Logistics Rates and Assumptions for Future Human Spaceflight Missions Beyond LEO

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As NASA prepares for future human spaceflight missions with extended crew duration in destinations beyond low Earth orbit (LEO), the Agency has focused itself on understanding the drivers to sustainably support human life beyond Earth's atmosphere. Future missions to deep space, the lunar surface, and eventually the Martian surface pose new challenges in ensuring the crew is sufficiently supplied with all necessary materials. To mitigate the risk of not delivering sufficient consumables and logistics for human spaceflight missions, NASA has examined past human space mission data and developed metabolic modeling to determine estimates for the crew consumption rates of fluids, solid consumables, and additional equipment needed. This paper is a compilation of guidelines, rates, and assumptions necessary to evaluate the logistics needs for future human exploration conceptual missions beyond LEO, providing a starting point and resource of information regarding usage rates and overall logistics supply planning for crewed exploration missions. Logistics represent all equipment and supplies not installed as part of the vehicle that are needed to support mission activities. Logistics can be further divided into specific categories, including consumables, maintenance items, spares, utilization, outfitting, and any packaging required. This paper will also provide use case examples of logistics needs to support human missions in deep space, including a conceptual lunar surface mission. The paper provides information necessary to calculate the mass and volume of known logistics for conceptual future human exploration missions beyond LEO. The assumptions in the paper are updated versions of previous assumptions made by the Agency and were derived from a number of sources, including International Space Station (ISS) historical usage and resupply rates, the Life Support Baseline Values and Assumptions Document (BVAD) 2022, Human Integration Design Handbook (HIDH) 2014, and data gathered from NASA human spaceflight programs and projects. The primary goal of the paper is to establish a set of consistent reference rates that multiple teams and groups can utilize to conduct logistics analysis and compare cases. This methodology is for initial estimates of conceptual human missions and does not take the place of detailed analysis for programs, nor does it provide requirements for programs.

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I. Nomenclature

$m_{a,g}$	=	Atomic mass of specified gas
CM	=	Crew Member
CO_2	=	Carbon Dioxide
H_2O	=	Water
H_2	=	Hydrogen
$LiOH$	=	Lithium Hydroxide
m_g	=	Mass of specified gas
mp_g	=	Partial percentage of mass of a specified gas
O_2	=	Oxygen
P	=	Pressure
R	=	Universal gas constant
T	=	Temperature
V	=	Volume

II. Introduction

Unlike uncrewed space missions, humans in space require a large amount of additional supplies in order to protect crew and vehicle health and support mission operations. These supplies, referred to in this document as logistics, must be thoughtfully planned ahead of a mission to ensure crew and vehicle safety and to minimize launch mass. Historical data along with human systems design guidelines and practices have been leveraged to establish logistics estimates that can be used in conceptual human exploration mission planning to compare and contrast various mission approaches under consideration.

The subdivisions of logistics—consumables, maintenance items, spares, utilization, outfitting, and packaging—each serve a unique purpose to support the crewed mission.

- Consumables include all commodities that support the conduct of mission activities (often related to mission crew needs) that are not related to a specific payload or research activity and do not include propellant. In some cases, this category also includes consumables driven by non-crew activities (e.g., air leakage, vestibule re-pressurizations). Examples of specific consumable items include food, clothing, personal items, operational supplies, hygiene items, trash and human waste collection containers, towels, extravehicular activity (EVA) consumables, and gases & liquids.
- Maintenance items include planned replacement hardware, and associated tools, for required replaceable system components that have known limited lifetimes and have a scheduled replacement plan. Planned maintenance items are largely system dependent and are categorized as preventive.
- Spares include **s**pare components or orbital replacement units (ORUs), and associated tools, which address corrective maintenance for unexpected or unplanned failures of systems' hardware. Spares needs are dependent on system architecture and risk acceptance levels and do not include a standard rate.
- Utilization includes additional hardware and items (e.g., science, research, capability demonstration, outreach, etc.) that take advantage of the space-based architecture but are not required for vehicle operation. For early exploration mission planning, mass and volume allocations are typically defined rather than specific utilization hardware as the latter is often mission dependent.
- Outfitting supplies are subsystem hardware or components that are flown after the initial module delivery for permanent installation or use. As items are identified for outfitting, they are expected to be tracked as part of the integrated logistics plan. Outfitting is often driven by insufficient resources to implement all the desired functions within the initial launch mass or schedule, so key systems are delivered on alternate flights. Outfitting estimates are mission dependent.
- Packaging includes materials required to safely and effectively transport and store each of the logistics items. This may include loose packaging or soft carriers, consumables stowage, or pressurized carriers that are delivered to support the mission. This category does not include any spacecraft secondary structures required to house or contain logistics.

This paper will walk through the initial assumptions and rates for the logistics categories, the relationship between logistics rates and requirements and the Environment Control and Life Support System (ECLSS) architecture, trash and waste considerations, outfitting needs, maintenance item and spares modeling and planning, utilization allocations, and packaging and carrier needs. A case study of crew to the lunar surface provides an example of how to use the data presented.

