Risk of Inadequate Food and Nutrition Causing Decrements in In-Mission Health and Performance and Long-term Health (Food and Nutrition Risk)

Revision D

Human System Risk Board

HSRB CR SA-C20023
Approved: 6/9/2025
Out of Board

Risk Custodian Team

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Purpose

- To preview updates to the Risk of Performance Decrement and Crew Illness Due to Inadequate Food and Nutrition via Change Request (CR) SA-C20023

This revision:

- Did not change the Likelihood x Consequence (LxC) scores assessed against updated Design Reference Missions (DRMs) and the 5x5 Risk Matrix
- Provides updated evidence that supports current LxCs.

This information was previously reviewed/dispositioned at:

Meeting	Date	Outcomes/Direction
HSEICB	3/26/2025	Agreement to present to the HSRB

Contents

1. Risk Title and Risk Statement

- **Risk Title**
  Risk of Inadequate Food and Nutrition Causing Decrements in In-Mission Health and Performance and Long-term Health (Food and Nutrition Risk)

- **Risk Statement**
  Given that there is a constrained ability to supply adequate food in spaceflight missions, there is a possibility that inadequate nutrition will result in performance decrement, crew illness, and long-term health effects.

2. Risk History

Meeting	Date	Outcome/Direction
HSRB Risk Presentation	6/9/2025	Decisional – CR SA-C20023, Update Risk Record, Approved Out-of-Board, Rev D
HSRB Risk Presentation	4/10/2025	Informational – CR SA-C20023 Update Risk Record, Rev D
CMB Status Update	9/13/2023	Concurrence.
HSRB Risk Presentation	7/21/2022	Decisional – CR Approved with Mods. Approve Risk Rev C
Risk Evaluated via CR	4/14/2022	CR evaluation period closed on 4/29/2022
HSRB Risk Presentation	4/14/2022	Informational - Content reviewed by the HSRB for release on CR
HSRB Risk Presentation	1/13/2022	Decisional - Approved to close CR: SA-04518 HSRB - Updates to Risk's Directed Acyclic Graphs (DAGs) and to update the DAG and DAG narrative in the Risk Records
HSRB Risk Presentation	2/20/2020	Decisional – CR Approved with Mods. Approve Risk Rev B
Risk Evaluated via CR	9/25/2019	CR evaluation period closed on 11/19/2019
HSRB Risk Presentation	9/19/2019	Informational - Content reviewed by the HSRB. Approval for release via CR
Risk Evaluated via CR (Released)	8/28/2015	Decisional – CR Approved as Written (format) – Rev A
Action Item Closure	5/4/2015	Decisional – % values were transposed in LxC driver section: Approved out-of-board
HSRB Risk Presentation	12/17/2014	Decisional – CR Approved with Mods. Approve risk baseline
Risk Evaluated via CR	12/1/2014	Decisional – Provide integrated risk (food & nutrition) based on new risk process (JSC 66705)
HSRB Risk Presentation	10/15/2014	Decisional – Action Item closure - integrated plan to provide better nutritional food systems for flight crews – Team working details with ISS & CB.
HSRB Risk Presentation	9/25/2014	Informational – Content to integrate both risks into one was reviewed by the HSRB
HSRB Risk Presentation	8/29/2012	Decisional – Partially approve CR for Mars DRM only – tabled

		for other missions (Food Risk)
Risk Evaluated via CR	8/21/2012	Decisional – Likelihood x Consequence (LxC) Assessment for the Food Risk
Risk Evaluated via CR	3/25/2009	Decisional – Approved with Mods 04/20/2009 (Nutrition Risk)
Risk Evaluated via CR	3/11/2009	Decisional – Approved with Mods 04/02/2009 (Food Risk)
HSRB Risk Presentation	3/10/2009	Informational – Content reviewed by the HSRB. Approval for release via CR regarding “Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System
HSRB Risk Presentation	2/24/2009	Informational – Content reviewed by the HSRB. Approval for release via CR regarding “Risk Factor of Inadequate Nutrition”

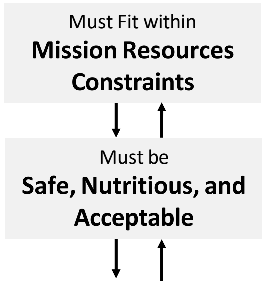
3. Executive Summary

Food and nutrition – the first line of defense to both physical and behavioral health as well as performance decrements.

- International Space Station (ISS) food system currently meets operational needs, but has many features that will go away with more stringent logistics in future missions
  - ISS examples include fresh fruits and vegetables, care packages, preference foods
- Data from ISS Food Intake Tracker (ISS FIT) Application suggest that crew are not within acceptable longer-term nutritional bounds in several categories.
  - Continuing to see weight loss from crews not eating enough (data from Gemini, Apollo, Shuttle, ISS)
  - Continuing to see dehydration inflight, which requires IV saline post flight.
- Increased likelihood of nutritional deficiencies or toxicities on exploration missions where food will be more constrained (prepositioning, no fresh fruits/vegetables).
- Human Exploration Research Analog (HERA) data show that reduced variety and acceptability further impact consumption.
- Do not have a food system that can get us to Mars and back with the quality and acceptability sufficient to maintain appropriate caloric and nutritional intake.

Given increased food restrictions on upcoming missions the impacts to crew health and performance could be significant but are currently unknown.

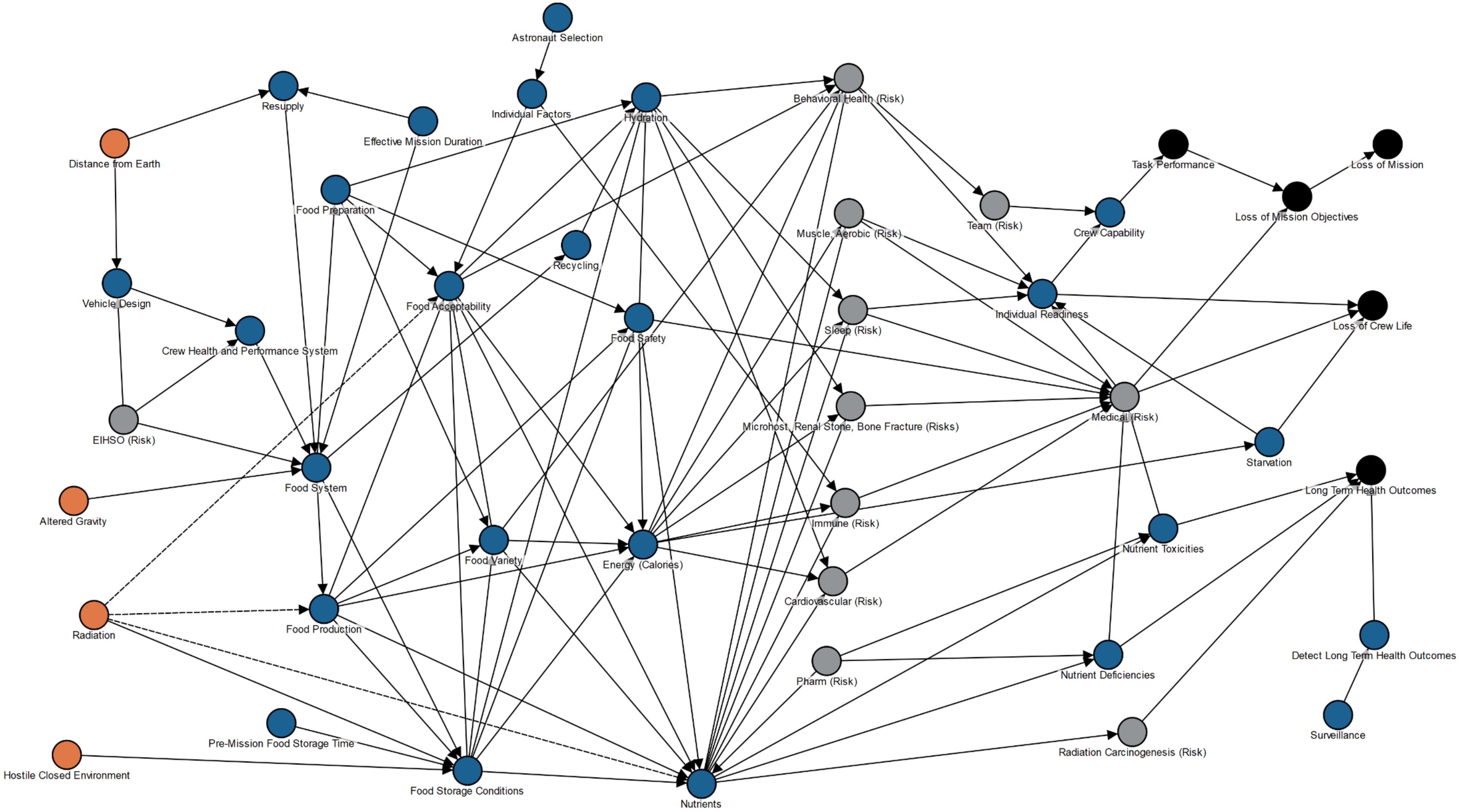
- Drivers include constrained mass and volume and / or prepositioning, Design Reference Mission (DRM) category changes



Food and nutrition are still a red risk for Mars

- Both the known capability gaps and the unknown health and performance impacts from the limitations of food and nutrition is a Mars Long Pole, already acknowledged by the HSRB.
- LxC risk postures have been set based on consideration for known risk and unknown impacts to crew health and performance that generates uncertainty for upcoming missions.

4. Food and Nutrition Risk Directed Acyclic Graph



Directed Acyclic Graph – DAG Narrative

The primary hazard for the Food and Nutrition Risk is distance from Earth due to feasibility to resupply and limited food shelf life.

The central issue in the Food and Nutrition Risk encompasses six nodes in the center of the diagram that highlight the contribution of food to human health and performance.

- **Energy (Calories)** - this is the amount of energy that food supplies to crew to enable them to live and perform. Insufficient energy in the diet leads to body mass loss, muscle loss, bone loss, oxidative stress, and cardiovascular deconditioning, and ultimately starvation and death.
- **Nutrients** - this includes macro and micronutrients that are a critical part of our diet and without which we develop nutrient deficiency diseases and other pathophysiologies. The term nutrition also encompasses thousands of phytochemicals that when sufficient can provide anti-inflammatory, anticarcinogenic, and other benefits. Some nutrients degrade with storage duration, which may be impacted either positively or negatively by storage conditions. There is some evidence that nutrients may be degraded by **radiation** but the few studies to date have used higher levels and different sources of radiation than expected in human spaceflight. The dotted line indicates the low amount of evidence in this area.
- **Hydration** – hydration status is determined by total water intake and exit from the body. Dehydration can affect multiple other risks, including cardiovascular, renal stone, cognition, performance, fatigue, and more.
- **Food Acceptability** – if food is not acceptable it does not matter if it has the required nutrition – they may not consume enough to get adequate nutrition. This is affected by storage duration and conditions and by Individual Factors such as food preferences and allergies which are part of the **Immune (Risk). Astronaut Selection** affects the extent of those factors present in a given crew.
- **Food Variety** – variety is part of acceptability – a nutritional variety of foods needs to prevent menu fatigue and provide choice to prevent risk of underconsumption and undernutrition
- **Food Safety** – if food is not safe it does not matter if it has the required nutrition – it will be a major risk to crew health and loss of mission.

In conflict with this is another critical concept - resources. To date, nutrition, energy, acceptability, and variety have been cut by programs, regardless of unknown risk, when resources are not available. Mass/volume and power are limited by the **Vehicle Design, Crew Health, and Performance System**, and highly dependent on **Distance from Earth** as well as the **EIHSO (Risk).** This is also dependent on **Resupply**.

Resources also impact:

- **Food Preparation** includes items such as a water dispenser, water heater, food warmer, and other equipment that can determine the amount of time that preparation activities add to the schedule as well as the acceptability and safety of the food for the astronauts. This is key to acceptability. Food and preparation equipment must be compatible with **Altered Gravity and Hostile Closed Environment.**
- **Food Storage Conditions** includes refrigeration and packaging of food and exposure to temperatures and pressures outside of acceptable ranges. This is key to nutrition and acceptability and is affected by **Pre-Mission Food Storage Time** which historically has ranged from weeks to years. Refrigeration and packaging must be compatible with **Hostile Closed Environment**.
- **Food Production** which, if designed into the system may include necessary equipment for

growing food and ensuring safety, and capability such as salad crops may be critical for acceptability on long duration missions with no resupply of fresh provisions. There is some evidence that **Radiation** may affect seed viability and nutrition of produce. Dotted line indicates the low amount of evidence in this area.

- **Recycling** primarily includes water.

In order to mitigate risk, crew must intake an appropriate amount of **Energy (Calories), Nutrients**, and **Hydration**. The system must provide the necessary food quality meeting **Food Acceptability, Food Variety**, and **Food Safety** requirements that supports adequate intake. Nutrition, acceptability, and safety must be maintained through the mission duration (adequate shelf life). Too little of these and **Nutrient Deficiencies, Starvation**, or medical conditions such as dehydration can occur. Excess nutrient intake may cause **Nutrient Toxicities** or other medical conditions such as polydipsia, hyponatremia, etc. Optimal nutrition can provide additional benefits, including anti-inflammatory (**Immune Risk**) and anticarcinogenic effects (**Radiation Carcinogenesis Risk**), which can be a key countermeasure to prevent disease on long duration missions. This balance affects other risks listed below that all contribute to non-optimal **Individual Readiness, Crew Capability** and through that affect **Task Performance**. Through the **Medical (Risk)** or through **Starvation**, **Nutrient Toxicities** or **Nutrient Deficiencies** these can also affect the likelihood of other **Mission Level Outcomes** including Loss **of Mission, Loss of Mission Objective, Loss of Crew Life**, and **Long-Term Health Outcomes**.

Food system (including nutrient deficiencies and/or toxicities) directly affects the likelihood of other risks listed below:

- **Behavioral (Risk)** Prolonged isolation and confinement can be a contributing factor to inadequate food and nutrition intake, and an inadequate food system / inadequate nutrition will adversely impact mood, cognition, and performance, serving as an additional stressor in the exploration environment.
- **Muscle** and **Aerobic (Risks)** fitness levels including stamina and strength can be affected.
- **Sleep (Risk)** affects factors such as physiological health, behavioral health, and cognitive function.
- **Microhost, Renal Stone, and Bone Fracture (Risks)** – all have nutritional underpinnings and can lead to specific medical conditions occurring in mission.
- **Immune (Risk)** system dysregulation can occur as a result of inadequate energy and nutrient intake. This also includes hypersensitivity reactions like food allergies which are affected by **Individual Factors**.
- **Cardiovascular (Risk)** function and **SANS (Risk)** through vitamin issues or other single nutrient deficiencies.
- **Nutrient Toxicities** occur when too much of a required nutrient is ingested. These can include vitamin and mineral toxicities if astronauts consume too much in-mission and affect **Long-Term Health Outcomes** (e.g., liver damage from Vitamin A overconsumption; neuropathy from excess B-vitamin or manganese intakes)
- **Nutrient Deficiencies** occur when too little of a required nutrient is ingested. Scurvy from a lack of vitamin C or rickets from a lack of vitamin D are historic examples that can lead to **Long-Term Health Outcomes**.
- Antioxidants and other nutrients may play a role in affecting **Radiation Carcinogenesis** likelihood and **Long-Term Health Outcomes** for long missions.

