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Hydrated Food Should Be Used on Long Space Missions

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In early space missions it was assumed that future astronauts would consume concentrated bite-sized cubes and rehydrated freeze-dried foods to minimize the mass of food that was launched. Such extreme space-designed foods were used but were found unsatisfactory, so more familiar food was substituted. Until recently, it was often assumed that long duration space missions would use dehydrated food and recycled water to save mass. Familiar normally hydrated food could provide higher quality and better nutrition, but would require a significantly higher launch mass. Designing a food system for space must trade-off nutrition, cost, and safety as well as familiarity and acceptability. In the past, the key variable in space food system design has been the food moisture content. Normal food is typically two-thirds water. Dehydrated food can eliminate most of the water mass but has much lower acceptability. The well planned food system for the International Space Station (ISS) balances acceptability and launch cost by using a mix of dehydrated, moisture reduced, and normal food. Now that commercial rocket systems have reduced the cost of launch to a small fraction of the shuttle cost, there is much less need to use dehydrated food to reduce food launch mass. Normally hydrated food should now be used on long space missions.

Nomenclature

CxP	=	Constellation Program
EVA	=	ExtraVehicular Activity
HSIR	=	Human Systems Integration Requirements
ISS	=	International Space Station
MTBF	=	Mean Time Before Failure
MTTR	=	Mean Time To Repair
MRE	=	Meal, Ready-to-Eat

I. Introduction

AT the start of the space age, it was thought that space food should be dehydrated and eaten directly or reconstituted in space using recycled water. Dehydrated food would save considerable launch mass on long missions. This approach was tested in the first brief manned missions using food cubes and powders, but after the initial experiences specialized space food was not well accepted. Current space food is more similar to Earth food and provides a more agreeable and familiar diet.

It was also believed that food could be produced in space using algae, fungi, or crop plants such as wheat and soybeans. Research continues, but such systems would provide a less balanced and satisfactory diet and require much higher launch mass and development cost than stored food.

Providing food in space is extremely complicated compared to providing water or oxygen. Nutrition is multifaceted and food is infinitely varied. Diet is subject to various habits, expectations, and inclinations toward familiarity or variety. Planning, preparing, and consuming meals is heavily laden with personal and social meanings. And of course, tastes differ.

Designing a space food system goes far beyond the usual systems engineering considerations, but it is still important to carefully consider performance compared to requirements, operability and the human interface, safety and reliability, and cost. The dehydrated food system used on the first flights was clearly objectionable, but given the extremely high costs of space missions, saving launch mass and cost wherever possible seemed necessary.

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The food system must compete for launch mass and cost, development cost, and crew maintenance time with other mission systems. The overall resource allocations depend on the system interactions and cost drivers. The food system has direct functional interactions with the habitation and life support systems, especially the water and oxygen systems. The crew's human metabolism uses oxygen to burn calories, and the demand for both oxygen and calories increases with exercise. Water is required to prepare dehydrated food, while hydrated food contributes additional water for potential recycling. The spacecraft water balance affects the desirability of using dehydrated food or hydrated food. Abundant "free" water, as derived from fuel cells on shuttle, makes dehydrated food attractive. But if water is launched and stored, as on Skylab, it might be better provided in hydrated food.

The food launch mass, which has been a major cost driver, increases directly with the food moisture content. Dehydrated food can approach zero moisture while normal food is typically two-thirds water. Food acceptability would usually increase with higher moisture content and launch mass but has been reduced to save cost.

Now commercial rocket systems have reduced the launch cost to a small fraction of the shuttle cost. The shuttle launch cost was about 75 $k/kg. This corresponds to the actual cost per launch of 1.2 billion dollars for 16,000 kg to Low Earth Orbit (LEO).[1] When the shuttle provided the International Space Station (ISS) with food, the ISS food system did save considerable launch mass and cost by using some dehydrated food. However, the shuttle has been retired since 2011 and recently SpaceX has provided significantly lower launch cost to ISS. A SpaceX Falcon 9 launch costs 62 million dollars and can place 22,800 kg in LEO.[2] The SpaceX Falcon 9 launch cost is 2.72 $k/kg. Launch cost has been reduced by a factor of about 28.

High launch cost was long recognized as a major impediment for space exploration.[3] Now that the hoped-for great reduction in launch cost has occurred, launch cost is not usually the major mission cost factor. The new lower launch cost has drastically changed the tradeoff between reduced food mass and launch cost versus higher mass, moisture content, and acceptability. It is now possible to increase food mass, moisture, and acceptability to the maximum desired and still have a food launch cost about an order of magnitude lower than in the shuttle era. Specifically, if food mass is increased by a factor of 3 for full moisture and launch cost is reduced by 1/28, the final launch cost is reduced by 3/28.

II. History of food in space

At the beginning of the space age it was usually assumed that future manned space stations and long term moon or Mars missions would use dehydrated foods produced by freeze-drying. "Freeze-dried food will provide the major part of the diet for the foreseeable future." And "a normal food diet … is probably impractical for a long-term mission."[4] "It is assumed that completely precooked and dehydrated foods will be employed."[5] Using dehydrated foods requires much less launch mass than providing hydrated food. A water recycling system is needed and was assumed to be available. Since future long missions would need dehydrated food, early short missions were planned to demonstrate it even though the mass savings were not large.