III. Logistics Rates Nomenclature

For each category of logistics, there are subcategories that have unique rates and are functions of unique parameters. Consumables rely on a number of factors, including crew specific parameters as well as mission parameters. For consumables, most logistics item rates are defined as a per crew member (CM) rate and a factor of mission duration, represented as kg/(CM x day), or kilograms per crew member day. Some rates may be defined as solely per crewmember, represented by kg/CM, or solely by mission duration, represented by kg/day. Other consumables may be functions of crew size and mission duration; however, they are defined by item life limits instead of a daily consumption rate. Life limits set a regular schedule for items to be replaced, unlike logistics that are modeled as a continuous rate.

Gases and liquids for crew consumption are defined as mass per crew member day, but the physical size of the crew member also factors into the crew consumption rate. In this paper, rates are provided for three cases: a 5th percentile astronaut, an 82 kg astronaut, and a 95th percentile astronaut. The 82 kg astronaut represents the nominal average astronaut size based on the four crew Orion crew control mass of 328 kg [1]. In addition to crew physical size, atmospheric conditions may have an effect on metabolic rates. The rates presented in this paper are consistent with the standard Earth atmospheric pressure of 14.7 psia and 21% of atmosphere volume is oxygen. As NASA expands to long-duration crew space missions, exploration vehicles and systems are also being considered with 8.2 psia and 10.2 psia with 34% oxygen by volume and 26.5% oxygen by volume atmospheres, respectively. For this paper, the assumption is that the effects of these atmospheric differences on metabolic rate are negligible, and they are not included. Gas and liquid rates are dependent on the crew and crew operations, but total gases and liquids requirements are also system dependent, as several vehicle operations and equipment require fluids and a regenerative ECLSS system is capable of recycling a percentage of fluids back into the system.

Maintenance items, spares, utilization, and outfitting equipment are all measured based on system and mission needs and are not necessarily crew dependent. Packaging is dependent on the other categories, as each specific logistics item delivered has a certain packaging mass associated with it.

IV. Crew Consumables Supply Rates

Supply rates are used to estimate the logistics needed for crew members during a crewed spaceflight mission. The supply rates are independent of any regenerative ECLSS fluid recovery and must be considered together with subsequent sections on crew and system requirements, crew outputs, and ECLSS processing. Although most consumable rates are the same across long-duration in-space transit and surface missions, some do vary and the unique rates for both missions are listed when necessary to differentiate.

A. Crew Consumables

Table 1 presents the supply rates for non-EVA crew consumables as well as a brief description of the items. The rates of some items are further detailed in the next several sections. For Recreation and Personal Stowage and Operational Supplies, the rates listed depend on mission duration and are further explained in the Comments column.

Table 1 Crew Consumable Supply Rates

System/Item	Rate	Unit	Comments
Food, non-EVA days, As Delivered	2.39	$\frac{kg}{(CM \times day)}$	See Section IV.B for further food details.
Food, EVA days, As Delivered	2.94	$\frac{kg}{(CM \times day)}$	See Section IV.B for further food details. EVA days are assumed to require higher levels of aerobic activity, so the food rate for the crew on these days is increased.
Wipes and Gloves	0.20	$\frac{kg}{(CM \times day)}$	Includes Dry Wipes, Wet Wipes, Disinfectant Wipes, and Nitrile Gloves.

System/Item	Rate	Unit	Comments
Hygiene Kits	f (CM × Duration)	kg	See Section IV.C for further hygiene kit details.
Recreation & Personal Stowage	5 ; 10 ; 25 ; 50	$\frac{kg}{CM}$	Includes personal items brought by the crew. Rates based as per crew member and depend on mission duration. Rates are based on the following mission durations: 0-14 days: 5 kg; 15-60 days: 10 kg; 61-360 days: 25 kg; 361-1100 days: 50 kg Base estimates derived from International Space Station (ISS) 180-day increments and historical usage data and scaled for other mission durations.
Operational Supplies	2.5 ; 5 ; 20 ; 25	$\frac{kg}{CM}$	Operational Supplies includes items such as notebooks, writing instruments, tablets, certain laptops, etc. Rates are per crew member and depend on mission duration. Rates are based on the following mission durations: 0-14 days: 2.5 kg; 15-60 days:5 kg; 61-360 days: 20 kg; 361-1100 days: 25 kg Estimates based on ISS and Shuttle Historical Usage Data.
Health Care Consumables	0.09	$\frac{kg}{(CM \times day)}$	Health Care consumables include personal medications, bandages, analgesics, and other consumable medical items that are specific to the crew. Does not include medical items required to be within the element, such as first-aid kits.
Clothing	f (CM × Duration)	kg	See Section IV.D for further clothing details.
Towels	f (CM × Duration)	kg	See Section IV.E for further towel details.
Wastes and Hygiene	0.30	$\frac{kg}{(CM \times day)}$	Waste and Hygiene consumables include trash bags, fecal canisters, and urine prefilters.
Fecal/Urine Collection Bags	0.17	$\frac{kg}{(CM \times Cont.day)}$	Includes waste collection bags that are applied to the planned number of contingency days during the mission.
LiOH Canisters	1.75	$\frac{kg}{(CM \times LiOH\ \ day)}$	LiOH canisters can be used either as a primary CO_2 removal system or as a contingency system due to possible primary system failure or power outage. Rate reflects one LiOH canister per crew member per planned LiOH CO_2 removal day.

