NASA-STD-3001 Technical Brief

Crew Survivability

OCHMO-TB-047

Executive Summary

As future spaceflight missions become increasingly complex, longer in duration, and a further distance from Earth, readily available rescue and evacuation options must be evaluated to protect crewmembers during off-nominal survival scenarios. This technical brief explores options to support rescue scenarios by reducing the human usage of consumables (i.e., oxygen, food, water, power) to extend the mission to enable rescue. By considering these potential survival scenarios during the planning and design phase, providers can make informed decisions on vehicle capabilities, mission supplies, crew make-up and rescue options.

Artemis I SLS waiting on the launchpad

Relevant Technical Requirements

NASA-STD-3001 Volume 1, Rev C

[V1 3004] In-Mission Medical Care

NASA-STD-3001 Volume 2, Rev D

[V2 4015] Aerobic Capacity
[V2 6001] Trend Analysis of Environmental and Suit Data
[V2 6003] O2 Partial Pressure Range for Crew Exposure
[V2 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels
[V2 6012] Crew Health Environmental Limits
[V2 6014] Crewmember Heat Storage
[V2 6017] Atmospheric Control
[V2 6109] Water Quantity
[V2 7003] Food Caloric Content
[V2 7100] Food Nutrient Composition

NOTE: The parameters discussed in this technical brief are for illustration purposes only. The details for a mission extension scenario must consider exact circumstances and crew complement.

Application

Survival Scenarios

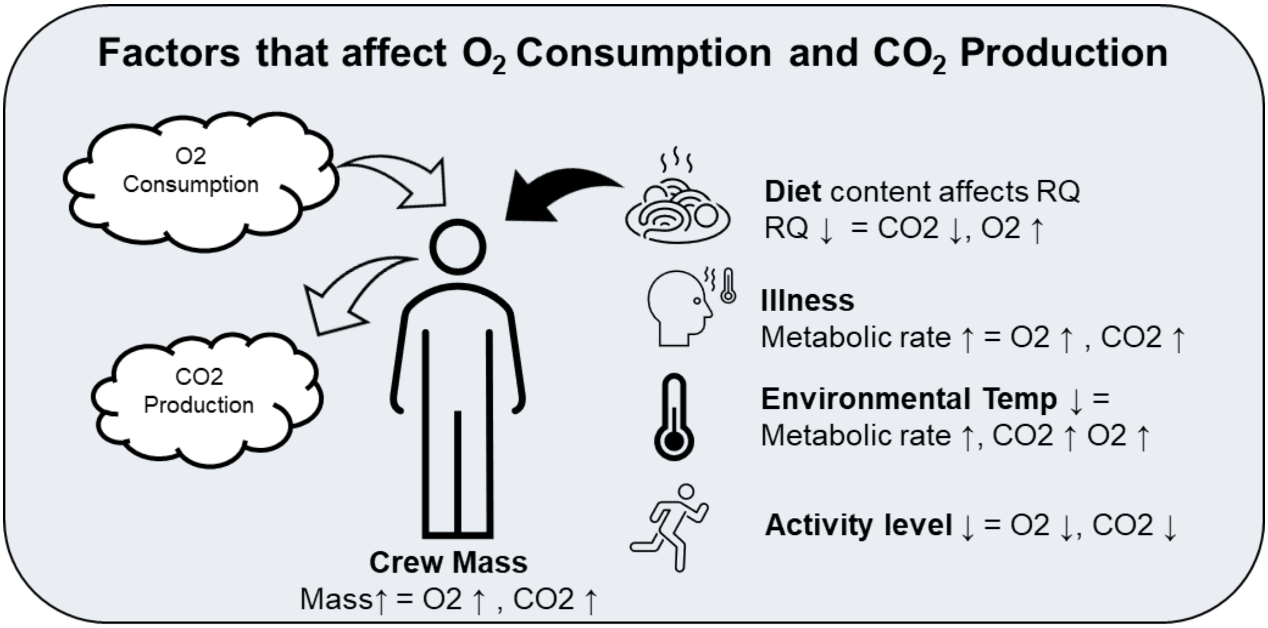
For the purposes of this technical brief, crew survival modes are separated into three categories:

Baseline – Full performance capabilities, continue with nominal operations including extravehicular activity (EVAs), providing full caloric and water intake, and nominal environmental control parameters.

