Space Food System Water Content: Considerations for ECLSS Water System Closure

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The water content of the food system has a direct impact on determining an efficient level of water system closure in the Environmental Control and Life Support System (ECLSS) on a spaceflight mission. The standard food system, which makes up the majority of the food on the International Space Station (ISS), consists of a variety of shelf stable foods that are provisioned to meet nutritional requirements. In this work, we compiled food system information to estimate water content within the standard food system, given varying usage rates. Outcomes indicate that, as provisioned and with a predicted consumption rate that meets nutritional requirements, approximately 46% of the current standard food system is water. Around 88% of the water content in the food system was determined to be in the retort thermostabilized foods. Recent mission analysis has indicated it is beneficial to life support processing to reduce the water content to 30%. With the assumptions used in this analysis, approximately 37% of the retort thermostabilized foods (ready-to-eat, fully hydrated at launch) would need to be replaced with freeze-dried foods to meet this goal. The feasibility of developing a similar nutritional variety of acceptable and stable freeze-dried foods to replace this percentage of thermostabilized foods is currently unknown. Some foods are not as compatible with freeze-drying, and consideration must be given for provisioning balanced macro and micro-nutrition, variety, and acceptability, in addition to water content. ISS crew members have commented that the variety from different types of foods is important to prevent menu fatigue and maintain intake, health and performance. The ready-to-eat, fully hydrated foods are especially critical when crew time is limited. The impact of reducing these options on overall intake and resulting health and performance is currently unknown and would need to be assessed.

I. Introduction

The water content of the food system has a direct impact on determining an efficient level of ECLSS water system closure on a spaceflight mission[1]. In order to understand the interaction with the water system, it is important to understand why the food system was developed as it is provisioned on ISS currently.

The ISS food system is provided as a standard food set with 10 container categories and six types of food (Figure 1). It is provisioned by the NASA JSC Space Food Systems Laboratory (SFSL) to meet nutritional requirements with a commonly accepted food set that provides a limited amount of choice[2]. This standard system was developed because food may be launched to ISS months ahead of crew, and resupply schedules shift, which will not support preference for late crew changes. The foods are developed and produced, or procured commercially and repackaged into

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spaceflight compatible packaging, by the SFSL. The standard foods make up the bulk of the food available on the ISS and provide the best estimate of food water content.

Container Categories	Food Types (Standard Variety Available)
Beverages	B - Beverages (25)
Breakfast	I - Irradiated (3)
Condiments	IM- Intermediate Moisture (3)
Desserts & Snacks	NF - Natural Form (59)
Fruits & Nuts	R - Rehydratable/Freeze-dried (49)
Meat & Fish	T - Retort Thermostabilized (68)
Nutrition Bars	
Rehydratable Meats	
Side Dishes	
Vegetables & Soups	

Figure 1: Container categories and food types in the ISS standard food system. The thermostabilized foods are fully hydrated and ready-to-eat when launched and have the highest water content. The beverages (all powdered) and freeze-dried foods have the lowest water content.

Food packaging varies by food type, but the majority is lightweight and flexible. It may include clear flexible laminates, aluminum laminates, plastic bottles (for condiments), septum adapter assemblies (plastic one-way valves that enable rehydration of drinks and freeze-dried foods in microgravity), and vecro attachments to manage food in microgravity. Foods are stowed, by category, into clear plastic laminate bags that serve as containers and include RFID tags[3].

The thermostabilized foods are fully hydrated and ready-to-eat when launched and have the highest water content, averaging around 70%, with some over 90%. The beverages (all powdered) and freeze-dried foods have the lowest water content, around 3%.

Not all foods are freeze-dried for several reasons. First, not all foods are compatible with freeze-drying, and do not rehydrate to acceptable textures. If food is not acceptable, it is not consumed in adequate quantities, and the nutritional benefit is not achieved even if it is provisioned. ISS crew members have commented that the variety from different types of foods is important to prevent menu fatigue and maintain intake, health, and performance. Second, freeze-dried foods take preparation time to rehydrate. The retort thermostabilized foods that do not require rehydration are especially critical to maintain adequate intake when crew time is limited. Third, nutritional stability varies by nutrient and food matrix[4], supporting the need for a variety of food processing methods and full understanding of the impacts of those methods with each matrix.