B. Food

Food mass required for crew during an exploration mission is dependent on food packaging, food hydration, and crew operations. Current estimates from Ref. [1] assume food packaging is roughly 17% of total food delivered mass. Food hydration reflects the water content in the food, as delivered, and affects the mass of the food and the mass of the water required for food rehydration prior to consumption. In addition to the standard food packaging assumption, the food is delivered in Bulk Overwrap Bags (BOBs) for stowage. The standard food mass rates for a 50% as-delivered food hydration level are shown in Table 2. As noted in Table 1, EVA days impose more physical strain on the crew, and more food is provided to the crew on these days.

Table 2 Delivered Food Mass Rates

Item	Rate, Non-EVA Days	Rate, EVA Days	Units
Food Packaging	0.40	0.40	$\frac{kg}{(CM \times day)}$
Food Water Content, as Shipped	0.98	1.26	$\frac{kg}{(CM \times day)}$
Food Dry Mass, as Shipped	0.98	1.26	$\frac{kg}{(CM \times day)}$
Total Packaged Food	2.36	2.91	$\frac{kg}{(CM \times day)}$
BOBs	0.03	0.03	$\frac{kg}{(CM \times day)}$
Total, As Shipped	2.39	2.94	$\frac{kg}{(CM \times day)}$

The rates in Table 2 reflect requirements for food delivered with a 50% food hydration level. However, delivered food hydration levels may change depending on mission needs and parameters. The mass rates for delivered food based on food hydration levels are shown in Table 3. The mass for food (without BOB mass) in Table 3 is shown as delivered and does not reflect the consumed food rates that do not change.

Table 3 Food Hydration Levels and Delivered Mass Rates

Food Hydration %	Food Mass, as shipped kg/(CM x day)	Water Rehydration Requirement kg/(CM x day)
50%	2.36	0.50
45%	2.18	0.68
40%	2.03	0.83
35%	1.91	0.95

Food Hydration %	Food Mass, as shipped kg/(CM x day)	Water Rehydration Requirement kg/(CM x day)
30%	1.80	1.06
25%	1.71	1.15

C. Hygiene

Hygiene kits are composed of personal hygiene and grooming items for crew members. The personal items modeled in this analysis are either per crew member or based on item life limits, and some items are specific to crew sex. Table 4 presents the unit mass and life limit for the hygiene items. The items listed in Table 4 are used to develop an initial allocation, actual hygiene items are selected by the crew.

Table 4 Hygiene Item Mass and Duration Allocations

Item	Unit Mass, kg	Allocation
Personal Hygiene Container	0.52	1 per crew per 90 days
Hairbrush	0.05	1 per crew
Cotton Swab Assembly	0.05	1 per crew per 7 days
Lip Balm	0.05	1 per crew per 30 days
Deodorant	0.13	1 per crew per 30 days
Toothbrush	0.02	1 per crew per 90 days
Toothpaste	0.20	1 per crew per 90 days
Floss	0.05	1 per crew per 90 days
Lotion	0.21	1 per crew per 90 days
Razor (electric)	0.16	1 per male crew
Shave Cream	0.09	1 per crew per 90 days
Tweezers	0.02	1 per crew
Feminine Hygiene Products	0.71	1 per female crew per 30 days
Emesis Bag	0.06	2 per crew per 7 days
Hygiene Disposal Bag	0.02	1 per crew per 7 days
Comb	0.05	1 per crew
Hair Ties	0.01	1 per crew
Shampoo	0.29	1 per crew per 90 days

Item	Unit Mass, kg	Allocation
Conditioner	0.32	1 per crew per 90 days
No Rinse Body Bath Pouch	0.03	1 per crew per 7 days
Soap & Ziplock (Ivory)	0.05	1 per crew per 7 days
Hand Cream, Aloe	0.21	1 per crew per 90 days
Razor	0.05	1 per crew per 90 days
Razor Cartridges	0.02	1 per crew per 7 days
Hygiene, Station Mirror Assy	0.33	1 per crew
Hygiene Mirror	0.33	1 per crew
Nail Clippers	0.05	1 per crew

D. Clothing

Clothing is modeled based on life limits of individual items. Outside of the crew's standard work-day clothes, additional items such as exercise and public affair items are included. Table 5 presents the unit mass and life limits for the modeled clothing items, and the values reflect that no laundry system is used during the mission. Table 5 also defines the type of mission to which the item is applicable (in-space transit, surface, or both). Some items may have different life limits depending on the type of mission, and these items, such as socks or t-shirts, include a life limit for surface missions and a different life limit for in-space missions. The items listed in Table 5 are used to develop an initial allocation, actual clothing items are selected by the crew.

