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Master Thesis

Feasibility Analysis of a Life Support Architecture for an Interplanetary Transport Ship

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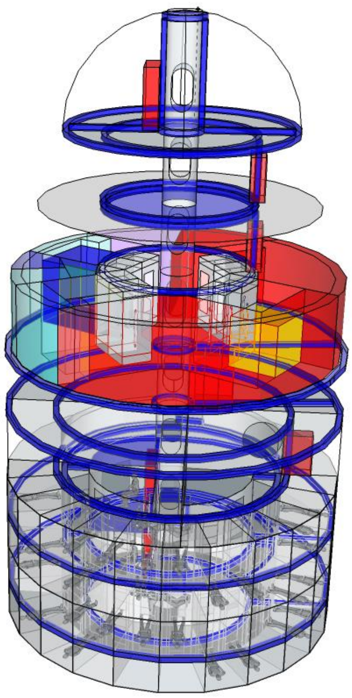

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Dedicated to my son Lukas

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Zusammenfassung

Am 27. September 2016 präsentierte Elon Musk, CEO, leitender Entwickler und Gründer von SpaceX, ein detailliertes Konzept für eine zweistufige, superschwere Rakete, genannt Interplanetary Transport System (ITS). Dieses System soll eine bis zu 100-köpfige Besatzung zum Mars transportieren können. Da der Weltraum eine gefährliche Umgebung ist, benötigen Menschen spezielle Ausrüstung zum Überleben. Diese Ausrüstung wird gewöhnlich Environmental Control and Life Support System (ECLSS) genannt und ermöglicht der Besatzung eine angemessene Umgebung und ausreichend Vorräte. Da nur beschränkte Ressourcen wie Nutzlastmasse und Energie zur Verfügung stehen, stellt die Entwicklung eines solchen Systems eine Herausforderung dar. Daher ist ein optimiertes System erforderlich.

Zur Auswahl eines geeigneten ECLSS wurde eine iterative, multi-kriterien Analyse anhand der Parameter Sicherheit, Zuverlässigkeit und des Technologie-Reifegrads in Verbindung mit einer Massen Äquivalenz Methode (ESM) durchgeführt. Zum Ausgleich des statischen Charakters der ESM Analyse wurde eine anfänglich transiente Analyse der ausgewählten Technologien über einen Tag durchgeführt, basierend auf einer Kompromiss-Analyse von 6 verschiedenen Besatzung-Zeitplänen. Hierfür wurde ein neues Programm entwickelt, genannt Life Support Trade Off Tool (LiSTOT). Mit Hilfe dieses Tabellenkalkulationsprogramms können Machbarkeitsstudien in kurzer Zeit durchgeführt werden.

Insgesamt 37 verschiedene Technologien wurden anfangs miteinander verglichen und die besten, basierend auf den ausgewählten Variablen, für die optimale Zusammensetzung ausgewählt. Die Variablen sind Besatzungsgröße, bedrucktes Volumen, Missionslänge, Nutzlastmasse und der ausgewählte Zeitplan.

Um sicher zu gehen, dass das entwickelte System in einer realistischen Umgebung praktikabel ist, wurde ein detailliertes ECLSS Model in Virtual Habitat erstellt. Virtual Habitat ist ein Simulationsprogramm der technischen Universität München das bereits erfolgreich zur Modellierung der ISS eingesetzt wurde. Dieses Model wurde verwendet um eine Reise zum Mars zu simulieren.

Die Ergebnisse zeigen, dass ein praktikables ECLSS mit den gemachten Annahmen und Beschränkungen machbar ist. Für eine 100-köpfige Besatzung ist nur ein System mit Lagerung aller benötigten Verbrauchsgüter technisch machbar, da der Energieverbauch eines derart großen, regenerativen Systems höher wäre als die zur Verfügung stehende Energie. Dies führt zu einem erheblichen Nachteil für die benötigte Masse und das Volumen. Es wird empfohlen, dass zusätzliche Ressourcen für Energie und Wärmeabstrahlung zur Verfügung gestellt werden, um die erwähnten Nachteile zu kompensieren.

Abstract

At the International Astronautical Congress IAC on 27th September 2016, Elon Musk, CEO, lead designer, and founder of SpaceX, presented a detailed concept for a super-heavy lift two-stage rocket, called Interplanetary Transport System (ITS). This system is expected to be capable to transport up-to one hundred passengers to Mars. Since space is a hazardous environment, humans can only survive in it with special equipment. This equipment is normally called Environmental Control and Life Support System (ECLSS), which must ensure suitable environmental conditions and a continuous consumable supply for the crew. For the anticipated system, the development of such an ECLSS will be a challenge because only limited resources like payload mass and power are available. Therefore, an optimized system is necessary.

For the selection of the ECLSS, an iterative multi-criteria system analysis of the safety, reliability and technology readiness level of different life support technologies were performed in conjunction with an equivalent system mass (ESM) analysis. To offset the static character of the ESM analysis, an initial transient (one day) analysis of the systems was performed based on a tradeoff for 6 different crew schedules. For this, a new tool was developed, called Life Support Trade Off Tool (LiSTOT). With the help of this spreadsheet tool, trade analyses can be made within a short time.

Overall 37 different technologies were initially compared with each other and down selected to yield the optimum arrangement based on the initially variables. The variables are crew size, mission duration, pressurized volume, payload mass, and selected crew schedule.

To ensure that the developed system remains feasible in a more realistic dynamic environment, a detailed model of the ECLSS was created in Virtual Habitat. Virtual Habitat is a simulation tool of the Technical University of Munich that was already used to successfully model the ISS ECLSS. This model was then used to dynamically simulate a journey to Mars.

The results show, that a feasible ECLSS is possible with the made assumptions and constraints. For a one-hundred-person crew only a system which stores all necessary consumables is technically feasible. This is necessary since the power consumption for a recycling system of such a large system would be higher than the power capability of the vehicle. This derives a vast drawback on the required mass and volume. It is recommended, that additional power and thermal heat rejection resources are installed to reduce the mentioned disadvantages.

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Symbols and Formulas

A	[kg CM-d^{-1}]	constant clothing mass
A_{flow}	[s³ m² kg^{-1}]	flow constant A
$A_{i,score}$	[-]	score of alternative i
$A_{triangle}$	[m²]	triangle area
a_{triangle}	[m]	length of triangle side a
a_{feet}	[m s^{-2}]	centrifugal force at feet height on bicycle
a_{ij}	[-]	value of criterion j for alternative i
B	[kg CM-d^{-1}]	variable clothing mass
B_{flow}	[m s]	flow constant B
C	[kW]	total cooling requirement of the system
C	[m³ CM-d^{-1}]	variable clothing volume
C_{eq}	[kg kW^{-1}]	mass equivalency factor for cooling infrastructure
c	[m]	length of triangle side c
c_{water}	[Wh kg^{-1} K^{-1}]	specific heat capacity of water
D	[y]	duration of the mission segment
D_{WT}	[m]	diameter of water tank
d	[-]	damping constant
$d_{ACS,tube}$	[m]	required diameter of tube
d_{inward}	[m]	inner diameter of bicycle track
$d_{outward}$	[m]	outer diameter of bicycle track
ESM	[kg]	equivalent system mass value
$f_{Certainty}$	[-]	certainty factor
$f_{CF,ij}$	[-]	certainty factor of criterion j for alternative i
f_{FF}	[-]	flow factor
f_{ij}	[-]	value function of criterion j for alternative i
$f_{RF,mass}$	[-]	rescale factor to scale the mass of a system to a bigger crew size
$f_{RF,mass,consumables}$	[-]	rescale factor to scale the mass of consumables of an assembly

$f_{RF,power}$	[-]	rescale factor to scale the power of a system to a bigger crew size
$f_{RF,thermal}$	[-]	rescale factor to scale the thermal heat rejection of a system to a bigger crew size
$f_{RF,volume}$	[-]	resale factor to scale the volume of a system to a bigger crew size
$f_{RF,volume,consumables}$	[-]	rescale factor to scale the volume of consumables of an assembly
$f_{SPF,cylinder}$	[-]	stowage penalty factor for a cylinder
$f_{SPF,sphere}$	[-]	stowage penalty factor for a sphere
$f(\ )$	[-]	function handle
g_0	[m s^{-2}]	standard gravity
h	[m]	height of SpaceHab
$h_{deck-buttom}$	[m]	height of bottom of deck measured from the top
h_{radius}	[m]	height of SpaceHab at given radius
I_{sp}	[s]	specific impulse
K_l	[kg]	fixed mass for bosses, mounting brackets etc.
k	[N s^2 m^{-2}]	air pressure constant
t_{given}	[days]	given mission time of component or assembly
$t_{mission}$	[days]	mission duration
$t_{required}$	[days]	required mission time
$t_{MTBF,i}$	[h]	mean time between failure of component i
l	[m]	tube length
M	[kg]	total mass of the system
M_{air}	[g mol^{-1}]	molar mass of dry air
M_{CO_2}	[g mol^{-1}]	molar mass of CO_2
M_{gas}	[g mol^{-1}]	molar mass of gas
M_{O_2}	[g mol^{-1}]	molar mass of oxygen
m	[kg]	mass of alternative
$m_{Astrine}$	[kg]	mass of astrine
m_{atmo}	[kg]	mass of present atmosphere
$m_{BOCS\ w/o\ cartridge}$	[kg]	mass for the BOCS

$m_{\mathrm{BOCS}\ cartridge}$	[kg]	BOCS cartridge mass
$m_{cartridge}$	[kg]	total mass of one cartridge
$m_{cartridges\ for\ leakage}$	[kg]	total cartridge mass for leakage
$m_{clothes}$	[kg]	total mass for clothes
$m_{CO_2,atmo}$	[kg]	CO_2 mass in atmosphere
$m_{CO_2 capacity,max}$	[kg]	maximum desorption capacity of astrine
$m_{CO_2,max}$	[kg]	maximum CO_2 mass in atmosphere
$m_{CO_2,produced}$	[kg]	produced CO_2 mass per CM
$m_{\mathrm{CO_2,removed}}$	[kg]	removed CO_2 per LiOH cartridge
m_{dry}	[kg]	structural mass of SpaceHab
m_{F9}	[kg]	mass of Falcon 9 booster
$m_{F9,legs}$	[kg]	mass of Falcon 9 legs
m_{fuel}	[kg]	fuel mass
m_{gas}	[kg]	gas mass
$m_{leakage\ system}$	[kg]	mass for thermal containment equipment and igniters for leakage system
$m_{\mathrm{LiClO_4}\ per\ cartridge}$	[kg]	$LiClO_4$ mass per cartridge
$m_{\mathrm{LiClO_4}\ per\ kg\ O_2}$	[kg]	required mass of $LiClO_4$ per kg O_2
$m_{\mathrm{LiClO_4}\ repressurisation}$	[kg]	total mass of required $LiClO_4$
$m_{LiOH,cartridge}$	[kg]	LiOH mass per cartridge
m_{max}	[kg]	maximum mass of alternatives
m_{min}	[kg]	minimum mass of alternatives
$m_{O_2\ produced}$	[kg]	O_2 production of one cartridge
$m_{O_2\ required}$	[kg]	required O_2 for repressurization
m_{needed}	[kg]	minimal O_2 mass needed for required partial pressure
m_{PL}	[kg]	payload mass
$m_{SpaceHab,Carbon}$	[kg]	mass of carbon used for SpaceHab
$m_{SpaceHab,legs}$	[kg]	mass for landing legs of the SpaceHab
$m_{stowage\ unit}$	[kg]	mass of cartridge stowage unit
m_{th}	[kg]	mass to heat or cool
$m_{water,available}$	[kg]	daily consumption water mass
$m_{water,recovered}$	[kg]	daily recovered water mass by WRM

m_{WT}	[kg]	mass of bladder tank
$\dot{m}_{consumption}$	[kg day^{-1}]	daily O_2 consumption mass
$\dot{m}_{flow}$	[kg s^{-1}]	mass flow rate through the hatch
$\dot{m}_{flow,old}$	[kg s^{-1}]	mass flow rate through the hatch from last time step
$\dot{m}_{production}$	[kg day^{-1}]	mean CO_2 production mass
$\dot{m}_{hole}$	[kg h^{-1}]	mass flow through hole
N_i	[-]	number of units of each component
n_{BFE}	[-]	number of required BFE and Diffusor
$n_{BFE,LAB}$	[-]	number of BFE´s in ISS laboratory
$n_{cartidges\ per\ stowage\ unit}$	[-]	number of cartidges per stowage unit
$n_{crew,given}$	[-]	given crew size of component or assembly
$n_{crew,mission}$	[-]	required crew size for the mission
$n_{criteria}$	[-]	number of criteria
n_{CM}	[-]	number of crew member
$n_{CM,deck2and3,max}$	[-]	maximum number of CM in decks 2 and 3
$n_{CM,deck5,max}$	[-]	maximum number of CM in deck 5
$n_{elements}$	[-]	number of elements in system
$n_{\mathrm{LiOH,cartridges}}$	[-]	required LiOH cartridges
$n_{\mathrm{LiClO_4},cartridges}$	[-]	required $LiClO_4$ cartridges
$n_{LiOHsystems}$	[-]	number of required LiOH systems
n_{MLI}	[-]	number of MLI layers
n_{spares}	[-]	number of spares considered for component
n_{tanks}	[-]	number of required tanks
n_{types}	[-]	number of different types of components
P	[kg cm^{-2}]	design pressure
P	[kW]	total power requirement of the system
P	[W]	total power of the alternative
P_{eq}	[kg kW^{-1}]	mass equivalency factor for power infrastructure
P_{max}	[W]	maximum power consumption of alternatives
P_{min}	[W]	minimum power consumption of alternatives

P_{th}	[W]	required heat removal of the component or assembly
$P_{th,decks2and3}$	[W]	total thermal load in decks 2 and 3
$P_{th,deck5}$	[W]	total thermal load in deck 5
$P_{th,max}$	[W]	maximum heat removal of alternatives
$P_{th,mim}$	[W]	minimum heat removal of alternatives
Δp	[Pa]	pressure decrease/loss or difference
$p_{CO_2,max}$	[Pa]	maximum allowable CO_2 partial pressure
p_{gas}	[Pa]	nominal partial pressure of gas
$p_{required}$	[Pa]	minimum required O_2 partial pressure
$\dot{Q}$	[J]	required energy to heat water
$\dot{q}$	[W]	radiant heat transfer per m²
R	[J mol^{-1}]	gas constant
$R(t)$	[h]	reliability of system or element
R_{max}	[h]	maximum reliability of the alternatives
R_{min}	[h]	minium reliability of the alternatives
R_r	[J m^{-1}]	rolling resistance
$r_{circle\ in\ triangle}$	[m]	maximum radius of circle in triangle
r_{deck}	[m]	radius of deck
r_{feet}	[m]	radius measured from the middle of the SpaceHab to the feet on bicycle
r_{low}	[m]	lower inner radius of SpaceHab
$r_{SpaceHab}$	[m]	radius of SpaceHab
r_{sphere}	[m]	sphere radius
$r_{unpressurized\ space}$	[m]	usable radius of unpressurized space
S	[kg cm^{-2}]	design stress
T	[K]	temperature
T	[kN]	thrust of engine
T_{env}	[K]	temperature of environment
T_{FD}	[%]	maximum tank filling degree
T_{wall}	[K]	temperature of tank wall
t	[h]	mission time
t_b	[m]	thickness of bladder

t_{crew}	[CM-h y^{-1}]	total crew time requirement of the system
$t_{crew,eq}$	[kg CM-h^{-1}]	mass equivalency factor for the crew time
$t_{detection}$	[h]	decompression detection time
t_{main}	[h]	maintenance time of component or subsystem
$t_{CO_2,hazard}$	[days]	time to CO_2 hazard
$t_{O_2,hazard}$	[days]	time to O_2 hazard
t_s	[m]	thickness of shell
t_{wall}	[m]	wall thickness
$U_{triangle}$	[m]	triangle extensive
$U_{unpressurized\ space}$	[m]	circumference of unpressurized space
V	[m³]	total pressurized volume of the system
V	[m³]	total volume of alternative
$V_{\mathrm{BOCS}\ cartridge}$	[m³]	volume of one BOCS cartridge
$V_{BOCS\ system}$	[m³]	volume of BOCS
$V_{bicycletrack}$	[m³]	required volume for bicycle track
V_{Carbon}	[m³]	total volume of carbon fiber
$V_{cartridge}$	[m³]	cartridge volume
$V_{cartridge,w,SPF}$	[m³]	cuboid volume of one cartridge
$V_{cartridges\ for\ leakage}$	[m³]	total cartridges volume for leakage
$V_{clothes}$	[m³]	total volume for clothes
$V_{ellipsoid}$	[m³]	volume for ellipsoid shape
V_{eq}	[kg m^{-3}]	volume equivalency factor for pressurized infrastructure
V_{gas}	[m³]	gas volume
$V_{healthcare}$	[m³]	volume for medical station
V_{LAB}	[m³]	pressurized volume of ISS laboratory
$V_{leakage\ system}$	[m³]	volume for thermal containment equipment and igniters for leakage system
$V_{\mathrm{LiClO_4}\ per\ cartridge}$	[m³]	volume of $LiClO_4$ in one cartridge
$V_{\mathrm{LiClO_4}\ repressurisation}$	[m³]	total volume of $LiClO_4$ for repressurisation
$V_{LowerDecks}$	[m³]	volume of lower decks
$V_{max,sphere}$	[m³]	maximum spherical volume inside unpressurized space

V_{max}	[m³]	maximum volume of alternatives
V_{min}	[m³]	minimum volume of alternatives
$V_{paraboloid}$	[m³]	volume for parabolid shape
$V_{repressurisation\ system}$	[m³]	total repressurization system volume
$V_{SpaceHab}$	[m³]	volume of SpaceHab
V_{tank}	[m³]	tank volume
$V_{UpperDecks}$	[m³]	volume of arimetric middle shape for upper decks
$V_{w/o,CQ}$	[m³]	pressurized volume of deck without CQ
$\dot{V}$	[m³ h⁻¹]	volume flow through pipe
Δv	[m s⁻¹]	change of velocity or specific impulse
v	[m s⁻¹]	velocity
v_{feet}	[m s⁻¹]	speed at feet height on bicycle
W	[kg]	mass of engine
$W_{cyclist}$	[W]	applied mechanical power from cyclist
$w_{bicycletrack}$	[m]	width of bicycle track
x_{radius}	[m]	variable for radius
δ	[W m⁻² K⁻⁴]	Stefan–Boltzmann constant
ε_{MLI}	[-]	emissity of MLI layers
ρ_{gas}	[kg m⁻³]	gas density
$\rho_{\mathrm{LiClO_4}}$	[kg m⁻³]	density of $LiClO_4$
ρ_b	[kg m⁻³]	density of bladder material
ρ_{Carbon}	[kg m⁻³]	carbon fiber density
ρ_s	[kg m⁻³]	density of shell material
λ	[h⁻¹]	failure rate of component
$\lambda_{assembly}$	[h⁻¹]	assembly failure rate
λ_i	[h⁻¹]	component failure rate
η_{LiOH}	[-]	LiOH desorption efficiency
μ	[Pa s]	dynamic viscosity of fluid
μ_{RE}	[-]	water recovery efficiency factor
$\gamma_{P,battery}$	[kg kW⁻¹]	equivalency factors for power storage
$\gamma_{P,solar}$	[kg kW⁻¹]	equivalency factors for solar array
$\gamma_{P,M,solar}$	[kg kW⁻¹]	specific solar array mass

$\gamma_{P,V,solar}$	[kg kW^{-1}]	specific solar stowage volume
γ_V	[-]	volume infrastructure cost factor

Abbreviations

2BMS	Two Bed Molecular Sieves	CCAA	Common Cabin Air Assembly
4BMS	Four Bed Molecular Sieves	CDS	Cascade Water Distillation Subsystem
ACLS	Advanced Closed Loop System	CEO	Chief Executive Officer
ACRS	Advanced Carbon-formation Reactor System	CFR	Carbon Formation Reactor
ACS	Atmosphere Control and Supply	CHX	Condensing Heat Exchanger
AES	Air Evaporation System	CM	Crew Member
ALSSAT	Advanced Life Support Sizing Analysis Tool	CM-d	Crew Member Day
APC	Air Polarized Concentrator	COA	Catalytic Oxidizer Assembly
AR	Atmosphere Revitalization	CoF	Contingency Factor
ARFTA	Advanced Recycle Filter Tank Assembly	ConOps	Concept of Operations
ATCS	Active Thermal Control System	CQ	Crew Quarter
BFE	Bacteria Filter Assembly	D&C assembly	Data and Control assembly
BOCS	Backup Oxygen Candle	DA	Distillation Assembly
BVAD	Baseline Values and Assumptions Document	DRM	Design Reference Mission
CADDA	Cabin Air Ducting Damper Assembly	ECLSS	Environmental Control and Life Support System
CAMRAS	Carbon Dioxide and Moisture Removal Amine Swing-Bed System	EDC	Electrochemical Depolarization Concentration
CBA	Charcoal Bed Assembly	EIA	Electronic Interface Assembly

EIB	Electronic Interface Box	LiSTOT	Life Support Trade-Off Tool
EMI	Electromagnetic Interference	LoC	Loss of Crew
ESM	Equivalent System Mass	LRT	Lehrstuhl für Raumfarttechnik
EVA	Extravehicular Activity	LS	Liquid Sensor
Evolved-SpaceHab	Modified concept of the ITS spaceship	LSS	Life Support System
FCA	Firmware Controller Assembly	LTL	Low-Temperature Loop
FCPA	Fluids Control and Pump Assembly	MCA	Major Constituent Analyzer
HIDH	Human Integration Design Handbook	MCDM	Multi-criteria Decision Making
HPE	High Pressure Electrolysis	MCM	Multi-Criteria-Method
HX	Heat exchanger	MCV	Microbial Check Valve
IAC	International Astronautical Congress	METOX	Metal Oxides
IMV	Intermodule Ventilation	MF	Multifiltration
INL	Idaho National Lab	MIR	Russian Spacestation: Мир, peace or world
ISS	International Space Station	MOF	Metal-Organic Frameworks
ITCS	Interal Thermal Control System	MPEV	Manual Pressure Equalization Valve
ITS	Interplanetary Transport System	MS assembly	Mass spectrometry assembly
JSC	Johnson Space Center	MSL	Mars Science Laboratory
LEO	Low Earth Orbit	MTBF	Mean Time between Failure
LiOH	Lithium Hydroxide	MTL	Moderate-Temperature Loop

NASA	National Aeronautics and Space Administration	SpaceX	Space Exploration Technologies Corporation
NIA	Nitrogen Interface Assembly	SpaceHab	Original concept proposed by SpaceX for the ITS spaceship
OGA	Oxygen Generation Assembly	SPWE	Solid Polymer Water Electrolysis
OGS	Oxygen Generation System	STS	Space Transportation System
ORU	Orbital Replacement Unit	TCCS	Trace Contaminant Control Subassembly
PCA	Pressure Control Assembly,	TCCV	Temperature Control and Check Valve
PCP	Pressure Control and Pump Assembly	TCS	Thermal Control System
PCWQM	Potable Control Water Quality Monitoring	THC	Temperature and Humidity Control
RH	Relative Humidity	TIMES	Thermoelectric Integrated Membrane Evaporation Subsystem
RHS	Reactor Health Sensor	TMA	Technology Maturity Assessment
RO	Reverse Osmosis	TMI	Trans-Mars Injection
SAVD	Solid Amine Vacuum Desorption	TRL	Technology Readiness Level
SAWD	Solid Amine Water Desorption	TS	Temperature Sensor
SBA	Postsorbent Bed Assembly	TUM	Technical University of Munich
SEOS	Solid Electrolyte Oxygen System	UF	Ultra-Filtration
SFWE	Static Feed Water Electrolysis	UPA	Urine Processor Assembly
SPA	Separator Plumbing Assembly	VCD	Vapor Compression Distillation
V-HAB	Virtual Habitat		

VTVL	Vertical Takeoff, Vertical Landing
w/o	without
WM	Waste Management
WPA	Water Processor Assembly
WRA	Water Recycling Architecture
WRM	Water Recovery and Management
WS	Water Separator
WSTA	Wastewater Storage Tank Assembly
WVE	Water Vapor Electrolysis

1 Introduction

At the International Astronautical Congress IAC on 27th September 2016, Elon Musk, CEO, lead designer, and founder of SpaceX, presented a detailed concept for a super-heavy lift two-stage rocket, called Interplanetary Transport System (ITS) [1]. This system is expected to be capable to transport up-to one hundred passengers to Mars. Since space is a hazardous environment, humans can only survive in it with special equipment. This equipment is normally called Environmental Control and Life Support System (ECLSS) which must ensure suitable environmental conditions and a continuous consumable supply for the crew. In short, an ECLSS is a buffer between the human and the environment. This is the reason why they must be very reliable. But as the mission time and distance from earth are increasing, the Life Support System (LSS) are becoming increasingly complex [2, pp. 39-77]. For the anticipated system, the development of such an LSS will be a challenge, because only limited resources like payload mass, volume and power are available. Therefore, an optimized system is necessary.

Most LSS design approaches are based on static hardware data and steady state considerations [3–5]. The Equivalent System Mass (ESM) [6] is a widely-used metric for such an approach, which is used by the Advanced Life Support Sizing Analysis Tool (ALSSAT). ALSSAT is a spreadsheet tool developed at Johnson Space Center (JSC) to make trade studies over different LSS architectures based on the ESM metric [7]. This tool is only available for US residents and was not available for this research. Also, it is only usable for a first guess and consequently additional parameters are necessary. Therefore, a new tool was developed during this thesis, called Life Support Trade Off Tool (LiSTOT). With the help of this spreadsheet tool, several trade analyses can be made in a short time. For the verification of the results, the already available dynamic simulation tool V-Hab is used. This software has been developed for over 8 years at the Institute of Astronautics of the Technical University Munich [8]. Because most components of this tool are verified through experimental data, it can be used for a trustworthy verification of the results gained from LiSTOT. The principles of systems engineering guided the whole progress.

1.1 Scope

To gain a verifiable and cohesive solution, the following objectives shall be met.

Main Objective

Goal of this thesis is the objective assessment of the Environmental Control and Life Support System feasibility for the proposed Interplanetary Transport System Spaceship based on statements made by SpaceX and Elon Musk and the technical information that the organization has made publicly available.

Secondary Objectives

- **When applicable, provide recommendations for the stated Interplanetary Transport System Spaceship architecture and operational strategy. In some instances, the implementation of a recommendation requires the relaxation of one or more of the constraints imposed by statements or assumptions made by SpaceX. When this is the case, recommendations are made with the intent of improving the Interplanetary Transport System Spaceship architecture while minimizing the number of SpaceX-specified constraints that are violated.**
- **All necessary Subsystems that provide a safe and comfortable habitation shall be considered.**
- **A representative selection of mission duration for an Earth-Mars trip shall be analyzed.**
- **The results should be transferable to other systems.**
- **In general, a conservative approach shall be applied.**

This analysis does not attempt to design the Interplanetary Transport System Spaceship architecture. Rather, recommendations are made and analyzed to extend the scope of this feasibility analysis to less-constrained variants.

To reach the presented requirements, this thesis is separated into several segments. In the first segment, the background of this study is highlighted. The proposed Interplanetary Transport System by SpaceX is examined and a special emphasis is given to investigate the capabilities of the Spaceship. For this, statements and assumption made publicly by SpaceX or Elon Musk are compiled.

In the following segment, the environment of the developed system is examined. The gathered information are used to develop a concept of operations plan, including a layout of the Spaceship and schedules for the crew. When insufficient data is available from mentioned sources, data is used from standard aerospace handbooks and data sources, such as the NASA Human Integration Design Handbook (HIDH) [9] and the NASA Baseline Values and Assumptions Document (BVAD) [10]. Additionally, the requirements and constraints for the follow up segment are outlined and the chosen assumptions and simplifications presented to understand the limitations and possible inaccuracies of the design process.

The design process is comprised of a detailed examination of possible life support technologies. All technologies that fulfill the essential requirements are scaled to the considered mission scenarios for a comparison in the subsequent trade analysis. The hereby selected candidate technologies are compared in a second design cycle to examine an ESM optimal architecture. Further, other aspects like safety and reliability of the life support equipment are presented. The crew accommodation, clothing and food system are also examined.

In the last segment, the developed systems and the hazard analysis are presented. The considered air management system is confirmed by a state-of-the-art dynamic simulation tool and the life support design is verified against the requirements and constraints. The results of this verification process are discussed in the last chapter and future work to be done is outlined.

A graphical breakdown of the overall structure of this thesis is shown in Figure 1-1.

For this thesis, the generic masculine will be used and any masculine designation is considered to entail females.

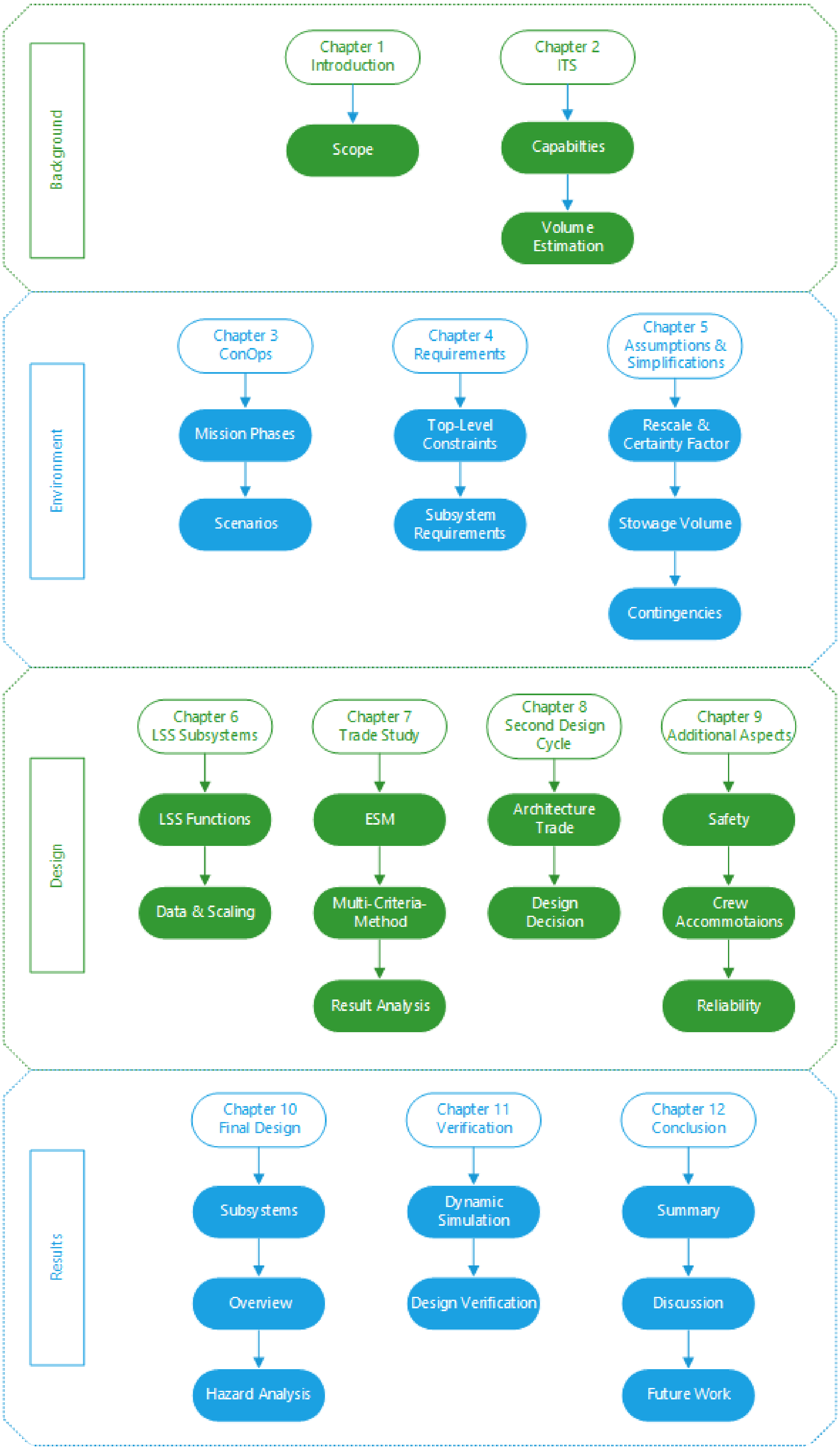

Figure 1-1: Thesis structure

2 Interplanetary Transport Spaceship

The Interplanetary Transport Spaceship, formerly known as Mars Colonial Transporter, is the primary vehicle of the Interplanetary Transport System (ITS) proposed by SpaceX to transport freight and humans in space. The principles of the system are full reusability, refueling in orbit, and fuel generation on Mars [11]. The main mission, defined by SpaceX, will be transports to Mars, even if it is capable to transport payload and humans nearly anywhere in the solar system. Because of this, the focus for the analysis of this thesis will be a mission to Mars.

The system consists of a booster stage and a second stage. Depending on the operational phase, the second stage is a tanker or the mentioned Interplanetary Transport Spaceship, called from now on SpaceHab. The tanker is used to refuel the SpaceHab in LEO. A detailed overview of this operation is given in chapter 3.1.

As can be seen in Figure 2-1, the ITS will be the largest rocket in history, far exceeding the payload capacity of past and near future rockets.

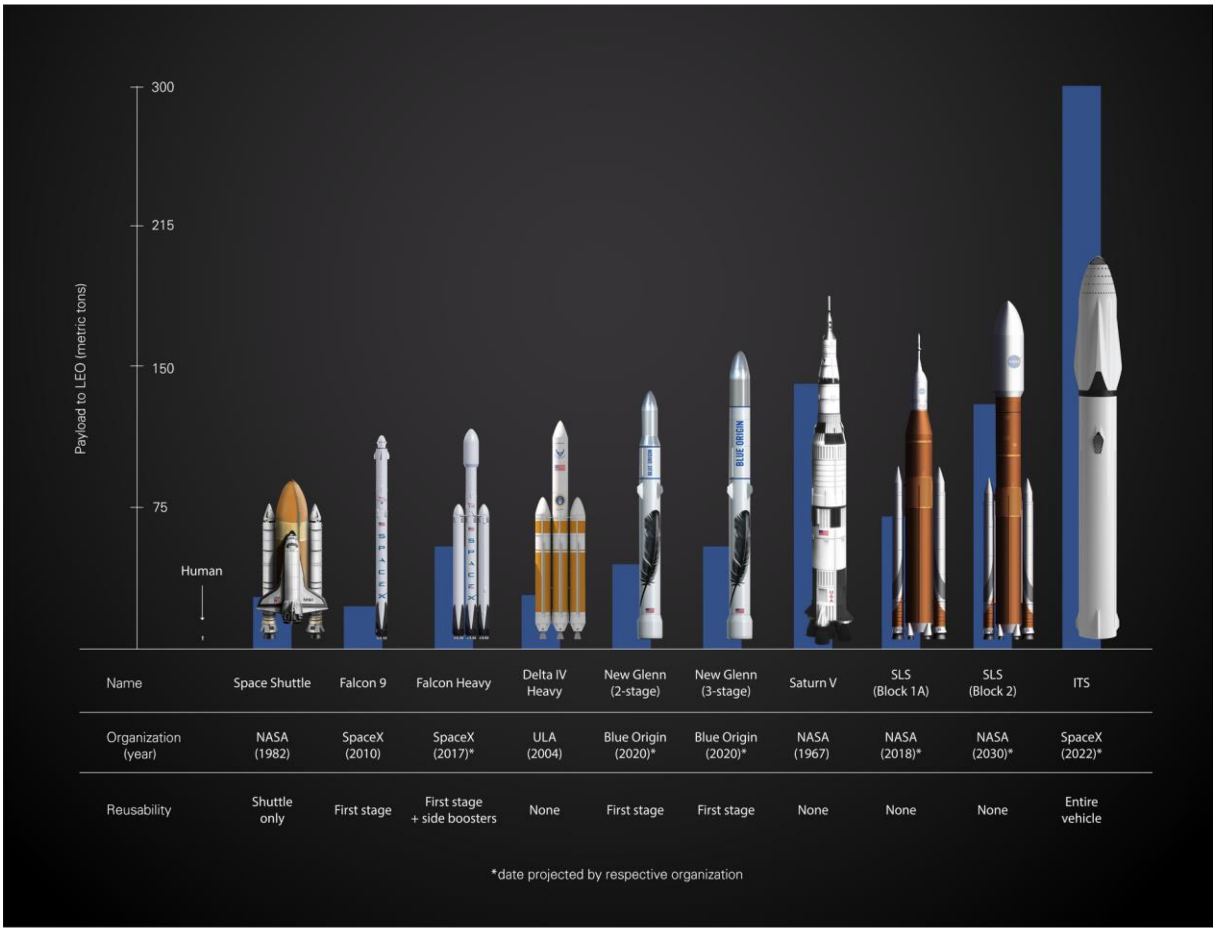

Figure 2-1: Comparison of ITS (right) with other Rockets [12]

The basic parameters of the ITS from [11] are summarized in Table 2-1.

Table 2-1: Parameters of the Interplanetary Transport System [11]

Parameter	Value	Unit
Expandable LEO Payload	550	[t]
Fully Reusable LEO Payload	300	[t]
Fully Reusable Payload to Mars	450	[t]
Diameter	12	[m]
Booster Length	77.5	[m]
SpaceHab / Tanker Length	49.5	[m]
Booster Propellant Mass	6,700	[t]
SpaceHab Propellant Mass	1,950	[t]
Tanker Propellant Mass	2,500	[t]
Booster Dry Mass	275	[t]
SpaceHab Dry Mass	150	[t]
Tanker Dry Mass	90	[t]
Booster Number of Engines	42	[-]
SpaceHab Number of Engines	9	[-]

The SpaceHab is basically the second stage of the ITS with an encompassed payload section. The dimensions of this vehicle are 49.5 m in length and a maximum diameter of 17 m including the legs or 12 m in diameter for the cylindrical shell. It has a dry mass of 150,000 kg and a payload capacity of 300,000 kg to LEO. If completely refueled in orbit, it can transport up to 450,000 kg to mars. Because the mass of the transported payload directly affects the Δv, this also affects the required time to travel to mars and therefore the number of consumables for the ECLSS (see also 2.4). A further detailed analysis of the transit times is provided in chapter 3.1 Mission Phases.

To find an optimized architecture for the ECLSS of this system, it is essential to know the different aspects of the environment in which the ECLSS should be operated. Especially important are the available power, the thermal heat rejection capability, the volume and the payload mass of the ITS. The limiting factor for all combined ECLSS components is the available power. This is discussed in 2.1. The same is true for the thermal heat rejection in chapter 2.2. The size of the components including pipes, spares etc. must fit into the existing volume and must be as small as possible to give the people on board as much habitable volume as possible. For an analysis of the available volume see chapter 2.3. Finally, the payload mass is analyzed which not only influences the travel time, but also drives the cost per trip. A breakdown of the possible payload and transfer duration is described in 2.4.

2.1 Power

The specified electrical power capability is 200 kW through solar cells [11]. It is not defined if this is the Begin of Life (BOL) or End of Life (EOL) ability, if they are replaced after a mission, and at what distance from the sun this power is generated. Because solar cells degenerate, they generate less electrical power over time. It is assumed for the following analysis, that the output is at 100 %, or BOL and that the solar cells will have no degeneration over the analyzed mission time. The total amount of received radiation (solar irradiance) is dependent of the cross-section R^{-2}, where R is the distance to the sun. Because of this, the mean available power at mars is only around 86.6 kW or 43.3 % compared to Earth [13, p. 55]. For this reason, the overall quantity of available power is assumed to 86.6 kW.

2.2 Thermal

There is no specification given for the thermal subsystem. It is assumed that the thermal system has a rejection capability half of the power capability. Therefore, the total heat rejection capability will be 100 kW. For comparison, the ISS has a EOL power capability of 208 kW [14, p. 50], while the heat rejection capability is 70 kW [15, p. 17]. Since this system is not dependent on the distance from the sun, the capability is constant.

2.3 Volume

At the time of this thesis, no direct information was given for the pressurized volume of the SpaceHab. Because the volume of the occupied space is of special interest for the design of the ECLSS, it is necessary to get a close estimate. It is known that the overall length of the Spaceship is 49.5 m and that the outer diameter is 12 m. Details of the inside of the SpaceHab can be seen in Figure 2-2. Even with an unfavorable perspective and no dimensions, the internal volume can be estimated. For measurements, it must be differed between the two major axes. As can be shown, the height and the width in Figure 2-2 are distorted. It can also be seen, that the SpaceHab consists of 8 decks. The lower two decks are designated for storage for the first missions and are unpressurized. Elon Musk mentioned in his speech at the IAC that later iterations of the ITS for more passengers are possible [16]. Assuming this means the lower two decks are also pressurized and included as habitable area, the height of the pressurized section is around 21,7 m or 43,8 % of the overall length of the Spaceship. The original concept presented by SpaceX with 6 decks will be called SpaceHab. The larger pressurized vehicle with additional two pressurized lower decks will be called Evolved-SpaceHab. Due to the fact, that a smaller pressurized volume is more challenging from an ECLSS development standpoint relative to system packaging and dynamic response times [17, p. 4], the SpaceHab design will be used for crews up to 40 passengers and the Evolved-SpaceHab design for more than 40 passengers. For a detailed analysis of this separation, see 3.2.2 Habitat.

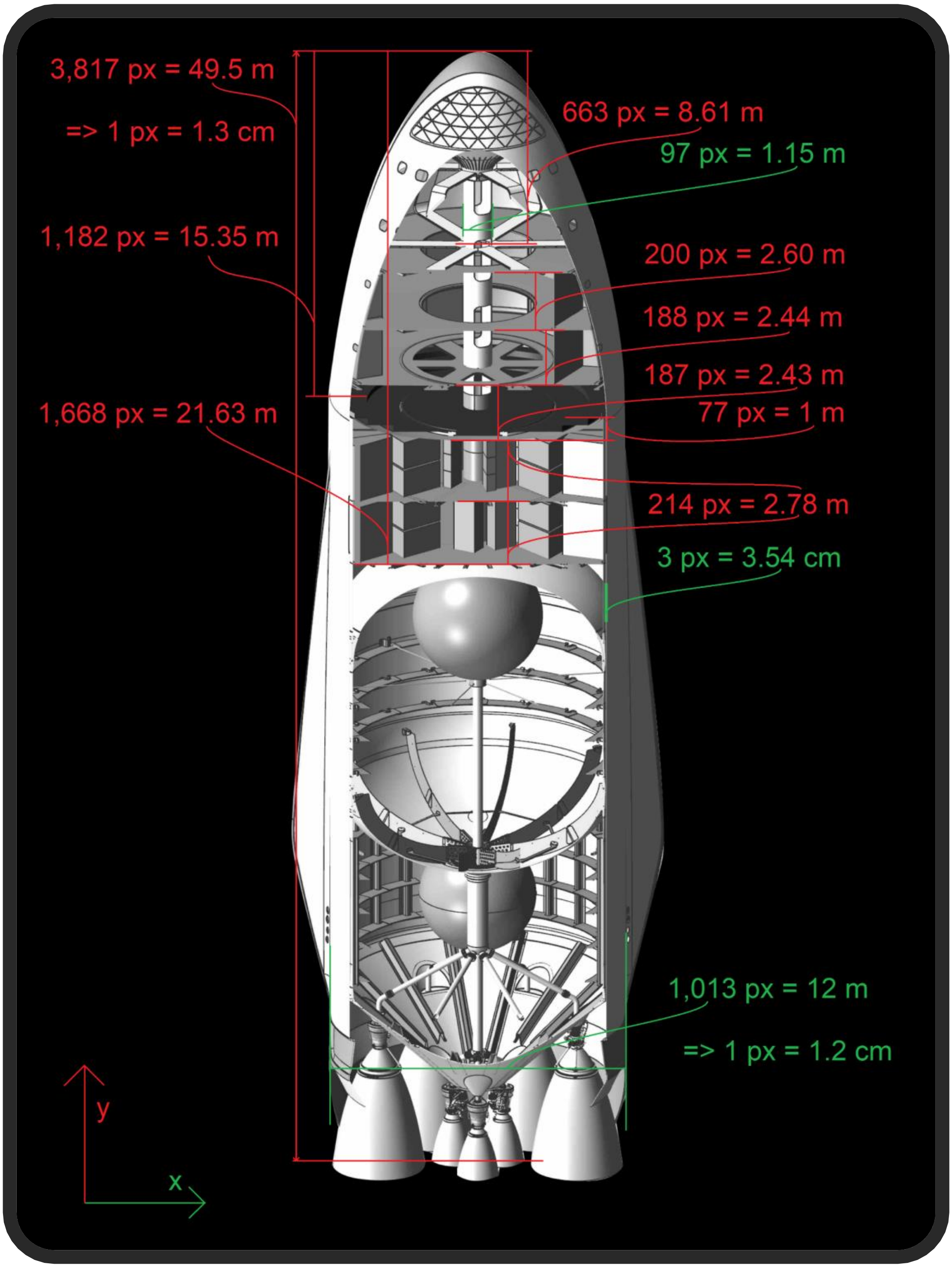

Figure 2-2: Spaceship dimensions [SpaceHab picture from [1]]

The shape of the upper part of the SpaceHab is currently not further specified by SpaceX. The types of geometry that are analyzed in the following are based on the pictures and videos from the presentation at IAC [16]. First an axis-symmetrical ellipsoid profile is considered because this shape is often used for analysis of large mars-entry vehicles, like the TransHab design from NASA [13, pp. 284-285] which is also an acceptable shape for the launch. As a second possibility, a paraboloid is considered, which has slightly lower drag than the elliptical shape. This vehicle can be seen as a high lift-to-drag shape, and therefore lower drag is preferable. Given the diameter and the length of the upper part of the SpaceHab, which both are measurable in Figure 2-2, an elliptical function (Eq. (2-1)) and a parabolic function (Eq. (2-2)) are defined and are representative of a side-on view of the upper portion of the SpaceHab (Figure 2-3). In these formulas, r stands for the radius (6 m) and h for the height (15,08 m) of the curved upper part of the SpaceHab and the variable x_{radius} goes between -6 and 6. All parameters are in meter.

$$h_{radius} = -\sqrt{1 - \frac{\mathrm{x}_{radius}^2}{\mathrm{r}^2}}\, h + h \qquad \textbf{Eq. (2-1)}$$

$$h_{radius} = h\frac{x_{radius}^2}{r^2} \qquad \textbf{Eq. (2-2)}$$

This analysis showed, that the elliptical form, depicted in yellow, is too wide, whereas the parabolic silhouette in red is a little too thin. The right shape of the SpaceHab is picture-perfect in the arimetric middle of the two and can be described by Eq. (2-3) (parameters are the same as for Eq. (2-1) and Eq. (2-2)), which is used for the remaining analysis.

$$h_{radius} = \frac{h}{2}\,(\frac{x_{radius}^2}{r^2} - \sqrt{1 - \frac{x_{radius}^2}{r^2}} + 1) \qquad \textbf{Eq. (2-3)}$$

For internal volume calculations, the thickness of the wall must be known. SpaceX does not provide any information about this, but as can be measured in Figure 2-2, the wall thickness is around 3.53 cm thick. For simpler calculations and because this measured value is only derived from 3 pixels, this is rounded to 4 cm. An additional analysis of the wall thickness can be found in chapter 9.1 Structural Analysis.

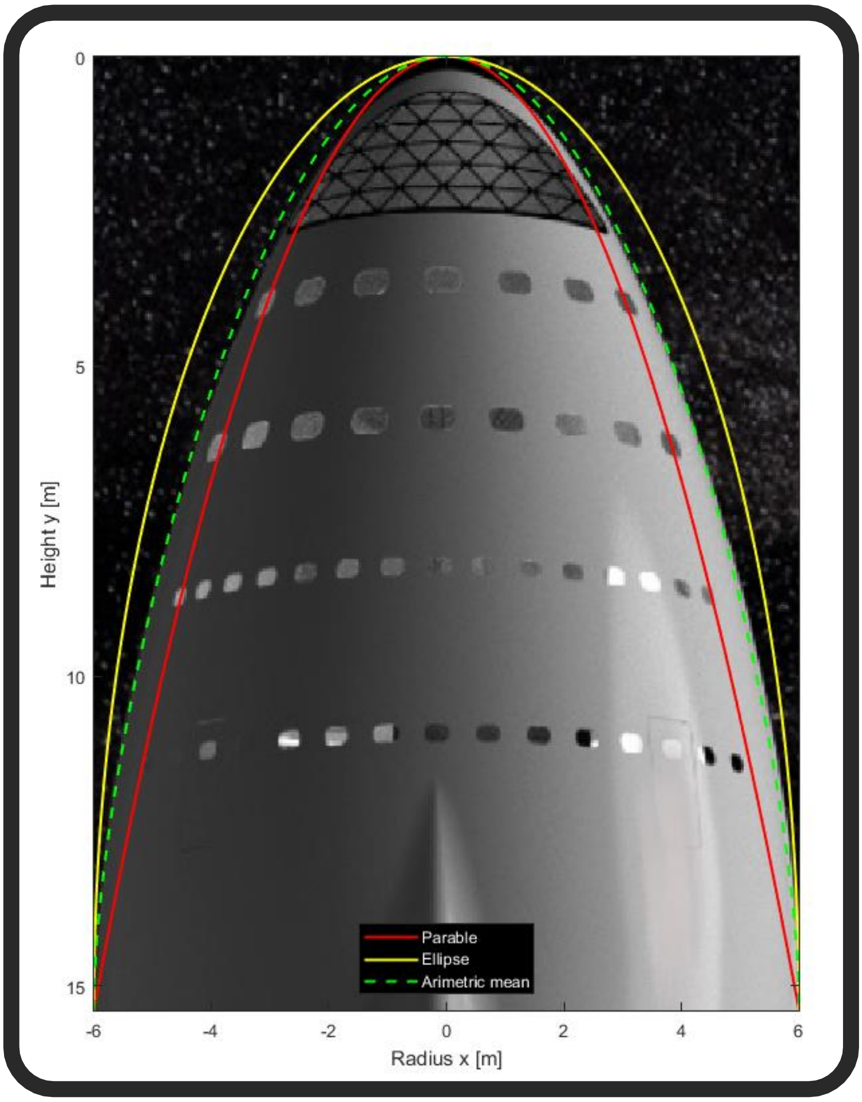

Figure 2-3: SpaceHab shape [SpaceHab picture from [1]]

To calculate the volume of the unpressurized cargo, it is assumed, based on available portrayals of the SpaceHab, that the inner diameter of this area is constant 11.92 meters. This is calculated by subtracting the wall thickness of 2 time 0.04 m from the diameter of 12 m. A simple cylindrical volume calculation (Eq. (2-4)), with r_{low} as the radius and h the high (5,56 m), both measured in meter, gives a volume of **620.47 m³** for the lower decks.

$$V_{LowerDecks} = \pi \, r_{low}{}^2 \, h \qquad \textbf{Eq. (2-4)}$$

To find the correct internal volume of the SpaceHab, the arimetric middle of the ellipsoid and paraboloid volumes given by Eq. (2-5) and Eq. (2-6) respectively, can be calculated to get Eq. (2-7). For all equations, r_{low} stands for the lower inner radius of 5.96 m (6 m – 0.04 m) and h for the inner height of 15.04 m (15.08 m – 0.04 m).

$$V_{ellipsoid} = \frac{2}{3} \pi \, \mathrm{r}_{low}{}^2 \, h \qquad \textbf{Eq. (2-5)}$$

$$V_{paraboloid} = \frac{1}{2} \pi \, \mathrm{r}_{low}{}^2 \, h \qquad \textbf{Eq. (2-6)}$$

$$V_{UpperDecks} = \frac{7}{12} \pi \, \mathrm{r}_{low}{}^2 \, h \qquad \textbf{Eq. (2-7)}$$

The Volume of the conical upper part of the SpaceHab would therefore be 979.06 m³.

Adding to this the volume of 111.23 m³ for the cylindrical section of Deck 3 with a height of just under 1 meter, as can be seen in the Figure 2-2, the total volume of the pressurized section would be **1090.29 m³**. If this cylindrical section is not accounted for, and the shape is assumed to be still curved to the bottom of the pressurized section, the volume would be 46.79 m³ less. Adding the volume of the lower 2 decks of 620.47 m³, the total pressurized volume of the Evolved-SpaceHab is **1710.76 m³**. For comparison, and to show how much the difference of the other shapes is, it can be shown that the volume of an ellipsoid form, given in Eq. (2-5), where h is the height in 14.89 meter and r the radius of 5.96 meter would be 1118.92 m³ total volume or 139.86 m³ too much. The volume of a paraboloid shape given in Eq. (2-6), where r is the radius in 5.96 meter and h is the height of 15.04 meter, would be 839.19 m³ total volume, or 139.87 m³ too less.

Table 2-2 is a summary of the assumed heights and volumes of all decks. The decks 6 to 8 are combined because the heights of these separate decks are not clear. In the first column are the numbers of the measured decks. This numbering will be used for the remainder of the thesis. The general shape of the deck is described in the second column. This is especially important for the volume calculation of the specific deck. The third to fifth columns shows the inner values of height, radius at the bottom and the volume of the decks in meters and cubic meters respectively. The radius (in meter) of the decks are determined by Eq. (2-8), where $h_{deck-buttom}$ is the height of the bottom of the deck measured from the top in meter, h an r_{low} are the height (15.04 m) and radius (5.96 m) of the curve respectively. This equation can be found by transforming Eq. (2-3) to x_{radius}, which is r_{deck} here.

$$r_{deck} = \mathrm{r}_{low}\sqrt{1-(1-\frac{h_{deck-buttom}}{h})^2} \qquad \textbf{Eq. (2-8)}$$

Table 2-2: SpaceHab volume summary

Deck	Shape	Height [m]	Lower radius [m]	Volume [m³]
1	parabolic	8.57	5.38	454.58
2	parabolic			
3	parabolic			
4	parabolic	2.60	5.76	224.57
5	parabolic	2.44	5.93	197.92
6	parabolic + cylindrical	2.43	5.96	213.22
7	cylindrical	2.78	5.96	310.24
8	cylindrical	2.78	5.96	310.24
Total		**21.6**		**1,710.76**

A further discussion of the volume is given in chapters 3.2.2 Habitat Arrangement and 9.1 Structural Analysis.

2.4 Payload Capacity and Mission Duration

A decent estimation of the payload capacity and trip time is necessary to verify the feasibility of the ECLSS and to get to a first estimation of the costs for the system. In this chapter, just the payload and duration is verified.

The payload of a rocket depends on the available impulse, which is measured as the achievable change of velocity also called Δv. It can be calculated by the Tsiolkovsky rocket equation, given in Eq. (2-9), where I_{sp} is the specific impulse in seconds, g_0 is the standard gravity of around 9.81 m s^{-2}, m_{dry} is the structural mass of SpaceHab in kg (150 t), m_{PL} is the payload mass in kg, and m_{fuel} is the mass of the fuel in kg.

$$\Delta v = I_{sp} \, g_0 \, ln \left(\frac{m_{dry} + m_{PL} + m_{fuel}}{m_{dry} + m_{PL}}\right) \qquad \textbf{Eq. (2-9)}$$

The specific impulse is a measurement of the efficiency of the rocket engines, therefore the higher the specific impulse the better. The raptor engines used for the SpaceHab have a specific impulse of 382 s for the vacuum nozzle. Also given is the total propellant mass of 1,950 t. [1] Using these numbers, it can be calculated that for a payload mass of 200 t the total available Δv would be 7.055 km s^{-1} and for 450 t it would be 5.422 km s^{-1}. Therefore, the required Δv for the final landing burn would be 1.055 or 1.422 km s^{-1}. These calculations can also be seen in Figure 2-4.

The higher the available Δv for a transfer, the shorter is the travel time. But this is limited by the acceleration forces during the burn and the entry velocity at the destination. While the first one is nearly negligible, the entry velocity is more limited. The maximum acceptable entry velocity for Mars depends on the shape of the spacecraft, the entry angle, and the thermal protection system. To reduce the entry velocity, an additional burn before mars entry would be possible to slow down the vehicle. But such a maneuver would require fuel and reduce the possible payload. The proposed maximum entry velocity is 8.5 km s^{-1} [1]. The Δv for final landing burn can be measured in Figure 2-4, which gives a maximum for the used Δv. The lower limit is the minimum necessary energy to reach Mars. This highly depends on the orbit around Earth, the payload mass and the year of the flight.

As can be seen in Figure 2-4, the Δv capability of the SpaceHab is between 6 and 4 km s^{-1} for payload masses of 200 to 450 t, respectively. It can also be seen, that even more Δv, and therefore shorter travel duration, is obtainable when fewer payload is transported. But it is not clear if the entry velocity at mars would become too high. This is similar with the possible higher payload capacity. The required energy to reach Mars is very variable and depends highly on the considered mission start time. Because of these limitations and uncertainties, only the two extremes of 200 t and 450 t are further considered in this thesis.

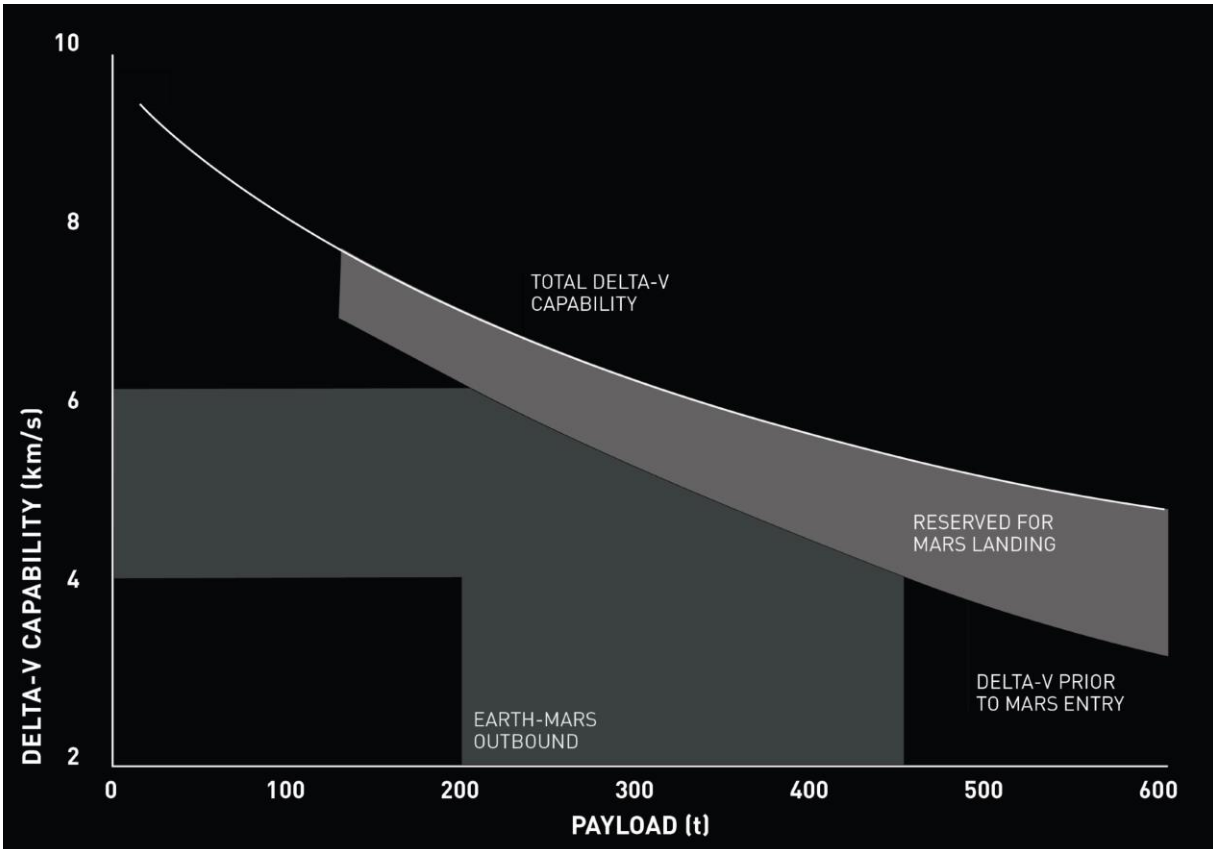

Figure 2-4: SpaceHab Δv and Payload capacity [1]

Besides the payload mass, the trip duration is one of the key elements when designing an ECLSS. The trip duration is a direct function of the available Δv. The projected travel times for a payload of 200 t and calculated travel times for 450 t are presented in Table 2-3. It can be shown, that the best-case is **80 days** for a payload of 200 t [1] and **112 days** for 450 t [18]. The worst-case is **150** and **192 days** for 200 t [1] and 450 t [18] of payload, respectively. The lowest and highest of these figures are used as the lower and upper payload and mission duration boundaries in the further analysis for this work. The mean trip duration is 132 days. Note that a contingency margin of 10 % (as specified in constraint 4.1.w) is added to these durations in the further analysis.

Table 2-3: Trip times dependent on departure and payload

Year of Departure	Trip time in days for 200 t payload [1]	Trip time in days for 450 t payload [18]
2027	**150**	**192**
2029	140	160
2031	110	144
2033	90	**112**
2035	**80**	128
2037	100	176

3 Concept of Operations

As defined in NASA´s Systems Engineering Handbook, the concept of operations, or short ConOps, is the description of operational characteristics of the system to understand the goals and limitations. [19, p. 35]

"[A complete] ConOps should consider all aspects of operations including integration, test, and launch through disposal." [19, p. 35] For the purpose of this work, the focus for the ConOps will be the transfer from earth to mars. This includes a description of the mission phases and operational scenarios including the operation timeline, habitat layout and crew schedule.

Most preliminary studies are using average values for the volume of the habitat and the metabolism of the crew is only considered on a per daily basis. At a NASA workshop [20] it was shown that it is necessary for long-duration space missions to define crew schedules and required functions early in the design cycle. Layout concepts should be created too. Additionally, for a well-designed ECLSS and for required inputs used in the Life Support Trade Off Tool (see 14A) thorough data of the habitat and the crew is necessary.

