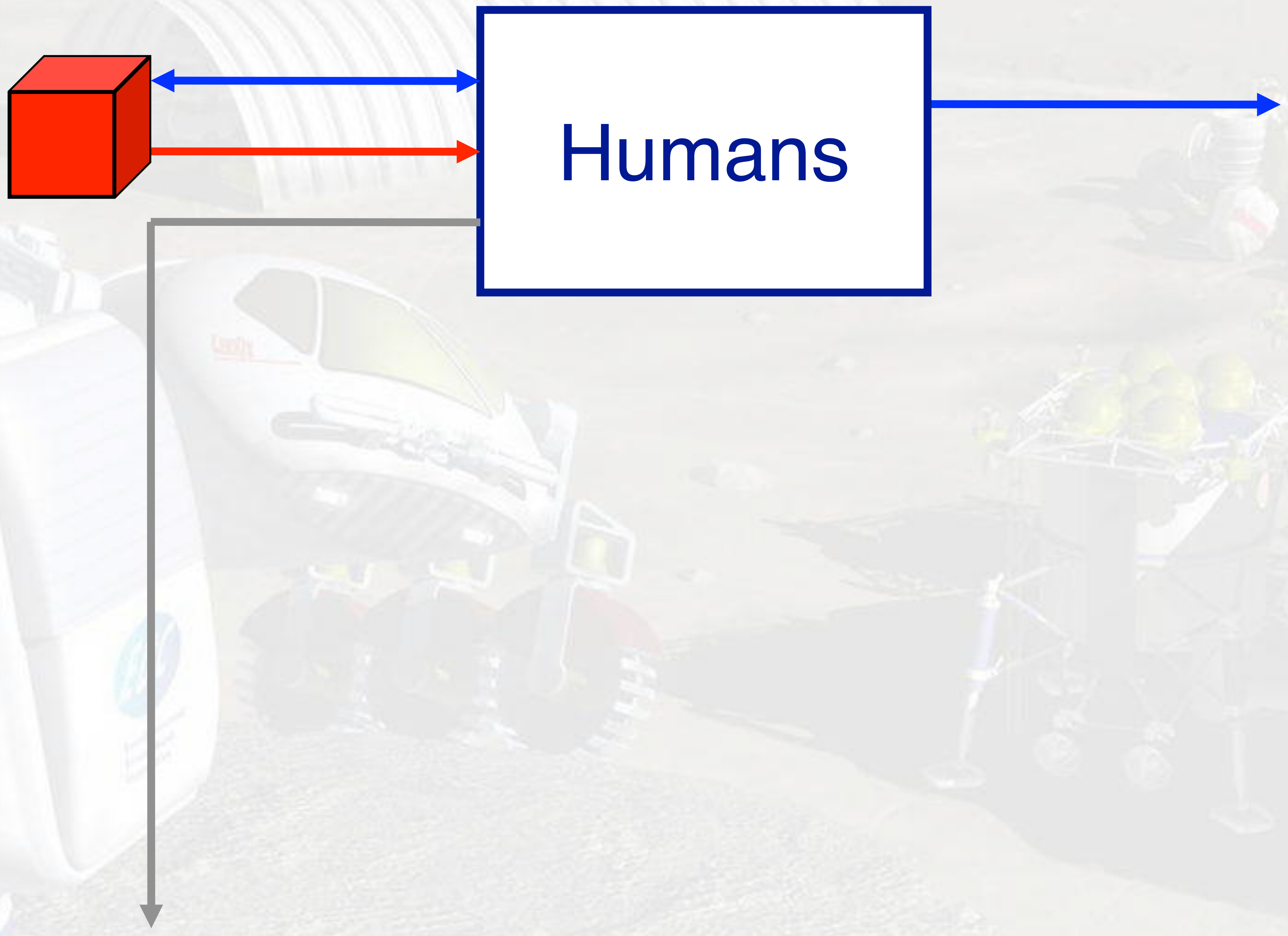
Introduction to Space Life Support

- Lecture #15 - October 17, 2023
- Life support systems overview
- Major component systems
- Open-loop life support
- Physico-chemical life support
- Bioregenerative life support
- Case study: UMd Minimum Functional Lunar Habitat Element

Life Support Block Diagram

O2
CO2
Water
Nutrients
Waste
Stores



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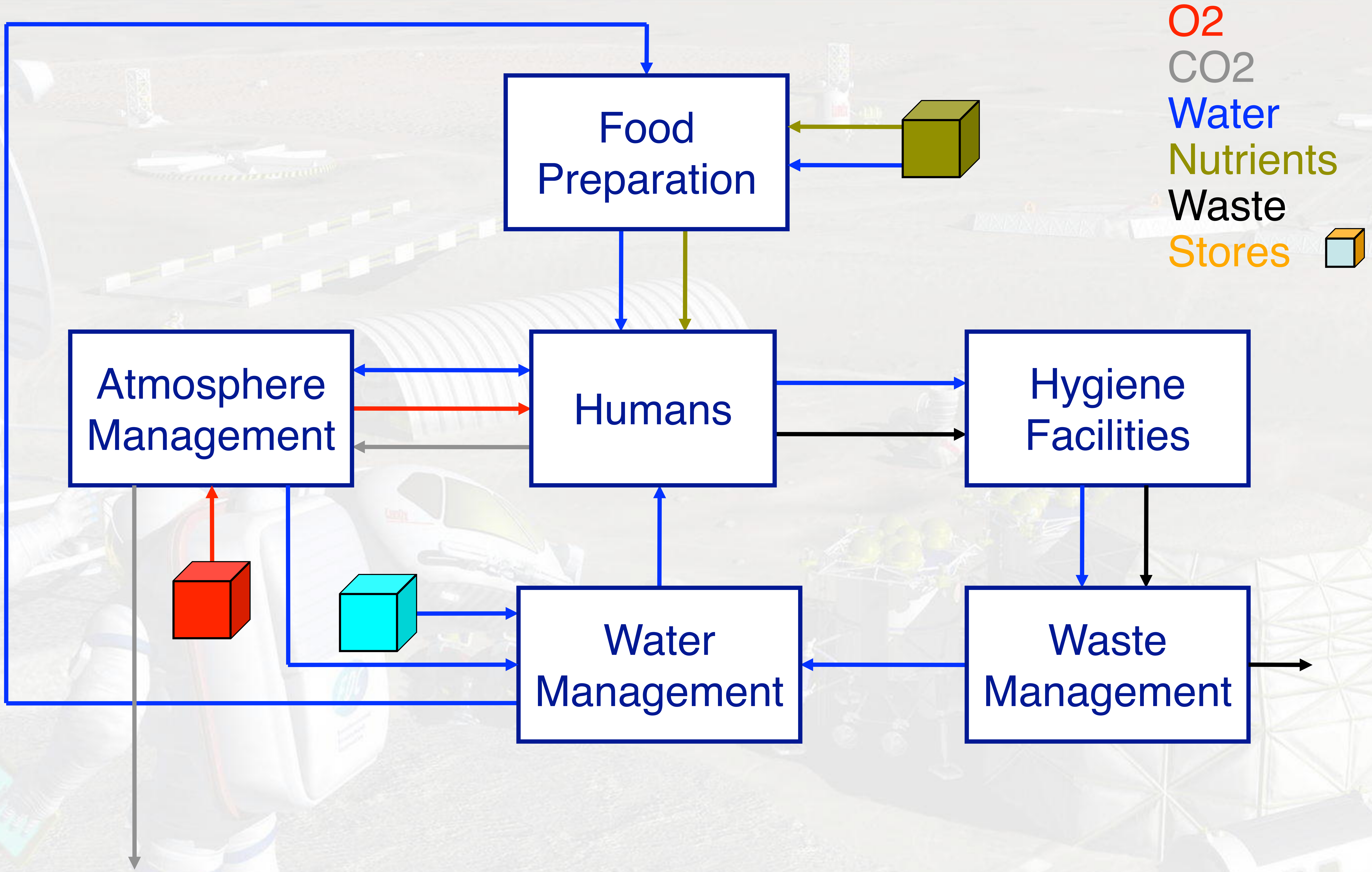

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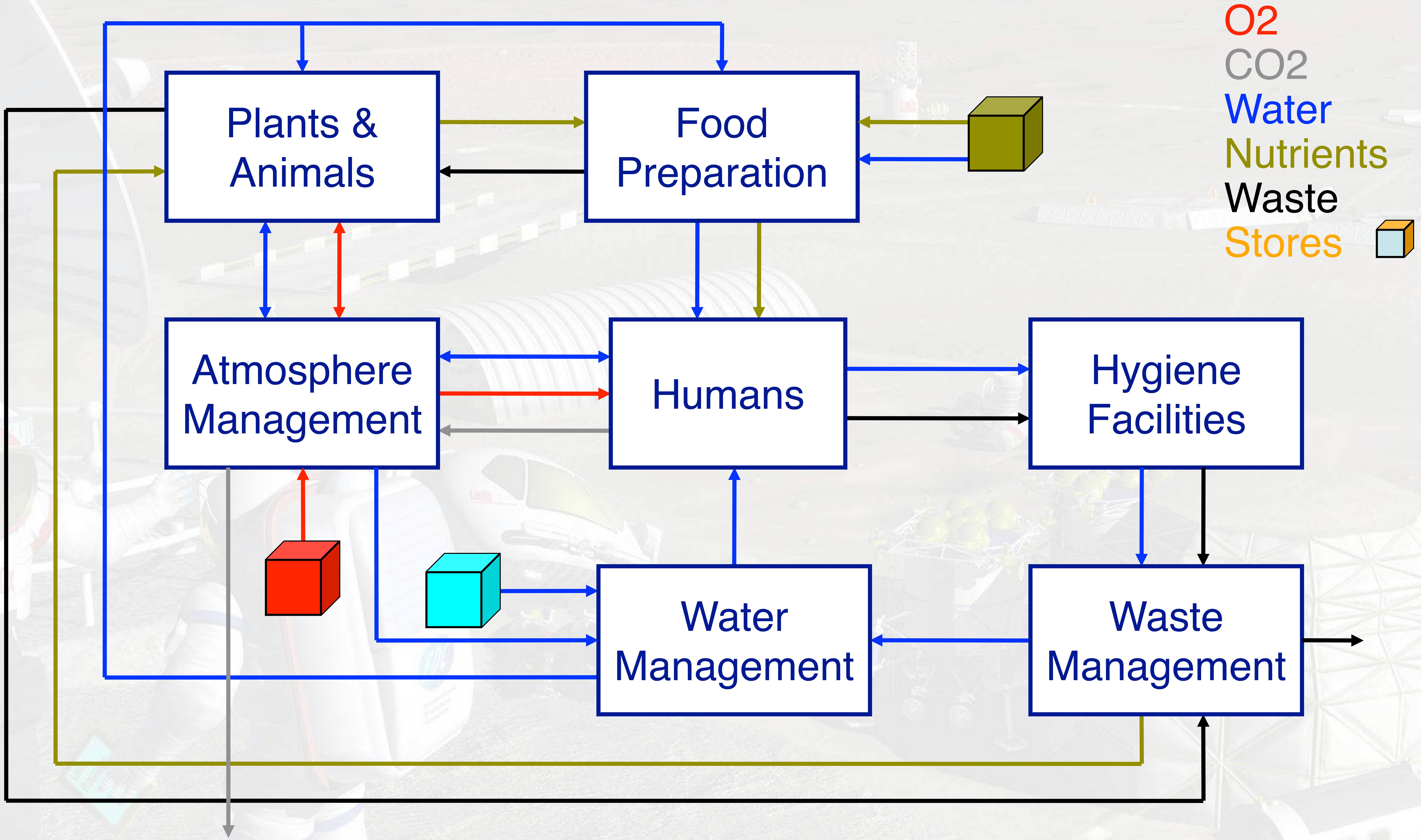