Surveillance enables us to detect **Long-Term Health Outcomes** and better characterize the risk as we gather more evidence.

5. Risk Summary

Primary Hazard:

Distance from Earth

Secondary Hazard(s):

Isolation and Confinement
Radiation
Altered Gravity
Hostile Closed Environment

Countermeasures in use:

Prevention

Validated nutrition requirements and acceptability standards, pre-packaged balanced/optimized food with stable nutrition, processing and packaging standards, microbial standard; astronaut selection

Monitoring

Dietary intake, track medical conditions and performance metrics, care team approach

Intervention

Dietary prescription as feasible

Contributing Factors

Mission design; changing nutritional requirements over long duration missions; no crew preference; food safety; food acceptability; nutritional stability of food; compromised storage, packaging, or handling of food; food preparation capability (e.g., heating, hot water, refrigeration) immune system function during spaceflight; spaceflight microbial environment; vehicle design for food storage including temp/pressure/mass/volume.

State of Knowledge

Much is known about the basic nutrition required to maintain performance and health during spaceflight. Standards/controls exist to maintain food safety during spaceflight. Ground data indicates that dehydration and "quicker than usual" weight loss in physically fit individuals will impact cognition and performance. Adequate nutrition and safe food have been demonstrated for 6-month missions and limited 1-year missions that have resupply. Ground data indicates that optimizing food/nutrient intake will likely benefit multiple systems, will drive nutrient requirement definitions, and food provisions. There is an uncharacterized risk during LO and LOS missions due to resource restrictions, high storage temperatures, potential pressure changes, and increased EVAs resulting in risk to food stability, and reduced food provisioning and preparation capability compared to ISS. Mass and volume restrictions on food will result in higher energy and lower nutrient densities (i.e., less fruits and vegetables). This will increase health and performance risks. The capability to provide safe pre-packaged food with a 5-year shelf life that provides adequate nutrition content, acceptability, safety, and variety is a gap. Some countermeasures (CMs) being investigated are: Bioregenerative supplementation and alternative processing, packaging, and storage. The impact of both the current and proposed exploration food systems on cognition, performance, behavior, and many other aspects of health is not adequately understood. Potential health impacts include 1) reductions in crew performance (loss of endurance, cognition); 2) crew illness (loss of bone and muscle mass, immune function, cardiovascular performance, gastrointestinal function, severe dehydration, nausea, diarrhea, endocrine function, ocular, psychological health, and the ability to mitigate oxidative damage); 3) long term health effects (cancer, bone, cardio, etc.), 4) interactions with other systems/countermeasures (e.g., drug/nutrient interactions, environment influences on oxidative stress, exercise-induced alterations in energy reqs.).

General Assumptions

- Assume current requirements specific to each vehicle have been met (these meet a subset of the NASA Standards 3001 for food and nutrition)
- Based on the HSRB LxC Matrix and the HSRB DRM Categories

DRM Categories	Mission Type and Duration	Assumptions
Low Earth Orbit (LEO)	Short (<30 days)	Regular resupply
	Long (30 d-1 yr.)	Regular resupply
Lunar Orbital	Short (<30 days)	Assumes there are no EVAs. No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital missions do not meet NASA Standard 3001*
	Long (30 d-1 yr.)	Assumes there are no EVAs. No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital missions do not meet NASA Standard 3001*
Lunar Orbital + Surface	Short (<30 days)	No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital + Surface missions do not meet NASA Standard 3001.*
	Long (30 d-1 yr.)	No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital + Surface missions do not meet NASA Standard 3001.*
Mars	Preparatory (<1 year)	No resupply, prepositioned food system, no crew personalization, expect food provisioning and preparation capability to meet NASA Standard 3001 but there is currently a shelf-life capability gap
	Planetary (730-1224 days)	No resupply, prepositioned food system, no crew personalization, expect food provisioning and preparation capability to meet NASA Standard 3001 but there is currently a shelf-life capability gap

6. LxC Quick Look

Previous (Approved July 2022)

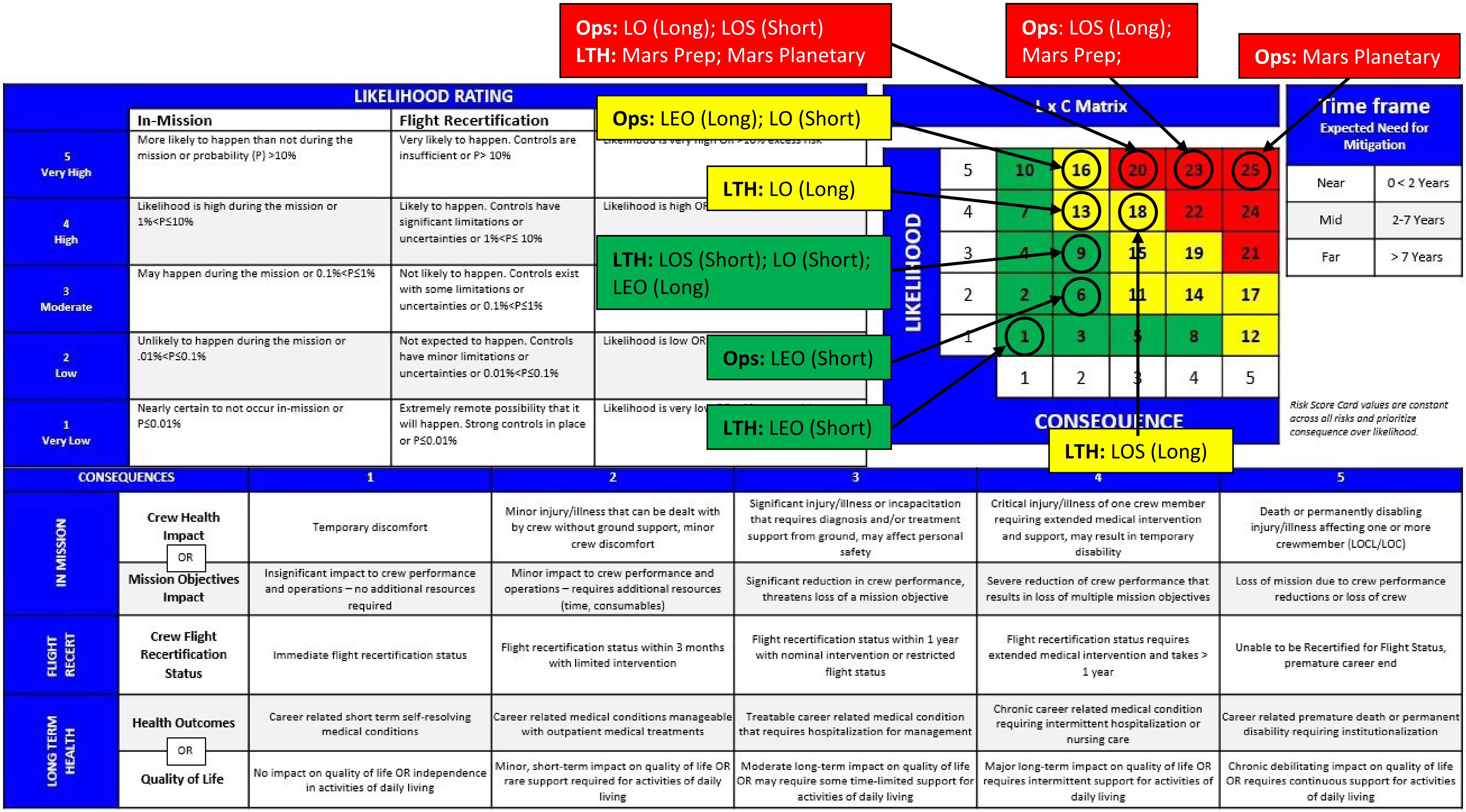
DRM Categories	Mission Type and Duration	LxC OPS	Risk Disposition	LxC LTH	Risk Disposition
Low Earth Orbit (LEO)	Short (<30 days)	**2x2**	Accepted with Monitoring	**1x1**	Accepted
	Long (30 d - 1 yr.)	**5x2**	Accepted with Optimization	**3x2**	Accepted with Monitoring
Lunar Orbital (LO)	Short (<30 days)	**5x2**	Accepted with Optimization	**3x2**	Accepted with Monitoring
	Long (30 d - 1 yr.)	**5x3**	Requires Mitigation	**4x2**	Requires Mitigation
Lunar Orbital + Surface (LOS)	Short (<30 days)	**5x3**	Requires Mitigation	**3x2**	Accepted with Monitoring
	Long (30 d - 1 yr.)	**5x4**	Requires Mitigation	**4x3**	Requires Mitigation
Mars	Preparatory (<1 year)	**5x4**	Requires Mitigation	**5x3**	Requires Mitigation
	Planetary (730-1224 days)	**5x5**	Requires Mitigation	**5x3**	Requires Mitigation

Current (no changes)

DRM Categories	Mission Type and Duration	LxC OPS	Risk Disposition	LxC LTH	Risk Disposition
Low Earth Orbit (LEO)	Short (<30 days)	**2x2**	Accepted with Monitoring	**1x1**	Accepted
	Long (30 d - 1 yr.)	**5x2**	Accepted with Optimization	**3x2**	Accepted with Monitoring
Lunar Orbital (LO)	Short (<30 days)	**5x2**	Accepted with Optimization	**3x2**	Accepted with Monitoring
	Long (30 d - 1 yr.)	**5x3**	Requires Mitigation	**4x2**	Requires Mitigation
Lunar Orbital + Surface (LOS)	Short (<30 days)	**5x3**	Requires Mitigation	**3x2**	Accepted with Monitoring
	Long (30 d - 1 yr.)	**5x4**	Requires Mitigation	**4x3**	Requires Mitigation
Mars	Preparatory (<1 year)	**5x4**	Requires Mitigation	**5x3**	Requires Mitigation
	Planetary (730-1224 days)	**5x5**	Requires Mitigation	**5x3**	Requires Mitigation

7. HSRB Risk Likelihood x Consequence Matrix

Current



Ops: LO (Long); LOS (Short)
LTH: Mars Prep; Mars Planetary

Ops: LOS (Long);
Mars Prep;

Ops: Mars Planetary

Ops: LEO (Long); LO (Short)

LTH: LO (Long)

LTH: LOS (Short); LO (Short);
LEO (Long)

Ops: LEO (Short)

LTH: LEO (Short)

LTH: LOS (Long)

LIKELIHOOD RATING	In-Mission	Flight Recertification	
5 Very High	More likely to happen than not during the mission or probability (P) >10%	Very likely to happen. Controls are insufficient or P> 10%	Likelihood is very high OR >10% excess risk
4 High	Likelihood is high during the mission or 1%<P≤10%	Likely to happen. Controls have significant limitations or uncertainties or 1%<P≤ 10%	Likelihood is high OR
3 Moderate	May happen during the mission or 0.1%<P≤1%	Not likely to happen. Controls exist with some limitations or uncertainties or 0.1%<P≤1%	
2 Low	Unlikely to happen during the mission or .01%<P≤0.1%	Not expected to happen. Controls have minor limitations or uncertainties or 0.01%<P≤0.1%	Likelihood is low OR
1 Very Low	Nearly certain to not occur in-mission or P≤0.01%	Extremely remote possibility that it will happen. Strong controls in place or P≤0.01%	Likelihood is very low

L x C Matrix

LIKELIHOOD					
5	10	16	20	23	25
4	7	13	18	22	24
3	4	9	15	19	21
2	2	6	11	14	17
1	1	3	5	8	12
	1	2	3	4	5
	CONSEQUENCE				

Time frame Expected Need for Mitigation	
Near	0 < 2 Years
Mid	2-7 Years
Far	> 7 Years

Risk Score Card values are constant across all risks and prioritize consequence over likelihood.

CONSEQUENCES		1	2	3	4	5
IN MISSION	Crew Health Impact OR	Temporary discomfort	Minor injury/illness that can be dealt with by crew without ground support, minor crew discomfort	Significant injury/illness or incapacitation that requires diagnosis and/or treatment support from ground, may affect personal safety	Critical injury/illness of one crew member requiring extended medical intervention and support, may result in temporary disability	Death or permanently disabling injury/illness affecting one or more crewmember (LOCL/LOC)
	Mission Objectives Impact	Insignificant impact to crew performance and operations – no additional resources required	Minor impact to crew performance and operations – requires additional resources (time, consumables)	Significant reduction in crew performance, threatens loss of a mission objective	Severe reduction of crew performance that results in loss of multiple mission objectives	Loss of mission due to crew performance reductions or loss of crew
FLIGHT RECERT	Crew Flight Recertification Status	Immediate flight recertification status	Flight recertification status within 3 months with limited intervention	Flight recertification status within 1 year with nominal intervention or restricted flight status	Flight recertification status requires extended medical intervention and takes > 1 year	Unable to be Recertified for Flight Status, premature career end
LONG TERM HEALTH	Health Outcomes OR	Career related short term self-resolving medical conditions	Career related medical conditions manageable with outpatient medical treatments	Treatable career related medical condition that requires hospitalization for management	Chronic career related medical condition requiring intermittent hospitalization or nursing care	Career related premature death or permanent disability requiring institutionalization
	Quality of Life	No impact on quality of life OR independence in activities of daily living	Minor, short-term impact on quality of life OR rare support required for activities of daily living	Moderate long-term impact on quality of life OR may require some time-limited support for activities of daily living	Major long-term impact on quality of life OR requires intermittent support for activities of daily living	Chronic debilitating impact on quality of life OR requires continuous support for activities of daily living

Assumptions for Long Term Health Risk Matrix:

- *Long Term Health extends from the end of the post mission time period and covers an astronaut's lifetime.*
- *Conditions considered within the LTH Risk Matrix are those that 1) are related to the astronaut career, 2) are beyond those expected as part of natural aging, and 3) include acute, chronic and latent conditions.*
- *Quality of Life is defined as impact on day-to-day physical and mental functional capability and/or lifetime loss of years*

8. Risk Postures

Low Earth Orbit (< 30 Days)

Operations

2x2	Accepted with Monitoring

- **LxC Drivers for Likelihood: (Low)** ≤0.1% probability of inadequate nutrition due to short duration of mission.

- **LxC Drivers for Consequence: (Minor impact) –** In these short duration missions with regular resupply, any potential weight loss and inadequate nutrition are likely associated with only minor health and performance decrements

- **Rationale for Risk Disposition:** Risk is **Accepted with Monitoring**. Dietary intake and body mass must be monitored to meet MedB, regular resupply at the required upmass as defined in the NASA STD 3001, and with galley infrastructure as defined in NASA STD 3001. Optimization of food system is desired.