3.1 Mission Phases

SpaceX proposes a system architecture, which is built around full reusability. All system elements are vertical take-off and vertical landing (VTVL) vehicles. As can be seen in Figure 3-1, the SpaceHab is launched into LEO on top of the booster. The booster takes the SpaceHab to a velocity of 2,402.8 m s^{-1} before separation and uses the leftover propellant to land back at the launch pad. The SpaceHab uses its own propellant to increase the required speed to around 7,800 m s^{-1} for a 200-km orbit. For a Trans-Mars Injection (TMI) refueling in orbit is necessary. This will be done with tankers, which are also launched by the booster. Depending on the time of departure, payload-mass, and travel-time to Mars, up to 5 tankers are required to fully refuel a SpaceHab. After refueling, the tanker returns to the launch pad and can be used again. If anything goes wrong, the SpaceHab can immediately return to earth. It is not clear currently if the passengers are in the SpaceHab during launch or if they launch separately. Similarly, it is not known how long the refueling will take. 6 vacuum optimized engines will be used for the TMI maneuver, which will set the SpaceHab on a trajectory to Mars. After TMI, it is impossible to return to Earth in the event of a system failure. After a travel time of 88 to 211 days (including a 10 % margin on the original duration), depending on payload mass and time of departure, the SpaceHab will be aerobraking and aerocapture, or will directly enter the Mars atmosphere. The aerodynamic lift capability and the heat shield are used to decelerate the SpaceHab during atmosphere entry. Finally, 3 engines are used for a vertical landing. The SpaceHab can be refueled at Mars and after one synodic cycle it can be launched and travel back to earth where it uses the same arrival schematic as on Mars arrival. [1]

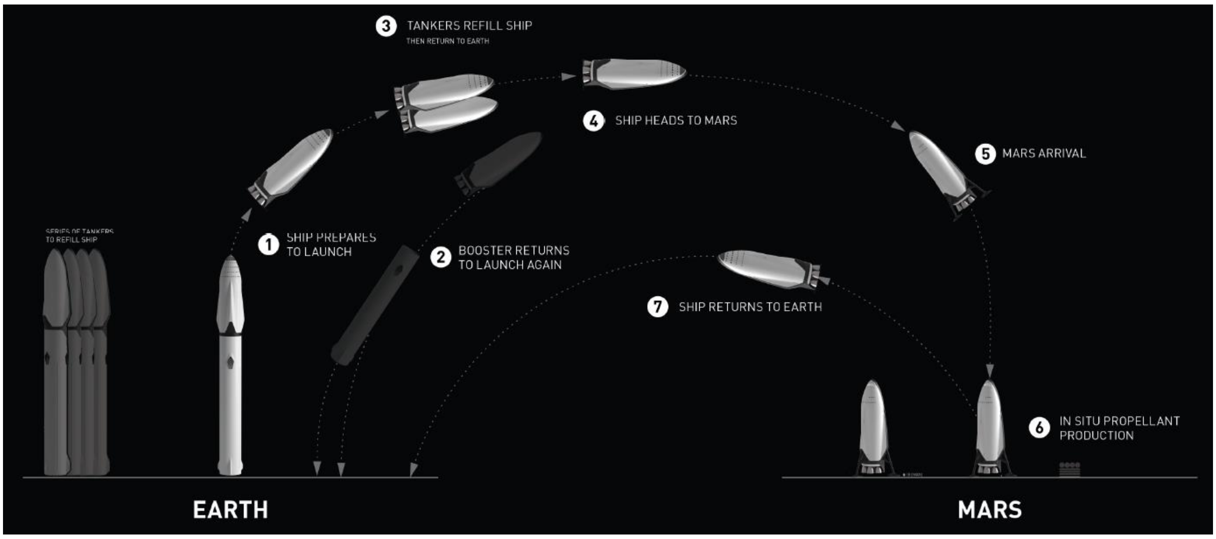

Figure 3-1: Proposed high-level operations profile by SpaceX [1]

The projected number of reuses per system element can be found in Table 3-1.

Table 3-1: Projected ITS Reuses [1]

System Element	Lifetime Launches
Booster	1,000
Tanker	100
SpaceHab	12

For this work, only the time after TMI and before arrival at Mars is analyzed, since there are too much uncertainties on the other phases. Designed for this period, the following design reference mission (DRM) is specified.

3.1.1 Design Reference Mission

The SpaceHab consist of a habitat with integrated propulsion stage. This habitat has a pressurized volume of 1,090.28 m^3 or 1,710.76 m^3, depending on the used design and divided into up to 8 floors. The dedicated floors from top to bottom are as follows: A galley, an education and training area, hygiene facilities, a gym, a lounge, and crew quarters. There is also a workshop and a medical bay. Additional space for storage and facilities for equipment is included. An overview of the complete system is given under 3.2.2 Habitat Arrangement. The main propulsion and RCS system uses methane as fuel and oxygen as oxidizer. For power generation, a photovoltaic array with a power capability of 200 kW in the vicinity of Earth and 86.6 kW in Mars orbit are used. The thermal control system has the ability to reject a heatflow of 100 kW to space.

The main mission is a transfer from Earth to Mars with a duration between 80 and 192 days, depending on the mass of the payload and the time of departure. Since a contingency margin of 10 % is assumed, these trip times are assumed to be 88 and 211 days respectively. During this trip, up to 100 people live and work in the habitat.

An estimated service Crew of 5 is assumed in this scenario (see also 3.2.3.1 Crew and Passengers). This crew consists of one captain, two engineers, one assistant and one doctor. The captain of the ship is in command and pilots the ship, while engineers have the duty to maintain all subsystems and give technical training for the rest of the crew. The doctor serves for medical events and also supports as a psychologist while supported by an assistant. The typical day of the crew is described in 3.2.3.

3.2 Operational Scenarios

A crew schedule is required to design the ECLSS and make decent tradeoffs. To develop accurate schedules, the general layout of the habitat is first necessary.

The assumed passenger size is derived by assuming a minimum crew of 12 people, analyzing the total pressurized volume (see 2.3) and then applying NASA requirements (3.2.2.1). This leads to the following options shown in Table 3-2 below based on the crew size and the chosen SpaceHab design. 40 crew members (CM) for the Evolved-SpaceHab design would meet the NASA requirement of 25 m^3 CM^{-1}. For the SpaceHab design this would be too small but it is included for comparison reasons. Also, the mentioned 100 passengers for the Evolved-SpaceHab design are analyzed.

Table 3-2: Trades for crew size, design, and duration

	Crew size	Design	Duration
Case1	12	SpaceHab	88
Case2	40	SpaceHab	88
Case3	40	Evolved-SpaceHab	211
Case4	100	Evolved-SpaceHab	211

3.2.1 Operations Timeline

The timeline of operations presented here and in Figure 3-2 is in time-sequenced order of the major events that span the full loop life-cycle of the SpaceHab, from launch on earth to maintenance and refueling after a successful mission. Operation phases like development, test and decommission are consciously excluded from this, because they play no role for the further study. Only the operation of the SpaceHab is considered, where the timelines for the booster, the tanker and maybe other system elements are excluded from a further analysis. In the following, a short overview of the different phases is provided to show the whole picture.

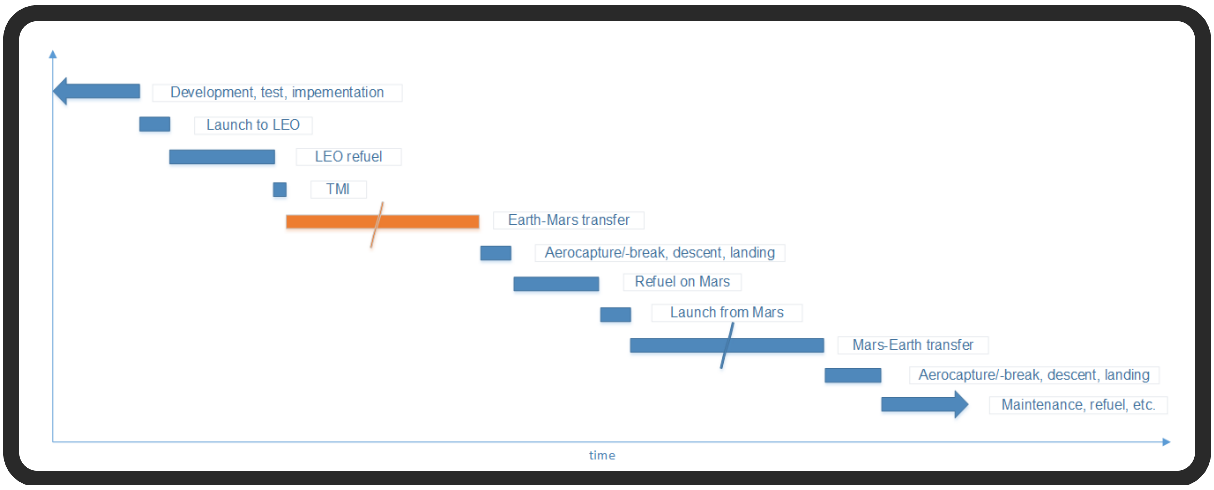

Figure 3-2: Operations Timeline

Beginning with the launch, the SpaceHab is brought into LEO with the help of the booster. This will be done in a relatively short amount of time. Normally this takes around 8 and a half minutes. The booster flies back to the landing pad within around 20 minutes. Then the refueling phase of the SpaceHab begins which is the most unknown variable. It is considered as the time between launch and TMI and can be between several hours to weeks. In this segment, the tankers carry the required propellant for the trip to Mars to the SpaceHab. Perhaps the passengers will also enter the SpaceHab during this phase when they were not in the ship in the first place. It is mentioned in [1] that additional 150 tons of payload can be added in LEO, because the ITS is not capable to lift over 300 tons into LEO. The refueling is followed by the TMI which will last only a few minutes and marks the point of no return. The most important phase afterwards is the Earth-Mars flight itself. Depending on the mass of the payload, the time of travel and the amount of used propellant this will be between 80 and 192 days plus a margin of 10 %. For an analysis of the payload capabilities of the SpaceHab see chapter 2.4. On arrival at Mars, the SpaceHab is performing an aerocapture followed by an aerobrake or a direct entry maneuver with subsequent descent and landing. An aerocapture operation followed by an aerobrake would take several days to weeks. It is not yet decided which maneuvers will be used therefore this phase is a significant uncertainty. On Mars, the SpaceHab is unloaded, refueled and some minor maintenance can be done. For the first missions, the SpaceHab will serve as the ground base habitat too, but it is not assumed that this will be the case in the long term with lots of passengers on board. Depending on the synodic cycle, this phase could last for hundreds of days. The return phases are similar to the previous ones except the spaceship lifts off on its own into a trans-Earth injection without a booster and no refueling in low mars orbit. The Mars-Earth flight would take a similar time compared to the earth-mars trip and the earth arrival would be similar to the mars entrance, but with higher entry velocities. On Earth, major maintenance on the SpaceHab would be necessary. With the refueling of the Ship, the loop is closed and the operation can restart with the first phase of the timeline, the launch from Earth. This loop is repeated 12 times before the SpaceHab is retired as planned by SpaceX.

The main objective of this work lies on the Earth-Mars flight, since the other phases have too much uncertainties and this phase will be by far the longest phase.

3.2.2 Habitat Arrangement

Several past studies (e.g. [20]) suggest, that the habitat arrangement should be analyzed early in the design process, since it can have a huge impact on the remaining system. The ECLSS especially depends on parameters like volume, but also on the size and location of demand and production of resources like metabolic CO_2 generation in the exercise area. Therefore, it is important to first conceptualize a general layout of the habitat and define when and how much crew members are in an area with a predefined schedule (see 3.2.3).

First it has to be analyzed if the total pressurized volume of the SpaceHab is acceptable (3.2.2.1). This is also necessary for a decision on passenger size boundaries for the different SpaceHab concepts. After that, the performed tasks are investigated (3.2.2.2) to determine the required functional areas. All required areas are then examined in detail in the following subchapters with emphasis on the necessary volume. The last subchapter of this section (3.2.2.9) is describing the locations of the functional areas which is also the basis for the crew schedules in the next chapter.

It should be noted that the passageway in the middle of the SpaceHab is measured to have a diameter of around 1.15 m. This would lead to a passage area of under 1.04 m² for the passengers. Because it must be used two-way, this violates NASA´s Human Integration Design Handbook requirement for a pass-through of 0.86 m² for a crewmember in one way [9, p. 566]. For the following analysis, this is neglected and it is assumed that two crewmembers can pass though this tunnel without any difficulty.

3.2.2.1 Minimum Required Pressurized Volume

As can be seen in the concept Figure 2-2, the SpaceHab overall consists of 8 decks. SpaceX states, the decks 1 to 6 are pressurized whereas the lower decks 7 and 8 are initially unpressurized cargo space. Detailed analyses of the internal volume of the different decks in chapter 2.3 shows, that the pressurized volume of the upper 6 decks is 1.090,28 m³ in total. It must be analyzed if this volume is enough to support the expected number of people on board the SpaceHab. As data from past space missions clearly reveals, crowding or deficiency of free volume is considered as a substantial influence for crew mistakes and problems in accomplishing mission objectives. In several occurrences, the mission had to be terminated prematurely due to interpersonal issues among the crew members. It is obvious that the timeline and the environment influence attitudes, behavior, performance, and the health of the crew [13, pp. 155-156, 13, pp. 149-150].

Per NASA definition [21], the minimum acceptable net habitable volume for exploration-type space mission can be calculated. This definition includes considerations for human factors and behavioral health perspectives to prevent negative consequences for psychosocial well-being and performance of the crew. The main parameters that determines the volume are crew size, mission duration, and functional task requirements. As a general rule, more free volume per crewmember is required as the mission gets longer [13, p. 149]. As stated in [21, 22, p. 5], at least 25 m³ of habitable volume per crewmember should be provided. Under the assumption that the average percentage of habitable volume in relation to pressurized volume is the same as for the Apollo crew module spacecraft of around 59.33 % [9, p. 568], the pressurized volume of the SpaceHab would be only 6.41 m³ CM^{-1} for 100 passengers.

To match the NASA advised volume only 26 passengers could be transported. For the Evolved-SpaceHab the habitable volume per crewmember would be 10.15 m^3 for 100 passengers, which is still far below the NASA requirement too. To match the 25 m^3 CM^{-1} the total number of passengers could be 40. Since NASA is assuming lots of science work to be done on a trip to mars, the crew size is 6 people at most, and the total mission time includes mars stay and earth return, the specified number of 25 m^3 seems too high for the analyzed design, because the focus is on transporting lots of people and payload rather than doing science.

For the further analysis, it must be differentiated between pressurized volume and habitable volume. Habitable volume is understood as the free volume, excluding volume occupied by equipment or stowage [23, p. 269, 24, p. 21], whereas the pressurized volume characterizes the total inner volume of the vehicle. For the feasibility of the pressurized volume it must be considered that the historical data for pressurized volume can only be a first estimate, because the missions are very different. Historical short duration missions are only for crew transport where the crew is constrained to a seat. Longer missions are science missions with lots of space for scientific equipment, like on ISS. Also, psychological or physical stresses are often not considered on trend lines, like the frequently-used Celentano curves which are also used in the well-established but no longer maintained Man-System Integration Standards from NASA (NASA-STD-3000). The original source for the Celanto curves [25] are not public available, therefore all description below are based on third party information. The Celanto plot has 3 curves which forecast the amount of pressurized volume required per crewmember to conduct a mission at “tolerable, performance, or optimal” levels. Figure 3-3 shows the slightly modified Celentano plot from NASA-STD-3000 that features the volume prediction growing steeply over the shorter missions, but leveling out after six months at about 19 to 20 m^3. It should be noted, that even though the label states ‘total habitable module volume’, the total pressurized volume is meant as stated in [26, p. 6]: “This graph follows a discussion of breathable atmospheres, so it is clear that they mean total volume.”

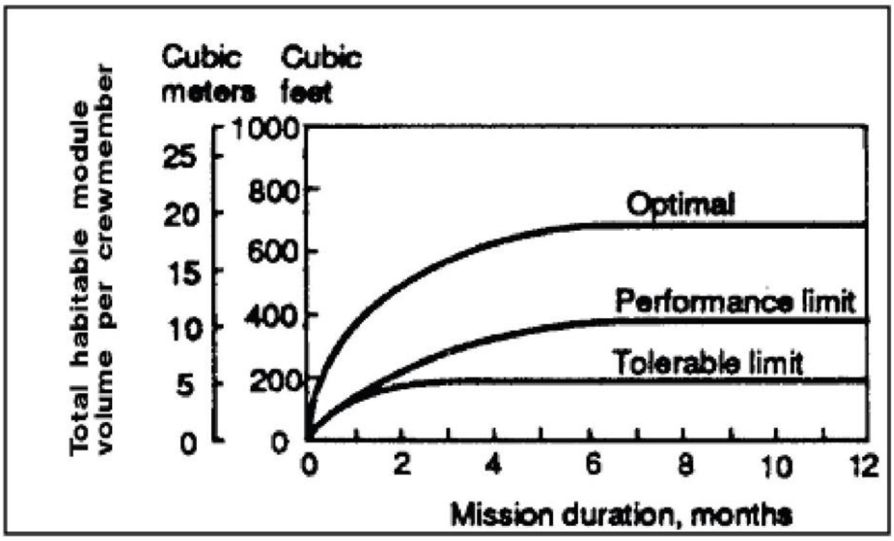

Figure 3-3: NASA-STD-3000 volume curves [26, p. 10]

Cohen [26] analyzed several metrics to calculate the necessary volume of a crewed spacecraft because he claims that more and more researchers are calling the Celentano habitability index into question. He concludes that the design of human space habitats should not only be based on curve fitting as it has a restricted validity and usefulness. Even though, the data of past spaceflights offers a margin for orientation. Another finding was that the total pressurized volume per crewmember increases as a direct function of mission duration and that unlike Celentano et. al., the pressurized volume does not level off. For the analysis in this thesis, the critical point is that the crew size does not affect the volume per crewmember. Several of the analyzed studies by Cohen divided the spacecraft data into transport and station like vehicles. Transport vehicles are primarily used to ferry crews while the stations are used for long-duration operations. Cohen concludes that his results support such an approach since the strict aerothermal shape of small capsules differs essentially from larger space habitats or vehicles and belong in separate data sets.

For the analysis of the pressurized volume per crewmember of the SpaceHab, data from historical transportation spacecraft's, given in Table 3-3, is used. For the further investigation, only the maximum mission duration and minimum volume per crewmember of every vehicle are considered to apply a conservative approach. It is noticeable, that all investigated vehicles have mission durations much less than the proposed SpaceHab. This is due the case that these vehicles are only operating in cislunar space. The method of linear least squares is used to approximate a correlation between the maximum mission duration and the minimum specific volume of the data given in Table 3-3. The applied linear extrapolation, as shown in Figure 3-4, is a conservative approach since it is not asymptotic like the Celanto curves shown in Figure 3-3. The pressurized volume required per crew member can therefore be calculated to around 16.27 $m^3\ CM^{-1}$ for the Evolved-SpaceHab with 100 passengers and a mission duration of 211 days. This is very close to the measured pressurized volume of 17.04 $m^3\ CM^{-1}$ from chapter 2.3 for the same passenger size and mission duration and lies above the minimum mark for shorter mission times. For instance, the best-case mission duration is 88 days and therefore the required volume per crewmember is 8.73 m^3 which is way below the given 17.04 $m^3\ CM^{-1}$. For smaller passenger sizes, the difference is even greater. Only in the case that the lower two decks are not habitable, the volume per passenger is 10.90 m^3 for 100 passengers as marked by the orange line in Figure 3-4. It can be calculated, that the break-even points in this case are 124 days for 100 passengers or 67 passengers for a 211-day mission.

Large groups and longer mission times have the effect to decline in deviance and conflict [27, p. 4]. Therefore, the analyzed worst-case scenario with 211 days and 100 passengers are supportive from a psychological viewpoint.

This draws to the conclusion, that the total pressurized volume of the SpaceHab is feasible for up to 100 passengers when comparing with historic human-transport spacecraft's.

Table 3-3: Data from historic transportation spacecraft's [26, p. 5]

Spacecraft	Maximum mission duration in days	Minimum Volume [m³ CM⁻¹]
Voskhod	1.08	1.91
Mercury	1.43	1.70
Vostok	5.00	5.73
Shenzhou	5.00	8.50
Apollo-Soyuz	9.04	3.33
Apollo CM	12.75	2.22
Gemini	14.00	1.28
Soyuz	14.00	1.28
STS	17.67	8.94

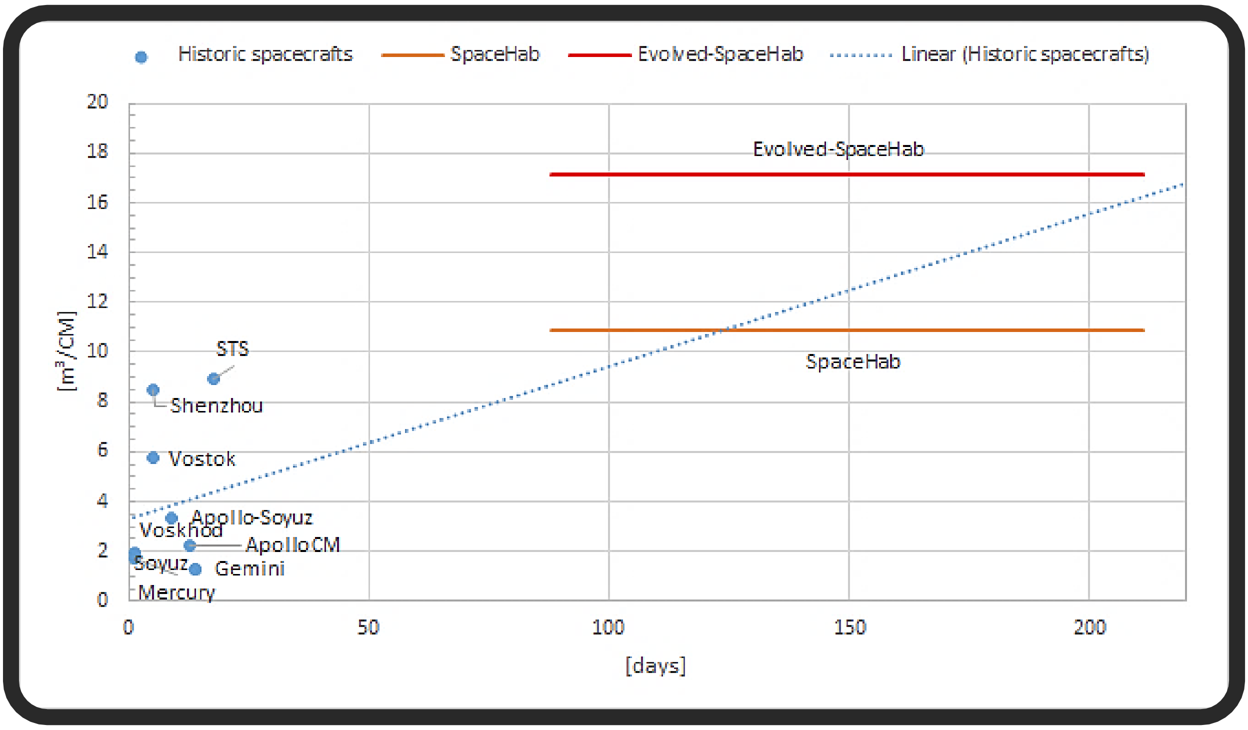

Figure 3-4: Plot of pressurized volume per CM for historic spacecraft's and the considered SpaceHab designs with 100 CM

3.2.2.2 Task Analysis

Volume should not be the only consideration to mitigate health risk like psychological-behavioral stressors. Crowding can be reduced by employing a shift schedule or enabling private spaces. Consequently layout considerations play an important role. [20]

The considered schedules are described in chapter 3.2.3. But before the schedules can be defined, the general layout of the SpaceHab must also be considered, because the different decks can only accommodate a limited number of people. The task to be performed in every deck drives the layout and necessary volume. For instance, sleeping persons need much less volume as persons who work out at a gym. Consequently, the tasks that drive the volume must first be determined and assigned to specific areas.

Unsurprisingly, sleep is a necessary task for every person. Restful sleep benefits the crews comfort, responsiveness, and well-being during waking hours. It eases a person's adjustment to the spaceflight environment and encourages group harmony and productivity. [13, pp. 578-588] Another essential task is eating. This can be separated into food preparation, group meet and eat, and meal cleanup. For group harmony, it is favorable that the group is eating together. Personal hygiene is important to a crew's health and well-being. Besides adding to the crew's comfort and psychological well-being, good personal hygiene helps prevent the spread of disease and improves the habitats internal environment. Whole body cleansing is a must for long flights. [13, pp. 578-588] Corresponding are urination and defecation. Recreation is needed on every spacecraft [9, p. 550]. The longer and more distant the mission, the more important recreation becomes. [13, pp. 579-592] This includes personal recreation as well as group leisure activities. To counter muscle and bone loss due to microgravity, exercise is mandatory during the trip. Other tasks to consider are waste collection and management, medical care, dressing and undressing, and clothing maintenance. [24, pp. 3-4, 28, p. 5]

To reduce the required total volume, some functions should share the same space. Obviously, food preparation, eating and meal cleanup shares the same place. Group meetings can also take in the same place along with group recreation activities. Another aggregation can be full body cleansing, personal hygiene, and urination/defecation. If cloth washing is considered, it could be added. Waste collection and management can share space with stowage [28, p. 10]. Most of the time, dressing or undressing will be done in the personal space where the crew sleeps. Here it is assumed that most of the personal activities, like chatting with friends and family on earth or reading a book, will be done there.

Besides of volume sharing, the required time for every task and the number of crew members is vital to decide how many different areas are needed. For this purpose, the crew has a predefined schedule. Several different possible schedules are considered. For clearness, the reader is referred to 3.2.3 Crew Schedules. Table 3-4 displays the different tasks mapped to functional areas. As can be seen, the task recreation is considered in multiple functional areas, because it is one of the most dynamic task which vastly depends on individual preferences of the crew member.

Table 3-4: Assignment of the tasks to functional areas

Crew Quarters	Galley	Gym	Hygiene Facilities	Medical Station	Lecture Hall
Sleep	Food Preparation	Exercise	Full Body Cleansing	Health Care	Training
Dressing/ Undressing	Group Meet and Eat	Recreation	Personal Hygiene		Recreation
Recreation	Meal Cleanup		Urination/ Defecation		
	Recreation		Clothing Maintenance		

The following subchapters describe the required functional areas and their volume requirements. This is necessary for a decision on the location of each in 3.2.2.9.

3.2.2.3 Crew Quarters

Private, dedicated crew quarters (CQ) for every person are essential, especially for the considered trip times, for two reasons. First, they are psychologically important to avoid group tensions, increase crew morale, and decrease stress by withdrawal from interaction and to relax. Second, only private quarters can be personalized with things like pictures and belongings, and by controls for light, airflow, and sound to give a feeling of security, privacy and replacement for “home”. Therefore, they should be closed off from others and should not be shared (“Hot-Bunking”). In addition, they should have no windows to reduce the exposure to radiation. Actually, as much as possible mass between the crew quarters and the outer walls should be provided to minimize the radiation exposure. Because most time is spent in the crew quarters, the radiation exposure there is the highest. [9, p. 538, 20, 22, 29]

The volume for each individual crew quarter is between a minimal 2.1 m^3 on the ISS, up to 5.4 m^3 which includes space for hygiene and temporary isolation of sick crewmembers [21, 24, p. 18]. NASA´s Human Integration Design Handbook (HIDH) has a comprehensive list of functions that must be done in the crew quarters. This includes for example space for donning and doffing of clothing and storage for personal stuff. [9, p. 539] Another consideration that influences the required volume are the expected gravity levels. Besides the volume of the person in the CQ, several equipment is inside the CQ, like a sleeping bag, pillow, personal laptop, and space for personal belongings. For partial gravity, the sleeping surface area must be horizontal and the general required volume is much higher. For this thesis, it is assumed that the SpaceHab is only inhabited during the transfer and thus in 0g. The assumed required volume per crew quarter is at least 3 m^3, including minimal personal space. Therefore, the total required net habitable volume is 36 m^3, 120 m^3, or 300 m^3 for the different trades of 12, 40, or 100 persons, respectively.

3.2.2.4 Galley

The galley is the area where the crew eats and meets. It is called a restaurant in [11]. Included are the utensils and equipment required to prepare and consume food, and to clean up afterwards. It is desirable to also store the food supplies in this area. For psychological reasons and to reduce traffic in the pass-through, a so-called lounge is assumed in addition to the galley. This area is only necessary for a large crew to avoid interpersonal tensions and give the passengers a better choice where they want to eat and spend their leisure time. The services in the lounge should be reduced to a minimum and the available meals are more limited than on the galley to reduce the needed space for this contingency area.

The required food preparation volume, excluding equipment, is around 4.35 m³ [24, p. 19]. It must be guaranteed that enough people can prepare their food simultaneously to avoid long waiting times. Therefore, it is assumed, that one food preparation area for every 5 people is available. Food preparation equipment includes a rehydration apparatus and a conduction oven. Additional, some space for a refrigerator should be considered. Supplementary volume is needed for eating and group meetings. This is assumed to be a minimum of 2.69 m³ per person [9, p. 563]. At least a minimum food stowage should be included in the galley, to avoid that people have to bring the food from another deck. It is assumed that around 5 m³ in the galley are dedicated for food and beverage storage. This would be enough for a crew of 12 and 88 days and nearly 10 days of supply for 100 CM. A summary for the trade-offs for the 12, 40, and 100 person scenarios is provided in Table 3-5. The volumes for the different parameters are calculated by considering the maximum persons in the galley at the same time, based on the schedules described under 3.2.3.

Table 3-5: Minimum required volume for the galley and the different trade cases

Parameter	Case1 [m³]	Case2/3 [m³]	Case4 [m³]
Food preparation	4.54	8.98	17.78
Eating and group meeting	5.38	21.52	53.80
Food storage[1]	7.35	7.35	7.35
Total volume	**17.27**	**37.85**[2]	**78.93**

For a more detailed analysis of needed food systems, especially the contribution to the ECLSS, see 9.4.1 Food.

3.2.2.5 Gym

The human body is not built for 0g. The weightlessness in space leads to bone degeneration and loss of cardiovascular conditioning. To avoid a health risk and to make sure that the crew can work as soon as possible after landing on mars, workout is necessary to counter these effects. Equipment normally used to work the cardiovascular system are treadmills, aerobic ergometers or lower-body negative-pressure enclosures. The incorporation of virtual reality technology would engage crewmembers in a larger repertoire of motor patterns and has many psychological gains. For skeletal and muscle training, gears like bench press are best. Active games

[1] This includes volume for food storage with 5 m³ and a refrigerator with 2.35 m³. For a crew size, larger than 12, additional refrigerator space needed on other decks.

[2] The required volume for trade cases 3 and 4 are assumed to be divided into galley and the lounge, since both cases are considered as Evolved-SpaceHab design.

are good for neuromuscular coordination and have the added benefit of better team spirit. [13, pp. 127-128, 20]

One special type of exercise equipment proposed here are bicycles. Because of the relatively large diameter of the SpaceHab, it is possible to include a racetrack on the outer walls in the gym. The possibilities of this type of equipment is not only the training of the cardiovascular system but also the application of centrifugal forces to simulate a gravitational acceleration. Therefore, muscle atrophy, cardiovascular deconditioning, and bone demineralization can be prohibited [30, p. 355]. To avoid negative effects on the SpaceHab through loads that are induced on the wall, it is necessary to implement counterrotating bicycle tracks and have at least 2 bicycle at both ends so that the loads cancel each other.

The required speed (v_{feet}) to simulate a gravitational equivalent at the feet of 9.81 m s^{-2} can be calculated with Eq. (3-1) [31, p. 212], where a_{feet} stands for the centrifugal force in m s^{-2} and r_{feet} stands for the radius measured from the middle of the SpaceHab in m (It is assumed that the radius to the feet and the cycle path radius are the same of 5.9 m).

$$v_{feet} = \sqrt{a_{feet}\, r_{feet}} \qquad \textbf{Eq. (3-1)}$$

This leads to a velocity of 7.61 m s^{-1} or 27.37 km h^{-1}. For the radius of 5.9 m, the ratio of the acceleration at the feet a_{feet} to that of the heat is around 1.5 and therefore acceptable. It is also important to know what mechanical power ($W_{cyclist}$) the cyclist must apply. This can be calculated by Eq. (3-2) [31, p. 213], where R_r is the rolling resistance in J m^{-1} and k the air pressure constant in N s^2 m^{-2}.

$$W = R_r\, v + k\, v^3 \qquad \textbf{Eq. (3-2)}$$

R_r is 5.8 J m^{-1} for a standard tire on a road and 1.8 J m^{-1} for a tubular tire on a track [30, p. 350]. The air pressure constant (k) is 0.271 N s^2 m^{-2} for a forward leaning recreational cyclist and 0.193 N s^2 m^{-2} for a racing cyclist with dropped posture [30, p. 350]. The two extremes for the mechanical power (W) are therefore 98.76 W or 163.57 W. Both values are within the capability of an average person [32, 9-3]. Also of interest is the blood pressure difference between the head and the feet. For the above system, the mean arterial pressures prevailing at the head is around 82 mmHg at the feet around 180 mmHg [30, p. 357]. This gives a ratio of 0.46, which is only slightly larger than the 0.44 value on earth [31, p. 211].

The required volume consists mainly of the racetrack. A minimal necessary radially height of 2 m is considered. The width ($w_{bicycletrack}$) is assumed to be 1.23 m, which is the same as for a treadmill [24, p. 18]. Therefore, the total volume for one racetrack can be calculated by Eq. (3-3) below to 75.74 m^3. Since two tracks are considered to avoid negative effects on the SpaceHab through loads that are induced on the wall, the volume must be doubled to 151.48 m^3. This volume is only required during exercise time with the bicycles, on other times it can be freely used. But the disadvantage of this concept is that no or at least less other exercise could be done at the same time.

$$V_{bicycletrack} = \frac{\pi\, w_{bicycletrack}}{4}\,(d_{outward}^2 - d_{inward}^2) \qquad \textbf{Eq. (3-3)}$$

with:

- $V_{bicycletrack}$ [m^3] - required volume for bicycle track

- $w_{bicycletrack}$ [m] - width of track
- $d_{outward}$ [m] - outer diameter of track (5.9 m)
- d_{inward} [m] - inner diameter of track or outer diameter minus height (2 m)

Table 3-6 lists various types of exercise equipment and their volume, including the human that workout. The volume for the different cases are based on required units for the maximum number of persons who work out at the same time, based on the schedules described under 3.2.3.

Table 3-6: Minimum required volume for exercise equipment and the different trade cases

Parameter	Unit volume [m³]	Case1 [m³]	Case2/3 [m³]	Case4 [m³]
Treadmill	6.13 [24, p. 18]	24.52	79.69	79.69
Cycle Ergometer	1.71 [24, p. 18]	6.84	22.23	22.23
Bicycle	1.71[3]	6.84	6.84	6.84
Total Volume		**38.20**	**108.76**	**108.76**

3.2.2.6 Hygiene Facilities

The hygiene facilities play a major role in the design of a LSS, because the exchanged mass between a human and the system at this location is by far the greatest. For a good first estimate of the dimensioning of the hygiene facilities, the following points should be considered. Full-body washing should be allowed to improve morale and enhance self-image. Likewise, privacy must be provided and these should be psychological and physiologically acceptable. Because redactable showers used on MIR and Skylab (see Figure 3-5) are shown to be less usable, dedicated rooms for full-body grooming should be available. This would minimize time and effort to use and maximizes privacy. If it is possible to include commodes, lots of other effects like odor pollution and risk of fecal contamination of the food system can be avoided by incorporating a robust ventilation system that is used for the shower as well as odor extraction. [9, p. 509]

[3] For the bicycle, the same volume as the cycle ergometer is assumed. Additional to this are the racetrack with a volume of 151.48 m³ during practice time.

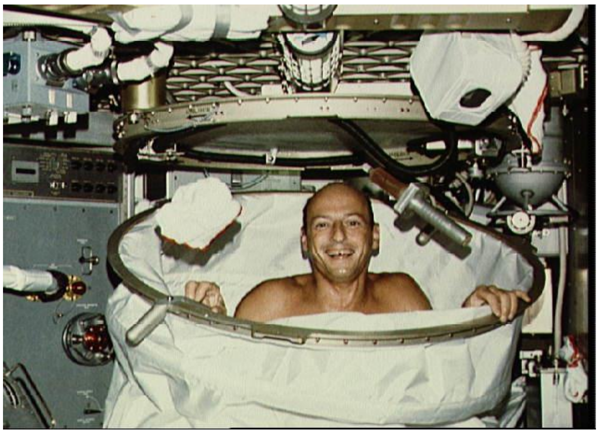

Figure 3-5: Astronaut Charles Conrad poses in shower on Skylab space station [33]

The necessary volume for whole body hygiene can be estimated by using the American Bureau of Shipping Guide for Crew Habitability. This states, that at least 1.15 m³ must be provided for a shower [24, p. 18]. In contrast [9, p. 563] states, that 4.34 m³ must be considered for partial body cleaning and 1.7 m³ for defecation. For the purpose of this thesis, 2.42 m³ are assumed to be used for one bathroom, measuring 1.1 m x 1.1 m x 2 m. As already mentioned, this room is designed to include the shower as well as commode to maximize the benefits. The volume of the accommodations is summarized in Table 3-7. It is assumed, that the use time is below 30 minutes for shower and around 5 minutes for defecation and urination. Additional, a complete failure of one shower should not restrict the operational use of the shower times specified in the schedule. Therefore, some redundancy must be considered. Also, a failure of a shower should not limit the use of the toilet and reverse. To save mass for cleansing material (gloves, wipes, etc.) and prevent the psychological undesirable task of toilet cleaning, the commode should be as far as possible self-cleaning.

Besides the shower and commodes, a possible clothes washer and dryer would be located in this area. A trade-off between expendable clothes and a washer/dryer is made under 9.4.2 Clothing.

Table 3-7: Minimum required volume for hygiene facilities and the different trade cases

	Unit volume [m³]	**Case1 [m³]**	**Case2/3 [m³]**	**Case4 [m³]**
Shower	2.42	7.26	12.10	19.36
Total Volume		**7.26**	**12.10**	**19.36**

3.2.2.7 Medical Station

The medical station on a spacecraft for the crew size considered, is of particular importance. In this area, all medical equipment is stowed and installed. This includes laboratory hardware, diagnostic treatment, along with restraints for patients. The CQ of the crew medical officer should preferably be located within close visual proximity of the patient care area. [20]

At least a level of care four should be considered, because the mission duration lies between 30 and 210 days [34, p. 17]. A level of care four means, that from first aid equipment like bandages up to an automated external defibrillator must be provided [34, pp. 46-47].

The volume for the crew health on the deep space hab demo unit is around 14.17 m³ for two persons [24, p. 19]. When this value is linear extrapolated to 100 CM, this would be 708.5 m³, which is unreasonable high. Therefore, the volume for the health area are assumed to follow a logarithmic function (see Eq. (3-4)), with a maximum of 50 m³ at 100 CM. The needed volume for the crew health care is calculated to be 30.58 m³ for Case1 and 41.61 m³ for the Cases 2 and 3.

$$V_{healthcare} = 9.16 \ln(n_{CM}) + 7.82 \quad \textbf{Eq. (3-4)}$$

3.2.2.8 Lecture Hall

This area is unique, since there never has been a colonial transporter in space. This space is mainly intended for training sessions and team meetings, but can also serve as recreational area outside these times. It is assumed that the people on board are colonialist who will perform a special purpose on mars. Consequently, it is expected that they will have training session during the voyage for skills that are later needed. The overall layout can be seen as a mix of a briefing and a conference room. Fairly few equipment is needed like spacechairs or some type of restraint, presentation equipment and virtual reality kits. It is challenging to estimate the required volume for this area. As a first guess, the minimum required volume for a neutral posture of a human is assumed, is 2.69 m³ CM^{-1} [9, p. 563]. The minimum required total volume for the lecture hall, without equipment, is then 32.28 m³ for Case1, 107.60 m³ for Case2 and 3, and 161.40 m³ for Case4.

3.2.2.9 Location of Functional Areas

Aside from volume sharing, some important parameters must be considered for the arrangement of the different functional areas. These constraints are mainly determined by psychological and health factors, where some areas are incompatible. The main parameters to consider are:

- Noise level (loud or quiet)
- Degree of pollution (dirty or clean)
- Privacy (private or public)

The crew should have private quarters for sleeping and personal recreation (like reading and communication) in the quietest location to enable a restful sleep [13, pp. 577-580]. An additional parameter is the direct influence of the location of the sleep quarters on several other areas. When considering a single shift for the whole crew, the exercise area can be near the crew quarters, otherwise it needs to be as far away as possible, because it is probably the noisiest activity during waking hours. Similarly, relatively distant from the sleeping zone must be the toilet, because it is the noisiest element operating during sleep periods. Both mentioned areas should also be far away from the sleep area because of the odor they produce. [9, p. 518, 13, pp. 149-151]

Things to consider for the location of the workout area are the control of increased heat, carbon dioxide and humidity with simultaneously maintenance a normal partial oxygen level. Besides the mentioned distance to the crew quarters, it must be far away from food preparation and eating areas to prevent contamination. It must further minimize interference with translation paths or other tasks due to volume of the exercise equipment. [9, p. 518, 20]

For the commode and the hygiene area, privacy is the number one requirement. The location is substantial influenced by the produced noise, the relatively dirty environment and the high flows of water. Since a space toilet can be relatively noisy, it must be far away from sleeping areas. Same is true for a shower when considering shift schedules. To prevent contamination of the food, it must also be far away from food preparation and eating areas. And because the liquid flows needed for the toilets and the showers are by far highest of the whole SpaceHab, the ECLSS water recovery subsystem should be in close proximity. Another point that must be considered for large vehicles like the SpaceHab is, that the toilets should be either relatively central or distributed to prevent long distances from any area to reach the commode and therefore ease a frequent access. Because the water reclamation system is assumed to be not distributed, only one hygiene facility area is considered. [9, p. 507, 13, pp. 149-151, 20]

As already mentioned, the galley has to be far away from the workout area and the commode to prevent contamination of food. Another point is, that it should be located to encouraging conversation between the crew members and provides a decent environment for relaxation. Additional the traffic flow should be minimized. For psychological reason like crowding and prevention of interpersonal conflicts, it is of favor to have more than one such place for a large crew. [9, p. 496, 20]

Figure 3-6 shows all six required functional areas with their respective parameters. It can be seen, the areas could be separated into two groups, quiet and clean for crew quarters, medical station, lecture hall, and galley and noisy and dirty for hygiene facilities and gym.

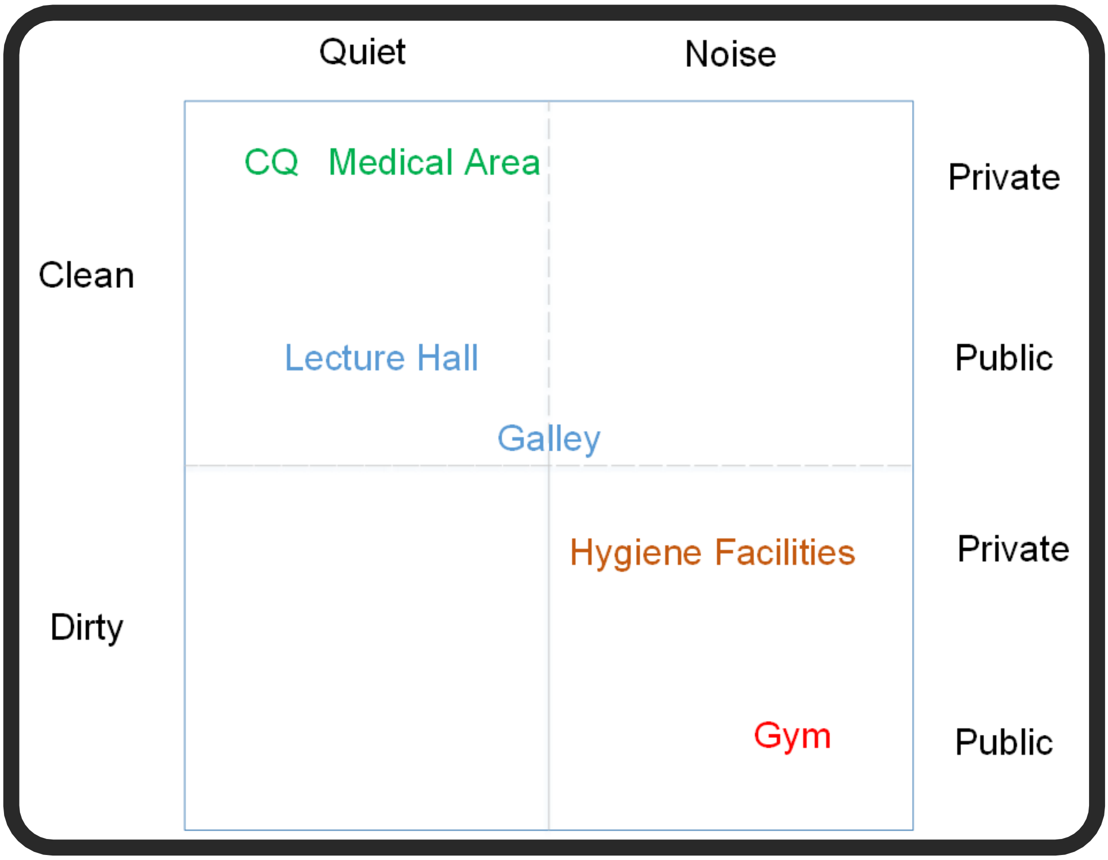

Figure 3-6: Area mapping to parameters

The last point considered for the final decision on the location of the areas are the required volumes for every task. Table 3-8 summaries the needed volume for all functional areas. Volume for recreation is not listed separately, because this can be handled in the already mentioned areas and therefore no additional space is required with the exception of stowage for recreation materials like books, musical instruments, games etc. These are assumed to be stored in the crew quarters. All listed volumes in Table 3-8 are minimum habitable volumes, meaning that no separating walls, pathways or additional required equipment like pipes or attachments are included.

Table 3-8: Summary of functional areas and the needed volume

Area	Case1 [m³]	Case2/3 [m³]	Case4 [m³]
Crew Quarters	36.00	120.00	300.00
Galley	17.27	37.85	78.93
Gym	38.20	108.76	108.76
Hygiene Facilities	7.44	12.28	19.54
Medical Station	30.58	41.61	50
Lecture Hall	32.28	107.60	161.40
Total	**161.77**	**428.1**	**718.63**

What can be seen in Table 3-8 is that for a crew of 100 people the CQ must be separated into two decks and that decks 1 and 2 would be too small since the decks, presented in Table 2-2, are not large enough. The lecture hall and gym for a crew size of 40 to 100 can also not be on deck 1. For 100 CM, even decks 2 and 3 alone would be too small. Apart from these restrictions, there are no other limitations related to the volume.

Considering all above requirements and restrictions for the different functional areas, the following deck layouts can be derived. For the SpaceHab configuration the upper limit of 40 people is considered and for the Evolved-SpaceHab the upper limit of 100 people is considered. For the other two trades, different configurations than the listed ones would be possible, but those are not further analyzed. For all arrangements, the hygiene facilities and the gym are always in close proximity, since the by far highest metabolic outputs are in the gym during exercise, and therefore a high requirement to remove humidity and heat is necessary. Further it is expected that the crew wants to wash and refresh themselves after workout and consequently close proximity to the hygiene facilities is an added benefit.

For the SpaceHab design two different configurations are listed in Table 3-9. For Configuration One the quiet and clean areas are located in the upper deck, whereas the others are in the lower two decks. The other point considered here is that public areas are located in the middle, whereas the private areas are on the outer edges. One major drawback of this configuration is that the hygiene facilities are on one end and therefore relative long distances are needed to reach them. The main consideration for Configuration Two is that public areas are in the upper part of the SpaceHab, whereas private areas are in the lower decks. One disadvantage is that the medical station and the hygiene facilities are in close proximity. The advantages are that the hygiene facility is centralized and the crew quarters are better shielded against radiation because the storage area and the fuel tanks give some kind of protection. Configuration Two is used for the detailed analysis of the ECLSS due to the greater advantages in contrast to configuration One.

Table 3-9: Possible SpaceHab arrangements

Deck	Configuration One	Configuration Two
1	Medical Station	Galley
2	Crew Quarters	Lecture Hall
3	Galley	Gym
4	Lecture Hall	Hygiene Facilities
5	Gym	Medical Station
6	Hygiene Facilities	Crew Quarters

For the Evolved SpaceHab design there were also two possible configurations selected. Table 3-10 shows, that Configuration One is of similar composition as Configuration Two of the SpaceHab design. But because two additional decks and a lounge is included in this configuration, the hygiene facilities and gym are switched to provide a better distance between the hygiene facilities and the medical station. The advantages of Configuration Two for the SpaceHab design are also true for this configuration. Configuration two is based on the separation of clean and quiet areas in the upper part and loud and noisy ones in the lower part of the Evolved-SpaceHab.

Like in Configuration One of the SpaceHab design, the weakness is the location of the hygiene facilities on the termination. Configuration One is used for the detailed analysis of the ECLSS due to the greater advantages in contrast to the other arrangements.

Table 3-10: Possible Evolved-SpaceHab arrangements

Deck	Configuration One	Configuration Two
1	Galley	Lounge, Lecture Hall
2	Lecture Hall	Lecture Hall
3	Lecture Hall	Medical Station
4	Hygiene Facilities	Crew Quarters
5	Gym	Crew Quarters
6	Lounge, Medical Station	Galley
7	Crew Quarters	Gym
8	Crew Quarters	Hygiene Facilities

3.2.3 Crew Schedules

The need to develop a schedule for the crew is determined for two reasons. The metabolism of a person depends heavily on the current task. For example, the oxygen consumption of exercise in contrast to sleep is 11 times higher. This is why scheduling exercise is important and often underestimated [35]. The other aspect is that a schedule is needed for a profound dynamic simulation (see chapter 11 for transient simulations). Since it is not clear in what manner the passengers are distributed in the SpaceHab and to make some tradeoffs, six different schedules for the people on board are considered. The schedules are varying mainly in the number of groups in which the crew is divided and how they are shifted. The only exception is the Emergency Schedule. The groups are named alpha through epsilon. Each timetable has a special purpose with pros and cons and are presented in the following subchapters. The crew schedules depend deeply on the previously described arrangement of the SpaceHab under 3.2.2 Habitat. It should be noted, that the presented schedules are intended for simulation and ECLSS design reasons and would not be that exact in reality.

The considered schedules follow a general rule for workload. The effort of an individual to do a task is measured as workload. While too much workload results in stress, exhaustion, and declining concentration, too little workload results in boredom, deprived morale, and loss of attentiveness. But workload is not just the quantity of work over time. Variation of dissimilar tasks that needs different levels of perceptual and cognitive activity is important. [13, pp. 141-143]

The nominal timeline of the schedules can be seen in Figure 3-7. The first column states the beginning times for every new task. The minimum interval length is half an hour in the developed Life Support Trade Off Tool. These specific times are only true for the alpha group of every schedule. Subsequent groups have times according to their shifts. The different tasks are listed in columns two and three, where the second column is the standard sequence of the tasks to be done. Education stands for training and meetings in the lecture hall. Column three is the emergency timeline, which is only used for the Emergency Schedule.

	standard	emergency
00:00:00	Sleep	Sleep
05:00:00	Post Sleep	Post Sleep
05:30:00	Breakfast	Breakfast
06:00:00	Personal Hygiene	Personal Hygiene
06:30:00	Education	Education
09:30:00	Exercise	Education
10:00:00	Post Exercise	Education
11:00:00	Lunch	Lunch
12:00:00	Recreation	Recreation
14:30:00	Exercise	Recreation
15:00:00	Post Exercise	Recreation
16:00:00	Recreation	Recreation
17:00:00	Dinner	Dinner
18:00:00	Education	Education
20:00:00	Pre-Sleep	Pre-Sleep
21:00:00	Sleep	Sleep

Figure 3-7: Nominal schedule structure

For sleep, 8 hours per day are planned, with half an hour for post sleep activities and one hour for pre-sleep activities [36, p. 5]. Breakfast time is planned as half an hour, while for lunch and dinner one hour is assigned. This is, because it is assumed that for lunch and dinner heating of the food is needed and therefore more time is required. For all mealtimes, pre-meal preparation and post-meal cleanup in addition to actual meal consumption are considered. More information about the considered diet can be found under 9.4.1 Food System. The 2.5 hours considered for meals are slightly different than the average times on the ISS (2.21 h CM-d^{-1}) or calculated ones for a Mars transit (2.57 h CM-d^{-1}) [36, p. 5]. This is again due to the fact that half hour intervals for the simulation are considered. After breakfast, half an hour of personal hygiene is assumed. This includes times for shower. The most time is assigned for education. 5 hours of training and learning per day are divided into 2 blocks, which is lower than average work time on the ISS (6.43 h d-CM^{-1}) [36, p. 5]. Daily workout is considered to be two times 30 minutes long. Following are the post exercise task, which each is 1 hour long and includes hygiene operations. Average exercise times, including pre- and post-activities, on ISS are 2.29 h d-cm^{-1} and presumed to be 2.57 h d-CM^{-1} on a Mars transit [36, p. 5]. The last activity is recreation with 3.5 hours divided into two blocks. Average recreation time on ISS is around 3.07 h d-CM^{-1} [36, p. 5].

When following the guidelines in the Baseline Values and Assumptions (BVAD) document [10, p. 46], the dedicated non-duty times should be at least 12.5 hours during weekdays and 18.5 hours during weekends. For the presented schedules, only training in the lecture hall is considered as duty time. Therefore, non-duty times sum up to 15.5 hours per day. This is slightly over the mean value stated in BVAD. Even when one or two free days per week are necessary, the design of the ECLSS would not be altered since the metabolic values of recreation and most other tasks are the same and exercise should be done on weekends too. Also notable is, that education and recreation in the emergency schedule is selected to simulate crew exchange in the SpaceHab and do not reflect the real tasks to perform.

3.2.3.1 Crew and Passengers

In this thesis, there is no distinction among crew and passengers. But there are some persons on board who are personnel from SpaceX or any other company and are at work during the mission time. Passengers are people on board that payed for the trip. The last ones are considered the majority of people on board and the described schedules below are primarily designed for them. For simplification, the personnel have the same schedules in the simulations and the times that are labeled as education in the schedule are considered as working time. The general metabolic values are similar. Personnel must be included, because only those have the specialized skills that are required for the mission. First of all, one crewmember with medical qualifications is needed to deal with medical problems. For a high passenger size, at least an assistant is needed. The ability to operate, maintain, and repair systems, like electrical and power, LSS, thermal control, etc., requires an engineer. If and how much engineers are required depends on the safety, redundancy and complexity of the ships systems. Even though it is not mentioned by SpaceX [11], it is assumed that the navigation of the SpaceHab is automatic. To prevent a life-threatening situation, a pilot should be included with the ability to safely control the vehicle to limit consequences of hazard incidents on the automatic system or subsystems. The pilot should also serve as mission commander, since the doctor is the contact person for others and should consequently not be in direct charge. For training sessions, it would be good to have an instructor on board, even if it is not mandatory. For this study, it is assumed that the passengers will study with the help of computers. Each expert shall have a cross-training to serve as a backup for another crewmember. [3, p. 40, 13, p. 143]

A summary of the required crewmembers and their responsibilities are outlined below.

1. Doctor
    a. Health and psychological supervision
    b. Interpersonal trouble-shooting
2. Engineer
    a. ECLSS
    b. Electrical system
    c. Structures
    d. Computer operations
    e. Maintenance
3. Pilot
    a. Mission commander
    b. Piloting

Depending on the number of passengers, at least one doctor and one pilot are needed. For the highest analyzed case one doctor, one medical assistant, two engineers and one pilot are needed which sums up to 5 crewmembers compared to 95 passengers.

The assumed crew repair times for a Mars transit mission is 5 h CM-w^{-1} for repairs and 7 h CM-w^{-1} for maintenance for a crew of 4, which leads to around 7 hours per day [36, p. 10]. Because the SpaceHab is much bigger in size and more complex, the times needed for repairs and especially for maintenance would be higher. From this perspective, the addition of at least two engineers seems to be logical.

3.2.3.2 One Hour Shift Schedule

The One Hour Shift Schedule was the first schedule that was considered. Foregone was an iterative approach to reach an optimal distribution of 100 people within the different decks of the Evolved-SpaceHab during the day.

Several assumptions and constraints shape this schedule. First and foremost, a maximum of 20 people at one time shall be allowed on a deck at the same time, excluding the crew quarters and the lecture hall. This is because it would otherwise get too crowded due to the limited volume. In the crew quarters deck, every person has his personal space and thus here is no limitation through the schedule. In the lecture hall, it is assumed that the people sit near each other during lectures and therefore up to 30 people are in this area when considering 100 people and the Evolved-SpaceHab design (5.71 m^3 CM^{-1} for under 1 h). To support these constraints, the passengers would be separated into 5 groups with 1 hour shifted wake up times as can be seen in Figure 3-8. This is chosen for optimal capacity of the limited hygiene facilities and a good balance of passengers in the galley at dining times. Additional it helps to keep noise from activities during sleep time at a minimum.

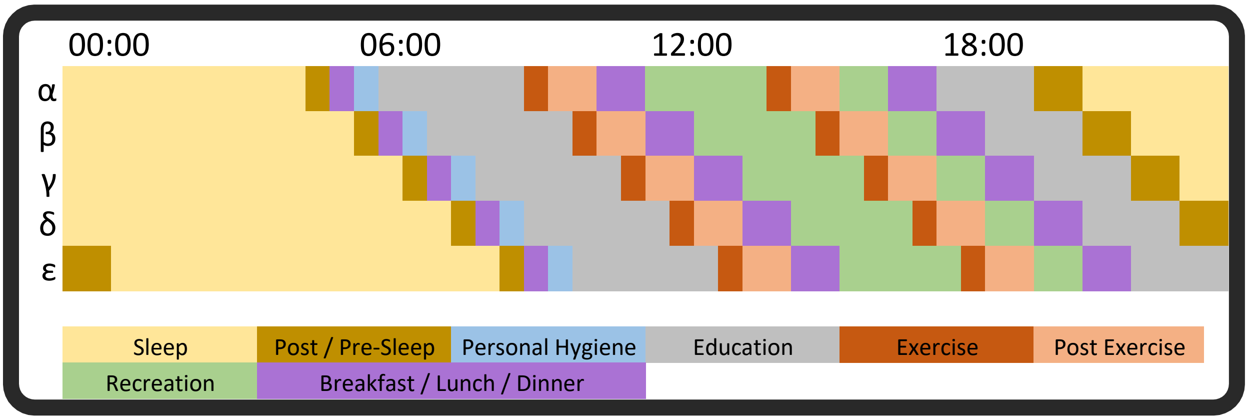

Figure 3-8: Group timeline of the one hour shift schedule

Interaction of groups is maintained in the lounge or during recreational times in the galley and the lecture halls. Because only the sum of persons per deck over time are considered, it is possible that individuals can switch a group or that someone of group alpha takes a meal longer while another one of group beta needs a shorter time. It should also be noted again, that these schedules are mainly for design and simulation reasons and that reality would be more flexible.

The advantages of this schedule are the moderate effects on the size of the ECLSS subsystems and through the high number of groups, this is maybe the closest schedule to reality. As can be shown in the following schedules, it is the only possible schedule for 100 passengers.

One disadvantage is that no interaction between the groups in the galley is possible when the schedule is strictly followed. As mentioned above, it is very likely that some exchange between the groups occurs.

Table 3-11 provides a listing of the maximum people per deck depending on the total crewmembers and the corresponding SpaceHab design. The represented volume per crewmember in parentheses represents the habitable volume. This is calculated by subtracting needed space for subsystems, consumables etc. from the total pressurized volume. The times in column 6 are derived for times a crewmember is on the specified deck with the maximum number of people at the same time, therefore longer total residence time are possible. If there is a slash, the first one refers to the SpaceHab design and the second one to the Evolved-SpaceHab design.

As can be seen in Table 3-11, the minimal net habitable volume per crewmember is in deck 2 when overall 30 crewmembers are present during education. This happens between 8:30 and 10:30. Only group gamma has this small space during the 3-hour session, all other groups have mostly more space available Because of this relatively short duration, it is considered to be feasible.

Table 3-11: Maximum people per deck and corresponding volumes per crewmember with worst case residence times for one hour shift schedule

1 Deck	2 Maximum @12CM (m^3 CM^{-1}) [SpaceHab]	3 Maximum @40CM (m^3 CM^{-1}) [SpaceHab]	4 Maximum @40CM (m^3 CM^{-1}) [Evolved-SpaceHab]	5 Maximum @100CM (m^3 CM^{-1}) [Evolved-SpaceHab]	6 Maximum Residence Time (hrs)
1	2 (42.87)	8 (12.77)	8 (12.83)	20 (5.09)	0.5
2	7 (21.64)	24 (6.29)	12 (11.32)	30 (3.74)	3.0
3	3 (62.57)	8 (23.39)	12 (14.34)	30 (4.95)	0.5 / 1.0
4	5 (41.63)	8 (18.84)	8 (18.41)	8 (4.57)	0.5
5	0	0	8 (22.13)	20 (7.36)	0 / 0.5
6	12 (17.59)	40 (5.29)	20 (07.18)	20 (7.04)	4.0 / 1.0
7	-	-	20 (15.40)	50 (5.26)	4.0
8	-	-	20 (15.40)	50 (5.26)	4.0

3.2.3.3 Four Groups Schedule

As the name suggest, the passengers in this schedule are divided into 4 groups. If these groups are equal shifted (6 hours), there would be a potential crowding problem in the galley. To avoid this, every group is two and a half hours shifted. This enables a good interaction in the galley with 2 groups at the same time, so interaction of different groups is ensured twice a day.

The ECLSS critical exercise times are more divided over the day in comparison to the One Hour Shift Schedule, which reduces the THC subsystem. The limiting factor of crew members for this schedule is the crowding problem in the Galley. If it is assumed that all group members are eating in the Galley, the crew size would be limited to 40 people, because 4.35 m³ is assumed per 5 people for food preparation and 2.69 m³ for eating per person, which sums up to 71.2 m³ (64 % of deck 1) for 20 people without stowage, equipment, or any passage volume. When the lounge (deck 6) is assumed to hold one half of the crew members during eating times, then the maximum number of crew members could be up to 80 people for the Evolved-SpaceHab.

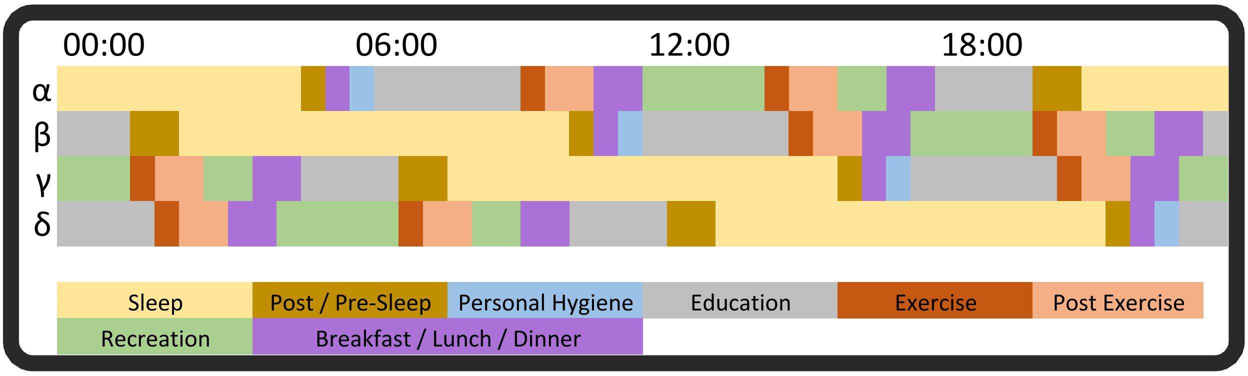

Figure 3-9: Group timeline of the four groups schedule

As can be seen in Table 3-12, the critical volume per crewmember is in deck 1 (galley) with a residence time of half an hour with 40 CM. On other times, the number of passengers are 20 and therefore the specific volume per CM is double. Since this time span is very short and it is likely that some passengers eating in the lounge, it is considered to be feasible. Overall it can be seen, that the volume per CM in the different decks for this schedule is slighter larger than in the previous schedule, since 20 persons less are considered.