Essentials of Life Support

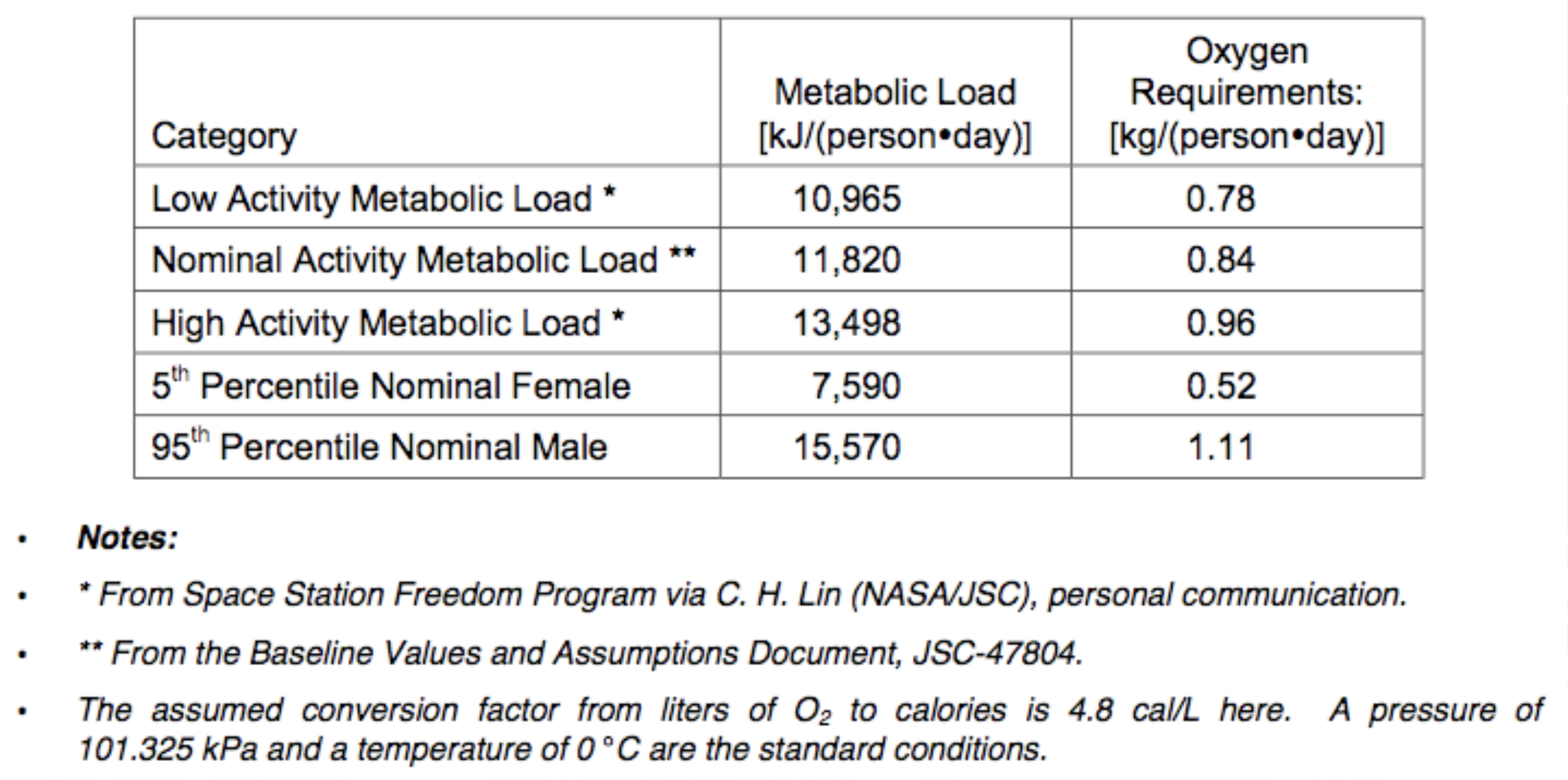
- Air
  - – Constituent control
    - CO_2 scrubbing
    - Humidity control
    - Particulate scrubbing
    - O_2, N_2 makeup
  - – Temperature control
- Water
- Food
- Waste Management

Human Metabolic Inputs and Outputs

Inputs	kg	Output	kg
Oxygen	0.84	Carbon dioxide	1.00
Food solids	0.62	Respiration & perspiration water	2.28
Water in food	1.15	Urine water	1.50
Food preparation water	0.76	Feces water	0.09
Drinking water	1.62	Sweat solids	0.02
		Urine solids	0.06
		Feces solids	0.03
(water subtotal)	3.53	(water subtotal)	3.87
Total mass	4.99		4.98

from Jones, “Design Rules for Space Life Support Systems” SAE 2003-01-2356, July 2003

Oxygen Requirements



Category	Metabolic Load [kJ/(person•day)]	Oxygen Requirements: [kg/(person•day)]
Low Activity Metabolic Load *	10,965	0.78
Nominal Activity Metabolic Load **	11,820	0.84
High Activity Metabolic Load *	13,498	0.96
5th Percentile Nominal Female	7,590	0.52
95th Percentile Nominal Male	15,570	1.11

- ***Notes:***
- ** From Space Station Freedom Program via C. H. Lin (NASA/JSC), personal communication.*
- *** From the Baseline Values and Assumptions Document, JSC-47804.*
- *The assumed conversion factor from liters of O_2 to calories is 4.8 cal/L here. A pressure of 101.325 kPa and a temperature of 0 °C are the standard conditions.*

from Lange et. al., "Advanced Life Support Requirements Document" JSC-38571B, Sept. 2002

Water Requirements

- Potable water - 2 L/crew-day (2 kg/crew-day)
- Hygiene water
  - Nominal - 2.84-5.16 L/crew-day
  - Contingency - 2.84 L/crew-day
- from Lange et. al., "Advanced Life Support Requirements Document" JSC-38571B, Sept. 2002

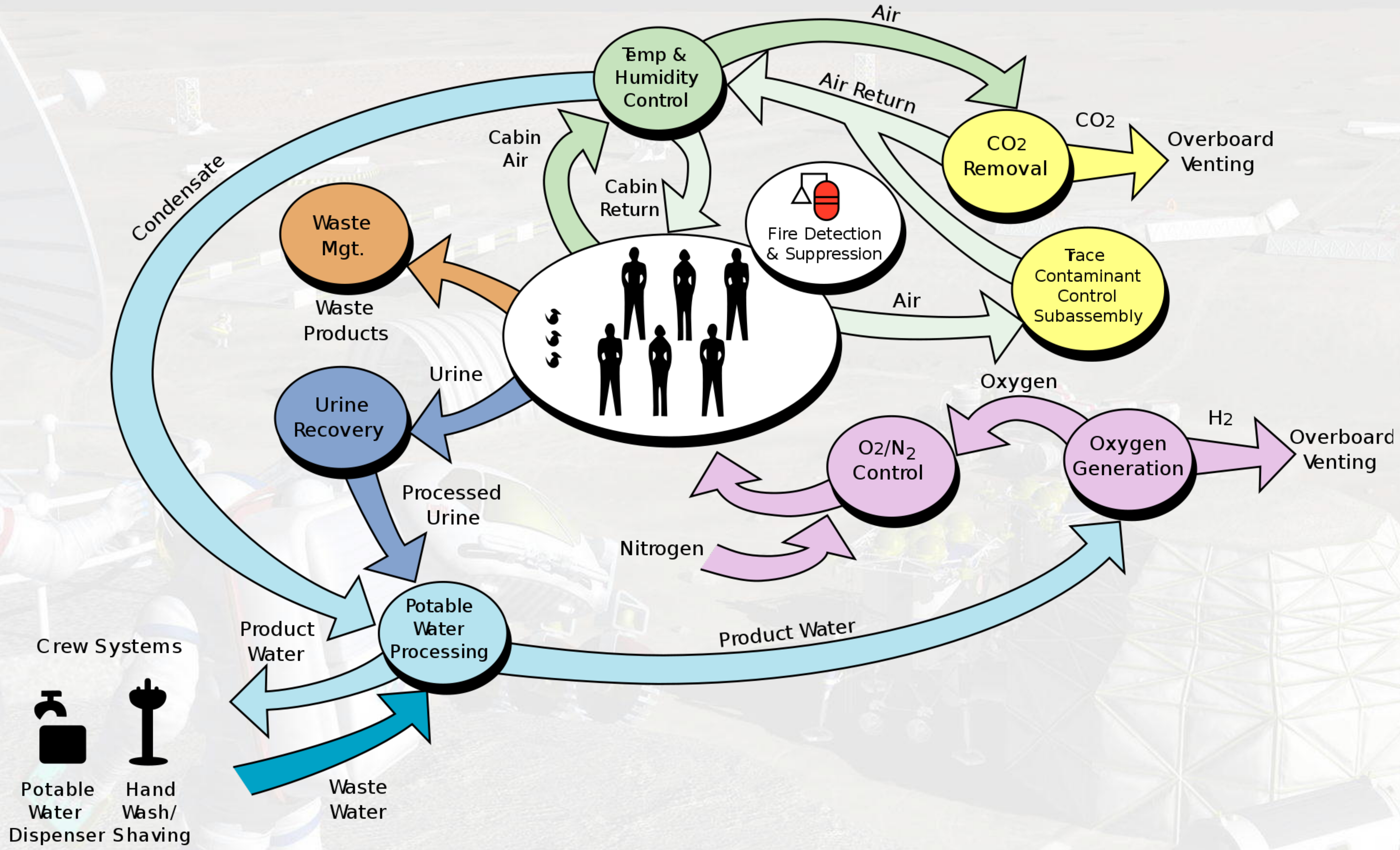
Metabolic Energy Requirements

- Men (W=mass in kg)
  - 18-30: 26W+1154 kcal/day
  - 30-60: 19.7W+1494 kcal/day
- Women (W=mass in kg)
  - 18-30: 23.5W+794 kcal/day
  - 30-60: 13.9W+1326 kcal/day
- Add 500 kcal/day for
  - EVA days
  - Moderate exercise days
  - End-of-mission countermeasure days