Survival Mode 1 (Moderate) – Continued performance of most crew tasks, no EVAs or routine exercise and reduced daily activity by approximately 15%; limit food and water intake to 50% of baseline levels. A moderate amount of crew performance impacts is expected in this survival mode with no long-term health impacts.

Survival Mode 2 (Severe) – Strictly limit crew activity, no EVAs or routine exercise and limit activity by approximately 28%, ideally spent sleeping or idle; significantly limit water and food intake by 1/3 basal metabolic rate needs and modify respiratory quotient (RQ) through diet modification. This survival mode will create severe performance limitations in crew with significant health effects (i.e., lethargy, flu-like symptoms) and has the strong possibility of leading to long-term health effects (such as renal stones or bone loss).

Factors for increasing mission duration and reducing the consumption of resources



Application

Overview of Physiological Factors Considered for the Survival Modes See following pages for more detail.

Activity – Nominal Metabolic Rates – *82 kg Crewmember, 45 ml/kg/min VO_2max*

- Sleep 88 Watts (300 BTU/hr, 76 kcal/hr)
- Nominal "awake" activity: 139 Watts (474 BTU/hr, 119 kcal/hr)
- Exercise: Aerobic 968 Watts (3303 BTU/hr) Resistive 347W (1184 BTU/hr)

Diet – Type of food intake affects respiratory quotient (RQ) = volume of CO_2 released over the volume of O_2 absorbed during respiration. The RQ can change be adjusted through intake of carbohydrates, fat, and protein.

- Physiologic range for RQ is between 0.7 to 1.2, although can be lower in illness
- An RQ over 1 has excessive carbohydrate intake that results in increased CO_2 production
- An RQ near 0.7 is ketonic/low carb high fat diet that results in decreased CO_2 production

RQ changes with intensity of activity:

- Low activity – the RQ is usually between 0.8 and 0.9 (fatty acids are the primary fuel)
  - NASA uses 0.85 RQ for missions during sleep and nominal activities
- Intense activity – the RQ is usually between 0.9 and 1.0 (carbohydrates are the primary fuel)
  - NASA uses 0.95 RQ for missions during exercise

Illness – If a crew member becomes ill, they will have an increased metabolic rate and consume more O_2 and produce more CO_2. The more severe the illness (fever, increased heart rate, etc.), the metabolic rate will increase.

Environmental temperature – If reduced, it will cause an increased metabolic rate. If increased, the metabolic rate will rise rapidly and then fall.

Factors Manipulated	Baseline	Survival Mode 1 Moderate	Survival Mode 2 Extreme
Food Calories	3600 calories/day	1800 calories/day	600 calories/day
Respiratory Quotient (RQ)[1]	0.85	0.75	0.70
Water	4 liters/day	1.25 L/day	0.75 L/day
Env. Temp (conservation of power)[2]	22C/71F	18C/65F	15C/60F
Humidity	30-60%	25-75%	25-75%
Carbon Dioxide (CO_2) scrubbing level	3 mmHg	7.6 mmHg	10-15 mmHg
Metabolic Rate (BTUs/hour)[3]			
Sleep (8 hrs)	300	300	300
Nominal Activity (14.5 hrs/16 hrs)	474	400	350
Exercise			
10 minutes resistive	1184		
20 minutes aerobic	3303		
1-hour post-exercise	500		
Heart Rate (range)[3]	Sleep baseline to 90% peak heart rate (aerobic exercise)	Sleep baseline to 400 BTU activity level (approx. +15-20 bpm)	Sleep baseline to 400 BTU activity level (approx. +10-15 bpm)
Oxygen (O_2) Consumption[3]	1.64 lb/day	1.49 lb/day	1.37 lb/day
CO_2 Production	1.92 lb/day	1.53 lbs/day	1.32 lb/day

[1]Modification of crewmember diet, including manipulation of macronutrients (i.e., fats, proteins, carbohydrates) consumed can be used to influence the RQ.