Table 3-12: Maximum people per deck and corresponding volumes per crewmember with worst case residence times for four groups schedule

1 **Deck**	2 **Maximum @12CM (m³ CM⁻¹) [SpaceHab]**	3 **Maximum @40CM (m³ CM⁻¹) [SpaceHab]**	4 **Maximum @40CM (m³ CM⁻¹) [Evolved-SpaceHab]**	5 **Maximum @80CM (m³ CM⁻¹) [Evolved-SpaceHab]**	6 **Maximum Residence Time (hrs)**
1	6 (17.15)	20 (5.12)	20 (5.13)	40 (2.55)	0.5
2	6 (25.24)	20 (7.56)	10 (13.58)	20 (6.00)	2.0
3	3 (62.57)	10 (18.74)	10 (17.21)	20 (7.82)	0.5 / 1.0
4	6 (33.38)	8 (18.99)	8 (18.62)	8 (9.53)	0.5
5	0	0	10 (17.65)	20 (7.80)	0 / 0.5
6	9 (23.46)	32 (6.61)	10 (14.40)	20 (7.07)	1.0 / 2.0
7	-	-	16 (19.24)	36 (7.72)	0.5
8	-	-	16 (19.24)	36 (7.72)	0.5

3.2.3.4 Eight-Hour Shift Schedule

Passenger in the eight-hour shift schedule are separated into 3 groups with equal splitting into 8 hour shifts. This means that every group sleeps at different times.

The critical exercise times are divided into 6 blocks over the day, which reduces the amount of sweat and heat produced in a short time frame greatly. But one big disadvantage of this schedule is that there is no interaction between the groups in the galley. And for very big groups there is a potential crowding problem on decks 5 and 1 (gym and galley) and therefore the passenger size is limited to 80 people.

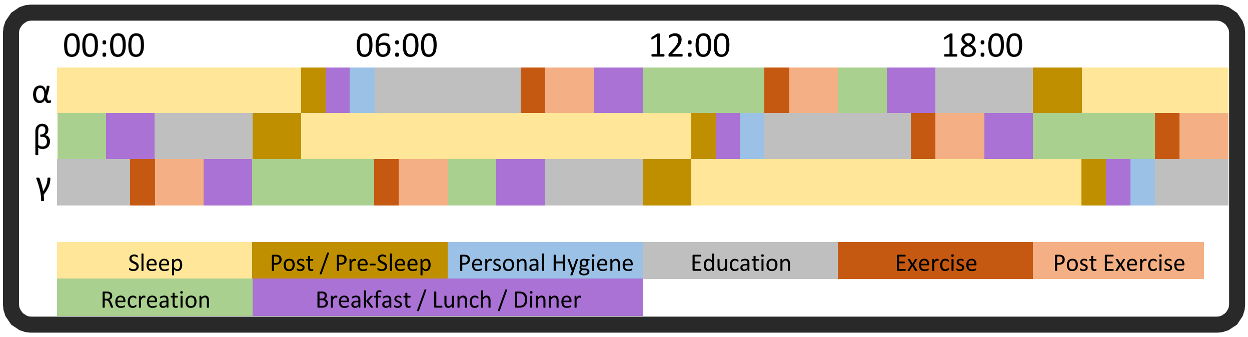

Figure 3-10: Group timeline of the eight-hour shift schedule

As can be seen in Table 3-13, the minimal volume per crewmember is in deck 1 (galley) with a maximum residence time of 1 hour. The calculated 3.83 m^3 CM^{-1} are more than the minimal required space per CM in the galley (3.33 m^3 CM^{-1} [4]) and thus it is considered to be feasible.

Table 3-13: Maximum people per deck and corresponding volumes per crewmember with worst case residence times for eight-hour shift schedule

1	2	3	4	5	6
Deck	**Maximum @12CM (m^3 CM^{-1}) [SpaceHab]**	**Maximum @40CM (m^3 CM^{-1}) [SpaceHab]**	**Maximum @40CM (m^3 CM^{-1}) [Evolved-SpaceHab]**	**Maximum @80CM (m^3 CM^{-1}) [Evolved-SpaceHab]**	**Maximum Residence Time (hrs)**
1	4 (25.72)	13 (7.68)	13 (7.71)	27 (3.83)	1.0
2	4 (37.87)	13 (11.62)	7 (19.43)	14 (8.59)	3.0
3	4 (46.93)	13 (14.40)	7 (24.60)	14 (11.18)	0.5 / 3.0
4	4 (50.16)	8 (18.99)	8 (18.63)	8 (9.63)	0.5
5	0	0	13 (13.16)	27 (5.79)	0 / 0.5
6	8 (26.39)	32 (6.61)	13 (10.80)	20 (7.07)	2.0 / 2.5
7	-	-	16 (33.00)	26 (10.70)	1.0
8	-	-	16 (33.00)	26 (10.70)	1.0

[4] 2.69 m^3 CM^{-1} for eating and 0.64 m^3 CM^{-1} for food preparation space for 27 passengers.

3.2.3.5 Alternating Schedule

This Schedule consists of 2 groups, with a twelve-hour shift between the activities as shown in Figure 3-11. Interaction between the two groups is possible twice a day, but this limits the total passenger size to under 50 people. There is a good division of the exercise times into 4 blocks over the day to reduce heat and sweat removal. For the limiting factor on the crew size, the same assumptions as for the Four Groups Schedule are valid. Therefore, the maximum number of people for this schedules is 80.

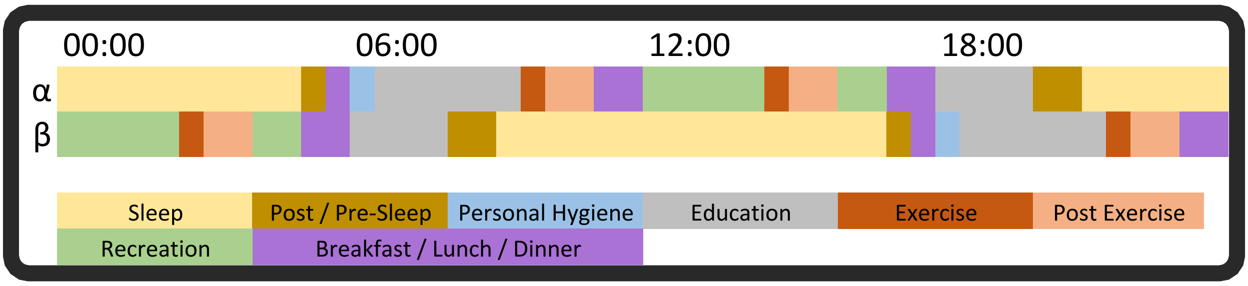

Figure 3-11: Group timeline of the alternating schedule

As can be seen in Table 3-14, there are several critical times, where the volume per crewmember is too low. For the SpaceHab design, the maximum considered number of 40 passengers leads to a very crowded galley, when both groups are eating at the same time. This happens twice a day for a duration of 30 minutes. The calculated habitable volume of 2.55 m^3 per CM is lower than the minimum required space for eating of 2.69 m^3. For the Evolved-SpaceHab, also the galley is the most critical deck. Even when considering that half of the CM are eating in the lounge, the specific volume per CM is still only 2.54 m^3. Consequently, this schedule is only feasible for 40 CM and SpaceHab design or 80 CM and the Evolved SpaceHab design respectively, when considering that some passengers needs less time for lunch or dinner, or they eat in their personal CQ. Another critical time is 1.5 hours of education in deck 2 for 80 passengers with only 2.98 m^3 CM^{-1}. Such a low value is considered to be tolerable for only short periods of time. For the purpose of this thesis, it is considered to be acceptable.

Table 3-14: Maximum people per deck and corresponding volumes per crewmember with worst case residence times for alternating schedule

1 Deck	2 Maximum @12CM (m^3 CM^{-1}) [SpaceHab]	3 Maximum @40CM (m^3 CM^{-1}) [SpaceHab]	4 Maximum @40CM (m^3 CM^{-1}) [Evolved-SpaceHab]	5 Maximum @80CM (m^3 CM^{-1}) [Evolved-SpaceHab]	6 Maximum Residence Time (hrs)
1	12 (8.57)	40 (2.55)	40 (2.56)	80 (1.27)	0.5
2	12 (12.62)	40 (3.77)	20 (6.78)	40 (2.98)	1.5
3	6 (31.29)	20 (9.35)	20 (8.59)	40 (3.89)	0.5 / 1.5
4	6 (33.40)	8 (19.08)	8 (18.73)	8 (9.75)	0.5
5	0	0	20 (8.69)	40 (3.78)	0 / 0.5
6	12 (17.59)	40 (5.29)	20 (7.18)	20 (7.07)	2.5
7	-	-	32 (19.24)	36 (7.72)	1.0
8	-	-	32 (19.24)	36 (7.72)	1.0

3.2.3.6 Crowd Schedule

For this schedule, only one group is considered and consequently all people are in the same area at the same time. This limits this schedule to 30 passengers at the most for the Evolved-SpaceHab design to avoid crowding problems in the galley, gym, and lecture hall. For the SpaceHab design, the passenger limit is 20 for the same reason.

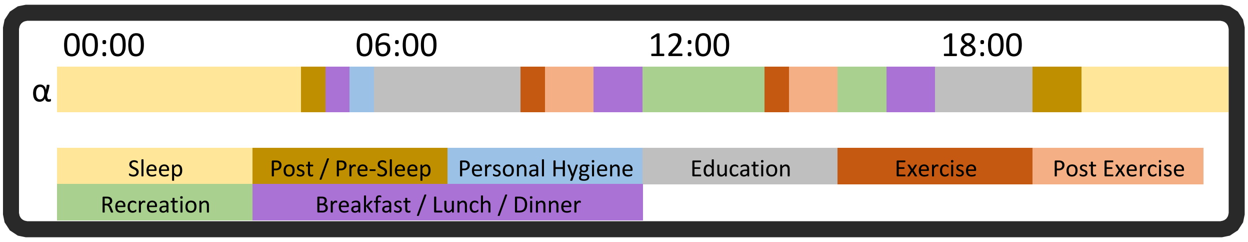

Figure 3-12: Group timeline of the crowd Schedule

As can be seen in Table 3-15, the minimal volume per crewmember is again in deck 1 (galley) with a residence time of 1 hour. Because of this short duration and the space is more than the minimal needed volume, it is considered to be feasible.

Table 3-15: Maximum people per deck and corresponding volumes per crewmember with worst case residence times for crowd schedule

1 Deck	2 Maximum @12CM (m^3 CM^{-1}) [SpaceHab]	3 Maximum @20CM (m^3 CM^{-1}) [SpaceHab]	4 Maximum @30CM (m^3 CM^{-1}) [Evolved-SpaceHab]	5 Maximum Residence Time (hrs)
1	12 (8.55)	20 (5.11)	30 (3.42)	1.0
2	12 (12.60)	20 (7.54)	15 (9.30)	3.0
3	12 (15.62)	20 (9.35)	15 (11.72)	0.5 / 3.0
4	8 (24.89)	8 (23.05)	8 (20.13)	0.5
5	0	0	30 (5.85)	0 / 0.5
6	12 (17.59)	20 (10.55)	20 (7.22)	8.0 / 2.5
7	-	-	30 (21.00)	8.0
8	-	-	30 (21.00)	8.0

3.2.3.7 Emergency Schedule

This is called the emergency schedule, because no exercise is considered and all passengers are in one group. This schedule can be used as a baseline, because it has the lowest demand on the ECLSS, but has the same passenger limits as the Crowd Schedule because of crowding problems.

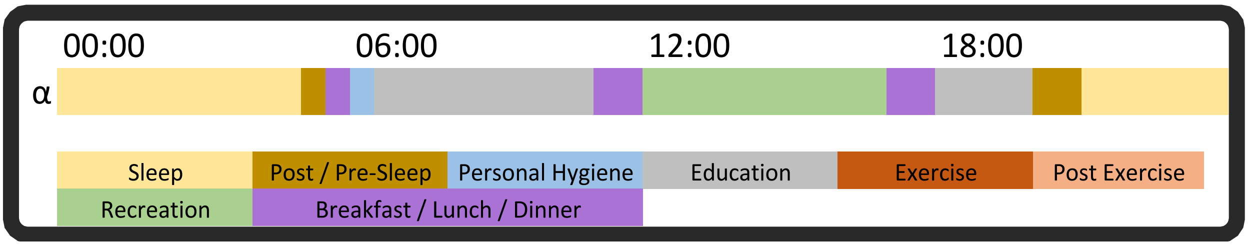

Figure 3-13: Group timeline of the emergency schedule

As can be seen in Table 3-16, the specific volumes per crewmember are nearly identical to the previous schedule (see Table 3-15). The slightly higher values result from less consumables needed, since no exercise is considered. Additional, no passengers are considered to be in deck 5 (gym), which is unrealistic. Considering this space to be occupied would result in better values for the decks 2, 3, and 6. Overall, this schedule is feasible with the mentioned restrictions.

Table 3-16: Maximum people per deck and corresponding volumes per crewmember with worst case residence times for emergency schedule

1 Deck	2 Maximum @12CM (m^3 CM^{-1}) [SpaceHab]	3 Maximum @20CM (m^3 CM^{-1}) [SpaceHab]	4 Maximum @30CM (m^3 CM^{-1}) [Evolved-SpaceHab]	5 Maximum Residence Time (hrs)
1	12 (8.57)	20 (5.13)	30 (3.42)	1.0
2	12 (10.10)	20 (7.57)	15 (9.30)	3.0
3	12 (12.51)	20 (9.38)	15 (11.72)	0.5 / 3.0
4	8 (25.59)	8 (24.10)	8 (21.94)	0.5
5	0	0	0	0
6	12 (17.59)	20 (10.55)	20 (7.22)	8.0 / 2.5
7	-	-	30 (21.02)	8.0
8	-	-	30 (21.02)	8.0

4 Requirements and Constraints

The development of the ECLSS for the SpaceHab is driven by the following requirements which determine the needed performance of every aspect of the system. Several constraints create a design space in which the final system must lie. The subsequent chapters define the specifications and boundaries and comply with the guides in the NASA Systems Engineering Handbook [19]. The requirements and constraints shall be written comprehensibly and unambiguously. The evaluation process for technologies to be considered is based on an iterative approach, where technologies are disqualified for further consideration when they do not meet the constraints described below. The final design must meet all specified requirements. The evaluation process is described in chapter 11 Verification.

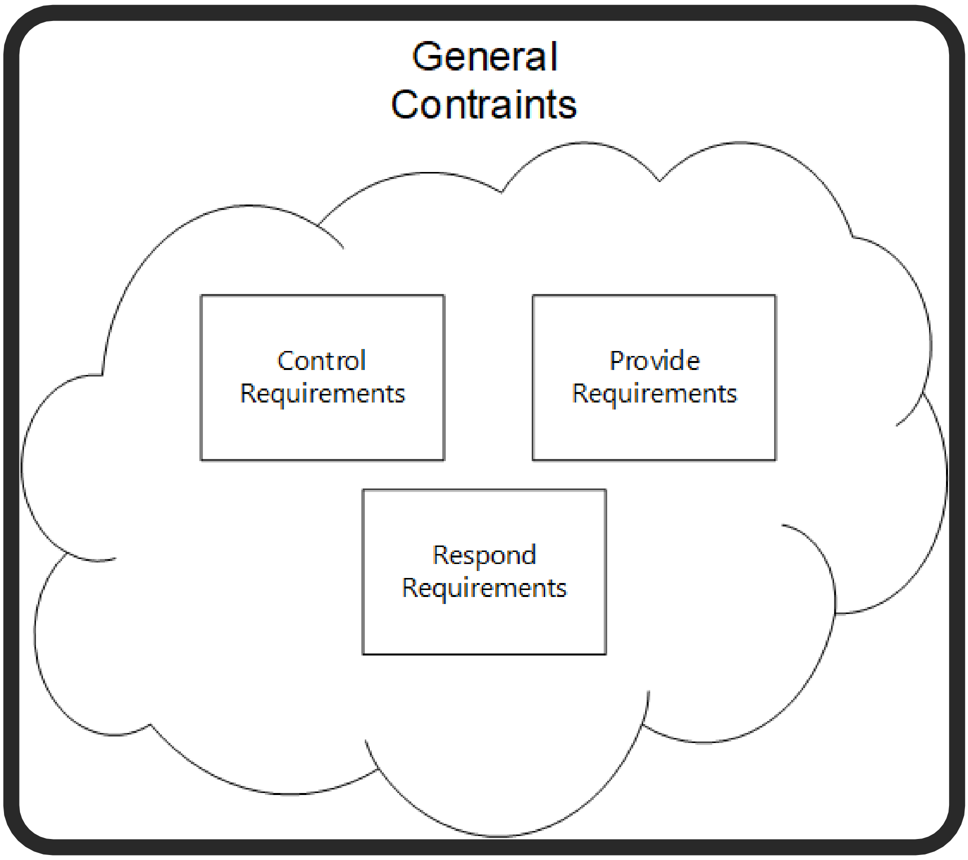

Figure 4-1: The different requirements are capsuled by the constraints for the life support system

4.1 General Constraints

The constraints of the system define the boundaries within which the whole system can be operated. The 23 major ones which are needed for this preliminary design are outlined below. A comprehensive list of complementary constraints for the design of a ECLSS can be found in [37]. Every technology to be considered must adhere to these constraints.

a. Maintain the Environment

Constraint: The life support system shall maintain an environment in the crew habitat that is adequate to support and maintain crew health, well-being, and comfort, and that is adequate to support and maintain satisfactory equipment operation. [37]

b. Safety

Constraint: No materials, systems or operations shall be used if they are a threat for the crew.

Rationale: Each concept is considered with respect to fire, contamination, explosion hazards, hot spots, bacteriological problems, and crew hazards to determine if any of these are present. If a problem cannot be eliminated reasonably by careful design, additional control equipment, using different materials, or similar engineering solutions, the concept is eliminated. Hazards are investigated and considered during normal operation, off-design operation, and maintenance downtime.

c. Power Capability

Constraint: The maximum available power is 200 kW at the vicinity of Earth and 86,6 kW at Mars.

Rationale: The maximum available solar irradiance at Mars is 43.3 % that at Earth.

d. Power Consumption

Constraint: The power consumption of the life support system shall be lower than 69.28 kW, with the goal to minimize it.

Rationale: The stated constraint stands for a power use of 80 % of the total available power at mars orbit. The remaining 20 % are assumed to be used by other systems like avionics or lighting. The goal to minimize the power consumption should be used during normal mission operations, but not for emergency phases.

e. Thermal Heat Rejection Capability

Constraint: The maximum heat rejection capability is 100 kW.

f. Thermal Heat Production

Constraint: The thermal heat production of the life support system shall be lower than 80 kW, with the goal to minimize it.

Rationale: The stated constraint stands for a thermal heat rejection of 80 % of the total heat rejection capability. The remaining 20 % are assumed to be used by other systems like avionics. The constraint should be used during normal mission operations, but not for emergency phases.

g. Failure Tolerance

Constraint: All critical systems essential for crew safety shall be designed to be two-fault tolerant, except inter- and intramodule ventilation, heat collection and distribution, and response to hazardous atmosphere, which shall be single-fault tolerant. When this is not practical, systems shall be designed so that no single failure shall cause loss of the crew. For the purpose of this requirement, maintenance can be considered as the third leg of redundancy so long as mission operations and logistics resupply permit it.

Rationale: For the ISS, the ECLSS is designed that no combination of two failures or operator errors result in a catastrophic hazard, and no single failure or operator error can result in a critical hazard. Maintenance and resupply is a key element of the reliability of the system. Fault tolerance can be seen as the minimum acceptable redundancy, but also has to include cross-link capabilities. For long duration missions, maintenance and system reconfiguration is a must. [38]

h. <u>Contingency</u>

Constraint: Life support equipment and commodity stores shall be sized to support a 10 % safety margin on mission duration. [37]

i. <u>Maintenance</u>

Constraint: The life support system shall enable maintenance by a trained crew member. The goal is to enabled this task as simple as possible and reduce it to a minimum of needed time, both for each task and for the entirety of all maintenance work.

j. <u>Level of Repair</u>

Constraint: Components shall be designed and built to be accessible for in-flight maintenance of components inside the box.

Rationale: Levels of repair can range from large assemblies, such as Orbital Replacement Unit (ORU), to small internal components. Repair of failed components at lower levels allows for sparing smaller components and focusing on the items most likely to fail. In many components, the largest mass and volume are in casings and mounting hardware that are very unlikely to fail. Failures are much more likely to occur in certain internal components such as electronic cards, motors, switches, seals, and numerous other small items. However, repairs at the box level can be much simpler to execute and thus to train the flight crew to perform. Lower repair levels also require more specialized tools, workbenches, and test equipment to verify successful repairs and require much more time. [39]

k. <u>Commonality</u>

Constraint: Commonality should be used to reduce spare parts and for reducing development and procurement costs.

Rationale: Commonality of components, materials, and tools can save much mass and volume needed for spares, even more if interchangeable components are considered. This includes cannibalism from other non-critical sub-systems. [39]

l. Redundancy

Constraint: Redundancy should be considered in the design of the different subsystems to increase the reliability of the system.

Rationale: Redundancy, Commonality and Failure Tolerance are heavily interconnected. Whenever rapid failover time is not required, spares are often the better alternative as built-in redundancy. Also, functional redundancy of different sub-system reduces further the need for component redundancy or spare parts. In general 2 types of redundancy can be considered: active or standby. [39]

m. Reliability

Constraint: The assemblies and subsystems of the life support system shall be maintaining a reliability of at least 0.9984. A lower reliability is possible when maintenance and redundancy is considered. The goal is highly reliable system with reliability of at least 0.995.

Rationale: Reliability directly influences the loss of crew (LoC) and the loss of mission. Because multiple failures for a mission of several months must be considered, reliability of components and the whole system plays a major role in the design of the ECLSS. While most components are relatively reliable, it is not likely that the general reliability of proven technologies will improve remarkable. The above stated 0.995 reliability of the ECLSS means, there should be a likelihood of a system failure no greater than 1 in 200 [40, p. 34]. Because the ECLSS subsystem are critical for crew survival and a failure of one subsystem results in loss of crew, the total system can be assumed to be in series. Therefore, they must all have the same reliability. The reliability of a system with elements in series can be calculated with Eq. (4-1) when the MTBF of the components is known. With the above assumption of equal reliability of every element, Eq. (4-1) can be simplified to Eq. (4-2). To get the required reliability of the elements from a series system with equal importance, Eq. (4-2) could be converted to Eq. (4-3) to get the stated reliability of 0.9984 for the 3 critical subsystems[5]. For the reliability of a system with parallel elements, Eq. (4-4) could be used. [41–43]

For all equations below, a constant failure rate was assumed, meaning components are in the middle region of their lifetime and therefore increasing time does not increase the failure rate. While this is an assumption, it is reasonable given the fact that LSS technologies are mature and the failure rates for components and systems are well known. Therefore, the systems are not susceptible to the higher failure rates at the early stage. Further it is assumed that components and systems sent into space are not reaching the end of their lifetime, as this would not be practical. Therefore, systems are also not subject to increased failure due to components reaching the end of their life span.

$$R_{series}(t) = \prod_{i=1}^{n_{elements}} R_i(t) = e^{-t\,\lambda_{assembly}} \qquad \textbf{Eq. (4-1)}$$

[5] The 3 considered critical subsystems are temperature and humidity control, atmosphere revitalization, and water recovery and management. Other subsystems like atmosphere control and supply are considered as independent.

$$R_{series,same}(t) = R(t)^n \qquad \text{Eq. (4-2)}$$

$$R_{required}(t) = \sqrt[n]{R_{series,same}(t)} \qquad \text{Eq. (4-3)}$$

$$R_{parallel}(t) = 1 - \prod_{i=1}^{n_{elements}} (1 - R_i(t)) \qquad \text{Eq. (4-4)}$$

$$\lambda_{assembly} = \sum_{i=1}^{n_{types}} \lambda_i \, N_i \qquad \text{Eq. (4-5)}$$

$$\lambda_i = \frac{1}{t_{MTBF,i}} \qquad \text{Eq. (4-6)}$$

with:

- $R(t)$ [h] - reliability of system or element
- $n_{elements}$ [-] - number of elements in system
- t [h] - mission time
- $\lambda_{assembly}$ [h] - assembly failure rate
- n_{types} [-] - number of different types of components
- N_i [-] - number of units of each component
- λ_i [h^{-1}] - component failure rate
- $t_{MTBF,i}$ [h] - mean time between failure of component i

n. Crew

Constraint: The life support system shall support 100 people. The goal is a modular and/or scalable system for different crew sizes.

o. Consideration of Schedule

Constraint: All subsystems shall consider the predefined schedules in chapter 3.2.3. From the nominal schedules[6], the one with the lowest impact on ECLSS mass, volume, and power has to be chosen. The goal is a ECLSS that can handle all defined schedules.

Rationale: It is important to know the daily variation and range of metabolic loads and demands to plan a robust LSS design. [17, p. 5]

p. TRL

Constraint: The TRL of components and assemblies shall be greater than 4.

Rationale: A TRL of 5 is described as a "Component and/or breadboard validation in relevant environment" [19]. For the scope of this thesis, a TRL of at least 5 is considered, because an even lower TRL would mean the technology is far from mature and therefore has a lower reliability, higher costs for development and increasing risk for under-performance.

q. Internal Interfaces

Constraint: Interfaces between different subsystems of the life support system shall be provided. The goal is to minimize the number and mass flows between different subsystems or assemblies.

Rationale: A low number of interfaces means a simpler and safer system. It would also be more cost-effective.

---

[6] All schedules with exercise are considered as nominal schedules.

r. Use Synergetic Effects

Constraint: Synergetic effects between subsystems or components should be observed and used.

Rationale: Synergy effects defined here, provide secondary functions for components or subsystems in addition to the main function, e.g. water can be used for drinking and oxygen generation.

s. Pressurized Volume

Constraint: The pressurized volume of the system will be 1,090.28 m³ for a crew up to 40 people and 1,710.76 m³ for crew above 40 persons.

Rationale: The storage area in the Evolved-SpaceHab design has to be accounted as habitable area too, because only the upper part would be too small for 100 people (see section 3.2.2.1 for further details). The pressurized volume of the storage area is around 620.47 m³.

t. Volume Usage

Constraint: The maximum volume of the life support system shall be less than one third of the pressurized volume. This includes all supply masses of gases, liquids, food and spare parts. The goal is to minimize the occupied space.

Rationale: The maximum allowable volume for the SpaceHab is 363.33 m³ and 570.33 m³ for the Evolved-SpaceHab design.

u. Payload Mass

Constraint: The useable total payload mass will be in the range of 200,000 to 450,000 kg, depending on the mission scenario (see chapter 3.2 Operational Scenarios).

Rationale: A payload boundary of 200,000 kg and 450,000 kg is given at a Δv of 6 km s^{-1} or 4 km s^{-1} respectively. The payload of 450,000 kg is only possible with a transfer in LEO, because the booster has a maximum capability of only 300,000 kg to LEO. (see section 2.4 Payload Capacity for further details)

v. Mass Usage

Constraint: The maximum mass of the life support system shall be less than 75 % of the total payload mass. This includes all supply masses of gases, liquids, food and spare parts. The goal is to minimize the needed total mass.

Rationale: Depending on the considered mission time, the maximum allowable ECLSS mass is 150,000 kg for 88 days and 337,500 kg for 211 days.

w. Mission Duration

Constraint: The mission duration will be between 88 and 211 days, depending on mission scenario (see section 3.2 Operational Scenarios). The worst-case scenario of 211 days, which includes a margin of 10 % on the longest trip time of 192 days, must be feasible.

Rationale: The best-case of 80 days is given in the year 2035 with a Δv of 6 km s^{-1}. Added to this are a margin of 10 %, or 8 days. The worst-case is 192 days in the years 2024 and 2029 at Δv of 4 km s^{-1}. See also section 2.4 Payload Capacity for further details.

4.2 Control Requirements

The requirements to control the ECLSS are the most essential part of the requirements engineering task, because they influence the performance most. They are divided into the different subsystems of the ECLSS (see chapter 6 Life Support Systems for a comprehensive overview).

4.2.1 Atmosphere Control and Supply Control Requirements

a. Control Atmosphere Total Pressure

Requirement: The total atmospheric pressure in the crew cabin shall be maintained within the range of 96.5 to 102.7 kPa, with a minimum of 95.8 kPa for 28-days emergencies. [13, 35, 37, 38]

Rationale: In principle, the needed total atmospheric pressure is dependent on the oxygen level. The minimum total pressure consists of pure oxygen at a pressure of 24.13 kPa but this is only feasible for short durations [44, pp. 2-3]. A higher total pressure means lower oxygen levels and reverse. A high pressure requires prolonged times for extravehicular activity (EVA) prebreathing, but since EVA´s not considered, this can be ignored. Since the driving factor on the wall thickness is radiation protection for interplanetary travel (see chapter 9.1), the stress caused by pressure are negligible. Additional the gas leakage is higher, but since the SpaceHab consist of one big module, this is minimal. The benefits of a high-pressure atmosphere are a better cooling efficiency of fans and therefore lower noise. Likewise, the voice communication at a distance is no problem. This is of special interest for a big volume like the SpaceHab. Another benefit is the better fire safety as the oxygen level is lower. And the pressure at sea levels means there are more standardized conditions for equipment. [13]

b. Relieve Overpressure

Requirement: Venting of atmosphere to space shall not occur at less than 103.4 kPa. [38]

c. Manage Leakage

Requirement: The life support system shall provide enough resources to compensate the atmospheric leakage during nominal operation, which is defined to 0.2 kg day^{-1}. [45, 46]

Rationale: Mean leakage on ISS in 2011 was around 0.227 kg day^{-1}, which includes losses for EVA, docking operations and leakage between modules [46]. In conclusion, a leakage rate of 0.2 kg day^{-1} for the closed environment of the ITS is a worst-case scenario. Furthermore, for the leakage rate no distinction will be made between the SpaceHab and Evolved-SpaceHab design.

d. Add Metabolically Inert Gas to Atmosphere

Requirement: The metabolically inert gas nitrogen shall be added to the cabin atmosphere as needed during normal operations and to restore the atmosphere following decompression. [13, 37]

Rationale: Two types of inert gases could be considered. Nitrogen is the natural inert gas on earth and commonly used in spaceflight. Helium is often used in deep-sea diving. The benefits of Helium over Nitrogen are the higher resistance to ionizing radiation without forming by-products, the much lower density (⅐) which would lead to reduced power requirements for fans and smaller gas stores since it could be more densified, and the shorter prebreathe time for EVA. On the other hand, the disadvantages are the 6 times higher thermal conductivity which brings a 4 to 6 °C warmer comfort zone, the higher molecular incidence rate and therefore higher loss rates from leakage, and the speech shift of 0.7 octaves to higher frequency which would require technical aids. [13]

e. Control Oxygen Partial Pressure

Requirement: The oxygen partial pressure in the crew cabin shall be maintained within the range of 19.5 to 23.1 kPa for normal operational phases, 16.5 to 23.8 kPa for 90-day degraded phases and 15.9 to 23.8 kPa for 28-day emergencies. The minimum partial oxygen pressure for 1 hour is 15.17 kPa [37, 45]

Rationale: The assumed Loss of Crew (LoC) limit is a decrease of the oxygen partial pressure of under 13.4 kPa for over 3 minutes. [43, p. 35]

f. Add Oxygen to Atmosphere

i. **Requirement**: Gaseous oxygen shall be added to the cabin atmosphere as needed during normal operations. [37]
ii. **Requirement**: Gaseous oxygen shall be added to the cabin to restore the atmosphere following decompression. [37]

4.2.2 Temperature and Humidity Control Control Requirements

a. Control Atmospheric Temperature

i. **Requirement**: The atmospheric temperature in the crew cabin shall be maintained in the range of 291.5 to 299.8 K (18.35 – 26.65 °C) during normal operations and 90-day degraded phases. It shall be in the range of 288.7 to 302.6 K (15.6 – 29.5 °C) during 28-day emergencies. [13, 37, 45]

   Rationale: The temperature range for the American section on the ISS is 17.8 to 26.7 °C and 18 to 28 °C for the Russian section. [38]

ii. **Requirement**: The atmospheric temperature in the crew cabin shall be crew selectable within the acceptable operational range. [37]

   Rationale: The crew on the ISS generally selects a temperature at or above 22.2 °C. [47]

iii. **Requirement**: The atmospheric temperature in the crew cabin shall be within ± 1.5 Kelvin of the selected temperature regardless of crew activities. [9, p. 345]

b. Remove or Add Sensible Heat

Requirement: Sensible heat shall be removed from and/or added to the cabin atmosphere as needed during normal operations. [37]

Rationale: Sensible heat is produced by humans and equipment.

c. Control Atmospheric Humidity

i. **Requirement**: The atmospheric relative humidity (RH) in the crew cabin shall be maintained in the range of 25 to 70 % independent of the current phase. The nominal value is assumed to be 40 %. For a 90-day degraded or 28-day emergency it could be up to 75 %. [13, 37, 45, 48]

Rationale: RH and dew point must be specified independently. The RH is required for crew comfort whereas the dew point is for prevention of condensation. A low RH causes drying of the skin and eyes while a high RH can lead to condensation on surfaces [9, p. 343].

"Note: Cabin atmospheric relative humidity and dew point are not independent quantities, but rather different assessments of the moisture in the cabin atmosphere. This understanding, however, does not waive either (relative humidity) or (dew point). Rather, both must be satisfied." [48]

ii. **Requirement**: The atmospheric dew point in the crew cabin shall be maintained in the range of 277.6 to 288.7 K for normal operational phases with the goal to no higher than 287.2 K, and 274.8 to 294.3 K during all other phases. [37, 38]

Rationale: It should be noted that a lower dew point means the reliability and redundancy gets better. [37]

d. Remove or Add Moisture

Requirement: Moisture shall be removed from and/or added to the cabin atmosphere as needed during normal operations. [37]

Rationale: Humidity condensate is delivered to the wastewater bus at a rate up to 1.45 kg h^{-1} and a pressure up to 55 kPa on ISS [38]

e. Ventilation Velocities in the Crew Habitable Volume

Requirement: Atmospheric velocities in the crew habitable volume shall been between 0.051 to 0.203 m s^{-1} for nominal operational situations with a lower and upper limit of 0.036 and 1.02 m s^{-1} respectively. [37, 38]

f. Exchange Atmosphere between Modules

Requirement: Atmosphere exchange between adjacent, non-isolated pressurized volumes shall be provided to maintain sufficiently uniform conditions for atmosphere composition control when atmospheric constituents are controlled by centralized systems. [37]

Rationale: The exchange rate between different modules on ISS is 63.7 to 68.4 L s^{-1} (229.32 to 246.24 m^3 hr^{-1}) [38]

4.2.3 Atmosphere Revitalization Control Requirements

a. Control Partial Pressures of Atmospheric Contaminants

Requirement: The partial pressures of contaminants, such as carbon dioxide and other trace contaminants, in the cabin atmosphere shall be maintained at or below current applicable Spacecraft Maximum Allowable Concentration limits for various exposure periods defined in [49]. The maximum allowable concentration of CO_2 is 0.68 to 0.72 kPa for up to 180 days. It also depends on total pressure. Therefore, it is allowed to rise up to 2.03 kPa for 1 hour, and 0.9066 kPa within 24 hours. The goal is a mean CO_2 partial pressure below 267 Pa (2 mmHg). [17, p. 5, 35, 37, 45]

Rationale: Several different sources of trace contaminants must be considered. These are humans, structural and aesthetic materials, payload chemicals, propellants (e.g. hydrazine), coolants, and thermodegradation of materials heated. [45]

The LoC limit is assumed to be CO2 partial pressure of over 3 kPa for longer than 15 minutes [43, p. 35].

b. <u>Remove Gaseous Atmospheric Contaminants</u>

Requirement: Atmospheric contaminants, such as carbon dioxide and other trace contaminants, shall be removed from the cabin atmosphere as needed. [37]

c. <u>Control Airborne Particulates</u>

Requirement: The concentration of airborne particulates greater than 0.5 µm in the cabin atmosphere shall be maintained to be lower or equal to 3,500,000 particles per m^3 (0.05 mg m^{-3} with periodic peaks to 1 mg m^{-3} are allowed) during normal operational phases. [37, 38]

Rationale: Typical sources of airborne particulates are hair, food debris, fabric lint, skin fragments, and paper and plastic debris. The typical generation load to control is between 0.6 and 1.6 mg CM-min^{-1}. [17, p. 6]

d. <u>Remove Airborne Particulates</u>

Requirement: Airborne particulates shall be removed from the cabin atmosphere as needed. [37]

e. <u>Control Microbes</u>

Requirement: The concentration of microbes within the cabin, whether airborne or on a surface, shall be controlled within less than 500 CFU[7] per m^3 during normal operational phases, less than 750 CFU per m^3 during 90-day degraded phases and less than 1000 CFU per m^3 during 28-day emergencies. [37]

f. <u>Remove Airborne Microbes</u>

Requirement: Airborne microbes shall be removed from the cabin atmosphere as needed. [37]

4.2.4 Water Recovery and Management Control Requirements

a. <u>Control Water Quality</u>

Requirement: Water provided for crew use and consumption shall meet current established water quality requirements as defined in [45]. [37]

[7] CFU stands for colony forming units

Rationale: The parameters to monitor includes total organic carbon, total inorganic carbon, total carbon, conductivity, pH, turbidity, color, iodine, iodide, and iodine compounds.

b. Water System Decontamination

Requirement: Capabilities shall be provided for in-flight decontamination of water processing and storage systems. [37]

4.3 Respond Requirements

The respond requirements rely on hazards during emergencies which need an immediate answer to the situation.

Requirement: The life support system shall respond to emergency events to protect the crew, vehicle, and equipment. [37]

4.3.1 Atmosphere Control and Supply Respond Requirements

a. Detect Rapid Decompression

Requirement: A rapid decompression event shall be detected independent of active crew observation or monitoring prior to the cabin total pressure decreasing by 3.4 % (or 3.4 kPa) based on a hole size of 1.3 cm to 5.1 cm in diameter. [37]

Rationale: The maximum flow through a hole the size of 1.3 cm is 76.03 $m^3\ h^{-1}$ and 1,170.06 $m^3\ h^{-1}$ for a 5.1 cm hole. The time to detect a 3.4 % decrease of total pressure can therefore be calculated with Eq. (4-7) to 28.88 minutes for the 1.3 cm hole and 1.88 minutes for the 5.1 cm hole, both for the SpaceHab design. The times for the Evolved-SpaceHab design are little bit longer, with 45.31 minutes for the 1.3 cm hole and 2.94 minutes for the 5.1 cm hole.

$$t_{detection} = \frac{m_{atmo} - \frac{M_{air}\,\Delta p\,V_{SpaceHab}}{R\,T}}{\dot{m}_{hole}} \qquad \textbf{Eq. (4-7)}$$

with:

- $t_{detection}$ [h] - detection time
- m_{atmo} [kg] - mass of present atmosphere
- M_{air} [$g\ mol^{-1}$] - molar mass of dry air
- Δp [Pa] - pressure decrease
- $V_{SpaceHab}$ [m^3] - volume of SpaceHab
- R [$J\ mol^{-1}$] - gas constant (8.314472)
- T [K] - nominal temperature (295.15 K)
- $\dot{m}_{hole}$ [$kg\ h^{-1}$] - mass flow through hole

b. Recover from Rapid Decompression

Requirement: The capability to recover from a rapid decompression event within 24 hours shall be provided. [37, 50, p. 68]

Rationale: The time for repressurisation of a module on ISS is 75 hours [38]. Because the ISS is separated in modules, whereas the ITS is one big module, a much lower time for repressurisation is required. When no emergency pressure suits are considered, the SpaceHab must be separated into an upper and lower compartment. The given 24 hours would still be valid for such a scenario.

4.3.2 Atmosphere Revitalization Respond Requirements

a. <u>Detect Hazardous Atmosphere</u>

Requirement: Potentially hazardous gaseous, vapor, aerosol and particulate atmospheric contaminants shall be detected independent of active crew observation and monitoring before they reach hazardous concentrations within the crew cabin. [37]

Rationale: Venting to space to achieve an O_2 concentration below 6.9 kPa can be achieved within 10 minutes on ISS [38]. As can be calculated with Eq. (4-7), the needed flow rate is 2,486.67 $m^3 h^{-1}$ for the SpaceHab design and 3,901.83 $m^3 h^{-1}$ for the Evolved-SpaceHab.

b. <u>Recover from Hazardous Atmosphere</u>

Requirement: The capability to recover from a hazardous atmosphere shall be provided. [37]

Rationale: To recover from a hazardous atmosphere it is permitted to replace the cabin atmosphere or increase the capacity of the contaminant removal system. Also, an emergency breathing apparatus for the crew could be included. Otherwise, the crew can move to a compartment that is not contaminated.

4.4 Provision Requirements

The number of requirements to provide resources are by far the largest part as many different aspects must be considered for every subsystem to ensure that the design of the ECLSS is robust.

4.4.1 Atmosphere Control and Supply Provision Requirements

a. <u>Supply Inert Gas</u>

Requirement: The inert gas nitrogen shall be supplied to points of use in accordance with applicable interface specifications for gas temperature, pressure and flow rate. [37]

b. <u>Store Inert Gas</u>

Requirement: Storage of the inert gas nitrogen shall be provided with a minimum capacity to meet usage and contingency needs, including cabin repressurization as stated in Table 4-2. [37]

Rationale: The required N_2 for one repressurisation can be calculated by Eq. (4-8) below.

$$m_{gas} = \frac{M\,p\,V}{R\,T} \qquad \textbf{Eq. (4-8)}$$

with:

- m_{gas} [kg] - mass of gas in volume

- M_{gas} [g mol^{-1}] - mol mass of gas
- p_{gas} [Pa] - nominal partial pressure of gas
- $V_{SpaceHab}$ [m^3] - volume of SpaceHab design
- R [J K^{-1}mol^{-1}] - ideal gas constant (8.314472)
- T [K] - nominal temperature

With a molar mass of 28.0134 g mol^{-1} and a nominal partial pressure of 79.76 kPa, the required N_2 mass is 992.67 kg for the SpaceHab design and 1,557.60 kg for the Evolved-SpaceHab design.

Table 4-1: N_2 repressurisation mass

SpaceHab [kg]	Evolved-SpaceHab [kg]
992.67	1,557.60

Besides the required mass for repressurisation, a leakage of 0.2 kg per day is assumed (see requirement 4.2.1.c). For simplicity, it is assumed that this value consists only of the components N_2 and O_2. The nominal N_2 level is around 79 % which means that the N_2 leakage per day is 0.158 kg. As can be seen in Figure 4-2 the total leakage mass is a linear function with a minimum mass of 13.90 kg for 88 days and a maximum mass of 33.34 kg for 211 days.

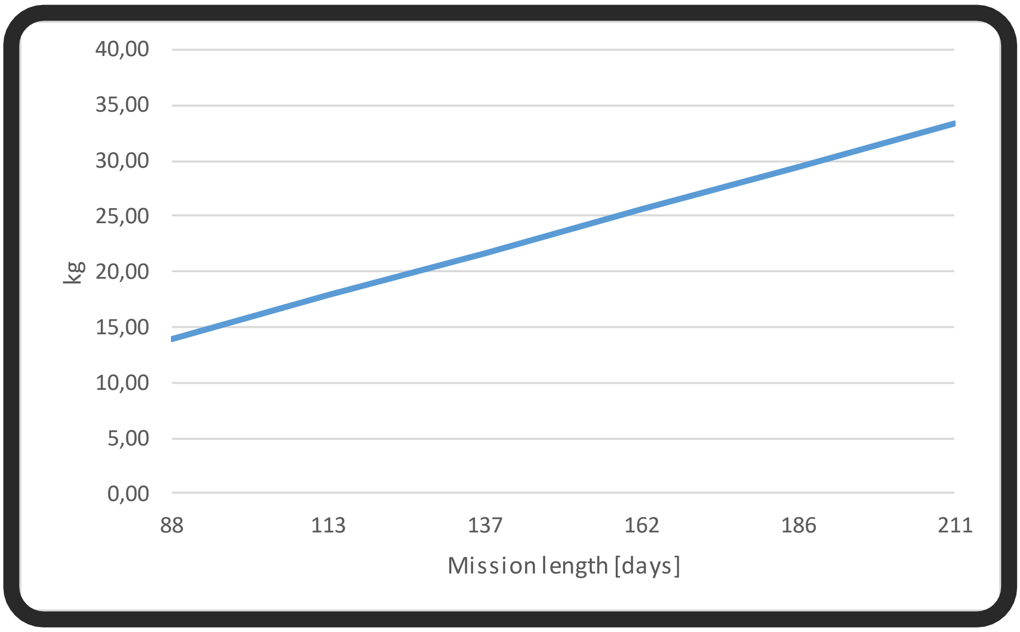

Figure 4-2: N2 leakage mass over mission length

Adding the required repressurisation and leakage masses, the total masses are summarized in Table 4-2.

Table 4-2: Masses for N_2 repressurisation and leakage

Total mass	88-day mission [kg]	211-day mission [kg]
SpaceHab	1,006.57	1,026.01
Evolved-SpaceHab	1,571.5	1,590.94

c. **Supply Oxygen**

Requirement: Oxygen shall be supplied to points of use in accordance with applicable interface specifications for gas temperature, pressure and flow rate. [37]

d. **Store Oxygen**

Requirement: Storage of oxygen or oxygen generating resources shall be provided with a minimum capacity to meet usage and contingency needs, including cabin repressurization as stated in Table 4-4, Table 4-5, Table 4-6, and Table 4-7. [37]

Rationale: The needed O_2 for one repressurisation can be calculated by Eq. (4-8). With a molar mass of 31.9988 g mol^{-1}, a partial pressure of 21.3 kPa, and a temperature of 295.15 K, Eq. (4-8) yields a O_2 mass of 302.82 kg for the SpaceHab design and 475.15 kg for the Evolved-SpaceHab design.

Table 4-3: O_2 repressurisation mass

SpaceHab [kg]	Evolved-SpaceHab [kg]
302.82	475.15

Besides the required mass for repressurisation, a leakage of 0.2 kg per day is assumed (see requirement 4.2.1.c). For simplicity, it is assumed that this value consists only of the components N_2 and O_2. The nominal O_2 level is around 21 % which means that the O_2 leakage per day is 0.042 kg. As can be seen in Figure 4-3 the total leakage mass is a linear function when assuming the total pressure is controlled at constant level with a minimum mass of 3.70 kg for 88 days and a maximum mass of 8.86 kg for 211 days. Of course, it would be possible to produce the needed O_2 for leakage by electrolysis, but because it is only around 2 % of the required repressurisation mass and the safety of the system is enhanced with this approach electrolysis for leakage is neglected.

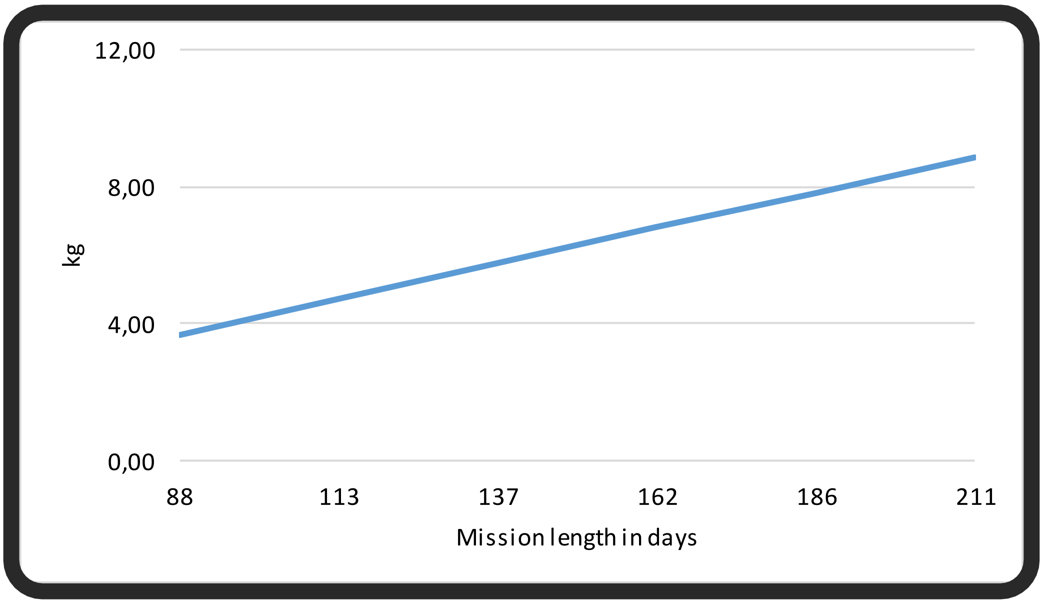

Figure 4-3: O_2 leakage mass over mission length

Adding the required repressurisation and leakage masses, the total masses are summarized in Table 4-4.

Table 4-4: Masses for O_2 repressurisation and leakage

Total mass	88-day mission [kg]	211-day mission [kg]
SpaceHab	306.52	311.68
Evolved-SpaceHab	478.85	484.01

For consumption, values from [10, p. 45] Table 3.22 are used. Depending on the used schedule (see 3.2.3), the O_2 consumption for one day is listed in Table 4-5 below.

Table 4-5: O_2 consumption rate

Schedule-type	O2 consumption [kg CM-d^{-1}]
Normal	0.92
Emergency	0.72

For a storage system, the above consumption rates multiplied with the mission duration gives the required O2 for the whole mission as stated in Table 4-6 and Table 4-7.

Table 4-6: O2 consumption mass for normal schedule-type depending on mission length and crew size

	88-day mission [kg]	211-day mission [kg]
12 crew member	971.94	2,330.45
40 crew member	3,239.81	7,768.18
100 crew member	8,099.52	19,420.44

Table 4-7: O2 consumption mass for emergency schedule-type depending on mission length and crew size

	88-day mission [kg]	211-day mission [kg]
12 crew member	758.29	1,818.18
40 crew member	2,527.64	6,060.60
100 crew member	6,319.10	15,151.49

4.4.2 Temperature and Humidity Control Provision Requirements

a. Maintain Thermal Conditioning

Requirement: The life support system shall maintain thermal conditioning of the SpaceHab to ensure crew health and comfort and warrant that all systems can be maintained within their operating temperature envelopes. [37]

Rationale: The total collected thermal energy is the sum of waste thermal energy from equipment, human metabolic thermal energy, and the gain or loss of thermal energy through the SpaceHab wall. The last point is neglected in this work.

b. Accept Thermal Energy

i. **Requirement**: Excess thermal energy shall be accepted from the SpaceHab atmosphere. [37]

ii. **Requirement**: Excess thermal energy shall be collected from equipment. [37]

Rationale: It is not known what equipment is planned for the SpaceHab. For this work, the thermal energy of the ECLSS and the assumed equipment outlined in chapter 10.2 are expected.

iii. **Requirement**: Excess thermal energy shall be accepted from internal sources of liquids that require cooling according to interface specifications. [37]

Rationale: Heat exchange between liquids is handled by heat exchangers.

c. Reject (Dispose of) Excess Thermal Energy

Requirement: Excess thermal energy shall be transferred to the external cooling interface. [37]

d. Reuse Thermal Energy

Requirement: It is permissible to transfer thermal energy to other vehicle processes and equipment. [37]

4.4.3 Atmosphere Revitalization Provision Requirements

a. (Re)generate Oxygen

Requirement: It is permissible to generate or regenerate oxygen. [37]

b. Process Gaseous Wastes

Requirement: It is permissible to process gaseous wastes to recover useful products. [37]

4.4.4 Water Recovery and Management Provision Requirements

a. Supply Water

Requirement: Water shall be supplied to points of use in accordance with applicable interface specifications for water temperature, pressure, flow rate and quality. This includes potable water for hot beverages and food hydration at a temperature between 68.3 °C and 79.4 °C, and cold beverage water with a maximum temperature of 15.6 °C. Hygiene water for personal grooming shall be at a temperature between 29.4 °C and 46.1 °C. Potable water for medical events shall be at a temperature between 18 °C and 28 °C. The water quality standards are specified in [45]. [9, p. 367, 37, 48]

The water dispense rate shall be at a rate of 500 mL min^{-1} [9, p. 373]

Rationale: For rehydration of beverages and food, a temperature of 79.4 °C allows a fast rehydration rate and prevents the beverage or food item to drop below 68.3 °C, which avoids microbial growth. In addition to this, a cold-water port (nominally between 7.2 and 11.7 °C) is needed to chill certain beverages and food items to make them more acceptable to the crew. [48]

b. Store Water

Rationale: Stored Water can be separated into different purposes. Potable water for drinking and food rehydration, hygiene water, and waste water. The later one can be further divided into hygiene waste water, condensate, and urine. On ISS, all waste water is mixed and recycled. In this study, different water loops are considered and compared. First, an open loop system is considered in which only potable water tanks for consumption are considered and all waste water is stored in the same tank. This is the simplest and most reliable solution. When recycling is considered, first only humidity condensate is recycled, because this is the easiest one. A step further is the recycling of hygiene waste water from the shower and when considered a clothes washer (see 9.4.2). Next is the recycling from urine and maybe brine. The last would be water recycled from waste and feces.

The assumed LoC limiting factor is a potable water consumption of under 2.05 kg CM^{-1} d^{-1} for a duration of at least 3 days. [43, p. 35]

i. **Requirement**: At minimum capacity, stored water shall meet peak usage demands during normal operations as specified in Table 4-8. [37]

Rationale: Usage peaks for consumption water are depending on the number of people and the chosen schedule. The highest potable water peaks during the day are meal times. For food rehydration and drinking, it is assumed that every person needs 0.717 kg of potable water within ½ hour during breakfast and 1 hour during lunch and dinner. Hygiene water peaks occur during shower times, which last up to 30 minutes and require 10 L for every person who is in the shower. The highest water peaks are summarized in Table 4-8 below.

Table 4-8: Potable and hygiene water peaks depending on crew size and schedule

	Potable water peak during meals[8] [kg]	**Hygiene water peak during shower[9] [kg]**
12 crew member	1.43 (08.60)	20.00
40 crew member	5.74 (28.68)	60.00
100 crew member	14.34 (57.36)	150.00

Other hygiene water peaks for ECLSS equipment must be considered.

ii. **Requirement**: Stored potable water shall provide sufficient capacity to meet mission specific contingency needs. [37]

Rationale: Needed potable water per person depends on the hydration of the food system which are described in chapter 9.4.1. Because a food system comparable to the ISS is assumed, the daily water need per person is around 2.5 liter, of which 2.0 kg CM-d^{-1} is assumed as drinking water and 0.5 kg CM-d^{-1} is for rehydration of food [51].

With these values, the needed water for a storage system can be calculated. As can be seen in Figure 4-4, the required water mass is between 2,640 kg for a best-case scenario with 12 person and 88 days, while the worst-case scenario needs 52,750 kg of potable water for 100 person and 211 days.

[8] First value is derived from one hour shift schedule (Table 3-11). Numbers in brackets are worst-case assumptions for alternating, crowd, and emergency schedules.
[9] Calculated by dividing number of crew member through 7 days and rounded up.

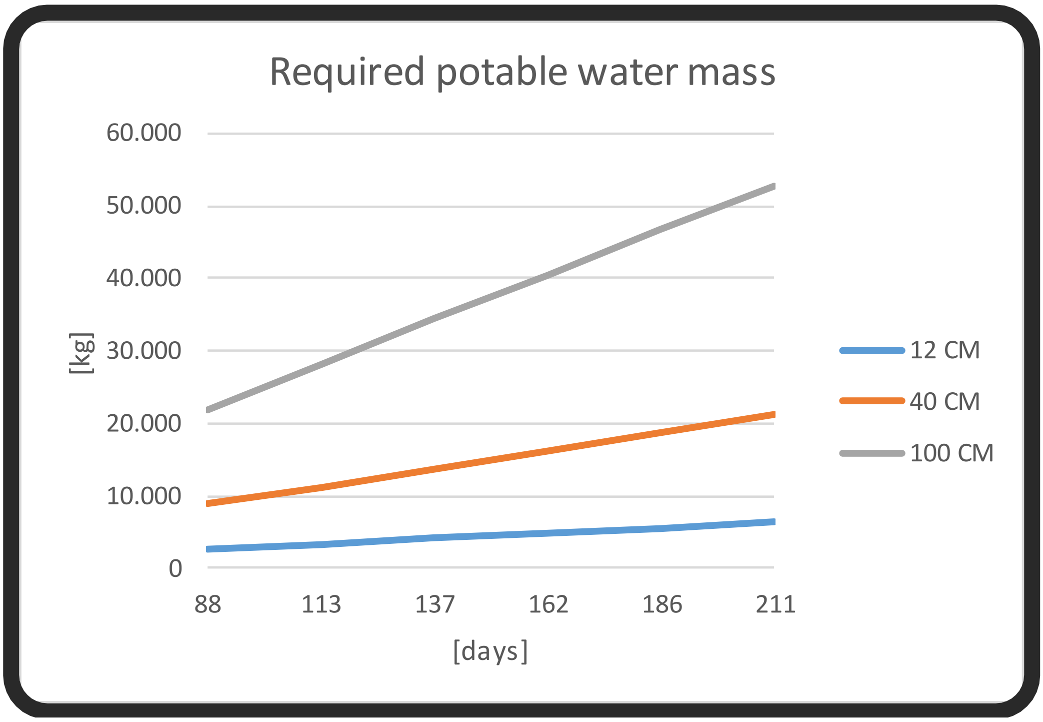

Figure 4-4: Required potable water mass of a storage system for the considered scenarios

iii. **Requirement**: Stored hygiene water shall provide sufficient capacity to meet mission specific contingency needs.

Rationale: Hygiene water is required for personal grooming, shower, and ECLSS equipment like the oxygen generation system. Personal grooming includes skin care, shaving, and hand wash after urination and defecation, after exercise during medical exams and health maintenance, and before and after meals [38, p. 35]. For this task the same value as on the ISS of 0.40 kg $CM\text{-}d^{-1}$ is assumed [10, p. 64]. For the shower, it is assumed that the passengers are allowed to use the shower once a week and that the water usage rate is 10 L per shower event (1.43 kg $CM\text{-}d^{-1}$), which is the same as on MIR and early ISS planning [38, p. 26]. The assumed flush water is 0.30 kg $CM\text{-}d^{-1}$ [10].

Figure 4-5 lists the accumulated hygiene water masses over the considered mission scenarios. The minimal required hygiene water mass for the best-case scenario for 12 crew member and 88 days is 2,247.77 kg, while the worst-case scenario needs 44,912.86 kg for 100 crew member and 211 days.

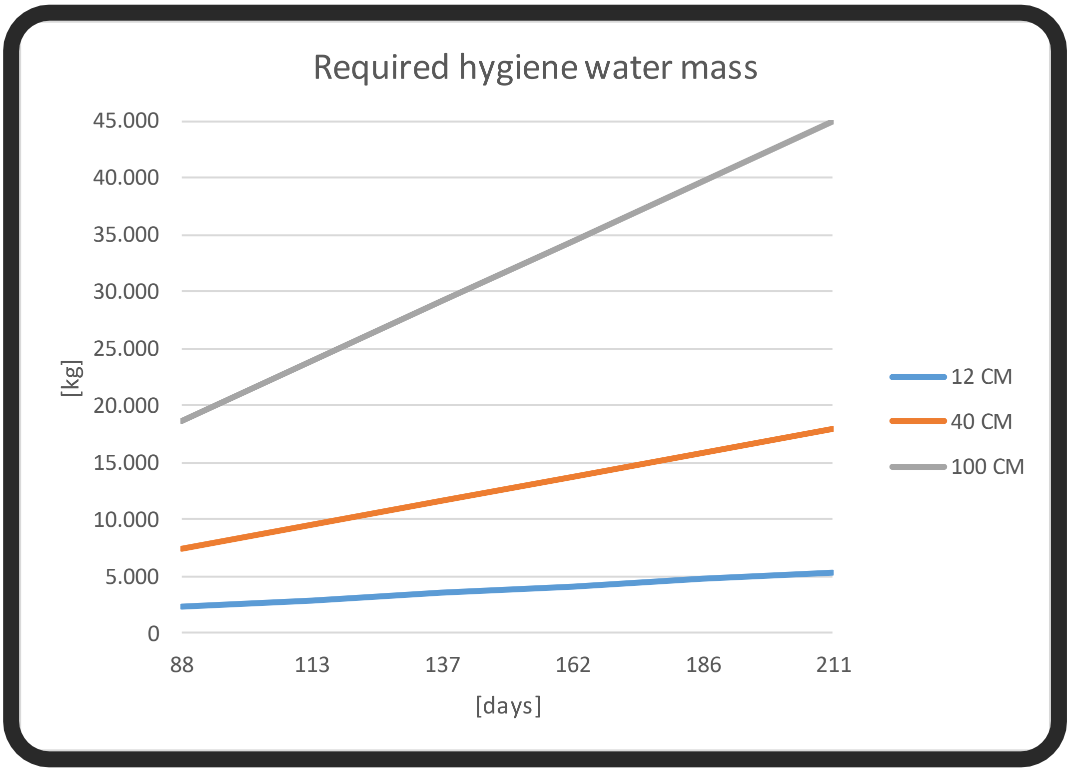

Figure 4-5: Required hygiene water mass of a storage system for the considered scenarios

iv. **Requirement**: It is permissible to store potable and hygiene water together when the hygiene water meets potable water quality standards specified in [45].

c. **Regenerate Water**

Requirement: It is permissible to regenerate potable and/or hygiene water. [37]

d. **Manage Wastewater**

Requirement: Wastewater shall be managed for resource recovery, storage, and/or disposal. [37]

e. **Accept Wastewater**

Requirement: Wastewater shall be accepted from points of collection in accordance with applicable interface specifications. [37]

f. **Transport Wastewater**

Requirement: It is permissible to transport wastewater between points of collection, storage facilities, and/or processing equipment in accordance with applicable interface specifications. [37]

Rationale: Wastewater storage, processing, and collection facilities could be placed away from each other. This may perhaps be required due to physical constraints, safety considerations or efficiency reasons. [37]

g. **Store Wastewater**

Requirement: Storage for wastewater shall provide the minimum capacity necessary to meet peak and contingency storage needs. [37]

Rationale: Wastewater sources are hygiene waste water from personal grooming and shower, urine with flush water, and different wastes. The last one belongs to the waste management system and is not considered here. The daily hygiene waste water rate is assumed to be 1.83 kg $CM\text{-}d^{-1}$, which is the sum of shower water and water for personal grooming [10]. The urinal waste water is considered to be 1.5 kg $CM\text{-}d^{-1}$ [10].

h. **Process Wastewater**

i. **Requirement**: It is permissible to process wastewater from humidity condensate to recover potable or hygiene water.

ii. **Requirement**: It is permissible to process hygiene wastewater to recover potable or hygiene water.

iii. **Requirement**: It is permissible to process wastewater from urine to recover potable or hygiene water and produce a concentrated waste. [37]

4.4.5 Waste Management Provision Requirements

a. **Manage Wastes**

Requirement: The life support system shall accept and process gaseous, liquid and solid wastes for resource recovery, transport, storage, and/or disposal. [37]

b. **Accept Gaseous Wastes**

Requirement: Gaseous wastes shall be accepted from points of collection in accordance with applicable interface specifications. [37]

c. **Transport Gaseous Wastes**

Requirement: It is permissible to transport gaseous wastes between points of collection, storage facilities, and/or processing equipment in accordance with applicable interface specifications. [37]

Rationale: Gaseous waste storage, processing, and collection facilities could be placed away from each other. This may perhaps be required due to physical constraints, safety considerations or efficiency reasons. [37]

d. **Store Gaseous Wastes**

Requirement: Storage for gaseous wastes shall provide the minimum capacity necessary to meet peak and contingency storage needs. [37]

e. **Dispose of Excess Gaseous Wastes**

Requirement: Excess gaseous wastes shall be disposed. [37]

Rationale: This is only adequate when no useful products can be obtained with reasonable effort and environment restrictions do not prevent this or when it is not economical.

f. **Accept Solid and Concentrated Liquid Wastes**

Requirement: Solid and concentrated liquid wastes shall be accepted from points of collection in accordance with applicable interface specifications. [37]

g. **Transport Solid and Concentrated Liquid Wastes**

Requirement: It is permissible to transport solid and concentrated liquid wastes between points of collection, storage facilities, and/or processing equipment in accordance with applicable interface specifications. [37]

Rationale: Solid and concentrated liquid waste storage, processing, and collection facilities could be placed away from each other. This may perhaps be required due to physical constraints, safety considerations or efficiency reasons. [37]

h. Store Solid and Concentrated Liquid Wastes

i. **Requirement**: Temporary storage of unprocessed solid and concentrated liquid wastes shall provide the minimum capacity necessary to meet peak and contingency storage needs. [37]

ii. **Requirement**: Long-term storage for residuals and non-recovered wastes shall be provided. [37]

i. Process Solid and Concentrated Liquid Wastes

Requirement: It is permissible to process solid and concentrated liquid wastes to recover useful products. [37]

5 Assumptions and Simplifications

For a decent analysis and interpretation of the results, assumptions and simplifications must be stated to understand the limitations and possible inaccuracies of the design process. Numerous general assumptions must be made to design an ECLSS for the SpaceHab because of missing data. Specific limitations related to the dynamic simulation in V-Hab (see 11.1.1) or the Life Support Trade Off Tool (see 14A.1) are described in the specific chapters. Additional and remarkable ones are outlined below:

- As stated in the requirements 4.4.2.d, 4.4.3.a, and 4.4.4.c, regeneration is allowed for oxygen and water. Even when allowed by the requirements (4.4.5.i), waste recycling is not considered as outlined in chapter 9.2.
- Integration of the ECLSS systems with other vehicle systems is considered to be flawless.
- Overboard dump is limited to gases, as specified in requirement 4.4.5.e. Liquids could be vented when vaporized.
- The Thermal management system is assumed to have two pumped, single phase coolant loops, similar to the ISS configuration with low temperature and moderate temperature loops. The heat in the coolant loops is delivered to external coolant loops where heat is transported to space radiators.
- Cabin leakage is assumed to be zero for the designing of the trace contaminant control subsystem to comply with a worst-case scenario.
- Manual handling of feces shall be precluded.
- Suit definition and consideration of EVA operations are not required.