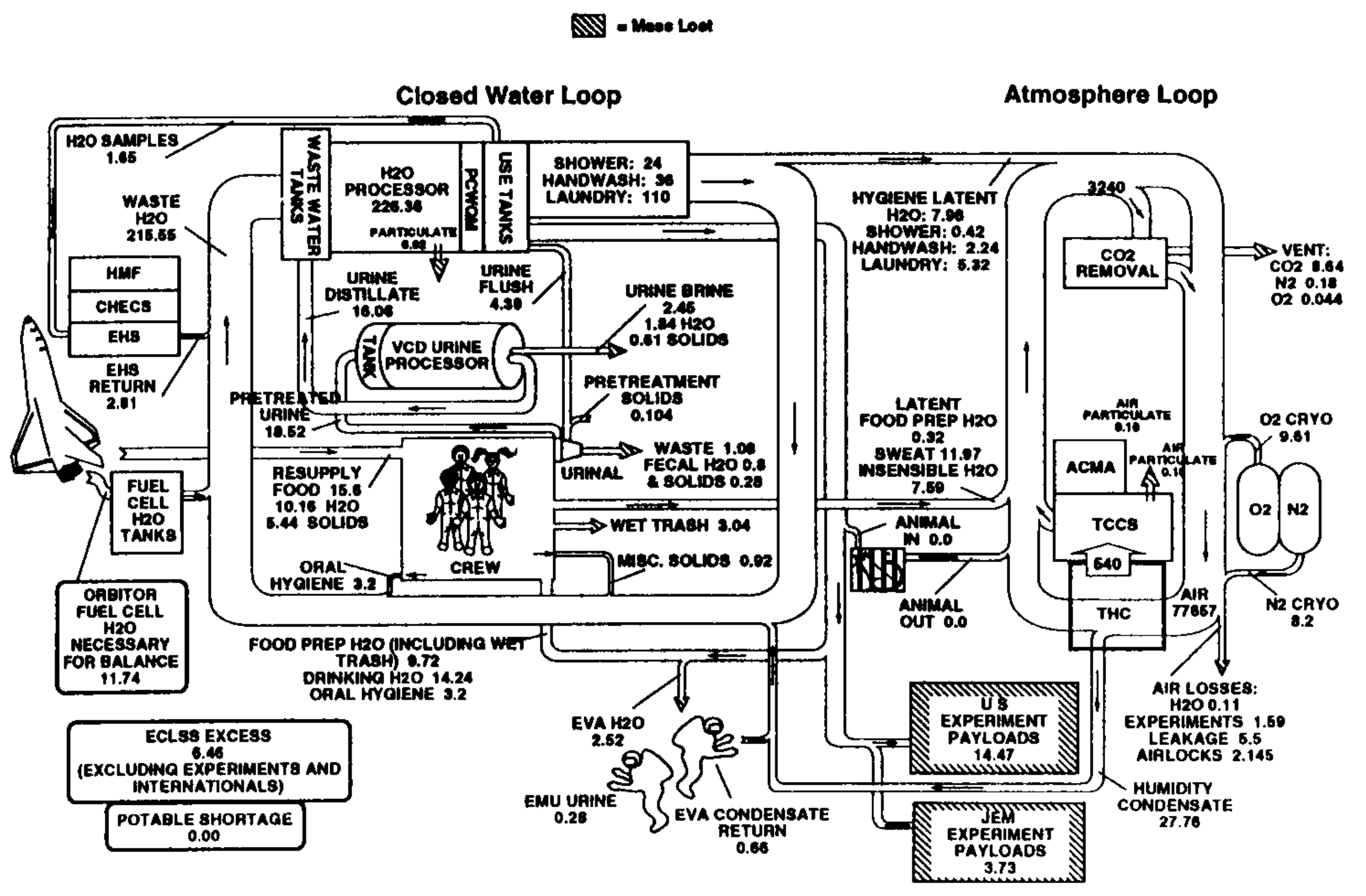
Life Support Design Rules of Thumb

- A crew member requires 5 kg of consumables/day
  - ~1/2 water, 1/3 food, 1/6 oxygen
  - (including water in food) 77% H_2O, 17% O_2, 12% food solids
  - Dehydration reduces food mass by 2/3
- Food solids produce about 5 calories/gm
- Respiration produces about 3.4 calories/gm O_2
- Males need about 1/3 more calories than females
  - Or, males need 1/7 more than average, females 1/7 less

ISS Life Support Block Diagram



ISS Life Support Schematic



From Peter Eckart, Spaceflight Life Support and Biospherics, Kluwer Academic, 1996

Equivalent Systems Mass

- Compress multiple decision criteria (mass, power, volume, thermal control) into one (mass)
- ESM relates consumables to marginal mass required to supply them
- ISS ESM values:
  - Volume: 67 kg/m^3
  - Power: 77 kg/kW
  - Thermal: 164 kg/kW

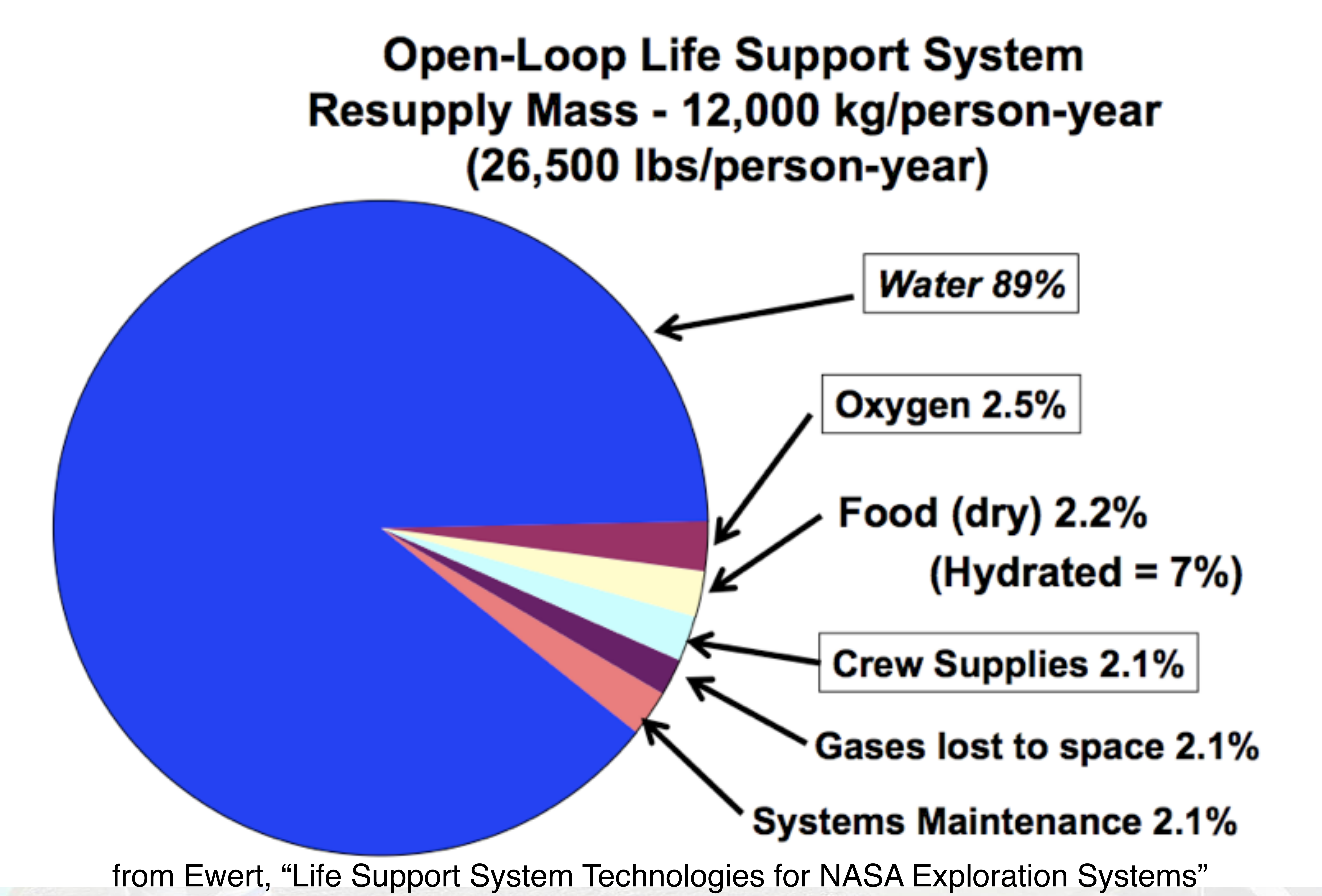
ESM Conversion Factors by Mission

Mission/ Segment	Volume kg/m3	Power kg/kW	Thermal kg/kW	Crew Time kg/crew-hr
ISS	67	476(cont) 77(day)	164	1.6
Mars transit	16	83	21	1.1
Mars surface	2.1	175	67	1.1
Minimal Lunar	51	300 (cont) 25 (day)	50	2

ISS Consumables Budget

Consumable	Design Load (kg/person-day)
Oxygen	0.85
Water (drinking)	1.6
Water (in food)	1.15
Water (clothes and dishes)	17.9
Water (sanitary)	7.3
Water (food prep)	0.75
Food solids	0.62