Table 5 Clothing Item Mass and Duration Allocations

Item	Unit Mass (kg)	No-Laundry Baseline Lifetime (days)	Applicable Missions
Male Underwear	0.11	2	All missions
Female Undergarment	0.19	2	All missions
Sports Bra	0.16	7	All missions
Socks	0.11	7 ; 14	Surface Missions ; In-Space Missions
T-Shirts	0.31	7 ; 14	Surface Mission ; In-Space Missions
Polo Shirts	0.68	15	All missions
Shorts / Pants / Cargo Pants	0.79	30	All Missions
Shoes	0.84	180	All Missions

Item	Unit Mass (kg)	No-Laundry Baseline Lifetime (days)	Applicable Missions
Eye Cover	0.06	30	All Missions
Sleepwear (top)	0.03	30	All Missions
Sleepwear (bottom)	0.03	30	All Missions
Handkerchief	0.01	7	In-Space Missions
Athletic Supporter	0.05	7	In-Space Missions
Exercise Shorts	0.16	7 ; 14	Surface Missions ; In-Space Missions
Exercise Shirts	0.26	5 ; 14	Surface Missions ; In-Space Missions
Exercise Socks	0.05	7 ; 14	Surface Missions ; In-Space Missions
Wristband	0.02	30	In-Space Missions
Athletic Band	0.05	30	In-Space Missions
Gloves	0.16	180	In-Space Missions
Polartec Socks	0.10	180	In-Space Missions
Sweater	0.83	180	In-Space Missions
Belt	0.23	360	In-Space Missions

E. Towels

Towels are used during crewed missions for cleaning, hygiene, and various other purposes as needed. There are three towel items for crewed spaceflight: towels, hygiene towels, and washcloths. The unit mass and life limit for each towel item is listed in Table 6.

Table 6 Towel Item Mass and Duration Allocations

Item	Unit Mass (kg)	Lifetime (days)	Allocation
Towel	0.155	7	All Missions
Hygiene Towel	0.138	2	All Missions
Washcloth	0.045	7	All Missions

F. Waste Management

The logistics items to support overall element waste management include trash bags, fecal canisters, urine prefilters, and fecal and urine collection bags. Fecal and urine collection bags are delivered for contingency operations in case of waste management system unavailability and are based on planned crew member contingency days. All other waste system logistics items are based on crew member days. Table 7 lists the mass rates for waste management items.

Table 7 Waste Management Mass Rates

System/Item	Rate	Unit	Comments
Trash Bags	0.03	$\frac{kg}{(CM \times day)}$	Includes soft-sided trashcans, which are discarded after a time.
Fecal Canisters	0.23	$\frac{kg}{(CM \times day)}$	Includes fecal cans, lids, and bags.
Urine Prefilter/Pretreat	0.04	$\frac{kg}{(CM \times day)}$	Includes urine filters, funnels, hoses and pretreat.
Fecal/Urine Collection Bags	0.17	$\frac{kg}{(CM \times Cont.Day)}$	Used to inform contingency waste collection. Applies only to days of planned contingency usage.

G. EVA Consumables and Spares

For crew EVAs, the crew will require specific consumables and spares to support activities and the EVA system. Both consumables and spares for EVA support are dependent on crew size, the number of EVAs, and the duration of the EVAs. Consumable and spare items include but are not limited to: drinking water bags, dust mitigation equipment, glove spares. As the EVA systems proposed for future missions beyond low Earth orbit (LEO) are still in development, the consumable and spare needs are not currently available for public release. However, depending on the mission and EVA rate, EVA consumables and spares can be relatively large.

H. Crew and System Oxygen and Water Requirements

Table 8 presents the required water and oxygen rates to support crew over a spaceflight mission. As mentioned in Section II, the metabolic rates for water and oxygen vary as a function of the physical size of each crew member. Additionally, metabolic rates depend on crew activity. The rates presented are representative of an intravehicular (IVA) work day with 1.5 hours per crew member of exercise [1,2].

Table 8 Water and Oxygen Supply Rates

Item	Long-Duration, In-Space			Surface	Units	Comments
	Rate for 5^{th} % Crew	Rate for 82 kg Crew	Rate for 95^{th} % Crew	Rate for 82 kg Crew		
Oxygen, Metabolic	0.89	0.89	1.08	0.84	$\frac{kg}{(CM \times day)}$	In-Space: 1.5 hours of Resistive exercise and Aerobic exercise per day, high fitness Surface: Assumes 0.5 hours of Resistive and Aerobic Exercise per day, on average.

Item	Long-Duration, In-Space			Surface	Units	Comments
	Rate for 5^{th} % Crew	Rate for 82 kg Crew	Rate for 95^{th} % Crew	Rate for 82 kg Crew		
Water, Drink	1.78	2.79	3.89	2.00	$\frac{kg}{(CM \times day)}$	
Oxygen, WPA Injection	0.0034				$\frac{kg\ O_2}{kg\ H_2O\ Processed}$	Applies only if equipment similar to the ISS Water Processing Assembly (WPA) is part of ECLSS system. Denominator is the total amount of wastewater processed through the WPA.
Water, Food Rehydration	0.50				$\frac{kg}{(CM \times day)}$	Assumes 50% food hydration as delivered. See Table 3 for varying food rehydration water rates.
Water, Hygiene	0.40				$\frac{kg}{(CM \times day)}$	Some of this water quantity can be met without water if towels are pre-wetted.
Water, Flush	0.30				$\frac{kg}{(CM \times day)}$	
Water, Sampling	2.0				$\frac{kg}{mission}$	This requirement is necessary to protect the quantity of water needed for crew consumption for the duration of the mission as water is a limited resource.

In addition to the rates listed in Table 8, there are oxygen and water requirements to support the crew and EVA suit and systems during EVAs. This includes drinking water, metabolic oxygen, and oxygen to maintain the suit atmosphere. As noted in Section IV.G, current EVA system requirements are not available for public release.

