to Mars may be as long as 2.5 years and will likely include an 18-month stay on the planetary surface. As a result of the possible prepositioning of the food, the shelf life of the prepackaged food system will have a five-year shelf life requirement (Cooper et al. 2011). Based on the specifications of the current NASA shelf-stable packaged food system, a Mars mission requires 9660 kg of packaged food to support a crew of six. Of that mass, approximately 15% (1440 kg) is contributed by packaging, which contributes directly to waste mass and volume in orbit (Teixeira et al. 2005).

Surface Food Systems for Future Missions

NASA's Advanced Food Technology (AFT) project team is investigating the possibility of a partially bioregenerative food system on the Martian surface. Fresh fruits and vegetables and possibly other commodities can be grown hydroponically in environmentally controlled chambers. Other raw commodities can be launched from Earth in bulk and processed into edible ingredients. These processed ingredients along with the fresh fruits and vegetables and other packaged foods and ingredients can be used to prepare the meals in a Martian galley (French & Perchonok 2006). The remainder of this paper discusses the various challenges that will need to be solved before NASA can implement this type of bioregenerative food system for a Mars mission.

DEPARTURE FROM THE CURRENT NASA FOOD SYSTEM

As discussed, NASA's current prepackaged food system is most appropriate for a six-month to one-year mission and for the continual resupply of stations in LEO, such as the ISS. As NASA missions gradually extend in duration, begin to involve large numbers of people, or include prolonged stays on an extraterrestrial surface, the food system, too, must evolve to best meet the needs of the mission. The aforementioned bioregenerative food system, currently under investigation to support a Mars mission, is an example of a significant departure from the prepackaged food systems that have supported NASA space initiatives to date. The inherent differences between a bioregenerative system and a prepackaged food system are significant, and form the basis of the decisions regarding design of the Martian food system.

Advantages of a Bioregenerative Food System

Undoubtedly, a bioregenerative food system offers phenomenal advantages over a prepackaged food system to support an extended duration mission to Mars. At the heart of the bioregenerative system is fresh crop growth. Fresh crop growth is an important avenue for NASA to explore, because any food that can be grown at the habitat does not have to be shipped from Earth. Food and food packaging currently represent the largest burden on consumables in the Shuttle program and command a significant portion of stowage volume on resupply vehicles to the ISS. A reduction in the mass and volume of stowed food allows potentially for the use of a smaller vehicle and less propellant to support a Mars mission than a method relying entirely on a prepackaged food system. Fresh crops are also an important component in the bioregeneration of gases and recycling of waste materials for a closed habitat system (Yamashita et al. 2009). The design of a closed biosystem relies on plants to absorb environmental carbon dioxide, release oxygen, and use the gray water (waste streams) created by a human crew. Rather than use extraneous plant life to accomplish this purpose, it is more efficient to support such a system with plants that also serve as a food source. The last mission-related advantage of a bioregenerative food system is the expected psychosocial benefit of agricultural activity that potentially serves to connect the crewmembers with their unfamiliar space environment. Recent work, such as that done by Wichrowski et al. (2005) and Hayashi et al. (2008), has documented the benefits of horticultural therapy.

The advantages of bioregenerative systems extend beyond mission-relevant savings and are also apparent in the quality of the individual foods and menu options themselves. First, fresh fruits and vegetables have been documented to have higher nutritive value than processed fruits and vegetables (Rickman et al. 2007a, 2007b). For example, vitamin losses to fruits after heating or processing have been documented, with principal losses occurring to the vitamin C and phenolic acid content of fruits (Kalt 2005). Similar losses have been observed in cooking or processing of fresh vegetables; for example, vitamin C in fresh spinach has been observed to be 60% higher than in canned, or even frozen, spinach (Weits et al. 1970). Although many vitamins present in fresh fruits and vegetables are susceptible to degradation during processing of this type, there are also some nutrients, such as carotenoid pigments and some polyphenolic compounds, that become more bioavailable as a result of cooking or other processing techniques (Rock et al 1998, van het Hof et al. 1999, Dewanto et al. 2002). Because a bioregenerative system includes fresh produce and cooking equipment, the crew is offered the flexibility to optimize nutrient intake for each foodstuff.

Aside from nutritional content, freshly made dishes are observed to have a distinctive taste relative to commercially processed meal items (Watson & Boyle 1996). Fresh or minimally processed foods are often perceived as being of higher quality and are therefore more appealing to crewmembers, which may promote greater food intake by the crew. Finally, because the food in a bioregenerative system is supplied as ingredients and not in prepared dishes, crewmembers are allowed the flexibility to personalize the menu to accommodate their individual likes and dislikes. This flexibility increases the menu variety tremendously and increases the likelihood of crew satisfaction with the food system (de Graaf et al. 2005).

Disadvantages of a Bioregenerative Food System

Although a bioregenerative food system has many advantages serious considerations accompany its implementation. First and foremost, a risk of food scarcity is introduced to space missions relying on a bioregenerative food system for crew provisions. Should crop failure occur across broad portions of a crop growth area, the food supply may be rendered inadequate to meet nutritive needs of the crew. This risk is not considered relevant to current missions that rely on a prepackaged food system, as the food supply and its backups are provided for crews in advance of their mission start. In fact, overconsumption of highly preferred food items is the only factor seen to date having any effect on food abundance in the current system.