The hierarchical level of ECLSS elements are outlined in Table 5-1. The term ‘system’ is often used synonymously for ‘subsystem’ and this thesis makes no difference. The lowest level considered for the trade analysis are components, while mainly complete assemblies will be compared.

Table 5-1: Element levels

Level	Description	Examples
System	Group of subsystems	ECLSS
Subsystem	Division of a system or group of related functions	AR, WRM
Assembly	Collection of related units within a subsystem	OGS, CCAA
Component	Functional unit in an assembly	Pump, blower
Part	Individual unit	Tube, bolt

5.1 Rescale Factors

For all systems in the database (see Appendix 14A), the mass, volume, power and thermal rejection are only given for a specified number of crewmembers, normally between 2 and 8, or for a specified processing rate. Therefore, it was needed to scale-up the parameters of the components or assemblies. The following scaling factors derived from [52, p. 7] are applied. When processing rates are given, they should always be preferred and $n_{crew,mission}$ and $n_{crew,given}$ has to be replaced by the needed and given processing rate respectively.

$$f_{RF,mass} = \frac{n_{crew,mission}}{n_{crew,given}} 0.75 \quad \textbf{Eq. (5-1)}$$

$$f_{RF,volume} = \frac{n_{crew,mission}}{n_{crew,given}} 0.75 \quad \textbf{Eq. (5-2)}$$

$$f_{RF,power} = \frac{n_{crew,mission}}{n_{crew,given}} \quad \textbf{Eq. (5-3)}$$

$$f_{RF,thermal} = \frac{n_{crew,mission}}{n_{crew,given}} \quad \textbf{Eq. (5-4)}$$

$$f_{RF,mass,consumables} = \frac{n_{crew,mission}}{n_{crew,given}} \frac{t_{required}}{t_{given}} 0.75 \quad \textbf{Eq. (5-5)}$$

$$f_{RF,volume,consumables} = \frac{n_{crew,mission}}{n_{crew,given}} \frac{t_{required}}{t_{given}} 0.75 \quad \textbf{Eq. (5-6)}$$

With:

- $f_{RF,mass}$ [-] - Rescale factor to scale the mass of a system to a bigger crew size
- $f_{RF,volume}$ [-] - Resale factor to scale the volume of a system to a bigger crew size
- $f_{RF,power}$ [-] - Rescale factor to scale the power of a system to a bigger crew size
- $f_{RF,thermal}$ [-] - Rescale factor to scale the thermal heat rejection of a system to a bigger crew size
- $f_{RF,mass,consumables}$ [-] - Rescale factor to scale the mass of consumables of an assembly
- $f_{RF,volume,consumables}$ [-] - Rescale factor to scale the volume of consumables of an assembly
- $n_{crew,mission}$ [-] - Required crew size for the mission
- $n_{crew,given}$ [-] - Given crew size of component or assembly
- $t_{required}$ [days] - Required mission time
- t_{given} [days] - Given mission time of component or assembly

As can be seen in the equations above, power and thermal increase linear, whereas for mass and volume only an increase of 75 % is assumed. The reason why mass and volume are not doubled for twice the crew size or processing rate is that the size of many components, such as tubing, increases less than linear with an increasing crew size or processing rate.

5.2 Certainty Factor

Certainty factors ($f_{Certainty}$) are used for the technology parameters mass, volume, power, thermal heat rejection, TRL, maintenance time, and reliability, since not for every technology all parameters are given. The following guidelines from [4] are used:

- 100% value confirmed through multiple references
- 75% value from reference or based on reasonable assumptions
- 50% value based on reference with questionable assumptions
- 25% value based only on assumptions
- 0% value based on 'educated guess'

This factor is applied for the multi-criteria-method in the trade-off analysis in chapter 7.

5.3 Stowage Volume

The volume of components and assemblies is often not the same as the needed stowage volume in the spacecraft. For example, the volume of spherical tanks requires more space than the sphere alone due to additional needed valves, tubes etc. and attachments. Hence, some assumptions (derived from [52, pp. 8-9]) must be made:

1. Cylindrical geometries need as much space as the circumscribed cuboid. The stowage penalty factor for a cylinder ($f_{SPF,cylinder}$) is given by Eq. (5-7) below. For derivation see [52, pp. 8-9].

$$f_{SPF,cylinder} = \frac{4}{\pi} \quad \textbf{Eq. (5-7)}$$

2. For spherical geometries, the needed stowage space is also assumed to be the circumscribed cube. The stowage penalty factor for spheres ($f_{SPF,sphere}$) are given by Eq. (5-8). The derivation can be found in [52, pp. 8-9].

$$f_{SPF,sphere} = \frac{6}{\pi} \quad \textbf{Eq. (5-8)}$$

3. For cubic shapes, no additional volume is considered
4. The wall thickness of the calculated circumscribed cube under points 1. and 2. are assumed to be zero.
5. Additional parts for a component or assemblies, like valves, tubes etc. that are much smaller than the volume of the core system are assumed to be included in the calculated cube from points 1. and 2.

5.4 Contingencies on Mass and Power

For a preliminary design as developed in this thesis, many assumptions and simplifications must be made. Consequently, it is important to add contingencies to get more realistic values and have some margin in later iterations. The contingencies used in this thesis are stated in Table 5-2 and are dependent on the mass of the component or assembly and the maturity of the technology. When referring to a column, like CoF 1, then 'new design or first-generation' is used etc. [13, p. 372]

Table 5-2: Mass and power contingencies [13, p. 372]

% increase		new design or first-generation	new generation based on previous concept	production level development based on existing design
CoF		**1**	**2**	**3**
0-50 kg	mass	35	25	3
	power	75	25	12
50-500 kg	mass	30	20	3
	power	65	22	12
500 - 2500 kg	mass	25	15	1
	power	60	20	12
>2500 kg	mass	22	12	0.8
	power	35	20	11

6 Life Support Systems

The classical elements of a life support system are water, air, and food. Several other functions should be considered, like vibration, noise, thermal and pressure management, radiation, waste, and gravity. Besides the preliminary observation in 3.2.2, vibration and noise are excluded from a detailed analysis. Habitability components and functions are analyzed under Crew Accommodations and Final Design of the ECLSS subsystems. The focus in this chapter are on ECLSS subsystems defined by NASA which consists of Atmosphere Control and Supply (ACS), Temperature and Humidity Control (THC), Atmosphere Revitalization (AR), and Water Recovery and Management (WRM). Waste Management (WM) is described in chapter 9.2. Fire Detection & Suppression (FDS) is not described in detail, since only portable breathing apparatus are considered (see Table 11-7 and Table 11-8) and monitoring of the atmosphere is done by the major constituent analyzer (Table 9-11). [38, p. 3]

Life support systems can be grouped into open-loop and closed-loop. For an open-loop system, all needed consumables must be brought in the first place or must be resupplied and no recycling is considered. The big advantage of such a system is the high reliability and simplicity. But the drawback is the heavy mass for long missions. Such a system is from now on called storage system. The opposite is a closed-loop system were nothing is supplied from outside the system resulting in less weight for long missions. Otherwise such systems often have a low TRL and higher thermal and power needs. Subcategories of the closed loop systems are physico-chemical (p/c) and biological processes. If they are encompassed in one system, it is called a hybrid LSS. While p/c processes are frequently used in past and present spacecraft's and therefore well understood, biological systems are relatively new and need much more power, volume, and maintenance. Biological systems are excluded from the trade study, since they have an insufficient TRL. For an analysis of such a system see chapter . [2, pp. 79-81, 13, p. 541]

The functions of a life support system could be divided into two classes: non-regenerative and regenerative. Non-regenerative functions are for example the replacement of system leakage losses. While regenerative functions include resources such as water or oxygen which can be recycled. The more recycling is considered, the more loop closure is achieved. The loop closure is especially important for the analyzed system since a lot of people are considered and the mission times are relatively long. [2, p. 82]

Several functions of the ECLSS needs p/c processes. These are pressure control, ventilation, monitoring, particulate removal, nitrogen supply, water distribution, and removal or storage of non-organic solids. [13, p. 552]

Because the complexity of an ECLSS for a mission to Mars is so high (see Figure 6-1), some researchers suggest that technologies from ISS should be used directly [17, p. 3], while other say this is not a feasible solution and specialized systems are needed [53]. For the purpose of this thesis, a thoroughly analysis of all eligible technologies is made to get to an optimized system that fulfills all requirements and constraints specified before.

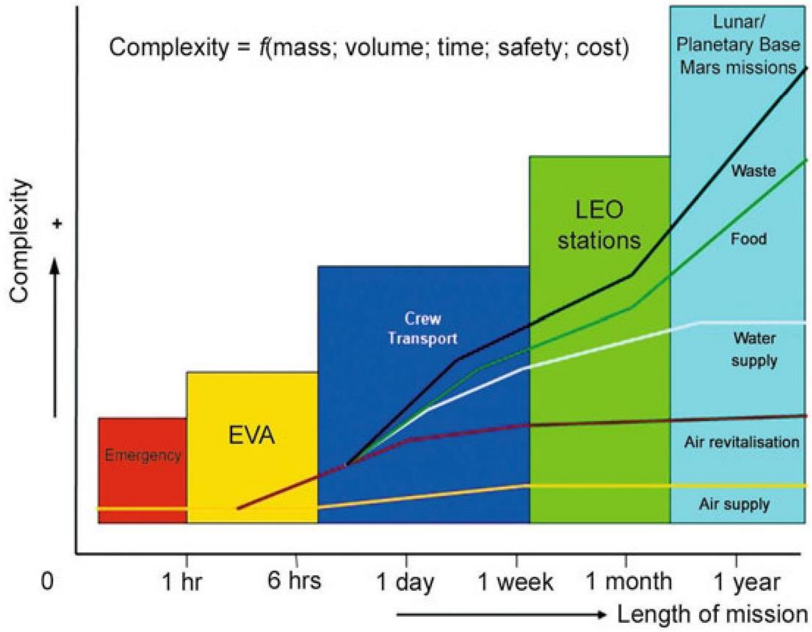

Figure 6-1: Complexity of ECLSS increases over time and is a function of mass, volume, time, safety, and cost [54, p. 163]

6.1 Atmosphere Control and Supply

The ACS subsystem consist of pressure and composition control functions to regulate and monitor partial and total pressures, which includes O_2 and N_2 pressure control vent and relief, storage, and distribution [2, pp. 176-178]. A breakdown of the system can be seen in Figure 6-2. Overall 4 different technologies where examined for the subsequent trade analysis in chapter 7.

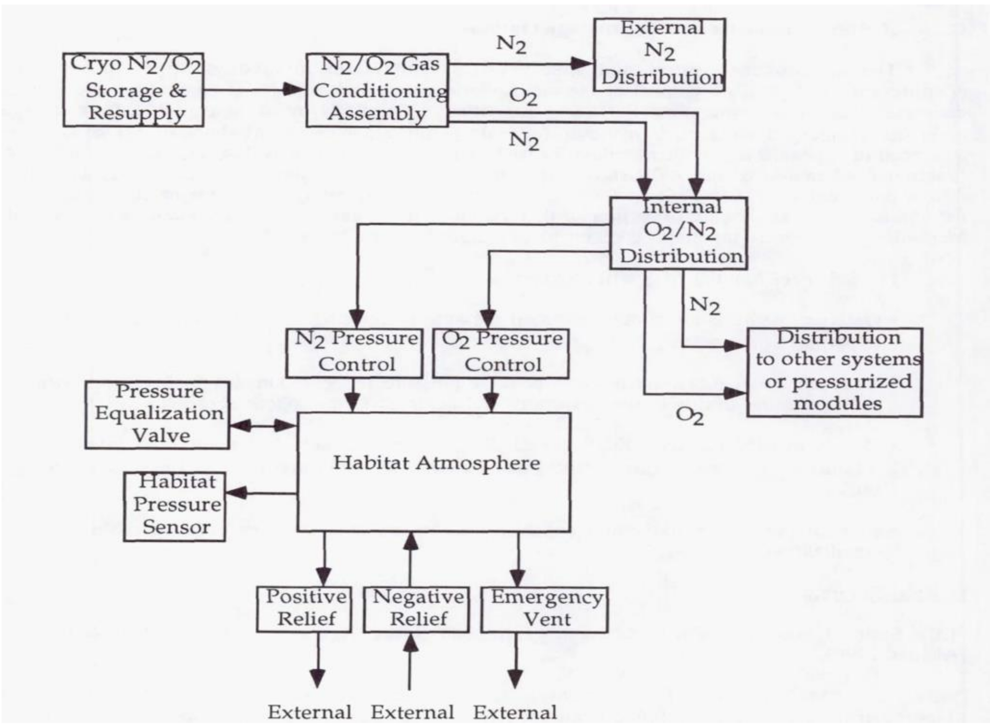

Figure 6-2: ACS schematic [55, p. 208]

For the calculations of the volumes and masses of the repressurisation and leakage tanks, always the maximum mission duration of 211 days is assumed. This is because the tanks are mainly for repressurisation and the leakage mass is only a fraction of the total needed mass. This complies with a worst-case approach.

There are 22 functions that the ACS system has to fulfill. For the trade-off analysis in chapter 7 only the O_2 and N_2 providing functions have significant different possible options. The other functions are included in the Final Design in chapter 10.1, but need no technology comparison.

The main functions of the ACS subsystem are providing oxygen and nitrogen through storage. While storing O_2 in the form of water is generally preferable (see 8.3), the ACS has to provide N_2 and O_2 in the event of an emergency as stated under requirements 4.4.1.a and 4.4.1.b or when only a storage system is considered. Because repressurisation times are required to be under 24 hours (requirement 4.3.1.b), water electrolysis is not feasible due to power and cooling restrictions. For a repressurization of the SpaceHab, over 390 kW of power and around 215 kW of cooling would be needed by water electrolysis to match the mentioned repressurisation times and therefore this approach does not match the necessities for an emergency backup system nor the constraints of the system.

6.1.1 High-pressure Storage

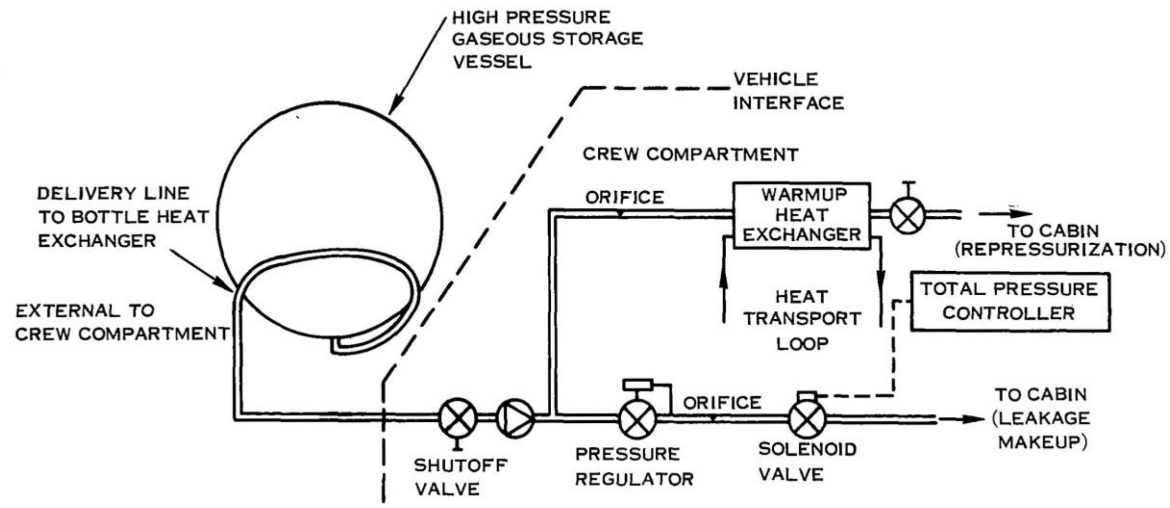

Figure 6-3: High pressure gaseous storage concept [50, p. 75]

6.1.1.1 Description

High-pressure storage tanks for O_2 and N_2 are at ambient temperature with an optimum pressure-to-volume ratio at a pressure of a few million Pa. As can be seen in Figure 6-3, this concept is very simple with only a limited number of parts and is therefore one of the most reliable and safest systems. For small amounts of fluid these systems are the optimum but the disadvantages are the high mass at high pressures and sometimes a material compatibility concern. For example titanium could not be used for oxygen storage. [2, 13, 50, p. 71]

6.1.1.2 Data and Sizing for Repressurisation and Leakage

Two geometries for high-pressure storage tanks can be considered, spherical and cylindrical tank. Spherical tanks have the advantage that they are very strong structures with no weak points due to the even distribution of stresses on the sphere´s surface. It is also the most weight efficient shape. Therefore, they are selected over cylindrical ones. The disadvantage is that they are more complicated to manufacture and therefore more expensive.

There are different types of pressure vessels. Type I vessels are all-metal construction. These are by far the cheapest types, but also the heaviest and that with the lowest possible pressure of all pressure vessel types. Type II are mostly steel or aluminum and have composite overwrap to save mass. Type III has only a metal liner with complete composite shell which hold the mechanical loads. The same is true for the Type IV pressure vessel with a polymer liner. Type III and Type IV tanks cost around twice as much as Type II vessels or 3.5 times more than Type I vessels comparing to a mass saving of around 30 % or 75 % respectively. Current development efforts are to get an 82.5 MPa rating for Type IV vessels, which would mean an even further mass saving. The newest development are Type V tanks which consist of composite without a liner. These vessels have even further mass savings and therefore are predestinated for space applications. A new developed tank for the ISS, called NORS for Nitrogen/oxygen recharge system, has a maximum pressure of 41.37 MPa and is a full-composite tank. Additional the propellant tanks of the ITS will be Type V pressure vessels and therefore it is assumed that a possible high pressure storage will be consisted of full-composite tanks. [2, 56, 57]

Oxygen and Nitrogen could potentially be already mixed in the tank. But such a system would be much less flexible and the mass and volume is comparable to a separate system. For that reason separate tanks for O_2 and N_2 are used. [50, p. 72]

A heater is needed to prevent regulator freeze-up and to warm the fluid for cabin delivery. This heater could use waste heat from the ITCS and would have the benefit to reduce the load on the radiators. But this effect is only appreciable during emergency repressurisation or when the system is constantly used in a storage system. [50, p. 76, 50, p. 72]

For the nitrogen tank, the used ratio of tank-mass to gas-mass (kg kg^{-1}) is 0.556 and for the oxygen tanks it is 0.364 [10, p. 55]. It is not stated for what pressure these values are and if needed equipment like valves are already included. But comparing this with other data from type IV pressure vessels, it is very likely that this values are at least for a type IV or even type V pressure vessel without any additional equipment [58].

The masses for the tanks can be calculated by multiplying the needed N_2 and O_2 masses given in Table 4-2 and Table 4-4 respectively with the tank ratio mentioned above. For the required valves, flowmeter, tubes etc., a conservative 20 kg per tank is assumed. The last point to consider for the mass is the contingency factor. Storage systems are commonly used in spaceflight and therefore a CoF of 3 is assumed. With these assumptions, the total mass for the storage tanks can be calculated. A breakdown of the masses is given in Table 6-1.

Eq. (6-1) can be used for the volume estimation of the tanks. The O_2 and N_2 masses are stated in Table 4-4 and Table 4-2 and their respective densities at 34.5 MPa of 451.12 kg m^{-3} and 336.35 kg m^{-3} [59]. The wall thickness including insulation is assumed to be 10 mm which must be accounted for in the final volume calculation. The maximum filling degree is assumed to be 95 %. Because the tanks are considered to be outside of the pressurized compartment, no stowage volume factor is applied. But volume for tank equipment will be inside the pressurized volume and must therefore considered. For simplicity, a cube with a side length of 40 cm is assumed to be sufficient, which would be 0.064 m³ per tank.

$$V_{tank} = (\sqrt[3]{\frac{m_{gas}}{\rho_{gas}} \frac{3}{4\pi}} + t_{wall})^3 \frac{4}{3} \pi \frac{1}{T_{FD}} + 0.064 \qquad \textbf{Eq. (6-1)}$$

$$V_{gas} = \frac{m_{gas}}{\rho_{gas}} = \frac{4}{3} \pi r_{sphere}^3 \qquad \textbf{Eq. (6-2)}$$

with:

- V_{tank} [m³] - volume of tank
- V_{gas} [m³] - volume of gas
- m_{gas} [kg] - mass of gas in volume
- ρ_{gas} [kg m^{-3}] - gas density
- r_{sphere} [m] - sphere radius
- t_{wall} [m] - wall thickness
- T_{FD} [%] - Maximum tank filling degree

For the number of tanks, it must be considered that they are assumed to be outside the pressurized compartment. The only bigger unpressurized volume for the Evolved-SpaceHab design is the space between the lowest deck and the propellant tank as can be seen in Figure 6-4. To geometrically determine the maximum usable area between the outer wall, the floor of the lowest deck and the propellant tank wall, a two-dimensional approximation is used. The dome of the propellant tank is assumed to be a half-sphere, or in 2-D a circle, with a radius of 6 m. With the help of a triangle, the maximum tank volume in this space can be calculated. A right, isosceles triangle must be used for this. Therefore, the isosceles sides of the triangle are 3.48 m, subtraction a margin of 10 % gives a side length of 3.13 m (a). With the Pythagorean theorem, the length of the hypotenuse can be calculated to 4.43 m (c). With Eq. (6-3), the maximum spherical volume inside this space can be calculated to 3.22 m³.

$$V_{max,sphere} = \frac{4}{3} \pi r_{circle\ in\ triangle}{}^3 \qquad \textbf{Eq. (6-3)}$$

$$r_{circle\ in\ triangle} = \frac{2A_{triangle}}{U_{triangle}} \qquad \textbf{Eq. (6-4)}$$

$$A_{triangle} = \frac{a_{triangle}{}^2}{2} \qquad \textbf{Eq. (6-5)}$$

$$U_{triangle} = 2\, a_{\mathrm{triangle}} + c \qquad \textbf{Eq. (6-6)}$$

with:

- $V_{max,sphere}$ [m³] - maximum spherical volume inside unpressurized space

- $r_{circle\ in\ triangle}$ [m] - maximum radius of circle in triangle
- $A_{triangle}$ [m²] - triangle area
- $U_{triangle}$ [m] - triangle extensive
- a_{triangle}, c [m] - length of triangle sides

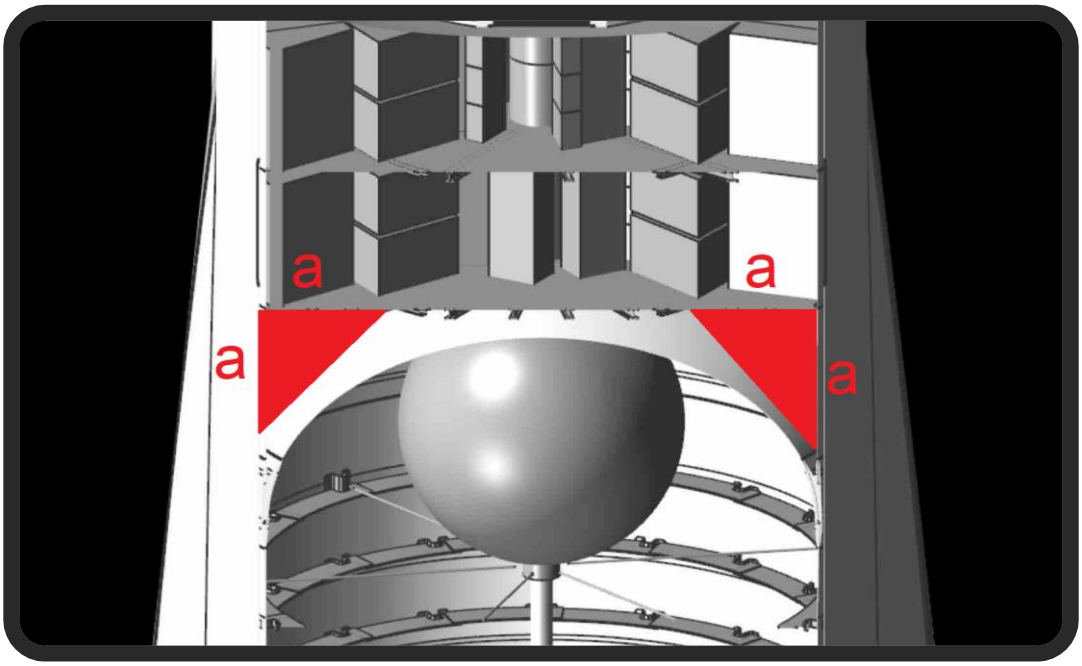

Figure 6-4: Unpressurized space between lowest deck and propellant tank [11]

Using Eq. (6-1) and Eq. (6-3), the number of required tanks (n_{tanks}) can be calculated with Eq. (6-7)[10]. For oxygen, it is further assumed, that at least 2 tanks are considered for safety reasons.

$$n_{tanks} = \frac{V_{tank}}{V_{max,sphere}} \quad \textbf{Eq. (6-7)}$$

This system is mostly passive. The only active component is the high-pressure transducer. A Ultra Precision Pressure Transducer from Honeywell has a power input of under 0.3 W [60], no losses in the transducer and the wiring are stated. To make up for these losses and to remain conservative, 1 W instead of 0.3 W is used for the required power in the further calculations, including an CoF of 3. With 2 O_2 tanks and assuming double redundancy per tank, this leads to a total power requirement of 9 W.

Since no active cooling or heating elements shall be integrated the thermal balance is negligible.

High-pressure N_2 and O_2 storage systems have been used in flight for years, which means the system has a TRL of 9.

For a reliability standpoint, the mean time between failure (MTBF) can be estimated to 328,000 hours when assuming 2 spares for each pressure regulator which is the component with the lowest MTBF in this system [50, pp. 73-74]. The reliability can then be calculated with Eq. (4-1).

[10] Volume for tank equipment is not stored in this space and must technically speaking be subtracted. Because this volume is only minor compared to the tank volume, this is neglected.

It is further assumed that the system is managed automatically so no crew time is needed for operation or maintenance.

The results from the calculations and considerations above for the O_2 system can be found in Table 6-1 and for the N_2 system in Table 6-2 below.

Table 6-1: Properties of the O_2 high-pressure storage system for repressurisation and leakage

Parameter	Value	Unit
Number of required O_2 tanks (SpaceHab)	2	[-]
Total O_2 tank mass (SpaceHab, empty)	156.12	[kg]
Total O_2 tank mass (SpaceHab with O_2)	462.63	[kg]
Total O_2 tank volume (SpaceHab)	0.88	[m³]
Number of required O_2 tanks (Evolved-SpaceHab)	2	[-]
Total O_2 tank mass (Evolved-SpaceHab, empty)	220.73	[kg]
Total O_2 tank mass (Evolved-SpaceHab with O_2)	699.57	[kg]
Total O_2 tank volume (Evolved-SpaceHab)	1.30	[m³]
Total O_2 tank equipment volume	0.13	[m³]
Required power	9	[W]
TRL	9	[-]
Reliability	0.9936	[-]

Table 6-2: Properties of the N_2 high-pressure storage system for repressurisation and leakage

Parameter	Value	Unit
Number of required N_2 tanks (SpaceHab)	2	[-]
Total N_2 tank mass (SpaceHab empty)	605.65	[kg]
Total N_2 tank mass (SpaceHab with N_2)	1,612.23	[kg]
Total N_2 tank volume (SpaceHab)	3.39	[m³]
Total N_2 tank equipment volume (SpaceHab)	0.13	[m³]
Required power (SpaceHab)	9	[W]
Number of required N_2 tanks (Evolved-SpaceHab)	3	[-]
Total N_2 tank mass (Evolved-SpaceHab empty)	943.09	[kg]
Total N_2 tank mass (Evolved-SpaceHab with N_2)	2,514.60	[kg]
Total N_2 tank volume (Evolved-SpaceHab)	5.25	[m³]
Total N_2 tank equipment volume (Evolved-SpaceHab)	0.19	[m³]
Required power (Evolved-SpaceHab)	14	[W]
TRL	9	[-]
Reliability	0.9847	[-]

6.1.1.3 Data and Sizing for Storage System

The needed oxygen mass for consumption by the crew depends on the selected schedule. For a description of the different considered schedules see chapter 3.2.3 and for the required masses see requirement 4.4.1.d. The O_2 tank design for a storage system is only depending on the sum of the total consumption during the mission.

It is further assumed, that for safety reasons, the repressurization tanks and O2 tanks for consumption are separated. This enhances redundancy and results in a more reliable system.

For the tank masses, the same ratio as for the O_2 repressurization tanks are used.

The required O_2 tank volumes for a storage system can be calculated by Eq. (6-1), where the gas mass is the required mass from 4.4.1.d. and the density of O_2 at 34.5 MPa is 451.12 kg m^{-3}.

The same transducer as for the repressurization system is assumed, with the same parameters.

The parameters TRL and MTBF are the same as for the oxygen tanks for repressurization.

Table 6-3 represent a breakdown of the O_2 tanks for the storage system. Only the best-case with 88 days and 12 crew members and the worst-case scenario for 211 days and 100 crew members are shown for clarity. For both scenarios, a nominal schedule is assumed.

For evaluation that the calculated number of tanks can fit inside the unpressurized space (shown in Figure 6-4), the circumference is used. By applying Eq. (6-8) and using 0.82 m as usable radius, the circumference of the unpressurized space can be calculated to 35.13 m. For the worst-case scenario with 100 people, 211 days and Evolved-SpaceHab design, 8.01 m of this circumference is used by tanks, or 27.12 m are still left. Actually 42 tanks with maximum radius could be installed inside the unpressurized space.

$$U_{unpressurized\ space} = r_{unpressurized\ space}\,\pi \qquad \textbf{Eq. (6-8)}$$

$$r_{unpressurized\ space} = r_{SpaceHab} - r_{circle\ in\ triangle} \qquad \textbf{Eq. (6-9)}$$

with:

- $U_{unpressurized\ space}$ [m] - circumference of unpressurized space
- $r_{unpressurized\ space}$ [m] - usable radius of unpressurized space
- $r_{SpaceHab}$ [m] - radius of SpaceHab (6 m)
- $r_{circle\ in\ triangle}$ [m] - maximum radius of circle in triangle

Table 6-3: Properties of O2 high-pressure storage system for consumption

Parameter	**Value**	**Unit**
Number of required O_2 tanks (best-case)	2	[-]
Total O_2 tank mass (best-case, empty)	405.60	[kg]
Total O_2 tank mass (best-case with O_2)	1,377.54	[kg]
Total O_2 tank volume (best-case)	2.48	[m³]
Total O_2 tank equipment volume (best-case)	0.13	[m³]
Required power (best-case)	9	[W]
Number of required O_2 tanks (worst-case)	21	[-]
Total O_2 tank mass (worst-case, empty)	7,713.71	[kg]
Total O_2 tank mass (worst-case with O_2)	27,134.15	[kg]
Total O_2 tank volume (worst-case)	47.29	[m³]
Total O_2 tank equipment volume (worst -case)	1.34	[m³]
Required power (worst-case)	94	[W]
TRL	9	[-]
Reliability (best-case)	0.9936	[-]
Reliability (worst-case)	0.9847	[-]

6.1.2 Cryogenic Storage

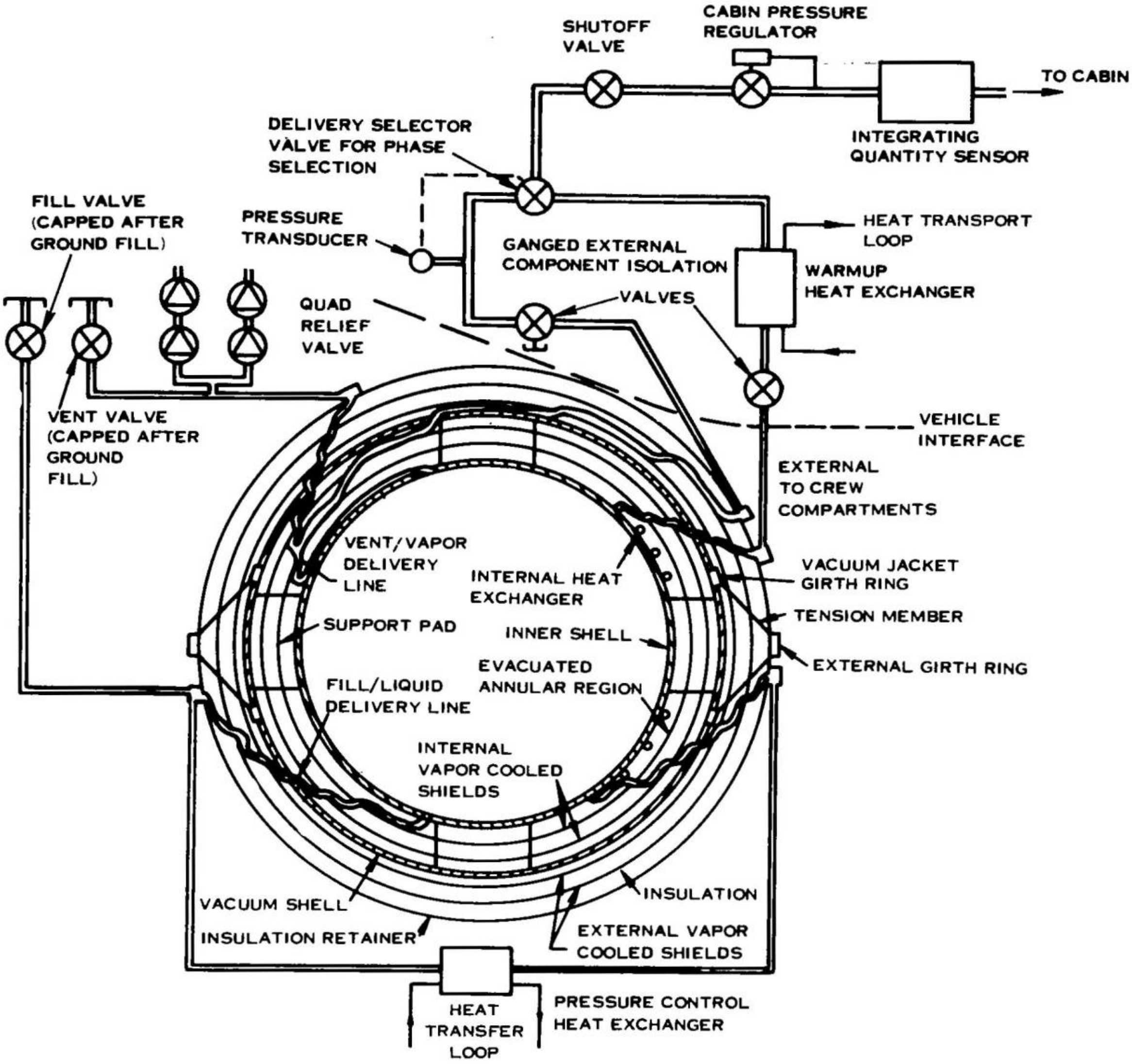

Figure 6-5: Cryogenic storage system schematic [50, p. 97]

6.1.2.1 Description

Two alternatives are considered for cryogenic O_2 storage. Dedicated storage tanks are of similar setup as the high-pressure tanks in section 6.1.1, and a size increase of the already existing O_2 propellant tank. Cryogenic N_2 storage is of comparable structure as the high-pressure tanks.

Subcritical cryogenic storage tanks, like the one in Figure 6-5, operate at relatively low pressures (around 340 kPa) but need to be isolated to hold the low temperatures and maybe require active thermal cooling. The envisioned cryogenic storage system will operate at a pressure of 34.5 MPa. Such a high pressure for cryogenic storage are common in industry [61, 62]. This approach has several advantages over the high-pressure tanks like a high storage density due the fact that the O_2 or N_2 are liquid. That means that the tanks have reduced volume. Eventually it could be used as a refrigeration source when designed properly. But there are also some disadvantages like the sensitive to heat leaks or that the fluid delivery is more complex. Additional, due the fact that some venting is occurring and that the specific tank mass is higher, the tank often weigh more than a high-pressure tank. [2, 11, 50, pp. 93-95, 61]

6.1.2.2 Data and Sizing for Repressurisation and Leakage

The same shape consideration as that of the high-pressure vessel under 6.1.1.2 are used and therefore a spherical shape is considered for both the O_2 and N_2 tanks.

For flexibility and safety reasons, the species are in separate tanks. SpaceX uses a cryogenic temperature of 66.15 K (-207°C) for their Falcon 9 LOX system which is slightly lower than the boiling point of O_2 of 90.19 K (−182.96 °C). For calculations, a temperature of 73.15 K for the liquid O_2 is assumed. The boiling point of N_2 is 77.36 K (−195.8 °C). For simplification, the same temperature for liquid N_2 as for O_2 is assumed.

The density of O_2 and N_2 at the cryogenic temperature of 73.15 K is around 1268.76 kg m^{-3} and 883.42 kg m^{-3} respectively. When further assuming that all tanks should be filled at 95 % at beginning of the mission, the required volumes can be calculated by dividing the needed masses stated in Table 4-2 through the densities to get to the required fluid volumes stated in Table 6-4. For the wall, only a single wall is assumed. Normally double walls are needed, because a vacuum is generated between the two walls to reduce the boil-off rate. Due to the fact that the tanks are assumed outside the pressurized section of the SpaceHab, a vacuum is already given and therefore only one wall is needed. The same type V for the wall material is assumed as for the high-pressure vessel. This is again in compliance with the proposed propellant tank design by SpaceX. The wall thickness is thus assumed to be 5 mm.

Table 6-4: Minimum required fluid volumes for cryogenic repressurization storage

Volume of fluid (m^3)	O_2	N_2
SpaceHab	0.24	1.14
Evolved-SpaceHab	0.38	1.78

The used tank-to-gas mass-ratio is 0.429 for the O_2 storage [63] and 0.524 for the N_2 tank [10, p. 55]. The same assumptions as stated for the high-pressure storage tanks are used.

Insulation is needed to prevent a pressure rise due to warming of the fluid. Normally a vacuum is used to reduce or prevent heat loading due to gas conduction. Because it is assumed that the tanks for the analyzed system are outside the crew compartments and not in the pressurized section of the SpaceHab, a near perfect vacuum can be assumed. But even then, the tanks can be heated up by radiation. Because of this, a multi-layer insulation shield around the tanks is considered to minimize the radiation effects. The heat transfer though MLI can be defined by Eq. (6-10). When assuming a 40 layer MLI consisting of aluminum foils and the tank wall has the same temperature as the liquid (73.15 K) and a conservative 200 K environment, the heat leak is around $9.0545*10^{-2}$ W m^{-2}. When considering the volumes of the tanks stated in Table 6-5 and

Table 6-6, the total heat transfer through the MLI is between 0.2820 W and 0.8063 W. Dividing the total heat transfer through the vaporization enthalpy of 214 kJ kg^{-1} for O_2 and 199 kJ kg^{-1} for N_2, gives the needed venting consumption or boil-off rate. The lowest is for one O_2 tank and assuming the shortest mission duration of 88 days with SpaceHab design which would be 12.02 kg of O_2, or 7.71 % of the oxygen in the tank. The highest is for one N_2 tank with the Evolved-SpaceHab design which is 36.93 kg or 4,64 % of the nitrogen in the tank. Because of this low boil-off rates, no active cooling is considered. The thickness of such a MLI shield would be around 42.7 mm. [64]

$$\dot{q} = \left(\frac{\varepsilon_{MLI}}{(n_{MLI}+1)(n_{MLI}-\varepsilon_{MLI})}\right) \delta \left(T_{env}^4 - T_{wall}^4\right) \qquad \textbf{Eq. (6-10)}$$

with:

- $\dot{q}$ [W] - radiant heat transfer per m²
- ε_{MLI} [-] - emissity of MLI layers (0.04 for Al-foil)
- n_{MLI} [-] - number of MLI layers
- δ [W m^{-2} K^{-4}] - Stefan–Boltzmann constant (5.67 10^{-8})
- T_{env} [K] - temperature of environment
- T_{wall} [K] - temperature of tank wall

For power calculations, the same transducers as described under 6.1.1.2 are used with the same total needed power. Because the system is otherwise passive, no additional power is required.

Cryogenic N_2 and O_2 storage systems have already been used in flight, which means the system has a TRL of 9.

The MTBF for the cryogenic system with minimal spares is 81,400 hours. [50, p. 96]

Like for the high-pressure system it is assumed that the system is managed automatic and consequently no crew time is needed for operation or maintenance.

The alternative concept for a cryogenic storage system is the use of the O_2 propellant tank of the SpaceHab. Because it is not clear if this approach is feasible, since the propellant tank is autogenous pressurized, it is not further considered in this thesis. The calculated values are showing, what considerable mass and volume could potentially be saved when such an approach is used. The N_2 storage system stays the same. To accommodate the O_2, the propellant tank must be slightly increased. The measured diameter in Figure 2-2 is around 5.27 m which leads to a total volume of 76.70 m³ for the spherical O_2 propellant tank. It is further assumed that the tank is filled at 95 % at the beginning of the mission. It is unlikely that the pressure of such a big tank will be the same as the previously calculated O_2 storage tank. Hence, a pressure of 1 MPa is assumed with the same temperature of 73.15 K. This leads to a density of 1,224 kg m^{-3} for the oxygen. With this assumption, it can be calculated that there would be 89,182.89 kg of O_2 in the tank. When the required oxygen for repressurisation and leakage are added to this tank (see Table 4-2), then there must be up to 89,661.74 kg O_2 into the tank, a O_2 mass increase of only 0.54 %. Using Eq. (6-2), the diameter of the tank must be 9.4 mm larger. This leads to a tank volume increase of 0.41 m³.

For the mass calculations, it is assumed that T1000G from TORAYCA® is used by SpaceX, as this is the most advanced carbon fiber created to date. T1000G has a density of 1,800 kg m^{-3} [65]. The Volume of fibers in a composite is normally 60%, where the other 40 % are an epoxy resin. Epoxy resins have a density of around 1,100 kg m^{-3} which means the composite has a density of around 1,520 kg m^{-3}. With an expected wall thickness of 10 mm, the mass increase of the O_2 propellant tank is maximal 4.75 kg.

The results from the calculations and considerations above for the O_2 system can be found in Table 6-5 and that for the N_2 system in

Table 6-6 below.

Table 6-5: Properties of the cryogenic O_2 storage system for repressurisation and leakage

Parameter	Value	Unit
Number of required O_2 tanks	2	[-]
Total O_2 tank mass (SpaceHab, empty)	189.54	[kg]
Total O_2 tank mass (SpaceHab with O_2)	525.24	[kg]
Total O_2 tank volume (SpaceHab)	0.52	[m³]
Growth O_2 propellant tank mass (SpaceHab, empty)	3.04	[kg]
Growth O_2 propellant tank mass (SpaceHab with O_2)	309.55	[kg]
Growth O_2 propellant tank volume (SpaceHab)	0.26	[m³]
Total O_2 tank mass (Evolved-SpaceHab, empty)	268.04	[kg]
Total O_2 tank mass (Evolved-SpaceHab with O_2)	781.41	[kg]
Total O_2 tank volume (Evolved-SpaceHab)	0.70	[m³]
Growth O_2 propellant tank mass (Evolved-SpaceHab, empty)	4.75	[kg]
Growth O_2 propellant tank mass (Evolved-SpaceHab with O_2)	483.59	[kg]
Growth O_2 propellant tank volume (Evolved-SpaceHab)	0.41	[m³]
Total O_2 tank equipment volume	0.13	[m³]
Required power	9	[W]
TRL	9	[-]
Reliability (best-case)	0.9744	[-]
Reliability (worst-case)	0.9397	[-]

Table 6-6: Properties of the cryogenic N_2 storage system for repressurisation and leakage

Parameter	Value	Unit
Number of required N_2 tanks	2	[-]
Total N_2 tank mass (SpaceHab empty)	613.79	[kg]
Total N_2 tank mass (SpaceHab with N_2)	1,697.21	[kg]
Total N_2 tank volume (SpaceHab)	1.71	[m³]
Total N_2 tank mass (Evolved-SpaceHab empty)	921.48	[kg]
Total N_2 tank mass (Evolved-SpaceHab with N_2)	2,586.28	[kg]
Total N_2 tank volume (Evolved-SpaceHab)	2.50	[m³]
Total N_2 tank equipment volume	0.13	[m³]
Required power	9	[W]
TRL	9	[-]
Reliability (best-case)	0.9744	[-]
Reliability (worst-case)	0.9397	[-]

The storage system for consumption consist of cryogenic oxygen tanks, where most parameters are identical to the O_2 repressurisation system. Notable are the fact, that the mass of the cryogenic tanks is around 10 % heavier than a high-pressurization system despite that 14 tanks less are required. This means that for the worst-case scenario of 100 people and 211 days, nearly 3 tons of mass could be saved when no cryogenic storage system is used. The properties of the cryogenic storage system for a best-case and worst-case scenario are listed below, including the propellant tank growth.

Table 6-7: Properties of the cryogenic O_2 storage system for consumption

Parameter	Value	Unit
Number of required O_2 tanks (best-case)	2	[-]
Total O_2 tank mass (best-case, empty)	562.81	[kg]
Total O_2 tank mass (best-case with O_2)	1,534.75	[kg]
Total O_2 tank volume (best-case)	1.17	[m³]
Total O_2 tank equipment volume (best-case)	0.13	[m³]
Growth O_2 propellant tank mass (best-case, empty)	9.62	[kg]
Growth O_2 propellant tank mass (best-case with O_2)	981.57	[kg]
Growth O_2 propellant tank volume (best-case)	0.84	[m³]
Required power (best-case)	9	[W]
Number of required O_2 tanks (worst-case)	7	[-]
Total O_2 tank mass (worst-case, empty)	10,535.69	[kg]
Total O_2 tank mass (worst-case with O_2)	29,956.13	[kg]
Total O_2 tank volume (worst-case)	18.31	[m³]
Total O_2 tank equipment volume (worst -case)	0.45	[m³]
Growth O_2 propellant tank mass (worst-case, empty)	186.24	[kg]
Growth O_2 propellant tank mass (worst-case with O_2)	19,606.68	[kg]
Growth O_2 propellant tank volume (worst-case)	16.70	[m³]
Required power (worst-case)	31	[W]
TRL	9	[-]
Reliability (best-case)	0.9744	[-]
Reliability (worst-case)	0.9397	[-]

6.1.3 Oxygen Candles

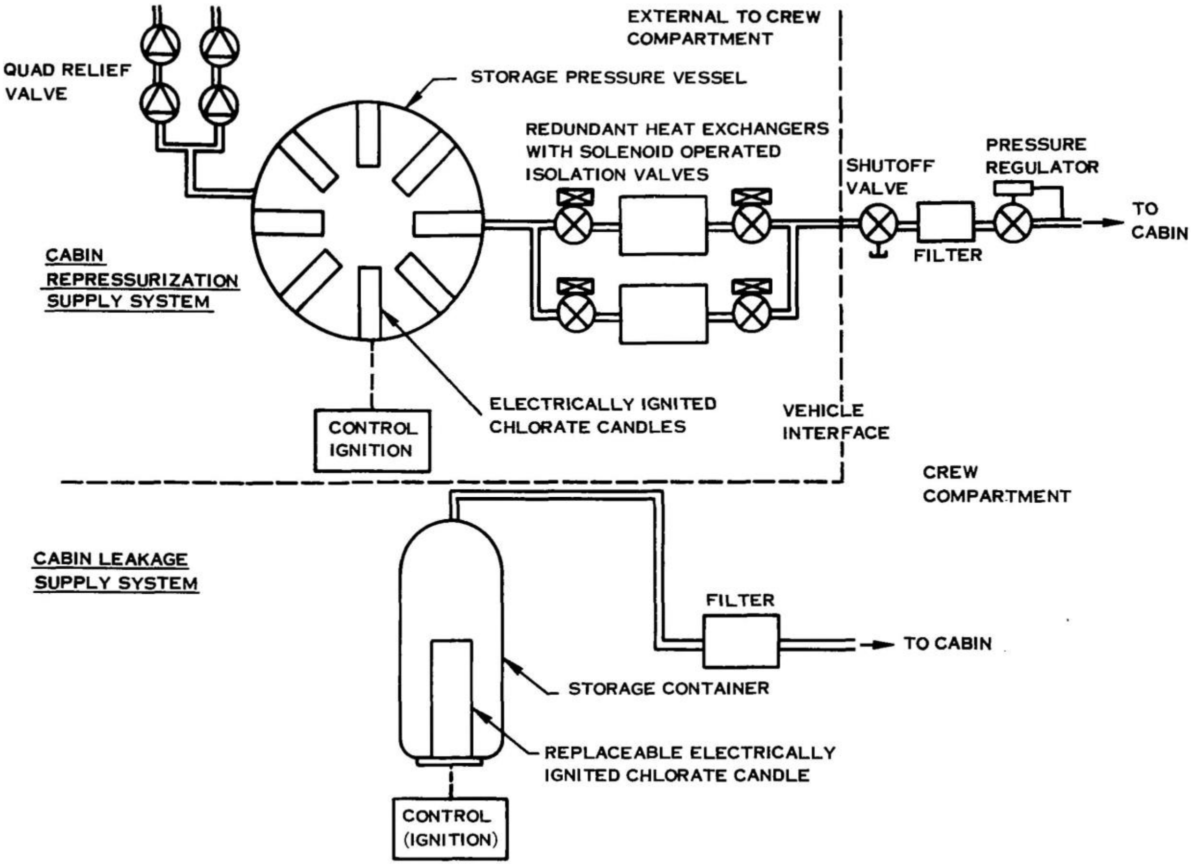

Figure 6-6: Oxygen candle system schematic [50, p. 79]

6.1.3.1 Description

Oxygen candles (or chlorate candles) yield O_2 through an exothermic reaction. Most used in space applications are lithium perchlorate $LiClO_4$ candles on MIR and Potassium perchlorate $KClO_4$ on ISS. The chemicals are enclosed in a long cylindrical canister and are ignited electrical. As can be seen in Figure 6-6, the candles for repressurisation are enclosed in a storage tank outside the pressurized section to enhance safety and reduce volume penalties. Candles for cabin leakage are stored, ignited, and replaced inside the habitat of a spacecraft, like the ones on the ISS. This is necessary because only small amounts of oxygen for leakage are needed and replacing the candle safes mass and volume, because then only one ignition control unit and filter are needed. [2, 50, p. 76]

6.1.3.2 Data and Sizing

A typical oxygen candles produces 0.79 kg O_2 from 2.2 kg $LiClO_4$ (see also chemical equation in Eq. (6-11)) and burns between 5 and 10 minutes. $KClO_4$ would be a little bit more effective with 0.4 kg O_2 per kg $KClO_4$ compared to 0.36 kg O_2 per kg $LiClO_4$. But not enough data could be found about that system and therefore a $LiClO_4$ system is analyzed. [66, 67, 68, p. 119]

$$LiClO_4 \xrightarrow{yields} ClLi + 2O_2$$ **Eq. (6-11)**

Table 6-8: LiClO4 system properties

Parameter	Value	Unit	Source
$LiClO_4$ per cartridge	2.2	[kg]	[67]
Mass stowage unit (20 cartridges per unit; consumables only)	53.89	[kg]	[69]
Mass of one cartridge	2.70	[kg]	
Produced O_2 per cartridge	0.79	[kg]	[66]
Volume of one cartridge (cylinder)	$2.83 \cdot 10^{-3}$	[m³]	[68, p. 119]
Volume of one cartridge (incl. stowage factor)	$3.6 \cdot 10^{-3}$	[m³]	

In Table 6-8 above, the cuboid volume of one cartridge ($V_{cartridge,w,SPF}$) can be calculated by applying the stowage factor for a cylinder ($f_{SPF,cylinder}$) to the cartridge volume ($V_{cartridge}$), as can be seen in Eq. (6-12). As can be seen in Table 6-8, the produced O_2 per cartridge is 0.79 kg. Because the assumed leakage of O_2 is 0,042 kg per day, only every 19 days a cartridge would be needed. A potential rise of the oxygen partial pressure when the cartridge is ignited can be neglected due to the size of the SpaceHab. By dividing the mission time through the calculated 19 days, between 5 and 11 cartridges are required ($n_{\mathrm{LiClO_4},cartridges}$) for mission length of 88 and 211 days respectively. With this value, the total cartridges volume ($V_{cartridges\ for\ leakage}$) needed for the leackage subsystem can be calculated with Eq. (6-13), which is between $1.8 \cdot 10^{-2}$ m³ and $3.96 \cdot 10^{-2}$ m³ for the SpaceHab and Evolved-SpaceHab respectively.

$$V_{cartridge,w,SPF} = V_{cartridge}\ f_{SPF,cylinder}$$ **Eq. (6-12)**

$$V_{cartridges\ for\ leakage} = V_{cartridge,w,SPF}\ n_{needed\ cartridges}$$ **Eq. (6-13)**

The total mass of one cartridge ($m_{cartridge}$) stated in Table 6-8 is calculated by Eq. (**6-14**). Similar to the volume calculation, the total cartridge mass ($m_{cartridges\ for\ leakage}$) needed for the leackage subsystem can be calculated with Eq. (**6-15**), to get 13.5 kg or 29.7 kg for the SpaceHab or Evolved-SpaceHab respectively.

$$m_{cartridge} = \frac{m_{stowage\ unit}}{n_{cartidges\ per\ stowage\ unit}}$$ **Eq. (6-14)**

$$m_{cartridges\ for\ leakage} = m_{cartridge}\ n_{\mathrm{LiClO_4},cartridges}$$ **Eq. (6-15)**

For the repressurization system, it is highly unlikely that single cartridges are used and therefore it is not valid to calculate with single cartridges because this would lead to false conclusions. Instead the needed volume and mass of $LiClO_4$ is calculated for one repressurisation first. Because it is known that one cartridge produces 0.79 kg O_2 and the $LiClO_4$ mass per cartridge is 2.2 kg, the required mass of $LiClO_4$ per kg O_2 ($m_{\mathrm{LiClO_4}\ per\ kg\ O_2}$) can simply be calculated with Eq. (6-17) to 2.79 kg $LiClO_4$ per kg O_2. Eq. (6-17) then yields the total mass of required $LiClO_4$ ($m_{\mathrm{LiClO_4}\ repressurisation}$) for a repressurisation event. For the SpaceHab design, this would be 844.87 kg and for the Evolved-SpaceHab design it would be 1325.57 kg of $LiClO_4$.

$$m_{\mathrm{LiClO_4}\,per\,kg\,O2} = \frac{m_{\mathrm{LiClO_4}\,per\,cartridge}}{m_{O_2\,produced}} \quad \textbf{Eq. (6-16)}$$

$$m_{\mathrm{LiClO_4}\,repressurisation} = m_{\mathrm{LiClO_4}\,per\,kg\,O_2}\ m_{O_2\,required} \quad \textbf{Eq. (6-17)}$$

With the mass of $LiClO_4$ per cartridge ($m_{\mathrm{LiClO_4}\,per\,cartridge}$) and the respective density ($\rho_{\mathrm{LiClO_4}}$) of 2.42 g cm^{-3}, the volume of $LiClO_4$ in one cartridge ($V_{\mathrm{LiClO_4}\,per\,cartridge}$) can be calculated by Eq. (6-18), to 9.09*10^{-4} m³. Multiplying this value with the number of theoretical cartridges (see Eq. (6-19)), the total volume of $LiClO_4$ for repressurisation ($V_{\mathrm{LiClO_4}\,repressurisation}$) is 0.35 m³ or 0.55 m³ for the SpaceHab or Evolved-SpaceHab respectively.

$$V_{\mathrm{LiClO_4}\,per\,cartridge} = \frac{m_{\mathrm{LiClO_4}\,per\,cartridge}}{\rho_{\mathrm{LiClO_4}}} \quad \textbf{Eq. (6-18)}$$

$$V_{\mathrm{LiClO_4}\,repressurisation} = V_{\mathrm{LiClO_4}\,per\,cartridge}\,\frac{m_{\mathrm{LiClO_4}\,repressurisation}}{m_{\mathrm{LiClO_4}\,per\,cartridge}} \quad \textbf{Eq. (6-19)}$$

So far, only the consumables were considered, but not the necessary ignition system, filter etc. The Backup Oxygen Candle System (BOCS) developed by NASA for the ISS is a passive system that utilizes $KClO_4$ for oxygen generation. One BOCS O_2 candle can produce 3.4 kg of O_2 and therefore data from the BOCS in Table 6-9 must be scaled for the leakage system.

Table 6-9: BOCS parameter [69, p. 3]

Parameter	Value	Unit
Produced O_2 per cartridge	3.40	[kg]
Mass of one cartridge	11.48	[kg]
Volume of one cartridge	6.55*10^{-3}	[m³]
Mass of system (w/o cartridge)	28.72	[kg]
Volume of system	0.12	[m³]

The mass for thermal containment equipment and igniters ($m_{leakage\,system}$) can be calculated (Eq. (6-20)) by using the known mass for the BOCS ($m_{BOCS\,w/o\,cartridge}$) scaled by dividing the cartridge mass of the leakage system ($m_{\mathrm{cartridge}}$) through the BOCS cartridge mass ($m_{\mathrm{BOCS}\,cartridge}$). The same approach can be done for the volume (Eq. (6-21)). Adding these values to the mass and volume of the cartridges leads to the total mass and volume of the leakage system, which is given in Table 6-10.

$$m_{leakage\,system} = m_{BOCS\,w/o\,cartridge}\,\frac{m_{\mathrm{cartridge}}}{m_{\mathrm{BOCS}\,cartridge}} \quad \textbf{Eq. (6-20)}$$

$$V_{leakage\,system} = V_{BOCS\,system}\,\frac{V_{\mathrm{cartridge}}}{V_{\mathrm{BOCS}\,cartridge}} \quad \textbf{Eq. (6-21)}$$

$LiClO_4$ systems have already been used in flight, which means the system has a TRL of 9.

The MTBF is high and therefore 100,000 hours are assumed. [67]

Like for the high-pressure system it is assumed that the system is managed automatic and consequently no crew time is needed for operation or maintenance.

Table 6-10: Properties of oxygen candle system for leakage

Parameter	Value	Unit
Number of required candles (SpaceHab)	5	[-]
Number of required candles (Evolved-SpaceHab)	11	[-]
Total expendables mass (SpaceHab)	13.50	[kg]
Total expendables mass (Evolved-SpaceHab)	29.70	[kg]
Total system mass (SpaceHab)	20.26	[kg]
Total system mass (Evolved-SpaceHab)	36.46	[kg]
Total expendables volume (SpaceHab)	$1.8 * 10^{-2}$	[m³]
Total expendables volume (Evolved-SpaceHab)	$3.96 * 10^{-2}$	[m³]
Total system volume (SpaceHab)	$6.99 * 10^{-2}$	[m³]
Total system volume (Evolved-SpaceHab)	$9.15 * 10^{-2}$	[m³]
Required power	0	[W]
TRL	9	[-]
Reliability (best-case)	0.9791	[-]
Reliability (worst-case)	0.9506	[-]

For the repressurization system, an equipment mass of 177.81 kg is assumed. [50, p. 78]

The volume is calculated by assuming a cylindrical shape for the $LiClO_4$ storage. It is unlikely that all mass is ignited at the same time, which could produce a hazard. Instead it is assumed that the $LiClO_4$ is stored in 8 separated sections each holding an equal mass and separated by a gap which is also used for passive cooling similar to BOCS. The gap is assumed to be 1 % of the total volume for simplification. Therefore, the total repressurization system volume ($V_{repressurisation\ system}$) can be calculated by applying the cylinder factor ($f_{SPF,cylinder}$), as stated in Eq. (6-22). It is further assumed that the volume of valves, filters etc. are much smaller than the storage volume and therefore are included in the stowage volume.

$$V_{repressurisation\ system} = V_{\mathrm{LiClO_4}\ repressurisation} 1.1\ f_{SPF,cylinder} \quad \textbf{Eq. (6-22)}$$

As stated above, the system is assumed to be passive. Power is only necessary during ignition, which is negligible.

Even when no identical unit like the presented one has ever been developed it is assumed that that the technology is comparable with the ones used on MIR and ISS. To stay in compliance of the NASA´s Technology Maturity Assessment (TMA), the TRL is reduced to 5.

It is assumed that the system is managed automatic except for ignition during an emergency and consequently no crew time is assumed for operation or maintenance.

The breakdown of the calculations above for the repressurisation system can be seen in Table 6-11.