- **DRM Specific Assumptions:** Regular resupply

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Low Earth Orbit (< 30 Days)

Long Term Health

1x1	Accepted

- **LxC Drivers for Likelihood: (Low)** Mass and infrastructure limitations on short duration missions increase the likelihood of reduced intake and post-flight nutritional deficiencies that fail to satisfy standards, but qualitatively remains a low risk

- **LxC Drivers for Consequence: (Temporary impact)** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., cancer risk, musculoskeletal risks) but are short term with no long-term impact on quality of life

- **Rationale for Risk Disposition:** Risk is **Accepted**, No anticipated LTH impact on quality of life for DRM

- **DRM Specific Assumptions:** Regular resupply

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Low Earth Orbit (30 d – 1 yr)

Operations

5x2	Accepted with Optimization

- **LxC Drivers for Likelihood: (Very High)** ≥10%. Although adequate nutrition/safe food is possible in 6m missions, empiric and historical evidence of the ISS program has shown >10% of long duration crew have lost weight or been dehydrated. 40% of ISS crews were dehydrated using urine osmolality and American College of Sports Medicine (ACSM) guidelines, and >8% were clinically dehydrated, and serum sodium > 145 nmol/L. Hydration data 2006-2018, n=65. Previous research showed 34% of crews lost more than 5% of body weight from 2000 to 2017 (E1-E57). Medical data from pre- and in-flight weight measures showed 25% of crew from 2000-2024 (E1-E72) lost more than 5% of body mass while in flight.

- **LxC Drivers for Consequence:** (**Minor Impact)** For these long LEO missions with regular resupply and with adequate ground assets on landing for recovery, the dehydration and weight loss have led to minor mission impacts.

- **Rationale for Risk Disposition:** Risk is **Accepted with Optimization** of food system. Crew is frequently required to consume food past it's best if used-by-date. We have yet to fly a food system that meets the nutritional requirements (e.g., insufficient fruits and vegetables, insufficient omega-3 sources, insufficient choline, excess fat and cholesterol, sodium, and iron). Crew preference and food choices impact nutritional intake. Data shows that astronauts make better food choices as the system improves.

- **DRM Specific Assumptions:** Regular resupply

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Low Earth Orbit (30 d – 1 yr)
Long Term Health

🟩 3x2	Accepted with Monitoring

- **LxC Drivers for Likelihood:** Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. This likelihood has been assessed to be moderate for 30d-1yr LEO. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due to lack of adequate food system during DRM.

- **LxC Drivers for Consequence:** (**Minor Impact)** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., Radiation Carcinogenesis Risk, SANS Risk, musculoskeletal risks, etc.) but are short term with manageable long-term impact on quality of life. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due lack of adequate food system during DRM.

- **Rationale for Risk Disposition: Accepted with monitoring** of clinical nutritional status of crew post-flight. We have no data from flight that would allow us to know what the physiological decrements would be compared to an optimal food system. Immune, Cardio, Muscle, Bone, etc... are all known to be impacted by inadequate caloric intake, let alone because of limited food choices.

- **DRM Specific Assumptions:** Regular resupply

- **DRM Specific Evidence/Level of Evidence:**

Lunar Orbital (< 30 Days)

Operations

5x2	Accepted with Optimization

- **LxC Drivers for Likelihood: (Very High)** ≥10%. There are more constraints on the food system (mass & volume, storage conditions, food warmer, water dispensing), prepositioning of food, lack of preference) than on previous missions with this duration and the impacts have not been evaluated. 40% of ISS crews were dehydrated using urine osmolality and American College of Sports Medicine (ACSM) guidelines, and >8% were clinically dehydrated, and serum sodium > 145 nmol/L. Hydration data 2006-2018, n=65. Previous research showed 34% of crews lost more than 5% of body weight from 2000 to 2017 (E1-E57). Medical data from pre- and in-flight weight measures showed 25% of crew from 2000-2024 (E1-E72) lost more than 5% of body mass while in flight.

- **LxC Drivers for Consequence: (Minor Impact)** For a <30 day mission with no EVAs and with adequate ground assets on landing for recovery, the dehydration and weight loss should have minor mission impacts. *The consequence may increase due to unpredicted changes in nutritional needs, increased radiation exposure, and behavioral health issues.*

- **Rationale for Risk Disposition:** Risk is **Accepted with Optimization** due to short duration, but validation of requirements is needed, and optimization of food system is required. We have yet to fly a food system that meets the nutritional requirements (e.g., insufficient fruits and vegetables, insufficient omega-3 sources, insufficient choline, excess fat and cholesterol, sodium, and iron). Mass and volume restrictions on food will result in higher energy and lower nutrient densities (i.e., less fruits and vegetables). This will increase health and performance risks (e.g., cognitive, behavioral, immune due to decrease in micronutrients and bioactive compounds). Vehicles are currently planning to store food outside of temperature limits and potentially include depressurization events, and the risk to nutrition is currently unknown.

- **DRM Specific Assumptions:** *Assumes there are no EVAs. If there are planned EVAs, posture would have to be re-evaluated. No crew personalization. Current food provisioning and preparation capability for Lunar Orbital missions do not meet NASA Standard 3001.*

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Lunar Orbital (< 30 Days)

Long Term Health

3x2	Accepted with Monitoring

- **LxC Drivers for Likelihood: (Moderate)** Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. This likelihood has been assessed to be moderate for missions less than 30 days beyond LEO. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due to lack of adequate food system during DRM. Likelihood same as 30d-1 yr LEO due to food system constraints and possibility of inadequate intake.

- **LxC Drivers for Consequence:** (**Minor Impact)** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., Radiation Carcinogenesis Risk, SANS Risk, musculoskeletal risks, etc.) but are short term with manageable long-term impact on quality of life. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due to lack of adequate food system during DRM.

- **Rationale for Risk Disposition: Accepted with monitoring** of clinical nutritional status of crew post-flight. We have no data from flight that would allow us to know the long-term health implications of inadequate nutrition during high radiation lunar orbital missions.

- **DRM Specific Assumptions:** Assumes there are no EVAs. If there are planned EVAs, posture would have to be re-evaluated. No crew personalization. Current food provisioning and preparation capability for Lunar Orbital missions do not meet NASA Standard 3001.

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Lunar Orbital (30 d – 1 yr) Operations

5x3	Requires Mitigation

- **LxC Drivers for Likelihood: In-mission (Ops) (Very High)** ≥10%. There are more constraints on the food system (mass & volume, storage conditions, food warmer, water dispensing), prepositioning of food, lack of preference than on previous missions with this duration and the impacts have not been evaluated. 40% of ISS crews were dehydrated using urine osmolality and ACSM guidelines and >8% were clinically dehydrated, and serum sodium > 145 nmol/L, Hydration data 2006-2018, n=65. Previous research showed 34% of crews lost more than 5% of body weight from 2000 to 2017 (E1-E57). Medical data from pre- and in-flight weight measures showed 25% of crew from 2000-2024 (E1-E72) lost more than 5% of body mass while in flight.

- **LxC Drivers for Consequence: (Significant)** and severe consequence (respectively) of inadequate nutrition and illness and unknown consequence to performance (error rate and ability to meet mission objectives) with inadequate nutrition. Fluid intake, which is intertwined with food intake is critical for health and performance. Dehydration is known to be associated with performance, cognition, cardiovascular function, and thermoregulation. ISS astronauts have documented higher core temps during flight, especially after exercise. *The consequence may increase due to unpredicted changes in nutritional needs, increased radiation exposure, and behavioral health issues.*

- **Rationale for Risk Disposition: Requires Mitigation** Duration of mission, prepositioning with the potential for crew changes and other vehicle delays, as well as resource constraints resulting in food restrictions such as reduced caloric provisioning, less time for crew to eat, and no or limited food preparation infrastructure accompanied by limited or no resupply are all in lunar trade space. Mass and volume restrictions on food will result in higher energy and lower nutrient densities (i.e., less fruits and vegetables). This will increase health and performance risks (e.g., cognitive, behavioral, immune due to decrease in micronutrients and bioactive compounds). Vehicles are currently planning to store food outside of temperature limits and potentially include depressurization events, and the risk to nutrition is currently unknown.

- **DRM Specific Assumptions:** This includes the assumption that there are no EVAs. If so, posture would have to be re-evaluated. No crew personalization. Current food provisioning and preparation capability for Lunar Orbital missions do not meet NASA Standard 3001.

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Lunar Orbital (30 d – 1 yr)
Long Term Health

4x2	Requires Mitigation

- **LxC Drivers for Likelihood: (Moderate)** Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due to lack of adequate food system during DRM. Higher likelihood than LEO due to food system constraints and possibility of inadequate intake over longer time period.

- **LxC Drivers for Consequence:** (**Minor Impact)** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., cancer risk, SANS, musculoskeletal risks) but are short term with manageable long-term impact on quality of life

- **Rationale for Risk Disposition: Requires Mitigation** Inadequate food and nutrition in higher radiation environment on these missions will increase risk of carcinogenesis, along with potential long-term impacts to cardiovascular, ocular, and bone health risks. We have no data from flight that would allow us to know the long-term health implications of inadequate food intake and nutritional status during high radiation lunar orbital missions

- **DRM Specific Assumptions:** This includes the assumption that there are no EVAs. If so, posture would have to be re-evaluated. No crew personalization. Current food provisioning and preparation capability for Lunar Orbital missions do not meet NASA Standard 3001.

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Lunar Orbital + Surface(< 30 Days) Operations

5x3 Requires Mitigation

- **LxC Drivers for Likelihood: (Very High)** ≥10%. There are more constraints on the food system (mass & volume, storage conditions, food warmer, water dispensing), prepositioning of food, lack of preference) than on previous missions with this length of time and EVA tempo and the impacts have not been evaluated. 40% of ISS crews were dehydrated using urine osmolality and ACSM guidelines, and >8% were clinically dehydrated, and serum sodium > 145 nmol/L. Hydration data 2006-2018, n=65. Previous research showed 34% of crews lost more than 5% of body weight from 2000 to 2017 (E1-E57). Medical data from pre- and in-flight weight measures showed 25% of crew from 2000-2024 (E1-E72) lost more than 5% of body mass while in flight.

- **LxC Drivers for Consequence: :** Significant and severe consequence (respectively) of inadequate nutrition and illness and unknown consequence to performance (error rate and ability to meet mission objectives) with inadequate nutrition. Fluid intake, which is intertwined with food intake is critical for health and performance. Dehydration and caloric intake are known to be associated with performance, cognition, cardiovascular function, and thermoregulation. ISS astronauts have documented higher core temps during flight, especially after exercise. EVAs (>5) expect high performance*. The consequence may increase due to unpredicted changes in nutritional needs, increased radiation exposure, and behavioral health issues.*

- **Rationale for Risk Disposition: (Requires Mitigation)** An adequate food system is needed. Prepositioning with the potential for crew changes and other vehicle delays, as well as resource constraints resulting in food restrictions such as reduced caloric provisioning, less time for crew to eat, and no or limited food preparation infrastructure accompanied by limited or no resupply with increased extravehicular activity (EVA) frequency and caloric expenditure, are all in lunar trade space. Mass and volume restrictions on food will result in higher energy and lower nutrient densities (i.e., less fruits and vegetables). This will increase health and performance risks (e.g., cognitive, behavioral, immune due to decrease in micronutrients and bioactive compounds). Vehicles are currently planning to store food outside of temperature limits and potentially include depressurization events, and the risk to nutrition is currently unknown.

- **DRM Specific Assumptions:** No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital + Surface missions do not meet NASA Standard 3001*

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Lunar Orbital + Surface (< 30 Days) Long Term Health

3x2 Accepted with Monitoring

- **LxC Drivers for Likelihood: (Moderate)** Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. This likelihood has been assessed to be moderate for missions less than 30 days beyond LEO. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due lack of adequate food system during DRM. Likelihood same as 30d-1 yr LEO due to food system constraints and possibility of inadequate intake.

- **LxC Drivers for Consequence**: (Minor Impact) Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., cancer risk, SANS, musculoskeletal risks) but are short term with manageable long-term impact on quality of life

- **Rationale for Risk Disposition: Accepted with monitoring** of clinical nutritional status of crew post-flight. We have no data from flight that would allow us to know the long-term health implications of inadequate nutrition during high radiation lunar orbital missions.

- **DRM Specific Assumptions:** No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital + Surface missions do not meet NASA Standard 3001*

- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Lunar Orbital + Surface (30 d – 1 yr) Operations

5x4	Requires Mitigation

- **LxC Drivers for Likelihood: (Very High)** ≥10%. There are more constraints on the food system (mass & volume, storage conditions, food warmer, water dispensing), prepositioning of food, lack of preference) than on previous missions with this length of time and EVA tempo and the impacts have not been evaluated. 40% of ISS crews were dehydrated using urine osmolality and ACSM guidelines, and >8% were clinically dehydrated, and serum sodium > 145 nmol/L. Hydration data 2006-2018, n=65. Previous research showed 34% of crews lost more than 5% of body weight from 2000 to 2017 (E1-E57). Medical data from pre- and in-flight weight measures showed 25% of crew from 2000-2024 (E1-E72) lost more than 5% of body mass while in flight.

- **LxC Drivers for Consequence:** Significant and severe consequence (respectively) of inadequate nutrition and illness and unknown consequence to performance (error rate and ability to meet mission objectives) with inadequate nutrition. Fluid intake, which is intertwined with food intake is critical for health and performance. Dehydration and caloric intake are known to be associated with performance, cognition, cardiovascular function, and thermoregulation. ISS astronauts have documented higher core temps during flight, especially after exercise. EVAs (>5) expect high performance. *The consequence may increase due to unpredicted changes in nutritional needs, increased radiation exposure, and behavioral health issues.*

-

- **Rationale for Risk Disposition:** An adequate food system is needed. Duration of mission, prepositioning with the potential for crew changes and other vehicle delays, as well as resource constraints resulting in food restrictions such as reduced caloric provisioning, less time for crew to eat, and no or limited food preparation infrastructure accompanied by limited or no resupply with increased extravehicular activity (EVA) frequency and caloric expenditure, are all in lunar trade space. Mass and volume restrictions on food will result in higher energy and lower nutrient densities (i.e., less fruits and vegetables). This will increase health and performance risks (e.g., cognitive, behavioral, immune due to decrease in micronutrients and bioactive compounds). Vehicles are currently planning to store food outside of temperature limits and potentially include depressurization events, and the risk to nutrition is currently unknown.

- **DRM Specific Assumptions:** No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital + Surface missions do not meet NASA Standard 3001*
- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Lunar Orbital + Surface (30 d – 1 yr)

Long Term Health

4x3	Requires Mitigation

- **LxC Drivers for Likelihood:** (High) Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due to lack of adequate food system during DRM. Higher likelihood than Lunar Orbital due to food system constraints and possibility of inadequate intake
- **LxC Drivers for Consequence: (Moderate)** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., cancer risk, SANS, musculoskeletal risks) but are short term with manageable long-term impact on quality of life. Higher consequence than Lunar Orbital due to food system constraints, and possibility of inadequate intake.
- **Rationale for Risk Disposition: Requires Mitigation** Inadequate food and nutrition in higher radiation environment on these missions will increase risk of carcinogenesis, along with potential long-term impacts to cardiovascular, ocular, and bone health risks. We have no data from flight that would allow us to know the long-term health implications of inadequate food intake and nutritional status during high radiation lunar orbital missions.
- **DRM Specific Assumptions:** No crew personalization. *Current food provisioning and preparation capability for Lunar Orbital + Surface missions do not meet NASA Standard 3001*
- **DRM Specific Evidence/Level of Evidence:** 2-Moderate

Mars Preparatory (<1 yr.)