The remaining disadvantages of the bioregenerative system counterbalance the mission resource usage benefits summarized in the preceding section. Specifically, with regard to mass utilization, the bioregenerative system has been suggested as a means to reduce shipped mass of the food system because it presumes the use of crop tonnage grown at the habitat site. However, when accounting for the infrastructure required to support a space agricultural production site (i.e., greenhouse), a bioregenerative system likely requires much more equipment mass and power usage than a prepackaged food system. The greenhouse and the apparatuses used to enable food processing, food preparation, and sanitation are expected to outweigh the food warmer and potable water dispenser used for the current prepackaged food system. Second, the power consumption of the food production system can be quite high relative to other power demands of a closed system. In fact, during the design of the Lunar Base Closed Ecological Life Support System (CELSS), the food production system emerged as the largest power consumer (Schwartzkopf 1997).

The third disadvantage in terms of resource utilization is the amount of crew time required to prepare food within a bioregenerative food system. In Biosphere 2, approximately 45% of the crew time was devoted to agricultural or food preparation tasks (Silverstone & Nelson 1996). Salad diets reduce the time but have the potential of becoming monotonous to the crew. More complex dishes and menus add to the variety of the food system, but they require a greater investment in preparation time by the crewmembers (French & Perchonok 2006). The final disadvantage of a bioregenerative food system relates to the amount of training that is expected to be required of crewmembers before implementing the system. In addition to their primary responsibilities, the crew essentially needs to function as farmers, stockroom managers, chefs, and health inspectors to sustain a bioregenerative food system. In contrast, the mode of operation for using a prepackaged food system is generally communicated to crewmembers within a short briefing meeting before their flight.

FOOD PRODUCTION FOR NASA MARS MISSIONS

Although the specifics of NASA's long duration manned missions have evolved somewhat over the years, much research remains to investigate the use of crops to sustain crewmembers in any space habitat. This research has included broad, systems level assessments of bioregenerative systems, as well as a multitude of specific trade studies comparing various costs and benefits of candidate crop varietals. Duffield (2008) provided a summary of the latest assumptions for long duration space habitats, in light of this research. Building on this, NASA's AFT project is refining a list of bulk ingredients and prepackaged foods to propose alongside these crops. **Table 1** provides a summary of the most recent list of crops, foods, and other ingredients being considered to support long duration space travel.

The growth of crops has been heavily investigated to date because it represents the greatest means of self-sufficiency for a crew habitat over the long-term. Crops farmed in situ provide human

Table 1 Candidate foods, their sources, and specific food items recommended to support NASA habitat missions

Candidate food type	Candidate sources	Candidate foods
Ready-to-eat salad crops[a]	Grown in situ	Cabbage, carrots, celery, green bell pepper, green onions, lettuce, mushrooms, peas, radish, snap beans, soybeans, spinach, strawberry, sweet potato, tomato, white potato
Ready-to-use staple crops[a]	Grown in situ, shipped	Red lentils, pinto beans, kidney beans, navy beans, black beans, white rice, brown rice, wheat flour, white flour, peanuts
Resupply ingredients[b]	Shipped	Assorted spices, bouillon, sugar ingredients, dried egg ingredients, water, starch, assorted dry pastas
Prepackaged foods[b]	Shipped	Assorted products, depending on frequency of resupply

[a]as reported in Duffield 2008.
[b]as reported in Cooper & Catauro 2010.

needs for food, while at the same time using and removing from the environment the waste CO_2 from human respiration (Duffield 2008, Wheeler 2004). Furthermore, plants farmed in situ also may offer a valuable means of water purification, as wastewater may be cycled through a plant system and released via transpiration as atmospheric moisture surrounding the plants. That moisture could then be collected and used as a clean water source (Wheeler 2004, Yamashita et al. 2009).

Fruit and Vegetable Crop Growth

Work began as early as the 1960s to assemble a list of perishable vegetable crops that might serve as a supplement to a crewmember's diet in space travel. In the mid-1980s, NASA research progressed even further to focus on identifying crops with acceptable growth qualities and nutritional properties that might serve to sustain humans in a bioregenerative space habitat (Wheeler 2004). Several growth selection criteria were established in all of these efforts and continue to drive the selection of suitable crops for use in spaceflight. These criteria include the potential yield of the crops (edible mass and O_2 and H_2O production), the crop's harvest index (ratio of edible mass to total biomass), crop efficiency (benefits per unit area, per unit time, and per unit volume), and the crop's horticultural requirements (planting, harvesting, pollination, processing needs) (Wheeler 2004, Yamashita et al. 2009). Many of the early lists included staple crops to provide levels of macronutrients to sustain crew and a limited assortment of vegetable crops to supplement the diet, provide variety, and facilitate adequate micronutrient intake of the crew (Wheeler 2004). The NASA Baseline Values and Assumptions Document currently contains the most recent list of crops assumed as potential candidates for incorporation into a space habitat (Duffield 2008).