Resupply with Open Loop Life Support

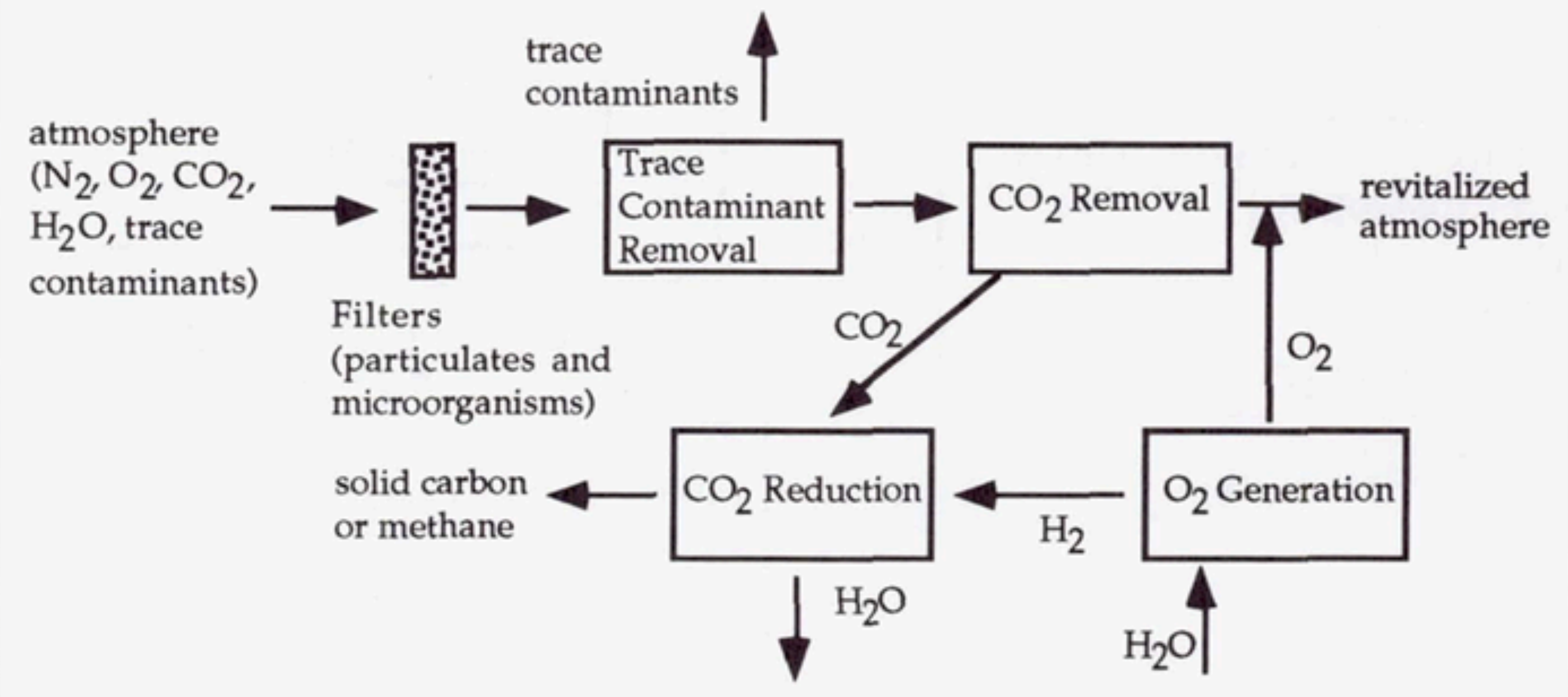


from Ewert, “Life Support System Technologies for NASA Exploration Systems”
ARO Workshop on Base Camp Sustainability, Sept. 2007

Effect of Regenerative Life Support

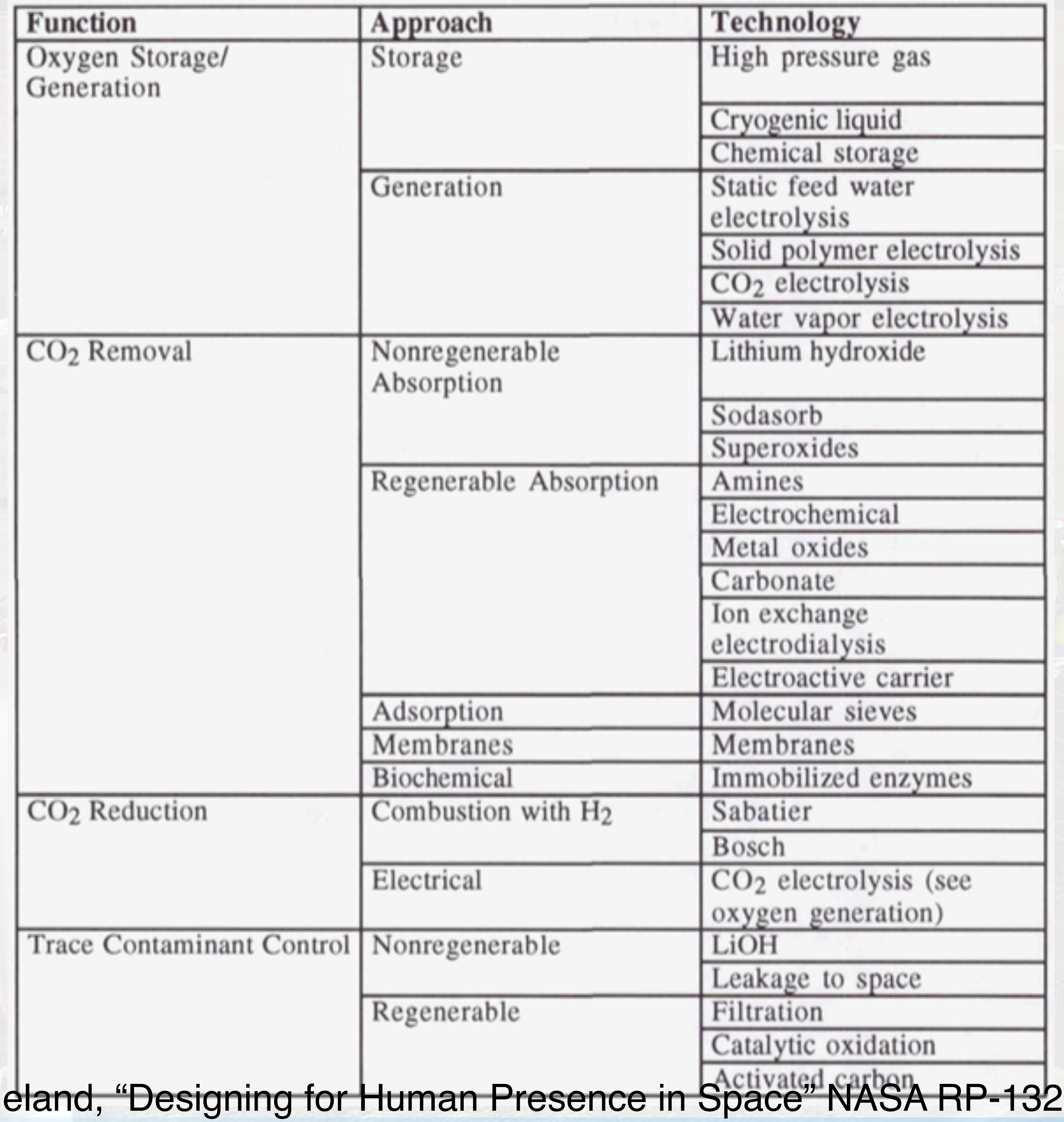
• Open loop life support	100% resupply
+ Waste water recycling	45%
+ CO_2 absorbent recycling	30%
+ O_2 regenerate from CO_2	20%
+ Food from wastes	10%
+ Eliminate leakage	5%

Air Revitalization Block Diagram



from Wieland, “Designing for Human Presence in Space…” NASA RP-1324, 1994

Air Revitalization Technologies



Function	Approach	Technology
Oxygen Storage/ Generation	Storage	High pressure gas
		Cryogenic liquid
		Chemical storage
	Generation	Static feed water electrolysis
		Solid polymer electrolysis
		CO_2 electrolysis
		Water vapor electrolysis
CO_2 Removal	Nonregenerable Absorption	Lithium hydroxide
		Sodasorb
		Superoxides
	Regenerable Absorption	Amines
		Electrochemical
		Metal oxides
		Carbonate
		Ion exchange electrodialysis
		Electroactive carrier
	Adsorption	Molecular sieves
	Membranes	Membranes
	Biochemical	Immobilized enzymes
CO_2 Reduction	Combustion with H_2	Sabatier
		Bosch
	Electrical	CO_2 electrolysis (see oxygen generation)
Trace Contaminant Control	Nonregenerable	LiOH
		Leakage to space
	Regenerable	Filtration
		Catalytic oxidation
		Activated carbon

from Wieland, “Designing for Human Presence in Space” NASA RP-1324, 1994

Atmospheric Gases Storage/Generation

- Storage
  - High pressure gas
  - Cryogenic liquid
  - Chemical storage
- Oxygen Generation
  - Static feed water electrolysis
  - Solid polymer electrolysis
  - CO2 electrolysis
  - Water vapor electrolysis

High Pressure Gas Tanks

- Typical pressures 200 atm (mass optimized) to 500-700 atm (volume optimized)
- GN2 tanks 0.56-1.7 x mass of contained gas
- GOx tank 0.36 x mass of contained gas

Air Component Storage

- Cryogenic Liquids
  - O_2: 1140 kg/m^3, T_{boil}= -183°C=84K (= -308°F)
  - N_2: 808 kg/m^3, T_{boil}= -196°C=77K (= -320°F)
  - H_2: 70 kg/m^3, T_{boil}= -253°C=20K (= -433°F)
- Gases
  - O_2: 1.43 kg/m^3 @ STP (292 kg/m^3 @ 3000 psi)
  - N_2: 1.25 kg/m^3 @ STP (255 kg/m^3 @ 3000 psi)
  - H_2: 0.09 kg/m^3 @ STP (18.4 kg/m^3 @ 3000 psi)

Cryogenic Tankage

- Volume-based relation

$$m<kg>=68.38\left[V<m^3>\right]^{0.75}$$

- Specific mass-based relations

$$m_{tank}<kg>=0.3485\left[M_{LOX}<kg>\right]^{0.75}$$

$$m_{tank}<kg>=0.4512\left[M_{LN_2}<kg>\right]^{0.75}$$

$$m_{tank}<kg>=2.826\left[M_{LH_2}<kg>\right]^{0.75}$$

- Generic mass-based nondimensional relation

$$\frac{m_{tank}}{m_{contents}}=68.38\left(\frac{\rho_{contents}}{m_{contents}}\right)^{0.25}$$

Solid Fuel Oxygen Generation (SFOG)

- Decomposition of lithium perchlorate generates oxygen – releases 60% of its weight as O2

$$LiClO4 \longrightarrow LiCl + 2O_2$$

- Vika SFOG system used on ISS – one cartridge O2 and burns for 5-20 minutes at 450°-500°C
- Oxygen is cooled and filtered and released int

Electrolytic Oxygen Generation

- Static Feed Water Electrolysis
- Solid Polymer Water Electrolysis
- Water Vapor Electrolysis
- CO2 Electrolysis

CO_2 Scrubbing Systems

- CO_2 production ~1 kg/person-day
- Lithium hydroxide (LiOH) absorption
  - Change out canisters as they reach saturation
  - 2.1 kg/kg CO_2 absorbed
  - Also works with $Ca(OH)_2$, Li_2O, KO_2, KO_3
- Molecular sieves (e.g., zeolites)
  - Porous on the molecular level
  - Voids sized to pass O_2, N_2; trap CO_2, H_2O
  - Heat to 350°-400°C to regenerate

CO_2 Regenerable Scrubbing Systems

- CO_2 production ~1 kg/person-day
- 4-Bed Molecular Sieves (4BMS)
  - Dual paths (one scrubbing, one regenerating)
  - Desiccant bed for moisture removal, 5 A zeolite sieve for CO2
  - Heat to 350°-400°C to regenerate
  - 30 kg; 0.11 m^3; 170 W (all per kg/day of CO_2 removal)
- 2-Bed Molecular Sieves (2BMS)
  - Carbon molecular sieve for CO_2
  - 16 kg; 0.09 m^3; 77 W (per kg/day CO_2)

CO_2 Regenerable Scrubbing Systems

- Solid Amine Water Desorption (SAWD)
  - Amine resin absorbs H_2O and CO_2; steam heat regenerates
    - Amine + H_2O --> Amine-H_2O (hydrated amine)
    - Amine-H_2O + CO_2 --> Amine-H_2CO_3 (bicarbonate)
    - Amine-H_2CO_3 + steam --> Amine + H_2O + CO_2
  - 17 kg; 0.07 m^3; 150 W (all per kg-day of CO_2 removal)