Operations

5x4	Requires Mitigation

- **LxC Drivers for Likelihood: (**Very High) ≥10%. There are expected to be more constraints on the food system (mass & volume, food warmer, water dispensing), prepositioning of food, lack of preference) than on previous missions with this length of time and the impacts have not been evaluated. 40% of ISS crews were dehydrated using urine osmolality and ACSM guidelines, and >8% were clinically dehydrated, and serum sodium > 145 nmol/L. Hydration data 2006-2018, n=65. Previous research showed 34% of crews lost more than 5% of body weight from 2000 to 2017 (E1-E57). Medical data from pre- and in-flight weight measures showed 25% of crew from 2000-2024 (E1-E72) lost more than 5% of body mass while in flight.

- **LxC Drivers for Consequence: (Severe)** Significant and severe consequence (respectively) of inadequate nutrition and illness and unknown consequence to performance (error rate and ability to meet mission objectives) with inadequate nutrition. Fluid intake, which is intertwined with food intake is critical for health and performance. Dehydration and caloric intake are known to be associated with performance, cognition, cardiovascular function, and thermoregulation. ISS astronauts have documented higher core temps during flight, especially after exercise. Assumes requiring re-supply is major loss of mission objectives**.** *The consequence may increase due to unpredicted changes in nutritional needs, increased radiation exposure, and behavioral health issues.*

- **Rationale for Risk Disposition:** Mitigation is required to provide a food system. Risks would generally be similar to lunar orbital long missions, although increased stress of comm delays, increased autonomy and dependence on equipment, and further constrained food system including lack of resupply could further increase stress and schedule constraints. All of this could impact dietary intake and nutritional status. *Further characterization related to performance/mission objectives is also needed.*

- **DRM Specific Assumptions:** No resupply, prepositioned food system, no crew personalization, expect food provisioning and preparation capability to meet NASA Standard 3001 but there is currently a shelf-life capability gap

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Mars Preparatory (<1 yr.)
Long Term Health

5x3	Requires Mitigation

- **LxC Drivers for Likelihood:** Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. Other risks assume adequate food/nutrition, this accounts for excess LTH risk due lack of adequate food system during DRM. Higher likelihood than Lunar Orbital due food system constraints and possibility of inadequate intake.

- **LxC Drivers for Consequence:** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., cancer risk, SANS, musculoskeletal risks) but are short term with manageable long-term impact on quality of life. Higher consequence than Lunar Orbital due to food system constraints, and possibility of inadequate intake.

- **Rationale for Risk Disposition: (Requires Mitigation)** Inadequate food and nutrition in higher radiation environment on these missions will increase risk of carcinogenesis, along with potential long-term impacts to cardiovascular, ocular, and bone health risks. We have no data from flight that would allow us to know the long-term health implications of inadequate food intake and nutritional status during high radiation lunar orbital missions.

- **DRM Specific Assumptions:** No resupply, prepositioned food system, no crew personalization, expect food provisioning and preparation capability to meet NASA Standard 3001 but there is currently a shelf-life capability gap

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Mars Planetary (730-1224 d) Operations

5x5	Requires Mitigation

- **LxC Drivers for Likelihood: (Requires Mitigation)** Inadequate food and nutrition in higher radiation environment on these missions will increase risk of carcinogenesis, along with potential long-term impacts to cardiovascular, ocular, and bone health risks. We have no data from flight that would allow us to know the long-term health implications of inadequate food intake and nutritional status during high radiation lunar orbital missions.

- **LxC Drivers for Consequence: (Loss of Mission Objectives/Death)** Lack of adequate food system (nutrition, acceptability, variety, and safety) and food shelf life will lead to significant nutritional deficiency and ultimately death. Food variety standards and refrigeration and freezing standards are not currently in 3001 and would need to be defined and added. The situation improves with adequate cold stowage. The food system mass may also exceed resource capabilities.

- **Rationale for Risk Disposition: (Requires Mitigation)** Mitigation is required to provide a food system that can maintain nutritious, acceptable, and safe food for five years and promotes health within resource restrictions (reduced mass/volume). In addition to food system constraints and lack of resupply, increased stress of comm delays, increased autonomy and dependence on equipment will all add to risks of impact on dietary intake and nutritional status, as well as failure of nutrition to support other systems (e.g., cardiovascular, musculoskeletal, behavioral, ocular, immune). Risk related to performance/mission objectives requires further characterization.

- **DRM Specific Assumptions:** No resupply, prepositioned food system, no crew personalization, expect food provisioning and preparation capability to meet NASA Standard 3001 but there is currently a shelf-life capability gap

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

Mars Planetary (730-1224 d)

5x3	Requires Mitigation

Long Term Health

- **LxC Drivers for Likelihood: (Very high)** Terrestrial evidence indicates that inadequate nutritional intake can impact many physiological systems within days to weeks. In missions up to a year it has been shown that muscle and bone have been impacted and nutrition contributes to these. Greater than 1 in 10.

- **LxC Drivers for Consequence: (Moderate)** Mission conditions may exacerbate post-flight recovery of food and nutrition deficits and impacts, including other risks/consequences (e.g., cancer risk, SANS, musculoskeletal risks) but are short term with manageable long-term impact on quality of life. Higher consequence than Lunar Orbital due to food system constraints and deficiencies, and possibility of inadequate intake. Unknown consequence of Premature Death/Permanent Disability. Some evidence in historical accounts on exploration missions with significant food restrictions, even after return and recovery.

- **Rationale for Risk Disposition: (Requires Mitigation)** Inadequate food and nutrition in higher radiation environment on these missions could increase risk of carcinogenesis, along with potential long-term impacts to cardiovascular, ocular, and bone health risks. We have no data from flight that would allow us to know the long-term health implications of inadequate food intake and nutritional status during high radiation lunar orbital missions.

- **DRM Specific Assumptions:** No resupply, prepositioned food system, no crew personalization, expect food provisioning and preparation capability to meet NASA Standard 3001 but there is currently a shelf-life capability gap

- **DRM Specific Evidence/Level of Evidence:** 1-Strong

9. Overall Assessment of the Evidence

The risk of impacts due to increased food system restrictions in spaceflight is not yet quantified, and yet supported by evidence that:

- High-performing individuals told that they need to eat to maintain health and performance may not eat enough if they do not like what is available.
  - Supporting evidence - ISS and analog debriefs.
- Crewmembers self-selecting or avoiding foods / food categories causes strife among crew.
  - Supporting evidence - ISS debriefs.

Extensive terrestrial evidence that a healthy diet can mitigate disease state, but

- ISS Food System:
  - Does not Provide enough foods generally considered as part of a healthy diet
  - Does not meet nutritional requirements
  - Should include:
    - More fruits and vegetables
    - More sources of omega-3 fatty acids
    - Lower sodium and iron
    - Adequate energy, protein, calcium, and potassium

Extensive terrestrial evidence that food and nutrition effect health and performance

- Scant spaceflight evidence of how the spaceflight diet or increasing food system restrictions impact health and performance

Artemis cross-program risk

Despite lack of evidence on health and performance impacts, the Artemis food system will be limited due to vehicle and equipment capability limitations, reduction in calories, reduction in variety and beverage options. The food system will likely be exposed to vehicle environment parameters outside of the current certification range.

10. State of Knowledge – New Evidence

Summary

Nutritional Requirements were reviewed by an extramural panel of experts

Nutritional Requirements for Exploration Missions up to 365 days developed including Estimated energy requirements (EERs) calculated with activity factor, age, body mass (kg), and height (m)

Crew receive foods on ISS that they may *not* receive on exploration missions

- Personal preference items augment the nominal food system and supplement micronutrients
- Fresh fruits and vegetables received with almost every visiting vehicle, approximately once per quarter
- Up to 25% of current food choices come from preference and fresh foods.

Despite the variety and preference available on ISS, the food system is shelf-stable and limited in variety and choice due to logistical constraints

- Is consistently under-consumed in most human spaceflight programs to date, which has contributed to weight loss and muscle and cardiovascular deconditioning even over short durations, and bone loss over longer missions

Current food system does not meet nutrition and acceptability requirements to support Mars missions or extensive prepositioning for lunar missions

Detailed dietary intake data document nutritional limitations of the ISS food system and the potential impacts on health and performance.

- Inadequate food (energy) and fluid intake – body mass loss, dehydration
- Excess protein intake – increased renal stone risk
- Excess iron intake – increased oxidative stress/DNA damage, bone loss
- Excess sodium intake – effects on bone and other systems
- Insufficient fruit and vegetable intake – impact on nutrient intakes: phytochemicals (carotenoids, flavonoids, etc.)
- Inadequate fiber intake – effects on gastrointestinal (GI) health and microbiome
- Excess cholesterol and saturated fat intake and effects on lipids and cardiovascular health
- Insufficient omega-3 fatty acid intakes

Body mass loss is associated with bone and muscle loss, impaired cardiovascular fitness, increased stone risk, increased oxidative stress, etc.

The current Food and Nutrition system is suboptimal. The ISS Food System does not meet ISS or Exploration mission requirements.

- The risk posture is increasing – our starting point for food and nutrition will be worse than ever as we move from ISS to Lunar/Gateway, and then to Exploration missions, as resources become more constrained.
- Has not been evaluated for impacts to cognitive, performance, and most health outcomes in spaceflights, although decrements are expected based on ground and military data

Longer missions, without preference foods, without cargo deliveries of fresh fruits/vegetables, with stricter mass and volume constraints, and longer prepositioning will increase risk of clinical issues

Optimizing the food system may offer a countermeasure to mitigate health risks on long-duration exploration

missions and reduce the burden to a constrained medical system

  - Increasing fruit and vegetable intake, sources of omega-3 fatty acids, and balancing other nutrients is critical for crew health and performance, demonstrated by analog subjects with lower cholesterol levels, lower stress (i.e. cortisol levels), better cognitive speed, accuracy, and attention, and a more stable microbiome and metatranscriptome than subjects consuming the standard ISS diet (study done 2017).
  - Terrestrial data demonstrate that adequacy of diet/nutrition can mitigate (or exacerbate) disease states, including cardiovascular, cancer, sarcopenia, osteoporosis, etc. Although data for the spaceflight food system for these lengths of time does not exist, we expect the same to be true for spaceflight.

New Evidence

Food Needs Are Risk Driver when Mission Profiles Change

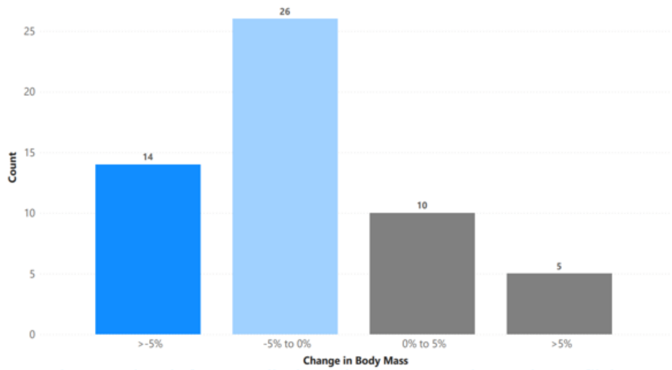
- Recent unexpected increase in number of crew on ISS resulted in greater need for food resupply
- Food resupply replaced science payloads; science mission objectives are at risk
- Mission objectives, crew loss, and mission loss risk increase if there is food loss or inadequate food available
- Mission plans will change due to crew food needs

11. Metrics

Body Mass

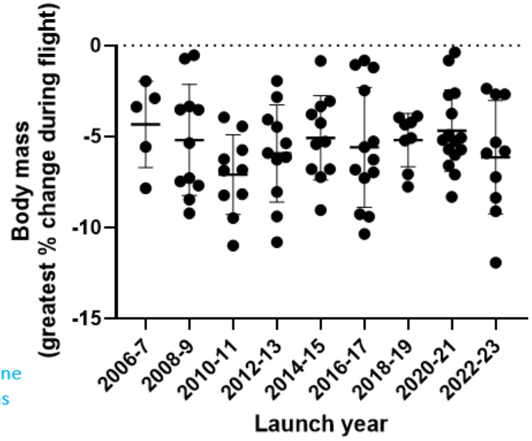
- Body Weight from ISS medical data through 2024
  - 73% showed some decrement of body mass
    - 25% lost >5% body mass

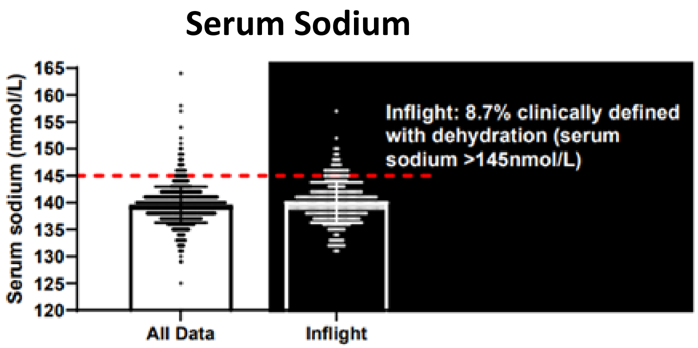
Change in Body Mass Between Pre-flight and In-flight Measure (n=55, E1-72)



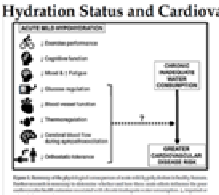
Note: Body mass data is from medical requirements pre-, in-, and post-flight.
Data does not include DXA information. Previous pre- and post-flight DXAs were not done fasted so body mass changes to date do not differentiate fat vs. lean mass. The AMB has already approved the change to the MRID to have DXA's done fasted in future.
DXA is done 5-30 days after flight (as opposed to R+0/1 for body weight measurements on a scale).

- Previous research measures from ISS showed 34% lost >5 (through 2017)
- Current research measures show 62% lost >5%
  - Differences in data may come from measurement time points and population.





Hydration Status and Cardiovascular Function



Watso and Farquhar, *Nutrients*, 2019

Dehydration Impairs Cognitive Performance: A Meta-analysis

Conclusions: Despite variability among studies, dehydration impairs cognitive performance, particularly for tasks involving attention, executive function, and motor coordination when water deficits exceed 2% BML.

Wittbrodt and Millard-Stafford, *Med Sci Sports Exerc*, 2018

- Between March 2015 and March 2023, 83% of ISS NASA crew (n=40) received IV saline postflight.
- In 2009, the UPA clogged because of high calcium excretion and low urine volume.
- No insight into dehydration effects on performance, cognition, etc.

Fig top: Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition* *(NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.

Watso and Farquhar, Nutrients 2019.