Table 6-11: Properties of oxygen candle for repressurisation

Parameter	Value	Unit
Total expendables mass (SpaceHab)	844.87	[kg]
Total expendables mass (Evolved-SpaceHab)	1,325.57	[kg]
Total system mass (SpaceHab)	1,022.68	[kg]
Total system mass (Evolved-SpaceHab)	1,503.38	[kg]
Total expendables volume (SpaceHab)	0.35	[m³]
Total expendables volume (Evolved-SpaceHab)	0.55	[m³]
Total system volume (SpaceHab)	0.49	[m³]
Total system volume (Evolved-SpaceHab)	0.77	[m³]
Required power	0	[W]
TRL	5	[-]

The oxygen candle system is not considered for a storage system, since it has the worst mass performance.

6.1.4 Hydrogen Peroxide

Hydrogen peroxide H_2O_2 is stored as a liquid in low pressure tanks. It produces oxygen and water in reaction with a catalyst as can be seen in Eq. (6-23). Residual H_2O_2 must be removed from the oxygen stream by an absorbent bed. It produces considerable heat (6.12 MJ per kg O_2), and therefore up to 33,641 W must be rejected for 24 hours in an repressurisation event. An additional disadvantage is, that only oxygen can be produced by this system and therefore nitrogen must still be provided by tanks. These drawbacks and the fact that no such system has ever been flown in space rejects it from a further analysis. [50, p. 80]

$$2H_2O_2 \xrightarrow{yields} O_2 + 2H_2O + heat \qquad \textbf{Eq. (6-23)}$$

6.1.5 Hydrazine

Hydrazine is commonly used on satellites as propellant for steering. In combination with the oxidizer nitrogen tetroxide N_2O_4 it could be used to produce nitrogen and water. The principal chemical equation can be seen in Eq. (6-24). This concept consists of a catalytic hydrazine decomposition reactor followed by a H_2 separator and the catalytic oxidizer to oxidize remaining ammonia and H_2 to N_2 and H_2O. The tank mass penalty for hydrazine is with 0.2 kg per kg hydrazine significant lower as for a cryogenic N_2 storage which is 0.524 kg per kg N_2. But there is a significant safety concern due to the fact that hydrazine and N_2O_4 are highly toxic. Additional the TRL is at a very low level which prevents a further analysis of this technology. [2, 50, p. 84]

$$3N_2H_4 \xrightarrow{yields} 3N_2 + 6H_2 + heat \qquad \textbf{Eq. (6-24)}$$

6.2 Temperature and Humidity Control

The temperature and humidity control (THC) subsystem removes heat and humidity from the air. It monitors and controls the temperature in the habitat as well as controls the ventilation to maintain a comfortable atmosphere for the crew and avoid condensing water by controlling the dew point. The removed water from the air is provided to the WRM subsystem, described in 6.4. The general schematic of the THC system and the interfaces can be seen in Figure 6-7. [2, p. 211, 50, p. 287, 70]

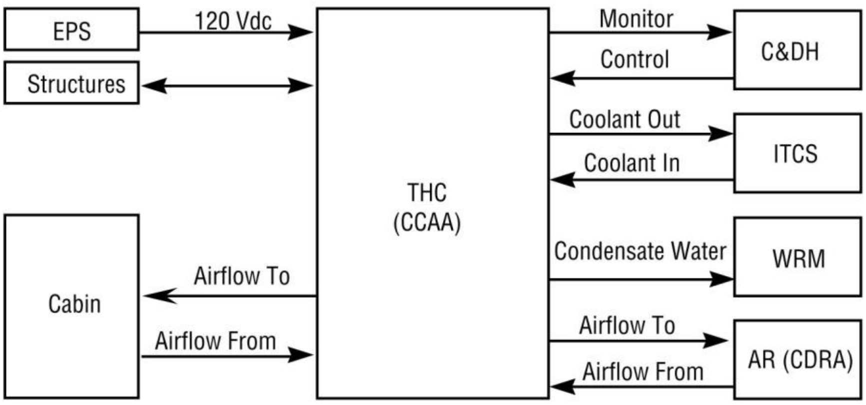

Figure 6-7: THC interface schematic [38, p. 96]

The THC has to fulfill 18 functions overall. The ventilation function can only be accomplished by a fan and hence no trade analysis is needed. The four temperature functions could be combined, as well as the 3 humidity functions. Because the only economical solution of temperature removal from air is a heat exchanger, the only trade off that is left is for the humidity control functions.

While vast different processes are possible to remove humidity from air, the focus in this chapter is on already developed assemblies, outlined in the chapter below.

6.2.1 Carbon Dioxide and Moisture Removal Amine Swing-Bed System

6.2.1.1 Description

The main function of the Carbon Dioxide and Moisture Removal Amine Swing-Bed System (CAMRAS) is to remove CO_2 from the air. The Amine swing bed is an amine-based, vacuum-regenerated adsorption technology for removing carbon dioxide and humidity from a habitable spacecraft environment and is the baseline technology for the Orion Program's Multi-Purpose Crew Vehicle (MPCV). It uses a pair of interleaved-layer beds filled with SA9T, the amine sorbent. A linear multiball valve rotates 270° back and forth to control the flow of air and vacuum to adsorbing and desorbing beds: one bed adsorbs CO_2 and H_2O from cabin air while the other bed is exposed to vacuum for regeneration by venting the CO_2 and H_2O. The two beds are thermally linked, so no additional heating or cooling is required. The technology can be applied to habitable environments where recycling CO_2 and H_2O is not required such as short duration missions. This last point excludes it for a consideration in a recycling system. For a storage system, this approach would still be valid. [71]

6.2.1.2 Data and Sizing

The CAMRAS CO_2 removal capacity equates a 1- to 2-person rate [71, p. 8]. Therefore, the humidity removal capacity can be estimated to be around the same. Notable for this technology is the relative high air loss of 49 % [71, p. 12], which means a high amount of oxygen and nitrogen is lost through this process. This leads to an air loss of around $0.73*10^{-4}$ kg/h. While the installed unit on ISS has a water safe wheel, this would be excluded, since the CAMRAS would only be used in a storage system where all humidity is vented.

No information about mass, volume and required power for the CAMRAS system could be found, but parameters (outlined in Table 6-12) were found for a CO2 removal system similar to the CAMRAS. This system is called “Rapid Cycle Amine” (RCA) 2.0 and is developed for a spacesuit. The RCA 2.0 uses the same amine-based CO_2/H_2O sorbent and the same multi-ball valve system as CAMRAS. [72, pp. 3-4]

Table 6-12: Properties of the rapid cycle amine 2.0 system [72, p. 12]

Parameter	**Value**	**Unit**
Mass	7.26	[kg]
Volume	0.01	[m³]
Power	3	[W]
Cooling	0	[W]

For sizing the RCA and CAMRAS system, a one-person equivalent is considered and Eq. (5-1) to Eq. (5-4) applied. Additionally, the air loss through CAMRAS has to be considered. Since CAMRAS is only implemented in a storage system, the N_2 and O_2 tanks must also be bigger. A high-pressure system as described in 6.1.1, is used for this. The final system is outlined in Table 6-13 below. Since all data is based only on an analogous system with a lower TRL, a $f_{Certainty}$ of 0.5 is applied.

No data for reliability is available for the system. The installed part with the lowest MTBF is a three-way valve with a typical value of 100,000 hours [73, pp. 355-358]. This value is used for the reliability analysis of the system, with a corresponding $f_{Certainty}$ of 0.25.

There is no scheduled maintenance expected for this system

Since CAMRAS is in operation on ISS since 2010, a TRL of 9 is applied.

Table 6-13: Properties of the CO_2 and moisture removal amine swing-bed system

Parameter	Unit	Case1	Case2	Case3	Case4
CAMRAS Mass	[kg]	65.34	217.80	217.80	544.50
Air Contingency	[kg]	2.35	2.35	5.63	5.63
Total mass	[kg]	67.69	220.15	223.43	550.13
Volume[11]	[m³]	0.12	0.40	0.40	1.00
Power	[W]	37	124	124	310
Cooling	[W]	0	0	0	0
Reliability	[-]	0.9386	0.9386	0.8591	0.8591
TRL		9	9	9	9

6.2.2 Common Cabin Air Assembly

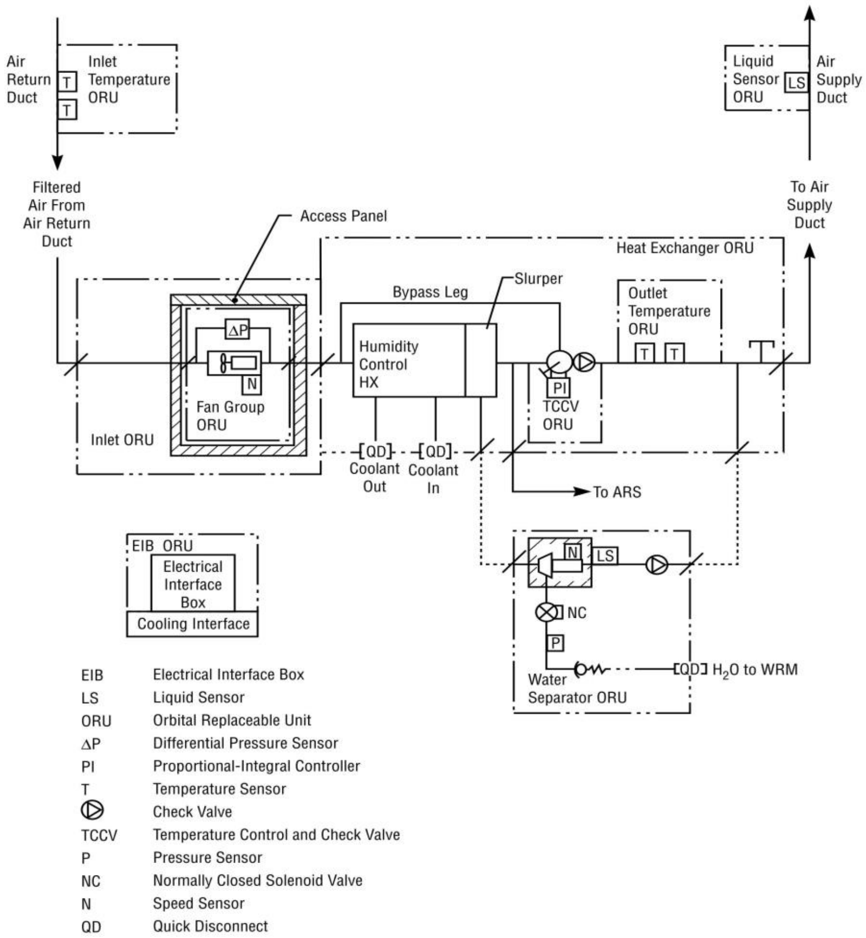

Figure 6-8: CCAA schematic [38, p. 113]

[11] Additional volume for the larger O2 and N2 tanks is insignificant.

6.2.2.1 Description

The Common Cabin Air Assembly (CCAA) is the main unit of the intramodular ventilation system on ISS. A schematic of the CCAA is given in Figure 6-8. Air from the cabin is sucked through bacteria filter elements (BFE) into a piping system. The temperature is measured by sensors in the pipes and after the CCAA to control the needed air flow by a fan. A condensing heat exchanger (CHX) in plate fin core design with a four-pass cross counter flow coolant circuit is used to remove humidity from air. The air-side passages are coated with a hydrophilic material that promotes film wetting on the surfaces and the condensed water is then sucked through slurper holes to the water separator (WS) (see Figure 6-9). To control the amount of removed heat and water, a bypass is used and controlled by the temperature control and check valve (TCCV). The WS is a centrifuge that separates air from the water which is transferred to the WRM subsystem. For safety, a liquid sensor (LS) at the outlet of the intramodule pipes is used to measure the water content in the air stream. [38, p. 104]

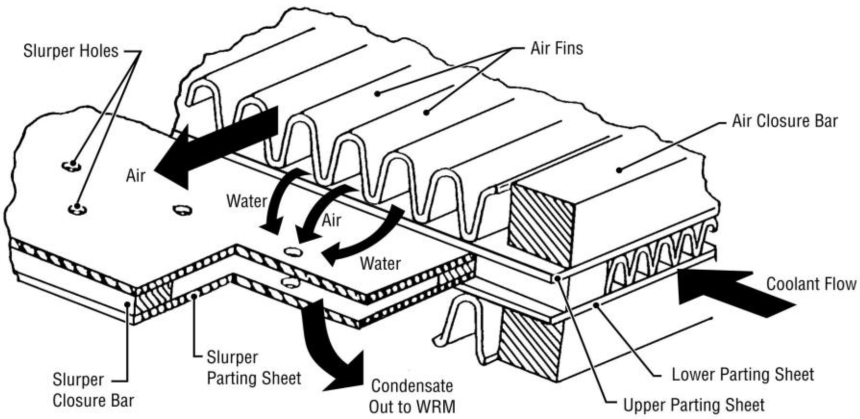

Figure 6-9: CHX slurper [38, p. 107]

6.2.2.2 Data and Sizing

Data for the CCAA in Table 6-14 is from ISS [38, p. 73], where the processing rate is stated to be 1.45 kg h^{-1} of water removed by the WS [38, p. 110]. This value is used for the resizing, using Eq. (5-5) to Eq. (5-8). Since only a negligible amount of air remains in the water after the WS, no increase of the storage system is considered.

Table 6-14: Data of the common cabin air assembly

Parameter	Value	Unit
Mass	112	[kg]
Volume	0.4	[m³]
Power	468	[W]
Cooling	468[12]	[W]

The MTBF for the CCAA components are derived from [63, p. 160].

[12] While not stated in [38], it is assumed that the same cooling as power is needed.

While the CHX requires to dry at least every 28 days to prevent microbial growth, it is assumed this maintenance task is automatic and no other scheduled maintenance is required by the CCAA system [74].

The CCAA has been used on ISS for years and therefore a TRL of 9 is applied.

Table 6-15: Properties for the common cabin air assembly system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	59.98	199,94	199.94	499.85
Volume	[m³]	0.31	1,04	1.04	2.60
Power	[W]	390	1,300	1,300	3,250
Cooling	[W]	390	1,300	1,300	3,250
Reliability	[-]	0.8874	0.8874	0.7509	0.7509
TRL		9	9	9	9

6.2.3 Desiccant Bed

Another possible solution to remove water from air is the use of adsorbent media like silica gel. This is used in the desiccant beds of the 4BMS (see 6.3.6). Since it is not developed with the main focus of humidity removal it has a very low TRL at best. Therefore, it is not considered further.

6.2.4 Water Vapor Electrolysis

A very different approach is the water vapor electrolysis (WVE) technology. This assembly electrolyzes directly from the cabin air. Moist air is fed to the anode of the SFWE-style (see 0) electrolysis cell to produce O_2 enriched steam at the anode and H_2 at the cathode. It helps to control the cabin humidity and has few interfaces. It is a potential candidate for providing a safe haven in a mobile atmospheric regeneration system. But because it has a very low TRL, it is excluded for the trade analysis. [2, pp. 204-205]

6.3 Atmosphere Revitalization

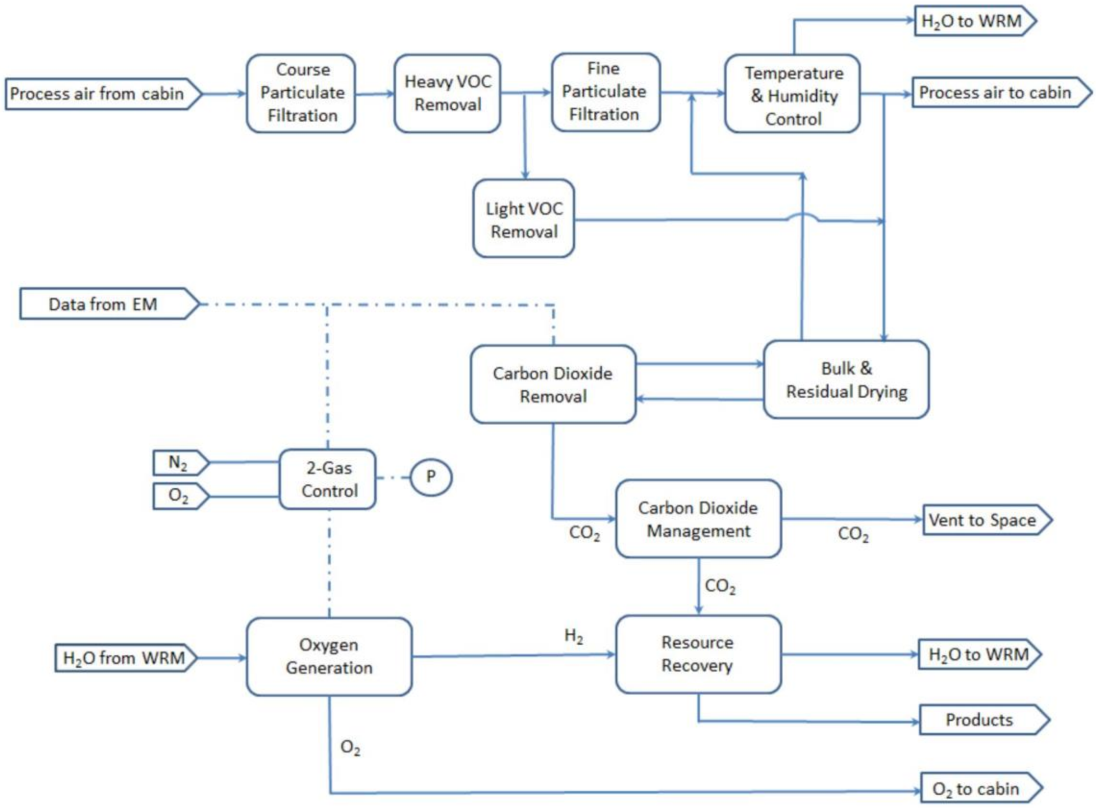

Figure 6-10: AR subsystem[17, p. 5]

The atmosphere revitalization (AR) subsystem has 3 major functions. It has to remove carbon dioxide from the air, generate oxygen for the crew, and remove potentially hazardous volatile trace contaminants generated by inadvertent spills, crew metabolic processes, and equipment off-gassing such that cabin contaminants levels are maintained within limits. When a more closed loop is desired, it must further reduce the removed CO_2 to usable products, like water. [70]

The CO_2 level has to maintained below 2 mmHg (0.5 kPa), since astronauts on the ISS have experienced negative health effects from the current levels of around 3 mmHg, like headaches and vision impairment. For this approach, membranes are considered to be not feasible, since they lack the good selectivity of the solid or liquid sorption alternatives. [75, p. 6]

The technologies considered for CO_2 removal are as follows:

- Lithium Hydroxide
- Metal Oxides
- Sodasorb
- Superoxides
- Two Bed Molecular Sieves
- Four Bed Molecular Sieves
- Solid Amine Water Desorption
- Solid Amine Vacuum Desorption
- Electrochemical Depolarization Concentration

- Air Polarized Concentrator
- Carbon Dioxide and Moisture Removal Amine Swing-Bed System

Since much oxygen is lost when the removed CO_2 is vented, reduction technologies are analyzed to further close the loop. These considered technologies are:

- Sabatier
- Bosch Reactor
- Advanced Carbon-Formation Reactor System

When no storage system is considered, the required oxygen has to be produced. The main technology considered for this is electrolysis. An important point for all electrolysis technologies is, that the feed water must be carefully controlled and that extra treatment steps must be implemented [35]. Additionally, oxygen generation systems cost up to ten times more than tanks, when considering the design, development, and operations costs [53]. Therefore, a trade-off is needed between a generation system and a tank system (see 6.1). Several technologies are analyzed:

- CO_2 Electrolysis
- Solid Polymer Water Electrolysis
- Static Feed Water Electrolysis
- Water Vapor Electrolysis
- Solid Electrolyte Oxygen System
- High Pressure Electrolysis

For treatment of particles and trace contaminants, the same technologies as on the ISS are considered since no practical other technologies are currently available. These are the Trace Contaminant Control System and bacteria filter elements (BFE).

6.3.1 Lithium Hydroxide

Figure 6-11: Apollo LiOH canister [75, p. 2]

6.3.1.1 Description

Lithium hydroxide (LiOH) is used in open-loop ECLSS as well as backup to remove CO_2 since Apollo (see Figure 6-11). The CO_2 laden air flows through a canister filled with LiOH granules. LiOH canisters are simple, lightweight, reliable, and effective. 1 kg LiOH can remove 0.84 kg CO_2. The chemical equation of the process is outlined below. [75, p. 1]

$$2LiOH + CO_2 \xrightarrow{yields} Li_2CO_3 + H_2O \qquad \textbf{Eq. (6-25)}$$

6.3.1.2 Data and Sizing

The parameters of the space shuttle LiOH system are given in Table 6-16 below. The system consists of a temperature control assembly, with valve and controller, and the LiOH controller.

Table 6-16: Data of the space shuttle LiOH system [76, p. 67, 76, p. 25]

Parameter	Value	Unit
Hardware mass	10.43	[kg]
LiOH per cartridge	2.27	[kg]
Cartridge mass	0.907	[kg]
Rack mass	3.63	[kg]
Rack volume	0.0311	[m^3]
Cartridges per rack	27	
Changeout time for 4 Men	12	[$h\ cart^{-1}$]
Changeout time for 6 Men	7.6	[$h\ cart^{-1}$]
Changeout time for 10 Men	3.2	[$h\ cart^{-1}$]

The number of required cartridges can be estimated by Eq. (6-26). For the best-case scenario, this gives 646 1,291 cartridges needed for the 88-day trip or 2,169.64 kg for the cartridges including the required racks.

$$n_{\text{LiOH,cartridges}} = \frac{m_{CO_2,produced}}{m_{\text{CO}_2\text{,removed}}} n_{CM}\, t \qquad \textbf{Eq. (6-26)}$$

$$m_{\text{CO}_2\text{,removed}} = m_{LiOH,cartridge}\, \eta_{\text{LiOH}} \qquad \textbf{Eq. (6-27)}$$

$$\eta_{\text{LiOH}} = \frac{0.84\ kg_{CO_2}}{1\ kg_{LiOH}} = 0.84 \qquad \textbf{Eq. (6-28)}$$

An analysis of the given changeout times from Table 6-16 reveals (Figure 6-12) that it is not practicable to use only one system for crew sizes larger than 12. The selected extrapolation function in Figure 6-12 is exponential, since this function has the best coefficient of determination[13] (R^2).

[13] A coefficient of determination of 1 stands for a perfect match.

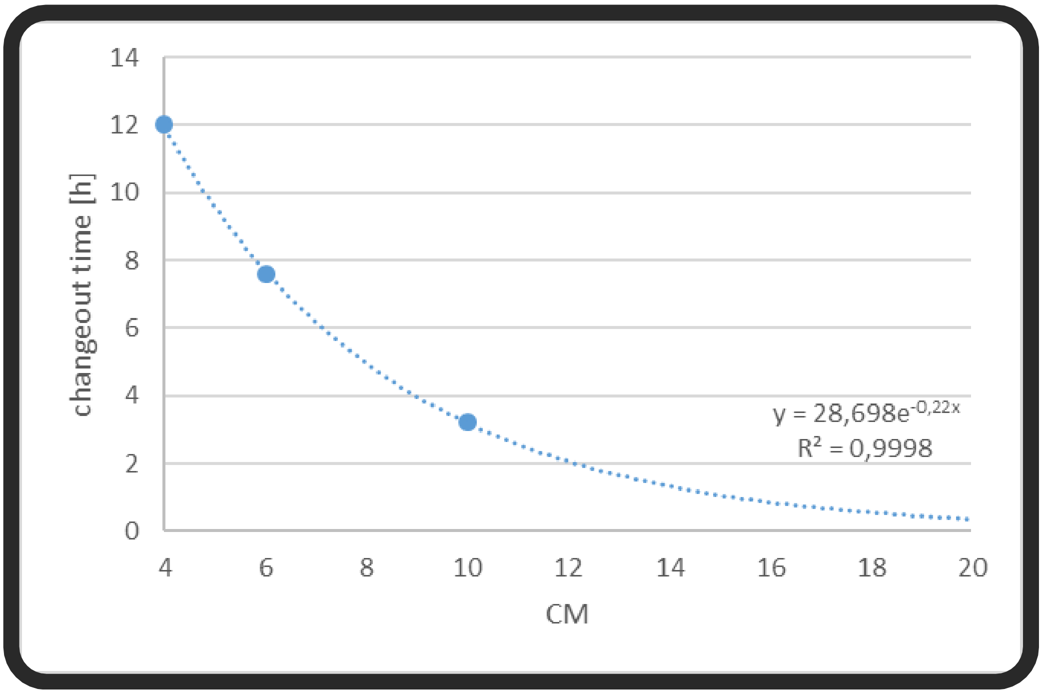

Figure 6-12: LiOH cartridge changeout time estimation

It is best to reduce the changeout time to 12 hours by accompanying more systems. The number of system ($n_{LiOHsystems}$) can be determined by dividing the number of CM (n_{CM}) through the 4 CM of the system with a 12 hour changout time (Eq. (6-31)).

$$n_{LiOHsystems} = \frac{n_{CM}}{4}$$ **Eq. (6-29)**

With the assumption that one changeout of a cartridge takes about 8 minutes for fetching a new cartridge from the stowage compartment right next to the unit, unpacking this cartridge, placing it in the cartridge housing and stowing the used-up cartridge in the stowage compartment, the daily needed maintenance can be estimated.

The only required power source is a fan. A commercial available centrifugal fan from Papst with 22.5 W is considered [77].

The system is considered as highly reliable. Since no MTBF data could be found, a MTBF of 10^6 hours is assumed.

The system is used since the dawn of the space age and therefore a TRL of 9 is used.

Table 6-17: Properties of the lithium hydroxide system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	2,169.64	7,232.14	17,190.54	42,976.36
Volume	[m³]	8.87	29.58	70.37	175.94
Power	[W]	68	225	225	563
Cooling[14]	[W]	0	0	0	0
Maintenance	[h]	86.06	286.87	687.84	1,719.60
Reliability	[-]	0.9979	0.9979	0.9949	0.9949
TRL	[-]	9	9	9	9
Produced water	[kg]	503.81	1,679.36	4,026.65	10,066.64

As can be seen in Table 6-17, LiOH is by far the worst alternative. The maintenance time for Case4 needs more than one crew member in full time, and the volume is nearly one full deck. Consequently, this technology is not further considered as a feasible CO_2 removal process for the SpaceHab.

6.3.2 Metal Oxides

Metal oxides (METOX) have been considered for use in space habitats and EMU suits. During a 1973 study a silver oxide formulation (80.3 % Ag_20, 10.4 % KOH, and 9.3 % Na_2Si0_3) was found to have the best overall characteristics (absorption capacity, strength, desorption characteristics, etc.). The silver dioxide formulation has an absorption capacity of 0.12 kg per kg oxide at a partial CO_2 pressure of 0.4 kPa with a power demand of $1.86 \cdot 10^6$ J per kg CO_2. Due to expansion and contraction during absorption and desorption, the metal oxide pellets structurally breakdown, and therefore have a limited life. The design goal is 50-60 regenerations with cycle times of 8 hours. Water is required for the absorption reaction and enhances the sorption capacity, reaction kinetics, and cycle life, so moisture in the process atmosphere is necessary and high humidity may be preferable. This technology is used in ISS EMUs. [2, p. 191, 55, p. 194]

The overall performance of METOX is considerable inferior to LiOH and consequently not further considered.

6.3.3 Sodasorb

Sodasorb is a mixture of calcium hydroxide ($Ca(OH)_2$) (95 % dry weight), sodium-, potassium-, and barium hydroxides as "activators". Water is necessary for reaction with 12-19 % of mixture. A series of reactions occurs whereby CO_2 goes into solution and forms carbonic acid, which then reacts with hydroxide to form sodium carbonate and regenerate the water consumed earlier. The sodium carbonate reacts with the hydrated lime to form calcium carbonate and regenerate caustic potash. The theoretical capacity is 0.488 kg CO_2 adsorption per kg sorbent. Data from Shearwater Research states, that 100 g Sodasorb absorbs 15 L CO_2 (1 kg Sodasorb adsorbs

[14] No active cooling is considered.

0.294 kg CO_2) and an 8 hour capacity holds around 1 kg absorbent [78]. [2, p. 193, 55, p. 190]

The overall performance of Sodasorb is significantly inferior to LiOH and consequently not further considered.

6.3.4 Superoxides

Alkali and alkaline earth metal superoxide were used on many historic space vehicles. They are solid chemicals which serves as dual purpose of scrubbing CO_2 and providing O_2. The most used superoxide in Soviet Union was potassium superoxide (KO_2), which has a low utilization efficiency of 50-80 % and some overheating problems. The density is 2.14 g cm^{-3}. The theoretical capacity is 0.309 kg CO2 per kg KO_2 sorbent and 0.388 kg O_2 per kg sorbent are produced. Better is $Ca(O_2)_2$ (2.91 g cm^{-3}) or a mixture of both. Carbonates, like potassium (K_2CO_3), or sodium superoxide are in this group. The superoxide reacts with moisture in the atmosphere to produce O_2 and potassium hydroxide (KOH^-). The KOH^- then absorbs the CO_2 in the atmosphere. The chemical equilibria are complex and depend on the levels of moisture and CO_2 and the temperature in the sorbent bed. The potassium carbonate is gradually consumed therefore limiting the life of the process to about 90 cycles. The $KHCO_3$ reverts back to K_2CO_3 when it is heated to about 150°C. [55, p. 190, 75]

The overall performance of Superoxides is inferior to LiOH and thus not further considered.

6.3.5 Two Bed Molecular Sieves

Two bed molecular sieves (2BMS) use two carbon molecular sieves to remove excess moisture and CO_2 from the atmosphere. The sorbent is regenerated by venting to space in the reverse direction so that water would not enter the CO_2 removal portion of the bed. For such open-loop operation the molecular sieve is also used for trace contaminant removal and humidity control. A continuous operation is achieved by cycling between two beds so that one could be desorbed while the other is adsorbing. [2, pp. 182-184, 55, p. 198]

This technology has only a TRL of 4 and is therefore not further considered [79].

6.3.6 Four Bed Molecular Sieves

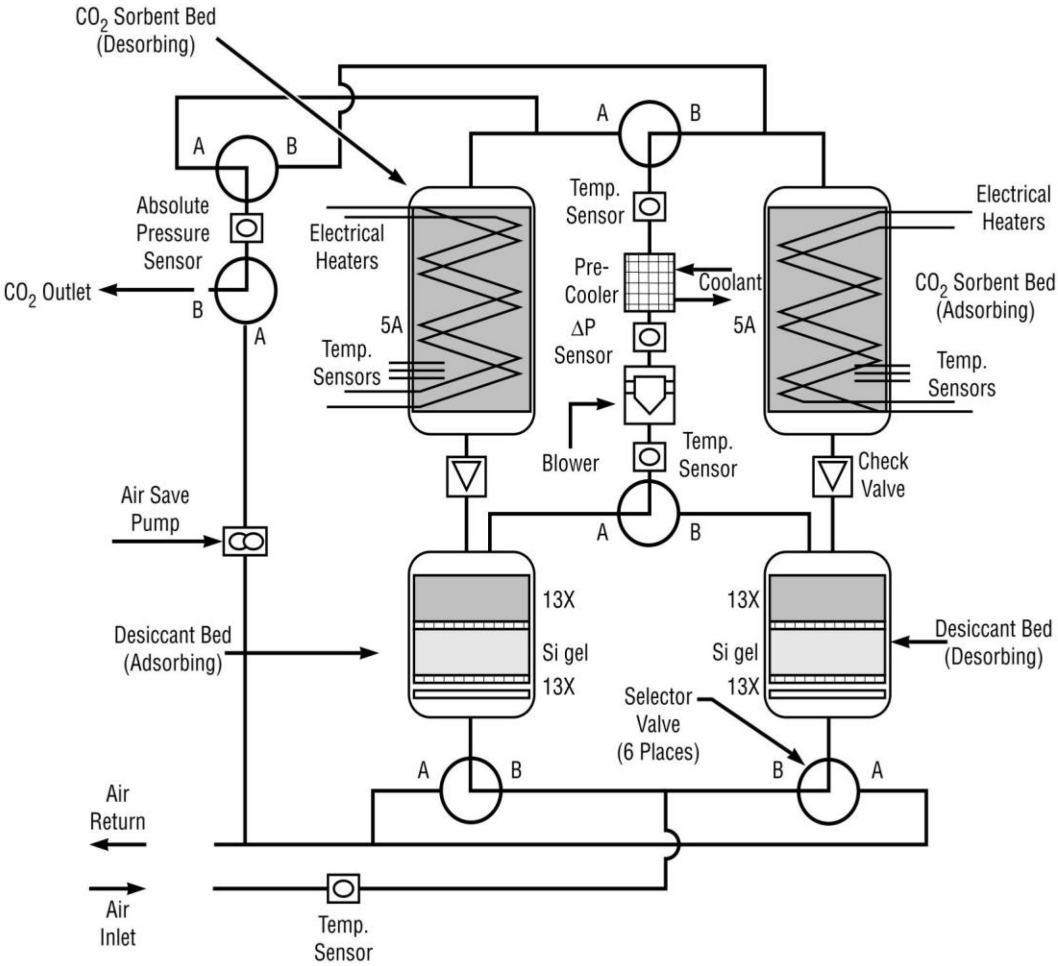

Figure 6-13: 4CMS CDRA schematic [38, p. 131]

6.3.6.1 Description

Four bed molecular sieves (4BMS) utilize synthetic zeolites or metal ion alumina-silicates for CO_2 collection. 2 synthetic zeolites are used alternatively for adsorption and desorption of CO_2. Silica gel beds are included to remove moisture before the air enters the sorbent beds. The process can be described as follows. Wet CO_2-laden process air enters the adsorbing desiccant bed where water vapor is removed. The dry air passes a blower to overcome the system pressure drop. Then it passes through a pre-cooler to remove the generated heat through blower compression and adsorption. The adsorbing CO_2 removal bed removes the CO_2. The CO_2 free air is then directed into a desorbing desiccant bed for rehumification and then back into the control system. The adsorption efficiency is highest at low temperatures, so there is a need for an air-liquid heat exchanger. The use of Zeolite 5A molecular sieve material requires much heat. Therefore, alternatives are currently investigated. A polymer-immobilized zeolite has better adsorption capacity than 5A, with a weight improvement of factor 1.6 and less dust problems [75, p. 7]. Another adsorbent is metal-organic frameworks (MOF). This molecular sieve is relatively new and shows better adsorption capacity as 5A, but currently has problems with chemical and thermal stability [75, p. 7]. [2, pp. 182-184, 55, p. 198]

6.3.6.2 Data and Sizing

To size the 4BMS, data from [38] is used. Since this source is from the late planning state of the ISS, current data about power and thermal requirements from [80] are used. The CDRA operates in a day-night cycle mode. During the night, the heater of the sorbent bed is switched off to safe power. Since the SpaceHab always has the same power available during transit, this would not be necessary. However, a close look at the operating sequence [38, p. 140] reveals, that the heater is sometimes also switched off during day cycles. It is therefore assumed that this operation would also be used for a SpaceHab 4BMS and the average power consumption is used. Eq. (**5-1**) to Eq. (5-4) are used for sizing.

Table 6-18: Data from CDRA [38, pp. 132-139, 80]

Parameter	Value	Unit
Mass	173.30	[kg]
Volume	0.39	[m^3]
Maintenance	2.72	[CM-h y^{-1}]
Human Equiv. Unit	6	[HEU]
Generation/Adsorption rate CO_2	6[15]	[kg d^{-1}]
Daylight Power consumption	1,070	[W]
Night Power consumption	204	[W]
Average Power Consumption	714	[W]
Thermal Heat Load, average	498	[W]

For the reliability analysis, the MTBF data from [63, p. 147] is used.

Since the CDRA has been used on the ISS for over 15 years [75, p. 5], a TRL of 9 is assumed.

[15] At a partial CO_2 pressure of 400 Pa.

Table 6-19: Properties of four bed molecular sieve system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	267.75	875.17	875.17	2,187.91
Volume	[m³]	0.58	1.93	1.93	4.83
Power	[W]	1,599	3,685	3,685	13,209
Cooling	[W]	1,116	5,284	5,284	9,213
Maintenance	[h]	1.31	4.37	10.48	26.21
Reliability	[-]	0.8610	0.8610	0.6985	0.6985
TRL	[-]	9	9	9	9

6.3.7 Solid Amine Water Desorption

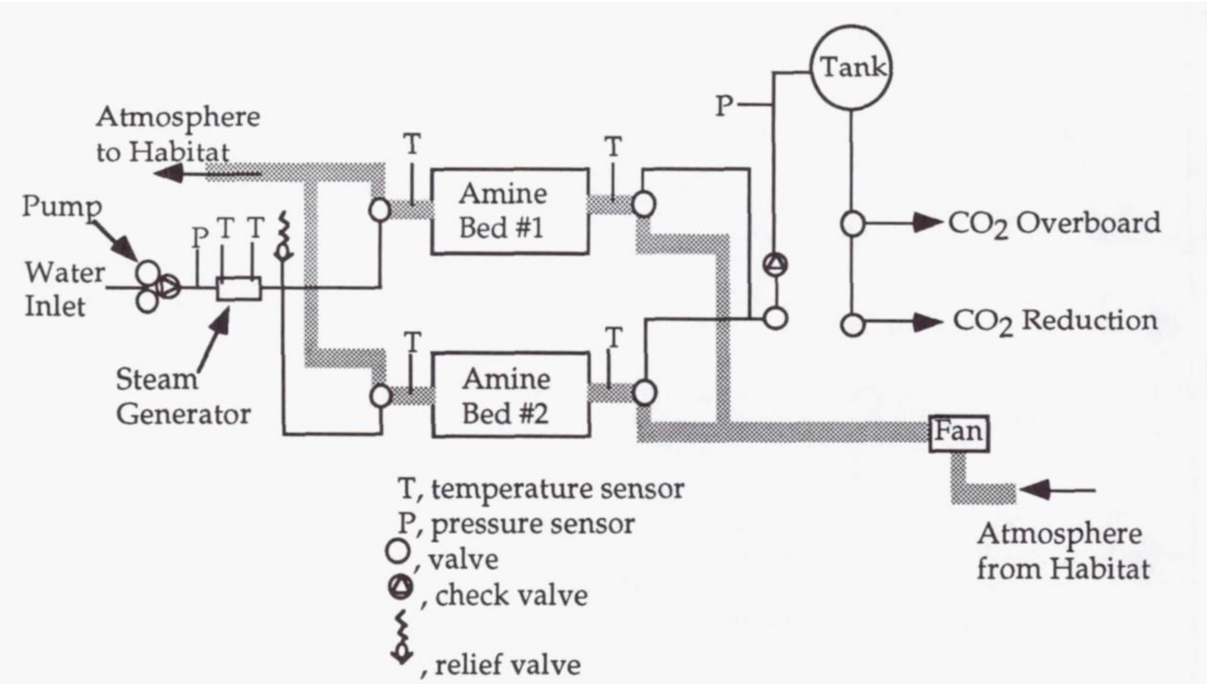

Figure 6-14: SAWD schematic [55, p. 192]

6.3.7.1 Description

The solid amine water desorption (SAWD) process is similar to the 2BMS (see 6.3.5) but uses steam heated solid amine (WA-21) instead of zeolite. Amines have a higher sorption rate and capacity than the 5A zeolite used in 4BMS (see 6.3.6), but also several disadvantages. Water and amine reacts and form a bicarbonate with CO_2. During desorption, the water vapor releases CO_2. Around 20-35 wt.-% of water in the resin bed is required for an optimum absorption. Disadvantages are the limited life time of the solid amine, since it degrades fairly rapidly with time. Also, hygiene water for steam is required which increases the load on the heat exchanger. One advantage is, that desorption takes place at cabin pressure and therefore venting is less power consuming when subsequent CO_2 reduction is considered. [2, pp. 184-188, 55, p. 191, 75, p. 7]

6.3.7.2 Data and Sizing

The carbon dioxide and moisture removal amine swing-bed (CAMRAS) system is a SAWD system too, but treated separately since it is used as humidity removal unit in a storage system. See 6.2.1 for more details about the system.

Instead, the carbon dioxide concentration assembly (CCA), used in the advanced close loop system (ACLS) is used for a baseline SAWD system. One big advantage of this system is, that astrine instead of WA-21 is used. Astrine adsorbent consists of polymer beads with low probability of dust formation and higher life time and thus one of the biggest drawback of the SAWD process is eliminated. Data from the CCA are provided in Table 6-20. [81]

Table 6-20: Data from carbon dioxide concentration assembly [81, 82]

Parameter	Value	Unit
Mass	44.45	[kg]
Volume	0.1048	[m³]
Human equiv. unit	3	[HEU]
Power consumption	250	[W]

There is no data available about the cooling requirement. To stay conservative, the same as power consumption is assumed.

There is further no reliability data available for the CCA. But a similar system has a given MTBF of 17,000 hours [50, p. 172]

No scheduled maintenance is currently assumed.

The ACLS system is currently scheduled for a flight to ISS in August 2018 [83] and therefore the TRL is 8.

Table 6-21: Properties of solid amine water desorption system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	137.35	457.84	457.84	1,122.36
Volume	[m³]	0.31	1.05	1.05	2.62
Power	[W]	1,120	3,700	3,700	9,250
Cooling	[W]	1,120	3,700	3,700	9,250
Maintenance	[h]	0	0	0	0
Reliability	[-]	0.8832	0.8832	0.7424	0.7424
TRL	[-]	8	8	8	8

6.3.8 Solid Amine Vacuum Desorption

The solid amine vacuum desorption process (SAVD) works similar like the SAWD except that it uses vacuum to pull CO_2 and H_2O from the solid amine beds. It includes a hydrophilic membrane stack prior to the amine bed, for moisture removal. If no venting to space vacuum is desirable, a compressor development would be required. This technology has a low TRL of 3 and is therefore rejected. [79]

6.3.9 Electrochemical Depolarization Concentration

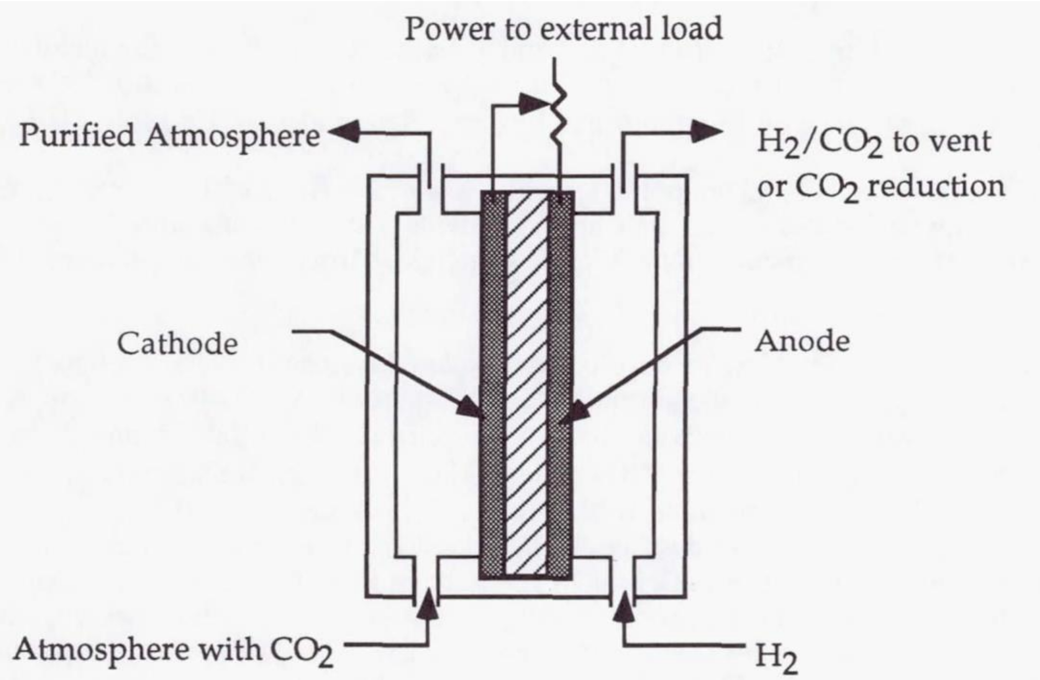

Figure 6-15: EDC schematic [55, p. 193]

6.3.9.1 Description

The electrochemical depolarization concentration (EDC) technology is an electrochemical CO_2 concentrator that is essentially an altered fuel cell that operates in the reverse direction electrochemically. H_2 and O_2 reacts with CO_2 inside an electrochemical cell (see Figure 6-15). On the anode-side, high concentration CO_2 with some H_2 streams out, while on the cathode-side air with low CO_2 concentration flows out. The process works similar to a H_2O_2 fuel cell, which means it generates power (DC). Around 25 % of the heat generated by reaction is removed by out-streams while the remaining heat requires a separate liquid cooling stream. The overall reaction is given in Eq. (6-30) below. [2, pp. 188-189, 55, p. 193]

$$CO_2 + \frac{1}{2}\mathrm{O}_2 + \mathrm{H}_2 \xrightarrow{yields} CO_2 + H_2O + electrical\ energy + heat \qquad \textbf{Eq. (6-30)}$$

Advantages are the generated electrical energy, as well the function that the CO_2 concentration capacity may be regulated by current adjustment which means the capacity could handle large CO_2 overload situations. It is additional a good cabin RH toler. [2, pp. 188-189]

But there are also some drawbacks. A relatively high amount of heat is generated through the process which must be removed and the required supply of H_2 must be accounted for. Since O_2 is consumed, it requires a larger O_2 generation system. And like every fuel cell, it has a potential H_2 leakage which means there is a fire and explosion hazard. [2, pp. 188-189]

6.3.9.2 Data and Sizing

Data for the EDC are given in [84]. Additional, a penalty for the required O_2 and H_2 must be considered. For a storage system, high-pressure tanks are considered[16], while for a closed-loop system a static feed water electrolyzer (SFWE, see 6.3.16) is used. A breakdown is given in Table 6-22.

Table 6-22: Data for electrochemical depolarization concentration [84]

Parameter	Value	Unit
EDC mass	61.24	[kg]
EDC volume	0.117	[m³]
Human Equiv. Unit	4	[HEU]
EDC power production	86	[W]
EDC cooling requirement	393	[W]
Mass penalty storage-system	1.0092	[kg CM-d^{-1}]
Volume penalty storage-system	0.0028	[m³ CM-d^{-1}]
Mass penalty SFWE[17]	2.53	[kg CM^{-1}]
Volume penalty SFWE	0.0014	[m³ CM^{-1}]
Power penalty SFWE	65	[W CM^{-1}]
Cooling penalty SFWE	16	[W CM^{-1}]

The only available MTBF data for the EDC is 4,600 hours [50, p. 184]. This makes this technology highly unreliable. Since the given data is from an early research phase, the applied $f_{Certainty}$ is 0.5.

The system requires periodically purging with N_2 as well as monitoring [2, pp. 188-189, 50, p. 184]. Both are considered to be automated and therefore no scheduled maintenance is necessary.

A TRL of 6 is given for this technology. [2, pp. 188-189, 79]

The data in Table 6-23 and Table 6-24 includes the penalty for H_2 and O_2 consumption by this process, outlined in Table 6-22.

[16] Power and Cooling penalty for the storage system is neglected.

[17] 1 kg CM-d^{-1} assumed as HEU. Therefore, the required O_2 is with Eq. (6-14): $m_{O_2} = \frac{1}{2}\frac{MO_2}{MCO_2} = 0.3635$

Table 6-23: Properties of the electrochemical depolarization concentration process for a storage system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	1,207.64	4,016.28	8,981.54	22,453.85
Volume	[m³]	3.22	10.73	24.51	61.27
Power	[W]	-258	-860	-860	-2,150
Cooling	[W]	1,179	3,930	3,930	9,825
Maintenance	[h]	0	0	0	0
Reliability	[-]	0.6318	0.6318	0.3326	0.3326
TRL	[-]	6	6	6	6

Table 6-24: Properties of the electrochemical depolarization concentration process for a closed-loop system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	172.28	565.07	565.07	1,407.75
Volume	[m³]	0.28	0.93	0.93	2.33
Power	[W]	523	1,722	1,722	4,304
Cooling	[W]	1,374	4,581	4,581	11,439
Maintenance	[h]	0	0	0	0
Reliability	[-]	0.6318	0.6318	0.3326	0.3326
TRL	[-]	6	6	6	6

6.3.10 Air Polarized Concentrator

The air polarized concentrator (APC) is very similar to the EDC, but does not require H_2. Because of this, it is a safer process, but also a net power consumer. Since this technology has only a TRL of 4, it is not further considered. [79]

6.3.11 Sabatier

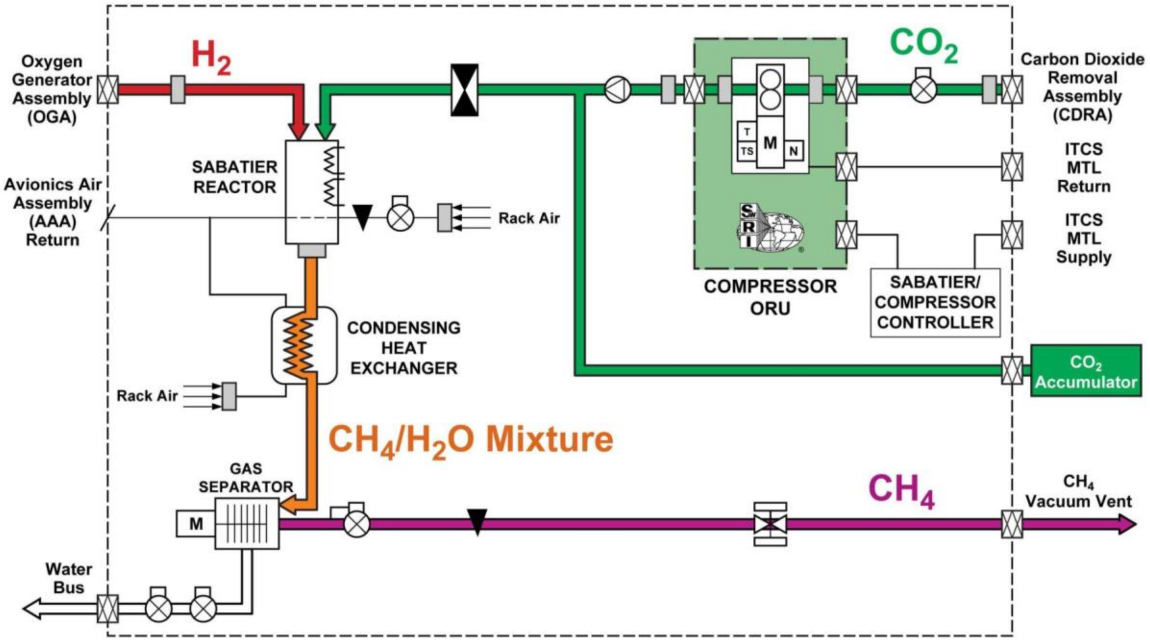

Figure 6-16: Sabatier functional schematic [85]

6.3.11.1 Description

The Sabatier reactor reduces CO_2 to CH_4 and water. CO_2 reacts with H_2 at a temperature of 480-800 K in the presence of a ruthenium catalyst on a high granular substrate producing methane and water. An effective catalyst is 20 wt.-% ruthenium supported on alumina. The reaction begins at 450 K and from then it is self-sustaining. Above 866 K a reverse endothermic reaction occurs which prevents overheating. Molar ratios of H_2:CO_2 ranging from 1.8 to 5 where the lean component is H_2. By-products (C or CO) are minimized when H_2:CO_2 feed ratios slightly below the stochiometric values of 4:1. Normally a ratio of 3.5:1 is used to process all H_2. [2, pp. 196-198, 86]

Advantages are the reliable operation and short start-up time. The design of major components, catalyst and subsystem configuration are on a mature level. The Sabatier has a single pass efficiency of over 99 % and significant savings in weight, power, volume and resupply are expected compared to Bosch (see 6.3.12). [2, pp. 196-198]

But there are also some disadvantages. The recovered water contains dissolved gases, like CO_2 and CH_4 which must be removed before the water can be further used. N_2 in the air will be vented with the CH_4 and the catalyst is susceptible to poisoning by solid amine vapors. Further it increases water resupply and requires methane handling. [2, pp. 196-198]

6.3.11.2 Data and Sizing

Data from [79] is used for a crew of 6 and a mission duration of 400 days. Since no cooling requirement is given in this source, the ratio between power and cooling must be determined. [2, pp. 196-198] states the necessary power is 50 W, while the generated heat is 268 W. This gives a power-heat ratio of 18.66 % which is further used.

Table 6-25: Data from Sabatier process [79]

Parameter	Value	Unit
Mass	31	[kg]
Volume	0.01	[m³]
Human Equiv. Unit	6	[HEU]
Power Consumption	130	[W]

When 4BMS is considered as the CO_2 removal technology, an additional compressor and tank is necessary. On ISS, this is a mechanical two-stage, reciprocating piston compressor. The tank has a volume of 0.0208 m^3 which is added to the volume stated in Table 6-25. No other data about the compressor or tank could be found. [86]

No data about reliability of the Sabatier could be found.

No scheduled maintenance is expected for this system.

The Sabatier is integrated into the AR subsystem of the ISS. Therefore, it has a TRL of 9.

Table 6-26: Properties of the Sabatier assembly

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	47.90	159.65	159.65	399.13
Volume	[m³]	0.02	0,05	0.05	0.13
Tank volume[18]	[m³]	0.04	0.14	0.14	0.35
Power	[W]	291	971	971	2,427
Cooling	[W]	1,561	5,202	5,202	13,005
Maintenance	[h]	0	0	0	0
Reliability	[-]	-	-	-	-
TRL	[-]	9	9	9	9

[18] The compressor tank is only needed for the 4BMS.

6.3.12 Bosch Reactor

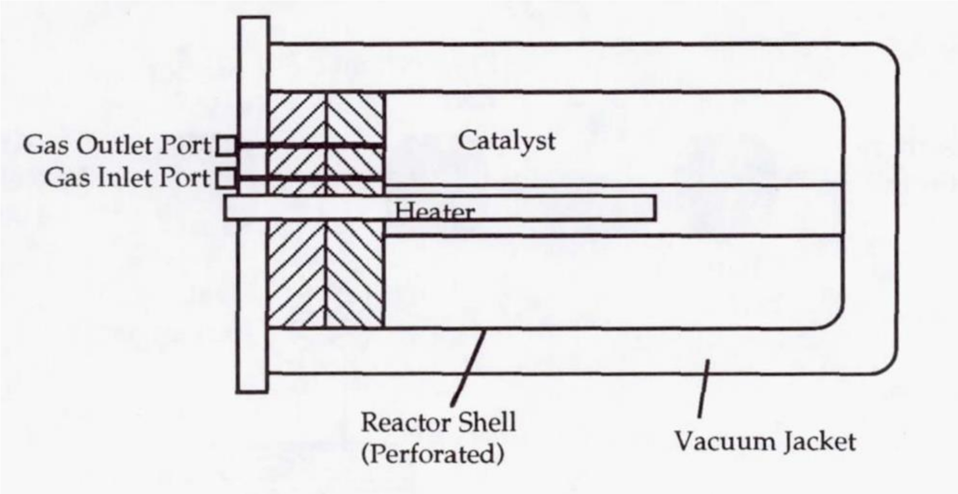

Figure 6-17: Bosch reactor [55, p. 199]

6.3.12.1 Description

In the Bosch reactor, CO_2 reacts with H_2 at a temperature of 700-1000 K in the presence of a catalyst, which produces solid C, potable H_2O and heat. Activated steel wool is generally used as catalyst. A better catalyst, like Ni, Ni/Fe, or Ru/Fe, is in development to increase the efficiency and lower the reactor temperature. The single-pass efficiency is only 10 % which makes a recycle mode necessary. The reactant molar H_2:CO_2 ratio should be 2:1. Further, a periodic replacement of the catalyst is necessary due to solid C deposits. Chemical reactions in the Bosch process are separated into low and high temperature. Therefore, it is better to use two reactors in series. Additionally, the efficiency can be increase by operating over a range of temperatures, since the optimum temperature changes as carbon is deposited. The use of a CO_2 laser would improve the reduction reaction. [2, pp. 193-196]

The biggest benefit of the Bosch process is the achievable 100 % conversion efficiency and therefore no overboard venting. [2, pp. 193-196]

But the drawbacks are that much crew time is required for maintenance since the catalyst beds must be replaced periodically and the reactor can only operate in semi-batch operation of catalyst beds. Moreover, the operating temperature is high and the used catalyst beds with solid C must be stored. [2, pp. 193-196]

6.3.12.2 Data and Sizing

The same data source [79] as for the Sabatier is used. To determine the cooling requirement, the power and cooling requirements are 239 W and 313 W [2, pp. 193-196] respectively to get a power to cooling ratio of 76.36 %. The catalyst expandable mass is 0.0645 kg $CM\text{-}d^{-1}$ and the volume is $5.864*10^{-4}$ m^3 $CM\text{-}d^{-1}$ [50, p. 226].

Table 6-27: Data for Bosch reactor [79]

Parameter	Value	Unit
Mass	68	[kg]
Volume	0.09	[m³]
Human equiv. unit	6	[HEU]
Power consumption	242	[W]

The maintenance for the Bosch reactor is high. It is assumed that the change of the cartridge requires about 8 min and that one cartridge holds 20 CM-d. [2, pp. 193-196]

The MTBF is stated to be 10^5 hours. [2, pp. 193-196]

The Bosch process has a relatively low TRL of 6. [2, pp. 193-196]

Table 6-28: Properties of the Bosch reactor system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	173.18	577.28	894.66	2,219.66
Volume	[m³]	0.75	2.51	5.40	13.50
Power	[W]	542	1,807	1,807	4,517
Cooling	[W]	710	2,366	2,366	5,916
Maintenance	[h]	7.04	23.47	56.27	140.67
Reliability	[-]	0.9791	0.9791	0.9506	0.9506
TRL	[-]	6	6	6	6

6.3.13 Advanced Carbon-Formation Reactor System

The advanced carbon-formation reactor system (ACRS) consists of a Sabatier reactor, a gas/liquid separator to remove water from methane, and a carbon formation reactor (CFR). The CFR packs carbon better than Bosch, but the operation temperature of CFR is over 1144 K. This technology has a TRL of 4 and is not further considered. [2, p. 198, 79]

6.3.14 CO_2 Electrolysis

CO_2 electrolysis is also called the INL (Idaho National Lab) co-electrolysis process. It has a dual purpose of reducing CO_2 directly from a concentrator as well as producing O_2. The solid electrolyte subsystem can electrolyze both CO_2 and H_2O vapor to continuously generate enough O_2 for a person and cabin leakage. Technical problems, such as high temperatures with over 1140 K and ceramic-to-ceramic seals must be overcome. Both sides of the electrolyte are coated with a porous metal catalyst-electrode, such as platinum. In the CO reactor (Boudouard reactor), Ni, Fe or Co catalyst are used. Since this is an electrolytic process, it is capable of operating at several times of its design capacity. Increased O_2 output is achieved by merely increasing the DC voltage. This technology is not selected, because it has a TRL of 4. [2, pp. 198-200, 79]

6.3.15 Solid Polymer Water Electrolysis

6.3.15.1 Description

The solid polymer water electrolysis (SPWE) electrolyzes water to produce O_2 and H_2. It requires feed water in direct contact with the cell anode to provide cooling. There is no need of a H_2O-O_2 separator but a dynamic 0-g phase separator pump for the separation of H_2O-H_2. It is very similar to the SFWE process (see 0). [2, pp. 203-204]

6.3.15.2 Data and Sizing

Since this technology is used on the ISS, sufficient data is available. It is also known under the name oxygen generation assembly (OGA). For better comparison with the SFWE process, [79] is used as source. Because no cooling requirements are given in this source, the relationship between power and cooling are necessary. The newest available power requirement for the OGS is 1,276 W, while the corresponding cooling is 567 W [80]. This gives a relationship of 44.44 %.

Table 6-29: Data from solid polymer water electrolysis [79]

Parameter	Value	Unit
Mass	64	[kg]
Volume	0.05	[m³]
Human equiv. unit	6	[HEU]
Power consumption	1,021	[W]

For the reliability analysis, MTBF data from [63, p. 158] is used.

The given crew time for maintenance is 10 CM-h for a 360 day mars transit mission. [87, p. 89]

In its current design, the OGS is mature and has operated for over 4.5 years without failure [70]. Thus, a TRL of 9 is applied.

Table 6-30: Properties of the solid polymer water electrolysis system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	98.88	329.60	329.60	808.00
Volume	[m³]	0.08	0.25	0.25	0.63
Power	[W]	2,287	7,555	7,555	18,889
Cooling	[W]	1,016	3,358	3,358	8,394
Maintenance	[h]	4.89	16.30	39.07	97.69
Reliability	[-]	0.7417	0.7417	0.4885	0.4885
TRL	[-]	9	9	9	9

6.3.16 Static Feed Water Electrolysis

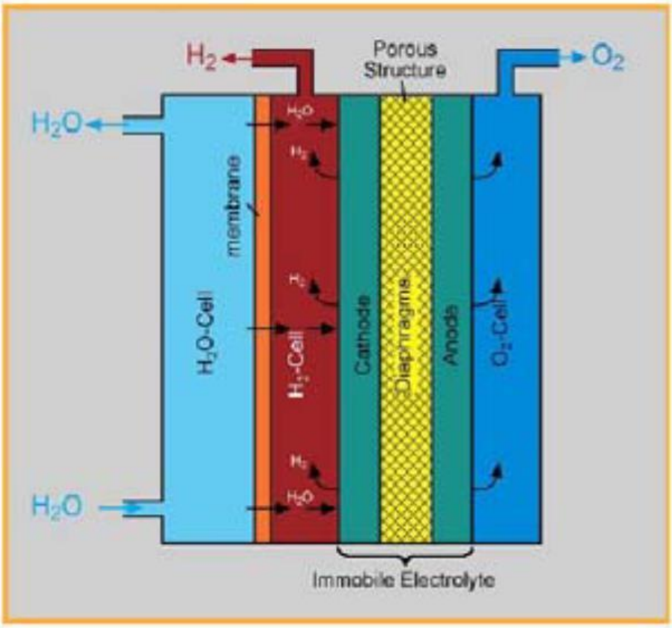

Figure 6-18: ACLS OGA electrolysis principle [88, p. 9]

6.3.16.1 Description

The static feed water electrolysis (SFWE) electrolyzes hygiene water to produce O_2 and H_2. The feed water rests statically in a feed compartment and diffuses as vapor through a membrane and into an aqueous KOH electrolyte. O_2 gas is produced at the anode together with H_2O vapor which must be removed by a separator. This technology has the capability of circulating feed water to provide any required cooling. Water feed and cell matrices consists of thin asbestos sheets which are saturated with a hygroscopic aqueous potassium hydroxide (KOH) solution. [2, pp. 202-203, 55, p. 186]

6.3.16.2 Data and Sizing

The Data for SFWE is from [79]. No cooling requirement is given in this source, but the power consumption from another SFWE assembly states that 243 W $CM\text{-}d^{-1}$ [89, p. 18] are required, while the necessary cooling is around 60 W $CM\text{-}d^{-1}$ [89, p. 22]. Therefore around 25 % of required power is required for cooling.