CO_2 Regenerable Scrubbing Systems

- Electrochemical Depolarization Concentration (EDC)
  - Uses fuel-cell type reaction to concentrate CO2 at the anode
  - $CO2 + 1/2O2 + H2 \text{-->} CO2 + H2O$ + electricity + heat
  - CO2 and H2 are collected at anode and directed to CO2 recycling system (combustible mixture!)
  - 11 kg; 0.02 m^3; 60 W (all per kg-day of CO_2 removal); does not include reactants for power output

CO2 Membrane Removal Systems

- Osmotic membranes
  - Poor gas selectivity
  - Returns CO2 to cabin air
- Electroactive carriers
  - Electroactive molecules act as CO2 “pump”
  - Very early in development
- Metal Oxides
  - AgO2 absorbs CO2 (0.12 kg O2/kg AgO2)
  - Regenerate at 140°C for 8 hrs (1 kW) - 50-60 cycles

CO_2 Reduction

- Sabatier reaction
  - $CO_2 + 4H_2 \dashrightarrow CH_4 + 2H_2O$
  - Lowest temperature (250°-300°C) with Ni catalyst
  - Electrolyze H_2O to get H_2, find use for CH_4
  - 91 kg; 3 m^3; 260 W (all per kg-day of CO_2 removal)
- Bosch reaction
  - $CO_2 + 2H_2 \dashrightarrow C + 2H_2O$
  - 1030°C with Fe catalyst
  - C residue hard to deal with (contaminates catalyst)

Nitrogen Makeup

- Nitrogen lost to airlock purges, leakage (can be ~1%/day)
- Need to replenish N_2 to maintain total atmospheric pressure
- Choices:
  - High pressure (4500 psi) N_2 gas bottles
  - Cryogenic liquid nitrogen
  - Storable nitrogen-bearing compounds (NH_3, N_2O, N_2H_4)

Trace Contaminant Control

- Particulate Filters (dusts and aerosols)
- Activated Charcoal (high molecular weight contaminants)
- Chemisorbant Beds (nitrogen and sulpher compounds, halogens and metal hybrids)
- Catalytic Burners (oxidize contaminants that can’t be absorbed)
- 100 kg; 0.3 m^3; 150 W (all per person-day)

Types of Water

- Potable water
  - Drinking and food preparation
  - Organic solids < $500 \mu g/liter$
- Hygiene water
  - Washing
  - Organic solids $<10,000\ \mu g/liter$
- Grey water (used hygiene water)
- Condensate water (from air system)

Water Management

- Distillation Processes
  - Vapor Compression Distillation (VCD)
  - Thermoelectric Integrated Membrane Evaporation (TIMES)
  - Vapor Phase Catalytic Ammonia Removal (VAPCAR)
  - Air Evaporation
- Filtration Processes
  - Reverse Osmosis (RO)
  - Multifiltration (MF)
  - Electrodialysis

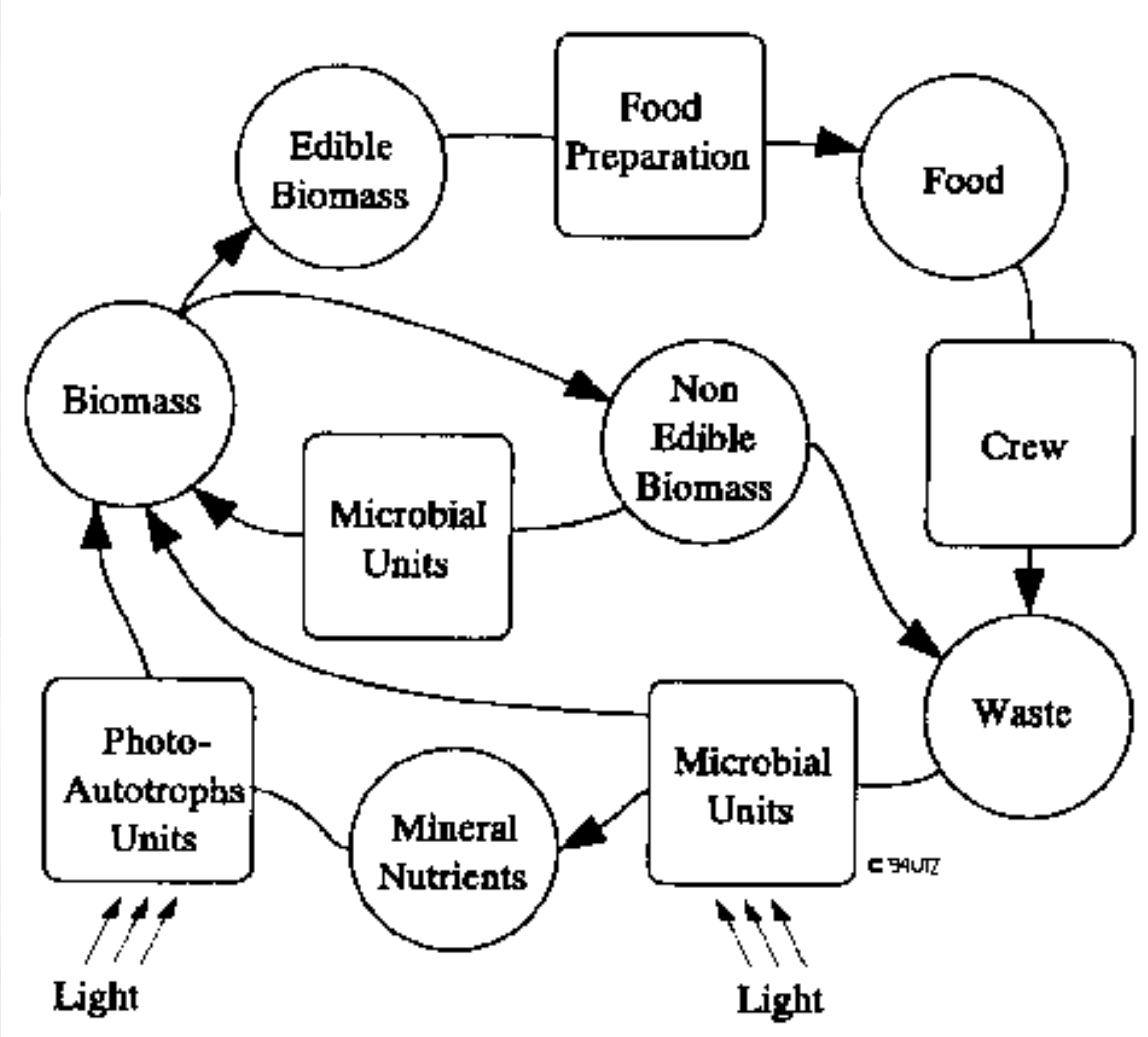
Water Distillation

- Vapor Compression Distillation (VCD)
  - 300 kg; 1.5 m^3; 350 W (for 100 kg H2O processed per day)
- VAPCAR
  - 550 kg; 2.0 m^3; 800 W (for 100 kg H2O processed per day)
- TIMES
  - 350 kg; 1.2 m^3; 850 W (for 100 kg H2O processed per day)

Solid Waste Disposal Technologies

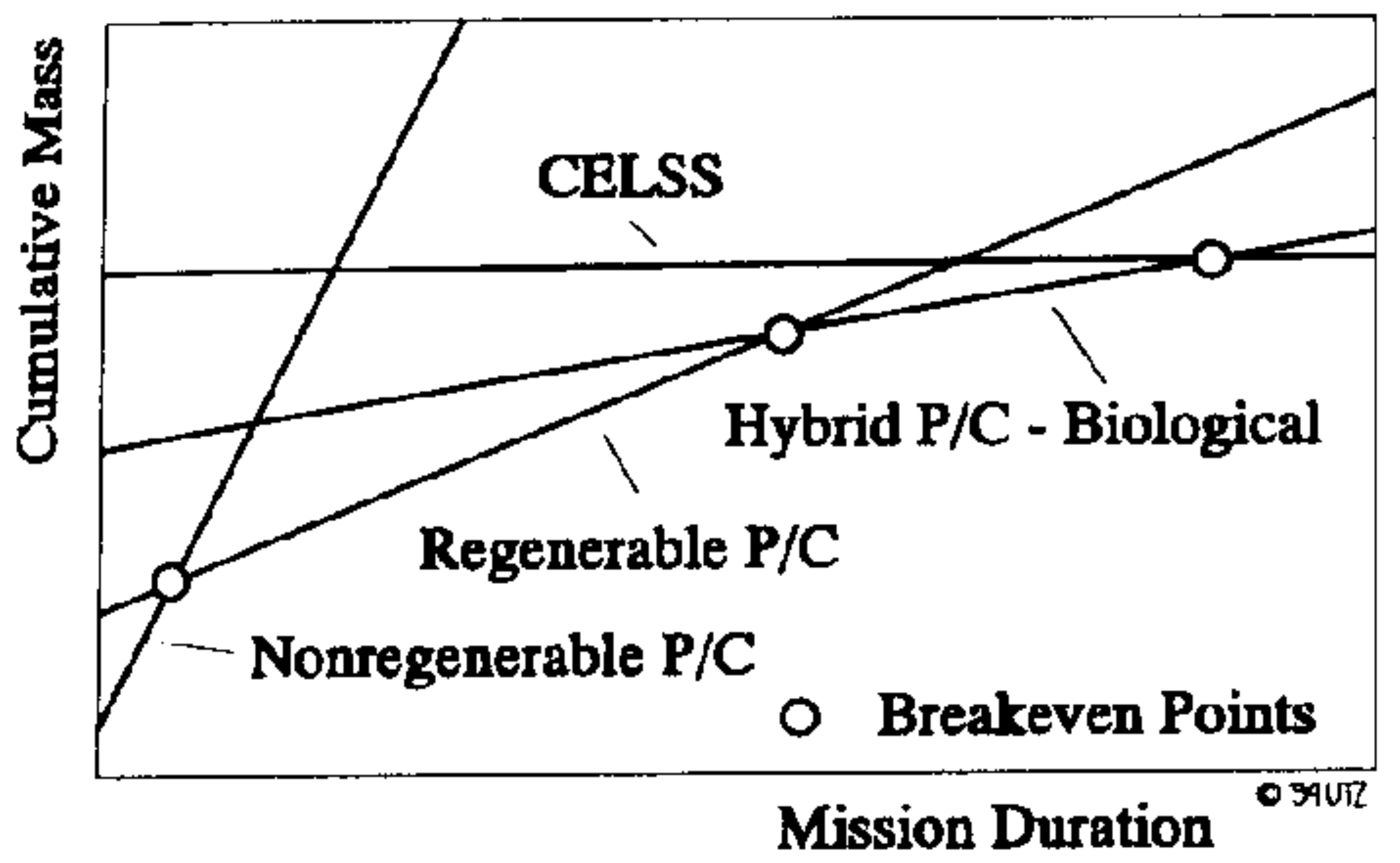
- Freeze Drying
- Thermal Drying
- Combustion Oxidation
- Wet Oxidation
- Supercritical Water Oxidation