Fourth, the current ECLSS oxygen and water systems are not fully closed and require the addition of water and oxygen to maintain the system balance[5]. On ISS, the existing overall water recovery rate is ~93%. Currently, makeup water is launched periodically from earth in addition to the water content of launched food and water produced by metabolic processes. Therefore, with the current ISS ECLSS partial loop closure there would be no mass savings from reducing the water content of the food system. Recycled water is added to launched food that requires rehydration. New urine brine processing hardware has been flown to ISS in 2021 and will be deployed soon. Afterward, the water recovery rate is estimated to increase to ~98%, which for practical reasons essentially closes the water loop[6]. However, recycled water is also used to produce some of the oxygen supply as well as hydrogen by electrolysis. The hydrogen is then used in the process of oxygen recovery from expired CO_2. Recovery from CO_2 is currently limited to ~47% due to limited availability of hydrogen[5]. The remainder of the oxygen is provided by resupply in tanks from Earth. If CO_2 recovery/reduction technologies that are currently in development and that do not need the recycled water are successful, oxygen recovery will increase to >75% and possibly >90%. For practical reasons, this will close the oxygen loop. Consequently, both the launched makeup water and some of the water content in the food system would no longer be beneficial and would result in excess water. Therefore, there is potential that closure of the oxygen loop would not be beneficial given the current water levels already in the food system, as additional water would not have a use and would be discarded. Estimates indicate that the best combined mass savings of increased oxygen recovery and water from ECLSS loop closure would require the food system to have a water content of 30%. A more detailed description of the food water content verses total vehicle depature mass, prior to the evaluation provided in this paper, can be found in reference 1. Hence improving the understanding of the current food system water content is very important to understanding the potential to reduce overall mass for long duration exploration vehicles.

Calculating the water content of the food system is complex, as containers have varying usage rates, depending on caloric needs, and the usage rate of each type of container can vary from crew to crew based on preference and choice. Additionally, each crewmember receives a subset of personally selected foods and beverages that varies with each mission. These personal foods can include commercially available foods that meet basic spaceflight requirements. Resupply vehicles also bring varying amounts of fresh foods in a fresh food kit (e.g. apples, oranges), extra crew specific items in shelf stable food kits, and crew care kits that may contain a variety of shelf stable foods. Occasionally, crew receive cheese or ice cream if a powered refrigerator or freezer has available space. These preference and extra food items vary, and water content is unpredictable.

In addition to the variability in provisioning, there is unpredictable variability at point of crew consumption, which will ultimately have the biggest impact on water system closure. Consumption of the standard food system containers, foods within those containers, and even the personally selected foods varies. Some foods are discarded, which changes by crew, and this is not currently tracked in detail. Therefore, some variability in water content addition to the ECLSS system must be accounted for beyond what is provisioned in the food system.

In this work, we compiled food system information to estimate water content within the food system, given varying usage rates. Overall, as provisioned and with a predicted consumption rate that meets nutritional requirements, approximately 46% of the current standard food system is water. In order to reduce the water content to 30%, approximately 37% of the retort thermostabilized foods (ready-to-eat, fully hydrated at launch) would need to be replaced with freeze-dried foods. Further work is needed to determine if this is achievable.

II. Objectives

1. Compile all 207 standard menu foods, food weights, packaging weights, and water contents to enable evaluations of the relationship of water content with food menu selections.
2. Determine water contents based on varying usage rates and assumptions.
3. Define a strategy with the potential to reduce water content of the standard food set to 30%.

III. Methods

Data Compilation: Information for all ISS standard menu foods and food weights were compiled from spaceflight specification sheets. Usage rate estimates for both containers and number of each item in a container was included. Water contents were obtained from NASA's Space Food Systems Laboratory (SFSL) analysis or records from contract lab analysis. In some cases, water contents were estimated from literature values or from similar products measured in the SFSL[7, 8]. Food packaging used by the SFSL was weighed in individual parts (e.g. septum, velcro, primary packaging, overwrap; n=10). All numbers can be adjusted for analysis of alternative scenarios. Water content was calculated based on predicted usage rates for the ISS food system items.

Potential Reduction Strategy: The 25 thermostabilized foods with the highest water content were identified. The relationship of these foods with food system water content was determined based on their actual water content. The relationship was then predicted with the water content of these foods reduced to the levels of freeze-dried foods. The relationship produced an equation between the thermostabilized foods and water content that will enable food impact predictions for any water content within that range, down to the goal of 30%.

It cannot be overemphasized that this method was theoretical to inform the bounds of what may be possible. It is one potential strategy, and the challenges of other strategies are included in the discussion section. Implementation of this strategy would require significant future work, including product development and shelf life testing of all foods, including nutritional comparisons and acceptability evaluations.