At the heart of crop selection for space habitation is the requirement that the selected plants be able to flourish in a growth chamber system. Controlled environment horticulture, although not uncommon on Earth, presents challenges when applied to a Martian habitat. Martian hypogravity, hypobaric conditions, and extreme temperatures are among these challenges. These unique environmental constraints have been the focus of many bioregenerative life support studies over the past 20 years. Spaceflight tests have offered NASA an opportunity to evaluate the effects of microgravity on seed and tuber development, oxygen and water production, and crop cultivation techniques. Meanwhile, ground-based tests have offered NASA a chance to evaluate the effects of growth chamber design on crop efficiencies and other relevant parameters (Wheeler 2004, Yamashita et al. 2009).

Although growth chambers have been characterized as an effective means to produce edible crops, there are several parameters that need to be optimized before they can be incorporated into spaceflight. Chamber lighting, harvest automation, and composition of the atmosphere surrounding the plants are all parameters that are currently being optimized to improve the efficiency of growth chamber agriculture to support spaceflight. Berkovich et al. (2004) recently identified a quantitative means to compare and optimize horticultural regimens to support space plant growth facilities. This research applied a single, quantitative metric (Q-criterion) to compare a breadth of research on candidate crop systems for space plant growth chambers and evaluate each crop's relative suitability to support spaceflight. The researchers' comparisons suggested the importance of optimizing the technical regimen of the plant growth chambers to encourage efficiency in crop production across a wide spectrum of crops.

Chamber lighting is one of the most important aspects of the technical regimen to consider in designing growth chambers to support a Martian food system (Wheeler 2004, Finetto et al. 2010). The two main approaches to providing acceptable lighting in space plant growth chambers are via electric lighting or solar lighting (Wheeler 2004). Electric lighting provides great real-time control over the intensity and photoperiod of the light available to plants in a growth chamber. However, despite its advantages, electric lighting is considered a consumable and requires power from the habitat's energy source. Much of the current research on this lighting for long duration spaceflight is therefore related to optimizing lamp technology to make it more efficient (Wheeler 2004).

Solar lighting is an attractive option to provide light in growth chambers, as it requires less power from the habitat and has lower thermal costs (Wheeler 2004). However, solar power relies on the harvesting of natural lighting from the Martian environment, and therefore offers less consistency and efficiency than electrical lighting, and is particularly vulnerable to Martian weather patterns (Cuello et al 1998, Wheeler 2004). Current work to improve solar lighting for use in space plant growth chambers is focused on harvesting light with mirrors and transmitting it in a more consistent manner via fiberoptic technology. Current research is also considering a need to identify chamber wall materials that allow solar light transmission and still withstand the pressure, temperature, and UV radiation of the Martian surface (Wheeler 2004).

Aside from lighting, the atmospheric composition of the environment surrounding the plants in a space plant growth chamber is also extremely important to consider (Wheeler 2004). It would be quite desirable to maintain space plant growth chambers for Mars at a relatively elevated partial pressure of carbon dioxide to take advantage of the fact that the gas is plentiful in the Martian atmosphere. To date, much research has indeed been conducted to document the effects of higher chamber concentrations of CO_2 on the growth characteristics (Monje & Bugbee 1998) and nutritional composition (McKeehen et al. 1996, Wheeler 1997) of plants in growth chambers. In general, these studies have suggested that an elevated concentration of carbon dioxide can be detrimental to plant productivity. Concentrations of CO_2 in excess of 0.4kPa have been observed to have negative effects on some plants; however, additional research is needed to understand the mechanism behind this phenomenon (Wheeler 2004).

Assuming effective growth and harvest of the plant crops in a Martian growth chamber can be achieved, there are also several postharvest considerations. Among these, the physical and chemical composition of the edible plant matter must provide a palatable source of nutrition to the crew. Many studies have evaluated food production scenarios that rely on Martian candidate crops (Levine et al. 2008, Moraru et al. 2004, Veillard et al. 2007), and have stressed the importance of final food quality as a selection criterion in selecting appropriate crops. Nutritional qualities of chamber-grown crops are also of great importance to ensuring the success of the food system (Cooper et al. 2011, McKeehen et al. 1996, Fu et al. 1996).

Another consideration of designing bioregenerative systems is that of ensuring the crops produced are safe to eat. As part of NASA-directed research, AFT examined cleaning protocols through which fresh produce shelf life might be extended in space. Hydrogen peroxide was used as an antimicrobial agent at varying levels to clean an assortment of produce items. The effectiveness of the hydrogen peroxide treatments was compared against the cleanliness of control samples of each produce item that were washed in distilled water. Most produce had an initial reduction in microbial count on day 0, followed by a rapid increase that essentially rendered counts across treatments indistinguishable. Additionally, degradation in color and texture occurred at hydrogen peroxide concentrations greater than or equal to 5% for some vegetables. The study did note some microbial reduction for carrots and radishes, which suggests that an item-specific washing procedure may be appropriate for use in space. Fine-tuning of the produce handling processes is required to ensure safety and maximize shelf life of the foods for use in a bioregenerative system (MH Perchonok & S French, unpublished results).

Supply of Baseline Crops

Aside from perishable vegetable crops, a bioregenerative system requires the use of several protein- and oil-rich staple (baseline) crops to meet NASA nutrition requirements (Fu et al. 1996). **Table 1** provides a summary of those crops currently being considered by NASA for this purpose. Owing to the nature of these crops, it is possible to either ship their edible matter, prepackaged in bulk, or produce them at the mission site as part of the bioregenerative food system. The main considerations that affect the determined source of these ingredients are related to the relative stability of the foods from bulk and fresh sources as well as the resource usage required to enable their consumption as part of each system.