Bioregenerative Life Support Schematic



From Peter Eckart, Spaceflight Life Support and Biospherics, Kluwer Academic, 1996

Life Support Systems Analysis (example)



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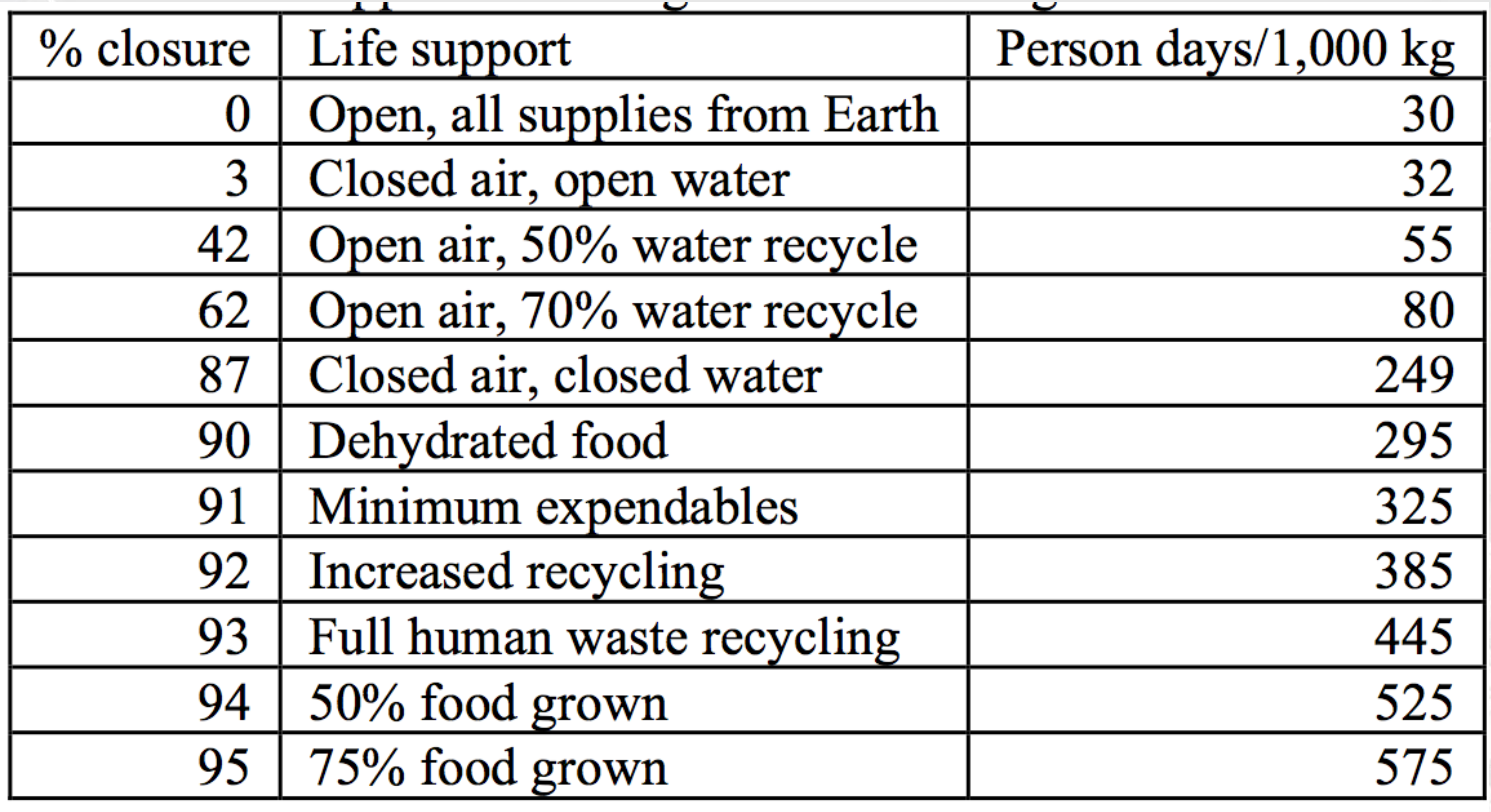
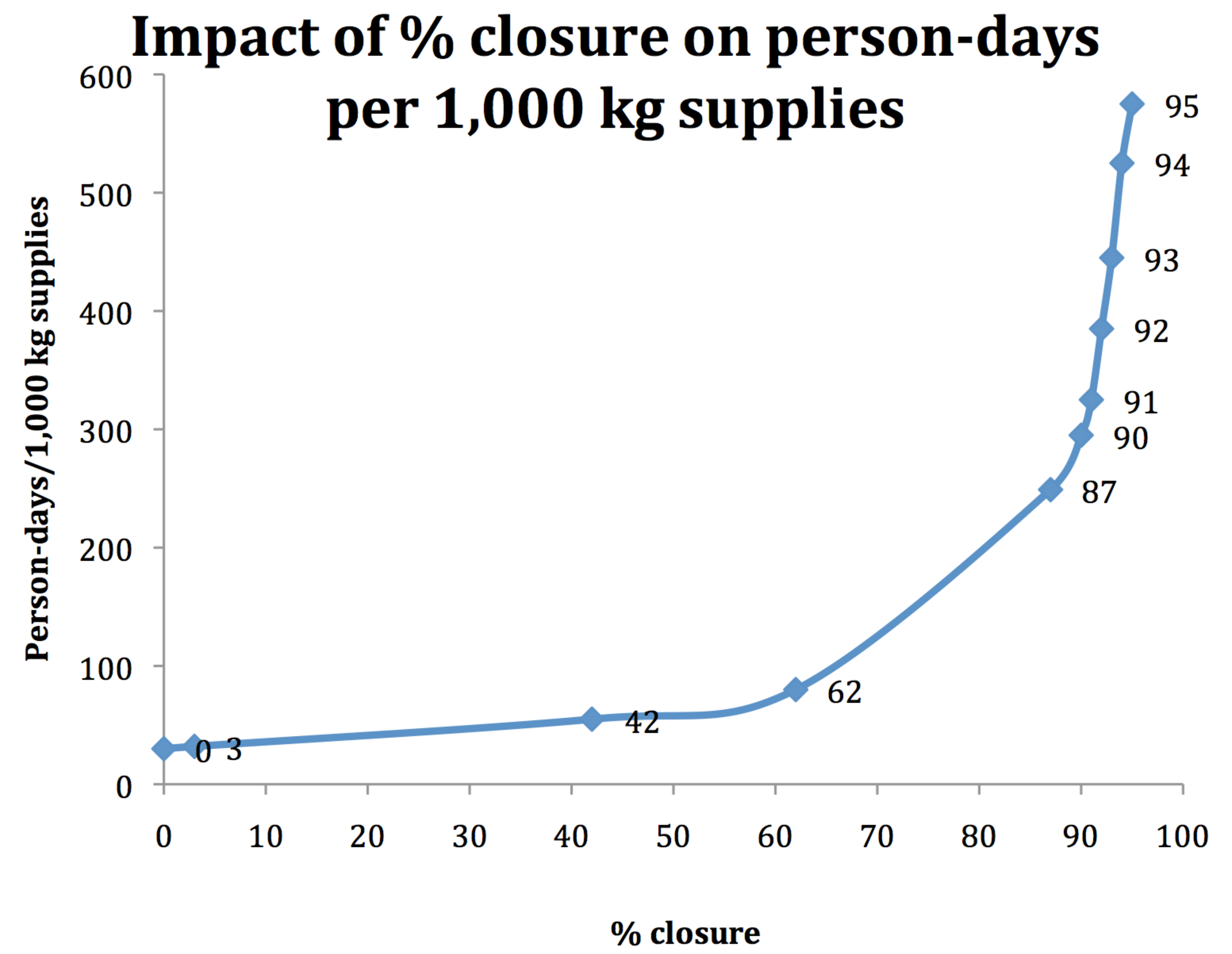
Impact of Closure on Duration



% closure	Life support	Person days/1,000 kg
0	Open, all supplies from Earth	30
3	Closed air, open water	32
42	Open air, 50% water recycle	55
62	Open air, 70% water recycle	80
87	Closed air, closed water	249
90	Dehydrated food	295
91	Minimum expendables	325
92	Increased recycling	385
93	Full human waste recycling	445
94	50% food grown	525
95	75% food grown	575

From Harry Jones, “Don’t Trust a Management Metric, Especially in Life Support”, ICES-2014-073, July 2014