IV. Results

Using a predicted consumption rate that would provide adequate calories and nutrition, the food system is about 46% water. Approximately 88% of the water content in the food system is in the retort thermostabilized foods. Therefore, water content was reduced in increasing numbers of retort thermostabilized foods to determine a relationship that would predict the number of thermostabilized foods that would need to be replaced with freeze-dried foods to achieve any target water content (Table 1). The 25 thermostabilized foods with the highest water contents would need to be replaced with a freeze-dried alternative in order to achieve a water content around 30%.

Table 1: Change in water content as thermostabilized foods are replaced with freeze-dried foods, based on ISS food system usage rates

Number of Thermos Replaced	% water with packaging	% solid food with packaging	% Packaging	% of Thermos Replaced	% of Food System Replaced (out of 207 items)
0	45.7	40.3	14.0	0	0
5	42.0	43.2	14.8	7.4	2.4
15	36.6	47.2	16.2	22.1	7.2
25	30.9	51.4	17.7	36.8	12.1

The relationship between the 25 thermostabilized foods with the highest water content and the % water content with packaging, as shown in Table 1 as they are replaced with freeze-dried versions, can be characterized by the following equation (R^2=0.9975). Reducing the water content further would require additional calculations and relationships, as water content of individual foods varies and is lower for all other foods in the system. The relationship would not remain linear.

$$\#\ of\ thermos\ to\ replace = \frac{(Target\ \%\ water\ with\ packaging - 45.352)}{-0.5807}$$

V. Discussion

In this work, we compiled food system information to estimate water content within the standard food system, given varying usage rates. Outcomes indicate that, as provisioned and with a predicted consumption rate that meets nutritional requirements, approximately 46% of the current standard food system is water. A three year mission to Mars with four crewmembers would require around 10,500 kg of food, with packaging, using the current food system. It has been estimated that a reduction to 30% water, and the mass savings from unneeded oxygen tanks, would generate overall mass savings even with the additional infrastructure required to further close the oxygen loop. One strategy to reduce the water content to 30% would require approximately 37% of the retort thermostabilized foods (ready-to-eat, fully hydrated at launch) to be replaced with freeze-dried foods.

The feasibility of developing a similar nutritional variety of acceptable and stable freeze-dried foods to replace this percentage of thermostabilized foods is currently unknown and may not be achievable. Some foods are not as compatible with freeze-drying, and consideration must be given for provisioning balanced macro and micro-nutrition, variety, and acceptability, in addition to water content[9]. ISS crew members have commented that the variety from different types of foods is important to prevent menu fatigue and maintain intake, health and performance. The retort thermostabilized foods that do not require rehydration are especially critical when crew time for food preparation/rehydration is limited. The impact of reducing these options on overall intake and resulting health and performance is currently unknown and would have to be assessed.

Other options for water reduction may be identified with the use of the compiled information. One potential option would be smaller water reductions in a wider variety of foods. However, foods are developed to have a moisture content that is expected, acceptable, and familiar. The acceptability of incremental water reduction of many foods that would be consumed as is, compared to the acceptability of developing freeze-dried versions where adequate water may be added at point of consumption, has not been evaluated. However,incremental decreases in water content would require a greater number of foods to be reformulated and tested to achieve 30% water in the food system than selecting foods with the highest water contents and developing freeze-dried versions.

Another option may be the use of powdered condiments that could be rehydrated at the point of consumption. Many condiments are over 50% water, but they are not generally available powdered. The feasibility of developing acceptable powdered alternatives that meet spaceflight requirements would need to be assessed. Although condiments contain a high percentage of water, the quantity of condiments is significantly smaller than thermostabilized foods. If powdered condiments were proven feasible, they would need to be used with other water saving strategies.

It is important to note that personally selected crew foods and other food augmentations (fresh foods, extra food kits, and International Partner foods) are not included in the compilation. Crew may eat 12-25% of their calories from these alternatives, which may include a range of water contents. We have determined that hundreds of commercial items have been included in personally selected food containers and much of the water content information is not publicly available. Given that the inclusion of personally selected foods on exploration missions is still unknown, and the foods that would be included cannot be predicted, we did not include any of these items in this assessment. However, it is possible that when personally selected foods are averaged across many missions, the water content likely would not appreciably change the conclusions of this initial study.

VI. Conclusions

Most of the water in the standard food system is available in fully hydrated, ready-to-eat thermostabilized foods, which provide variety and a fast meal option in limited crew time scenarios. The current system contains approximately 46% water, based on a nutritionally complete usage rate. Nearly 40% of the thermostabilized foods would need to be replaced by or reformulated as freeze-dried foods to reduce this water content to 30%. The feasibility, nutritional impacts, and acceptability of any level of reduction would need to be assessed prior to implementation.

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