If shipping these foods in bulk, it would greatly benefit NASA to consider the changes to the functionality of these foods during storage. In addition to the product quality changes that occur over time to products stored in an Earth environment, the Martian environment presents other factors, namely irradiation, that affect the shelf life of bulk-packaged baseline crops (Gregson & Lee 2001).

There is very limited information regarding the effect of space radiation on prolonged food storage. Ionizing radiation can generate reactive species within foodstuffs that result in destruction of macromolecules, such as carbohydrates, lipids, and proteins, altering their functional and textural properties (Mollins 2001, Potter & Hotchkiss 1998). Despite these effects, ionizing radiation has been used as a food safety aid for the past century to control pests in foods and reduce the risk of microbial contamination (Gregson & Lee 2001). It is unknown what specific effect space radiation sources have on foodstuffs or how it might differ from irradiation sources conventionally used by the food industry.

The impact of irradiation on soybeans for use on Mars missions has been considered extensively throughout the past decade by investigators working under NASA direction. Wilson (2004) found that surface irradiation of whole dry soybeans using electron beam or gamma rays at 10 or 30 kGy provides microbial safety of the bulk commodity. However, oxidative quality changes were imparted to the beans from the exposure, rendering them unacceptable for producing adequate soymilk and tofu. Some of the functional qualities altered by the radiation exposure included the soybean color, aroma, solid content, and the germinating capacity of the individual seeds (Wilson 2004). Further testing showed E-beam irradiation of bulk soybeans greater than 1 kGy provided microbial safety but did not ensure sterility (Wilson & Chia 2005).

Soy food quality was compromised from the radiation—off-odor was detected in soymilk, and tofu texture was softer and less cohesive (Wilson & Chia 2005). Soybeans exposed to 1–5 kGy doses of gamma radiation, the environmental levels of radiation expected on Mars, can be used for soymilk and tofu production, but a flavor/aroma masking agent may be needed to cover oxidation and more beans may be needed to offset yield losses (Wilson & Chia 2005). Thus, with his final conclusion, Wilson summarized that the choice of soybeans for Mars missions must include cultivar, crop year, storage conditions/time, presence of stone beans, composition, and packaging requirements in order to deliver functional soybeans for at least one year (Wilson 2006).

In contrast to soybeans, irradiated wheat has been shown to have minimal processing impacts in comparison with nonirradiated wheat. Zaied et al. (2006), while examining wheat treated with gamma irradiation, found that acceptable balady bread could be produced from wheat treated with 2, 4, and 8 kGy despite a significant reduction in reducing sugars with increasing doses. Other studies suggest that low doses of gamma irradiation (1.16 kGy) of flour may improve bread quality (Lorenz & Miller 1975). Similarly, Pixton et al. (1976) found no major chemical, physical, or baking properties of wheat changed after alpha irradiation. The flour, once treated with radiation of 1 kGy, proved to be microbiologically stable for up to two years (Lorenz & Miller 1975).

Shipping staple crops in a bulk, shelf-stable form continues to be investigated by NASA because it can offer advantages of increased safety, lower resource utilization, and a lesser burden on crew time. Shipment of staple crops may also allow crewmembers access to raw materials having more desirable functional properties, which may not have been successfully obtained from a plant growth chamber. However, the advantages of shipping shelf-stable staple crops needs to be considered against the likely impact it would have on the shipped mass of the food system and the potential quality loss that could affect the foods during prolonged storage.

Supply of Other Consumable Ingredients

To supplement the staple and perishable crops that exist in a bioregenerative food system, NASA would need to supply a stock of additional shelf-stable ingredients that facilitate recipe preparation and increase menu variety. Items proposed for this are summarized broadly in **Table 1** and include an assortment of seasonings and functional ingredients typically found in a home pantry or restaurant kitchen. Refining the list of consumable ingredients to support a bioregenerative system requires careful consideration of the available crops, proposed recipes, and anticipated shelf life of each consumable ingredient.

NASA's AFT project has explored the shelf life of many of the proposed bulk ingredients and minor ingredients that could be provided if resupply missions to the Martian surface were implemented by the agency. The specific frequency of such resupply missions has not yet been determined by NASA; however, these resupply missions are not likely to occur more frequently than once every two years. Therefore, AFT currently holds a working assumption that the minimum shelf-life requirement of ingredients for use in a resupply scenario is 36 months, to account for pre-shipment processing and packaging time of these items. Working with AFT, in 2003 G.L. Cramp conducted a thorough review of literature to compile shelf life values of proposed bulk ingredients and commodities (G.L. Cramp, not publically available). Although five years of product quality data was desirable, the scientific data compiled in this work showed that commodity life generally ends after 24 months because of limited commercial and academic interest. The shelf lives of beans, cocoa powder, egg powder, milk powder, and white rice are postulated to last the five-year span but have not been verified empirically (Durtschi 2009). Further development of crop systems and additional investigation of the stability of ingredients is required before NASA is able to refine its list of commodity ingredients required to support a bioregenerative system.