A. Mercury and Gemini food (1961-1966)

America' first astronaut, John Glenn, showed in his fifteen-minute flight that it was possible to eat in zero gravity. Later Mercury astronauts were provided with three kinds of food: bite-sized cubes that produced annoying crumbs, unappetizing pastes in squeeze tubes, and freeze-dried powders that were hard to rehydrate. Gemini, so called because two astronauts flew, had somewhat improved food. The squeeze tubes, used by Uri Gagarin when he was the first man in space, were abandoned. The bite-sized food cubes were coated with gelatin to reduce crumbling. The freeze-dried foods were provided in plastic containers to make rehydration easier. The food quality and variety were improved in Gemini. Shrimp cocktail, chicken, vegetables, butterscotch pudding, and applesauce were added. Astronauts were able to select their own menus.[6] The two longest Gemini flights were eight days, the duration of the first Apollo moon landing mission, and fourteen days, equal to the longest Apollo moon mission.

The space food provided in Mercury and Gemini was designed by engineers to meet the basic requirements of spaceflight. It provided balanced nutrition and was processed and packaged to be compact, survive launch, and last indefinitely. The crews did not complain but they did not like the food.[7]

> "Compressed, processed, and packaged, space food was an engineering triumph: it took up little space, it would survive launch without disintegrating, and it would last almost indefinitely. Furthermore, it provided balanced nutrition to sustain life up to 90 days-provided, as one official put it, a way could be found 'to influence the crews to eat [it].' "[7]

B. Apollo and Skylab food (1966-1974)

Apollo like Gemini provided dehydrated foods, tube paste foods, and bite-sized cubes, but added more familiar food preserved in thermostablized pouches.[8] Hot water made rehydrating the freeze-dried foods easier and improved the food's taste. The rehydrated moist food could be kept in plastic zip-lock containers called "spoon bowls" and would stick to a spoon in zero gravity.[9] Despite these improvements, the Apollo astronauts, even Gemini veterans, complained strongly about the food and did not eat as much as needed to maintain weight.[8]

To assess these complaints, a self-described "human garbage can" agreed to live on Apollo food for four days. He had regrets at the first meal, breakfast. The sausage patties seemed like flavored ground rubber and left a long lasting and sickening aftertaste. After one day, the tester's appetite was much less than usual and by the third day mealtimes were unwelcome and eating was unenjoyable work. Space food similar to normal every day food was good but food designed for space was very bad. Chocolate and peanuts, which could have been left alone, were ground up and converted into bite-size cubes that stuck to the teeth.[7]

It seemed that future crews should have better food, and that bad food would make the planned one, two, and three month Skylab missions even more difficult. Rather than pastes squeezed from tubes, annoying cubes, or rehydrated powders, it would be much better to provide conventional and appealing meals that could be eaten in a more normal way. This was reinforced when the Apollo 8 crew that first orbited the moon greatly appreciated a Christmas dinner of hot turkey and gravy.[7]

The Saturn V designed for Apollo was used to launch Skylab, a large laboratory module, into low Earth orbit. The much larger living area allowed the Skylab food system to be much more elaborate and well-appointed than anything else ever used in space. The larder and galley included a refrigerator and freezer to store perishable and frozen food and pressurized storage for aluminum cans.[7] "No other space vehicle before, or since, has had the capability to provide these."[8] Skylab had a dining room with table and chairs that were fastened to the deck. Foot and thigh restraints held the astronauts sitting in Earth-normal positions. Cutlery included knife, fork, spoon, and scissors for cutting open plastic food containers. The dining table had magnets to hold the utensils and trays to warm the food.[7]

Skylab had five kinds of food: dehydrated, intermediate moisture, wet-pack thermo-stabilized food (similar to the turkey dinner provided on Apollo 8), frozen, and refrigerated fresh foods.[7] There were 72 different foods provided on a six-day menu cycle. Dehydrated foods include meats, pasta, and beverages. Some were in plastic pouches that could be connected to a galley hot water source for rehydration. Foil was used for beverage pouches for longer shelf life. Thermo-stabilized food is stored in tin cans at room temperature and includes fruits, vegetables, soups, and deserts. The freezer provided ice cream, filet mignon, and lobster, and the refrigerator supplied chilled beverages and desserts. Since all of the food for missions extending over two years had to be launched in Skylab, most of it was provided in aluminum cans to ensure adequate shelf life.[10, 11]

The Skylab crews liked the food better than Apollo crews, but still found it unsatisfying because it did not taste like food on Earth. Head congestion in weightlessness seems to reduce the astronauts' ability to smell and taste.[7] The metabolic studies of the Skylab astronauts required them to eat all their food. Skylab has been the only space mission where the astronauts not loose weight. [8]

C. Space Shuttle food (1981-2011)

Since the space shuttle and the International Space Station (ISS) do not have refrigerators or freezers, all food must be stored at ambient temperature. Both shuttle and ISS use freeze-dried, thermostablized, irradiated, intermediate moisture, and natural food. Natural food includes nuts, granola bars, cookies, and sometimes fruit. The beverages are dried powders. Twelve irradiated meat items were used. The thermostabilized and irradiated food is packaged in flexible plastic and foil pouches that require less mass and storage volume than ordinary round cans. The freeze-dried foods are vacuum packed in clear, flexible packages. Hot and cold water and heat are used to prepare them. The crewmembers taste and select from the more than 200 available foods. Individual menus are checked and revised by a dietitian to provide adequate nutrition.[8, 10]