[2]Environmental temperatures are based on parameters at which point energy expenditure increases below a certain temperature. Additionally, the recommended environmental temperatures assume that crew do not have access to additional sources of warmth (i.e., clothing layers); these temperatures can be reduced significantly lower with the availability of additional warming sources.

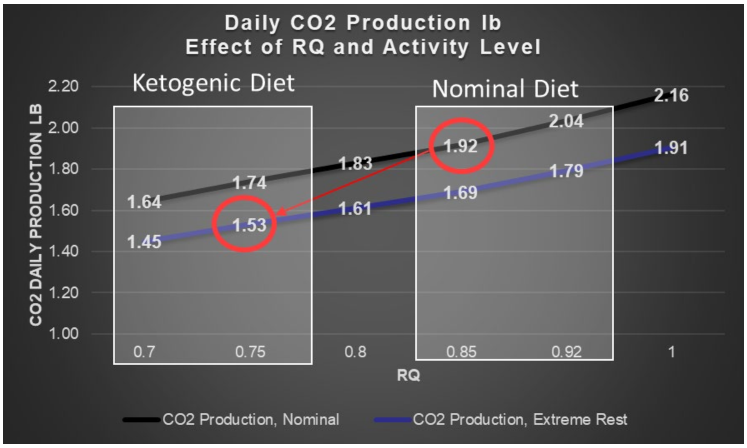
[3]Guidelines based on the assumption that all crewmembers are considered 'healthy'. A fever increases metabolic rate by approximately 10-12% for every 1C increase over 37C body temperature, leading to increased O_2 consumption rates of 1.86lbs/days for mild illness and 2.86lbs/day for moderate to severe illness. A severely ill crewmember (+2-3C) is expected to increase average metabolic rate by 24-36%. For every 1C increase in body temperature, the heart rate increases by approximately 7bpm.

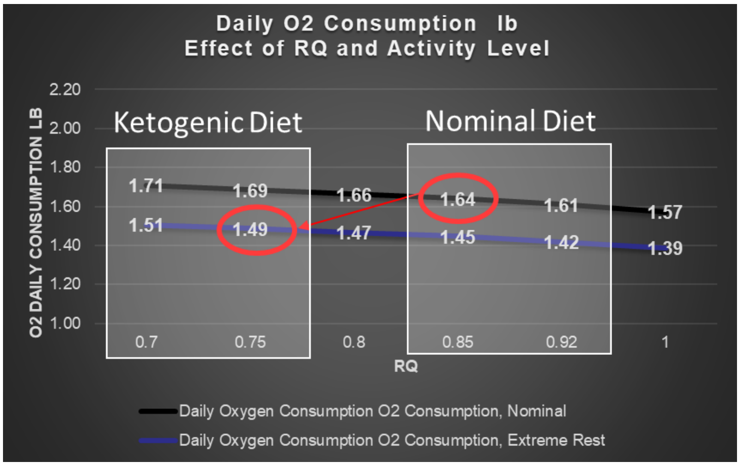
Application

Respiratory Quotient

The respiratory quotient (RQ) is a measurement of energy expenditure defined as the amount in volume of CO_2 that is produced over the amount in volume of O_2 that is consumed during respiration (RQ = Vol CO_2 released/Vol O_2 absorbed). Carbohydrates are oxidized during the aerobic respiration process in an equal ratio of CO_2 released and O_2 consumed, resulting in a RQ of 1.0. The metabolism of fats produces less CO_2 per volume of O_2 consumed, resulting in a RQ of 0.7. When an individual consumes a mixed diet of macronutrients, the RQ ratio is collectively equal to 0.8 to .825. It is proposed that by sending the body into ketosis, which is a metabolic state that burns fat instead of glucose for energy, the RQ can be reduced to decrease O_2 consumption and limit CO_2 production as demonstrated in the table below. To enter ketosis, the diet is modified to strictly limit the amount of carbohydrates and increase the amount of fats consumed. Additionally, evidence suggests that consuming a high-fat and energy dense diet mitigates negative physiological effects from being in an energy deficit and helps to sustain physical performance during cold-weather military operations.

It is important to note the potential environmental impacts of crewmembers being in a state of ketosis, due to the increase of ketones in the bloodstream leading to higher levels of acetone expelled during respiration.