FOOD PROCESSING AND PREPARATION FOR NASA MARS MISSIONS

The equipment used to process the food ingredients into various food streams and to prepare the actual meal dishes is as vital to the food system success as the food itself. Along with the growth of fresh produce, an ability to process food extends the food system exponentially in shelf life and variety. Bourland (1993) reasoned that access to food processing and packaging follows crop production as a means to stock excess food in space. This logic is quite true for the early stages of deep-space exploration. However, equipment usage within established habitat food system scoping is directly affected by the quantity of crops available to be processed and the habitat population requiring support. Equipment usage is not simply for the preservation of extra salad crops but also allows the derivation of more specialized ingredients from the crops and a broadening of the menu variety available to the crew.

General Specifications of Food Processing Equipment

Establishing the food equipment list for a Mars habitat mission is not a simple process; selection is subjected to a plethora of considerations, from mass contributions to food system necessity. Mass is traditionally one of the biggest concerns for any payload contribution because it directly impacts the cost and feasibility of the mission. Every kilogram of mass payload directly leads to tens of kilograms of propellant required at launch from Earth, depending upon the propulsion system used (Hoffman & Kaplan 1997). Thus, it is advantageous to use smaller, lighter equipment when possible. Often considered simultaneously with mass of payload is the volume of the payload. Interplanetary vehicles are designed with a compact architecture to ensure minimal mass of the vehicle itself. The resultant available volume limits the size of equipment that can be sent to Mars; similarly, habitat stowage volume limits galley equipment size. The final consideration with respect to payload contribution is a preference toward multi-use equipment. The utility-knife premise is to supply a single piece of equipment that can perform multiple functions, either through specialized parts or accessories. Another option is to use equipment that shares a motor and/or shell, thereby saving the mass of a second motor or shell in payload.

Independent of payload considerations, essential equipment must be optimal for use and resource utilization in a space habitat environment. As an example, a french fry cutter produces fantastically uniform french fries but weighs 16 pounds, and can easily be replaced in function with a knife and cutting board. Other equipment considerations are provided within the Mars Reference Mission document as follows:

> Electronic and mechanical equipment must be highly autonomous, self-maintained or crew-maintained, and possibly self-repairing. The amount of time taken to do routine operations must be minimized through system design. In principle, the operation of supporting systems (such as power, life support, in situ resource recovery) should be transparent to the crew. The best approach in this area is to define the requirement for technological development based on the mission requirements for a given crew size. (Hoffman & Kaplan 1997)

Hence, along with necessity of function, the ease of the use and cleaning, the ability to maintain, the robustness, and the level of automation are equipment considerations in the selection process.

Last but not least, the equipment must operate as intended at the habitat. Food processing in space is inherently different due to the hypogravity and reduced pressure of Mars. Colloidal stability may be improved, but mixing, fluid transport, boiling, condensation, and natural convection are all processes likely to be affected negatively by the reduction in gravity (Fu & Nelson 1994). Thus, any equipment evaluation must consider if the equipment depends on physical phenomena that fail to exist in a hypogravity or hypobaric environment like Mars. Certain food processing operations like milling of flour, baking of bread, and pressing of oilseeds can be adapted to a hypogravity environment, and vacuum drying, freeze drying, and freezing may be benefited by the natural conditions on Mars (Fu & Nelson 1994, Gregson & Lee 2001).

After all of these considerations are weighed, the equipment list between various researchers still varies based on individual diet assumptions and the designer's preference. Zasypkin & Lee (1999) suggested a drum dryer/separator, compact mill, combined food processor, forced-air microwave/convection oven, high air velocity oven, bread maker, multifunctional cooking pan, extruder, flaking rolls, homogenizer, compact centrifuge, and refrigerator and freezer to outfit an isolated, inhabited station in a hypogravity environment. With this equipment, the researchers proposed that a wide variety of foods could be produced with reduced time and labor in processing. Ruminsky & Hentges (2000) stated that ingredient processing equipment, including an extruder, expeller, centrifuge, soy hull floater, microwave/convection oven, and incubator, are required to produce just the peanut oil and tempeh from raw peanut and soybean crops, respectively, but at a significant time cost. French & Perchonok (2006) suggested that a bulk commodity supply menu could be provided with preparation equipment (blender, bread maker, convection oven, food processor, juicer, pressure cooker, range, and tortilla press), a grind mill, concentrator, dehydrator, refrigerator/freezer, soymilk/tofu maker, and oil press.

To enable a quantitative evaluation of food system and other life-support system options for NASA missions, an equivalent system mass (ESM) metric was developed by the Advanced Life Support (ALS) program (Levri et al. 2003). The ESM metric allows standardization of several parameters to result in a single quantity that represents the launch cost of a given life support system. The parameters incorporated in the metric are mass, pressurized volume, power generation, cooling, and crew time requirements. The ESM metric can also be used to evaluate the individual components of a food system (such as technologies, equipment, hardware configurations, or usage procedures). In both cases, an ESM value is extremely dependent upon the particular mission of interest, as well as upon all corresponding assumptions.

Processing of Crops and Bulk Ingredients

Wheat, peanuts, and soy—each a candidate crop—have much broader utilization in the diet after ingredient processing, and such processing is necessary to provide flour, cooking oil, milk analogs, and meat analogs. Terrestrially, large-scale processing plants produce these specialized food streams through cost- and time-efficient operations. At a space habitat, the prime goal is to produce functional ingredients on optimally sized equipment with minimal waste and minimal crew time input. The equipment for ingredient processing largely depends on the final crops and/or bulk commodities that are chosen as the base of the habitat diet.