12. Risk Mitigation Framework - Color Changes

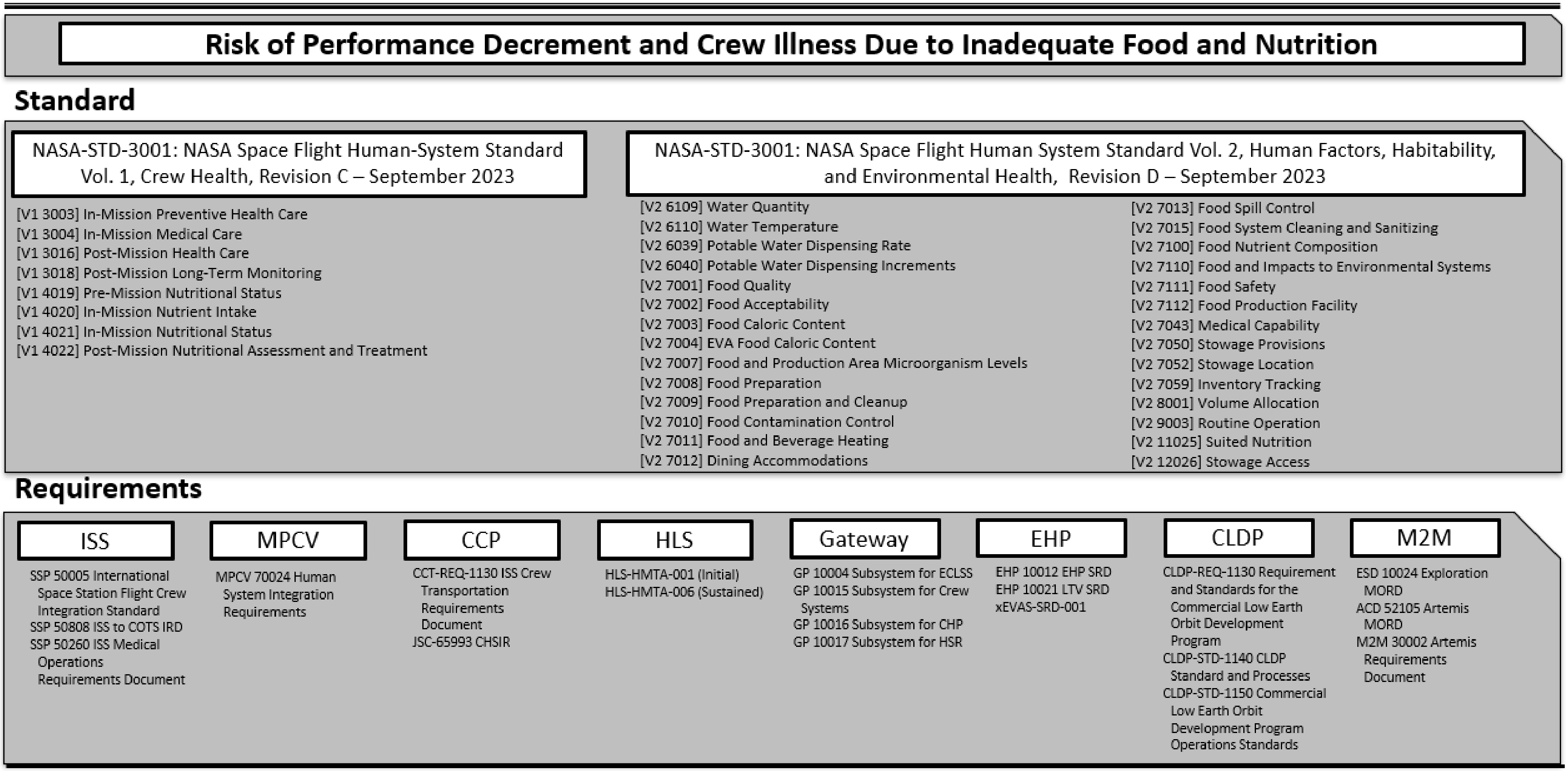
How do we know when we go from red → yellow?

- Demonstrate food system can provide adequate nutrition, safety, and acceptability for the mission duration
- Ability to validate crew are consuming adequate nutrition from the available diet
  - Monitor nutritional status of crews in-flight and clinical status in-flight and post-flight

How do we know when we go from yellow → green?

- Demonstrate nutritional requirements are optimized to serve as a countermeasure for other health and performance risks
  - Examples include cardiovascular, musculoskeletal, immune, behavioral health and cognition.
- Validate that flight and analog crews consuming those requirements exhibit improvements in markers of other health risks.

13. Risk → Standard → Requirements Flow



Risk of Performance Decrement and Crew Illness Due to Inadequate Food and Nutrition

Standard

NASA-STD-3001: NASA Space Flight Human-System Standard Vol. 1, Crew Health, Revision C – September 2023

- [V1 3003] In-Mission Preventive Health Care
- [V1 3004] In-Mission Medical Care
- [V1 3016] Post-Mission Health Care
- [V1 3018] Post-Mission Long-Term Monitoring
- [V1 4019] Pre-Mission Nutritional Status
- [V1 4020] In-Mission Nutrient Intake
- [V1 4021] In-Mission Nutritional Status
- [V1 4022] Post-Mission Nutritional Assessment and Treatment

NASA-STD-3001: NASA Space Flight Human System Standard Vol. 2, Human Factors, Habitability, and Environmental Health, Revision D – September 2023

- [V2 6109] Water Quantity
- [V2 6110] Water Temperature
- [V2 6039] Potable Water Dispensing Rate
- [V2 6040] Potable Water Dispensing Increments
- [V2 7001] Food Quality
- [V2 7002] Food Acceptability
- [V2 7003] Food Caloric Content
- [V2 7004] EVA Food Caloric Content
- [V2 7007] Food and Production Area Microorganism Levels
- [V2 7008] Food Preparation
- [V2 7009] Food Preparation and Cleanup
- [V2 7010] Food Contamination Control
- [V2 7011] Food and Beverage Heating
- [V2 7012] Dining Accommodations
- [V2 7013] Food Spill Control
- [V2 7015] Food System Cleaning and Sanitizing
- [V2 7100] Food Nutrient Composition
- [V2 7110] Food and Impacts to Environmental Systems
- [V2 7111] Food Safety
- [V2 7112] Food Production Facility
- [V2 7043] Medical Capability
- [V2 7050] Stowage Provisions
- [V2 7052] Stowage Location
- [V2 7059] Inventory Tracking
- [V2 8001] Volume Allocation
- [V2 9003] Routine Operation
- [V2 11025] Suited Nutrition
- [V2 12026] Stowage Access

Requirements

ISS
- SSP 50005 International Space Station Flight Crew Integration Standard
- SSP 50808 ISS to COTS IRD
- SSP 50260 ISS Medical Operations Requirements Document

MPCV
- MPCV 70024 Human System Integration Requirements

CCP
- CCT-REQ-1130 ISS Crew Transportation Requirements Document
- JSC-65993 CHSIR

HLS
- HLS-HMTA-001 (Initial)
- HLS-HMTA-006 (Sustained)

Gateway
- GP 10004 Subsystem for ECLSS
- GP 10015 Subsystem for Crew Systems
- GP 10016 Subsystem for CHP
- GP 10017 Subsystem for HSR

EHP
- EHP 10012 EHP SRD
- EHP 10021 LTV SRD
- xEVAS-SRD-001

CLDP
- CLDP-REQ-1130 Requirement and Standards for the Commercial Low Earth Orbit Development Program
- CLDP-STD-1140 CLDP Standard and Processes
- CLDP-STD-1150 Commercial Low Earth Orbit Development Program Operations Standards

M2M
- ESD 10024 Exploration MORD
- ACD 52105 Artemis MORD
- M2M 30002 Artemis Requirements Document

14. Proposed Standard Updates

Recommendation for requirement addition to NASA-STD-3001 to include food variety availability for crew.

- OCHMO Standards Team will review suggestions and other received comments that could impact Food and Nutrition Risk in the next revision of NASA-STD-3001.

Need to add temperature and pressure requirements.

Note:
Since last CR, additions have been made to NASA-STD-3001 that support this risk, which include:

- [V2 7110] Food and Impacts to Environmental Systems
- [V2 7111] Food Safety
- [V2 7112] Food Production Facility

15. High Value Risk Mitigation Targets

1. Determine the:
    - Interaction of food and nutrition with other human health risks – e.g., impact of nutrition on sleep, behavioral health, cognition, cardiovascular and immune health, physical performance, etc. – in all mission scenarios (HRP)
    - Impacts of food system restrictions on food intake, mission objectives, health, and performance, including cognitive outcomes in both ground analogs and spaceflight (HRP, MCO, Space Biology, Gateway, Orion, HLS, EHP all have a part**)**
        - Exploration food systems with preparation limitations and less variety and choice (e.g., Gateway due to prepositioning, Mars due lack of resupply) could lead to an increased risk to both physical and psychological health and performance as a result of:
            - Prolonged inadequate intake and nutritional deficiencies
            - Social conflict and crew cohesion issues
        - Test platforms:
            - Ground analog – Crew Health and Performance Exploration Analog (CHAPEA)
            - In-Flight – ISS

**This information is needed to determine human health and performance risk trades with food system resources to define food system requirements and validate the food system plan for exploration missions.

2. Determine the requirements, methods, and technologies that can provide a food system that is safe, nutritious, and acceptable for at least five years, within resource limitations. This includes understanding the impact of the space environment on the food system, including on seeds/plants, ingredients, etc. (HRP, MCO, Space Biology, Gateway, Orion, HLS, EHP all have a part)

**Storage condition impacts on nutrition and acceptability across the food system (whether packaged or crops) is needed to determine food system resource requirements, such as cold storage, and validate the food system plan for exploration missions. Validation will occur with nutrition, acceptability, safety, variety, and preparation requirements in the given vehicle conditions and schedule of the mission.

3. Add requirements on temperature and pressure and on food variety to NASA-3001 (OCHMO).

4. Establish dietary tracking on all vehicles for both crew and ground monitoring (MCO).

16. Conclusions

- No changes to LXC
- Updates were made to include new risk from high temperature and potential pressure changes on Artemis vehicles
- Operational data added in addition to research data that similarly supports risk posture
- Minor edits were included throughout

17. Recommendations Accepted

- The revisions:
    - Did not change the Likelihood x Consequence (LxC) scores assessed against updated Design Reference Missions (DRMs) and the 5x5 Risk Matrix
    - Provide updated evidence that supports current LxCs.

18. Acronyms and Abbreviations

ACD	Artemis Campaign Development
Aerobic Risk	Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity ASCM American College of Sports Medicine
Behavioral Risk	Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorder
Bone Fracture Risk	Risk of Bone Fracture due to Spaceflight-induced Changes to Bone
Cardiovascular Risk	Risk of Cardiovascular Adaptations Contributing to Adverse Mission Performance and Health Outcomes
CHAPEA	Crew Health and Performance Exploration Analog
CMs	Countermeasures
CR	Change Request
DAG	Directed Acyclic Graph
DRM	Design Reference Mission
EER	Estimated energy requirements
EVA	Extravehicular Activity
GFE	Government Furnished Equipment
GI	gastrointestinal
HERA	Human Exploration Research Analog
HLS	Human Landing System
HSEICB	Human Systems Engineering & Integration Control Board
HSIA Risk	Risk of Adverse Outcome Due to Inadequate Human Systems Integration Architecture
HSRB	Human System Risk Board
Immune Risk	Risk of Adverse Health Event Due To Altered Immune Response
ISS	International Space Station
ISS FIT	ISS Food Intake Tracker
kg	kilogram
LEO	Low Earth Orbit
LETS	Lunar Exploration Transportation Services
LM	Logistics Module
LO	Lunar Orbital
LOE	Levels of Evidence
LOS	Lunar Orbital + Surface
LTH	Long-Term Health
LxC	Likelihood and Consequence
m	meter
MedB	JSC-28913 Medical Requirements Integration Documents Medical

	Evaluation Documents Volume B
Medical Risk	Risk of Adverse Health Outcomes & Decrements in Performance due to Inflight Medical Conditions
Microhost Risk	Risk of Adverse Health Effects Due to Host-Microorganism Interactions
Muscle Risk	Risk of Impaired Performance Due to Reduced Muscle Size, Strength & Endurance nmol/L nanomoles per liter
Ops	Operations
Pharm Risk	Risk of Ineffective or Toxic Medications During Long-Duration Exploration Spaceflight
Radiation Carcinogenesis	Risk of Radiation Carcinogenesis
Renal Stone Risk	Risk of Renal Stone Formation
SD	Space Medicine Operations Division (Division Code)
SF	Human Systems Engineering & Integration Division (Division Code)
SK	Biomedical Research and Environmental Sciences Division (Division Code)
Sleep Risk	Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload
Team Risk	Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team
VTE Concern	Concern of Venous Thromboembolism

19. Reference Materials

Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition (NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.

Watso JC, Farquhar WB. Hydration status and cardiovascular function. Nutrients. 2019 Aug 11;11(8):1866. https://doi.org/10.3390/nu11081866

Wittbrodt MT, Millard-Stafford M. Dehydration impairs cognitive performance: a meta-analysis. Med Sci Sports Exerc. 2018 Nov 1;50(11):2360-8. DOI: 10.1249/MSS.000000000000168

Appendix - Existing Evidence Base

Existing Evidence — Rev C

Stacking the Risks

Despite these known limitations, mass and resource challenges have driven additional food system cuts in each vehicle program. The food system across Artemis is more restricted than any vehicle since Gemini, despite that:

- The entire Artemis mission may be several weeks longer than Gemini
- Crew is expected to perform at very high levels, both cognitively and physically, even during periods with the greatest food system limitations
- Crew will be in small vehicles with few health and performance capabilities (e.g., exercise and medical support)
- Each program is levying expectations on other programs that have not been communicated or agreed to [e.g., they will eat better on Gateway & Orion, so they can take the cuts on Human Landing System (HLS)]

Varied Requirements Across Vehicles (New Evidence)

Artemis Campaign Development (ACD) Risks for Inadequate Food and Nutrition Artemis II-V

Orion (up to 21 days)

No hot or cold potable water

Wide "ambient" potable water

temp range Cumbersome water

dispense method

No refrigeration

Volume and power limitations for food warmer

Long food prep time

Reduced calories & flavored beverages

Gateway (up to 25 days)

Hot water TBD

Food warmer capability TBD

Delayed Galley ops if Logistics Module (LM) not available

Prepositioned food shelf

life No cold storage,

even 30+ days

General

Program requirements

tailored, do not always

align across programs or

to established NA DRM

category changes

exacerbate requirement

deviations

HLS Option A / Lunar Exploration Transportation Services (LETS) (Up to 8 days)

Optional Government Furnished Equipment (GFE)

Unknown preparation capabilities

Potential higher fat meals (no prior spaceflight data)

Potential restricted EVA-day mealtimes (30mins x 2)

xEVA

No current capability to provide in-suit nutrition (though reqt exists)

Optional GFP for EVAs

We cannot extrapolate from ISS to define the potential health and performance risks on these Artemis missions

Due to prepositioning and meal restrictions, food / beverage preferences, food allergies or food restrictions cannot be accommodated

Existing Evidence — Rev B

- 1912 Antarctic expedition – food lost in a crevasse. Ate dog meat as dogs perished.100 g of husky liver
- >>1000000 IU vitamin A… vitamin A toxicity killed several explorers.
- “As many expeditions failed due to vitamin C deficiency as due to vitamin A toxicity”
- In 1753, Lind found that lemons prevent scurvy. Some expeditions failed b/c they brought limes instead (1/2 the
- amount of vitamin C).
- Scurvy was considered to have been eliminated. Except on Franklin's last arctic exploration, despite providing 1 ounce lemon juice/d. It is possible that the lemon juice began to ferment and was boiled to prevent this—destroying the ascorbic acid.
- Lead poisoning due to the soldering of the cans that contained the preserved meats. The technology canning meat was new, patented in 1811, sealing cans with a solder of tin and lead.
- It is believed that some died from beri beri (thiamine deficiency) due to the baking powder in the biscuits – which destroys thiamine and that was likely their only source.