V. Element Atmospheric Losses

Outside of crew metabolic gas requirements, additional gas is needed to maintain habitat atmospheric levels. In-space and surface elements have an assumed leakage rate per module. In this context, a module represents an extension of a habitable vehicle with its own independent environment. For example, a transit habitat with a secondary safe haven module—that has its own environment control—would be considered two modules. Table 9 lists standard leakage rates based on experience. Additional atmospheric losses should be considered depending on the type of ECLSS CO_2 and humidity removal systems used.

Table 9 Cabin Leakage Rates

Item	Rate at 14.7 psia/21% Oxygen	Rate at 10.2 psia/26.5% Oxygen	Rate at 8.2 psia/34% Oxygen	Units
Cabin Air Leakage, Oxygen	0.005	0.004	0.004	$\frac{kg}{(day \times module)}$
Cabin Air Leakage, Nitrogen	0.016	0.010	0.007	$\frac{kg}{(day \times module)}$

In addition to leakage, the elements supporting crew ingress and egress for EVAs must be pressurized following depressurization. The gas needed to support pressurizations is dependent on the cabin or element pressure and pressurized volume. The equation for a single element pressurization is listed in Eq. (1).

$$m_g = \frac{mp_g V P m_{a,g}}{RT} \quad (1)$$

VI. Crew Outputs

Following a basic mass-balance model, the mass of crew food and fluid inputs are equal to the mass of solid and fluid outputs [2]. The mass balance of crew consumption and output is described in Fig. 1 [3].

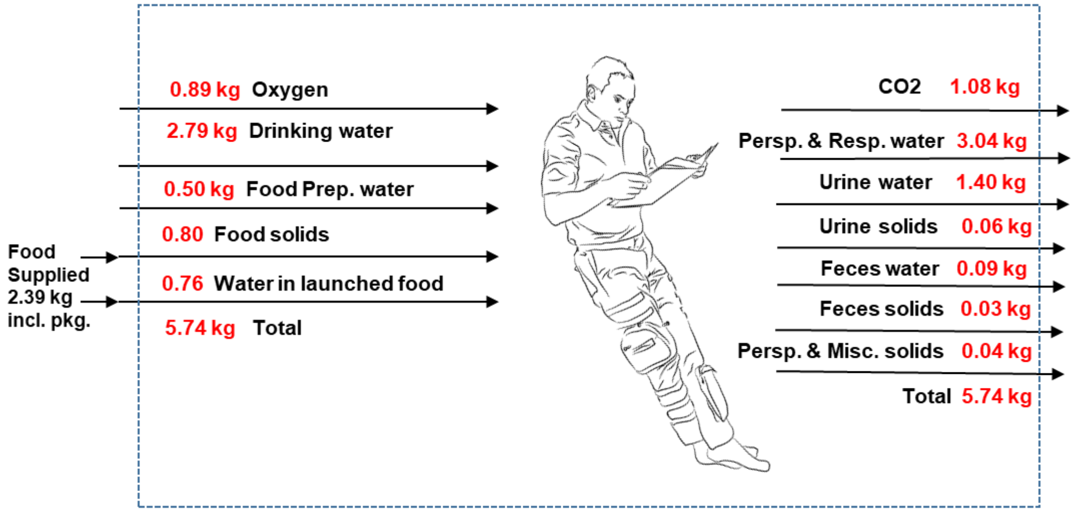

Fig. 1 Crew metabolic inputs and outputs.

Similar to the rates described in Section IV.G, crew metabolic outputs are dependent on crew physical size and activity. Table 10 lists the crew metabolic outputs for a 5th percentile sized crew, an 82 kg sized crew, and a 95th percentile sized crew [1,2]. The rates shown in Table 10 follow the same crew activity and exercise assumptions detailed in Section IV.G.

Table 10 Crew Metabolic Output Rates

Item	Long-Duration, In-Space			Surface	Units	Comments
	Rate for 5th % Crew	Rate for 82 kg Crew	Rate for 95th % Crew	Rate for 82 kg Crew		
Carbon Dioxide, metabolic	0.74	1.08	1.31	1.08	$\frac{kg}{(CM \times day)}$	In-Space: 1.5 hours of Resistive exercise and Aerobic exercise per day, high fitness in the 95% case. Surface: Assumes 0.5 hours of Resistive and Aerobic Exercise per day, on average.
Water, Perspiration & Respiration	1.57	3.04	4.46	3.04	$\frac{kg}{(CM \times day)}$	In-Space: 1.5 hours of Resistive exercise and Aerobic exercise per day, high fitness in the 95% case. Surface: Assumes 0.5 hours of Resistive and Aerobic Exercise per day, on average.
Misc. Losses	0.04				$\frac{kg}{(CM \times day)}$	Includes all other human outputs: solids, hair, skin, mucus, menses, etc. [2].
Water, urine	1.4				$\frac{kg}{(CM \times day)}$	
Fecal, dry mass	0.03				$\frac{kg}{(CM \times day)}$	
Urine Solids	0.06				$\frac{kg}{(CM \times day)}$	
Water, fecal	0.09				$\frac{kg}{(CM \times day)}$	

VII. ECLSS Processes

Regenerative ECLSS systems can be used to reduce delivered consumables mass by recovering and recycling the crew waste products described in Section VI. The capability of the regenerative ECLSS systems to recycle fluids back into the usable products, instead of remaining as waste products, can greatly affect the amount of logistics mass that is supplied for a crewed mission. Fig. 2 shows a representation of the fluid processes between regenerative ECLSS subsystems from crew and system output through recovery. The systems represented in Fig. 2 are an Oxygen Generation System (OGS), a CO_2 reduction system, a urine recovery system, a brine recovery system, and a solid waste dewatering system. An example of logistics flow through crew member consumption, output, and ECLSS processing is outlined in Fig. 2 [3].