Wheat-derived products have a dominant role in the proposed space diet scenarios, prompting further examination of the requirements to produce flour. The ESM values of yeast bread production versus flat bread production were compared by Weiss et al. (2004). In this study, wheat berries were milled using either a Brabender Quadrumat Jr. or the Kitchen-Aid grain mill attachment, and multiple methods were followed to make the final bread. The mass discrepancy between the two mills drove the difference in the final ESM for the bread productions, with the Kitchen-Aid grain mill attachment (2.0 kg) highly favored over the Brabender unit (63 kg). However, no quality or nutritional assessment was conducted on the bread itself so researchers hesitated to make a definitive recommendation.

Cooking oil is also an important ingredient in many recipes, adding to mouthfeel of products, aiding in heat transfer, and increasing the caloric content. The presumption of early food system trade studies was that oil must be produced at the habitat to ensure nonoxidized oil was available for cooking throughout long duration missions, but packaging film technologies now allow the lightweight storage of oil for extended times. French (2006) used the ESM metric in a trade study analysis of peanut processing versus bulk provision of peanut oil for a Martian surface mission. The resource estimates incorporated into the ESM calculation were based on the requirements of the 10-day menu cycle derived in French & Perchonok (2006). After determining that an oil-processing scenario that used the Skeppsta Maskin AB Type 20 oil press possesses a low yield efficiency (35%) and high mass penalty (582 kg), a bulk commodity provision was recommended for peanut oil supply. The peanut oil processing, although technologically feasible, was not a prudent operation for the habitat given the bulk commodity alternative.

Wilson & Zehr (2003) examined the Soymilk, Tofu, Okara, and Whey (STOW) Processor developed for space habitat processing of soybeans. **Figure 1** shows the STOW assembly as tested. The initial deliverable processor was brought to NASA Johnson Space Center (JSC)

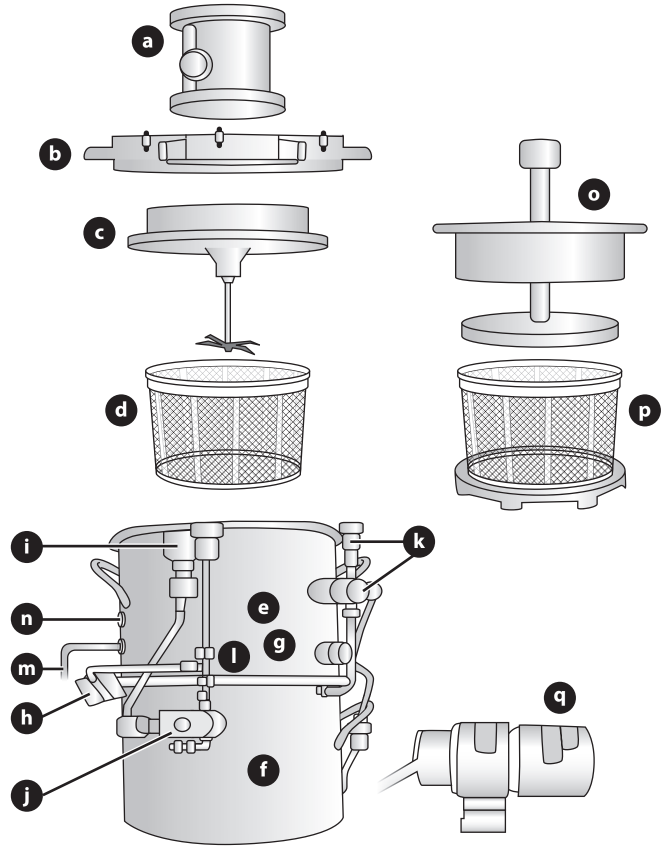

Figure 1

Diagram of soybean, tofu, okara, and whey processor: (*a*) grinder motor, (*b*) process tank lid, (*c*) grinding blade assembly, (*d*) filtration basket, (*e*) process tank, (*f*) coagulation tank, (*g*) inlet valve (rear of tank), (*h*) flow meter, (*i*) process tank valve, (*j*) coagulation tank valve, (*k*) coagulant solution inlet and valve, (*l*) heating element connection (rear of tank), (*m*) process tank temperature probe connection, (*n*) process tank drain valve connection, (*o*) manual press head, (*p*) curd filtration tank, and (*q*) transfer pump.

(Houston, TX) in May 2001 to be evaluated for its ability to process raw soybeans into acceptable soymilk and tofu. Concurrently, waste products (okara, whey, and cleaning fluids) were to be quantified. The equipment itself had design flaws, but researchers did determine that the Hoyt soybean varietal, although ideal for hydroponic farming, did not process well for soybean and tofu production. A redesigned STOW, as well as soybeans with clear hila, high protein, and low beany flavor, was recommended for subsequent testing.