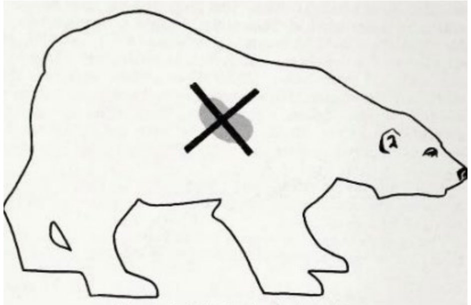
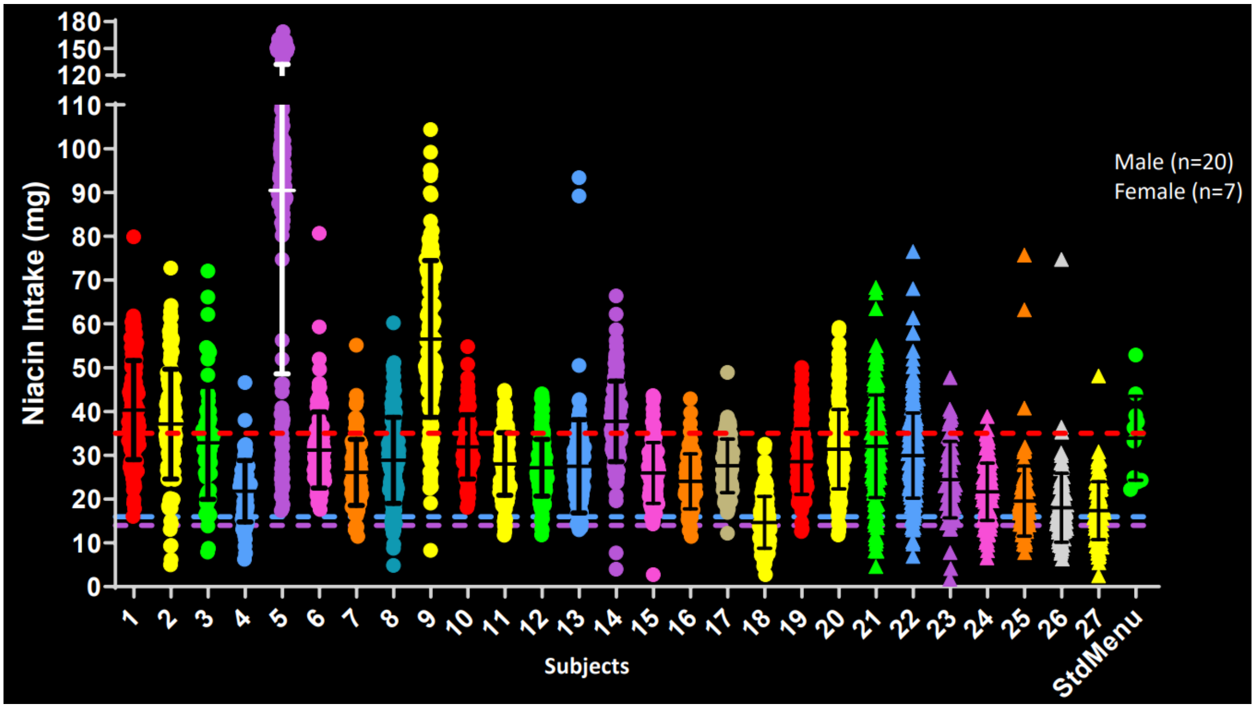


Figure 6-9.—Polar bear liver is poisonous!

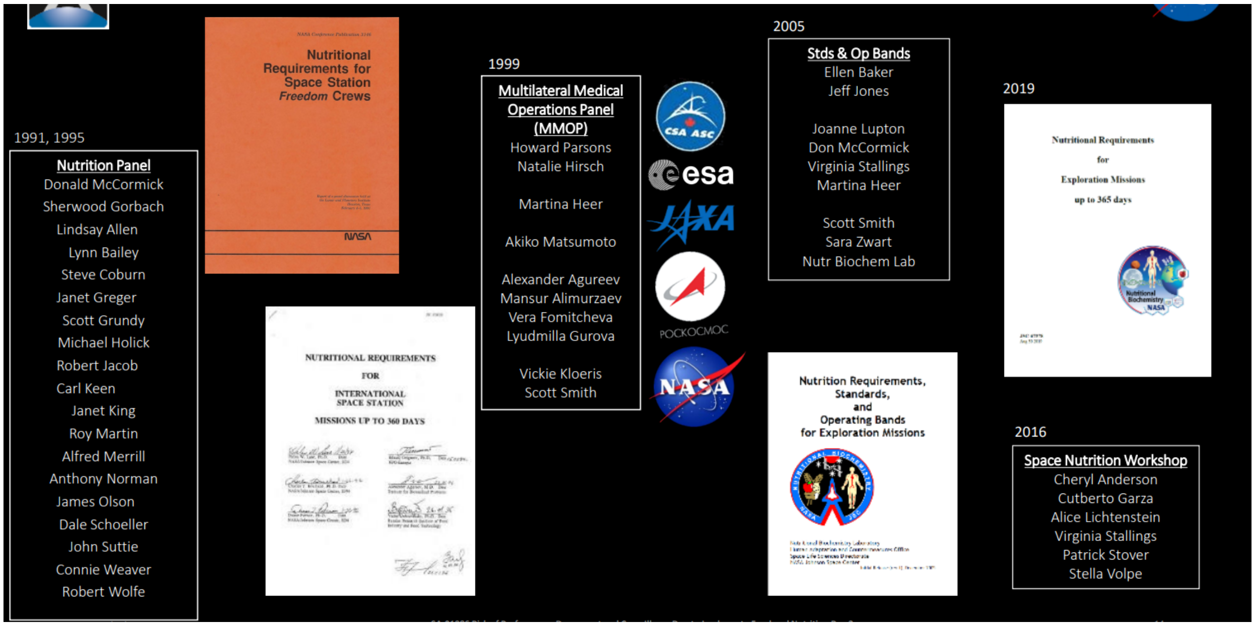


Nutrient	Toxicity Symptoms
Niacin	UL= 35 mg. Flushing, itching, headaches, increased intracranial blood flow

Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2^{nd} edition* *(NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.

Nutritional Requirements Review

- In July 2016, an extramural panel of experts to reviewed all of our work and helped establish an updated set of nutritional requirements.
- The panel had extensive experience with National Academy of Medicine (NAMs) Food and Nutrition Board (FNB), i.e., the group that sets the Daily Recommended Intake (DRIs), including the Chair of the FNB.
- Based largely on the panel's recommendation, and evaluation of existing DRIs and Dietary Guidelines for Americans [U.S. Department of Health and Human Services (USDHHS) and United States Department of Agriculture (USDA)], we have developed the Nutritional Requirements for Exploration Missions document.



1991, 1995

Nutrition Panel
Donald McCormick
Sherwood Gorbach
Lindsay Allen
Lynn Bailey
Steve Coburn
Janet Greger
Scott Grundy
Michael Holick
Robert Jacob
Carl Keen
Janet King
Roy Martin
Alfred Merrill
Anthony Norman
James Olson
Dale Schoeller
John Suttie
Connie Weaver
Robert Wolfe

Nutritional Requirements for Space Station *Freedom* Crews

NUTRITIONAL REQUIREMENTS
FOR
INTERNATIONAL SPACE STATION
MISSIONS UP TO 360 DAYS

1999

Multilateral Medical Operations Panel (MMOP)
Howard Parsons
Natalie Hirsch

Martina Heer

Akiko Matsumoto

Alexander Agureev
Mansur Alimurzaev
Vera Fomitcheva
Lyudmilla Gurova

Vickie Kloeris
Scott Smith

2005

Stds & Op Bands
Ellen Baker
Jeff Jones

Joanne Lupton
Don McCormick
Virginia Stallings
Martina Heer

Scott Smith
Sara Zwart
Nutr Biochem Lab

Nutrition Requirements, Standards, and Operating Bands for Exploration Missions

2019

Nutritional Requirements
for
Exploration Missions
up to 365 days

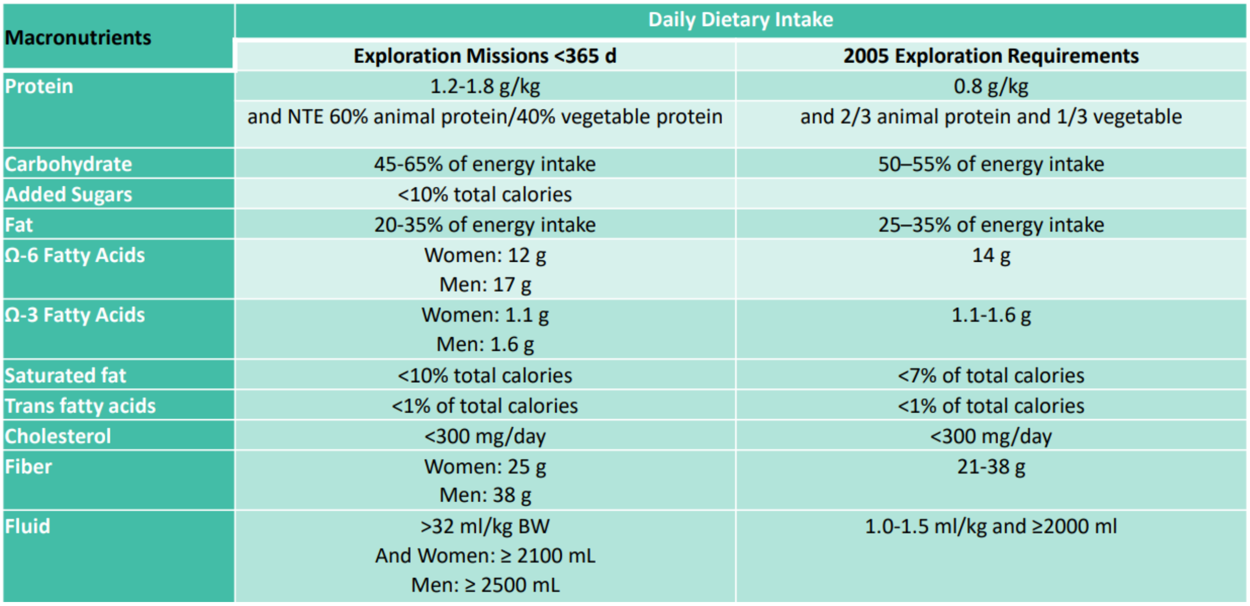
2016

Space Nutrition Workshop
Cheryl Anderson
Cutberto Garza
Alice Lichtenstein
Virginia Stallings
Patrick Stover
Stella Volpe

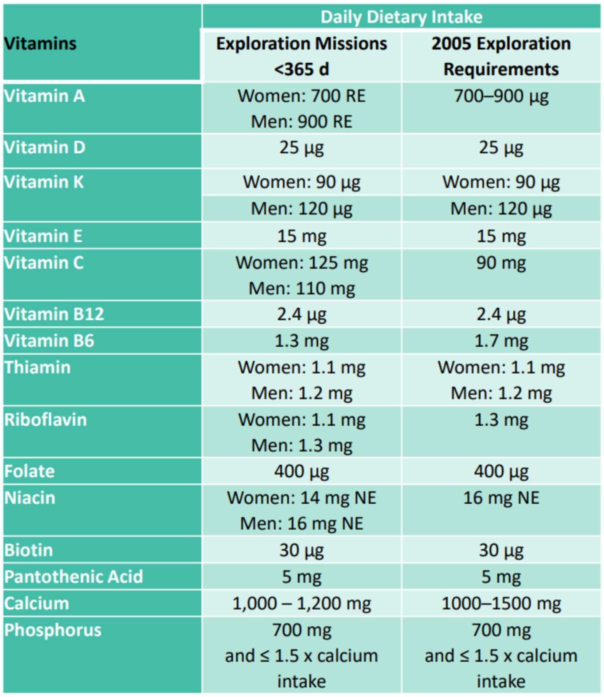
Estimated energy requirements (EERs) are based on calculations from the NAM Dietary Reference Intake (DRI) reports, for Orion using an activity factor of 1.11 ("low active"; higher for ISS and Gateway, lower for lunar) along with age, body mass (kg), and height (m) in the following calculations:

Men: $\text{EER} = 622 - 9.53 \times \text{Age [y]} + 1.11 \times (15.9 \times \text{Mass [kg]} + 539.6 \times \text{Height [m]})$

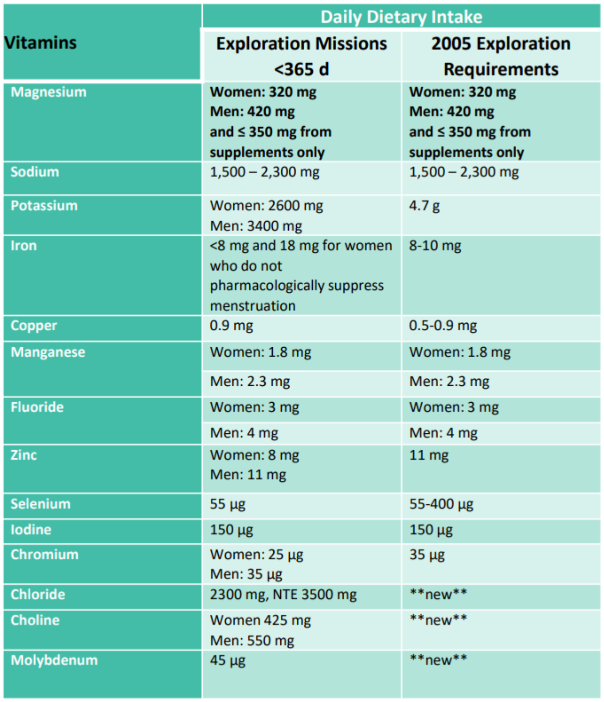
Women: $\text{EER} = 354 - 6.91 \times \text{Age [y]} + 1.11 \times (9.36 \times \text{Mass [kg]} + 726 \times \text{Height [m]})$



Macronutrients	Daily Dietary Intake	
	Exploration Missions <365 d	2005 Exploration Requirements
Protein	1.2-1.8 g/kg	0.8 g/kg
	and NTE 60% animal protein/40% vegetable protein	and 2/3 animal protein and 1/3 vegetable
Carbohydrate	45-65% of energy intake	50–55% of energy intake
Added Sugars	<10% total calories	
Fat	20-35% of energy intake	25–35% of energy intake
Ω-6 Fatty Acids	Women: 12 g Men: 17 g	14 g
Ω-3 Fatty Acids	Women: 1.1 g Men: 1.6 g	1.1-1.6 g
Saturated fat	<10% total calories	<7% of total calories
Trans fatty acids	<1% of total calories	<1% of total calories
Cholesterol	<300 mg/day	<300 mg/day
Fiber	Women: 25 g Men: 38 g	21-38 g
Fluid	>32 ml/kg BW And Women: ≥ 2100 mL Men: ≥ 2500 mL	1.0-1.5 ml/kg and ≥2000 ml



Vitamins	Daily Dietary Intake	
	Exploration Missions <365 d	2005 Exploration Requirements
Vitamin A	Women: 700 RE Men: 900 RE	700–900 µg
Vitamin D	25 µg	25 µg
Vitamin K	Women: 90 µg	Women: 90 µg
	Men: 120 µg	Men: 120 µg
Vitamin E	15 mg	15 mg
Vitamin C	Women: 125 mg Men: 110 mg	90 mg
Vitamin B12	2.4 µg	2.4 µg
Vitamin B6	1.3 mg	1.7 mg
Thiamin	Women: 1.1 mg Men: 1.2 mg	Women: 1.1 mg Men: 1.2 mg
Riboflavin	Women: 1.1 mg Men: 1.3 mg	1.3 mg
Folate	400 µg	400 µg
Niacin	Women: 14 mg NE Men: 16 mg NE	16 mg NE
Biotin	30 µg	30 µg
Pantothenic Acid	5 mg	5 mg
Calcium	1,000 – 1,200 mg	1000–1500 mg
Phosphorus	700 mg and ≤ 1.5 x calcium intake	700 mg and ≤ 1.5 x calcium intake



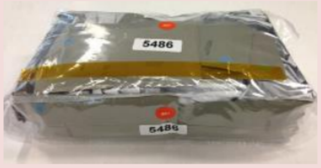
Vitamins	Daily Dietary Intake	
	Exploration Missions <365 d	2005 Exploration Requirements
Magnesium	**Women: 320 mg Men: 420 mg and ≤ 350 mg from supplements only**	**Women: 320 mg Men: 420 mg and ≤ 350 mg from supplements only**
Sodium	1,500 – 2,300 mg	1,500 – 2,300 mg
Potassium	Women: 2600 mg Men: 3400 mg	4.7 g
Iron	<8 mg and 18 mg for women who do not pharmacologically suppress menstruation	8-10 mg
Copper	0.9 mg	0.5-0.9 mg
Manganese	Women: 1.8 mg	Women: 1.8 mg
	Men: 2.3 mg	Men: 2.3 mg
Fluoride	Women: 3 mg	Women: 3 mg
	Men: 4 mg	Men: 4 mg
Zinc	Women: 8 mg Men: 11 mg	11 mg
Selenium	55 µg	55-400 µg
Iodine	150 µg	150 µg
Chromium	Women: 25 µg Men: 35 µg	35 µg
Chloride	2300 mg, NTE 3500 mg	**new**
Choline	Women 425 mg Men: 550 mg	**new**
Molybdenum	45 µg	**new**

Nutritional Requirements for Exploration Missions up to 365 Days (JSC-67378) Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2020.