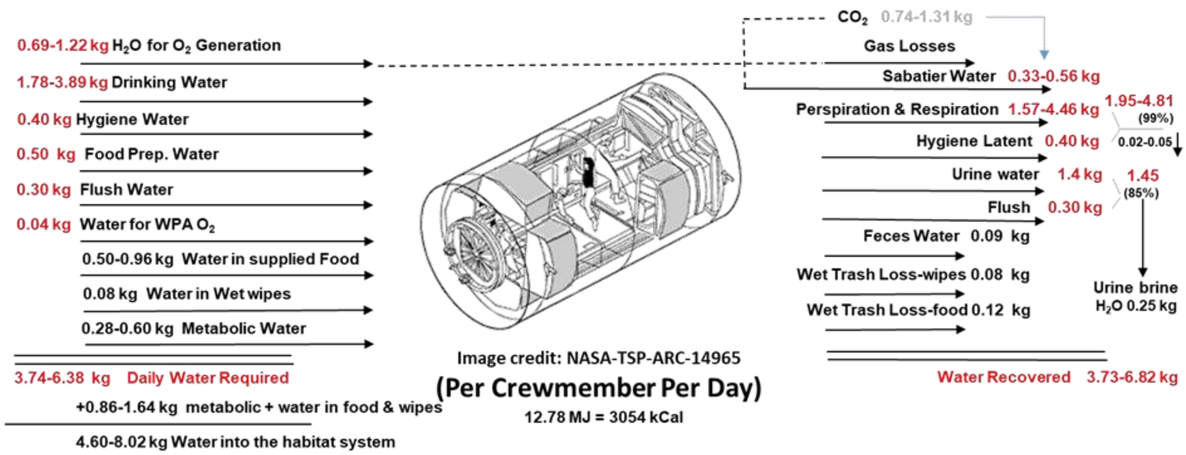

Fig. 2 Process flow through the regenerative ECLSS system [3].

The water recovery system assumed in this paper uses a Water Processing Assembly (WPA) as the final step with a recovery efficiency of 100% in converting waste water to fresh water. The urine recovery system, assumed to be a Urine Processing Assembly (UPA), is assumed to have 85% efficiency in recovering urine and flush water and producing cleaner waste water which then flows into the WPA. A brine recovery system releases its recovered water into the air, which subsequently makes its way to the WPA. The solid waste dewatering system recovers water from fecal waste and is assumed to have a 100% recovery efficiency. The OGS is assumed to have 100% efficiency through the electrolysis process, converting 100% of the water input into oxygen and hydrogen. It is assumed that if CO_2 reduction is used, a Sabatier Assembly will be utilized. Other advanced CO_2 reduction technologies, such as a Sabatier plus Plasma Pyrolysis Assembly (PPA) or Bosch, are currently being evaluated by the ECLSS community. The conversion rates and processes for oxygen generation and CO_2 reduction are based on molecular masses and efficiency. The conversion rates for oxygen generation and CO_2 reduction are listed in Table 11.

Table 11 Oxygen Generation and CO2 Reduction Conversion Rates

Item	Rate	Units	Comments
OGS Conversion Rates	0.889	$\frac{kg\ O_2\ produced}{kg\ H_2O\ converted}$	Based on molecular masses.
	0.111	$\frac{kg\ H_2\ produced}{kg\ H_2O\ converted}$	
Sabatier Conversion Rates	0.183	$\frac{kg\ H_2\ required}{kg\ CO_2\ processed}$	Based on molecular masses. Reaction limited by availability of CO_2 or availability of H_2. Excess CO_2 or H_2 remains after processing. Assumes 90% efficiency.
	0.819	$\frac{kg\ H_2O\ produced}{kg\ CO_2\ processed}$	
	0.364	$\frac{kg\ CH_4\ produced}{kg\ CO_2\ processed}$	

The waste water output of CO_2 reduction is a factor of the availability of CO_2 and H_2 during the reduction process. Any input gas (CO_2 or H_2) beyond the amounts required for reduction will be vented.

VIII. Outfitting, Maintenance and Spares, and Utilization

Unlike the preceding logistics items discussed in this document, outfitting equipment, maintenance and spares, and utilization equipment are mission dependent and are not simply represented by a fixed rate. The demands for each of these items are dependent on mission, program, and agency goals. Although precise allocations cannot be made for these items prior to defining a mission, placeholders may be used to provide a best estimate of the mass required for delivery.