Calculations based on NASA 41-Node Metabolic Man Model. See page 8.

Examples

At RQ 0.68
Total O_2 Consumption = 1.717 lbm/day
Total CO_2 Production = 1.61 lbm/day
Normal diet (0.85)
Total O_2 Consumption = 1.641 lbm/day
Total CO_2 Production = 1.92 lbm/day
Normal diet (0.92)
Total O_2 Consumption = 1.609 lbm/day
Total CO_2 Production = 2.04 lbm/day
For a crew of 4 over a 7-day period for 0.85 vs. 0.68 diet:
Increased O_2 Consumption by 2.128 lbm
Decreased of CO_2 production by 8.68 lbm
For a crew of 4 over a 7-day period for 0.92 vs. 0.68 diet:
Increased O_2 Consumption by 3.024 lbm
Decreased of CO_2 production 12.04 lbm

Background

Food/Nutrition

- Studies exploring the physiological effects of extreme caloric restrictions observed that after 24-weeks of soldier intake being reduced in half to 1,800 kcal/day, resting energy expenditure decreased by 40%.[4–6]
- Additionally, body weight loss of approximately 10 percent resulted in a 10-15% decline in VO_{2max}.[7,8] Studies have also found that an energy deficit resulting in less than 10% loss of body weight does not impair physical performance[7,9,10], and mild to moderate underconsumption has not been found to impact cognitive performance.[4]
- Approximately 1lb. of body weight loss is equivalent to a 3,500-calorie deficit. For the baseline crewmember reference body weight of 82 kg (180lbs) and BTU expenditure, the average basal metabolic rate (BMR) would be approximately 1,800 calories/day. At Survival Mode 2 with crewmembers limiting physical activity and consuming 1,800 calories, there would be a negligible amount of body weight loss expected. In Survival Mode 3, a calorie reduction to 600 calories/day resulting in about a 1,200 calorie/day deficit would result in a 10 percent loss of body weight in approximately 52 days.

Water

- Daily water requirements vary widely based on diet, metabolism, fat free mass, activity level, environmental conditions, and other factors.[27] Some of the most important factors are physical activity level and athletic status, not necessarily anthropometric factors. [27,29] An adult's daily total water intake consists of water consumed from pure water and water-containing beverages as well as approximately 20% from food intake.[11] Research has sought to establish both a 'liberal standard' of recommended total water intake as well as minimum daily requirements for water in survival conditions. General recommendations for water intake are 1 to 1.5 ml/kcal expended per day.[28] Some guidelines have concluded that 2.1 L per day is the minimum water intake amount for adult men, with a 'liberal standard' of approximately 1 mL of water for every calorie expended.[11,12] Further studies suggest a survival amount of water intake no less than 0.91 L per day. An additional factor to consider is with altitude there is a positive correlation with water turnover (WT). [27] A 1000 m increase in altitude induces an approximately 500 ml increase in WT. [27]
- Mild to moderate dehydration can have physiological and psychological performance ramifications, including fatigue, lethargy, medical complications, confusion, mood impacts, and memory loss, though these observations are inconsistent.[14] In addition, it has been found that cold-weather environments can lead to dehydration levels similar to hot climates due to factors such as cold-induced diuresis and increased respiratory water loss correlated with decreased temperature and humidity levels.[15]

See OCHMO-TB-013 Food and Nutrition and OCHMO-TB-027 Water for additional information.