Astronauts find that the food does not taste the same and is not as flavorful in space. Condiments are appreciated and include commercial packets of catsup, mustard, mayonnaise, taco sauce, and hot pepper sauce. Bulk pepper in oil and salt in water are provided in dropper bottles.[10]

> "Diets are designed to supply each Shuttle crew member with all the Recommended Dietary Allowances (RDA) of vitamins and minerals necessary to perform in the environment of space. Caloric requirements are determined by the National Research Council formula for basal energy expenditure (BEE)." [9]

Each Shuttle astronaut's menu included three balanced meals and snacks and was repeated every seven days. Each individual's food single service containers were identified by a colored dot. The Space Shuttle galley included a hot and cold water dispenser for rehydrating foods and a convection oven for warming foods.[9, 10]

A meal tray holds several open food containers and is attached to the astronaut's lap or a wall using Velcro, magnets, or a bungee cord. As on Skylab, the utensils are a knife, fork, spoon, and scissors to open packages. Set up time is about five minutes. Rehydrating and heating the food is another 20 to 30 minutes. Empty food containers are discarded in the trash compartment. The utensils and food trays are cleaned using moistened towelettes.[9]

The space shuttle used fuel cells that produce water as a by-product. Because of the availability of water at no cost, dehydrated foods were emphasized. About half of the Shuttle food was dehydrated, including beverages. The ISS uses solar panels for electrical energy rather than fuel cells, and the net water balance has sometimes been negative, so more thermostabilized foods are used in ISS.[8, 10]

D. International Space Station (ISS) food (1998-)

A typical shuttle mission was 11 to 14 days but ISS missions are six months, so the ISS food system must pay even more attention to nutrition, acceptability, and variety. The initial ISS menu cycle was six days but it has gradually increased to a ten-day menu cycle. 65 new foods were developed for the ISS menu.[8]

Because of the longer duration of ISS missions, logistics, packaging, storage, and waste are important issues. On the ISS food is stored by categories in different boxes so that crewmembers can choose what to eat during each meal. Until future space stations and planetary bases have refrigerators and freezers, most of the astronauts' diet is expected to be dehydrated and thermostablized foods.[8] The relative amount of each will partly depend on the water recycling system and overall water balance.

Dehydrated foods include soups such as chicken consommé and cream of mushroom, casseroles such as macaroni and cheese and chicken and rice, appetizers such as shrimp cocktail, and breakfast foods such as scrambled eggs and cereals. The dehydrated food package is flexible to aid in trash compression. Velcro holds it in the meal tray. After water is added, the package is heated in the serving tray. Thermostabilized foods are also heated to destroy microorganisms. Fruits and fish are thermostabilized in cans with easy-open lids. Puddings are packaged in plastic cups. Most meat and vegetables are packaged in flexible pouches that are heated and cut open with scissors. Natural form foods are ready to eat and packaged in clear, flexible pouches. Fresh flour tortillas have long been used to solve the breadcrumb problem.[9]

E. Astronaut weight loss

All astronauts except those on Skylab had daily food consumption that was less than required to meet their energy needs and maintain their body weight. They lost between 5% and 10% of their preflight weight. Since energy needs in space are about the same as on Earth, the weight loss is due to under consumption of food.[12]

Early food researchers thought the solution was simply to order astronauts to eat the food.

> "(I)n our system the food discipline of the crewmembers has been poor. I have said this to them, so I will say it in public: Food and water discipline is something that soldiers learn early or they do not survive. The space crews have not been very disciplined about their eating - they have picked, traded, and done as they pleased."[13]

The three reasons for the astronauts' under-consumption of food are poor appetite, less palatability, and insufficient direction. The astronauts found space food unsatisfying because it did not taste like food on Earth due to the effects of weightlessness.[7] Earlier space foods especially were less appetizing, and the food discipline needed for early metabolic studies was relaxed.[8]

F. Space food incidents

Food evens can make interesting stories in space.

1. Corned beef sandwich on Gemini

Gemini III Mission Commander Gus Grissom loved corned beef sandwiches, so Pilot John Young brought one along, even though Grissom was not supposed to eat anything. Grissom enjoyed the sandwich but floating bread crumbs were a potential problem and Grissom did not finish it. The astronauts were only mildly rebuked by NASA but NASA deputy administrator George Mueller had to promise a congressional hearing that it wouldn't happen again.[14]

2. Wine almost flew on Skylab

There was interest in providing wine on Skylab, possibly to extend even further its unequaled space dining luxury. The industry hopefully provided many samples, but a University of California expert recommended a sherry because it is more stable, already oxidized with alcohol added. Once opened, it won't deteriorate. NASA bought Paul Masson Rare Cream Sherry, repackaged it out of the original heart shaped bottle into a plastic pouch in a pudding can, and flew it on a zero g parabolic flight aircraft. When the wine was opened, all on board instantly became sick. The Skylab crews were not particularly interested in having wine and "NASA was afraid of the response of us serving wine on board a Space Station, so they decided to cancel it. So we drank all of the cream sherry."[15]