ISS Standard Food System

8 Standard Categories –
feeds a crew of three for 7-9 days
1. Breakfast
2. Rehydratable Meats
3. Meat and Fish
4. Side Dishes
5. Vegetables and Soups
6. Fruits and Nuts
7. Desserts and Snacks
8. Beverages

Supplemental Categories
9. Personal Preference (one/CM/20 days)
10. Condiments
11. Fresh foods (periodic)



Expected to Meet NASA STD 3001
Nutritional Requirements
Current Average:
Calories 2337
Fat 30% / Sat Fat 10%
Carbs 50%
Protein 20%
Sodium 2621mg

Food Prep Equipment
Hot metered water
Ambient water
Food warmer
Small chiller

Changes in Standard Menu over Last Twenty Years
- Switch from preference to standard menu in 2008
- Increase in variety (from 130 to 200 items) – Limited product development opportunities
- Reduction in sodium (from 5300 to 3300 mg)

ISS Food and Nutrition

- ❖ Crew receive foods on ISS that they may not receive on an exploration mission.
  - Crew on ISS augment the nominal food system with personal preference items (many of which supplement micronutrients or are too high in fat and sodium).
  - Crew on ISS receive fresh fruits and vegetables with almost every visiting vehicle, approximately once per month.
  - Up to 25% of current food choices come from preference and fresh foods.
    - Many crews comment on the importance of these foods in particular, and the increased importance of food in general during flight.

Known Limitations/Capability Gaps

- ❖ Despite the variety and preference available on ISS, it's still a limited system:
  - Body mass loss still averages >5%.
  - Crew often comment that they tire of the available variety over six months
  - Stuster Journals: food in top 10 of most discussed topics
  - Expedition 56 Top 4 comment: "Given increasing mission duration… fresh fruit and vegetables should no longer be viewed as a luxury"
- ❖ The current food system does not meet ISS nutrition requirements
  - Sodium, iron, fat, fiber, etc.
  - Not enough fruits/vegetables, sources of omega-3s
- ❖ The current food system does not meet nutrition and acceptability requirements to support Mars missions or extensive prepositioning for Gateway/lunar missions.

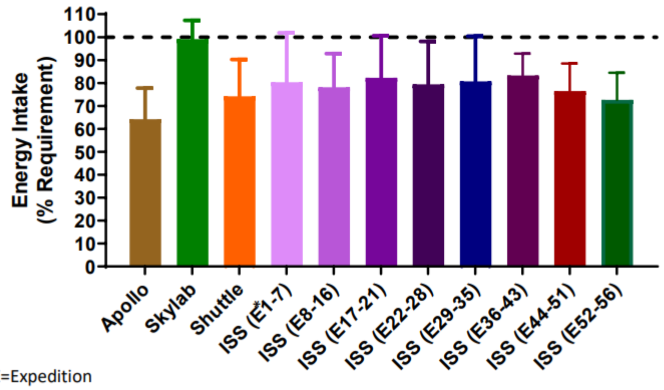
Military and Terrestrial Evidence

- ❖ Terrestrial and military data demonstrate that there are links between food/nutrition intake and other risks, including:
  - Cardiovascular

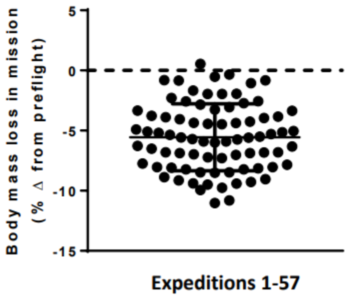
  - Musculoskeletal
  - Behavioral health
  - Cognition
  - Immune health
  - Sleep
  - Physical performance
- The military limits the use of Meal Ready to Eat (MREs) to 21 consecutive days to prevent health and performance impacts due to inadequate food consumption.

Findings

- Data obtained from ISS FIT App document limitations of the food system and the potential impacts on health and performance.
  - Inadequate food (energy) and fluid intake – body mass loss, dehydration
  - Excess protein intake – increased renal stone risk.
  - Excess iron intake – increased oxidative stress/DNA damage, bone loss
  - Excess sodium intake – effects on bone and other systems
  - Insufficient fruit and vegetable intake – impact on nutrient intakes: phytochemicals (carotenoids, flavonols, etc.)
    - could provide antioxidant protection, Gastrointestinal (GI) and cardiovascular health, improve behavioral performance/morale
  - Inadequate fiber intake – effects on GI health and microbiome
  - Excess cholesterol and saturated fat intake and effects on lipids and cardiovascular health
  - Insufficient omega-3 fatty acid intakes
    - could benefit cardiovascular and bone health, radiation protection
- Insufficient choline intake – associated with increased oxidative stress



*E=Expedition



3% with >10% weight loss
57% with 5-10% weight loss

Body mass loss is associated with **bone** and **muscle** loss, impaired **cardiovascular** fitness, increased **stone risk**, increased **oxidative stress**, etc.

Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition* *(NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.

Renal Stone Risk

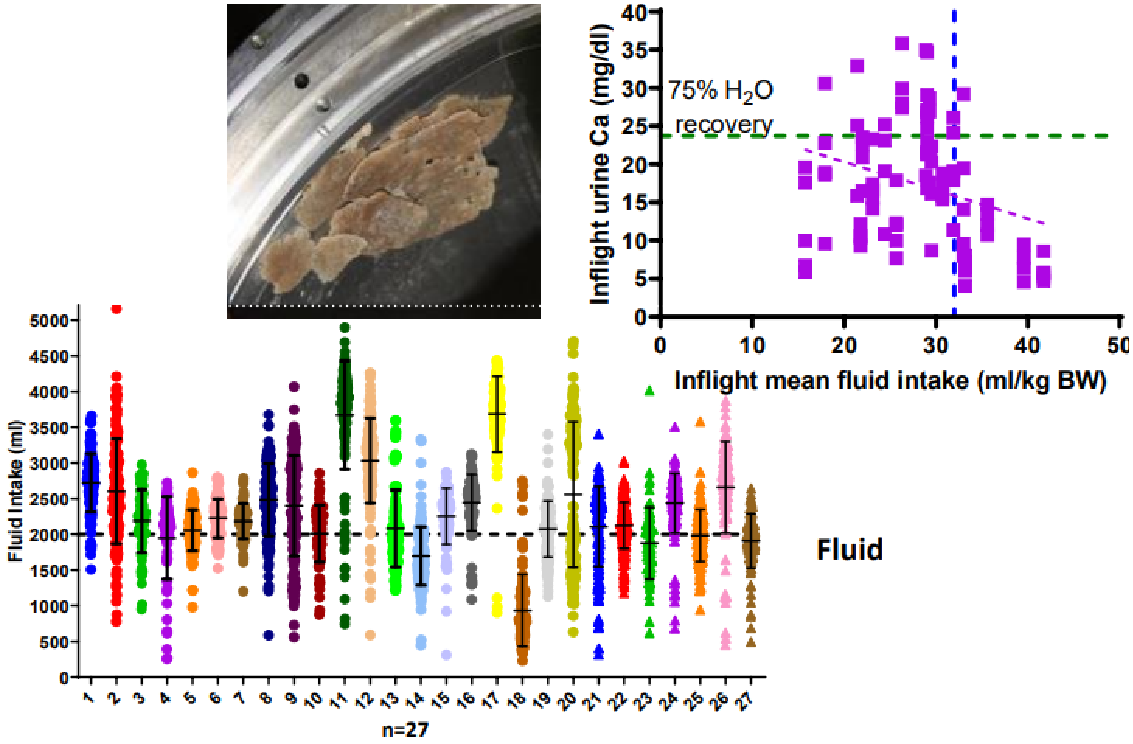
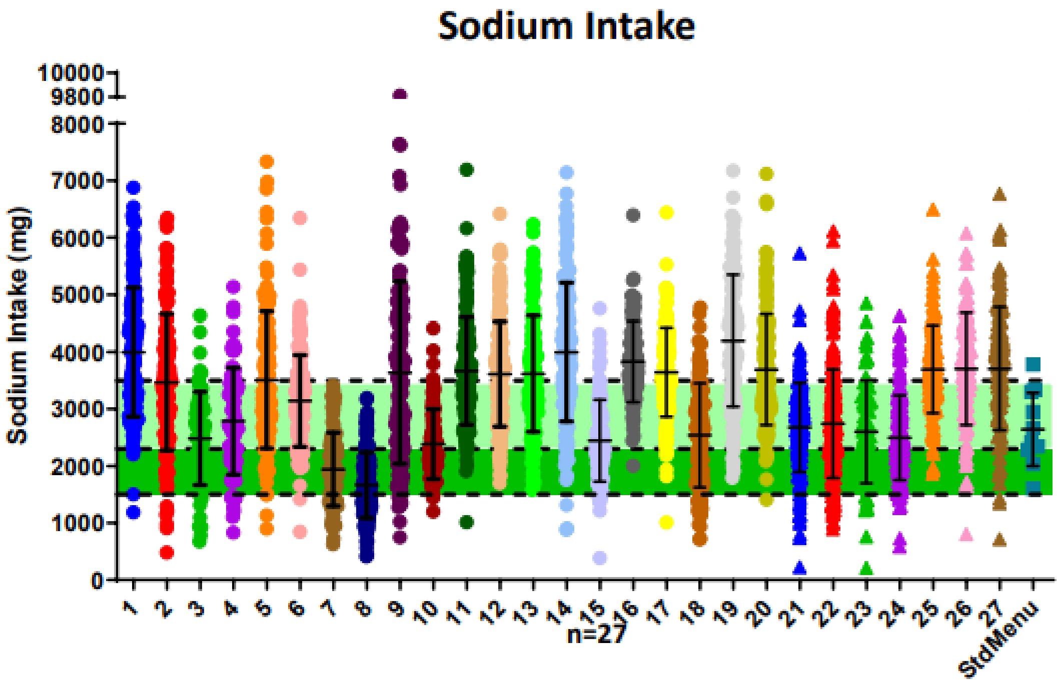


Image at top left - Smith et al., Nutrients, 2012.© 2012 The Authors. Open-access article distributed under the terms of the Creative Commons Attribution License (CC BY).

Images top right and lower - Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition* *(NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.



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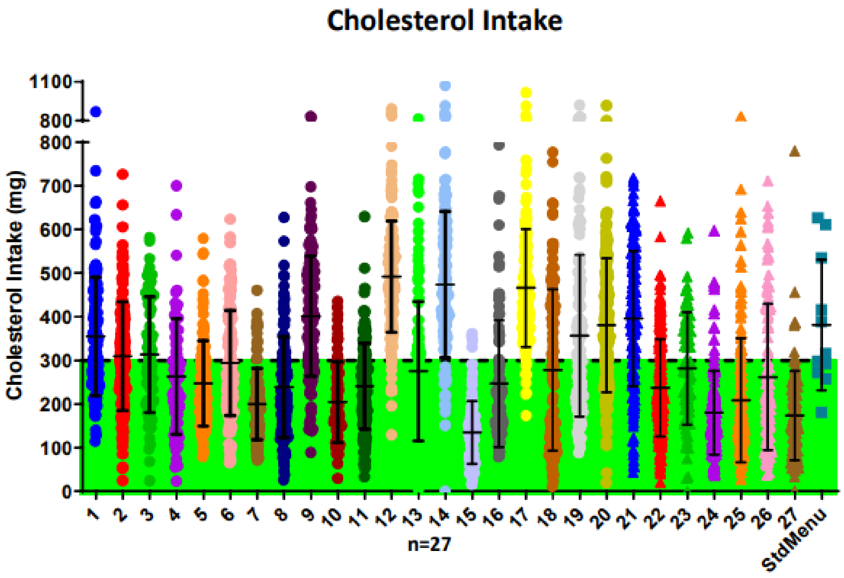
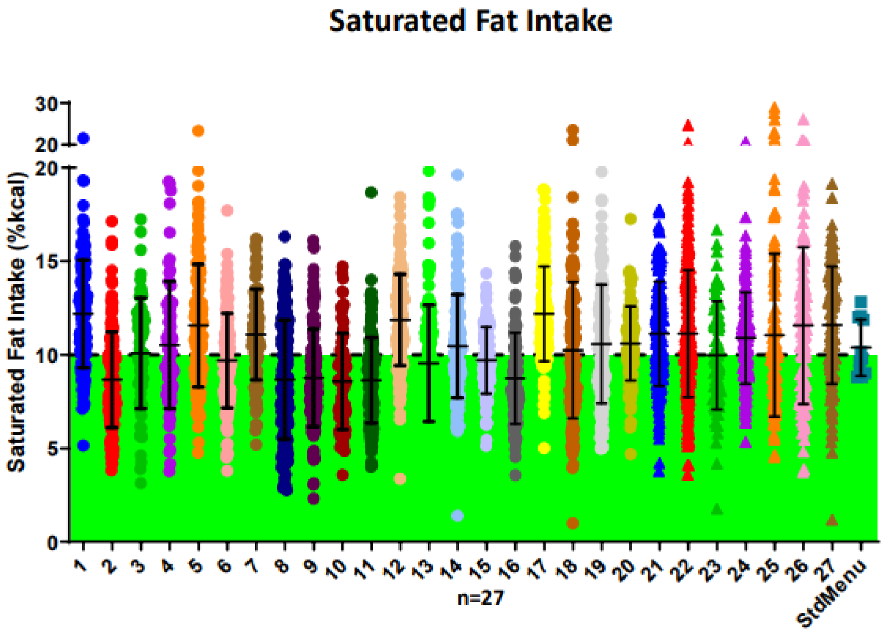
Diet effects on bone heath and renal stone risks are significant.
Terrestrial data document that hydration affects cardio, performance/cognition, etc.