Background

Environmental Parameters

- Baseline environmental parameter requirements are informed by established knowledge of human physiology, performance, and spaceflight experience, and are summarized in Section 6 of NASA-STD-3001 Volume 2. A vehicle's ability to control the environmental parameters across varying survival modes is limited to the capabilities of the vehicle's Environmental Control and Life Support System (ECLSS).[20]
- Environmental temperatures and humidity levels in Survival Modes 2 and 3 are based on parameters at which point energy expenditure increases below a certain temperature. Studies exploring the effects of temperature exposure on metabolic rates has found that temperatures at approximately 65°F and below lead to an increase in energy expenditure attributable to efforts to keep the body temperature warm (i.e., shivering, blood flow.).[21,22]
- Additionally, the recommended environmental temperatures assume that crew do not have access to additional sources of warmth (i.e., clothing layers, blankets). The recommended temperatures may be reduced with the availability of additional warming sources.
- The CO_2 levels are based on evidence collected throughout the years from both spaceflight experience and terrestrial guidelines such as those established by the National Institute for Occupational Safety and Health (NIOSH).[23,24] Elevated atmospheric CO_2 levels are related to symptoms of hypercapnia such as respiratory distress, increased heart rate and blood pressure, dizziness, headaches, confusion, and eventually unconsciousness.[23] ISS experience suggests that spaceflight crewmembers experience CO_2-related symptoms at lower levels of CO_2 than is expected terrestrially.[24] While levels up to 15 mmHg are typically considered safe for short-term (i.e., 8 hour) exposure terrestrially with headaches and mild respiratory symptomology being associated with this level, utilizing levels up to 15 mmHg during an extreme survival mode would require continuous monitoring of crew symptoms.[24]

See OCHMO-TB-002 Environmental Control and Life Support System (ECLSS) for additional information.

Crew Illness

- The guidelines are based on the assumption that all crewmembers are considered 'healthy'. Additional considerations must be taken if one or more crewmembers develop illness ranging from mild (low fever, fatigue, stomach discomforts) to severe (vomiting, diarrhea, high fever). Crew illness can create an impact on both O_2 consumption and CO_2 production, as well as alter the needs for crew environmental temperature/humidity tolerance, food and nutrition, and hydration needs. As the body fights off an infection, there are physiological changes such as increased body temperature, inflammation, or the release of certain hormones. These changes lead to an elevated heart rate, which in turn stimulates an increase in respiratory rate to support O_2 delivery. It is estimated that for every 1°C increase in body temperature, the heart rate increases by approximately 7bpm.[25] A fever also increases metabolic rate by approximately 10-12% for every 1°C increase over 37°C body temperature, leading to increased O_2 consumption rates of 1.86lbs/days for mild illness and 2.86lbs/day for moderate to severe illness. A severely ill crewmember (+2-3°C) is expected to increase average metabolic rate by 24-36%.[26]

Background

One of the most valuable sources of future innovation is learning and implementing lessons from past experience. The STS-400 mission contingency support flight plan offers valuable insight to the factors that are considered when forming plans for different vehicles, crew sizes, and mission lengths. STS-400 was the contingency support shuttle for the STS-125 Hubble Telescope repair mission.
If STS-125 was stranded with 7 crew, they calculated for a CO_2 scrubbing capability of 1 canister every 16-18 hours. They were prepping for a worst-case scenario of less than 22 days and planned on halting all exercise after emergency was declared. They planned to use food bars that followed a mixed diet of 40% fat and 20% carbohydrates with a Respiratory Quotient (RQ) of 0.85.

The Contingency Food Bars Carried on Board:

- 20 Kcal/Kg diet
- RQ goal of 0.85 (40% fat, 20% carbohydrates)
- Per US Navy Disabled Submarine Experience consultation
- Food Bars totaled = 141 for a mass of 8,291 grams

Space shuttle Endeavour begins to roll out of Orbiter Processing Facility 2 to head to the Vehicle Assembly Building at NASA's Kennedy Space Center. After additional preparations are made, the shuttle will be rolled out to Launch Pad 39B. Endeavour was the backup shuttle, if needed for rescue, for space shuttle Atlantis' STS-125 mission to NASA's Hubble Space Telescope in October 2008.

Reference Data

Crewmember Assumptions

There are multiple individualistic factors that contribute to metabolic rates, O_2 consumption, and CO_2 production. The Life Support Baseline Values and Assumptions Document (BVAD)[1] provides a range of metabolic rates for the lowest percentile (5th percentile female) to the largest percentile (95th percentile male), which suggests a variation of approximately +/- 25%.

For the purposes of estimating the datapoints and parameters presented in the table below, the following assumptions and conditions were established by the 41-Node Metabolic Man computer program[2] and Life Support Baseline Values and Assumptions Document[1] to represent the average NASA crewmember mass of 82 kg (180lbs.) and VO_{2max} 45 mL/kg-min.