3. US astronaut enjoyed food on Mir

U.S. Mir astronaut Andy Thomas said,

> "There was an abundance of food up there. I had my choice of American food and Russian food, much more food than I could eat. It was really a good selection of food, actually. The food is largely canned food and rehydratable foods, much like you might use on a camping trip or something like that, and I had more than enough to eat. … I really enjoyed the food that was available to me."[16]

4. Taco Bell tortillas in space

The familiar problem of bread crumbs in space was solved when Mexican astronaut Rodolfo Neri-Vela brought tortillas on shuttle in 1985. They were crumb-less and easier than bread to use in zero gravity. But the commercial tortillas had limited shelf life, so NASA produced its own for multi-week shuttle missions. In the late 1990's, just in time for the six month long ISS missions, Taco Bell began producing tortillas designed and packaged to last nine months and NASA quit making them.[17, 18]

III. Future food concepts for space

Most experts expect future food systems to be like those used in the past, but some interesting ideas have been suggested.

A. Shuttle and ISS food for future long missions

Currently in the United States space program is it usually assumed that future food systems will be similar to those used for shuttle and ISS. They will primarily use freeze-dried and thermostablized, vacuum packed food, with perhaps some irradiated, reduced moisture, and natural food. "The majority of authors writing today consider freeze-dried, vacuum-packed, and frozen products and dishes to be the most promising for use on long-term flights."[19] But frozen foods need a freezer that requires significant mass, power, and volume.

Until crop growing and food preparation systems are developed, "dehydrated and thermostabilized foods will continue to exist, providing the bulk of the astronauts' food." [8, 12]

B. Food production in space

Several interesting methods to produce food in space have been suggested. These include food crops, chemical synthesis, and 3 D printing. They are not currently feasible but may be more practical in the future.

1. Food production by crop plants

NASA has in the past extensively studied growing crops for food in space. Suggested food plants include wheat, potato, soybean, sweet potato peanut, lettuce, and tomato.[20]

A food producing crop chamber can produce all a space crew's oxygen, water, and food, but it would require a large launch mass for the chamber, power source, and supporting equipment. For a Mars mission, the launch mass of the crop food system is many times larger than the mass to provide oxygen and water recycling systems and stored food. Growing crops requires more launch mass than simply launching and storing all the food, water and oxygen needed, so it is not a practical current food system option.[21]

2. Chemical and microbial synthesis of food in space

It is argued that,

> "Food is the most costly expendable resource for long space missions. Prepackaged food is massive and has limited shelf life. Bio-regenerative food production by higher plants entails large investments of energy, equipment and labor per unit of food energy produced, and has a lengthy recovery time in the case of crop failure. Direct chemical and hybrid chemical/microbial synthesis of food ingredients could furnish food ingredients such as glycerol, fats, functional proteins and even sugars from waste materials."[22]

However, much research is required before synthetic food can be expected.

3. 3 D printing of food in space

It is claimed that,

> "Biological food chamber systems require careful round-the-clock monitoring and input adjustments for optimal performance. Newer and readily available three-dimensional printing/extruding technology presents a quicker and more reliable option, opening up the possibilities of use in the concoction of new flavors, creative and aesthetically pleasing design, aroma, and presentation of food and meat protein substitutes for space missions."[23]

C. Space food concepts from similar Earth applications

It would be helpful if astronaut food was light in weight, easy to prepare, and had long shelf life. Some situations on Earth have similar requirements, including camping, combat, and animal feeding.

1. Camping food

Food for camping is often a combination of freeze-dried, dehydrated, and precooked ingredients. Freeze-dried and dehydrated meals save weight but some high moisture food can be carried as a treat. Camping foods must be shelf-stable, meaning that they do not need refrigeration or freezing. As in space, campers sometimes take perishable fresh food to be used in the first few days. Cooking over a campfire can be interesting, but many campers prefer to just add hot water, as often done in space. Camping can require high levels of calories, also similar to space. Campers often prefer freeze-dried ingredients over dehydrated because they are easier to prepare and retain more flavor. Dehydrated foods can be complete meals or ingredients such as vegetables for cooking. The most common other precooked foods used in camping are meats such as tuna in metal foil laminate pouches or the similar surplus Meals, Ready-to-Eat (MREs), discussed next. Common everyday food can also be used camping, such as dried soup, instant mashed potatoes, pasta, polenta, ramen, and grits.[24] Camping food could provide a low cost, well tested, safe supplement to especially developed astronaut foods.

The Russians have fed volunteers exclusively freeze-dried food for up to one year. These studies show a completely dehydrated diet is possible, but adaptation requires up to two months.[19]

2. Meal, Ready-to-Eat (MRE)

The Meal, Ready-to-Eat (MRE) is the current individual U.S. military combat ration. MREs contain precooked foods in retort pouches. A retort pouch is a plastic and metal foil laminate bag that is heat sterilized at pressure and is an alternative to traditional industrial canning methods. Retort pouches are used for camping food, space food, and consumer foods and drinks.