Table 6-31: Data from static feed water electrolysis [79]

Parameter	Value	Unit
Mass	54	[kg]
Volume	0.03	[m^3]
Human equiv. unit	6	[HEU]
Power consumption	959	[W]

No scheduled maintenance is assumed.

No data about reliability could be found. But since this is an electrolysis process, the reliability of the SPWE (see 6.3.15) is used, since this process is similar.

The TRL of this technology is 8. [43]

Table 6-32: Properties of the static feed water electrolysis system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	83.43	278.10	278.10	681.75
Volume	[m³]	0.05	0.15	0.15	0.38
Power	[W]	2,148	7,097	7,097	17,742
Cooling	[W]	537	1,790	1,790	4,435
Maintenance	[h]	4.89	16.30	39.07	97.69
Reliability	[-]	0.7417	0.7417	0.4885	0.4885
TRL	[-]	8	8	8	8

6.3.17 Water Vapor Electrolysis

The water vapor electrolysis process electrolyzes directly from the cabin air. Moist air is fed to the anode of the SFWE-style electrolysis cell, producing an O_2 enriched steam at the anode and H_2 at the cathode. It helps to control the humidity in the cabin and has few interfaces. It is a potential candidate for providing a safe haven atmospheric regeneration system. This technology has a TRL of 4 and is not further considered. [2, pp. 204-205, 79]

6.3.18 Solid Electrolyte Oxygen System

The solid electrolyte oxygen system (SEOS) is considered for development of the capability to recharge extravehicular activity (EVA) tanks as well as provide on-demand medical oxygen. It is in its early stages of development and has a TRL of 3. Therefore it is not further considered. [90]

6.3.19 High Pressure Electrolysis

High pressure oxygen supply by high pressure water electrolysis (HPE) at 24.8 MPa provides a promising technology to repressurize high-pressure tanks on-demand. Currently different cells are in development, but no complete breadboard is developed yet. Because of this, the TRL is 3 and the technology selected out. [90]

6.3.20 Trace Contaminant Control System

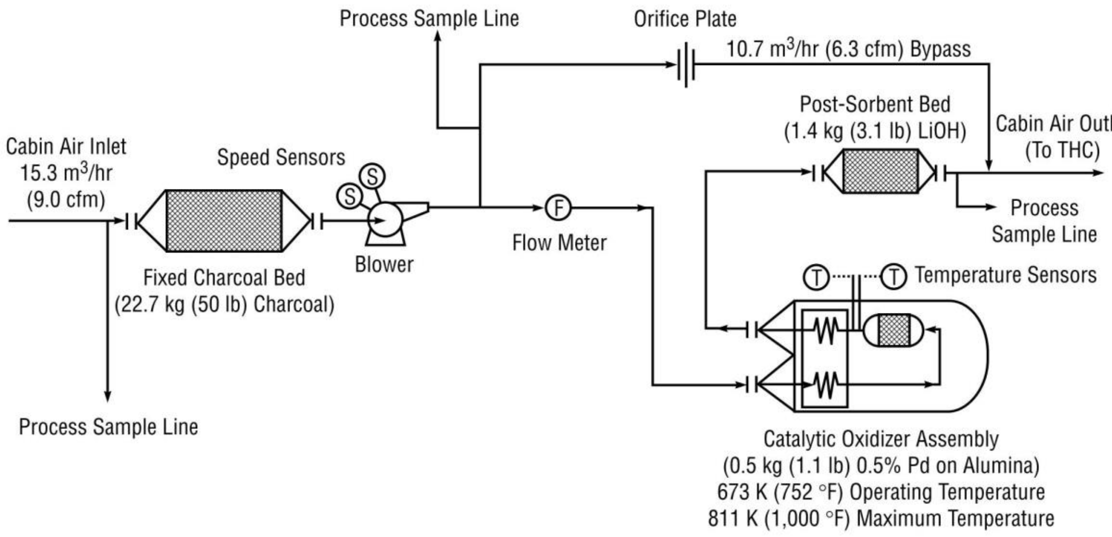

Figure 6-19: TCCS schematic [38, p. 154]

6.3.20.1 Description

The optimal material selection and control process can only minimize the overall contamination load. The load cannot be completely eliminated because all materials off gas chemical contaminants to some degree and people always produce a variety of contaminants. An active contamination control system is necessary on board the spacecraft to prevent buildup to noxious levels. Therefore, the trace contaminant control system (TCCS) is used to remove hazardous trace gas contaminants from the air. The air first flows through a no regenerable activated charcoal bed, impregnated with phosphoric acid, for control of well-adsorbed contaminants, ammonia and water-soluble contaminants. A filter downstream prevents particulates from entering other parts of the system. About 30 % enters the smaller activated charcoal bed while the remaining is ducted to the cabin. The low air-flow rate there aids in removal of contaminants that are poorly adsorbed by charcoal. A no regenerable LiOH presorbant bed prevent acid gases, like HCl, HF, or SO_2, from entering the catalytic oxidizer downstream. The high temperature catalytic oxidizer contains an oxidation catalyst, like palladium on alumina, and operates at 673 K. His primary function is to oxidize hydrocarbons that are not adsorbed in the charcoal beds. The air then flows to the no regenerable postsorbant LiOH bed which removes any undesirable acidic products of oxidation. [2, pp. 206-210, 55, pp. 202-203, 91, p. 3]

Advantages of this technology are the versatility for non-specific contaminants, since it can control many different organic and inorganic airborne trace pollutants. It further provides a country-fresh air environment. [2, pp. 206-210]

6.3.20.2 Data and Sizing

The TCCS on ISS is used as the baseline technology [63, p. 159]. Data of this system is given in Table 6-33.

Table 6-33: Data from trace contaminant control system on ISS [63, p. 159]

Parameter	Value	Unit
Mass	79.83	[kg]
Volume	0.279	[m³]
Human equiv. unit	6	[HEU]
Power consumption	180	[W]
Cooling [38, p. 149]	130	[W]

Data for MTBF is also used from [63, p. 159] to calculate the reliability.

Necessary maintenance is given to 4.37 CM-h y^{-1} [38, p. 74].

Since this technology is used on the ISS for years, a TRL of 9 is applied.

Table 6-34: Properties of the trace contaminant control system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	123.34	411.13	411.13	1,007.88
Volume	[m³]	0.41	1.36	1.36	3.40
Power	[W]	403	1,344	1,344	3,360
Cooling	[W]	291	971	971	2,427
Maintenance	[h]	2.11	7.02	16.84	42.10
Reliability	[-]	0.9359	0.9359	0.8532	0.8532
TRL	[-]	9	9	9	9

6.4 Water Recovery and Management

The water recovery and management (WRM) subsystem controls all water storage and flows. Water is used by the crew for drinking and food rehydration as well as hygiene. When a dish or clothes washer are considered, both would be in this subsystem. It is the ECLSS subsystem with by far the highest mass flow. It has therefore the highest potential to reduce the consumables mass when recycling is considered. The general WRM schematic with the different water flows and assemblies of the system as well the interfaces to other subsystems is shown in Figure 6-20. [68, p. 130]

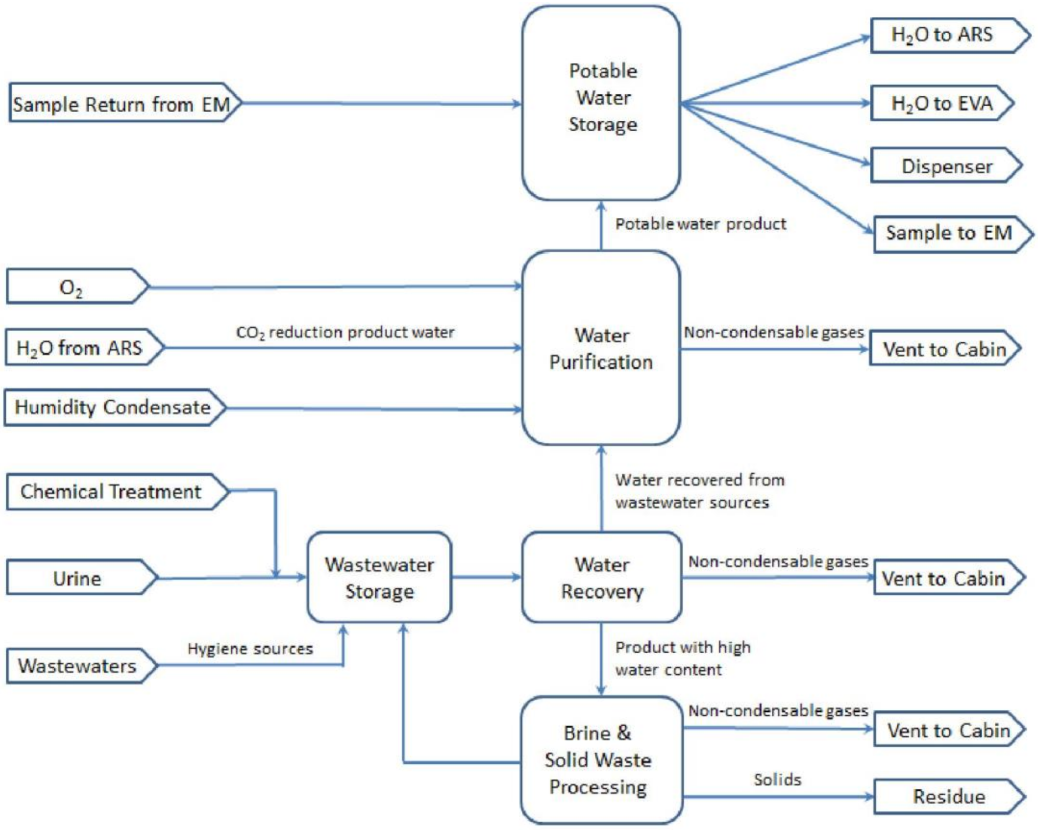

Figure 6-20: WRM schematic [17, p. 7]

There are two process categories for physico/chemical water recovery: filtration and distillation. Filtration is normally used for relatively clean waste water sources like condensate and hygiene water. Distillation is mainly considered for urine recovery. [2, pp. 218-219]

The following 3 filtration processes are considered for the trade study:

- Multifiltration (MF)
- Reverse Osmosis (RO)
- Electrodialysis (EDI)

For distillation or phase change the following approaches are considered:

- Vapor Compression Distillation (Urine Processing Assembly) (VCD)
- Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)

The WRM has to fulfill 12 functions. For the subsequent trade analysis in chapter 7, only the storing and processing functions are compared for the different possible processes outlined above. The water quality monitoring described in section 6.4.9 is an essential and vital element of the WRM and will be analyzed in detail in this chapter.

All above mentioned processes are analyzed in the following sections. Beforehand the needed water and produced waste water are examined and the considered architectures are explained.

Consumption water falls into two categories: potable and hygiene water, while the later has slightly lower quality requirements (see also requirement 4.2.4.a). Potable water is used for drinking (2.0 kg $CM\text{-}d^{-1}$ [10]) and food rehydration (0.5 kg $CM\text{-}d^{-1}$ [10]), while hygiene water is used for personal grooming (0.4 kg CM-d^{-1} [10]), shower (1.43 kg CM-d^{-1} [20]), and flush water (0.3 kg CM-d^{-1} [10]). Water usage for other payloads is not considered. This consumption water can be stored or recycled from waste water outlined below.

Waste water could be vented by gasification or recycled. There are 3 different types of waste water. Urinal water consist of urine and flush water and is the highest contaminated waste water [50, p. 347]. The typical mass flow is 1.2 kg CM-d^{-1} of urine and 0.3 kg CM-d^{-1} for flush water [10, p. 45, 10, 51]. The shower and personal grooming water are combined to hygiene waste water and are heavily contaminated by chemicals [50, p. 345]. It is assumed that 0.4 kg CM-d^{-1} from personal grooming[19] and 1.43 kg CM-d^{-1} from shower[20] are produced. The waste water with the lowest contamination is humidity condensate reclaimed from the air [50, p. 345]. This depends largely on the considered exercise and is 2.41 kg CM-d^{-1} for a nominal schedule and 1.43 kg CM-d^{-1} for a schedule without exercise (see chapter 3.2.3 for considered schedules) [10, p. 45]. Other potential waste water sources like feces and unused food are discussed in chapter 9.2 Waste Management.

Additional possible sources are a laundry system which would use 3.79 kg CM-d^{-1} [87] or a dish washing machine with a consumption of 3.54 kg CM-d^{-1} [10]. Because both technologies have a TRL of under 5, they are no further considered in the analysis of the WRM. Especially a laundry system would provide a huge benefit for the clothes system, as described in chapter 9.4.2 Clothing.

It is beneficial to separate the recycling loops into condensate, hygiene waste water, and urinal water to allow redundant independent subsystems or flexible operation if a failure occurs. It would even be possible to directly use condensate water for cleaning and flush, but this is not further considered in this analysis. [5]

Accordingly, the possible five waste water groupings are listed in Table 6-35 with the corresponding specific mass outlined above.

[19] Wash water for personal grooming is normally evaporated and recycled as humidity condensate [5].
[20] As stated in requirement 4.4.4.b.iii, crew members are allowed to use a 10 L shower every 7 days.

Table 6-35: Waste water grouping and corresponding specific masses

	[kg CM-d^{-1}]
• Urinal water • Humidity condensate • Hygiene waste water	1.50 2.41 1.83
• Urinal water & humidity condensate • Hygiene waste water	3.91 1.83
• Urinal water • Humidity condensate & hygiene waste water	1.50 4.24
• Urinal water & hygiene waste water • Humidity condensate	3.33 2.41
• Urinal water & Hygiene waste water & humidity condensate	5.74

The state of the art water recovery system on ISS process urinal water in the urine processor assembly (UPA). The corresponding technology (VCD) is described in section 6.4.4. The resulting distillate is mixed with humidity condensate and other water sources not considered here, like Sabatier, and recycled in the Water Processor Assembly (WPA). The WPA consists on multifiltration which is described in chapter6.4.2. [82, 90]

Hygiene waste water from the shower was recycled on MIR.

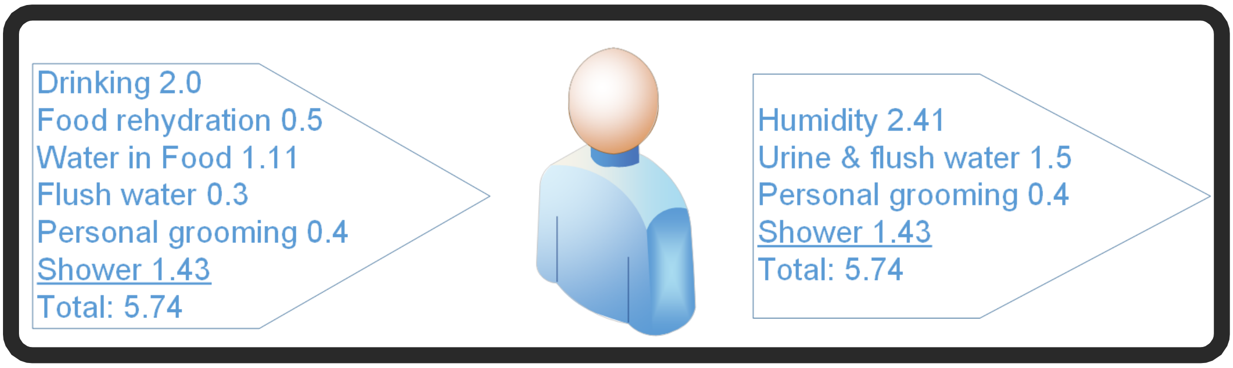

Figure 6-21: Water balance in [kg CM-d^{-1}]

As can be seen from the water balance in Figure 6-21, the total water consumption is around 4.63 kg CM-d^{-1}, excluding 1.11 kg CM-d^{-1} for water content in food. On the other side is a total waste water production of 5.74 kg CM-d^{-1}. Therefore, the needed water recovery efficiency can be calculated by Eq. (6-31) to 0.81. For comparison, the efficiency of the ISS WPA has been approximately 88% [92]. The water recovery efficiency is considered to be the key factor for technology selection [93].

$$\mu_{RE} = \frac{m_{recovered}}{m_{available}} \qquad \textbf{Eq. (6-31)}$$

with:

- μ_{RE} [-] - water recovery efficiency factor

- $m_{water,recovered}$ [kg d^-1] - daily recovered water mass by WRM
- $m_{water,available}$ [kg d^-1] - daily consumption water mass

The following 4 water recycling architectures (WRA) in Table 6-36 are considered in the further analysis with rising recycling capacity. Case 1 is a storage system without any recycling. This is the most reliable one but also the one with the highest mass and volume. For case 2, only potable water must be stored and the recovery efficiency is within the capability of state-of-the-art technologies. This case is considered, since humidity condensate is relatively simple to recycle and because of the contemplated use as hygiene and flush water it may be processed to less than potable standards [5]. For use as flush water, no further processing is necessary and it can be directly used [5]. Case 3 needs a minimal storage of potable water with the considered waste water amounts, but needs a processing to potable water standard. Case 4 recycles all waste water and needs only an efficiency of 0.81 because of the high water content in the considered food of 1.11 kg CM-d^{-1} (see also 9.4.1).

Table 6-36: Water recycling architectures

Name	Recycled water sources	Target consumable water	μ_{RE}	Required stored water [kg CM-d^{-1}]
WRA1	none		0	4.63
WRA2	humidity condensate	hygiene water + flush water	0.88	2.50
WRA3	humidity condensate + hygiene waste water	potable water + hygiene water + flush water	> 1	> 0.39
WRA4	humidity condensate + hygiene waste water + urinal water	potable water + hygiene water + flush water	0.81	0

The above considered processes can therefore be divided into the matrix in Table 6-37. The filtering processes MF and RO are only considered for relatively clean waste water, because otherwise the changeout rate and mass would be to large. VAPCAR is only considered for urinal water recycling, because, as the name suggest, the main purpose of this process is the treatment of ammonia from urine.

Table 6-37: Process to waste water matrix

Process	humidity condensate	hygiene waste water	urinal water
MF	X	X	
RO	X	X	
EDI	X	X	X
VCD	X	X	X
TIMES	X	X	X
AES	X	X	X
VAPCAR			X

To make the trade-off analysis as reasonable as possible, it is necessary to use data from the same source. This is especially apparent when comparing available data for MF. While the WPA, which is a MF process, has an installed mass of 781 kg on ISS, other sources states 232 kg for a Mars transit mission over 450 days and 4 crewmembers [5], 51.26 kg for a 500-day mission of 9 people [50, p. 396], or even as low as 3.8 kg for 4 people [2, p. 233]. The only available source that has sufficient data for all considered processes at a comparable level is [50]. Therefore, it was decided to use this source as it has the most and best defined data of all other sources, although this is the oldest source.

6.4.1 Water Storage

Two different approaches for water systems are analyzed: a storage system and a partial-closed-loop system. A completely closed-loop system is only possible in a bio regenerative system, which is excluded from further analysis (see 9.3).

A storage system does not recycle and has therefore the highest mass and volume requirements, but it is much more reliable.

To prevent growth of pathogens and biofilm creation, a robust microorganism control is necessary. Several approaches are possible, like chemical treatment with iodine, ozone, or silver. Other techniques are the use of thermal heating, UV light or mechanical filtration. For bacteria control in the water tanks, silver will be used. On ISS, silver is used in the Russian segment while iodine is used in the US section. The disadvantage of iodine is, that is has to be removed from the water before consumption and consequently requires additional hardware, complex operations and more consumables. [55, p. 233, 90]

6.4.1.1 Water Tank Data

Another point to consider are the various tank volume definitions. The total capacity describes the internal volume of the water tank. The total mass of water in a tank is constraint by the filling degree. On ISS, the waste water tank has only a maximum filling degree of 65 % due to concern of biofouling. For clean water, the maximum filling degree is assumed to be 95 %. There is also a minimum volume of water in the tank, which can´t be removed. This is around 4 % of the total capacity. The working volume is the difference between the maximum filling volume and the minimum volume, hence 61 % for waste water tanks and 91 % for clean water tanks. [51]

Water tanks in microgravity have the problem, that the liquid could contain gas bubbles. Therefore, normally rubber bladders and metal bellows are used. For example, the Russian potable water storage tank SVO-ZV is a 22-liter bladder tank in a hard shell. This has the disadvantage that, besides more mass, the material is flexing and therefore the lifetime is limited. To minimize this effect, bigger tanks and/or less filling and draining are preferable. [55, p. 226, 94, p. 4]

The tank mass can be calculated with Eq. (6-32) [73, 266–270]. The diameter of the tank can be directly calculated by dividing the maximum water mass in the tank through the density of water. For minimal volume, a spherical shape is assumed. Further the shell material is assumed to be aluminum with a density of 2,710 kg m^{-3}, and the minimum thickness is 0.5 mm due to handling and launch load considerations. The design pressure is assumed to be 3.5 kg cm^{-2} and the design stress to be 700 kg cm^{-2}. The typical value for the bladder material density is 1,500 kg m^{-3}, while the thickness is assumed to be 0.5 mm. For the fixed mass term K_l the value 2.3 kg is used. [73, 266–270]

$$m_{WT} = \pi\, D_{WT}^2\, \rho_s\, t_s + \pi\, D_{WT}^2\, \rho_b\, t_b + K_l \qquad \textbf{Eq. (6-32)}$$

$$t_s = \frac{P\, D_{WT}}{4\, S} \geq 0.5\, mm \qquad \textbf{Eq. (6-33)}$$

with:

- m_{WT} [kg] - mass of bladder tank
- D_{WT} [m] - diameter of tank
- ρ_s [kg m^{-3}] - density of shell material
- t_s [m] - thickness of shell
- ρ_b [kg m^{-3}] - density of bladder material
- t_b [m] - thickness of bladder
- K_l [kg] - fixed mass for bosses, mounting brackets etc.
- P [kg cm^{-2}] - design pressure
- S [kg cm^{-2}] - design stress

A plot of the tank mass over the water mass for a bladder tank is given in Figure 6-22. When dividing the tank mass through the water mass to get the specific tank weight, it can be seen in Figure 6-23, that this value is falling considerable under 500 L for low masses and gets nearly constant for higher masses.

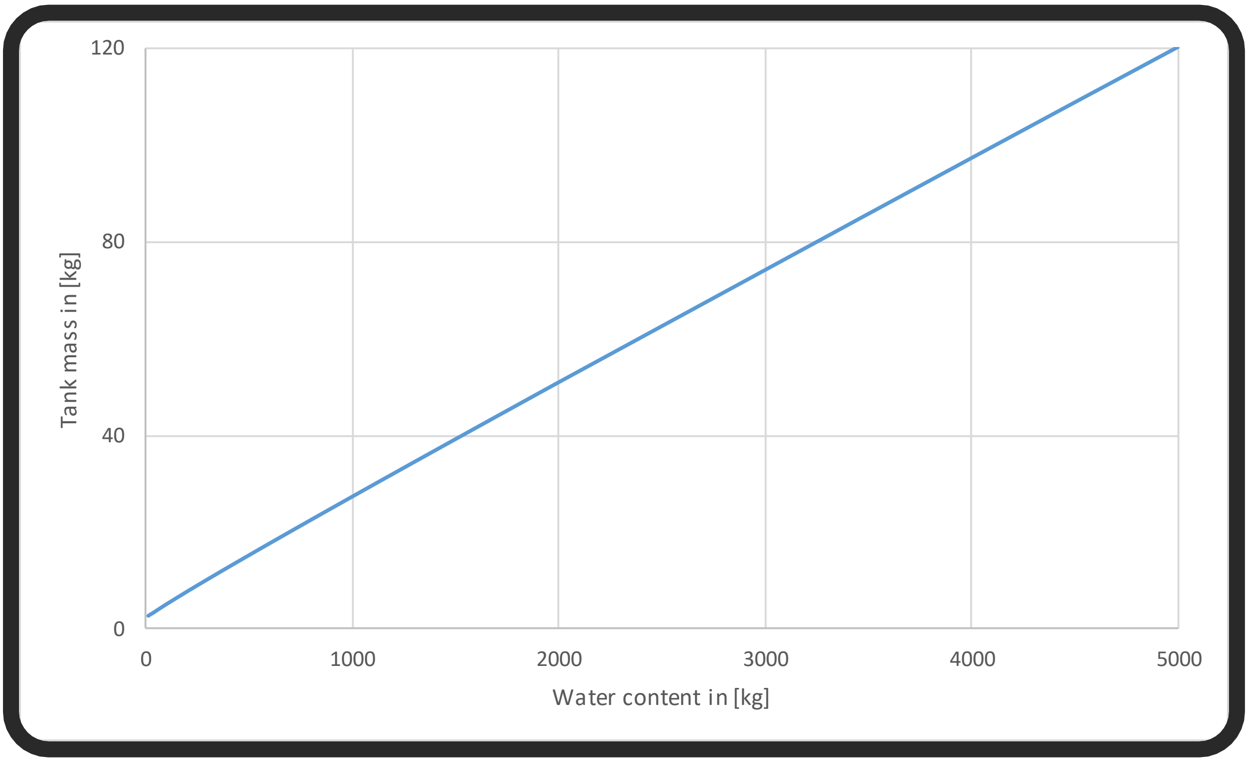

Figure 6-22: Bladder tank mass for water masses between 10 and 5,000 kg.

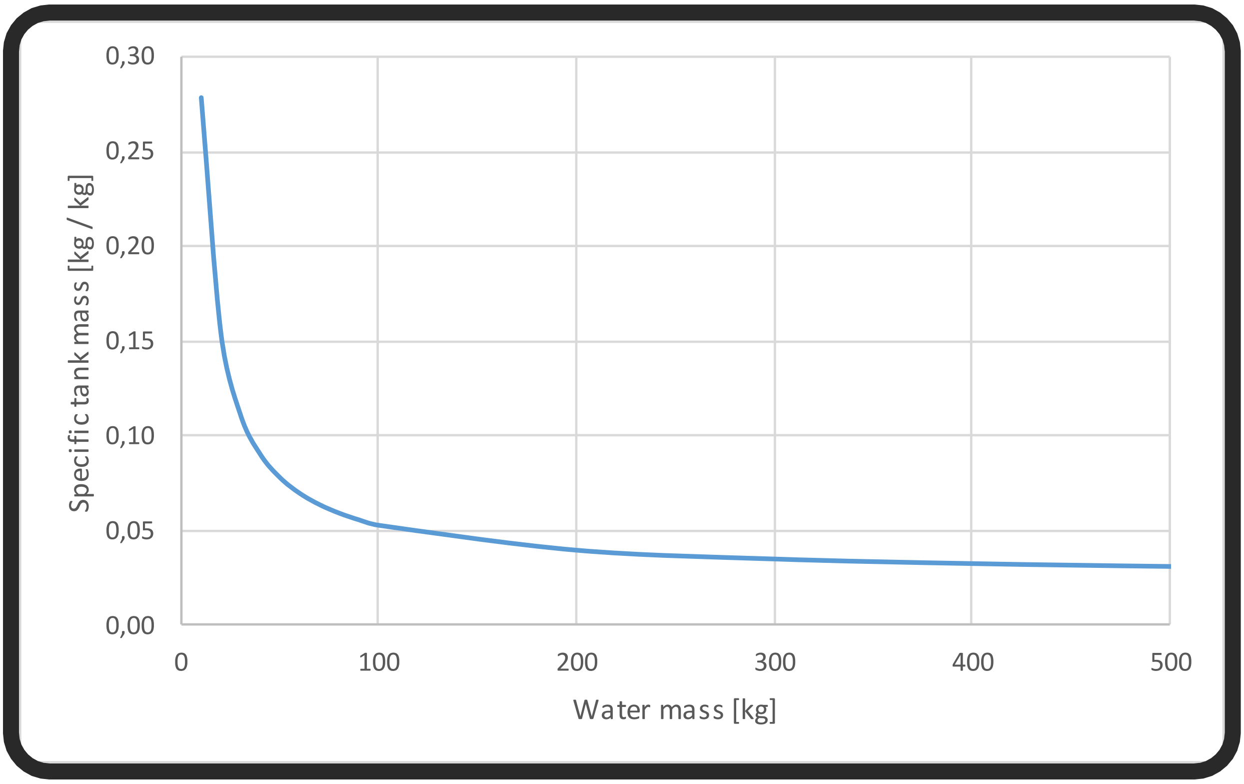

Figure 6-23: Specific water tank mass for water masses up to 5,000 L

The MTBF of a bladder water tank is $1e^8$ hours [73, pp. 355-358]. This value seems high, but was the only source for bladder tanks found.

Besides the tanks the system requires one water pump and one valve per tank. Data from the water delivery pump of the WPA is used from [63, p. 162]. This pump has a mass of 47.54 kg, a volume of 0.1 m³, power requirement of around 5 W [38, p. 76], and a MTBF of 64,561 hours. Cooling of the pump is assumed to be provided by the processed water stream and not further considered. The pump is sized for a typical flow rate of 63.1 kg d^{-1} [38, p. 180]. The control valve has a mass of 1.97 kg, a volume of under 0.01 m³ and MTBF of 100,000 hours. The power and cooling requirement for the valves are neglected. For every tank, a redundant valve is needed.

Water tank systems are commonly used in past and current spacecraft and hence the system has a TRL of 9.

The heating of water before consumption is not analyzed here, since it is necessary for every water system and thus do not provide additional data for a comparison. See chapter 10.4 for an analysis of the consumption water heating.

6.4.1.2 Water Tank Sizing for Storage System

The water tank storage system consists of initially filled potable water tank and vents all waste water to save mass and volume for waste water tanks. For venting, space vacuum is used to reduce the pressure and thus vaporizing the waste water. Only one tank is considered, since the reliability is very high and additional tanks would only add additional unnecessary mass.

The required water mass is shown in Figure 4-4. With these values, the volume and mass of the system can be calculated by assuming that the tank is filled to 95 % at the beginning and a residual mass of 4 % is assumed. The tank wall thickness is neglected for the volume analysis. Since the tank is assumed to be spherical, the stowage volume factor from Eq. (5-8) is applied. Because the volume of equipment like the pump or the valves are relatively small, they are included in the calculated cubic volume of the tank. The hereby calculated volume is shown in Figure 6-24. For the best-case scenario with 12 people and 88 days, 10.24 m³ are needed, while for the worst-case scenario with 100 people and 211 days 204.56 m³ are required.

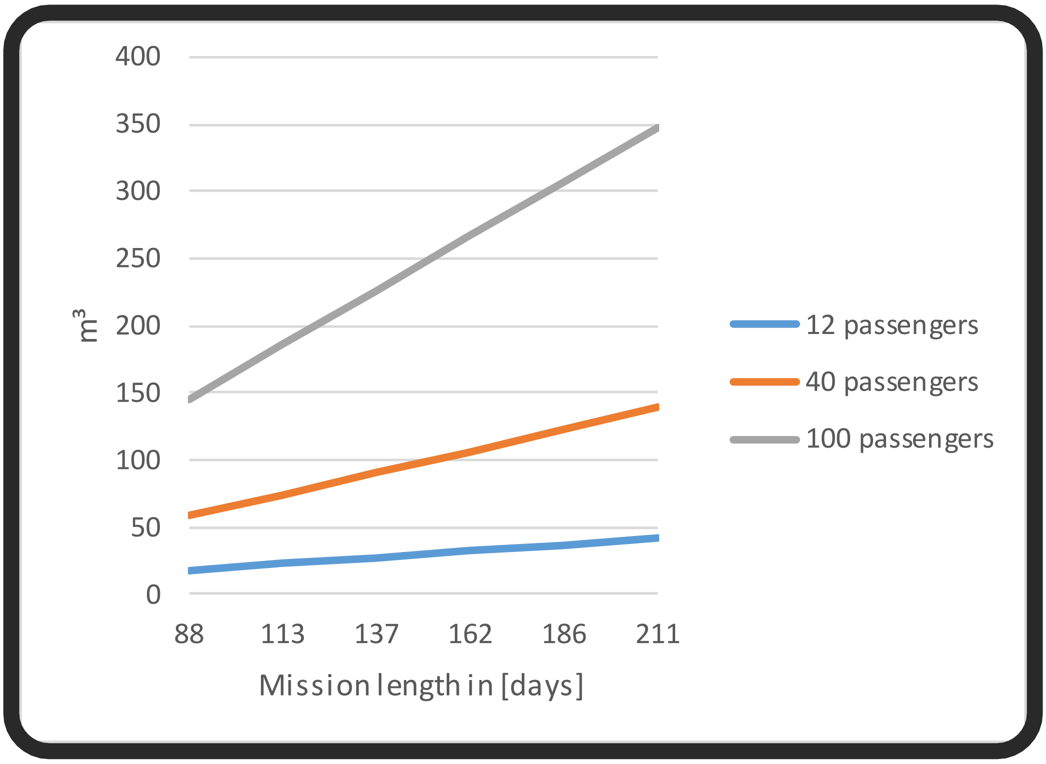

Figure 6-24: Required volume for the water storage system depending on mission length and crew size

For the tank mass, the water mass with additional 4 % residual mass, multiplied with the specific tank mass from Figure 6-23, leads to the data shown in Figure 6-25, including equipment mass. The potable water tanks with a total mass of 127.62 kg holds the required 5,083.28 kg potable water for the best-case scenario. The 101,569.37 kg water for the worst-case scenario needs water tanks with a total mass of 2,284.14 kg.

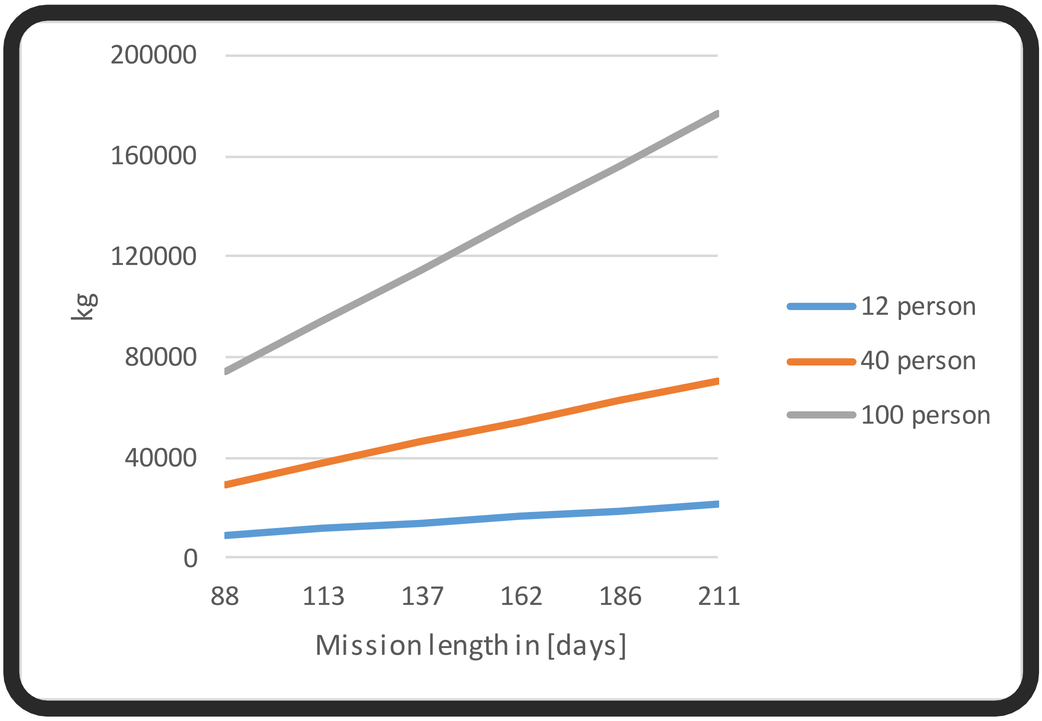

Figure 6-25: Required mass for the water storage system including potable water mass depending on mission length and crew size

The reliability of the storage system consists of the reliability of the tanks, the pump, and the redundant valves for the tank. Since all are considered in series, Eq. (4-1) is applied.

No scheduled maintenance is considered for this system.

The parameters for the analyzed water storage system from the best-case to the worst-case scenario is listed in Table 6-38.

Table 6-38: Properties of the water storage system

Parameter	Unit	Case1	Case2	Case3	Case4
Tank Mass (empty)	[kg]	127.62	402.60	926.94	2,284.14
Total System mass	[kg]	5,253.98	17,481.25	41,689.06	104,183.55
Total System volume	[m³]	10.24	34.13	81.82	204.56
Power	[W]	4	14	14	34
Cooling	[W]	0	0	0	0
Reliability	[-]	0.9995	0.9995	0.9974	0.9974
Maintenance	[h]	0	0	0	0
TRL		9	9	9	9

6.4.2 Multifiltration

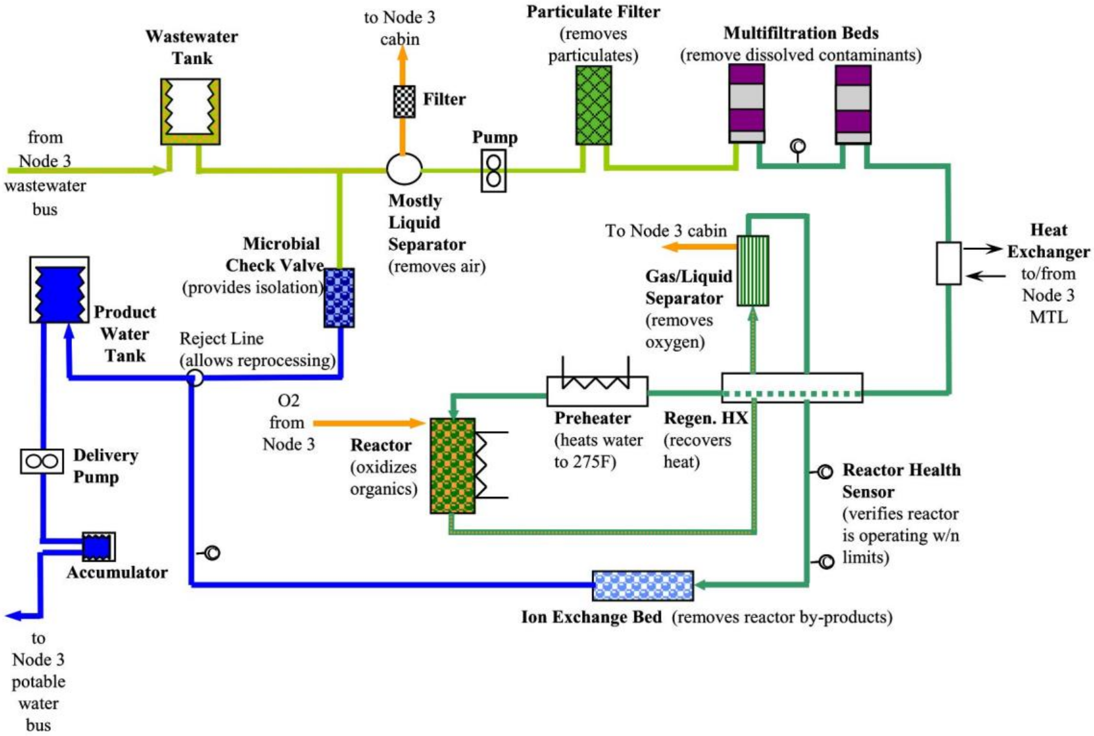

Figure 6-26: WPA schematic [95]

6.4.2.1 Description

Multifiltration (MF) is a filter technology to purify relatively clean waste water like humidity condensate or distillate from urine processing. A schematic of the Water processing assembly (WPA) used on the ISS is shown in Figure 6-26. Several MF beds are connected in series to remove dissolved contaminants. When the first bed is saturated, it is removed and the subsequent bed becomes the first one while a new bed is added to the end. Organic contaminants are oxidized by a reactor and removed by an ion exchange bed down-stream. [2, pp. 231-232, 5, 55, p. 227]

The advantage of MF is that all cleaning elements are contained in one cartridge which makes it reliable and easy to use. The disadvantages are that it cannot be regenerated practically and the beds must be replaced and trashed. [2]

6.4.2.2 Data and Sizing

The assumed baseline assembly for MF is the WPA. Because the WPA operated for years on the ISS and a comparable system (SRV-K) is used for humidity recovery in the Russian segment of the ISS, the TRL is 9.

There are no safety concerns for this technology.

The hardware data differs greatly between the different considered sources. [63] states 781 kg for the WPA mass, [5] states 232 kg for a Mars transit mission over 450 days and 4 crewmembers, and [50, p. 396] states 51.26 kg for a 500-day mission of 9 people. Because [50] is the only source with sufficient data on reverse osmosis found, and to maintain a reasonable comparison between the technologies, this source is also used for MF even when the values seem too optimistic. Data from [50, p. 396] are listed in Table 6-39.

Table 6-39: Data for the multi filtration process [50, p. 396]

Parameter	Value	Unit
Mass	51.26	[kg]
Volume	0.11	[m³]
Power	12	[W]
Cooling	0	[W]
Consumables mass	93.44	[kg]
Consumables volume	0.18	[m³]

The stated values in Table 6-39 are first resized to one CM by applying Eq. (5-1) to Eq. (5-8). For mass and power a CoF of 3 is used due the fact that this process is used on the ISS. Since the above stated values differ significantly from other sources, a $f_{Certainty}$ of 0.5 is used.

The MTBF is given to 40,600 h [50, p. 396], which result in a reliability of 0.9493 for the best-case scenario and 0.8827 for the worst-case. For comparison, the reliability of the WPA assembly can be calculated from MTBF values of the components [63, p. 162] in series with Eq. (4-1) to 0.653 for 88 days and 0.36 for 211 days. But it should be noted that several components of the WPA on ISS have shown that the MTBF are lower than the theoretical ones [90].

Since the MF bed must be changed out periodically, the maintenance time is fairly high. The stated scheduled maintenance for a 500 day mission is 128 hours [50, p. 396]. Converting this value to the best-case scenario, 30.04 hours are calculated while it is 54.02 hours for the worst-case scenario.

The stated values in Table 6-40 are for the four defined cases in Table 3-2.

Table 6-40: Properties of the multi filtration system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	75.38	251.28	356.50	891.26
Volume	[m³]	0.16	0.52	0.71	1.78
Power	[W]	18	60	60	149
Cooling	[W]	0	0	0	0
Reliability	[-]	0.9493	0.9493	0.8827	0.8827
Maintenance	[h]	30.04	100.12	240.07	600.18
TRL		9	9	9	9

6.4.3 Reverse Osmosis

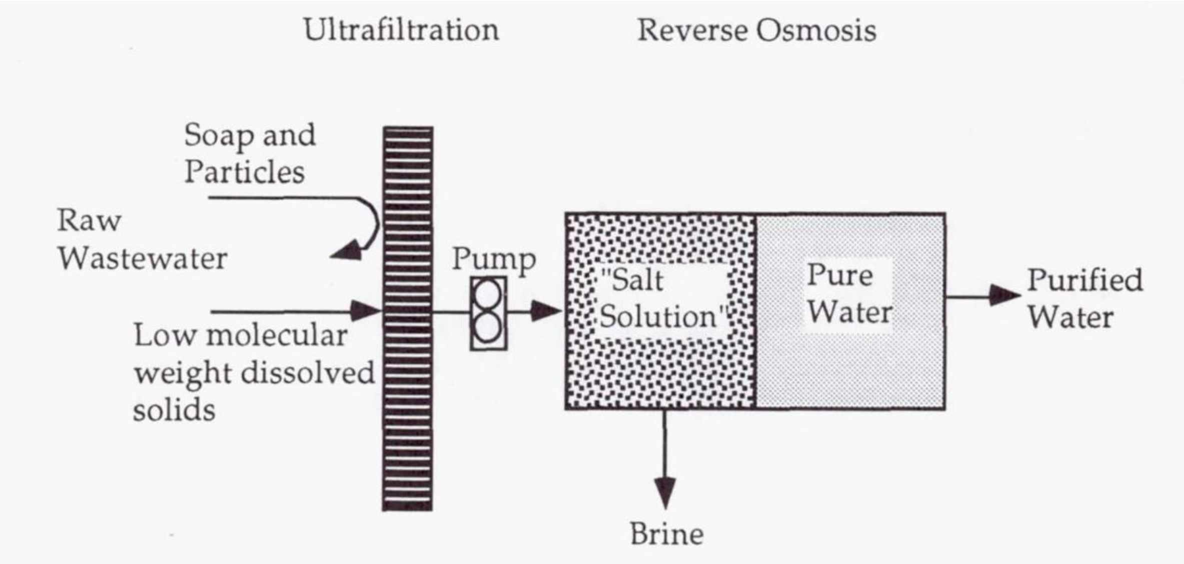

Figure 6-27: Reverse Osmosis Schematic [55, p. 227]

6.4.3.1 Description

The reverse osmosis technology shown in Figure 6-27 is based on membrane technology where pressure is applied to the saline waste water. This forces the liquid to pass through a semi-permeable membrane while ions, organic solids, and microorganisms remain in the salty solution which could potentially be further processed by VCD (see 6.4.4). Current membranes are incapable of removing small organics and require pretreatment of ultrafiltration (UF) and posttreatment with MF (see6.4.2). The UF process filters most suspended solids and macromolecules, while allowing low molecular weight salts and water to permeate the membrane. The waste water is typically pressurized to 690 to 5,500 kPa and the water temperature is ideally above the pasteurization temperature of 347 K to prevent microbial growth. Two types of membranes are applicable. A hollow fiber membrane that consists of a porous polysulfone base with a proprietary solute rejecting thin skin deposited in the fiber interior. This configuration has a high membrane surface area-to-volume ratio which increases module compactness. Waste water is fed to the interior to minimize fouling or the collection of contaminants on the membrane surface. The other type is a dual layer membrane which is made from a mixture of zirconium oxide and polyacrylic acid deposited on the interior of a porous metal or ceramic tube. It has a 70 % higher water flux or throughput and is stable at pasteurization temperature. Specific energy for both membranes is about 10 Wh kg^{-1} water recovered. [2, pp. 230-231, 55, p. 227]

The advantages are a very low energy consumption and no requirement for a gas-liquid phase separator. The operating temperature of around 350 K is lower than that of most distillation processes. On the other hand, high pressure and the pre- and post-treatment increase complexity and mass. A membrane improvement could prevent the pre- and post-treatment. [2, pp. 230-231]

6.4.3.2 Data and Sizing

This technology was considered in the early ISS development process and reached a TRL of 6 [5]. Because other sources mention this technology as a TRL of 5 a $f_{Certainty}$ of 0.5 is used.

RO is considered safe under the prerequisite that the high pressure can be handled safely.

The only found source for data on mass, volume, power, and cooling is [50, p. 392] for a crew size of 9 and a mission length of 500 days. In this preliminary analysis, no pre-treatment was assumed. Consequently, all values stated in Table 6-41 are multiplied with an $f_{Certainty}$ of 0.5.

Table 6-41: Properties for the reverse osmosis process [50, p. 392]

Parameter	value	Unit
Mass	55.79	[kg]
Volume	0.17	[m³]
Power	12	[W]
Cooling	0	[W]
Consumables mass	33.11	[kg]
Consumables volume	0.10	[m³]

The MTBF for the system is given to 20,700 hours without spares [50, p. 392]. This is equivalent to a reliability of 0.9030 for the best-case scenario or 0.7830 for the worst-case scenario. A $f_{Certainty}$ of 0.5 is applied to the reliability.

For scheduled maintenance, 56 hour for the 500 day mission is given [50, p. 392]. Converting this to the best-case scenario, 9.86 hours are calculated while it is 23.63 hours for the worst-case scenario.

Table 6-42: Properties of the reverse osmosis system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	65.47	218.22	255.51	626.37
Volume	[m³]	0.19	0.64	0.75	1.88
Power	[W]	110	366	366	898
Cooling	[W]	0	0	0	0
Reliability	[-]	0.9030	0.9030	0.7830	0.7830
Maintenance	[h]	13.14	43.80	105.03	262.58
TRL		6	6	6	6

6.4.4 Vapor Compression Distillation (Urine Processing Assembly)

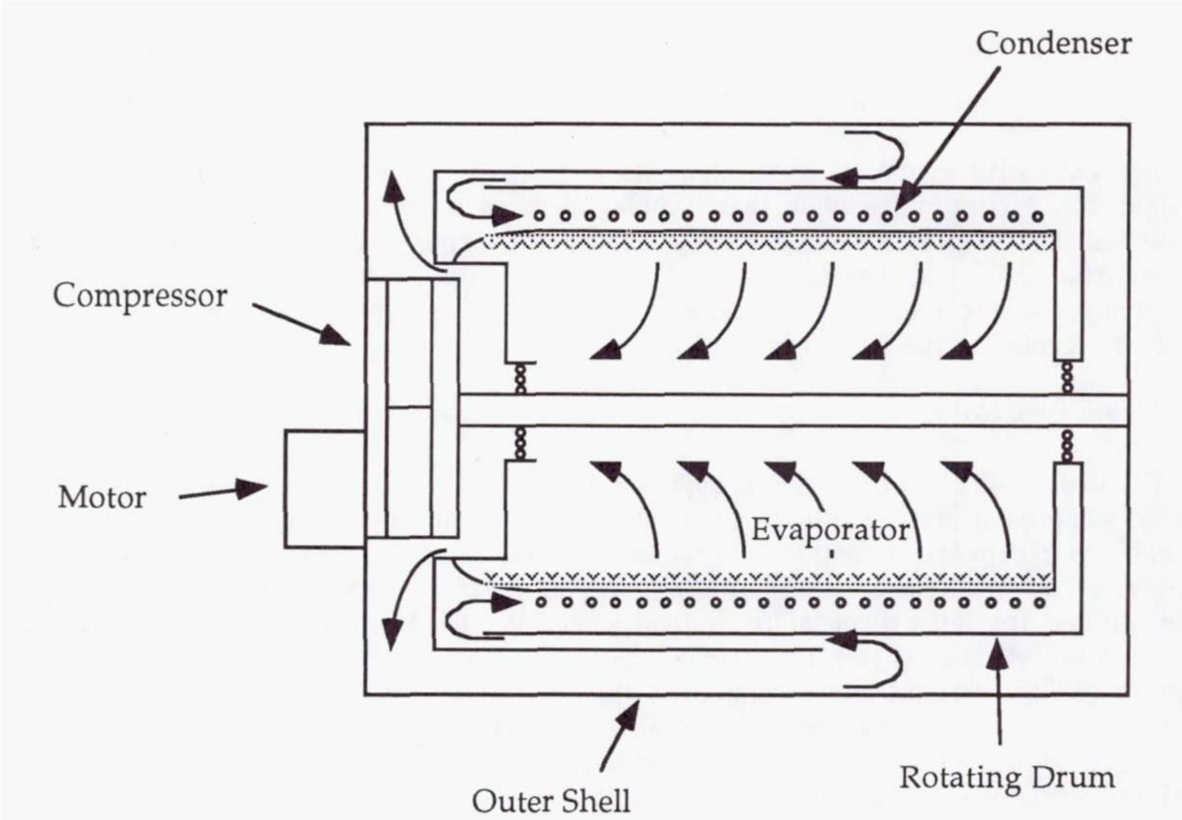

Figure 6-28: Vapor compression distillation schematic [55, p. 229]

6.4.4.1 Description

The main component of the vapor compression distillation process is a rotating drum as depicted in Figure 6-28. Waste water flows into the rotating drum where it is compressed and evaporated. The vapor heat is transferred through the drum wall to recover the thermal energy needed for evaporation of the water. Therefore, this is a thermally passive process. Unevaporated waste water is recirculated until the solid density reaches a specified concentration. This yields a high recovery rate from urine and the remaining water consist to over 50 % of solids. Pre- and post-treatment is required. On ISS, the urine processing assembly (UPA) uses phosphoric acid for pretreatment of urine and MF (WPA, see 6.4.2) for post-treatment. The brine is collected in a special tank and could be processed further. The total recovery rate on ISS is currently 85 % with the goal to reach 90 % by additional brine treatment. The schematic of the UPA is shown in Figure 6-29. Another assembly that is promising and may displace the UPA in the future is the cascade water distillation subsystem (CDS), which is a high-capacity, five-stage rotary vacuum distillation machine. Because this technology has only a TRL of 4, it is not considered in this thesis. [2, p. 221, 55, p. 229, 90, 96, 97]

Advantages are a low power consumption due to passive latent heat recovery, high solid concentration within the recycle loop are tolerable, insensitivity to plugging or rupture, and the self-regulating process. The weaknesses are that current design cannot operate in steady state mode and that the feed stream must be pretreated. [2, p. 221]

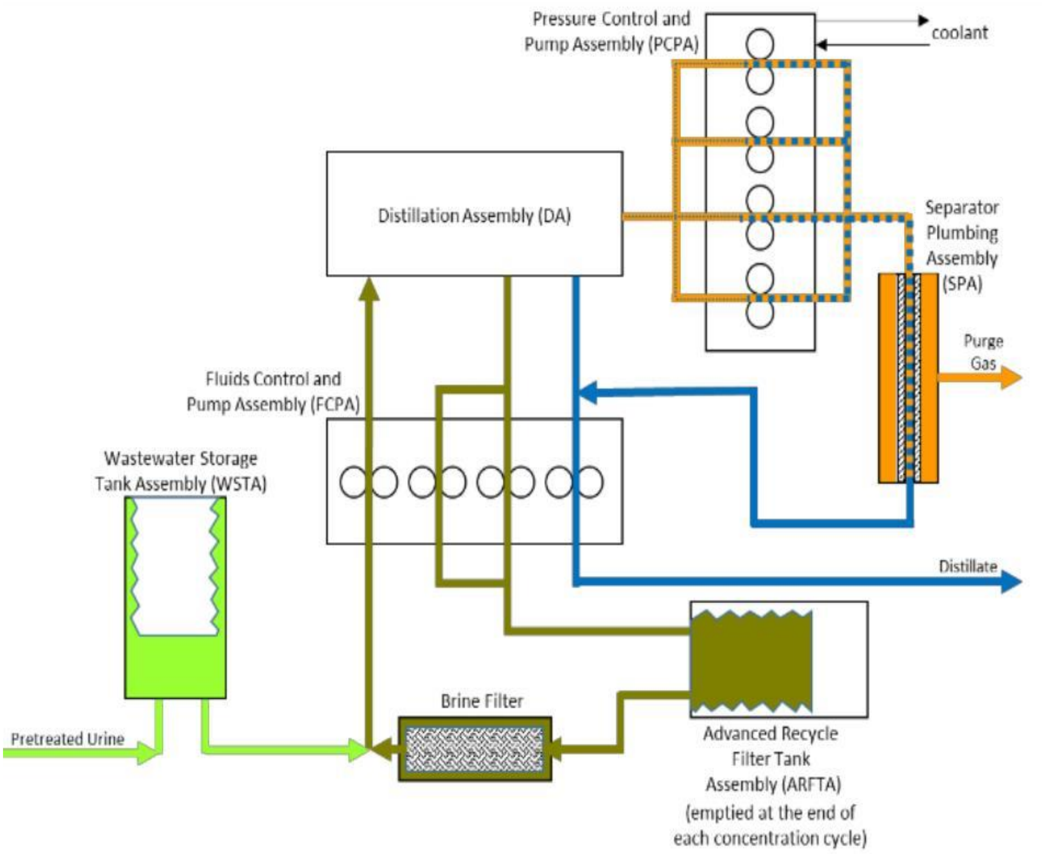

Figure 6-29: Urine processing assembly schematic with ARFTA brine tank [92]

6.4.4.2 Data and Sizing

As the base technology for the VCD the installed UPA on ISS is used. This means the TRL is 9, since the UPA has been working on the space station for years.

Because no high pressures and temperatures are used, the technology is assumed to be safe.

Stated data from [50, p. 356] is used for this analysis. Because this source uses very optimistic assumptions and other sources give much higher values for mass and volume, a $f_{Certainty}$ of 0.5 are used.

Table 6-43: Properties for the vacuum compression distillation process [50, p. 356]

Parameter	Value	Unit
Mass	156.94	[kg]
Volume	0.34	[m³]
Power	1,005	[W]
Cooling	0	[W]
Consumables mass	131.09	[kg]
Consumables volume	0.21	[m³]

The MTBF is given to 13,600 hours without spares [50, p. 356]. This gives a reliability of 0.8562 for the best-case scenario and 0.6891 for the worst-case.

For scheduled maintenance, 13.1 h for a 500 day mission are assumed [50, p. 356]. Recalculated to the best-case scenario, this would be 3.07 hours and 61.42 hour for the worst-case scenario.

Table 6-44: Properties of the vacuum compression distillation system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	193.33	631.93	776.69	1,941.72
Volume	[m³]	0,39	1.30	1.53	3.82
Power	[W]	1,501	5,003	5,003	12,507
Cooling	[W]	0	0	0	0
Reliability	[-]	0.8562	0.8562	0.6891	0.6891
Maintenance	[h]	3.07	10.25	24.57	61.42
TRL		9	9	9	9

6.4.5 Thermoelectric Integrated Membrane Evaporation Subsystem (TIMES)

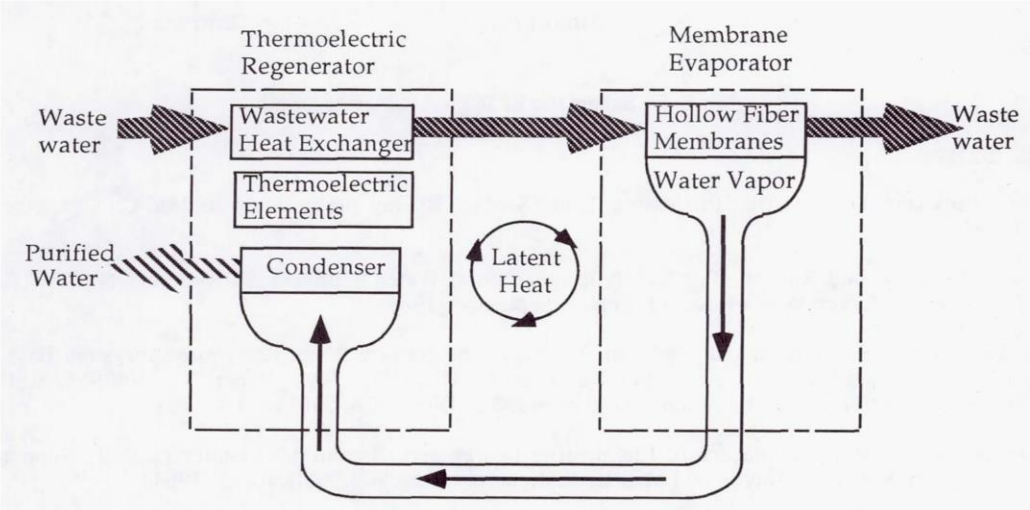

Figure 6-30: TIMES schematic [55, p. 230]

6.4.5.1 Description

The thermoelectric integrated membrane evaporation subsystem (TIMES) uses evaporation through a bundle of hollow fiber membranes with reduced pressure on the outside of the membrane to enable evaporation as can be seen in Figure 6-30. To reduce power for heating the water, a thermoelectric heat pump transfers heat from the condenser to the evaporator. Not shown in Figure 6-30 are an NH_3 oxidation catalyst bed to oxidize the ammonia to N_2O and N_2 and volatile hydrocarbons to CO_2 and H_2O at an operation temperature of 523 K. The H_2O is then condensed on the mentioned CHX and the resulting purified water requires only pH adjustments because it contains only little NH_3, few hydrocarbons and has a low conductivity. A second bed is used for catalytic decomposition of the produced N_2O from the first bed to N_2 and O_2 at a temperature of 723 K. The whole loop is maintained above pasteurization temperature of 347 K to maintain water quality and minimizing or even eliminating growth of microorganisms. [2, pp. 225-226, 55, pp. 229-230]

Benefits of this system are the containment of the circulating waste fluid within hollow fiber membranes in the evaporating section which makes the process safer and the recycle fluid loop is at atmospheric pressure. The drawbacks are the large number of organic fibers that could be attacked by the acid oxidizing environment. Plugging of the small diameter tubes can result in plugging or maintenance problem, and pretreatment might be necessary. [2, pp. 225-226]

6.4.5.2 Data and Sizing

The TRL is assumed to be 6 [5] and the system is considered safe.

The data given in Table 6-45 is based on [50, p. 384] for 9 crew members and a 500-day mission. As the considered design delivers water at close to the tank temperature of 344 K, no heating is required. Since the other concepts require such heating, a credit for this concept must be applied which is represented by the negative cooling value. As for all water recycling technologies from [50], the $f_{Certainty}$ is 0.5.

Table 6-45: Properties for the thermoelectric integrated membrane evaporation subsystem

Parameter	Value	Unit
Mass	225.89	[kg]
Volume	0.40	[m³]
Power	1,634	[W]
Cooling	-300	[W]
Consumables mass	90.27	[kg]
Consumables volume	0.17	[m³]

A MTBF of 14,300 hours is considered [50, p. 384]. This means, the reliability for 88 days is 0.8627 and for 211 days it is 0.7018.

Overall, 36 hours of scheduled maintenance are given in [50, p. 384]. Recalculating this to the best-case scenario results in 8.45 hours and for the worst-case 168.8 hours.

Table 6-46: Properties of the thermoelectric integrated membrane evaporation subsystem

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	254.49	831.81	931.50	2,328.74
Volume	[m³]	0.44	1.45	1.63	4.08
Power	[W]	2,244	7,335	7,335	18,337
Cooling	[W]	-412	-1,347	-1,347	-3,367
Reliability	[-]	0.8627	0.8627	0.7018	0.7018
Maintenance	[h]	8.45	28.16	67.52	168.80
TRL		6	6	6	6

6.4.6 Air Evaporation System

6.4.6.1 Description

The air evaporation system is an evaporation process in which pretreated urine is pumped through a particulate filter to a wick package using a pulse feed technique. A circulating heated air stream evaporates water from the urine, leaving urine solids in the wicks. When sufficient urine solids accumulated in the wicks, the feed pump is stopped and the loaded wicks are dried down and replaced with a new wick package. Humid air leaving the package is condensed by a heat exchanger. A water separator downstream removes the water from the air stream. Acceptable water passes through a microbial check valve to a posttreatment section, where it is filtered. This results in nearly 100% water recovery. [2, p. 226]

The advantages of this process are that nearly complete water recovery is possible, it is a very simple device, and is insensitive to food stock. Additionally, it operates at ambient internal pressure and thus is easy to seal and it can either operate intermittently or continuously. The disadvantages are the very high energy consumption and the large logistic resupply requirements due to the mass and volume of the wicks. [2, p. 226]

6.4.6.2 Data and Sizing

The TRL of this technology is stated on several sources as 5 [2, p. 226, 5, 79] and consequently the corresponding $f_{Certainty}$ is 1.

It is further assumed to be a safe process as long as a closed cycle for the air is used and sufficient pretreatment of the urine is done, because the conditions in the wick are ideal for microbial growth. [50, p. 377]

The data for mass, volume, power, and cooling is given for a 500-day mission with 9 person [50, p. 378]. The $f_{Certainty}$ for all values is 0.5.

Table 6-47: Properties for the air evaporation process

Parameter	value	unit
Mass	117.93	[kg]
Volume	0.34	[m³]
Power	3,330	[W]
Cooling	0	[W]
Consumables mass	225.83	[kg]
Consumables volume	1.19	[m³]

The MTBF for the assembly is stated to 20,000 hours [50, p. 378]. This results in a reliability of 0.8998 for 88 days and 0.7763 for 211 days.