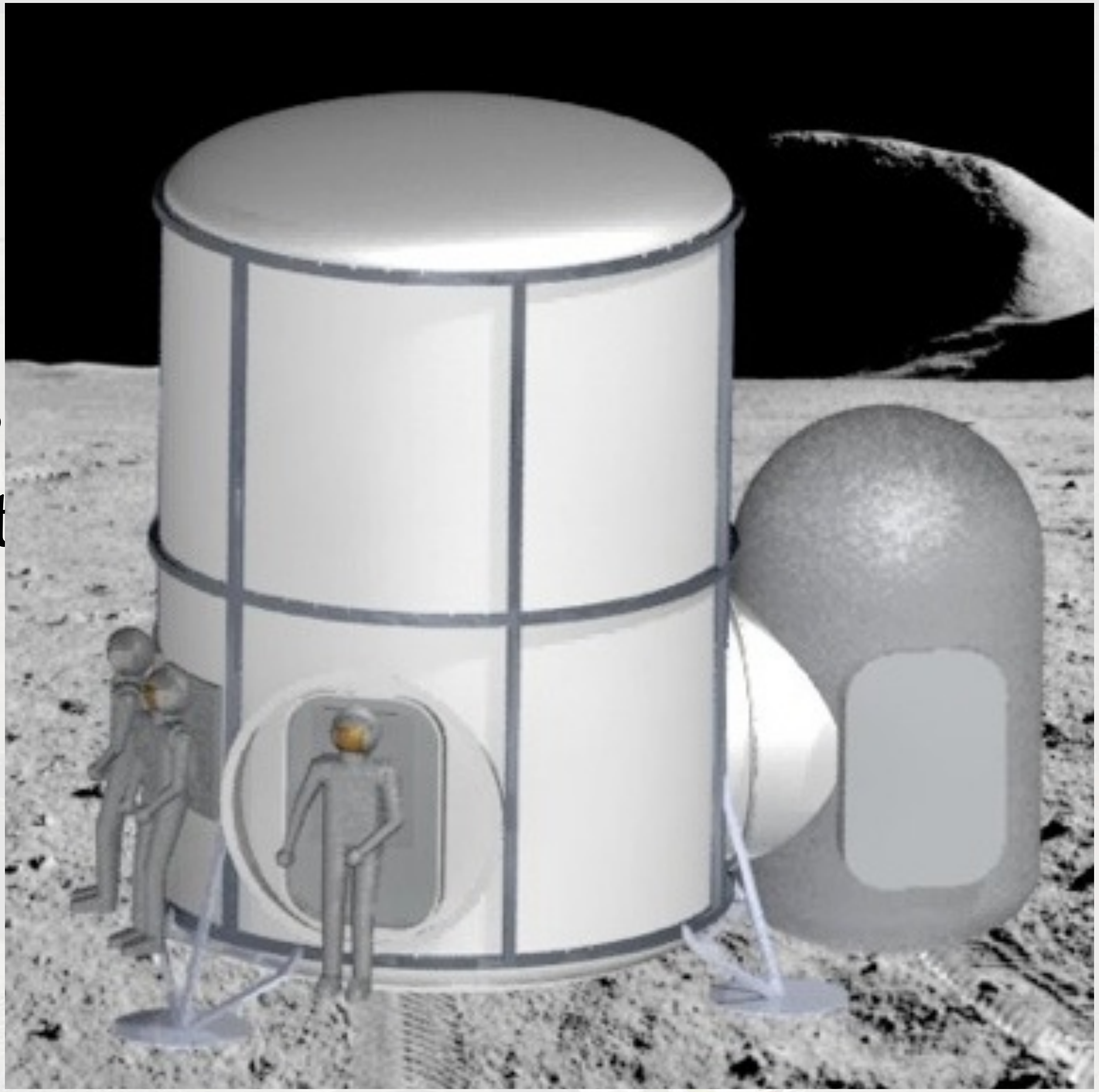
Impact of Closure on Duration



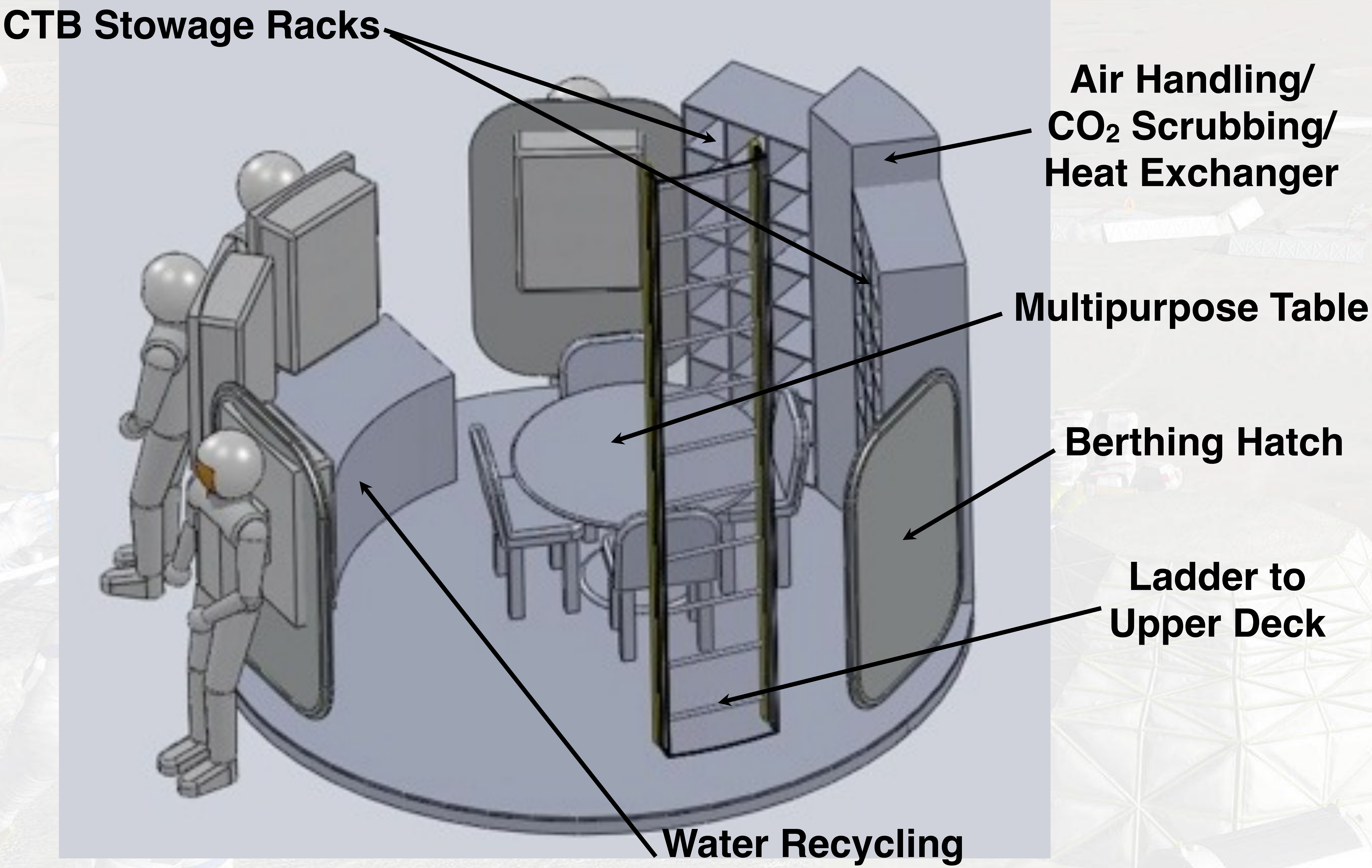
From Harry Jones, “Don’t Trust a Management Metric, Especially in Life Support”, ICES-2014-073, July 2014

UMd Final MFH Design

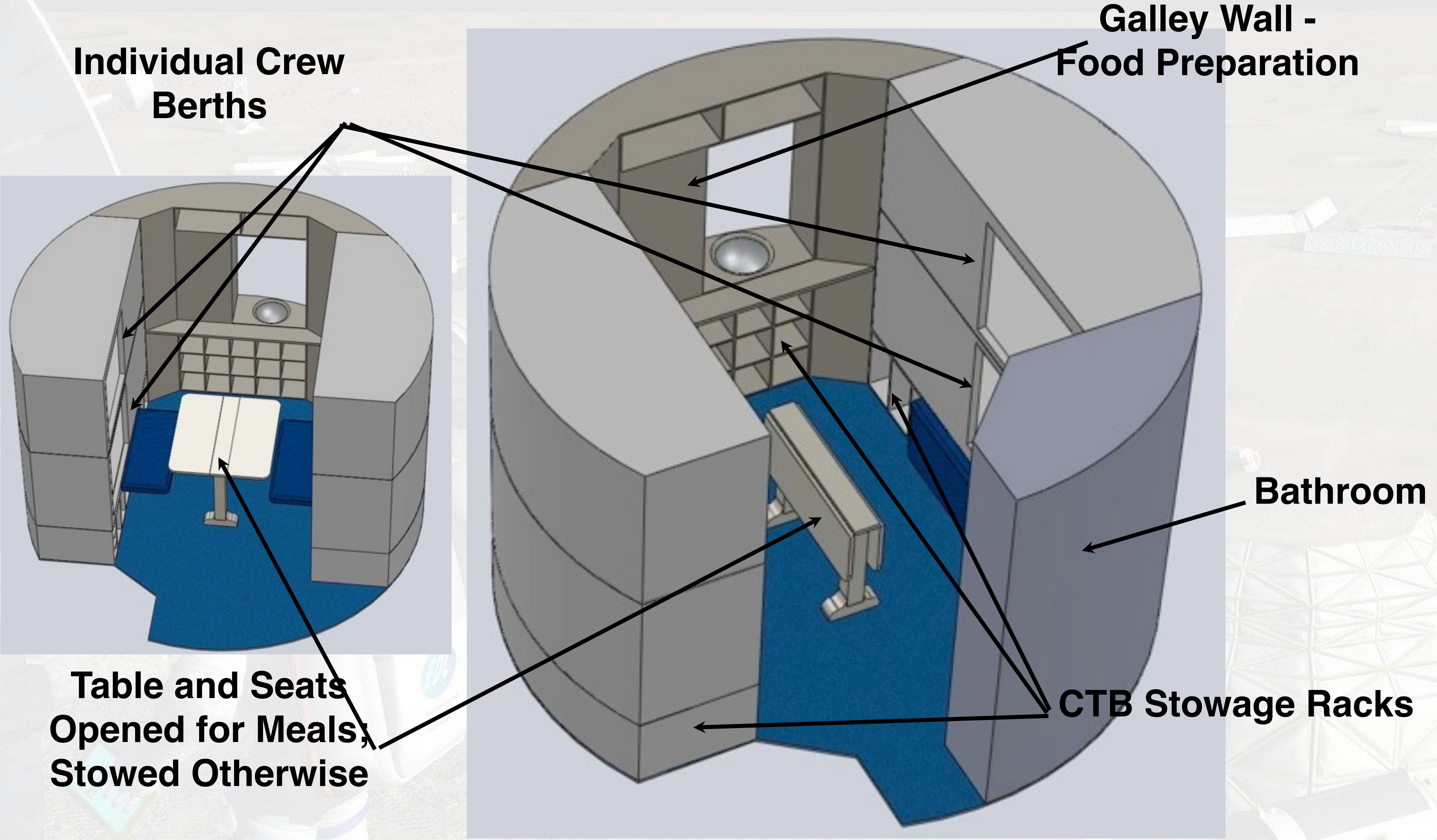
- 3.65 m diameter
- 5.5 m tall
- 4:1 ellipsoidal endcaps
- Three module berthing ports (Cx s
- Four suitports (two in berthing hat
- Inflatable airlock
- All 6063-T6 structure