The MRE replaced the canned C-ration of WWII, Korea, and Vietnam as standard issue in 1986. The C-ration provided a nutritionally balanced meal but it was heavy, not considered palatable, and made it difficult to persuade soldiers to consume sufficient nutrition. MREs are an only partially successful attempt to solve these problems. Continuing development has produced dozens of main dishes and more than 100 other food items. A flameless ration heater uses a water-activated exothermic reaction to produce a hot meal. Powdered beverages also can be mixed with water and heated.[25]

MREs meet difficult requirements. They must survive a 100 ft drop and three and a half years of shelf storage. An MRE contains a main course, side dish, bread, dessert, flameless ration heater, and spoon. Each has about 1,200 Calories. MREs are high-fat, averaging about 40% fat calories, and high-salt, far from ideal for a normal diet. MREs are not dehydrated and contain roughly the normal amount of water in food, but some require a little water to be added.[25]

Typical service members, highly active men aged 18 to 30, burn about 4,200 Calories per day, but they consume only 2,400 Calories a day during combat. They do not eat all their MRE rations, trading or throwing away nearly half. Some MREs are not very palatable. Their low dietary fiber causes serious constipation. They are supposed to be eaten for only three weeks but have been used for up to a full year.[25] The MRE approach is attractive, but current military MREs are not suitable for camping, emergency, or space food.

3. Pet chow, kibble and food bars for animals and humans

There is interest in a cheap, simple-to-prepare, fast, and nutritionally complete food for people that would be similar to Purina cat and dog chow or other pet foods such as kibble, biscuits, and bars. People chow might be used by campers, computer programmers, soldiers, disaster victims, and astronauts.[26]

Lab Diet old world primate food bars provide a complete life-cycle diet for all old world primates and seem suitable for humans. It is claimed to be highly palatable and readily consumed. It contains 60% carbohydrates, 26% protein, and 14% fat with vitamins C and D. The ingredients include corn, soybeans, pork fat, sucrose, fish meal, yeast, whey, and many vitamins, minerals, and preservatives. It should be fed twice per day at the rate of about 3% of body weight per day, in a sufficient amount to maintain constant body weight. It is designed to be uniform to reduce diet induced variation in long term primate studies.[27]

Mary Roach investigated the chemistry of kibble, "To meet nutritional requirements, pet food manufacturers blend animal fats and meals with soy and wheat grains and vitamins and minerals. This yields a cheap, nutritious pellet that no one wants to eat." The solution is to apply different flavor coatings, in the same way that corn and potato chip snacks are made.[28]

People have tried to live consuming only monkey chow, "I started off eating it dry, which is difficult to eat because it's so hard. Then I switched to soaking it in water, which is easier to swallow but disgusting. It's got the texture of soggy bread. When I switched back to dry I was like, 'Man, that's not bad. ...' "[29] But after four days, the experimenter was "miserable, starving and probably going nuts."[30]

It seems physically possible but psychologically very difficult for humans to subsist on a dry processed food similar to pet kibble or primate bars. Food bars might be useful as supplemental or emergency rations.

4. NASA food bar

NASA is working on a 700-Calorie breakfast bar.

> "NASA food scientists are developing a food bar to replace a typical 700- to 800-calorie meal astronauts eat for breakfast." Ordinary food "takes up a lot of space and you get a lot of trash… If we had just one meal replacement bar, it's dense, but it saves a ton in terms of mass and packaging volume… we are doing testing to see what the satiety level is in terms of the bar and at what point … does mood start to change, in terms of frequency" of eating them.[31]

IV. Food system requirements

Developing a good set of system performance requirements is very difficult. Care must be taken to include all the important factors but also to avoid excessively restricting the system design. The true meaning of a requirement is determined by its actual verification, made by test, demonstration, inspection, or analysis.

A. Constellation food system requirements

The Constellation Program (CxP) included NASA's most recently planned long duration and deep space missions, a moon base and Mars exploration. The NASA Constellation Program required the food system to be able to rehydrate and heat food and drinks and to prepare a meal for all four crewmembers within 30 minutes. The menu was to provide 3,035 calories per crewmember per day and also meet specific detailed nutritional requirements. 200 additional calories were required for EVA (ExtraVehicular Activity).[32] The required packaged food shelf life would have been mission dependent.

B. Basic food system performance requirements

The suggested requirements below provide for the fundamental nutritional needs of the crew and can be implemented by different space food systems. Food system performance requirements are organized under major headings such as performance, environment, cost, etc., as shown in Table 1.

Table 1. Basic food system performance requirements.

Category	Requirement	Specification	Verification
Performance			
	Provide everyday calories	> 3,035 per day per crewmember.[32]	Laboratory test, long term crew test.
	Provide EVA calories	> 200 per EVA per crewmember.[32]	"
	Nutritional composition	Percentages of carbohydrates, proteins, fats, minimum daily requirements of vitamins and minerals, etc., per Table 3.5-1 - Nutrition Composition Breakdown Table (TBR-006-021)[32]	"
	Heat food and drinks	Between 68°C (155 °F) and 79°C (175 °F)[32]	Laboratory and ISS test and demonstration
	Rehydrate food using hot or cold potable water	Ref. 32	"
	Meal preparation time	< 30 minutes for 4 crewmembers.[32]	"
	Cleanup time	< 3 minutes for 4 crewmembers.	"
	Contamination	No detectable loss, spillage, or residue.	"
Packaging and labeling			
	Packaging	Individual servings	Inspection
	Labeling	Content and intended consumer	"
Shelf life and food storage reliability			
	Shelf life	> 1,000 days (Mars conjunction)	Test 2,000 days
	Reliability	< 1 in 1,000 failures in 1,000 days	"
Operating environment			
	Gravity	Microgravity, Earth, moon, Mars	Test in 1 g, parabolic flight, and ISS.
	Atmosphere	Earth normal, Constellation Exploration	Test
Storage environment			
	Pressure	Vacuum to twice Earth sea level	Chamber test
	Temperature	- 25 to +50 C	"
	Vibration, acceleration	Launch	Shake table test, ISS
Equipment operations			
	Reliability, MTBF	10 years	Test and analysis
	Maintainability	< 0.5 hr crew time/week	Demonstration
	Reparability, MTTR	< 3 hours	"
Safety			
	No hazards, no critical failures, no contaminants, no toxics		Analysis
Mission cost factors			
	Food mass	≤ 2 kg per day per crewmember.	Measurement
	Food volume	≤ 2 liters per day per crewmember.	"
	Added packaging mass	< 20% food mass	"
	Added packaging volume	<100% food volume	"
	Power, average	< 100 W	"
	Power, peak	< 400 W	"
	Cooling	= power	"