Formulas for calculating O_2 consumption and CO_2 production based on metabolic rate:

O_2 Utilization rate:

$$\dot{m}_{O2cons} = q_{met}\,(2.0265\text{x}10^{-4} - 4.5055\text{x}10^{-5}\,R_{resp}) \quad (\text{lbm/hr})$$

where $\dot{m}\ O_{2cons}$ is the rate of O_2 disappearance and R_{resp} is the respiratory quotient, the ratio of the number of CO_2 molecules produced to O_2 molecules consumed. The O_2 consumption rate is then used with the respiratory quotient to determine the **CO_2 Production rate**:

$$\dot{m}_{CO2prod} = \dot{m}_{O2cons}\left(\frac{44.0}{32.0}\right) R_{resp} \qquad (\text{lbm/hr})$$

Case	Metabolic Rate (BTUs/day)
Reference Crewmember	12,111
5th Percentile	8,223
95th Percentile	14,598

Back-Up

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

Referenced Technical Requirements

NASA-STD-3001 Volume 1 Revision C

[V1 3004] In-Mission Medical Care All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, individual crewmember needs, clinical practice guidelines, flight surgeon expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses consider the needs and limitations of each specific vehicle and design reference mission (DRM) with particular attention to parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, and behavioral care, are to include, but are not limited to: (see NASA-STD-3001 Volume 1 Rev C for full technical requirement).

NASA-STD-3001 Volume 2 Revision D

[V2 4015] Aerobic Capacity The system shall be operable by crewmembers with the aerobic capacity as defined in NASA-STD-3001, Volume 1.

[V2 6001] Trend Analysis of Environmental and Suit Data The system shall provide environmental and suit monitoring data in formats compatible with performing temporal trend analyses.

[V2 6003] O_2 Partial Pressure Range for Crew Exposure The system shall maintain inspired oxygen partial pressure (PIO2) in accordance with Table 1, Inspired Oxygen Partial Pressure Exposure Ranges.

[V2 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels The system shall limit the average one-hour CO_2 partial pressure ($ppCO_2$) in the habitable volume to no more than 3 mmHg.

[V2 6012] Crew Health Environmental Limits The system shall maintain levels of cabin humidity and temperature within the boundaries of the Operating Limits as shown in Figure 6.2-2—Crew Health Environmental Limits, to protect for crew health during pressurized operations when crew occupies the cabin, excluding suited operations, ascent, entry, landing, and post landing.

[V2 6014] Crewmember Heat Storage The system shall prevent the energy stored by each crewmember from exceeding the cognitive deficit onset (CDO) limits defined by the range 4.7 kJ/kg (2.0 Btu/lb) > ΔQ stored > -4.1 kJ/kg (-1.8 Btu/lb) during pre-launch operations, ascent, entry, descent, landing, postlanding, contingency, and suited operations longer than 12 hours, where ΔQ stored is calculated using a validated and NASA approved thermoregulatory model, such as 41-Node Man (JSC-33124, 41-Node Transient Metabolic Man Computer Program Documentation – A thermal regulatory model of the human body with environmental suit applications) or the Wissler model.

[V2 6017] Atmospheric Control The system shall allow for local and remote control of atmospheric pressure, humidity, temperature, ventilation, and ppO2.

[V2 6109] Water Quantity The system shall provide a minimum water quantity as specified in Table 6.3-1—Water Quantities and Temperatures, for the expected needs of each mission, which should be considered mutually independent.

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

Referenced Technical Requirements

NASA-STD-3001 Volume 2 Revision D

[V2 7003] Food Caloric Content The system shall provide each crewmember with an average of 12,698 kJ (3,035 kcal) per day, else an average energy requirement value is determined using Table 7.1-1—EER Equations and applying an activity factor appropriate to the mission gravity and planned level of physical activity.

[V2 7100] Food Nutrient Composition The system shall provide a food system with a diet including the nutrient composition that is indicated in the Dietary Reference Intake (DRI) values as recommended by the National Institutes of Health, with the exception of those adjusted for spaceflight as noted in Table 7.1-2—Nutrient Guidelines for Spaceflight.

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