Lower Deck Layout



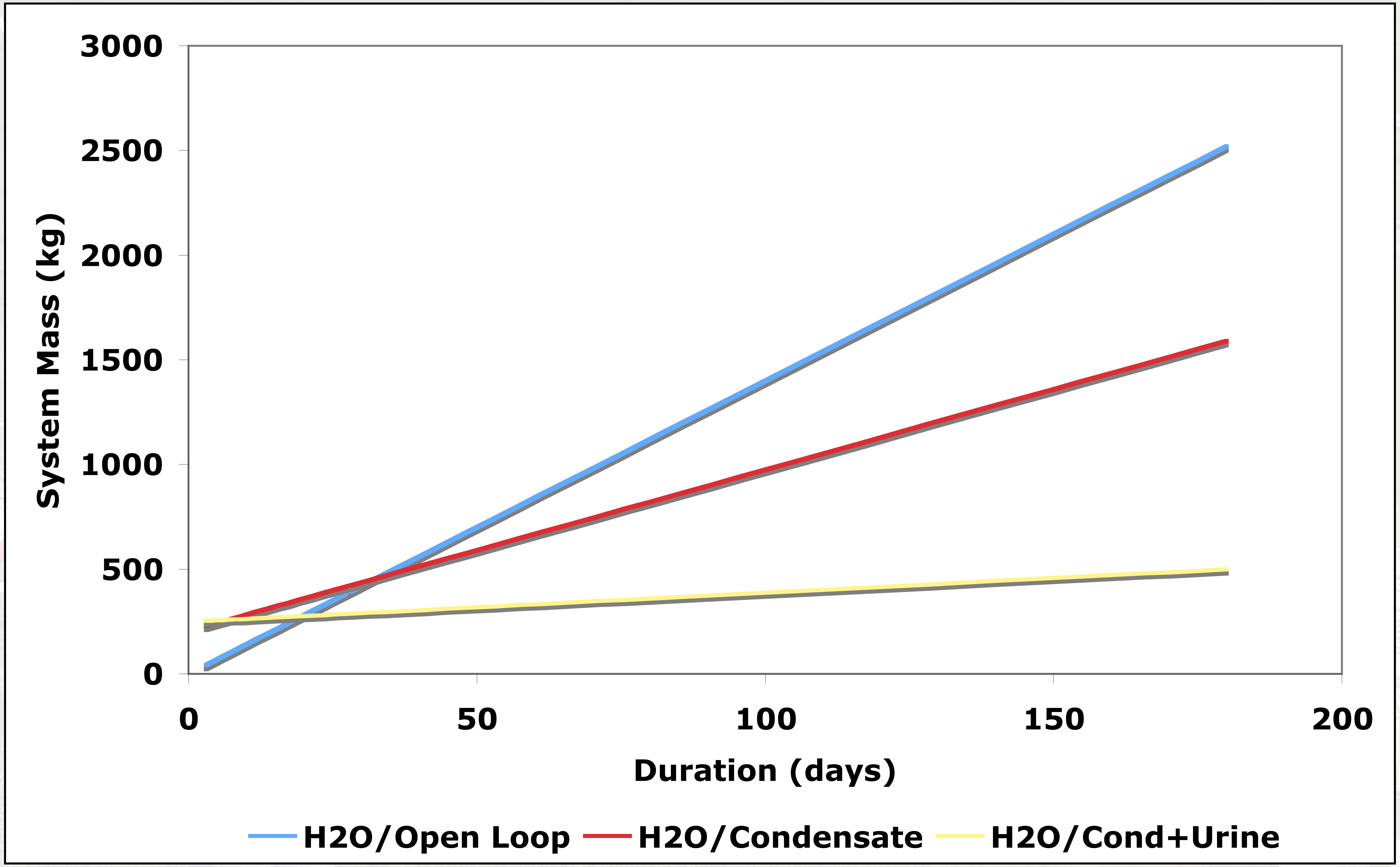
Upper Deck Layout



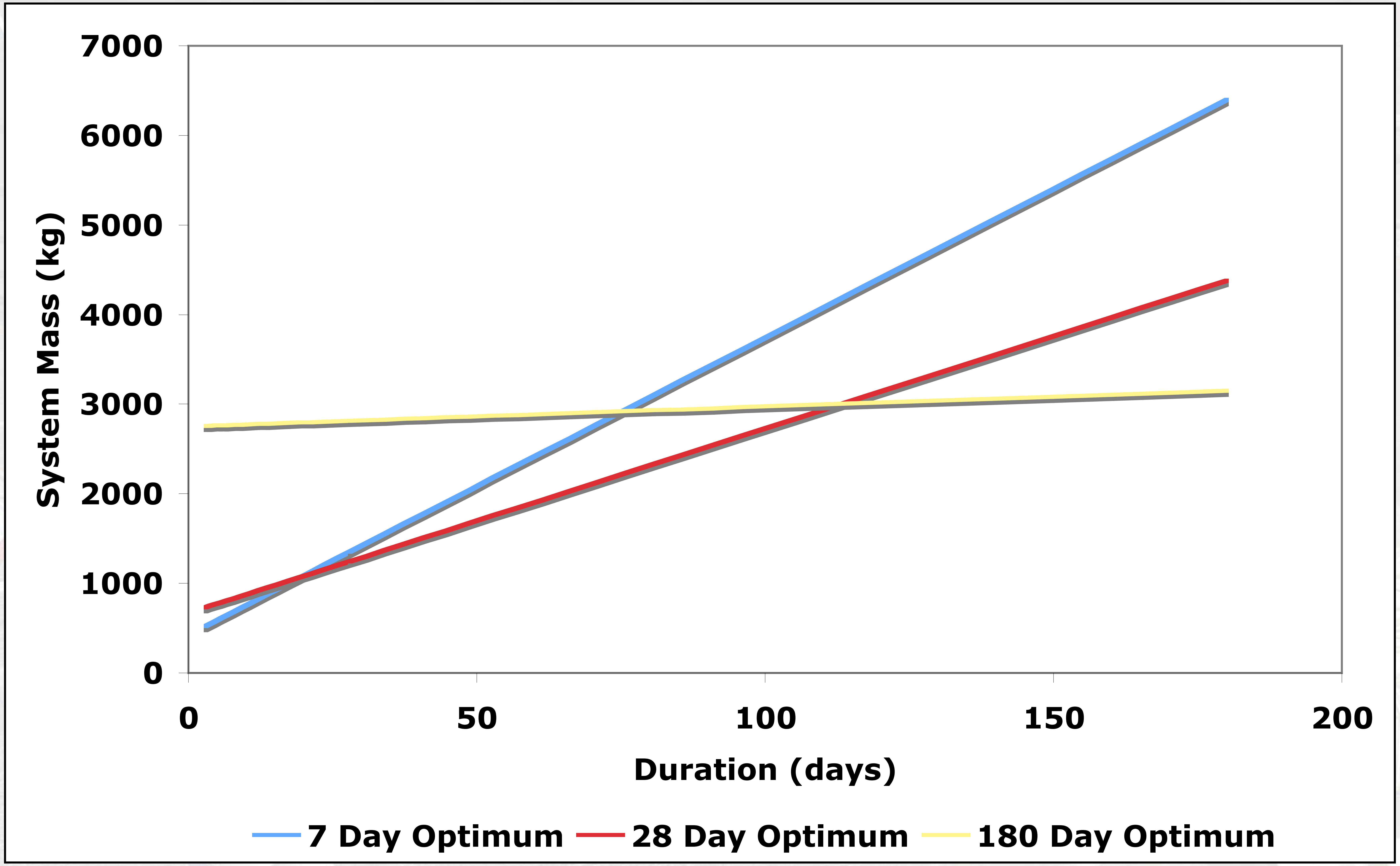
MFHE Life Support Requirements

- 4 crew for nominal mission of 28 days
- Additional contingency mission of 30 days
- 8 crew in handoff mode for 48 hours
  - 4 95th percentile American males for 60 days

Lunar Habitat Water Recycling Trades



Effect of Duration on Life Support



MFHE Operational Assumptions

- Daily two-person EVAs during nominal operations
- One two-person airlock cycle per week and two two-person cycles in support of crew rotation for 12 suit transits/six airlock pressurize/depress cycles (all other EVAs performed using suitports)
- No appreciable atmosphere loss with a suitport cycle
- No EVAs during the contingency support period
- One four-person EVA at the end of the mission for the crew to return to the ascent vehicle
- 64 EVA suit operations during a nominal mission, based on the preceding assumptions
- Power supplied by a Constellation program Mobile Power Unit (MPU) and not charged against habitat mass
- Systems to be considered should have the maximum TRL of the possible candidates (proven systems should be used for simplicity and mission assurance)

EVA Support Requirements

- 64 suit operations in a nominal mission (no EVA during contingency phase)
- Suit CO_2 scrubbing options
  - LiOH canister (6.4 kg, expendable)
  - METOC canister (14.5 kg, reusable)
- METOX regeneration oven
  - Regenerates two canisters over 14 hours
  - 48 kg and 1000 W
- Each EVA uses 0.72 kg of O_2 and 2.1 kg of H_2O --> total 46.1 kg O_2 and 135 kg H_2O

Airlock Operating Requirements

- 6.5 m^3 with 90% scavenging on depress
- Cabin atmosphere 8 psi (30% O_2)
- Atmospheric density 0.667 kg/m^3
- 0.43 kg of atmosphere mix lost per airlock cycle
- 6 cycles/mission --> 6.93 kg (2.1 kg O_2, 4.9 kg N_2)

CO_2 Scrubbing Options

- LiOH canisters
- METOX canisters and regeneration
- Four bed molecular sieve (4BMS - preferred over 2BMS due to higher TRL and better recovery of atmospheric moisture)

CO_2 Scrubbing Analysis

- LiOH canisters
- METOX canisters and regeneration
- Four bed molecular sieve (4BMS - preferred over 2BMS due to higher TRL and better recovery of atmospheric moisture)

Technology	Mission Mass (kg)	Power (W)
LiOH	420	–
METOX	106	1000
4BMS	120	680

Support of EVA CO_2 Systems

- Requires two METOX canisters and second oven (8 hour EVA with pre- and post-EVA prep, 14 hour regeneration cycle with cool-down)
- To stay below 50-55 cycle limits and relieve operational constraints, baseline 4 METOX canisters
- System with EVA support will double mass and power from habitat alone (212 kg, 2000 W)
- Alternative would require 410 kg of LiOH canisters

Support of Rover CO_2 System

- Multi-day pressurized rover (e.g., LEV/SEV)
- Designed to use same life support system as EVA portable life support system (PLSS)
- Required 3 METOX canisters/day (two EVAs and cabin at reduced activity levels)
- No capability for regeneration during sortie - 18 canisters returned to habitat following 6-day sortie
- Regeneration of canisters will require third oven and 5.25 days
- Total METOX canister mass (2x18) is 522 kg

Alternative Rover CO_2 Options

- LiOH canisters will mass 115 kg/sortie
- Four 6-day sorties over 28 day nominal mission --> 461 kg for LiOH canisters
- Compare to total METOX mass of 570 kg for two 18-canister sets and dedicated regeneration oven
- Optimal approach is to use METOX for habitat and local EVA, LiOH for rovers and remote EVA

References - Textbooks

- Peter Eckart, Spaceflight Life Support and Biospherics, Kluwer Academic, 1996
- Wiley Larson and Linda Pranke, Human Spaceflight: Mission Analysis and Design, McGraw-Hill
- A. E. Nicogossian, et. al., eds., Space Biology and Medicine - Volume II: Life Support and Habitability, American Institute of Aeronautics and Astronautics, 1994
- Susanne Churchill, ed., Fundamentals of Space Life Sciences, Krieger Publishing, 1997

References - NASA Design Documents (online)

- B. E. Duffield, “Advanced Life Support Requirements Document” JSC-38571C/CTSD-ADV-245C, February 2003
- A. J. Hanford, “Advanced Life Support Baseline Values and Assumptions Document” JSC-47804A/CTSD-ADV-484A, August 2004
- Kristin W. Stafford, et. al., “Advanced Life Support Systems Integration, Modeling, and Analysis Reference Missions Document” JSC-39502/CTSD-ADV-383, November 2001
- Molly Anderson, et. al., “Life Support Baseline Values and Assumptions Document” NASA/TP-2015-218570, March 2015