A. Outfitting

Outfitting refers to hardware and soft goods delivered and installed after initial launch in order to complete the capabilities for planned functional requirements for the vehicle or providing new capabilities within the vehicle and can include components, subsystems, or new systems. Outfitting systems do not include any systems, subsystems, or equipment that was required in the initial element master equipment list. Mass and volume requirements for outfitting will be based on the program-specific challenges and projected life-cycle planning and are not the same for each mission.

B. Maintenance and Spares

Maintenance and spare supplies contribute to the integrated logistics demands for any sustainable missions. NASA policy NPD 7500.1 [4] establishes that flight projects should be reusable or maintainable to aid in controlling and reducing life-cycle costs and risks. Although developments into system and component reliability are worthwhile for crew safety during space exploration, there is a tradeoff from a system perspective between reliability and maintainability. Maximizing system reliability is not always the most effective strategy in ensuring crew safety. NASA Standard 3001 [5] states that all systems on board "shall provide the means necessary for the crew to safely and efficiently perform routine service, maintenance, and anticipated unscheduled maintenance activities."

Maintenance items refer to the hardware and components delivered to replace systems or components that have a known life limit and are replaced at regular, scheduled intervals. The demand for these items is dependent on system operating schedules and individual life limits.

Spares are replacement components or ORUs that are used to address random failures in systems. Random failures within elements may cause loss of vehicle, loss of mission, or loss of crew. The severity of consequences due to a failure is referred to as the component's "criticality." A random failure of a component with high criticality could cause vehicle loss or loss of the crew if it is not able to be mitigated quickly.

Maintenance items can be planned for deterministically because each item has a known life limit and maintenance can be scheduled ahead of end of life to ensure vehicle health. However, spare requirements are driven by random failures. Random failures that occur over a mission cannot be known precisely ahead of time. Probabilistic analysis of potential random failures can characterize the relationship between the spares allocation plan and the probability that the supplied spares will be enough to cover all random failures over a mission, called the Probability of Sufficiency (POS). This relationship is based on component data including duty cycle, failure rates, quantities, and other relevant maintenance information [6].

C. Utilization

Utilization and science have been the driving forces behind most NASA missions. The utilization mass and volume requirements for a given mission depend on mission, program, and agency objectives. When planning ahead for future crew missions, identifying an appropriate allocation for utilization that addresses research needs as well as system and structure needs will allow for flexibility as mission plans mature.

IX. Packaging

For every consumable delivered for spaceflight missions, packaging is required for delivery and stowage. This packaging helps the logistics survive the environments that will be encountered, including the vibration of launch. Consumables packaging can be split into three categories: solid goods packaging, gas carriers, and water carriers. This analysis assumes the use of portable fluid carriers, although concept investigations include incorporating integral tanks for fluids into vehicle design.

A. Solid Goods Packaging

For organization and protection during delivery, solid goods consumables are packaged into Cargo Transfer Bags (CTBs). CTB mass and volume parameters are listed in Table 12 [7]. CTBs have been used in both Space Shuttle and ISS operations for both delivery and item storage within the vehicle. The CTB values listed in Table 12 represent a projected new reduced-mass bag, utilizing new materials and design compared to the ISS variant bag. Although the single CTB is the base unit, in reality, various CTB sizes will be used to fit logistics. For in-space transit missions, a CTB liner is included in each CTB. These liners may be removed and transferred from the launch vehicle prior to Earth-vicinity departure to reduce mass for the next leg of the journey. To simplify tracking the volume of solid goods, analysts use the volume unit Cargo Transfer Bag Equivalent (CTBE), which is defined as the volume limit of one CTB. CTBE values are an average volume across a representative mixture of CTB sizes.

Table 12 CTB Mass and Volume Parameters [7]

Item	Rate	Units
CTBE Mass	0.83	kg
CTBE Liner Mass	0.10	kg
CTBE Cargo Mass Limit	26.81	kg
CTBE Cargo Volume Limit	0.049 (1)	m^3 (CTBE)
CTBE External Volume	0.053	m^3

For each consumable item, a density—which includes volume for foam and voids—is assumed based on historical ISS data. The density for each consumable is used to determine the volume and CTB requirements. The assumed densities for each solid goods consumable are presented in Table 13 [7].

Table 13 Solid Goods Consumable Densities, as Packed [7]

Item	Rate	Units
Food	388	kg/m^3
Wipes and Gloves	186	kg/m^3
Operational Supplies	235	kg/m^3
Recreation & Personal Stowage	235	kg/m^3
Health Care Consumables	186	kg/m^3
Trash Bags	186	kg/m^3
Hygiene Kits	186	kg/m^3
Clothing	170	kg/m^3
Towels	186	kg/m^3
Fecal Canisters	186	kg/m^3
Urine Prefilter	186	kg/m^3

Item	Rate	Units
Fecal/Urine Collection Bags	186	kg/m^3
Pressurized Spares and Maintenance	557	kg/m^3
Pressurized Utilization	557	kg/m^3

B. Gas Carriers

Delivery of required gases is assumed to occur via assumed High Pressure Gas Carriers (HPGCs). As mentioned earlier in this section, gases may also be stored in the vehicle via integral tanks. The HPGCs described in this paper assume next generation tanks evolved from current ISS systems at 4500 psi resupply capacity. Resupply capacity refers to the state of the gas in the HPGC when delivered for crewed missions. HPGCs are delivered and stowed in M01 bags, which have an empty mass of 4.83 kg and a volume limit of 6 CTBE, in order to simplify tank transfer and improve stowage organization. M01 bags are transfer bags similar to CTBs, but larger. The gas carrier parameters are listed in Table 14.