The performance requirements include nutrition and meal preparation. Food handling is covered by packaging, storage, and environment requirements. Food preparation equipment reliability is specified by Mean Time Before

Failure (MTBF), maintainability by crew time, and reparability by Mean Time To Repair (MTTR). The cost of food to the mission, not including development cost, is essentially the cost of launching the food and packaging mass and volume. The probably small cost of providing heat and cooling for food preparation should be included.

C. Expanded food system performance requirements

Meeting the basic requirements of Table 1 would provide a practical minimum food system, but improvements could be provided at increased cost. Some possible improvements are better food, advanced food systems, good meal environment, and improved food system results.

1. Better food

Table 1 has no requirements that food in space be acceptable, palatable, or tasty, or that it provide quality, variety, and choice. If normally hydrated food is provided in foil pouches, improving quality and variety would require development work but would not increase mission launch cost. If dehydrated food or food bars are used, partially substituting hydrated food would increase mission cost. Providing traditional food for holidays and special food to celebrate mission milestones would probably not increase cost much.

2. Advanced food systems

Many advanced food systems have been suggested as a way to provide better food. Skylab provided frozen food, a freezer, and a microwave oven for heating. Bulk food requiring preparation could be used, with a mixer and oven. A small plant growth chamber, a salad machine, could grow fresh lettuce and tomatoes.

3. Good meal environment

It might be useful to try to keep up morale by encouraging social interaction at certain mealtimes. This might be done by providing a large enough area with food trays and tethered crew positions.

4. Improved food system results

Probably the best way to set requirements is similar to the best way to manage projects, by specifying results and products, not actions or inputs. The food system should operate to maintain astronaut weight and to improve rather than reduce morale. It might be possible to change the diet or add supplements to counter the effects of microgravity and radiation. The food storage system might be designed to provide some radiation shielding. Since the food and water systems are closely coupled, providing a store of hydrated food and even drinks could help cope with water system interruptions.

V. Food systems analysis and design

The past and current food system designs are based on significant knowledge and experience and clearly indicate the expected way forward. Future food for long space missions has been planned to be very similar to the food now used on ISS. However, there are some new specific considerations that may require significant changes. A Mars mission cannot receive incremental additional food supplies, so the food shelf life must be much longer than for ISS. The cost of launching mass is much greater for the moon and Mars than for ISS, so the benefits of increasing dehydration and reducing mass are greater. Since a crew cannot return quickly from Mars, the reliability of the food supply must be greater than for ISS or the moon. The recent much lower launch cost makes fully hydrated food much less expensive.

The tight coupling of the food supply and the water supply causes a further complication. The water supplied in the food is usually a significant positive contribution to the overall water balance on a long mission, since it is exhaled or excreted by the crew and can be recycled. The water in the food can allow the water system to have lower recovery efficiency and can make up for losses and allow accumulation of water storage buffers to cover interruptions and down time. The water system design could require a significant provision of stored water from Earth to achieve sufficient reliability. If so, the required stored water should probably be provided as water in food, since this would improve the food palatability with no additional launch mass. The current moderately hydrated food could be replaced with fully hydrated food, improving palatability and supplementing the water supply.

Since the appropriate food system for long missions is difficult to determine and may differ for a moon base and Mars, it may be useful to investigate the overall systems engineering of space food supply, to define trade-offs, and compare alternatives.

A. Standard unmixed food systems

Although the best system could be mixed, its easier to analyze the standard unmixed food systems and consider mixtures later. The standard unmixed food systems are frozen, precooked and preserved, dehydrated, and bars. All these are possible food approaches that have been used. They are listed in order of decreasing familiarity, palatability, hydration, and launch mass, which are all strongly correlated.

Some suggested systems currently seem impractical. These include preparing and cooking food, growing food crops, synthesizing food, and 3-D printing of food.

B. Food system evaluation criteria and weights

The food systems can be evaluated by considering their more salient aspects and including the key discriminators. What must the food system do? The food system for long space missions must provide safe, nutritious, acceptable food that is affordable, reliable, and robust under mission conditions.

Food is safe if it is free from spoilage, contamination, and degradation that might harm the crew. Food is nutritious if it meets all human dietary requirements. Food is acceptable if the astronauts eat enough to perform their assignments and maintain body weight. Space food has clearly been safe and nutritious, but not acceptable.