In response to a NASA small business innovation research call for Martian food equipment development, Insta-Pro International, in combination with a Purdue research team, set out to develop a miniaturized extruder to produce wheat and rice extrudate and expel oil from peanuts and soybeans (Gandolph et al. 2007). Extruded products were produced by the scaled extruder unit, but pasta was not successful due to an inability to develop the gluten structure within the wheat and rice (Penner 2008). One researcher recommendation was to produce the pasta using a small pasta maker that could be hand powered to better control moisture addition and mixing (Penner 2008). Minimal oil was expressed when the raw peanut or soybean was placed into the extruder, but the extrusion process resulted in approximately 10% of liquid oil and 90% solid meal that has an oil content of approximately 16% when starting with raw soychips or peanut flour (Penner 2008, Wijaya 2007). Key processing parameters were identified for both grain and oilseed processing, but additional work is required to finish the scale-down of the extruder and address limitations in using the crops with minimal treatment after harvest.

Aside from the purposeful segregation of foodstuff components, equipment for Mars is also being considered that reduces the active time that the crew has to attend to food processing operations. Fruit and vegetable processing were considered in the context of ingredient processing, particularly to achieve concentrated tomato products. Voit et al. (2006) worked to identify an integrated membrane approach that allows for the concentration of tomato pulp from tomato crop in a single automated unit. The percentage solids of the concentrate was limited by particle retention at the membrane, which prevented the juice from being fully extracted. Optimization of the temperature and pressure during operation is anticipated to diminish some of the permeate flux problems and reduce the processing time but increase overall power consumption. It is unknown whether the equipment would fair favorably in ESM against a manual, stovetop production of tomato sauce or reconstituted tomato sauce from tomato powder. The latter processes have less equipment mass and may require more active time in processing but are expected to have less associated food waste, less cleaning time, and comparable food quality.

A comprehensive look at equipment was conducted by Gandolph et al. (2004) when their team completed a series of detailed ESM-based estimates for small-scale, food-processing equipment that might be used in an ALS food system. The study was an effort by researchers to identify relevant commercial processing equipment for ALS missions as well as to assemble and calculate appropriate ESM parameters. Researchers considered 250 pieces of equipment, including heat transfer equipment, mixing technologies, size reduction processes, and separation unit operations. The ESM calculations did not incorporate crew time, and resulting ESM values were not adjusted to account for varying equipment capacities, throughputs, or duplicate functions. Nevertheless, detailed datasets have been maintained, and further modification of the Gandolph et al. (2004) ESM calculations can easily be achieved to support future trade studies.

Food Preparation in a Martian Galley

Although the Mars habitat kitchen will more likely resemble the compact kitchen of a recreational vehicle, the facility capability will still be greatly expanded over the food warmer and potable water dispenser that make up the cooking facilities on the ISS. The final galley equipment determines

Table 2 The mode of heat transfer for common cooking methods (Zimmerman 2007)

Method	Conduction	Convection	Radiation
Steaming	High	High	Low
Boiling	High	Moderate	Low
Deep frying	High	Moderate	Low
Sautéing	High	Low	Low
Broiling	Moderate	Low	High
Baking	High	High	Moderate
Grilling	Moderate	Moderate	High
Microwaving	Low	Low	High

the level of variation in the menu and how much crew time is required for meal preparation. However, not all equipment will be appropriate for Mars. The physical phenomena manifested in the cooking process determines what equipment is feasible and if any modifications are required. Zimmerman (2007) identified the modes of heat transfer associated with common cooking unit operations (**Table 2**).

Conductive heat transfer is unaffected in the hypogravity of Mars unless the contact between the cooking surface and the heating element is compromised (Fu & Nelson 1994, Gregson & Lee 2001). Most range processes have high dependence upon conduction. Rather than traditional gas or electric stovetops, though, an induction cooktop, pressure cooker, and/or multifunctional cooking pan may be considered for traditional range cooking in space so that volatile control, more rapid cooking, and safer cooking processes are achieved. An induction cooktop uses electromagnetic transfer phenomena to induce heat in a magnetic-based pan, which subsequently heats the food in the pan. Because there is no flame and even the cooktop itself does not heat, the apparatus is safer and cleaner than other ranges. The method is also faster than electric cooktops, approximately halving the time to boil water from the same starting temperature in the same vessel. A pressure cooker is considered advantageous for space because the cooker directly counters the reduced pressure of the space habitat environment. At reduced pressure conditions, water boils at much lower temperatures, which slows the heat transfer into the food in the water. However, by containing the cooking volatiles and increasing the system pressure, as in a pressure cooker, the temperature at which water boils is raised, a higher temperature is achieved in the cooker, and the food is cooked more quickly. The wide variety of cooking operations that can be performed in the pressure cooker, as well as the reduction in water required to make recipes, render the unit attractive for space operations as well. Finally, the multifunctional cooking pan was proposed by Zasypkin & Lee (1999) to handle the heating of all cooking, boiling, extracting, and fermenting procedures. Because the unit was hermetically sealed with a valve, it could also blend powders or act as a pressure cooker.

Free convective heat transfer is affected in the hypogravity of Mars; buoyancy forces that normally drive the movement of particles as they change temperature and density are absent. Thus, for Mars, a forced air convection oven is recommended for baking operations (Fu & Nelson 1994, Zasypkin & Lee 1999, Gandolph et al. 2004).