Table 14 Gas Carrier Mass Parameters

Item	Empty Mass incl. Ullage	Max Usable Content Capacity Mass	Units
Oxygen HPGC Mass	53.7	35.6	kg
Nitrogen HPGC	53.7	31.2	kg

C. Water Carriers

Water is delivered and stored in portable tanks referred to as Contingency Water Carriers - Iodine (CWC-Is). These carriers are smaller than the HPGCs and need to be delivered and stowed in a pressurized environment. The CWCs are assumed to be delivered and stowed in M02 bags, which are heavier versions of M01 bags with a smaller volume. M02 bags have an empty mass and volume of 8.16 kg and 4 CTBEs, respectively [7]. One M02 bag can carry up to 3 CWCs. The CWC mass parameters are listed in Table 15.

Table 15 Water Carrier Mass Parameters

Item	Empty Mass incl. Ullage	Max Usable Content Capacity Mass	Units
CWC-I	1.22	21.7	kg

X. Lunar Surface Example

This section presents an analysis of a notional 2-crew, 14-day lunar surface mission in order to provide an example of how the rates and assumptions presented in this paper affect possible mission needs. The case parameters are listed in Table 16. The habitat examined here—a stationary habitat with an airlock for crew ingress and egress—does not include regenerative ECLSS. As described in Section IV.G, EVA data is not available for public release and therefore the IVA metabolic O_2 rate and drinking water rate will be assumed to cover the crew during the activities. In addition, the gas requirements to support pressurization due to EVAs will be included in this example. Additional assumptions include a 50% food hydration level, 4 airlock pressurizations, 82 kg crew members, and one female and one male crew member.

Table 16 Example Lunar Surface Mission Parameters

Parameter	Value	Unit
Crew Members	2	#
Duration	14	days
Habitat Volume	20	m^3
Habitat Pressure	8.2	psi
Habitat O_2 by Volume	34	%
EVAs	4	#
Airlock Volume	10	m^3

The required solid goods consumables masses to support this mission are listed in Table 17, the water and water carrier needs to support this mission are listed in Table 18, and the gas and gas carrier requirements to support the mission are listed in Table 19 and Table 20. The combined total of solid goods, water, gases, and carriers and packaging is listed in Table 21.

Table 17 Required Solid Good Consumables Mass and Volumes for Lunar Surface Example

Item	Mass (kg)	Volume (m^3)
Food	47.8	0.12
Food, EVA Days	23.5	0.06
Wipes and Gloves	5.6	0.03
Hygiene Kits	4.8	0.03
Recreation & Personal Stowage	10.0	0.04
Operational Supplies	5.0	0.02
Health Care Consumables	2.5	0.01
Clothing	11.4	0.07
Towels	2.7	0.01
Wastes and Hygiene	8.4	0.05
CTBs (Volume listed as # of CTBs)	8.3	10
TOTAL, Solid Goods	**130.0**	**0.53**

Table 18 Required Water and Water Carriers for Lunar Surface Example

Item	#	Mass (kg)
Water, Drink	-	78.1
Water, Food Hydration	-	14.0
Water, Hygiene	-	11.2
Water, Flush	-	8.4
Water, Sampling	-	2.0
Water, Total	**-**	**113.7**
CWCs	6	7.3
M02 Bags	2	16.3
TOTAL, Water and Water Carriers		**137.4**

Table 19 Required Oxygen and Oxygen Carriers for Lunar Surface Example

Item	#	Mass (kg)
Oxygen, Metabolic	-	24.9
Oxygen, Leakage	-	0.06
Oxygen, Airlock Represses	-	10.3
Oxygen, Total	**-**	**35.3**
Oxygen HPGCs	1	53.7
M01 Bags	1	4.8
TOTAL, Oxygen and Oxygen Carriers		**93.8**

Table 20 Required Nitrogen and Nitrogen Carriers for Lunar Surface Example

Item	#	Mass (kg)
Nitrogen, Leakage	-	0.1
Nitrogen, Represses	-	17.0
Nitrogen, Total	-	17.1
Nitrogen HPGCs	1	53.7
M01 Bags	1	4.8
TOTAL, Nitrogen and Nitrogen Carriers		**75.6**

Table 21 Required Delivery Mass for Lunar Surface Example

Item	Mass (kg)
Solid Goods	130.0
Water	137.4
Gas	169.4
TOTAL	**436.7**

The needed logistics mass of applicable items and categories to support a 2-crew, 14-day mission with the parameters listed in Table 15 is 436.7 kg. This is the mass based on the provided rates, and it excludes EVA consumables and spares, vehicle spares and maintenance items, utilization mass, and pressurized carriers for solid goods.

XI. Conclusion

This paper describes logistics rates and assumptions for conceptual crewed spaceflight missions beyond LEO to provide a reference for mission analysis. Although some necessary crew logistics were omitted from this document, the rates and assumptions derived reflect aggregated rates and assumptions from historical missions such as Shuttle and ISS and can be applied toward future Artemis and Mars crewed missions.

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