The second three suggested evaluation criteria are more subjective and more difficult to define and assess. The cost of space systems is usually measured as life cycle cost, which includes development, launch, and operations costs. Considerable effort has been expended in developing food systems for space and clearly more is required. The launch cost of food depends on its mass and water content, and also the mass of packaging. Operations costs on the ground would be small, but the crew will spend considerable time preparing meals and cleaning up afterward. The food system can also include freezing, heating, and rehydrating equipment, with its development, launch, and operations costs. The food system is reliable if the food supply is not interrupted, for instance by a freezer failure or loss of rehydration capability. Failure modes are not easy to anticipate. A system is robust if it can operate successfully over a wide range of conditions that go beyond the intended design environment. Would the food system be unaffected if a moon base was evacuated in an emergency? If power was lost also?

These six suggested evaluation criteria are not all equally important. Safe and nutritious are more important than the other criteria, so they will be double weighted in numerical scoring.

C. Standard unmixed food system scoring

There are four standard single technology food systems, and six factors to score them against. Each system has a score of 1 to 10 assigned to each attribute. With the scores for safe and nutritious double weighted, the maximum score is 80.

The scores are shown in Table 2.

Table 2. Criteria scores for the four unmixed food technologies.

Factor	Safe	Nutritious	Acceptable	Affordable	Reliable	Robust	Total score
Weight	2	2	1	1	1	1	
System							
Frozen	5	10	10	2	5	5	52
Precooked	10	10	6	5	10	9	70
Dehydrated	10	10	4	9	8	6	67
Bars	10	10	2	10	10	7	69

Dehydrated solid food bars are very safe, rated 10. Dehydrated food safety is also rated 10. Precooked preserved food in pouches, such as MREs, are also very safe and rated 10. Frozen food can be spoiled if unfrozen in transit and usually has a wider variety that makes quality control more difficult, so it is rated 5 on safety.

All the food systems can provide completely nutritious food and all are rated 10. None of the food systems is really acceptable. How can a group of healthy, vigorous, active men supplied with all the nutritious food they want all loose weight unless compelled to eat? What makes them loose interest in food? The Skylab crew, supplied frozen food and compelled to eat, did not loose weight. Acceptability is estimated at frozen food, 10, food bars, 2, dehydrated 4, and precooked similar to MREs, 6.

Fully dehydrated food bars are most affordable, with minimum development cost, launch mass, operational equipment, and crew time, rated 10. Dehydrated food also has minimal launch mass but requires more development, equipment, and crew time, rated 9. Precooked and preserved food is nearly fully hydrated, and requires development for space, but needs minimal equipment and crew time, score 5. Frozen food is fully hydrated, and requires freezers, ovens, and crew time, so its affordability score is only 2.

Dehydrated solid food bars are very reliable, rated 10. Dehydrated food is very difficult to eat without water, but water is vitally important and should be reliable, so reliability is rated 8. Precooked preserved food in pouches, such as MREs, are also reliable and rated 10. Frozen food can be spoiled if the freezer fails and is difficult to eat if the heating oven fails, so is rated 5.

Robustness is the property of surviving unanticipated challenges, which might include loss of power, temperature and pressure extremes, and unattended or long extended operation. Food bars seem robust to such problems, and would be rated 10 based on them. But an additional unanticipated challenge is failure of the water recycling system. This is not the fault of the food system and would doom the crew, but the crew could probably survive if fully hydrated food was provided, as done by precooked and frozen food. [The absolute minimum water for human survival is about 1.2–1.4 kg/CM-day.[33] The water in food is about 1.15 kg/CM-day.[34]] Food bar robustness is rated 7 because they do not supply water. Dehydrated preserved foods in metalized pouches might suffer from temperature and pressure beyond design limits and also do not supply water, rated 6. Precooked and preserved foods supply water but also might suffer from temperature and pressure beyond design limits, rated 9. Frozen food does supply water but must remain frozen, rated 5.

D. Standard unmixed food system comparisons

The total weighted scores are shown in the last column of Table 2. Frozen food has by far the lowest total score, reflecting its lowest scores for safety, affordability, reliability, and robustness. Precooked, dehydrated, and bars have similar total scores. Precooked and bars have the two highest nearly identical scores. Both systems provide food ready to eat under almost any circumstances, but they differ in acceptability and affordability due to their complete hydration or dehydration.

The criteria scores for the four food systems are shown in Figure 1.