Cholesterol and Saturated Fat Intakes



"…Consumption of…cholesterol should be as low as possible, …not to exceed 300 mg/d."

Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition* *(NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.



"…Consumption of saturated fat…should be as low as possible, …not to exceed 10% of kcals,"

Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition* *(NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.

Vitamin D: Case Study

This case is to be included in a review article that is in preparation for submission to a journal.
The case shows that Vitamin D intake can facilitate absorption of inorganic elements. Elevated serum copper is associated with headaches, etc.

Insufficient

- The ISS Food System fails to meet many nutrient requirements, including:
  - fiber, iron, choline, fat (saturated fats, cholesterol, omega-3 fatty acids), sugar, phosphorus, etc.
- The ISS Food System does not provide enough foods considered part of a healthy diet:
  - More fruits and vegetables
    - Will increase flavonoid, lycopene, and carotenoid intakes
  - More sources of omega-3 fatty acids
  - Lower sodium and iron intakes
  - Adequate energy, protein, calcium, and potassium intakes
- Longer missions, without preference foods, without cargo deliveries of fresh fruits/vegetables, and longer prepositioning will increase risk of clinical issues

Exploration Food and Nutrition: Optimization

- Diet/Nutrition can mitigate (or exacerbate) disease states, including cardiovascular, cancer, sarcopenia, osteoporosis, etc.
- Optimizing the food system may offer a countermeasure to mitigate health risks on long-duration exploration missions and reduce the burden on a constrained medical system.
  - Increasing fruit and vegetable intake (along with the thousands of phytonutrients they provide), and omega-3 fatty acid intake, is critical for crew health and performance.
  - Recent HERA testing and ISS testing that is currently underway will evaluate the effects of improved food and nutrition intake on health and performance.
  - Initial project data are shown on the following charts.
- Longer missions, without preference foods, without cargo deliveries of fresh fruits/vegetables, and longer prepositioning will increase risk of clinical issues

Food Physiology Study: Enhanced Diets

INPUTS

Four 45-Day missions
Four astronaut-like individuals
Isolation and confinement
Operationally relevant stressors
Calculated caloric provisioning
Randomized missions to either
Enhanced or Standard diet

↑ Enhanced Diet
Fruits and Vegetables
(Flavonoids, Lycopene)
Fish (Omega-3 Fatty Acids)

OUTPUTS

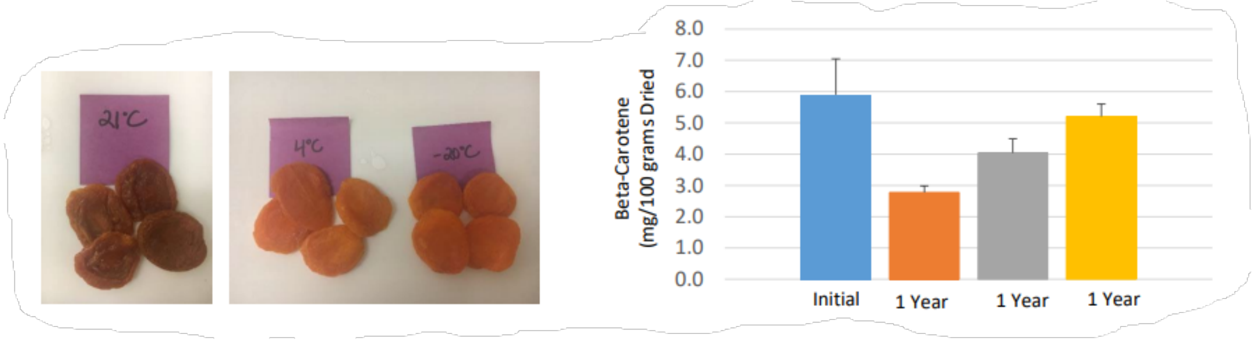
Associations with
Enhanced Diet

↓ Cortisol Levels
Viral Reactivation
Microbiome Changes

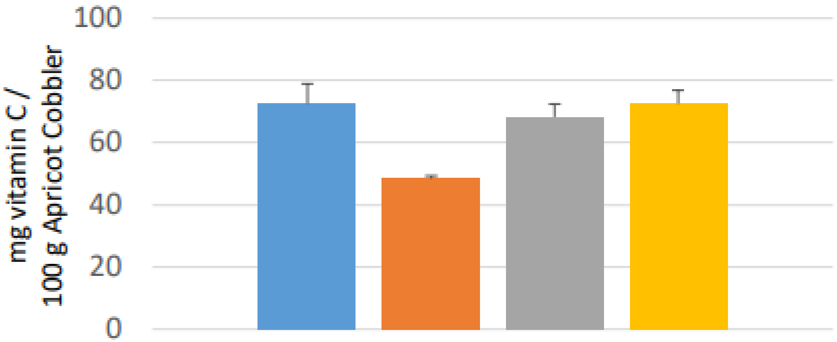
Conditioned Storage Study

Initial look:

Beta-Carotene and Color Change of Dried Apricots after One Year of Storage at 21°C, 4°C, or -20°C



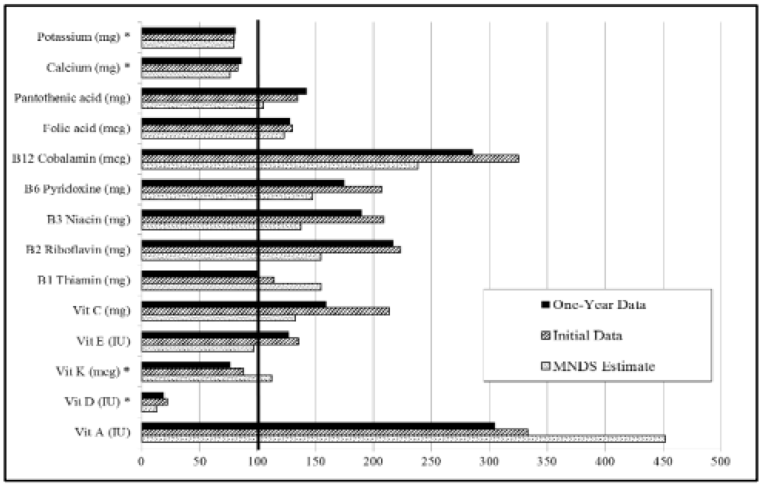
Vitamin C in Apricot Cobbler after One Year of Storage at 21°C, 4°C, or -20°C



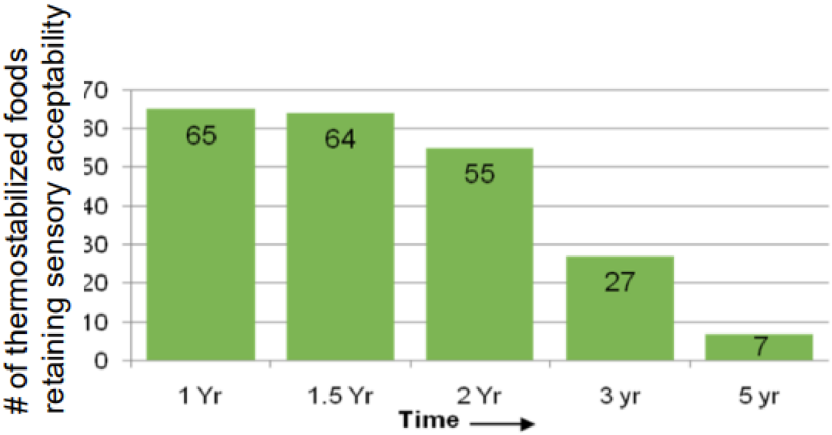
Existing Evidence — Rev A and Baseline

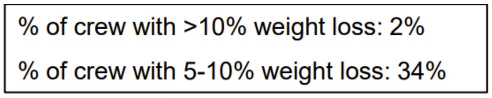
Current Status

- ❖ The capability of the current shelf stable space food system to meet nutrition and acceptability requirements over a 5 year duration is currently being investigated.
- ❖ Micro-nutritional analysis indicates that several key nutrients may not be adequately sustained to meet daily intake requirements in the food system for the duration of a Mars mission or are only sustained in a restrictive number of foods.
- ❖ Quality analysis indicates that food acceptability may not be adequately sustained for the duration of a Mars mission. Military, Apollo mission and ISS mission data demonstrate that if the food system is not acceptable, it may not be adequately consumed, and crew may not receive adequate nutrition.
- ❖ The following nutrition slides from ISS crew indicate that under consumption and inadequate micro-nutrition in a variety of foods over mission duration is measurable in crew biomarkers.



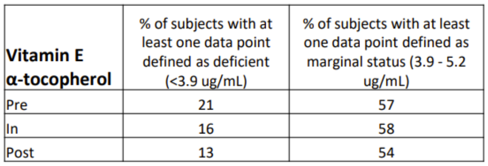
- ❖ Operational and Research protocols on ISS have expanded our understanding of the role of nutrition in crew health, before, during, and after flight.
  - Data summarized here (details in backup charts) highlight incidence of several nutritional issues for ISS (USOS) crews.



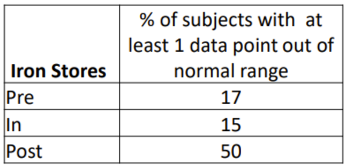


% of crew with >10% weight loss: 2%

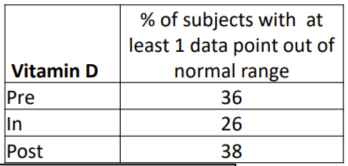
% of crew with 5-10% weight loss: 34%



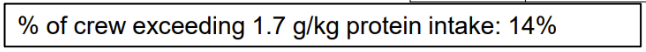
Vitamin E α-tocopherol	% of subjects with at least one data point defined as deficient (<3.9 ug/mL)	% of subjects with at least one data point defined as marginal status (3.9 - 5.2 ug/mL)
Pre	21	57
In	16	58
Post	13	54



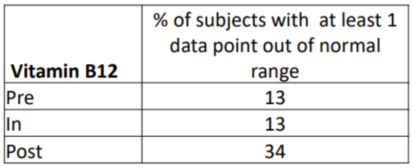
Iron Stores	% of subjects with at least 1 data point out of normal range
Pre	17
In	15
Post	50



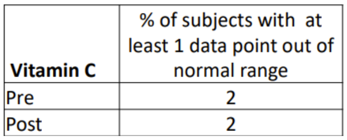
Vitamin D	% of subjects with at least 1 data point out of normal range
Pre	36
In	26
Post	38



% of crew exceeding 1.7 g/kg protein intake: 14%



Vitamin B12	% of subjects with at least 1 data point out of normal range
Pre	13
In	13
Post	34



Vitamin C	% of subjects with at least 1 data point out of normal range
Pre	2
Post	2

- These data highlight the complex relationship between food and nutrition requirements, as some of these nutrients (e.g., vitamin B12 and vitamin E) are provided in the food system but may reflect altered requirements.

Ongoing Research

- ❖ We are investigating countermeasures that will improve the nutritional stability and acceptability of the food system over time:
  - Processing: Pressure assisted thermal sterilization (PATS); microwave sterilization; bulk automated processing; and lyophilization process improvements
  - Packaging: Novel commercial high barrier packaging compatible with novel processing; prototype development for in-suit delivery
  - Formulation: Health promoting ingredients; stabilizing food matrices; fortification
  - Variety: Analog evaluations
  - Storage conditions: Temperature; vacuum; radiation
  - Bioregenerative: In-flight plant chambers with pick-and-eat vegetable and fruits

Even if we determine how to provide stable nutrition, we cannot provide adequate nutrition until exploration requirements are fully developed

- ❖ We are investigating mass reduction strategies:
  - Meal replacements: Nutrient dense, nutritionally balanced, shelf stable, sensory, and psychosocial acceptability
  - Reformulation: Reduce moisture or increase fat (already at saturated fat limit)
  - Trades: Packaging and storage conditions

- ❖ We are investigating dietary ability to mitigate negative effects of space flight on physiology and nutritional health
  - Pro K (diet/bone)
- ❖ We are evaluating nutritional role and relationship with VIIP
  - One Carbon Metabolism study
- ❖ We are monitoring the role of nutrition in other systems (e.g., Cardio, Bone, Muscle, Immune, Radiation) with the Biochem Profile project.
- ❖ This will help identify gaps in current food system relative to physiological systems and changes in nutritional requirements in flight, which will inform/help define exploration requirements.

- ESA studies ongoing to evaluate long-duration energy requirements.
- We are not currently evaluating the role of nutrition and BHP or Pharm risks, which remain critical gaps

Forward Work

Collaborative cross-Element effort between Space Food Systems and Nutritional Biochemistry to Focus on Promotion of Crew Health through Food Countermeasures

Nutrition SRP 2013 Executive Summary: *"The SRP considers the planned Integrated Nutrition task to be an important and necessary strategic part of the research plan."*

Planned work with CA/CB and OC to implement the HRP approved project to meet multiple interests.

- Food upmass a critical issue
- HRP suggesting this should be approached operationally, and not as research
- Looking for direction from HSRB

References

Chen, Y. M., Ho, S. C., & Woo, J. L. (2006). Greater fruit and vegetable intake is associated with increased bone mass among postmenopausal Chinese women. *British journal of nutrition*, *96*(4), 745-751.

Sahni, S., Hannan, M. T., Blumberg, J., Cupples, L. A., Kiel, D. P., & Tucker, K. L. (2009). Protective effect of total carotenoid and lycopene intake on the risk of hip fracture: a 17-year follow-up from the Framingham Osteoporosis Study. *Journal of Bone and Mineral Research*, *24*(6), 1086-1094.

Mackinnon, E. S., Rao, A. V., Josse, R. G., & Rao, L. G. (2011). Supplementation with the antioxidant lycopene significantly decreases oxidative stress parameters and the bone resorption marker N-telopeptide of type I collagen in postmenopausal women. *Osteoporosis International*, *22*(4), 1091-1101.

Nutritional Requirements for Exploration Missions up to 365 Days (JSC-67378) Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2020.

Smith, S. M., McCoy, T., Gazda, D., Morgan, J. L., Heer, M., & Zwart, S. R. (2012). Space flight calcium: implications for astronaut health, spacecraft operations, and Earth. *Nutrients*, *4*(12), 2047-2068.

Smith SM, Zwart SR, Douglas GL, Heer M. *Human Adaptation to Spaceflight: The Role of Food and Nutrition, 2nd edition (NP-2021-03-003-JSC).* Houston, TX: National Aeronautics and Space Administration Lyndon B. Johnson Space Center; 2021.

Virtanen, J. K., Mozaffarian, D., Cauley, J. A., Mukamal, K. J., Robbins, J., & Siscovick, D. S. (2010). Fish consumption, bone mineral density, and risk of hip fracture among older adults: the cardiovascular health study. *Journal of Bone and Mineral Research*, *25*(9), 1972-1979.