Because the wicks must be replaced frequently the scheduled maintenance is fairly high. For a 500-day mission with 8 crew members, this is stated to be 207 hours [50, p. 378]. Adapting this to the best-case scenario gives a crew maintenance requirement of 48.58 hours and 970.60 hours for the worst-case.

Table 6-48: Properties of air evaporation system

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	172.63	575.45	824.82	2,062.06
Volume	[m³]	0.62	2.06	3.36	8.41
Power	[W]	4,973	16,576	16,576	41,440
Cooling	[W]	0	0	0	0
Reliability	[-]	0.8998	0.8998	0.7763	0.7763
Maintenance	[h]	48.58	161.92	388.24	970.60
TRL		5	5	5	5

6.4.7 Electrodialysis

The electrodialysis system consists of a diluting compartment bordered on either side by a concentrating compartment where waste water enters. An electrical current induces migration of ionized particles perpendicular to the direction of fluid flow. The ion concentration will decrease in the concentrating compartment because of the semi permeability properties of the ion exchange membranes till a brine is created. Pre- and post-treatment is required to remove nonionized organic compounds and microorganisms. [2, p. 234, 55, p. 228]

Because this technology has only a TRL of 4 [2, p. 234], it is not considered for a further analysis.

6.4.8 Vapor Phase Catalytic Ammonia Removal

This process uses hollow fiber membranes for evaporation, similar to TIMES. The vapor is mixed with air and recycled process vapor. In the downstream catalyst bed at an operating temperature of 523 K, the ammonia is oxidized to N_2O and N_2, and volatile hydrocarbons to CO_2 and water. The water is separated by an CHX and contains less NH_3, few hydrocarbons and low conductivity. The water quality is higher than from VCD or TIMES. The N_2O is further catalytically decomposed to N_2 and O_2 in a second bed at a temperature of 723 K. The rest is recycled in the loop. [2, p. 223, 55, p. 230]

Because this technology has only a TRL of 4, it is not further considered [5].

6.4.9 Water Quality Monitoring

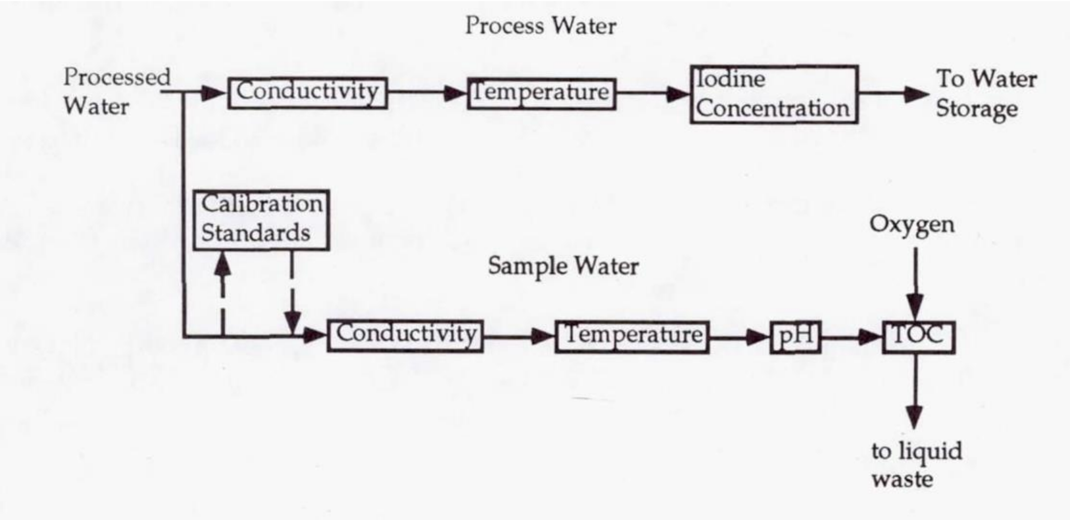

Figure 6-31: Water Quality monitoring process schematic [55, p. 232]

6.4.9.1 Description

Potable and hygiene water must meet the defined water quality requirements (see 4.2.4.a). To ensure this, the water must be continuously or frequently measured on pH, ammonia content, total organic carbon, electrical conductivity and microbial concentration. Less frequent parameters are color, odor, turbidity, foaming and heavy metal concentrations. [2, p. 236]

6.4.9.2 Data and Sizing

The potable control water quality monitoring (PCWQM) assembly on the ISS constantly measures the quality of the stored water. Hence this technology has a TRL of 9.

Data for mass, volume, power, and cooling is given in [38] for the potable control water quality monitor system on the ISS. For this assembly, no linear scaling is needed, since it measures only a fraction of the stored water.

No MTBF or reliability data were found. Instead, since the PCWQM was installed in November 2008, a cumulated operating time of 3150 days without a failure leads to a MTBF of 75,600 hours. Hence the reliability for 88 days is 0.9725 and for 211 days it is 0.9352.

For scheduled maintenance, 1 hour per year is given [38]. Consequently, the needed time for 88 days is 0.24 hours and for 211 days it is 0.58 hours.

The parameters in Table 6-49 are valid for all trade cases.

Table 6-49: Properties for water quality monitoring

Parameter	value	unit
Mass	38.00	[kg]
Volume	0.05	[m³]
Power	30	[W]
Cooling	30	[W]
TRL	9	[-]

7 Trade Study

In the previous chapter, different technologies for all required functions of the ECLSS were described and scaled to the different scenarios described under 3.1.1 and both SpaceHab designs. In the next step, these technologies are compared in terms of mass, volume, required power and cooling, and several other parameters.

Two different evaluations for parameters could be used. The first is the so called “advantage/disadvantage” method which is used when less information about a technology is available or when a quantification is difficult. The other is the “weighted factors” method when lots of data is known and the alternatives are specified decently. [55, p. 70]

For the trade study in this thesis, the assemblies developed in chapter 6 are verified against the General Constraints in chapter 4.1. This is done to predict an optimal candidate that satisfies a particular function within the subsystem. To get to this, different approaches are used. While countless methods exist for such a task, two are selected that are often used for ECLSS trade studies. These are the equivalent system mass (ESM) metric and a multi-criteria method. Both are further described in the respective chapters below.

7.1 Equivalent System Mass

The equivalent system mass (ESM) metric is commonly used in the ECLSS community. The analyzed parameters are mass, volume, required power, cooling, and crew time used to operate and maintain the LSS. For conversion into kg, mission specific mass equivalency factors must be determined and applied to the parameters. The ESM is an indicator to give a rough understanding what type of loop closure is optimal and to develop a mass-based metric to compare between different technologies. For the use in this thesis it is of special interest, because the ITS is planned for reusability and therefore the launch costs are very important. While normally for an ESM analysis no technologies are selected out by parameters like safety or TRL, this is done in this thesis, since the overall system would otherwise not fulfill the constraints.

The advantages of ESM are:

- It is an easy to use, straightforward method that can even be automated when used in computer programs like Excel.
- Transportation costs for a technology are proportional to its mass and ESM can therefore be used to quantify these costs.
- ESM is an objective approach since the mass equivalency factors are based on verifiable numbers.

But there are some disadvantages as well:

- There is a focus on only 5 parameters. Other important parameters like TRL or complexity are not analyzed.
- Precise values for the ESM parameters must be known.
- Non-feasible technologies may perhaps be advised.
- Especially the crew factor is somewhat controversial [98] and not included in most of the trades in this thesis.

7.1.1 Calculation

The simplified formula for ESM calculation from [6] is outlined in Eq. (7-1) below.

$$ESM = M + (V\,V_{eq}) + (P\,P_{eq}) + (C\,C_{eq}) + (t_{crew}\,D\,t_{crew,eq}) \quad \textbf{Eq. (7-1)}$$

with:

- ESM [kg] - ESM value of the ECLSS
- M [kg] - Total mass of the system
- V [m³] - Total pressurized volume of the system
- V_{eq} [kg m^{-3}] - Volume equivalency factor for pressurized infrastructure
- P [kW] - Total power requirement of the system
- P_{eq} [kg kW^{-1}] - Mass equivalency factor for power infrastructure
- C [kW] - Total cooling requirement of the system
- C_{eq} [kg kW^{-1}] - Mass equivalency factor for cooling infrastructure
- t_{crew} [CM-h y^{-1}] - Total crew time requirement of the system
- D [y] - Duration of the mission segment
- $t_{crew,eq}$ [kg CM-h^{-1}] - Mass equivalency factor for the crew time

The total mass of the system (M) includes ECLSS hardware as well as connections, working masses and gases in the pressurized habitat. For the pressurized volume (V) it is important not to include the free space for the crew, because this volume is not considered to be part of the ECLSS. The corresponding equivalency factor (V_{eq}) is driven by the pressure loads, the radiation and micrometeroid protection shields, as well as the ablative thermal shielding. For the crew time (t_{crew}), only scheduled maintaince should be included. Unscheduled maintenance, like repairs, are only included for off-nominal studies. The corresponding factor ($t_{crew,eq}$) could be set to zero if only the equivalent mass is desired to be analyzed.

7.1.2 ESM Mass Equivalency Factors

As already stated above, mass equivalency factors are required to translate the non-mass parameters to mass equivalencies. These mass equivalency factors can be found in the BVAD ([10, p. 23]), [87, p. 57], and [5]. When not applicable, more suitable mass equivalency factors can be established.

The mass equivalency factor assumptions for a Mars transit mission from the sources above are outlined in Table 7-1.

Table 7-1: ESM mass equivalency factors for Mars transit mission [5, 10, p. 23, 10, p. 48, 10, p. 37, 87, p. 57]

Parameter	Lower	Nominal	Upper	Unit
Shielded volume		215.50	219.70	[kg m^{-3}]
Unshielded volume		9.16	13.40	[kg m^{-3}]
Power	12 (nuclear)	149		[kg kW^{-1}]
Thermal control	30	60	70	[kg kW^{-1}]
Crew time	0.526	0.802		[kg CM-h^{-1}]

Both mass equivalency factors for volume (shielded volume and unshielded volume) in Table 7-1 are for primary structures in pressurized and debris protected environments. Contrary to the unshielded volume, the upper value of shielded volume provides a sufficient radiation protection so that this environment is safe for the crew and radiation sensitive technology. For equipment outside the pressurized cabin, like pressure tanks, only minimal structures with micrometeoroid shields are needed and the value would be around 6 kg m^{-3} (γ_V). All volume values are assumed for an inflatable module like the TransHab. Because the SpaceHab consists of a composite structure, these values can´t be used. Furthermore, contrary to NASA designs the SpaceHab includes propellant structures and engines. For the calculation of a decent equivalent volume factor, the total mass of the pressure shell and the volume must be known. As stated in [11], the dry mass of the SpaceHab is 150,000 kg (m_{dry}). For the pressurized volume, detailed calculations were made in chapter 2.3 Volume, which revealed that the pressurized volume (V) of the SpaceHab is 1090.28 m³ and for the Evolved-SpaceHab design it is 1710.76 m³. Therefore, the volume equivalency factor can be calculated with Eq. (7-2) to 137.58 kg m^{-3} for the SpaceHab design and 87.68 kg m^{-3} for the Evolved-SpaceHab design.

$$V_{eq} = \frac{m_{dry}}{V} \qquad \textbf{Eq. (7-2)}$$

The lower mass equivalency factor for power is based on a Rankine cycle nuclear power plant that produces 572 kW. The nominal value is based on a 28 % efficient solar photovoltaic array without any storage [10, p. 37]. Solar photovoltaic will be the main power source for the SpaceHab. To get to an actual equivalent power value for the SpaceHab, a UltraFlex™ solar array from Orbital ATK [99] is assumed in combination with battery storage. The UltraFlex™ solar array is a state-of-the-art lightweight solar array with 30 % efficient triple-junction cells and scalability up-to 350 kW. Eq. (7-3) shows, that the power equivalency factor (P_{eq}) is a combination of the equivalency factors for the solar array ($\gamma_{P,solar}$) and the power storage ($\gamma_{P,battery}$). The equivalency factor of the solar array is the sum of the specific mass ($\gamma_{P,M,solar}$) with the product of the specific stowage volume ($\gamma_{P,V,solar}$) and the volume infrastructure cost factor (γ_V). The specific mass and stowage volume given in [99], are 6.67 kg kW^{-1} and 0.025 m³ kW^{-1}, respectively. The equivalency factor for the battery can be estimated using table 3.14 in [63] and by subtracting the specific power of "Solar Photovoltaic Cells w/o Energy Storage" (101 kg kW^{-1}) from "Solar Photovoltaic Cells w/ Battery Storage" (133 kg kW^{-1}), which gives a equivalency factor for the batteries ($\gamma_{P,battery}$) of 32 kg kW^{-1}. Adding the solar photovoltaic and the battery equivalency factors gives 38.82 kg kW^{-1} for the power equivalency factor.

$$P_{eq} = \gamma_{P,solar} + \gamma_{P,battery} \quad \textbf{Eq. (7-3)}$$

$$\gamma_{P,solar} = \gamma_{P,M,solar} + \gamma_{P,V,solar}\ \gamma_V \quad \textbf{Eq. (7-4)}$$

The lower thermal control equivalency factor is for a lightweight, flow-through radiator with a supplemental expendable cooling subsystem [10, p. 39]. Because the ITS is optimized on low weight, this value is used for the further analysis.

The values for the crew time equivalency factor in Table 7-1 are for a Mars transit vehicle. But because the Concept of Operations in this thesis is assuming that at least one engineer is included in the crew for maintenance, the crew time equivalency factor is only 0.1 kg CM-h^{-1}, which is on the lower end of typical values for the crew time stated in [10].

Depicted in Table 7-2 is a breakdown of the equivalency factors used in this thesis.

Table 7-2: ESM equivalency factors for SpaceHab and Evolved-SpaceHab

Parameter	Value	Unit
Volume	137.58 or 87.68	[kg m^{-3}]
Power	38.82	[kg kW^{-1}]
Thermal control	30	[kg kW^{-1}]
Crew time	0.1	[kg CM-h^{-1}]

7.2 Multi-Criteria-Method

As mentioned in the previous chapter, one main disadvantage of ESM is the nonobservance of important parameters like TRL. The Multi-criteria decision making (MCDM) is a very common branch of decision making which is independent of the type of criteria. It is used to solve problems within a discrete decision space. In multi-attribute decision making, the set of alternatives (like O_2 storage technologies) is established at the beginning of the process.

Selected technical terms associated with MCDM are defined below [100, pp. 1-2]:

- **Alternatives**: This describes the different choices that can be made. These are the assemblies and components to be compared.
- **Multiple Attributes** or **decision criteria**: MCDM problems are related to multiple criteria. These criteria represent the characteristics by which the different alternatives shall be compared.
- **Decision Matrix**: An MCDM problem can simply be summarized in a matrix. The resulting m x n matrix is called decision matrix and consists of the elements a_{ij} that represent the performance of alternative A_i with respect to a certain criterion C_j, where i = 1, 2, 3, …, m and j = 1, 2, 3, …, n.

In contrast to most MCDM methods, no criteria weights are used, because these are mostly subjective. Depending on the choice the decision maker has made for the weight, the outcome can differ greatly. Therefore, no weights between the different criteria are used. But it should be noted that the ESM is part of the final decision (7.3) and this has inherently a weight on the different parameters.

The advantages are:

- Information about the relative distances of the values within one criterion is given
- Other criteria than mass, volume, power, cooling, and crew time can be considered.
- Critical factors can be defined.

But there are also several disadvantages:

- If weighting factors are used, they are subjective and are dependent on the knowledge about the system behavior of the person, who performs the analysis.
- The application is time consuming
- Precise values for the criteria have to be known.
- The values for the criteria have to be cardinally scaled (except if the criterion is used as a critical factor).

The decision process is divided into the several constitutive steps below. With the exception of the absolute step, the rank of every alternative is determined by Eq. (**7-5**). For the AR subsystem, the best 3 alternatives are selected for a more detailed trade-off in 8.3 Second Design Cycle for Atmosphere Revitalization. For all other subsystems, the two best alternatives are selected in the Decision Step for a more detailed architecture trade-off in 8 Second Design Cycle. The values a_{ij} for the alternatives are calculated by value functions (f_{ij}) described in the particular sections multiplied with the certainty factor ($f_{CF,ij}$).

$$A_{i,score} = \frac{\sum_{j=1}^{n_{criteria}} a_{ij}}{n} \qquad \textbf{Eq. (7-5)}$$

$$a_{ij} = f_{ij} f_{CF,ij} \qquad \textbf{Eq. (7-6)}$$

with:

- $A_{i,score}$ [-] - score of alternative i
- a_{ij} [-] - value of criterion j for alternative i
- $n_{criteria}$ [-] - number of criteria
- f_{ij} [-] - value function of criterion j for alternative i
- $f_{CF,ij}$ [-] - certainty factor of criterion j for alternative i

7.2.1 Absolute Step

The absolute step is the first step that has to be made. It consists of the criterions safety and TRL which both must be fulfilled before a technology is further considered. The purpose of this step is to reduce the number of alternatives early before much information about the technology is needed.

7.2.1.1 Safety

As stated in the constraint 4.1.b, no materials, systems or operations shall be used if they are a threat for the crew. Therefore, all alternatives are inspected if they fulfill this constraint. Hazardous materials, like hydrazine, or high-pressures together with high temperatures are considered as unsafe. A more detailed safety analysis for every alternative technology is given in their respective analysis in chapter 6.

7.2.1.2 TRL

For the scope of this thesis, a TRL of at least 5 is considered, because an even lower TRL would mean the technology is far from mature and therefore has a lower reliability, higher costs for development and increasing risk to under-performance.

For the Decision Step, the value function is defined in Eq. (7-7), where TRL stands for the current technology readiness level.

$$f(TRL) = \frac{TRL-5}{4} \qquad \textbf{Eq. (7-7)}$$

7.2.2 Decision Step

The Decision Step is the second step in the multi-criteria process. Only alternatives that are selected in the first step are considered here. Much more information about the alternatives is required. The criterions in this step are reliability, mass, volume, power, cooling, and maintenance (often referred to as crew time). All functions in this step are quadratic, because the resources are very limited and therefore a quadratic function instead of a linear one depicts the differences better. A discussion and comparison for a linear approach is given in chapter 7.4.3. Figure 7-1 below shows a plot of the general function with a linear function as dotted line for comparison.

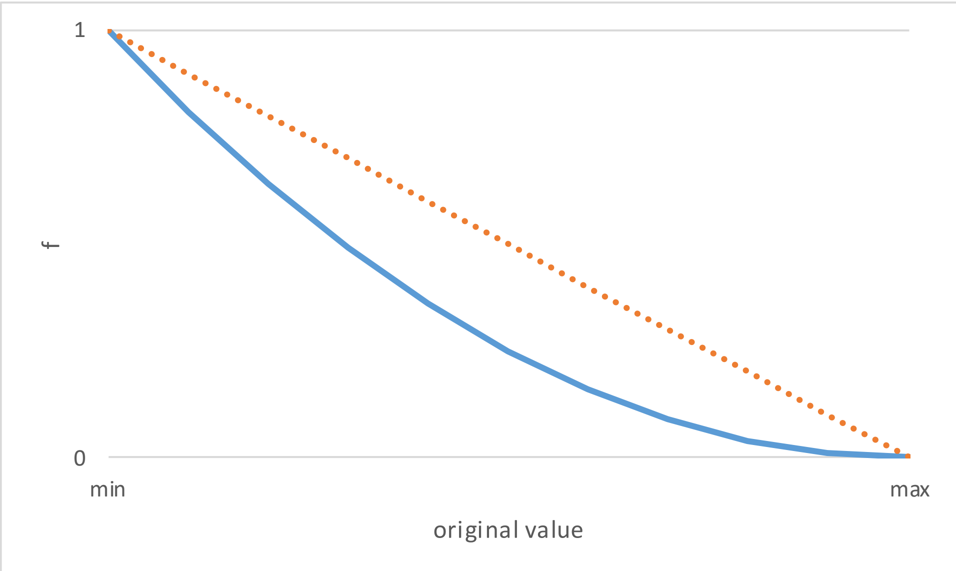

Figure 7-1: Quadratic value function used in multi-criteria-method

7.2.2.1 Reliability

The figure of merit for reliability is described by Eq. (7-8). R stands for the reliability of the alternative, while R_{max} and R_{min} are the maximum and minium reliability of the alternatives.

$$f(R) = \frac{R^2 - R\,R_{min}}{{R_{max}}^2 - R_{max}R_{min}} \qquad \textbf{Eq. (7-8)}$$

7.2.2.2 Mass

The figure of merit for mass is defined by Eq. (7-9).The maximum mass (m_{max}) is defined by the maximum mass of the alternatives considered. Respectively it is the minimum mass for m_{min}. m is the total mass of the alternative, including consumables. All parameters are in kg.

$$f(m) = \frac{m^2 - 2\, m\, m_{max} + m_{max}{}^2}{(m_{min} - m_{max})^2} \qquad \text{Eq. (7-9)}$$

7.2.2.3 Volume

The figure of merit for volume is defined by Eq. (7-10).The maximum volume (V_{max}) is defined by the maximum volume of the alternatives considered. Respectively it is the minimum volume for V_{min}. V is the total volume of the LSS, including consumables. All parameters are in m³.

$$f(V) = \frac{V^2 - 2\, V\, V_{max} + V_{max}{}^2}{(V_{min} - V_{max})^2} \qquad \text{Eq. (7-10)}$$

7.2.2.4 Power

The figure of merit function for power is given in Eq. (7-11), where P stands for the needed power of the component or assembly, P_{max} and P_{min} for the maximum and minimum power consumption of all alternatives, respectively. It is a quadratic function, because available power is one of the most limited resources on a solar powered spacecraft like the SpaceHab. The unit of all values is Watt.

$$f(P) = \frac{P^2 - 2\, P\, P_{max} + P_{max}^2}{(P_{min} - P_{max})^2} \qquad \text{Eq. (7-11)}$$

7.2.2.5 Cooling

The corresponding function for cooling is given in Eq. (7-12), where P_{th} stands for the required heat removal of the component or assembly, $P_{th,max}$ and $P_{th,mim}$ for the maximum and minimum heat removal of items in the same group respectively. The unit of all values is Watt.

$$f(P_{th}) = \frac{P_{th}^2 - 2\, P_{th}\, P_{th,max} + P_{th,max}^2}{(P_{th,min} - P_{th,max})^2} \qquad \text{Eq. (7-12)}$$

7.2.2.6 Maintenance

The figure of merit is given in Eq. (7-13), where t_{main} is the assumed maintenance time of the component or subsystem divided through the mission length.

$$f(t_{main}) = t_{main}^2 - 2\, t_{main} + 1 \qquad \text{Eq. (7-13)}$$

7.3 Application and Results

7.3.1 ESM-Results

The approach described in 7.1 is applied to the different functions of the subsystems. Below are the results of this analysis.

7.3.1.1 ESM Atmosphere Control and Supply

Hydrogen peroxide is selected out due the reasons mentioned in 6.1.4. The remaining 3 technologies for oxygen storage are stated in Table 7-3. As can be seen, the cryogenic storage is superior for short durations, while the high-pressure system is better for longer mission times. This is because the tank mass of the cryogenic system increases more than the high-pressure tank and the additional mass for leakage is just over the break-even point. The ESM values in Table 7-3 are for the Evolved-SpaceHab design, while the used design has no influence on the ranking. The oxygen candles are by far the worst system and should not be used. The break-even point between the cryogenic and the high-pressure system are outlined in 8.1.

Table 7-3: ESM ranking of oxygen storages for repressurisation and leakage

	Case1		Case4	
Technology	**ESM [kg]**	**Rank**	**ESM [kg]**	**Rank**
Cryogenic	808	1	843	2
High-pressure	814	2	822	1
$LiClO_4$	1,615	3	1,615	3

For the storage system, Table 7-4 shows, that cryogenic and high-pressure systems have comparable ESM values. While the values for mass, volume, power, and cooling stay the same, the ESM volume factor changes. This results in a ranking change between the cryogenic and the high-pressure system, since the cryogenic one needs far less volume, the stricter ESM volume factor for the SpaceHab prefers the cryogenic system. The oxygen candle system is not considered for a storage system.

Table 7-4: ESM ranking for oxygen storage system

	Case1		Case4	
Technology	**ESM [kg]**	**Rank**	**ESM [kg]**	**Rank**
Cryogenic	1,696	1	31,561	2
High-pressure	1,711	2	31,116	1

For nitrogen repressurization and leakage, a different behavior can be seen in Table 7-5 where cryogenic storage is always superior. Much bigger tanks are needed for N_2 repressurisation, because 76 % in the air are N_2 and the fact that N_2 has a lower density at high-pressure cryogenic temperatures than O_2. Therefore, the difference for leakage is lower than for oxygen repressurization and no ranking switch occurs. Hydrazine is selected out due to safety concerns.

Table 7-5: ESM ranking of nitrogen storages for repressurisation and leakage

	Case1		Case4	
Technology	**ESM [kg]**	**Rank**	**ESM [kg]**	**Rank**
Cryogenic	1,841	1	2,806	1
High-pressure	2,078	2	3,011	2

7.3.1.2 ESM Temperature and Humidity Control

Only the CAMRAS and CCAA are considered for humidity removal of a storage system, since the other technologies have a too low TRL. This step is used in advance of the ESM analysis, as explained in 7.1. For a recycling system, only the CCAA is feasible as explained in 6.2.1. As can be seen in Table 7-6, the CAMRAS is superior in all cases (only Case4 is shown for clarity).

Table 7-6: ESM ranking of humidity removal assemblies for storage system

Technology	**ESM [kg]**	**Rank**
CAMRAS	650	1
CCAA	951	2

7.3.1.3 ESM Atmosphere Revitalization

The atmosphere revitalization (AR) analysis is separated into CO_2 removal, CO_2 reduction, and finally O_2 generation.

Several technologies were selected out due their low TRL of under 5. These are 2BMS, SAWD, and APC. This step is used in advance of the ESM analysis, as explained in chapter 7.1. Additional, LiOH, METOX, sodasorb, as well superoxide is not considered since they all have an inferior performance. The CAMRAS system is only considered for a storage system, since it vents high amounts of water vapor. As can be seen in Table 7-7, the SAWD process has the lowest ESM, closed followed by the EDC.

Table 7-7: ESM ranking of CO_2 removal technologies for recycling system

Technology	**ESM [kg]**	**Rank**
EDC	2,122	2
4BMS	3,403	3
SAWD	1,989	1

The ranking for a storage system is different. The CAMRAS system is superior, since it has a low power consumption and by far the lowest mass. Following are the SAWD, which uses the same process as CAMRAS. The EDC has a considerable higher ESM as in the recycling system analysis, since no production of oxygen or hydrogen are considered for a storage system and therefore tanks must be used for this technology.

Table 7-8: ESM ranking of CO_2 removal technologies for storage system

Technology	ESM [kg]	Rank
CAMRAS	657	1
EDC	28,038	4
4BMS	3,403	3
SAWD	1,989	2

For the carbon dioxide reduction analysis, only the Sabatier and the Bosch process are further considered, since the ACRS has to too low TRL. As can be seen in Table 7-9, the Sabatier requires over 4 times less resources as the Bosch.

Table 7-9: ESM ranking of CO_2 reduction technologies

Technology	ESM [kg]	Rank
Bosch	3,770	2
Sabatier	894	1

Only electrolysis processes are considered for oxygen generation. CO_2 electrolysis, WVE, SEOS, and HPE are selected out, since they have a TRL of lower than 5. The remaining two technologies can be seen in Table 7-10, where SFWE is best ranked.

Table 7-10: ESM ranking of oxygen generation technologies

Technology	ESM [kg]	Rank
SPWE	1,858	2
SFWE	1,546	1

7.3.1.4 ESM Water Recovery and Management

Electrodialysis is selected out due to a TRL of 4. This step is used in advance of the ESM analysis, as explained in 7.1. As can be seen in Table 7-11, RO and VCD are ranked first and second respectively. The analysis of the different trade cases and water recycling architectures have shown, that there is no difference in the ranking of the considered alternatives with variation in duration and crew size and not even with the processed amount of waste water. Therefore, RO should be used for humidity condensate and hygiene waste water recycling.

Table 7-11: ESM ranking of humidity condensate recycling processes

Process	ESM [kg]	Rank
AES	785	4
MF	843	5
RO	279	1
TIMES	549	3
VCD	443	2

For the combination of all waste waters, EDI and VAPCAR processes are selected out due their low TRL. MF and RO are no longer included because they are only considered for relatively clean waste water, as explained in chapters 6.4.2 and 6.4.3 respectively. The remaining ones are ranked in Table 7-12. VCD is best for all considered trade cases and should therefore be used for waste water recycling.

Table 7-12: ESM ranking of waste water recycling processes

Process	ESM [kg]	Rank
AES	1,821	3
TIMES	1,332	2
VCD	1,086	1

7.3.2 Multi-Criteria-Model Results

7.3.2.1 Atmosphere Control and Supply Results

Because the storage tanks for all compared storage technologies are outside the pressurized compartment, it would make no sense to include a volume rating. Therefore, the figure of merit for volume is deactivated in the multi-criteria-model for this subsystem.

As already mentioned, Hydrogen peroxide is not further considered. The ranking of the O_2 storages for repressurisation and leakage can be seen in Table 7-13. Contrary to the ESM analysis, there is no change of ranking over duration. The high-pressure storage is always superior, since it has the highest reliability and the lowest mass.

Table 7-13: Multi-Criteria-Model ranking of oxygen storages for repressurisation and leakage

Technology	$A_{i,score}$	Rank
Cryogenic	0.36	2
High-pressure	0.50	1
$LiClO_4$	0.33	3

For the O_2 storage system, the high-pressure system is by far the best ranked system as seen in Table 7-14, since the considerable necessary higher volume of this system is not considered for the multi-criteria-method score.

Table 7-14: Multi-Criteria-Model ranking of oxygen storages system

Technology	$A_{i,score}$	Rank
Cryogenic	0.38	2
High-pressure	0.59	1

As can be seen in Table 7-15, High-pressure storage is the highest ranked storage, independent of trade case. Hydrazine is not considered for safety reasons.

Table 7-15: Multi-Criteria-Model ranking of nitrogen storages for repressurisation and leakage

Technology	$A_{i,score}$	Rank
Cryogenic	0.38	2
High-pressure	0.59	1

7.3.2.2 Temperature and Humidity Control Results

As already mentioned, only CAMRAS and CCAA are considered as humidity removal assemblies for a storage system. The ranking in the multi-criteria-model is shown in Table 7-16 for Case4. All other cases have the same ranking.

Table 7-16: Multi-Criteria-Model ranking of humidity removal assemblies for a storage system

Technology	$A_{i,score}$	Rank
CAMRAS	0.41	1
CCAA	0.31	2

7.3.2.3 Atmosphere Revitalization Results

The down selected technologies for CO_2 removal for a recycling system are shown in Table 7-17 below. The SAWD system is superior, since it has the highest reliability and lowest mass. The EDC is rated considerably lower, because the TRL is only 6.

Table 7-17: Multi-Criteria-Model ranking of CO2 removal technologies for a recycling system

Technology	$A_{i,score}$	Rank
EDC	0.30	2
4BMS	0.29	3
SAWD	0.44	1

For a storage system, the ranking is given in Table 7-18. The CAMRAS is ranked best, followed by the 4BMS. The EDC is again inferior, because of the necessary additional tanks. As can be seen in the table below, 4BMS is ranked before SAWD, since the relative differences between the technologies decreases.

Table 7-18: Multi-Criteria-Model ranking of CO2 removal technologies for a storage system

Technology	$A_{i,score}$	Rank
CAMRAS	0.42	1
EDC	0.16	4
4BMS	0.39	2
SAWD	0.32	3

The Sabatier is superior to the Bosch reactor, since it has a better score in every category with the exception of reliability, since no data about this could be found for the Sabatier.

Table 7-19: Multi-Criteria-Model ranking of CO2 reduction technologies

Technology	$A_{i,score}$	Rank
Bosch	0.24	2
Sabatier	0.44	1

The SFWE electrolysis is clearly superior, as Table 7-20 reveals. It has nearly half the cooling requirement as SPWE and needs slightly more than half the volume.

Table 7-20: Multi-Criteria-Model ranking of oxygen generation technologies

Technology	$A_{i,score}$	Rank
SPWE	0.31	2
SFWE	0.54	1

7.3.2.4 Water Recovery and Management Results

For the recycling of humidity condensate, electrodialysis is selected out in the absolute step due to a TRL of 4. All other processes are rated in the following decision step and as can be seen in Table 7-21, vacuum compression distillation should be used for humidity condensate recycling, independent of the considered trade case. TIMES and

RO are second with nearly identical scores for small crew sizes and duration, while TIMES performs a little better for long missions and big crew sizes because it needs less consumables. The identical results are achieved by combining humidity condensate with hygiene waste water. Interestingly, the crew size and processing rate has negligible effects on the scores.

Table 7-21: Multi-Criteria-Model ranking of humidity condensate recycling processes

Technology	$A_{i,score}$	Rank
AES	0.05	5
MF	0.26	2
RO	0.26	3
TIMES	0.23	4
VCD	0.31	1

Waste water processing technologies, including urine, flush and hygiene waste water, and humidity condensate, are ranked in Table 7-22. As for the ranking analysis before, electrodialysis is selected out in the absolute step because of TRL. The same is true for VAPCAR which has a TRL of 4 too. This analysis confirms that VCD is by far the best process of all waste water recycling processes and should be used.

Table 7-22: Multi-Criteria-Model ranking of waste water recycling processes

Technology	$A_{i,score}$	Rank
AES	0.09	3
TIMES	0.23	2
VCD	0.38	1

7.3.3 Comparison of ESM and Multi-Criteria-Model Results

For a first decision on the technology selection, both analysis methods should be considered and the best two or three technologies selected for a further analysis. While ESM is more focused on the launch aspect and therefore the cost, the multi-criteria-model also includes operational aspects.

7.3.3.1 Atmosphere Control and Supply

3 different functions for the ACS subsystem are analyzed. The first one is the oxygen storage for repressurisation and leakage, the second is a storage system for O_2 and the last one nitrogen storage for repressuration and leakage. As can be seen in Table 7-23, the high-pressure storage system is best in 2 of 3 cases. Only for short-durations the cryogenic tank is slightly better. Since the pressure tanks are outside the pressurized compartment and the high-pressure storage system is considerable better when further considering operational aspects, this system should be used for repressurisation and leakage.

Table 7-23: Ranking of oxygen storages for repressurisation and leakage based on different analysis methods

Technology	Multi-criteria-model	ESM short-duration	ESM long-duration
Cryogenic	2	1	2
High-pressure	1	2	1
$LiClO_4$	3	3	3

As can be seen in Table 7-24, the high-pressure is best ranked on both, the ESM and the multi-criteria-method, and should therefore be used for a O_2 storage system.

Table 7-24: Ranking of oxygen storages system based on different analysis methods

Technology	Multi-criteria-model	ESM
Cryogenic	2	2
High-pressure	1	1

The difference for the N2 storage system in Table 7-25 is caused by the circumstance, that only two technologies are compared. Since the high-pressure storage has a slightly better reliability and slightly lower mass, it is better rated.

Table 7-25: Ranking of nitrogen storage for repressuration and leakage based on different analysis methods

Technology	Multi-criteria-model	ESM
Cryogenic	2	1
High-pressure	1	2

7.3.3.2 Temperature and Humidity Control

As can be seen in Table 7-26, there is no difference between the ESM ranking and the multi-criteria-model ranking, independent of the analyzed case. In all cases, the CAMRAS system is best and should therefore be used for a storage system.

Table 7-26: Ranking of humidity removal assemblies for a storage system based on different analysis methods

Technology	Multi-criteria-model	ESM
CAMRAS	1	1
CCAA	2	2

7.3.3.3 Atmosphere Revitalization

The comparison of the ESM and multi-criteria-model results for the CO_2 removal technologies reveals no vast changes between the two analysis methods. As can be seen in Table 7-27, SAWD is selected first on both analysis methods. In the storage system analysis in Table 7-28, CAMRAS is superior and SAWD second in the ESM analysis while 4BMS is second in the multi-criteria-model. This is due to the fact, that 4BMS has a TRL of 9, while SAWD has a lower TRL. SAWD is in all other parameters better or even, which can be seen in the better ESM result.

Table 7-27: Ranking of CO# removal technologies for recycling system based on different analysis methods

Technology	Multi-criteria-model	ESM
EDC	2	2
4BMS	3	3
SAWD	1	1

Table 7-28: Ranking of CO_2 removal technologies for storage system based on different analysis methods

Technology	Multi-criteria-model	ESM
CAMRAS	1	1
EDC	4	4
4BMS	2	3
SAWD	3	2

The Sabatier is best-ranked in both analysis methods, as can be seen in Table 7-29. It is therefore used for CO_2 reduction instead of the Bosch process.

Table 7-29: Ranking of CO_2 reduction technologies based on different analysis methods

Technology	Multi-criteria-model	ESM
Bosch	2	2
Sabatier	1	1

As Table 7-30 shows, SFWE is on both analysis methods superior and should therefore be used.

Table 7-30: Ranking of oxygen generation technologies based on different analysis methods

Technology	Multi-criteria-model	ESM
SPWE	2	2
SFWE	1	1

7.3.3.4 Water Recovery and Management

The different recycling processes for water recovery and management are analyzed by the multi-criteria-model and the ESM. Comparing the results of these two methods on the humidity condensate and hygiene waste water processes, it can be seen in Table 7-31 that the best two systems differ significantly. While VCD is superior for the multi-criteria-model, RO is best by ESM. Additional to the criteria considered in the ESM Analysis, the current TRL and the reliability of the systems are considered. RO has a TRL of 6 which is much lower compared to the second ranked system VCD with a TRL of 9. That means that the top systems selected with multi-criteria-model are more realizable concepts that should be working reliably and that they are not too complex, which highlights another advantage of the multi-criteria-model compared to the ESM Analysis.

Table 7-31: Ranking of humidity condensate recycling processes based on different analysis methods

Technology	Multi-criteria-model	ESM
AES	5	4
MF	2	5
RO	3	1
TIMES	4	3
VCD	1	2

There is no difference between the multi-criterion-model and the ESM for the waste water recycling process. On both analysis methods, VCD is superior.

Table 7-32: Ranking of urine recycling processes based on different analysis methods

Technology	Multi-criteria-model	ESM
AES	3	3
TIMES	2	2
VCD	1	1

As the above analysis, has shown that VCD is in nearly all cases the superior process, with RO and TIMES close. Therefore these 3 technologies are further analyzed in a second design step in chapter 8.4.

7.4 Sensitivity Analysis

A sensitivity analysis has to be performed to determine how sensitive the results are to changes in small variations in the considered parameters. If a high sensitivity occurs, the best system cannot be determined with certainty. Many parameter values are approximate values, differ in various sources or are based on estimations. Thus, the optimal system has to be robust with relation to the selection.

For this, trade Case4 is used because it is the scenario of most interest and the system that is used for the final concept in chapter 10. Further this sensitivity analysis is only done for assessments, where a decision between more than 2 technologies is necessary. For only 2 technologies this is not necessary since both are automatically analyzed in the Second Design Cycle in chapter 8.

7.4.1 Variation of the values for the multi-criteria-method parameters mass, volume, power, cooling, and maintenance

For several systems, the values for mass, volume, power and crew time are based on assumptions or differ in various sources. Consequently, it must be tested how minor changes affect the order in the ranking of the two best systems.

To perform the test 10 % are added at once to mass, volume, power, cooling, and maintenance of the system that ranked in the top position, which represents the case that the values for mass, volume, power and crew time were underestimated. If a change in the ranking occurs 10 %, are added successively to mass, volume, power, cooling, and maintenance to figure out if one parameter is sensitive to a 10 % change or if the ranking only changes in the worst-case scenario where all parameters are penalized with 10 %. In the next step, a similar examination is done by subtracting 10 % from the system ranked second, which represents the case where the values used for mass, volume, power, cooling, and maintenance were overestimated.

7.4.1.1 Atmosphere Control and Supply

The variation of the parameters mass, power, cooling, and maintenance does not change the ranking for the O_2 storage system for repressuration and leakage as can be seen in Table 7-33. Volume was not increased, since it is not considered in the multi-criteria-method for this subsystem. A decrease of 60 % for the parameters of the cryogenic storage would be needed for this system to be first. Therefore, the ranking based on ESM parameters is solid.

Table 7-33: Ranking change test with 10 % increase of mass, power, cooling, and maintenance of high-pressure storage

Technology	Original	New
Cryogenic	2	2
High-pressure	1	1

Table 7-34: Ranking change test with 10 % decrease of mass, power, cooling, and maintenance of cryogenic storage

Technology	Original	New
Cryogenic	2	2
High-pressure	1	1

7.4.1.2 Atmosphere Revitalization

The variation of the ESM parameters does not change the ranking of the two best CO_2 removal systems as can be seen in Table 7-35 and Table 7-36. The needed increase on SAWD parameters for a ranking change is 15 %.

Table 7-35: Ranking change test with 10 % increase of mass, volume, power, cooling, and maintenance of SAWD

Technology	Original	New
EDC	2	2
SAWD	1	1

Table 7-36: Ranking change test with 10 % increase of mass, volume, power, cooling, and maintenance of EDC

Technology	Original	New
EDC	2	2
SAWD	1	1

For the storage system, there is also no change of the ranking when the CAMRAS parameters where increased or the 4BMS parameters decreased.

7.4.1.3 Water Recovery and Management

The same test where performed for the water reclamation management with top ranked VCD and TIMES ranked as second. As for both processes, no cooling is assumed, a percentage change would have no impact. Consequently, only mass, volume, power, and maintenance are varied.

Table 7-37: Ranking change test with 10% increase of mass, volume, power, and maintenance of VCD

Technology	Original	New
TIMES	2	2
VCD	1	1

Table 7-38: Ranking change test with 10 % decrease of mass, volume, power, and maintenance of TIMES

Technology	Original	New
TIMES	2	2
VCD	1	1

As can be seen in Table 7-37 and Table 7-38, the ranking does not change for a 10% increases in the VCD parameters mass, volume, power, cooling, and crew time nor at a 10% decreases in the same TIMES parameters. Actually, over 50 % increase on the VCD parameters would be necessary to place it second.

7.4.2 Multi-Criteria-Model with only ESM Criteria

In this test, it is observed how the results of the Multi-Criteria-Model would change if only the parameters mass, volume, power, cooling, and crew time, i.e. the parameters on which the ESM analysis is based, are considered.

7.4.2.1 Atmosphere Control and Supply

The analysis with ESM criteria for the multi-criteria-model on the O_2 storage system for repressurization and leakage shown in Table 7-39, that no change happens, since the ranking of the ESM and the multi-criteria-model are nearly the same.

Table 7-39: Ranking of oxygen storage for repressurisation and leakage when TRL and reliability are not considered

Technology	Original	New
Cryogenic	2	2
High-pressure	1	1
$LiClO_4$	3	3

7.4.2.2 Atmosphere Revitalization

There are no surprises on the ranking in Table 7-40, since SAWD is also best ranked in the ESM and consequently should be best ranked when the parameters TRL and reliability are not considered.

Table 7-40: Ranking of CO_2 removal technologies when TRL and reliability are not considered for a recycling system

Technology	Original	New
EDC	2	2
4BMS	3	3
SAWD	1	1

As can be seen in Table 7-41, SAWD is placed second instead of third, since the better TRL of the 4BMS has a big effect on the ranking.

Table 7-41: Ranking of CO_2 removal technologies when TRL and reliability are not considered for a storage system

Technology	Original	New
CAMRAS	1	1
EDC	4	4
4BMS	2	3
SAWD	3	2

7.4.2.3 Water Recovery and Management

As Table 7-42 shows, the ranking is influenced by the additional parameters. The relatively unreliable and low TRL process RO would be the best solution, since it has the lowest mass and volume of the compared processes. The high reliable and mature MF process would be last, because it needs a lot of expendables. This shows the importance of considering other criteria than just the ESM parameters. For recycling of all waste water, there would be no change as can be seen in Table 7-43, because the ranking of the multi-criteria-model and the ESM was already the same and therefore this sensitivity analysis showed no unexpected sensitivity to the input parameters.

Table 7-42: Ranking of WRM processes for humidity condensate recycling when TRL and reliability are not considered

Technology	Original	New
MF	2	4
RO	3	1
TIMES	4	2
VCD	1	3

Table 7-43: Ranking of WRM processes for waste water recycling when TRL and reliability are not considered

Technology	Original	New
AES	3	3
TIMES	2	2
VCD	1	1

7.4.3 Variation of Constraint Function for Multi-criteria-method

All constraint functions, with exception of TRL, are using a quadratic function for the assessment of the parameters, because additional resources burden the system disproportionately high. In this analysis, it is investigated how the ranking would be influenced when a linear approach would be used.

7.4.3.1 Atmosphere Control and Supply

As can be seen in Table 7-13, the score between the cryogenic storage and $LiClO_4$ for repressurisation and leakage are very close. When a linear function instead of the quadratic one is used, the cryogenic storage would be the worst alternative. The high-pressure storage is still superior and reveals again that this technology should be used for repressurisation and leakage.

Table 7-44: Ranking change test of oxygen storage for repressurisation and leakage when a linear function instead of a quadratic function is used

Technology	Original	New
Cryogenic	2	3
High-pressure	1	1
$LiClO_4$	3	2

7.4.3.2 Atmosphere Revitalization

The ranking of the CO_2 removal technologies between the quadratic and the linear function does not change for the recycling nor for the storage system, as can be seen in Table 7-45 and Table 7-46.

Table 7-45: Ranking change test for CO_2 removal when linear function instead of quadratic function is used for a recycling system

Technology	Original	New
EDC	2	2
4BMS	3	3
SAWD	1	1

Table 7-46: Ranking change test for CO_2 removal when linear function instead of quadratic function is used for a storage system

Technology	Original	New
CAMRAS	1	1
EDC	4	4
4BMS	2	2
SAWD	3	3

7.4.3.3 Water Recovery and Management

The relative ranking of the humidity condensate recycling system does not change when a linear function instead of quadratic function is used (see Table 7-47), nor does the ranking change for the waste water recycling system (see Table 7-48). While the ranking did not change, the values of the function become similar. The delta between TIMES and VCD are 0.1504 for the quadratic function and 0.1240 for the linear function. This shows that the used quadratic function emphasizes the difference of the processes better.

Table 7-47: Ranking change test for humidity condensate recycling when linear function instead of quadratic function is used

Technology	Original	New
MF	2	2
VCD	1	1

Table 7-48: Ranking change test for waste water recycling when linear function instead of quadratic function is used

Technology	Original	New
TIMES	2	2
VCD	1	1

7.4.4 Omittance of Certainty Factor

The certainty factor ($f_{Certainty}$) has great influence on the rating of the parameters and therefore on the result of the trade analysis. It is important to test how the $f_{Certainty}$

influences the results, because the $f_{Certainty}$ is based on a restricted investigation for the data of the different technologies.

7.4.4.1 Atmosphere Control and Supply

The certainty factor has no influence on the ranking for the O_2 repressurisation and leakage system as shown in Table 7-49.

Table 7-49: Ranking change test of oxygen storage for repressurisation and leakage when no certainty factor is used

Technology	Original	New
Cryogenic	2	2
High-pressure	1	1
$LiClO_4$	3	3

7.4.4.2 Atmosphere Revitalization

As can be seen in Table 7-50, the certainty factor has no influence on the ranking for CO_2 removal for a recycling system.

Table 7-50: Ranking change test for CO_2 removal when no certainty factor is used for a recycling system

Technology	Original	New
EDC	2	2
4BMS	3	3
SAWD	1	1

For a storage system, the certainty factor has some influence. Table 7-51 shows, that 4BMS and SAWD change ranks, because 4BMS has a higher $f_{Certainty}$ for most parameters. Considerable more and better data is available for the 4BMS and therefore values are confirmed through several references which results in a higher $f_{Certainty}$. For the SAWD less sources are available since the TRL is lower.

Table 7-51: Ranking change test for CO_2 removal when no certainty factor is used for a storage system

Technology	Original	New
CAMRAS	1	1
EDC	4	4
4BMS	2	3
SAWD	3	2

7.4.4.3 Water Recovery and Management

As can be seen in Table 7-52, the ranking of the humidity condensate recycling processes changes when no $f_{Certainty}$ is considered. Since the water reclamation processes are all based on the same source, the $f_{Certainty}$ is the same for all ESM parameters. The only different $f_{Certainty}$ is for the TRL, where 0.75 is used for RO and TIMES, since only one source stated the corresponding TRL values for these processes. For all other processes, it is 1, because several sources with the same TRL were found. This sensitivity analysis further revealed, that the result of the multi-criteria method depends on a comprehensive and precise investigation of the technologies considered. For waste water recycling, no change in ranking occurred.

Table 7-52: Ranking change test for humidity condensate recycling when no certainty factor is used

Technology	Original	New
AES	5	5
MF	2	4
RO	3	1
TIMES	4	3
VCD	1	2

Table 7-53: Ranking change test for waste water recycling when no certainty factor is used

Technology	Original	New
AES	3	3
TIMES	2	2
VCD	1	1

7.4.5 Variation of ESM-factors

The ESM-factors given in Table 7-2 are mostly based on assumptions. Therefore, it must be tested how small changes affect the order in the ranking of the best systems.

To perform the test 10 % are added at once to volume, power, cooling, and maintenance of the system that ranked in the top position, which represents the case that the values for volume, power and crew time were underestimated. If a change in the ranking occurs 10 %, are added successively to volume, power, cooling, and maintenance to figure out if one parameter is sensitive to a 10 % change or if the ranking only changes in the worst-case scenario where all parameters are penalized with 10 %. In the next step, a similar examination is done by subtracting 10 % from the system ranked second, which represents the case where the values used for volume, power, cooling, and maintenance were overestimated.

There is no stowage factor for the mass considered.

7.4.5.1 Atmosphere Control and Supply

The ESM-factor variation for the O_2 storage system for repressurisation and leakage in Table 7-54 and Table 7-55 presented that neither an increase of the best ranked nor a decrease of the second ranked system changes the ranking. For both analysis, a long duration for 211 days was used.

Table 7-54: Ranking change test with 10% increase of ESM-factors for volume, power, and maintenance of high-pressure O_2 storage for repressurisation and leakage

Technology	Original	New
Cryogenic	2	2
High-pressure	1	1
$LiClO_4$	3	3

Table 7-55: Ranking change test with 10% decrease of ESM-factors for volume, power, and maintenance of cryogenic O_2 storage for repressurisation and leakage

Technology	Original	New
Cryogenic	2	2
High-pressure	1	1
$LiClO_4$	3	3

7.4.5.2 Atmosphere Revitalization

No ranking changes are measurable through the ESM-factor variation on the CO_2 removal technologies as can be seen in Table 7-56 and Table 7-57. Also, a 10 % decrease of the ESM-factors for EDC in the recycling system, as well for SAWD in the storage system revealed any ranking changes.

Table 7-56: Ranking change test with 10% increase of ESM-factors for mass, volume, power, and maintenance of SAWD

Technology	Original	New
EDC	2	2
4BMS	3	3
SAWD	1	1

Table 7-57: Ranking change test with 10% increase of ESM-factors for mass, volume, power, and maintenance of CAMRAS

Technology	Original	New
CAMRAS	1	1
EDC	4	4
4BMS	3	3
SAWD	2	2

7.4.5.3 Water Recovery and Management

For the WRM system, the variation on ESM-factors for the best three systems are presented in the following.

Table 7-58: Ranking change test with 10% increase of ESM-factors for mass, volume, power, and maintenance of RO

Technology	Original	New
RO	1	1
TIMES	3	3
VCD	2	2

Table 7-59: Ranking change test with 10% decrease of ESM-factors for mass, volume, power, and maintenance of VCD

Technology	Original	New
RO	1	1
TIMES	3	3
VCD	2	2

The tables above state the rankings of the top three processes for humidity condensate recycling. As can be seen in Table 7-58, a 10 % increase of all ESM-factors of the top-ranked process RO has no influence on the ranking. The same is true for a 10 % decrease on the ESM-factors for the second-ranked process VCD, as can be seen in Table 7-59. This means, the ESM-factors for this analysis are correct.

Table 7-60: Ranking change test with 10% increase of ESM-factors for volume, power, and maintenance of VCD

Technology	Original	New
AES	3	3
TIMES	2	2
VCD	1	1

Table 7-61: Ranking change test with 10% decrease of ESM-factors for volume, power, and maintenance of TIMES

Technology	Original	New
AES	3	3
TIMES	2	2
VCD	1	1

The same behavior as above is detected for the waste water recycling processes. As can be seen in Table 7-60 and Table 7-61, the ranking stays the same when the ESM-factors for top-ranked process VCD are increased by 10 % or when the second-ranked process TIMES get a 10 % decrease of the ESM-factors. Over 22 % increase on the VCD ESM-factors, or over 18 % decrease on the TIMES ones are needed before TIMES process gets first rank.

8 Second Design Cycle

This chapter is dedicated to a further investigation of the subsystems. In chapter 7.3, the optimal technologies and processes are assessed. Now, the optimal architecture of the subsystem has to be found, based on the result of the first design cycle. For this, either the top-ranked technology or several ones are used for a specific function. All functions and their assigned assemblies build the subsystem. The different possible options are compared by using the ESM with and without crew time. The results of this design step are the foundation for the detailed Final design in chapter 10.

8.1 Second Design Cycle for Atmosphere Control System

Several considerations outlined below lead to the conclusion, that a high-pressure storage system for repressuriation and leakage should be used instead of a cryogenic storage system.

No different technologies for comparable functions should be used to have more commonality and synergetic effects. For N_2 repressurisation and leakage as well as for an O_2 storage system, high-pressure is the superior technology.

The multi-criteria-method like all sensitivity analysis prefers a high-pressure system.

The mass of a cryogenic system is much higher and the volume savings could not be taken into account, since the tanks are outside the pressurized compartment.

The break-even point for ESM on the O_2 repressurisation and leakage system is after 114 days as can be seen in Figure 8-1. This is shorter than the mean mission time of 132 days.

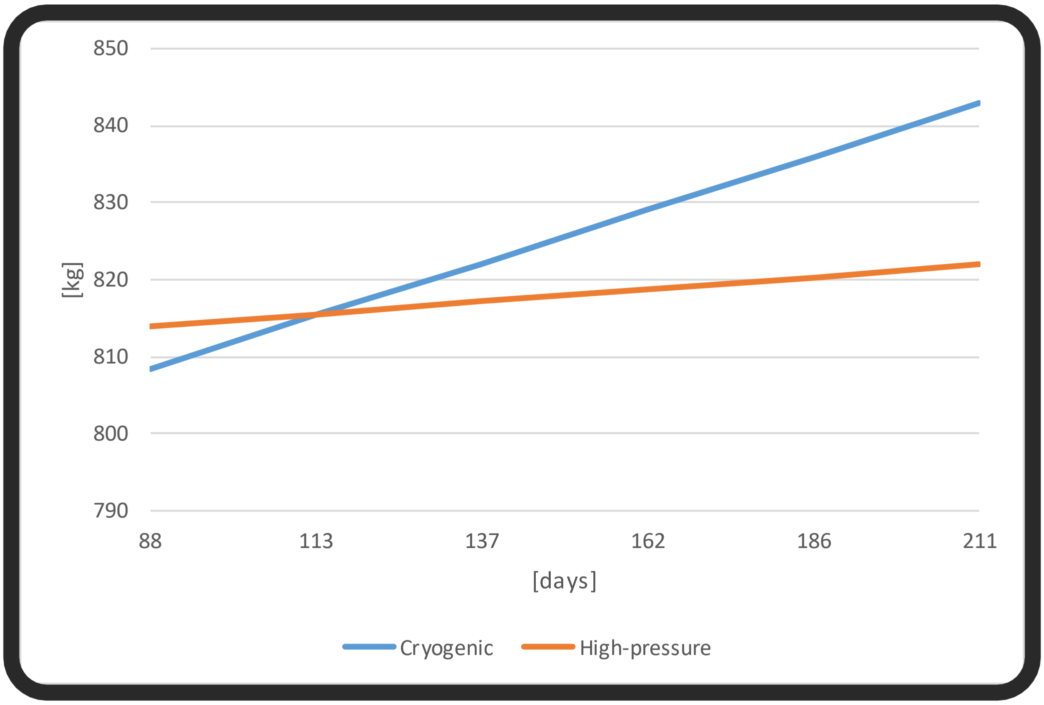

Figure 8-1: ESM break-even point between cryogenic and high-pressure system for repressurisation and leakage

8.2 Second Design Cycle for Thermal and Humidity Control

The purpose of this design cycle is to measure, if the CAMRAS is worthwhile to include, since the CCAA is already needed to remove heat, but the WS could be removed. This unit has a mass of 11.93 kg [63, p. 160], which is around 12.41 % of the mass of the CCAA, while the volume is around 1.46 % of the whole assembly. The average power of the WS is 44 W [38, p. 73]. A breakdown of the different considered assemblies for the function with the measured ESM for Case4 is listed in TAB. As can be seen, CAMRAS has a bigger impact on the ESM as the removal of WS from the CCAA. The ranking did not change for the other cases. Hence, only the CCAA and IMV will be used in the final system (see 10.2).

Table 8-1: ESM analysis of the thermal and humidity control subsystem in the second design cycle

Option	Control Atmospheric Temperature (4.2.2.a & 4.2.2.b)	Control Atmospheric Humidity (4.2.2.c & 4.2.2.d)	Ventilation Velocities in the Crew Habitable Volume (4.2.2.e & 4.2.2.f)	ESM
1	CCAA	CCAA	IMV	3,401
2	CCAA	CAMRAS	IMV	4,032

8.3 Second Design Cycle for Atmosphere Revitalization

Before a final conclusion about the optimum AR architecture can be made, several architectures must be compared. The trade study in chapter 7 selected the best alternatives for every function. Overall, 14 different options are compared based on ESM as can be seen in Table 8-2. There are no differences on the ranking between the shown ESM and a non-crew time ESM. Not shown in the table above are function for which the same technology is used for every option. These are Multi Bed Trace Contaminant Control (TCCS) for requirement 4.2.3.b, BFE for the requirements Control Airborne Particulates (4.2.3.d) and Control Microbes (4.2.3.f), and major constituent analyzer (MCA) for requirement Detect Hazardous Atmosphere (4.3.2.a). The calculations in Table 8-2below includes considerations like an oxygen and hydrogen storage for option 2. As can be seen, the combination of SAWD, SFWE, and Sabatier has the least equivalent weight, followed by the similar configuration with EDC instead of SAWD. The ISS system (option 7) is only ranked fifth, while the best storage system (option 1) uses the CAMRAS and has an over 5 times higher ESM. For the final design, the best ranked option (14) is used.

Table 8-2: ESM analysis of the atmosphere revitalization subsystem in the second design cycle

Option	Remove Gaseous Atmospheric Contaminants (4.2.3.b)	(Re)generate Oxygen (4.4.3.a)	Process Gaseous Wastes (4.4.3.b)	ESM	Rank
1	CAMRAS	none	none	33,521	11
2	EDC	none	none	54,667	14
3	EDC	SFWE	none	30,298	7
4	EDC	SFWE	Sabatier	6,311	2
5	4BMS	none	none	36,267	13
6	4BMS	SPWE	none	32,021	10
7	4BMS	SPWE	Sabatier	8,064	5
8	4BMS	SFWE	none	31,579	9
9	4BMS	SFWE	Sabatier	7,622	4
10	SAWD	none	none	34,853	12
11	SAWD	SPWE	none	30,607	8
12	SAWD	SPWE	Sabatier	6,620	3
13	SAWD	SFWE	none	30,164	6
14	SAWD	SFWE	Sabatier	6,177	1

After the selection of the final system, additional trade-offs where made to make a decent decision on the final system architecture.

8.3.1 System Trade

To minimize the necessary power for the AR system, several options between the SFWE and the Sabatier are analyzed. Overall 11 different operational options, given in Table 8-3, are considered.

Table 8-3: Considered operational options for oxygen generation and CO_2 reduction

Option	SAWD	Sabatier
1	metabolic demand	H_2 demand
2	metabolic demand	constant
3	metabolic power safe	H_2 demand
4	metabolic power safe	constant
5	reduction demand	CO_2 demand
6	reduction demand (constant)	Constant
7	reduction power safe	CO_2 demand
8	reduction power safe	Constant
9	fuel cell	H_2 demand
10	fuel cell	Constant
11	metabolic constant	Constant

Besides this operational consideration, 4 different system architectures where considered:

1) One central TCCS and CO_2 removal assembly on Deck 4 and oxygen generation for the minimum metabolic need with altered working time (Option 3).
2) CBA´s in each level and one big COA & SBA and the CO_2 removal assembly on deck 4, while the SFWE is oversized to produce enough H_2 for full CO_2 reduction through the Sabatier maximum (Option 6). SAWD and Sabatier are also on deck 4.
3) TCCS´s in each Level before CCAA and SAWD on deck 4, while the SFWE produces minimum required O_2 for metabolic needs which means the Sabatier is also sized to a minimum. Both have altered working times (Option3) on deck 4.
4) All AR equipment is decentralized and housed in every deck.

The final system with the best compromise between mass, volume, and power requirements are system architecture 1 with a total ESM of 24,188 kg. For comparison, the worst-case system (4) has a ESM of 34,986 kg. The result of the ESM analyses is shown in Figure 8-2. The power demand of the chosen operational option 3 is given in Figure 8-3.

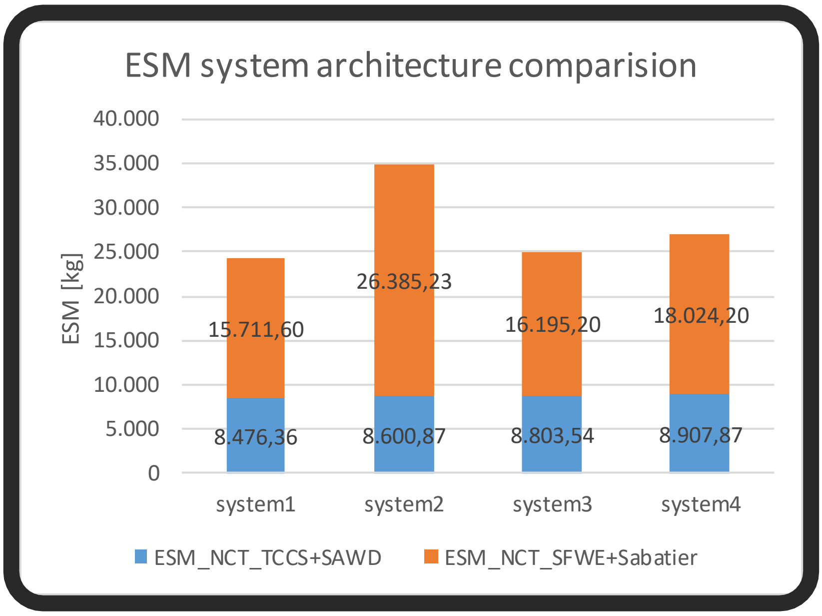

Figure 8-2: Final system architecture trade

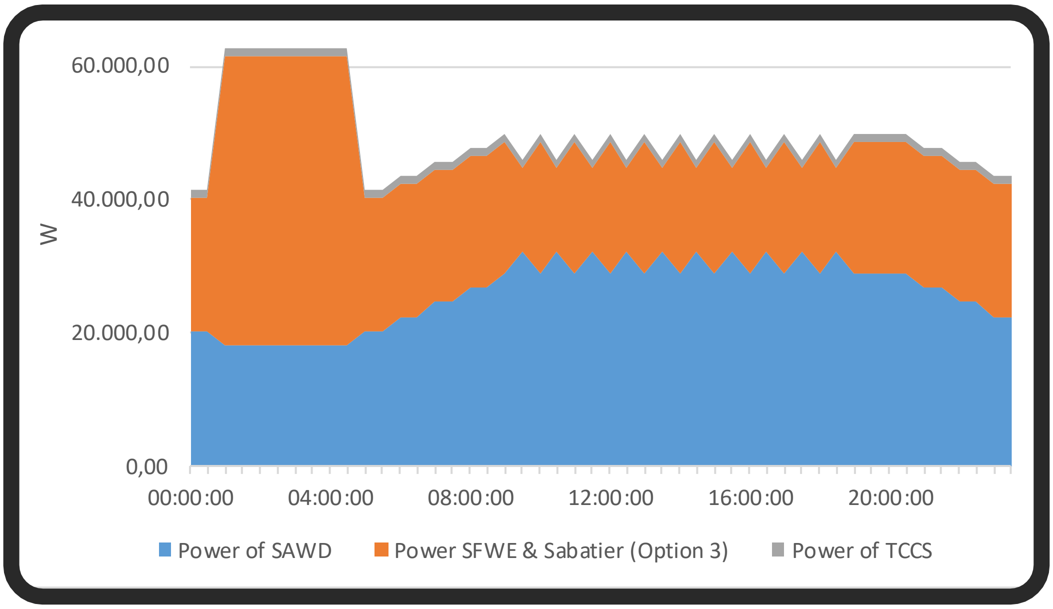

Figure 8-3: Total power demand of AR subsystem with operational option 3

8.4 Second Design Cycle for Water Reclamation Management

The considered water recycling architectures (WRA) in Table 6-36 are evaluated in this section. First, the needed water and the corresponding tanks are assessed and then an ESM analysis is performed based on selected technologies for the functions of the WRM subsystem.