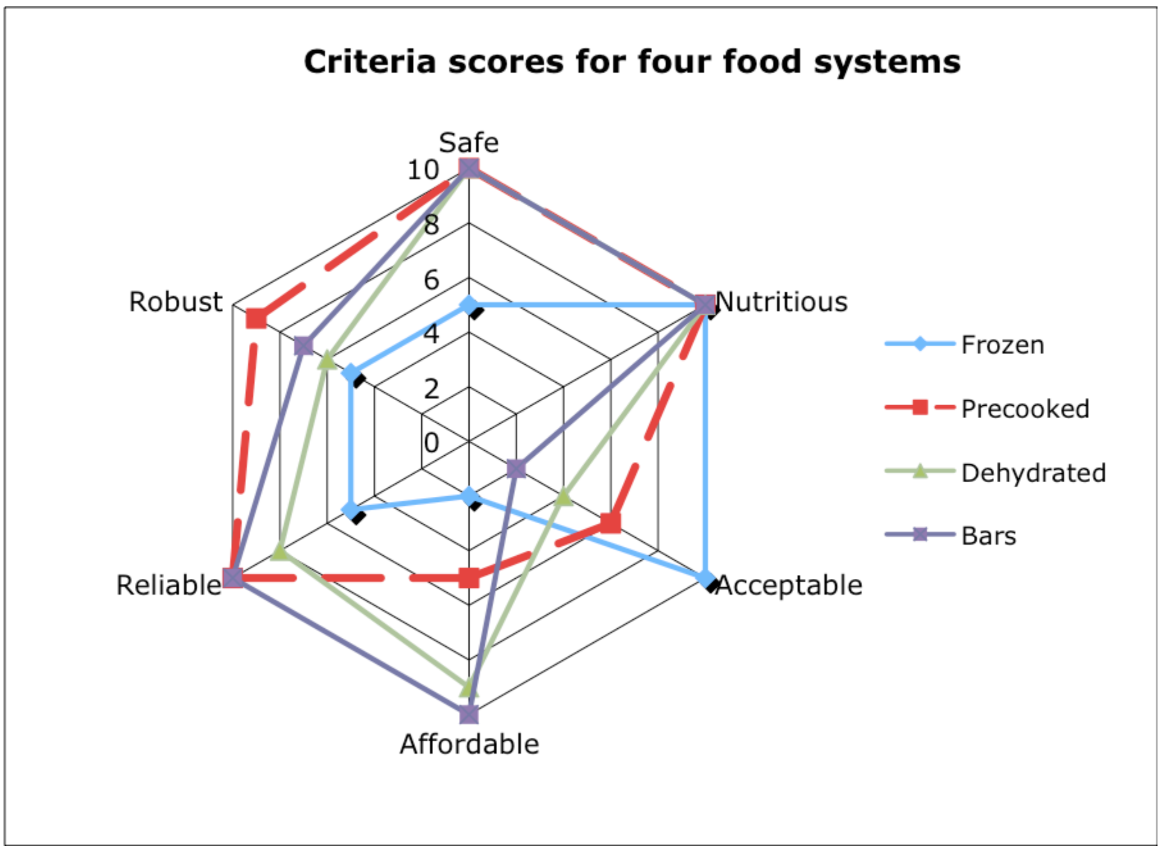

Figure 1. Criteria scores for the four food systems.

Figure 1 is an Excel radar chart that plots the data of Table 2, specifically the six scores for Safe, Nutritious, Acceptable, Affordable, Reliable, and Robust for the four different food systems, Frozen, Precooked, Dehydrated, and Bars. The system scores for each criterion can be read along each of the six criteria axes. The smaller area of the line figure for the frozen system reflects its lower total score, while the other systems have similar areas and similar total scores. The differences between precooked food and dehydrated food are shown in Figure 2.

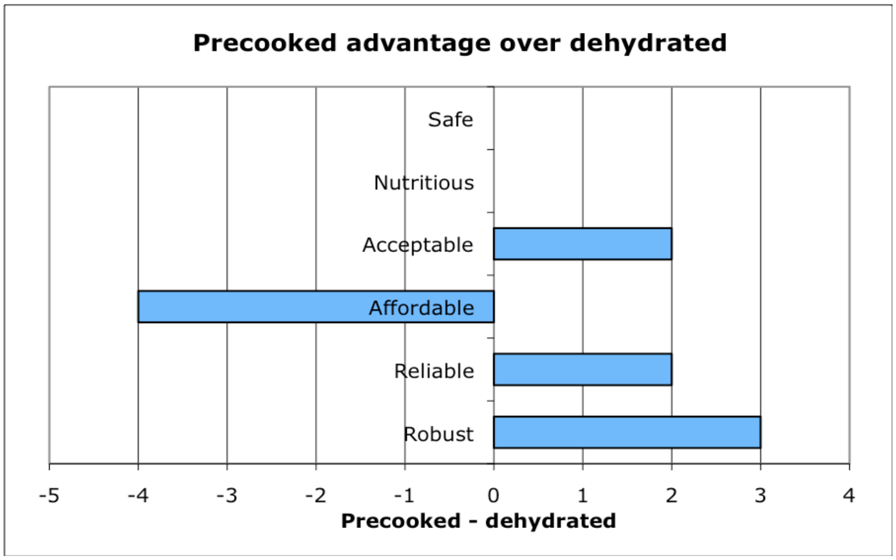

Figure 2. Factor differences between precooked and dehydrated food.

Precooked, fully hydrated food similar to MREs is more acceptable but less affordable than dehydrated food. It is also more reliable and robust, not requiring water itself and providing water that may be needed if the water recycling system fails.

VI. Conclusion

The key variable parameter in food system design is the degree of food hydration, the fraction of the original water remaining in the food. More water in the food increases acceptability but decreases affordability. A compromise between acceptability and affordability would lead to a mixed food system, partly hydrated food, partly dehydrated. An overriding need to minimize launch mass and cost, coupled with a high confidence in the water system reliability, would force the extensive use of dehydrated food or food bars. Since launch cost is much lower than before, it seems reasonable to provide fully hydrated food and maximize food nutrition and acceptability. Fully hydrated food is a safe, secure, store of water, and comes close to supplying all the water needed for crew survival. It seems clear that hydrated food should be used on future long space missions.

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