A bread maker is commonly included in the Mars food equipment list because of the predicted availability of wheat, either through hydroponic farming or bulk commodity stowage. French & Perchonok (2004) evaluated four bread-maker technologies that differed in mixing/kneading actions and pan orientations. The TR3000 had the lowest calculated ESM value, was able to produce a loaf with large particle bran and low hardness value, and was the easiest bread maker to operate, but it is unknown how the unit performs in hypogravity. The bread maker uses one paddle for mixing and kneading in a vertical pan, which may prove inadequate for the mixing process. A Bready prototype bread maker uses a mixing bag to squeeze the ingredients together; such a modification may be necessary for operation and outweighs ESM results in equipment selection.

Safety Considerations of an in situ–Based Space Food System

The change from a commercially sterile, prepackaged food supply to a more dynamic stream food supply introduces the risk of microbial contamination of the food supply. Because of the risk of microbial contamination of the food supply in storage and cooking, the bioregenerative food system is considered a high microbial food system.

Most terrestrial foodborne illnesses result from mistakes at the processing facility or in the preparers' kitchen, not with the ingredients themselves. McCabe-Sellers & Beattie (2004) reported that the top five contributing factors of recognized foodborne illness in the United States from 1993–1997, listed high frequency to low frequency, were improper holding of hot or cold food, poor personal hygiene, cross contamination, inadequate cooking, and unsafe food source. The translation of these factors to a space habitat is primarily affected by the absence of raw animal products and constraints on water and power usage.

The resource constraints of a space habitat (e.g., water, power, living volume) increase the risk that foodborne illness will result from the ingredient processing, food preparation, or human handling. For example, calcivirus, the leading cause of gastroenteritis in the United States, is spread by the fecal-oral route of transmission and has demonstrated remarkable virulence on cruise ships because of the contained environment (McCabe-Sellers & Beattie 2004). Calcivirus can be transmitted via contaminated surfaces, hands, people, food, and water supply. Limited resources impact the ability to proactively control microbial populations in closed environments.

Water will likely be the most demanded consumable resource during a habitat mission. Without adequate hot water for hygiene, dish washing, and food preparation, the probability of spreading calcivirus and other viruses increases. In the FMARS2007 study—an Antarctica-based Mars analog—crew members showered only once per week and used hand sanitizer in lieu of washing hands to conserve water (Bamsey et al. 2009). The water conservation methods seen during FMARS2007 could prove dangerous to a Mars mission crew, as studies have shown alcohol-based sanitizer to be ineffective against calcivirus populations (Liu et al. 2010).

Power is required to keep hot foods hot and cold foods cold and to generate hot water. In a bioregenerative system, where multiple menu items are being prepared in a small galley area, the need to warm foods for an hour or more while a complementary dish is being prepared is probable. The food warming time is extended even longer if the crew eats at staggered meal times due to mission responsibilities. Maintaining the correct food temperature requires power inputs. Additionally, hot water and, in some cases, steam, are required for food processing equipment and dish sanitation; hot water is required for hand sanitation. If power usage becomes a concern during the mission, power used during food preparation may be limited, thereby increasing risk of foodborne illness.

The microbial impact of the bioregenerative system is mitigated through the food system safety program implemented at the remote habitat location. A variety of methodologies and practices are used to promote and verify the microbial safety of food systems or food production facilities terrestrially from farm to table. Notermans et al. (1997) present these avenues as shown in **Table 3** below. A similar safety program would need to be implemented for an extraterrestrial bioregenerative food system.

Table 3 Conventional and rapid microbiological methods in safe food production

Use of microbiological methods	Relative importance[a]	Most suited methods	
		Conventional[b]	Rapid and automated[c]
Safe food production			
Monitoring and surveillance			
Detection of pathogens	−	−	++
Detection of indicator organisms	+	+	−
Detection of bacterial toxins	−	−	++
Storage tests	++	+	+
Microbial challenge testing	++	+	+
Predictive models			
Performance testing	+	+	+
Mathematical models	−	−	−
Management of safe food production			
Good manufacturing practice	+	++	++
Hazard analysis critical control points			
Hazard analysis	+	+	−
Identification of critical control points	±	+	−
Monitoring	−	−	−
Verification	−	−	−
Failure analysis	+	++	−
Food borne disorders			
Testing of reported outbreaks	+	++	−
Sentinel studies	++	−	++
Risk assessment studies	++	++	+

[a]Necessity and convenience of a microbiological technique for obtaining reliable and/or applicable results.
[b]Methods based on enumeration of organisms, such as determination of colony-forming particles, and methods allowing organisms to be obtained in a pure state for a further characterization. Conventional methods for detecting bacterial toxins are those using animal models.
[c]Methods that detect organisms on the basis of production of metabolic products or compounds. Such methods for bacterial toxins use a direct test system for the toxin itself.

CONCLUSIONS

As NASA's mission focus expands to enable manned space exploration of the Martian surface, its food system must also continue to evolve. Increasing autonomy of these missions necessitates a departure from complete reliance on a shipped prepackaged food system and instead requires crews to demonstrate increasing reliance on a bioregenerative food system. Research conducted to date to identify crop varieties, growth chamber designs, and food processing equipment to support such a system was summarized in the present document. In spite of this tremendous research progress, there are still significant needs regarding food safety, refinement in crop selection, and galley design that will need to be addressed before NASA can support Mars missions with an effective food system.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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