8.4.1 Water Tank Assessment

The required water tanks for the different water reclamation architectures (see Table 6-36) are depicted in the following sections.

8.4.1.1 Water Tanks for Storage System

The mass and volume of the water tanks for the storage system are already calculated in chapter 6.4.1.2 and summarized in Table 6-38.

8.4.1.2 Water Tanks for Humidity Condensate Recycling

The tanks for the water recycling architecture 2 (WRA2) consist of a potable water tank with water for the whole mission, a hygiene water tank, and a waste water tank. For all 3 water tank types, it is assumed that they consist of one cubic tank with 4 % residual mass and a CoF of 3.

The hygiene water storage tank is assumed to hold at least enough water for 3-day contingency to make the system more flexible and robust. Besides the contingency water mass, the tank must be large enough to accept the input water. This resulting working volume is assumed to be the flow of the recycled humidity condensate at a recovery rate of 0.95 for three days. This relatively large working volume ensures that no venting of recycled water is needed when consumption is temporarily lower.

The waste water storage is assumed to hold up to 3-days contingency of collected humidity condensate from the THC subsystem. During nominal operation, it is assumed that the waste water tank does not exceed 33 % of the working volume so that there is enough margin if the VCD needs maintenance.

Table 8-4: Tank properties for the water recycling architecture 2

WRA2	Unit	Case1	Case2	Case3	Case4
Potable water tank empty	[kg]	216.54	454.71	787.72	1414.25
Potable water tank full	[kg]	2,962.14	9,606.71	22,731.72	56,274.25
Potable water tank volume	[m³]	2.90	9.65	23.14	57.85
Hygiene water tank empty	[kg]	34.07	66.42	66.42	120.76
Hygiene water tank full	[kg]	193.23	596.95	596.95	1,447.08
Hygiene water tank volume	[m³]	0.17	0.56	0.56	1.40
Waste water tank empty	[kg]	20.82	44.68	44.68	84.22
Waste water tank full	[kg]	111.13	345.68	345.68	836.72
Waste water tank volume	[m³]	0.14	0.46	0.46	1.16

8.4.1.3 Water Tanks for Humidity Condensate and Hygiene Waste Water Recycling

For the WRA3, no hygiene water tank is assumed, because all recycled water is expected to be potable water quality. The potable and waste water tank are assumed to be of cubic shape and have a residual mass of 4 % and a CoF of 3.

Because the recycled humidity condensate and hygiene waste water is not enough to satisfy the consumption need, some potable water has to be stored. This contingency water is calculated by assuming a minimal reclamation rate of 95 %. The additional working volume is assumed to be the accumulated recycling water flow from 3 days at a reclamation rate of 95 %.

The waste water storage is assumed to hold up to 3-day contingency of collected humidity condensate from the THC subsystem and collect hygiene water from the shower. During nominal operation, it is assumed that the waste water tank does not exceed 33 % of the working volume so that there is enough margin if the VCD needs maintenance.

Table 8-5: Tank properties for the water recycling architecture 3

WRA3	Unit	Case1	Case2	Case3	Case4
Potable water tank empty	[kg]	55.41	124.68	196.49	340.60
Potable water tank full	[kg]	466.23	1,494.08	2,531.03	6,327.57
Potable water tank volume	[m³]	0.43	1.44	2.63	6.57
Waste water tank empty	[kg]	36.39	70.94	70.94	125.83
Waste water tank full	[kg]	206.39	637.59	637.59	1,542.45
Waste water tank volume	[m³]	0.26	0.87	0.87	2.18

8.4.1.4 Water Tanks for All Waste Water Recycling

Like WRA3, the WRA4 consists of a potable and waste water tank. The residual mass is also assumed to be 4 % with a cubic shape and a CoF of 3.

Since all waste water is recycled, the needed reclamation rate is only 0.81. Therefore, the working water mass in the potable water tank is considered to hold up to 3 days of recycled waste water with a reclamation rate of 0.81. The contingency water mass is assumed to be one week of the daily consumable water. This ensures that enough time is provided to repair the VCD in the event of a failure. If this would fail, even enough potable water for 14-day survival is stored when assuming a reduced drinking and rehydration rate of 2.05 kg CM-d^{-1} and no further hygiene usage during the emergency.

The waste water storage is assumed to hold up to 3-day contingency of collected waste water from the different subsystems. During nominal operation, it is assumed that the waste water tank does not exceed 33 % of the working volume so that there is enough margin if the VCD needs maintenance.

Table 8-6: Tank properties for the water recycling architecture 4

WRA4	Unit	Case1	Case2	Case3	Case4
Potable water tank empty	[kg]	54.16	121.88	121.88	263.94
Potable water tank full	[kg]	455.74	1,460.50	1,460.50	3,610.48
Potable water tank volume	[m³]	0.42	1.41	1.41	3.53
Waste water tank empty	[kg]	38.43	84.37	84.37	153.95
Waste water tank full	[kg]	264.58	838.21	838.21	2,038.57
Waste water tank volume	[m³]	0.35	1.16	1.16	2.90

8.4.2 Additional Equipment for the Water Reclamation Management

The only considered equipment for the water reclamation system besides the tanks and VCD is the water quality monitoring described in 6.4.9. Only insufficient data could be found about the potable water dispenser and therefore it is excluded in this analysis.

8.4.3 ESM Analysis

The requirements for the WRM defined in 4.2.4 and 4.4.4 are used in this follow-on design step to compare the different water reclamation architecture options from Table 6-36.

For the water quality control function, the water quality monitoring described in 6.4.9 is used for every option since there is no other technology considered.

For the water storage function, the only reasonable assembly is a water tank obviously.

For waste water storage, also water tanks are considered for WRA2, WRA3, and WRA4, while for WRA1 venting of waste water is assumed.

For the three recycling processes, only the VCD process is considered, since any other process would result in an inferior result. Therefore, VCD is considered for the humidity condensate recycling for all options except the storage system WRA1. Additional hygiene waste water recycling by VCD is considered for WRA3 and WRA4, and the processing of urine by VCD is considered for WRA4.

Table 8-7: Considered technologies for the water reclamation architectures

	WRA1	WRA2	WRA3	WRA4
Potable water tank	X	X	X	[21]
Waste water tank		X	X	X
VCD		X	X	X

[21] A buffer tank is still be needed.

The ESM results of this assessment and the corresponding ranks are stated in Table 8-8. As can be seen, the storage system (WRA1) is always ranked last as expected and WRA2 is third, due to the big potable water tank. For small crews and mission durations, urine reclamation is not best, especially when taking note of the higher complexity and reliability considerations. For longer missions and more crew, the urine recycling has a considerable saving.

Table 8-8: ESM analysis of the second design cycle on the water reclamation management

	Case1		Case2		Case3		Case4	
Option	**ESM**	**Rank**	**ESM**	**Rank**	**ESM**	**Rank**		**ESM**
WRA1	5,916	4	19,224	4	45,609	4	113,529	4
WRA2	3,546	3	11,375	3	25,726	3	63,603	3
WRA3	685	1	2,084	1	3,479	2	8,425	2
WRA4	714	2	2,177	2	2,244	1	5,454	1

9 Additional Aspects to Consider

In the following, several important aspects that are not part of the trade analysis before are examined. While biological systems, bulk packaging for food, and a clothes washer are not considered for the SpaceHab due to their low TRL, they are analyzed in more detail for implementation in LiSTOT.

9.1 Structural Analysis

The SpaceHab is build lightweight due to its carbon fiber makeup. For radiation shielding estimations, a rough knowledge of the thickness of the walls is necessary. To get an approximation for the width of carbon fiber throughout the Ship, two analyses are possible. The first one is by direct measurement in the given pictures. This leads to around 3.53 cm thickness. Because this measurement is only based on 3 pixels, another analysis is desirable. This second analysis is based on mass estimations. The structural mass of the SpaceHab is known to be 150 tons. There are 9 engines, named raptors, on the ship with different nozzle types. The trust-to-weight ratio for both the sea level and vacuum raptors are assumed to be an optimistic 200. The thrust (T) of a sea level raptor is 3,050 kN where the vacuum raptor has a thrust of 3,500 kN. To get the mass (W) of every engine, Eq. (9-1) is used. [11]

$$W = \frac{T}{200} \qquad \textbf{Eq. (9-1)}$$

This leads to a mass of 1,555.07 kg for one sea level raptor and 1,784.50 kg for one vacuum engines. With 3 sea level raptors and 6 vacuum raptors total, this leads to a total engine mass of 15,373 kg.

The four legs of a Falcon 9 are made of state-of-the-art carbon fiber with aluminum honeycomb and have a mass of around 2,100 kg ($m_{F9,legs}$) [101, 102] they can hold a nearly empty Falcon 9 booster with a mass of around 26,000 kg (m_{F9}) [102]. Assuming the landing legs of the SpaceHab are linear scaled up versions of the Falcon 9 legs, it can be calculated by Eq. (9-2) that this would lead to a mass of 27,259.62 kg ($m_{SpaceHab,legs}$) for the 3 landing legs of the SpaceHab at a landing weight of 450,000 kg ($m_{SpaceHab}$).

$$m_{SpaceHab,legs} = \frac{m_{F9,legs}}{4}\frac{m_{SpaceHab}}{m_{F9}}\,3 \qquad \textbf{Eq. (9-2)}$$

Not considered here are the much higher safety requirements, because these legs must be man-rated instead of the Falcon 9 legs. So even if they do scale up less than linear, this number should be in the right order of magnitude.

It is further assumed that the solar panels and the thermal systems are included in the dry mass. As described in chapter 2.1, the solar panels have a power of 200 kW. To get an estimation of the mass for the solar panels, it has to be divided by the specific weight of the solar panel (assuming here 150 W kg^{-1} [99]), which leads to a total mass of around 1,333 kg for the solar panel. For the thermal system, it is assumed that 100 kW of thermal energy has to be refused. An Active Thermal Control System (ATCS) consists mainly of pumps (4.8 kg per loop capacity in kW), pumps and valves (15 % of ATCS), instruments and controls (5 % of ATCS), and radiators (8.5 kg per m^2). To determine the area needed for the radiator, the needed total heat rejection can be divided by a specific heat rejection of 251 W m^{-2} [13, p. 519], which gives a needed radiator area of 398.41 m². Summing up the necessary ATCS subsystem, the total mass for the ATCS is around 3,960 kg. This is a very low estimate without any redundancy, Internal Thermal Control System (ITCS) and any needed heat exchangers.

The sum of the masses of the engines, the landing legs, the solar panels, and the TCS is over 47,900 kg. Subtracting this from the dry mass of the SpaceHab leads to around 102,000 kg. This leftover mass includes all surface masses and masses for pipes etc.

The masses of the structures are assessable by determination of the surface areas of the separate components of the SpaceHab, including the internal components. For this, only simple surface areas of the various geometries are considered. All following calculations are based on measurements from Figure 2-2. The propellant tanks are considered to be 12 m wide and the cylindrical section has height of 14.72 m. This gives an area of about 452 m² for the spherical part and 271 m² for the cylinder. The spherical inner O2 tank has a diameter of 5.25 m which leads to an area of around 87 m². The methane tank is slightly smaller with 4.77 m which gives an area of roughly 70 m². The left outer shell of the cylindrical part has a high of 21.58 m with a diameter of 12 m. Therefore, the total area of the unpressurized shell is around 1,142 m². The engines are protected by a heatshield. This area is around 810 m² large. The area for the pressurized section is separated into the lower cylindrical part with approximately 210 m² and the upper part with 1,115 m². Further, the decks and the habitat tube in the middle must be considered. The floors have a total area of nearly 620 m² (see Table 2-2 for the specific radii) and the tube can be measured to have a length of 16.67 m and a diameter of 1.14 m which gives about 60 m². A summary of the different components is given in Table 9-1.

Table 9-1: Surface summary

Component	Quantity	Total Surface Area [m²]
Windows	46	9
Panorama Window	1	108
Pressurized Section	1	497
Unpressurized Section	1	210
External cylindrical shell	1	1,115
Lower heat shield	1	81
O2 propellant spheres	2	452
CH4 propellant cone	1	271
Floors	7	620
Hab tube	1	60
Total composite surface area		**3,306**

There are 47 windows of different sizes, with the biggest on Deck 1, the panorama window. Together, they cover an area of around 117 m². With an assumed density of $2.2 \cdot 10^3$ kg m^{-3} [103] and a thickness of around 7 cm, this would lead to a mass of nearly 18,000 kg for the windows alone. For comparison, the windows in the cupola on ISS are 14.3 cm thick, but are more in danger of orbital debris [14, p. 96]. The leftover mass after removing the engine mass, the legs mass and the windows mass is around 84,080 kg.

For reentry purposes, one half of the outer wall is covered with a heatshield to withstand the heat. This heatshield will be of PICA-X, which is currently used for the Dragon capsules. PICA-X is a further developed version of PICA from NASA. It is unknown how thick the heatshield will be. For this thesis, it is assumed to be the same as the rest of the wall, which is 3.53 cm. It should be noted that this is a very rough estimate, but for a fist prediction sufficient. The wall thickness of the Apollo command module for comparison was between 2.8 cm and 3.8 cm, with 5.1 cm for the heatshield alone [104], and the heatshield thickness on MSL which uses PICA was 3.175 cm [105]. The density of PICA is around 0.27 g cm^{-3} [106] and covering an area of around 835 m^3. This means that for the heat shield alone, approximately 7,163 kg are needed. Subtracting the heat shield mass from the remaining mass gives a mass of about 76,920 kg.

Because it is not possible to measure the masses for the pipes, valves, etc. a rough 10 percent of the remaining mass is assumed which is 7,692 kg. This means, around 69,230 kg are left for the surface masses.

To find the thickness of the wall structure, the remaining mass ($m_{SpaceHab,Carbon}$) is first divided though the density of the carbon fiber. T1000G from TORAYCA® is assumed to be used by SpaceX, as this is the most advanced carbon fiber created to date. T1000G has a density of 1,800 kg m^{-3} [65]. The mass-% of fibers in a composite is normally 60 %, where the other 40 % is epoxy resin. Epoxy resins have a density of around 1,100 kg/m^3 which means the composite has a density of around 1,520 kg m^{-3} (ρ_{Carbon}). Using Eq. (9-3) the volume of the carbon fiber (V_{Carbon}) can be found.

$$V_{Carbon} = \frac{m_{SpaceHab,Carbon}}{\rho_{Carbon}} \qquad \textbf{Eq. (9-3)}$$

From this, the obtained volume is nearly 41 m^3 of carbon fiber making up the structure of the ITS. Dividing this number by the surface area of 3,306 m^2 to obtain a net carbon fiber composite thickness of 0.0138 m, or 1.38 cm. It is unlikely that this will be consisting of one layer. The measured value of 3.54 cm in Figure 2-2, should be true when considering multiple layers and maybe an integrated honeycomb between the layers for greater stiffness. In the volume calculations in chapter 2.3, 4 cm are used for the wall thickness. For comparison, the wall thickness of ISS is overall 11.4 cm, but with great space between different shells, where the net wall thickness is around 0.88 cm with an areal density of 2.77 g cm^{-2} [107, 32, 107, p. 58, 107, p. 50]. The corresponding areal density of the SpaceHab is 2.1 g cm^{-2}. But it should be noted, that the wall design of the ISS is mainly driven by orbital debris and micrometeoroid protection. While orbital debris is only problematic in LEO, micrometeoroids are basically constant in interplanetary space although this is much less of a threat than the hazard from orbital debris [13, p. 73]. To protect the crew sufficiently during a mars transfer, an aluminum areal density of 20 to 25 g cm^{-2} should be considered [13, p. 115].

9.2 Waste Management

Several promising technologies to reduce waste, as well to recycle most of the usable contents are currently in development. These are dry incineration, wet oxidation, or the heat melt compactor just to name a few. Nearly all have in common that they have a low TRL of under 5. One of the more developed technologies is the ionomer-membrane water processor. This is a dual-membrane distillation process to dry urine brine [90]. This and other waste management technologies are not considered, since they have the already mentioned low TRL and they would add additional power and volume requirements. Instead it is assumed that the following waste is mechanically compacted to save volume.

Table 9-2: Data of waste sources [10]

Parameter	**Mass [kg CM-d^{-1}]**	**Volume [m^3 CM-d^{-1}]**
Sweat solids	0.018	
Urine pretreatment (chemicals)	0.040	
Urine solids, dry	0.066	
Fecal solids (dry or wet)	0.117	
Fecal collection mittens[22]	0.230	0.0008
Fecal water	0.077	
Toilet paper	0.006	0.0013
Gloves	0.007	
Hygiene consumable[23]	0.079	0.0015
Food packaging	0.234	
Food scraps and flakes	0.200	
Uneaten food and beverages	0.100	
Grey or duct tape	0.033	
Trash bags[22]	0.050	
Wipes (housekeeping)	0.178	0.000018
Health care consumables	0.200	
Skin epithelium, shed to air and surfaces	0.007	
Total	**1.6422**	**0.003618**

[22] [13]
[23] [39] includes toothpaste, brushes, shaving provisions, lip balms, deodorants, tampons, contact lenses etc.

The total waste mass is given in Figure 9-1. It can be seen that for Case4, nearly 8 % of the maximum possible payload mass of 450,000 kg is occupied by waste.

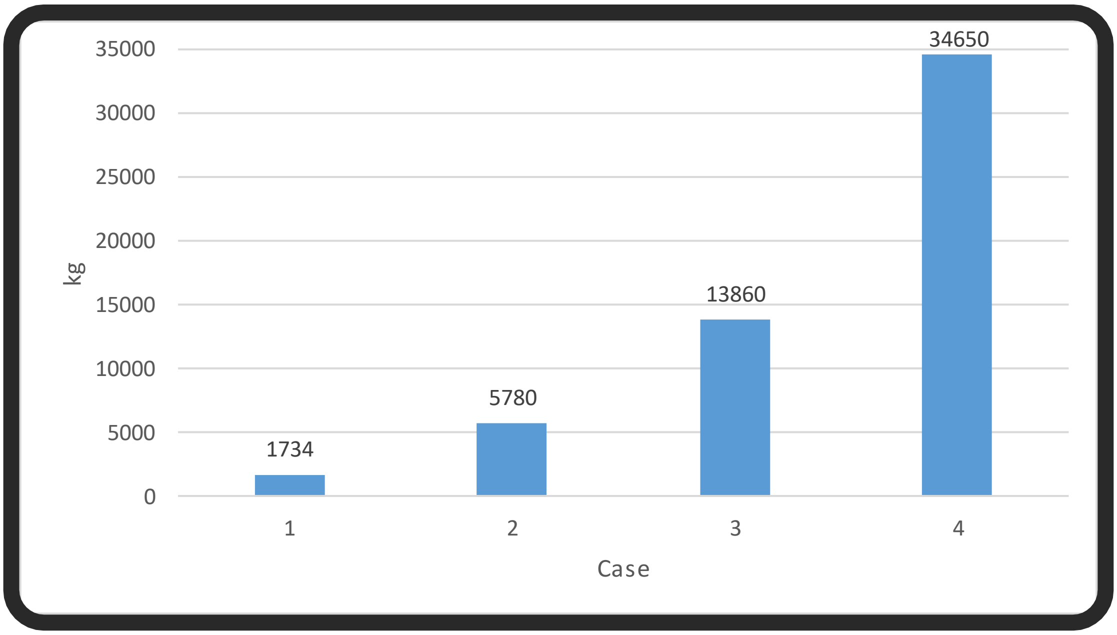

Figure 9-1: Total waste mass at the end of the mission for the different trade cases

9.3 Biological System

Biological systems are required to fully close the loop of a ECLSS since this is the only system that provides food. Beside food production, a biological system also removes CO_2 from the air and produces O_2. On top of that, it also cleans waste water, as long as it is not too contaminated. Besides these physical benefits, it has psychological benefits since it stimulates multiple senses during cultivation. But the drawbacks cannot be neglected. These range from the liability of the plant to ethylene, even at very low levels, to the high power and volume requirements of such a system. Additionally, it is very difficult to control. [20, 35, 108, pp. 213-216]

The required area for plants per CM-d is given in Table 9-3.

Table 9-3: Data of required area for plants [13, p. 561, 54, p. 195, 108, p. 212]

	Unit	Low-value	High-value
Higher plants for food	[m² CM^{-1}]	15	20
Only water & O_2	[m² CM^{-1}]	6	10
Only water	[m² CM^{-1}]	3	5
CO_2	[g $(m^2d)^{-1}$]	40	300
CO_2 level	[ppm]	350	2,000
Water	[kg $(m^2d)^{-1}$]	5	10
Minerals	[mg m^{-2}]	10	100
Lighting period	[h]	8	24
Lighting power	[W m^{-2}]	13	170
Temperature	[K]	288	303

With the values in Table 9-3, the required volumes and power can be calculated. The required volume is given in Figure 9-3 and the corresponding power requirement in Figure 9-4. Not shown in Figure 9-4 is the maximum assumed power requirement for food plant growth, since it begins at 30.6 kW for 12 CM and ends at 255 kW for 100 CM. For the maximum available volume, it is assumed that one of the lower decks is used for plant growth. Further, the inner 2 diameters are free space as there must be access to the floors and small passageways to access the entire growth area. The hereby attainable growth area requires around 69 m² floor area, as the mockup in Figure 9-2 shows. The green areas are possible plant growth areas. Overall, 5 layers with a 40-cm gap between each are considered to maximizing the growth area to 345 m².

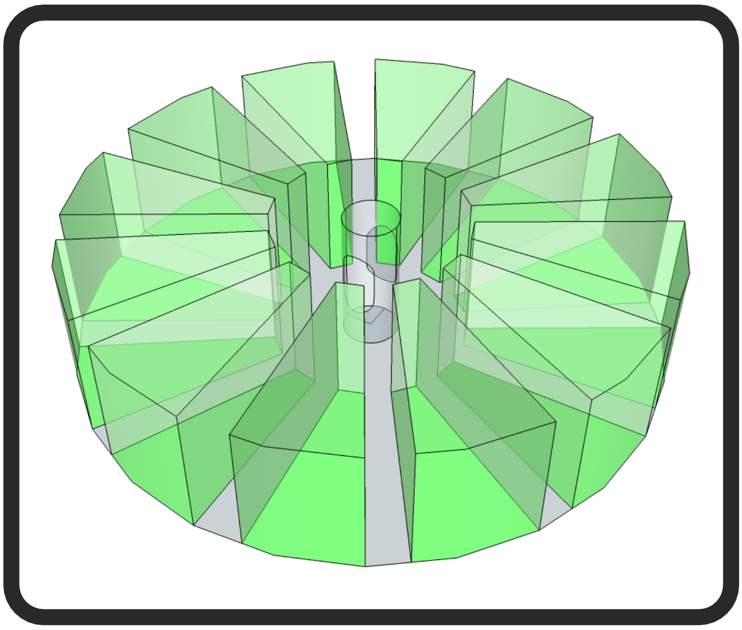

Figure 9-2: Possible growth area for plants in the lower decks

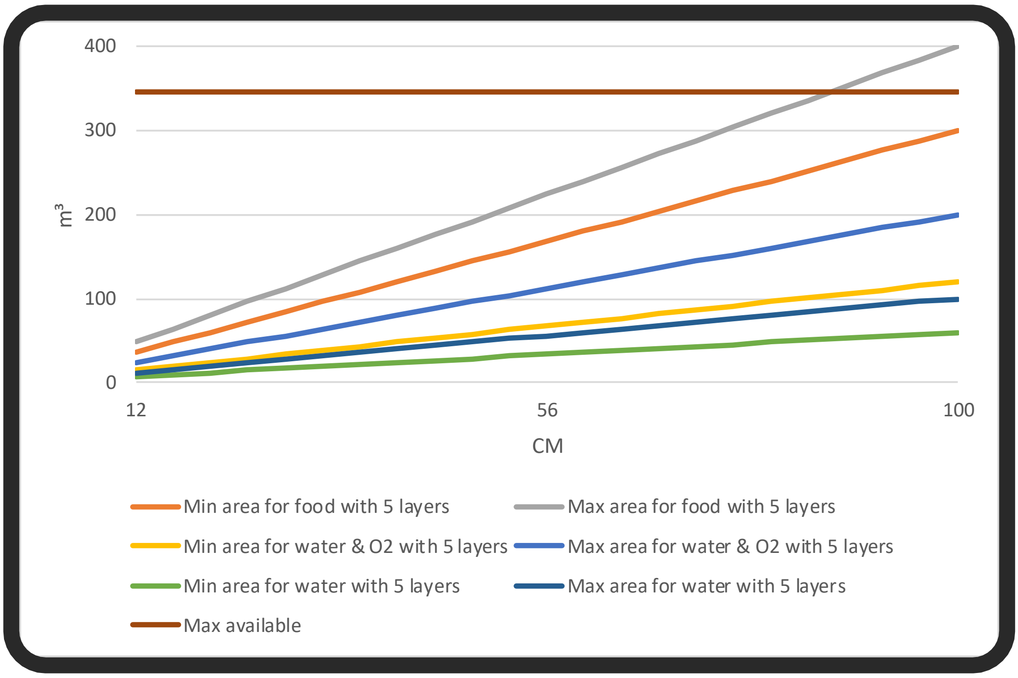

Figure 9-3: Required area for plant growth

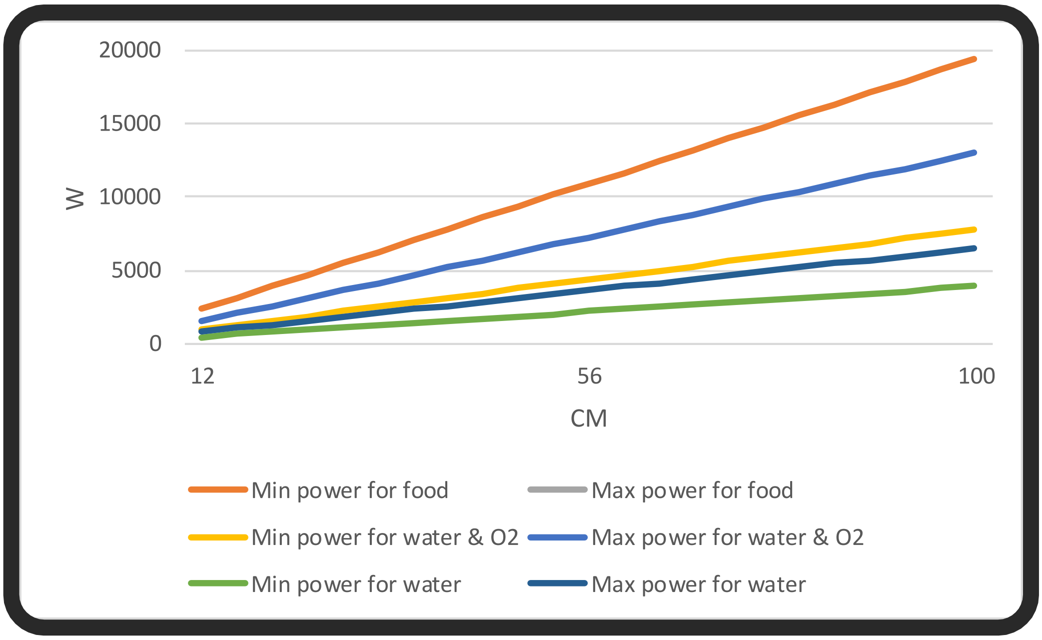

Figure 9-4: Required power for plant growth

As this analysis shows, from a power and volume standpoint, a sufficient plant growth area would be possible. The high amount of required buffer water could be a problem, but is not further analyzed. Also not included in the above calculations are specialized equipment for food preparation, which would add much mass, volume, and power requirements [108, p. 212]. See also chapter 9.4.1 Food System for details about possible bulk equipment.

A biological system is not further considered in this thesis, since the TRL is very low and therefore the needed reliability is not given. But it is a promising approach to include such a system, at least for water and oxygen generation.

9.4 Crew Accommodations

9.4.1 Food System

Food is one of the main contributors to the ECLSS mass. Because of this, the type of food options must be selected wisely. The different food supply approaches are bio regenerative, prepacked food, and bulk packaging. Bio regenerative and bulk packaging food has several advantages over prepacked food. It has a higher nutrient density, is more customizable and thus more variety of meals and a positive psychological effect. But there are also drawbacks like the risks of food scarcity or microbial infections. Additional, extensive crew time is needed for processing of the raw plants or ingredients and the mass for the infrastructure is high. The bio regenerative system also needs harvesting which is very time consuming. In contrast are the lower risks of prepacked food, the much lesser infrastructure mass and the quick preparation times. But there are also some disadvantages for prepacked food like a quality and nutrient loss over long times and the high mass and volume because all food for the whole mission length has to be stowed. [9, p. 500, 13, pp. 578-586, 109, 109]

As revealed in chapter 9.3 Biological System, the mass and especially risk for a bio regenerative system is too high to be considered. A bulk packaging system is only favorable when packing mass and thereby waste and volume is lower. The nominal ISS food supply mass is 1.831 kg $CM\text{-}d^{-1}$ of which around 16.5 % are packaging mass and 333 g for the food container [10, p. 106]. This means for the worst-case of 100 persons and 211 days, the food packaging mass is around 12,247 kg. Even when neglecting the food container, the waste mass is still 5,072 kg. Comparing this with an equipment mass of at least 726 kg for bulk packaging, **considerable mass could potentially be saved**.[24] Not included in this estimate are packaging mass for the bulk ingredients. But because there is not even a breadboard unit for such a food system, only prepacked food is considered for this thesis.

Prepacked food comes in 5 different options, outlined below. Generally, it can be said, that the higher the water content, the better it tastes. A high water content has also the additional effect that the system is more reliable, because less rehydration water from the LSS is needed. [5, 13, pp. 578-586]

Completely dehydrated foods have the smallest mass but also least taste. These foods are dried by heating or freezing and must be rehydrated with hot water before eating. Examples are soups, chicken salad, shrimp cocktail, or breakfast cereals. The volume of such a meal is 735 cm^3 in average and has a mass, including the package, of around 50.6 g. [9, p. 500, 9, p. 501, 110, p. 2]

Thermo-stabilized food has more mass as dehydrated food, because the water content is not reduced. The food is stowed in cans or pouches which gives them a high shelf life of 3 to 5 years. Menus of thermo-stabilized food are ham, pudding, or fish. The average volume is around 460 cm^3 with a mass of 191 g. [9, p. 499, 9, p. 500, 110, p. 2]

[24] Bulk packaging equipment mass from [10, p. 115] is 718 kg for processing rate of around 18,9 kg h^{-1}. A crew of 100 persons has a daily need of around 153 kg of food. Assuming the equipment is working for 8 hours a day, the total mass would be 726 kg.

To reduce processes like ripening or senescence of raw fruits and vegetables, food can be irradiated. These foods weight a little bit less than thermo-stabilized foods because the package weight is smaller. Irradiated food is meat and the already mentioned fruits and vegetables. The shelf life is comparable to thermo-stabilized food with a mean volume of 313 cm^3 at a mass of 124 g. [9, p. 499, 9, p. 501]

Hydrated or natural-form food, is not further processed before packed and includes food such as peanuts, cookies, or granola bars, but also fresh foods like raw vegetable and fruits. Most such food has a higher mass than the previous mentioned ones. The average volume is 358 cm^3 and the mean mass is 50 g. A big advantage of this type of food is the great reduction of needed recycling efficiency of the WRM and therefore better flexibility and ability to deal with interruptions, failures, and losses. [9, p. 500, 9, p. 502, 110, p. 2]

Beverages are a separate category. Examples are coffee, tea, or lemonade. To safe mass, they only have to be powdered form and must be rehydrated with hot or cold water. The mean volume is 260 cm^3 and the corresponding mass is 26 g. [9, p. 500, 110, p. 2, 111, p. 180]

All types of food needed for a variable, tasteful meal, especially fresh food like fruits are important for psychological and health points. The nominal mass breakdown for an ISS comparable food system can be found in Table 9-4 below. Note that the mentioned food container in Table 9-4 is not considered for the further analysis, because an ISS “pantry-style” storage is considered as sufficient.

Table 9-4: International Space Station Food Systems [10, p. 106]

Parameter	Value	Unit
Food mass w/o packaging	1.25	[kg $CM \cdot d^{-1}$]
Packaged food volume	0.00472	[m^3 $CM \cdot d^{-1}$]
Individual meal package	0.25	[kg $CM \cdot d^{-1}$]
Food container[25]	1.00	[kg]
	0.02	[m^3]
ISS “pantry-style” storage	0.35	[kg $CM \cdot d^{-1}$]

There are ongoing developments by NASA to reduce the mass of food for space missions. For example, a 10 % mass reduction is achieved by a four-meal replacement bar with the goal to decrease the overall food mass by 25 % [109]. Because it is unclear how much mass reduction could potentially be saved for the different kinds of food and to stay conservative, no such mass saving is considered in the further analysis.

Additional to the consumables mass of the foods, the equipment weight has to be considered. Depending on the selected types of food, different assemblies are needed, like microwaves, refrigerators, or simple shelfs. Fresh food for example needs refrigeration for longer missions to prevent spoiling [110, p. 2], while a freezer can expand the shelf-life of food. Space-Dishwashers were avoided in the past by using single-service, disposable food containers [110, p. 3]. A breakdown of the different equipment considered can be found in Table 9-5 and Table 9-6 below.

[25] Food container mass without food [112, p. 79]

The nominal meal preparation time is under 5 minutes. When reconstituting and heating is needed, additional 20 to 30 minutes are needed. For cleaning of food trays and utensils, a moist sanitizing towel was used in past and current space ships. These pre- and post-preparation times for meals are included in the schedules in chapter 3.2.3. [110, p. 3]

Table 9-5: Best-case food system for 88 days and 12 people

Parameter	Value	Unit
Food with individual packaging	1,538.48	[kg]
	3.74	[m³]
Food packaging waste	253.85	[kg]
ISS "pantry-style" storage	369.60	[kg]
Refrigerator / Freezer (2.03 ISS equivalents[26])	651.45	[kg]
	2.35	[m³]
	416	[W]power
	463	[W]thermal
2x space shuttle rehydration apparatus and conduction oven[27]	72.60	[kg]
	0.19	[m³]
	420	[W]power
	420	[W]thermal
Total mass	**2,632.13**	**[kg]**
Total volume	**6.28**	**[m³]**
Total power	**836**	**[W]**
Total cooling	**883**	**[W]**

[26] Based on ISS refrigerator / freezer with internal volume of 0.614 m³ [10, p. 107], where it is assumed that ¼ of all needed food is stored in the refrigerator. Therefore, the needed volume is 1.245 m³ for the best-case scenario and 24.90 m³ for the worst-case.

[27] [10, pp. 106-107] Rehydration apparatus excluded for power and thermal load (see 6.4.1)

Table 9-6: Worst-case food system for 211 days and 100 people

Parameter	value	unit
Food with individual packaging	30,740.44	[kg]
	74.90	[m³]
Food packaging waste	5,072.17	[kg]
ISS "pantry-style" storage	7,385.00	[kg]
Refrigerator / Freezer (40,55 ISS equivalents[26])	13,016.71	[kg]
	47.04	[m³]
	8,313	[W]power
	9,246	[W]thermal
4x space shuttle rehydration apparatus and conduction oven[27]	145.20	[kg]
	0.38	[m³]
	1,680	[W]power
	1,680	[W]thermal
Total mass	**51,287.35**	**[kg]**
Total volume	**122.11**	**[m³]**
Total power	**9,993**	**[W]**
Total cooling	**10,926**	**[W]**

9.4.2 Clothing

Clothes are analyzed in this thesis because their mass influences the outcome of the feasibility of the SpaceHab.

Things to consider for the analysis of the clothing system are, that clothes are used exclusive by every crewmember, they have to be comfortable and easy to change. Further the materials and fabrics play an important role, together with the size and the corresponding stowage. Normally, 1 pair of pants or shorts and one non-workout t-shirt per week are used. Underwear is changed daily and workout clothing, like socks, shorts, and t-shirt, are changed every two days. [9, pp. 540-541]

When considering the statements above, the mass and volume needed for the clothes can be estimated. One simple formula for the mass that could be used is Eq. (9-4) [10, p. 99].

$$m_{clothes} = (A + B\, t_{mission})\, y \qquad \textbf{Eq. (9-4)}$$

$$V_{clothes} = C\ t_{mission}\ n_{CM} \qquad \textbf{Eq. (9-5)}$$

with:

- $m_{clothes}$ [kg] - total mass for clothes
- $V_{clothes}$ [m³] - total volume for clothes
- A [kg CM-d^{-1}] - constant clothing mass (4.99)

- B [kg CM-d^{-1}] - variable clothing mass (0.3323)
- C [m³ CM-d^{-1}] - variable clothing volume (0.0013)
- $t_{mission}$ [days] - mission duration
- n_{CM} [-] - number of crew members

The clothes needed by one passenger over one year would be 126.28 kg. By using wool instead of polyester shirts for workout, and replacing cotton shirts with modacrylic ones for routine wear, the mass saving per year would be 15 kg [90]. Accounting for this, parameter B in Eq. (9-4) would get to 0.2912 kg CM^{-1}. The total required mass and volume for the different trade cases can be seen in Table 9-7.

Table 9-7: Mass and volume for disposal clothes

Parameter	Unit	Case1	Case2	Case3	Case4
Mass	[kg]	367.39	1,224.62	2,657.33	6,643.32
Volume	[m³]	1.37	4.58	10.97	27.43

Using a washer/dryer for clothes has the potential to reduce the needed mass and volume of clothes when included in a water recycling system. On past and current manned spacecraft's, only disposal clothes where used, since a washer and dryer had no benefit for the crew sizes and mission durations in the past. Because the considered passengers in this thesis are much more than past crew sizes, a tradeoff is appropriate. Besides the mass and volume for a washer/dryer, the power and thermal requirements must also be considered. The following advanced washer/dryer [10, p. 101] is used for the trade analysis. [13, pp. 578-589]

Table 9-8: Properties of an advanced washer/dryer [10, p. 101]

Parameter	Value	Unit
Mass	80.00	[kg]
Volume	0.18	[m³]
Capacity	4.50	[kg load^{-1}]
Water usage	51.30	[kg load^{-1}]
Detergents	0.01	[kg load^{-1}]
Crew time	0.42	[CM-h load^{-1}]
Power for washing	300	[W]
Washing time	0.67	[h]
Power for drying	750	[W]
Drying time	1.00	[h]

For the trade analysis between disposal clothes and a washer/dryer system, the ESM metric is used. This analysis in the Life Support Trade Off Tool revealed, that washer/dryer has a much larger mass than disposal clothes. This is caused by the large water usage of the machine and the assumed specific ESM of the VCD in 10.4 (1.34 kg $kg_{processed\ water}^{-1}$). Only when the specific VCD ESM could be massively reduced to under 0.07, a washer/dryer would be economical. Only when considering the proposed 12 travel uses of the SpaceHab with a maximum travel time of 211 days and assuming no spares for the washer/dryer, it would be economical.

Besides that, the TRL of a washer/dryer is currently below the required TRL of 5 and therefore not further considered. But it should be noted that such an approach has the potential to greatly reduce the needed mass over several launches.

9.5 Reliability

The reliability of a system or component can be calculated by the mean time between failure (MTBF). Most components have a MTBF of only a few years. The likelihood that they fail during a mission of the considered time is relatively high. While it is not likely to assume that the reliability of such components can be greatly enhanced, redundancy or sparing is necessary. Redundancy is very mass and volume intensive, whereas spares for critical or unreliable components can save much mass and volume. [43]

The reliability of a component with considered spares can be calculated with the help of the Poisson distribution which is given in Eq. (9-6). [41]

$$R_{component}(t) = e^{-\lambda t} \sum_{i=0}^{n_{spares}} \frac{(\lambda t)^i}{i!} \qquad \textbf{Eq. (9-6)}$$

with:

- $R_{component}$ [-] - reliability of the component for a given time t
- λ [h^{-1}] - failure rate of the component (inverse of MTBF)
- t [h] - mission duration
- n_{spares} [-] - number of spares considered for the component

While the reliability of the different subsystem is enhanced in the following, it must be aware, that such an approach presumes that the failure of one component can be identified and located in time, and that the component can be easily replaced with the spare. But such an estimate does not guarantee success. Further it can be assumed, that while the used MTBF values in this thesis are mostly based on state of the art ISS technologies, the reliability of some components will be enhanced before a mission like the analyzed one is started. [53, 113, p. 220]

9.5.1 Atmosphere Control and Supply

The required reliability of the ACS subsystem is considered to be the same as for the other subsystems, which is 0.9984

Most components of the ACS subsystem have a low reliability. For example, the pressure control assembly (PCA), the nitrogen interface assembly (NIA), as well as the tank equipment have an assumed MTBF of 100,000 hours, since pressure sensors, reducers etc. have such low values [73, p. 355]. The PCAs are installed in every deck, they are considered as parallel, since the decks are linked together a failure of one unit can be compensated by another. This is why they need no spares. The NIA, MPEV, and tank equipment are assumed to be in series and therefore need some spares.

The high-pressure tanks have a given MTBF of $2.7{*}e^7$ hours [73, p. 355]. For such a high reliability, no spares are needed.

All components and the corresponding spares are listed in Table 9-9.

Table 9-9: Components and spares for the atmosphere control and supply subsystem

Component		Mass [kg]	Vol [m³]	MTBF [h]	N_S	R_{88days}	$R_{211days}$
PCA		31.32	0.05	100,000	0	1.000000	1.000000
NIA		75.00	0.29	100,000	1;2	0.999780	0.999979
MPEV		1.08	0.01	167,000	0;1	0.999842	1.000000
Tank equipment		80.00	0.32	100,000	1;2	0.999780	0.999979
O2 Tank		156.12	1.31	24,000,000	0	0.999912	0.999789
N2 Tank		605.65	5.32	24,000,000	0	0.999912	0.999789
Total	**Case1**	**1,142.14**	**5.10**			**0.9986**	
	Case2	**1,157.14**	**5.13**			**0.9986**	
	Case3	**1,705.76**	**7.77**				**0.9985**
	Case4	**1,773.26**	**7.88**				**0.9985**

9.5.2 Temperature and Humidity Control

As stated in requirement 4.1.m, the THC subsystem requires a reliability of at least 0.9984. The calculated reliability of the THC system without redundancy and spares is 0.8833 for 88 days and 0.7426 for 211 days. Both are below the required reliability. Therefore, several spares are needed, as listed in Table 9-10. The first 10 entries in the table below are components of the CCAA, while the IMV ones belong the ventilation system between the different decks. The tubes are for both systems.

Table 9-10: Components and spares for the temperature and humidity control subsystem

Component		Mass [kg]	Vol [m³]	MTBF [h]	N_S	R_{88days}	$R_{211days}$
CHX		49.71	0.39	832,600	1	0.999997	0.999982
EIB		4.04	0.02	2,350,600	1	1.000000	0.999998
LS		0.64	0.00	1,136,300	1;2	0.999998	1.000000
Inlet ORU		25.31	0.13	332,900	1;2	0.999980	0.999999
TCCV		7.45	0.01	32,880	2	0.999958	0.999457
TS		0.26	0.00	37,594,000	0;1	0.999944	1.000000
WS		11.93	0.06	130,800	1;2	0.999871	0.999991
IMV fan assembly		4.17	0.01	332,900	1;2	0.999980	0.999999
IMV valve assembly		5.10	0.01	167,000	1;2	0.999921	0.999995
tubes		1,742.00	20.52	5,000,000	0	0.999578	0.998988
CADDA		2,72	0.01	167,000	2	1.000000	0.999995
Total	**Case1**	**2,058.04**	**17.41**			**0.9992**	
	Case2	**2,404.82**	**19.71**			**0.9992**	
	Case3	**3,516.27**	**29.99**				**0.9984**
	Case4	**4,616.67**	**36.95**				**0.9984**

9.5.3 Atmosphere Revitalization

There was no data available about reliability for the Sabatier and no detailed data for SAWD. To stay conservative, it is assumed that two spares for every component for a mission time of 88 days, and three spare for 211 days is sufficient. This means, the systems are double, respectively tripled in mass and volume. For the SFWE, or CCA, the MTBF of 17,000 hours for a similar system is used, as described in 6.3.16.2. Thus, 2 spare systems are needed for 88 days and 3 for 211 days. The needed components and spares for the MCA and TCCS assemblies are outlined in Table 9-11 and Table 9-12 respectively.

Table 9-11: Components and spares for the MCA

Component	Mass [kg]	Vol [m³]	MTBF [h]	N_S	R_{88days}	$R_{211days}$
D&C assembly	8.02	0.01	43,500	1	0.999997	0.999927
MS assembly	13.30	0.02	8,180	2;3	0.999976	0.999887
Power assembly	5.67	0.01	199,000	0;1	0.999889	1.000000
Sample pump A.	3.13	0.00	11,900	1;2	0.999647	0.999683
Sample distr. A.	2.11	0.00	70,900	1	1.000000	0.999989
EMI filter A.	1.45	0.00	1,160,000		0.999997	0.999981
Verif. gas A.	5.76	0.01	52,100	1	0.999999	0.999963
Total **Case1**	**139.82**	**0.59**			**0.9995**	
Case2	**139.82**	**0.59**			**0.9995**	
Case3	**161.92**	**0.62**				**0.9994**
Case4	**161.92**	**0.62**				**0.9994**

Table 9-12: Components and spare for the TCCS

Component	Mass [kg]	Vol [m³]	MTBF [h]	N_S	R_{88days}	$R_{211days}$
CBA	36.65	0.08	215,000	1	0.999952	0.999727
Blower	2.94	0.01	121,500	1;2	0.999851	0.999988
COA	11.04	0.02	89,500	1;2	0.999726	0.999971
EIA	3.42	0.00	483,000	1	0.999990	0.999945
Flowmeter	1.09	0.00	936,000	1	0.999997	0.999985
SBA	4.10	0.01	241,000	1;2	0.999962	0.999998
Total **Case1**	**139.08**	**0.39**			**0.9995**	
Case2	**139.08**	**0.39**			**0.9995**	
Case3	**157.17**	**0.43**				**0.9996**
Case4	**157.17**	**0.43**				**0.9996**

The total needed mass and volume including spares for the different cases are outlined in Table 9-13.

Table 9-13: Mass and volume of the atmosphere revitalization system with spares

Parameter	Case1	Case2	Case3	Case4
Mass [kg]	1,084.93	2,965.65	3,901.43	9,132.04
Volume [m³]	2.10	4.72	6.04	13.53

9.5.4 Water Recovery and Management

The MTBF for a potable bladder tank is $1e^8$ hours, as stated in [73, pp. 355-358]. With such a high reliability, no redundant or spare tanks are needed. For the analyzed 88 day missions, no additional spares are needed. Only for 211 days, one valve spare is required to get to a reliability of 0.9999. The mass and volume for the storage system including spares are listed in Table 9-14 for the 4 trade cases.

Table 9-14: Mass and volume of the water storage system with spares

Parameter	Case1	Case2	Case3	Case4
Mass [kg]	5,253.98	17,481.25	41,691.03	104,185.52
Volume [m^3]	10.24	34.13	83.79	206.53

The calculated reliability of the water recovery and management system without redundancy and spares is 0.5612 for 88 days and 0.2503 for 211 days. Both are far below the required reliability of 0.9984 for the WRM (see 4.1.m). Therefore, spares for several components are necessary.

The considered component spares are outlined in Table 9-15 below. The parameters mass, volume, and MTBF are measured for one unit. The number of spares for every component are stated in column N_S, where the first number is for an 88-day mission and the second number represents the spare quantity for 211 days. As can be seen, the number of needed spares is at least one for every component of the WRM system, with the exception of the water tanks. Figure 9-5 shows, that the mass of the spares is slightly more than the installed system mass, but still less than assuming complete redundant systems, where at least ten redundant systems would be needed to get to the same reliability.

Table 9-15: Components with spares for the water recovery and management system

Component		Mass [kg]	Vol [m³]	MTBF [h]	N_S	R_{88days}	$R_{211days}$
Catalytic Reactor		67.04	0.01	25,579	2;3	0.999912	0,999945
Gas Separator		39.15	0.07	84,008	2	0.999997	0.999965
Ion Exchange Bed		13.02	0.02	296,701	1;2	0.999975	0.999999
MCV		5.76	0.01	143,489	2	0.999999	0.999993
pH Adjuster		2.54	0.01	137,182	1;2	0,999883	0.999992
Pump Separator		31.34	0.09	42,398	2;3	0.999980	0.999992
RHS		16.83	0.04	56,677	2;3	0.999992	0.999998
Sensor		4.81	0.01	143,664	2	0.999999	0.999993
Separator Filter		7.67	0.01	359,072	1;2	0.999983	1.000000
Start-up Filter		9.44	0.02	226,884	1;2	0.999957	0.999998
Water Delivery		47.54	0.10	64,561	2	0.999994	0.999924
DA		92.76	0.14	142,525	1;2	0.999891	0.999993
FCA		23.09	0.03	27,331	2;3	0.999927	0.999958
FCPA		47.58	0.07	90,140	1;2	0.999730	0.999972
PCP		49.08	0.12	181,507	1;2	0.999933	0.999996
SPA		16.78	0.02	384,652	1	0.999985	0.999914
WSTA		45.95	0.04	184,223	1;2	0.999935	0.999997
ARFTA		70.08	0.10	199,640	1;2	0.999944	0.999997
Potable water tank		54.16	0.42	64,561	0	0.999979	0.999924
Waste water tank		33.57	0.35	53,611	0	0.999979	0.999997
PCWQM		38.00	0.05	75,600	1	1.000000	0.998988
Total	**Case1**	**7,965.77**	**14.02**			**0.9986**	
	Case2	**26,191.63**	**46.34**			**0.9986**	
	Case3	**35,274.11**	**59.59**				**0.9985**
	Case4	**87,898.66**	**148.73**				**0.9985**

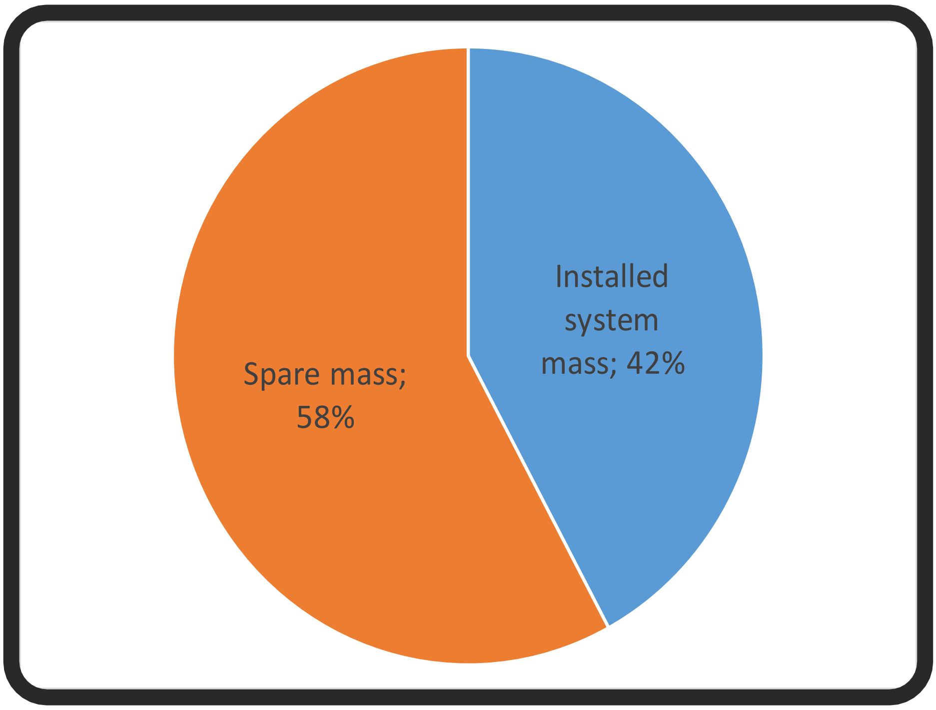

Figure 9-5: Contingent of spare mass for the water recovery system

10 Final Design of the ECLSS subsystems

10.1 Final Design of Atmosphere Control and Supply

The general layout of the atmosphere control and supply (ACS) system is derived from the ISS architecture. The tanks for oxygen and nitrogen repressurisation and leakage are outside the pressurized compartment for safety reasons. The benefit is, they do not occupy any volume. Only the equipment, like valves, regulators etc. are inside the habitat for control and maintenance. For pressure control, aluminum tubes with 42.42 mm inner diameter are used and arranged separately for O_2 and N_2 into every deck.

Besides the tanks, Pressure Control Assemblies (PCA) are installed in every deck. This units monitor and control total pressure by controlling O_2 and N_2 partial pressures. They provide a controlled venting to space and provide controlled repressurization capability. [38]

Further several Nitrogen Interface Assembly (NIA) are assumed. The purpose of these elements is the supply of nitrogen. On ISS, they are used to pressurize the accumulator in the Internal Thermal Control System (ITCS) pump package assembly in the Low- and Moderate-Temperature Loop (LTL, MTL) and purge the lines of the OGA after shutdown [38]. It is assumed that such units are used for numerous ECLSS equipment on deck 4.

Since it is assumed that the crew quarter decks 7 and 8 for the Evolved-SpaceHab or deck 6 for the SpaceHab respectively are used as safe haven in the event of depressurization or contaminated air, Manual Pressurization Equalization Valves (MPEV) are required. Such units are used to equalize pressure in two adjacent pressurized modules prior to opening a hatch between them [38]. For a hazard analysis see 10.6.1.

A schematic of the ACS system can be found in Figure 10-1. Please note, that not all components of the subsystem are included for a better overview.

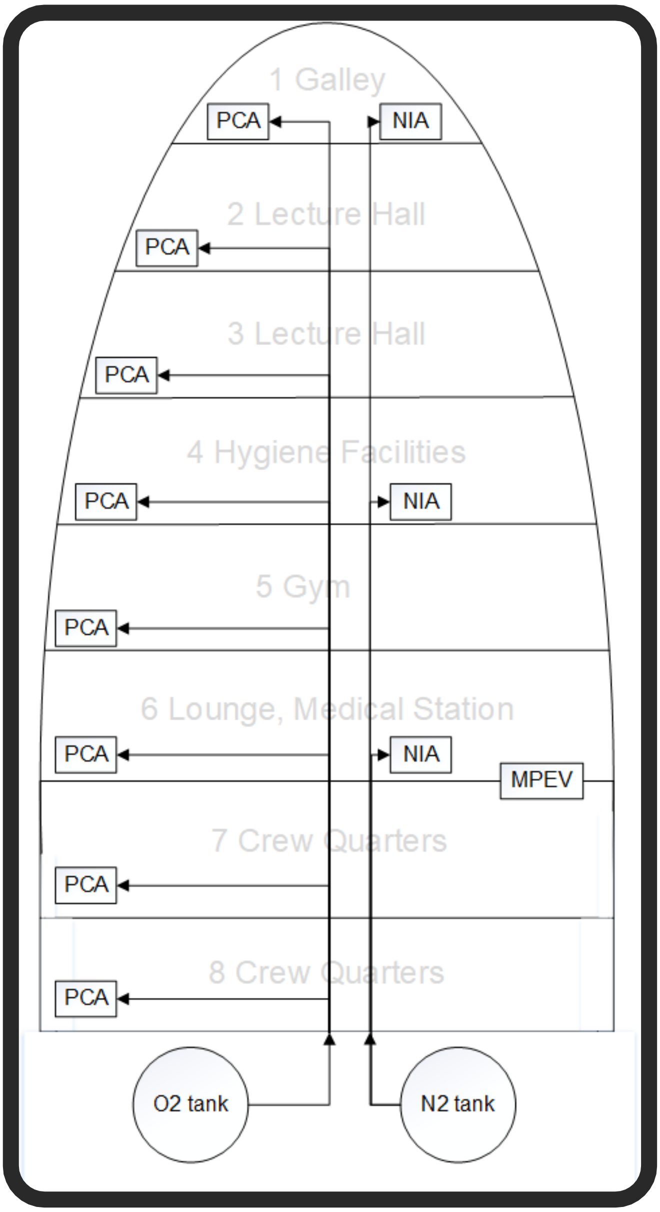

Figure 10-1: Schematic of the ACS system

The breakdown of the components for the ACS system for the trade Case1 can be found in Table 10-1, while case4 is given in Table 10-2. The calculated spares from Table 9-9 in chapter 9.5.1 are included. For the tubes, it is required that the pressurized volume, excluding the crew quarters as safe heaven, needs to be repressurized within 24 hours. Therefore, the needed performance is 45.43 $m^3 h^{-1}$. To calculate the needed diameter, Eq. (10-1) can be used. For the flow velocity, 5 $m s^{-1}$ are assumed to prevent turbulent flow in the tube. With this, the diameter of the pipe is calculated to 23.14 mm. For comparison, the ACS tubes on ISS are 9.5 mm, but are designed to repressurize one module at a time. The meter weight of the tube is 0.1 $kg m^{-1}$, when assuming the material is aluminum with a density of $2.71 \cdot 10^3$ $kg m^{-3}$ and a wall thickness of 0.5 mm. Additional the pressure loss can be determined with Eq. (10-2), to test if the assumed diameter at the given volume flow is feasible. This equation is the transformed Hagen-Poiseuille formula. The dynamic viscosity of dry air at 20 °C is $18.232 \cdot 10^{-6}$ Pa s. For the maximum assumed distance between deck 1 and 8, the pressure loss would be then 707.21 Pa. For O_2 and N_2, separated tubes are assumed. Such a pressure loss is at the upper end of a feasible passive system, especially since no duct branches or curves are considered which would raise the pressure loss through the ducts.

$$d_{ACS,tube} = \sqrt{\frac{4\,\dot{V}}{\pi\,v}} \qquad \textbf{Eq. (10-1)}$$

$$\Delta p = \frac{\dot{V}\,l\,128\,\mu}{\pi\,{d_{ACS,tube}}^4} \qquad \textbf{Eq. (10-2)}$$

with:

- $d_{ACS,tube}$ [m] - required diameter of tube
- $\dot{V}$ [$m^3\,h^{-1}$] - volume flow through pipe
- v [$m\,s^{-1}$] - flow velocity
- Δp [Pa] - pressure difference or pressure loss
- l [m] - tube length
- μ [Pa s] - dynamic viscosity of fluid

Table 10-1: Properties of the atmosphere control and supply system for 12 passengers and 88 days (Case1)

Component	**Dry mass [kg]**	**Total mass [kg]**	**Volume outside [28] [m³]**	**Volume inside [m³]**	**Power [W]**	**Cooling [W]**	**ESM [kg]**
PCA	187.92	187.92	0.00	0.31	678	0	26,551
NIA	75.00	82.50	0.00	0.13	55	0	2,236
MPEV	2.16	2.16	0.00	0.00	0	0	3
Tubes	4.36	4.36	0.00	0.02	0	0	6
O2 + Tank	156.12	462.63	0.88	0.13	0	0	602
N2 + Tank	605.65	1,612.23	3.39	0.13	9	0	2,445
Total	**1,031.21**	**2,351.80**	**4.27**	**0.73**	**742**	**0**	**31,846**

[28] The considered volume is divided into component inside and outside for the pressurized compartment.

Table 10-2: Properties of the atmosphere control and supply system for 100 passengers and 211 days (Case4)

Component	Dry mass [kg]	Total mass [kg]	Volume outside [28] [m³]	Volume inside [m³]	Power [W]	Cooling [W]	ESM [kg]
PCA	250.56	250.56	0.00	0.42	904	0	35,381
NIA	180.00	195.00	0.00	0.32	132	0	5,347
MPEV	2.16	3.24	0.00	0.01	0	0	4
Tubes	4.36	4.36	0.00	0.02	0	0	6
O2 + Tank	222.66	706.67	1.31	0.13	0	0	833
N2 + Tank	954.01	2,544.95	5.32	0.13	9	0	3,372
Total	**1,613.75**	**3,704.78**	**6.63**	**1.02**	**1,045**	**0**	**44,942**

10.2 Final Design of Temperature and Humidity Control

The final design of the temperature and humidity control (THC) subsystem consists of the intramodule atmosphere circulation and intermodule ventilation (IMV) systems. The system described below employs built-in redundancy and a worst-case approach to ensure a reliable operation [96].

The intramodule ventilation uses common cabin air assemblies (CCAA) to remove heat and humidity and has interfaces to the other subsystems (ACS, AR, and WRM). See section 6.2.2.1 for a detailed description of the CCAA. The used diameter of the pipe system is 193 mm, which is the same as on ISS [38, p. 202]. Besides the CCAA, temperature and liquid sensors are installed in the return and supply duct respectively. The conditioned air is supplied to the cabin by diffusors. The intramodule atmosphere circulation system for every deck is described in detail in the following subchapters.

The intermodule ventilation is used to circulate air between the different decks. One fan and duct are used per direction and deck interface. The diameter of the pipe is at least the same as on ISS with 119 mm [38, p. 202], depending on the assumed IMV loop. The first operation mode is the deck-mode, in which enough THC equipment, mainly depending on the CHX, is used to remove the heat and humidity produced in the corresponding deck. This operation modus is comparable to the one on the ISS, where the IMV network is used to transport air between the different modules and revitalize the CO_2 laden air with fresh one. For CO_2 considerations, even another additional mode is considered, which is described in 11.1.1.2. However, this has only minor impacts on the THC system and is therefore not further considered here. The other mode is the racetrack loop, where air is blown from the upper most deck through every deck and then from the lowest one back to the highest one [114]. A trade-off has shown that the other direction, down to up, needs more CHX and is more unbalanced. The big advantage of such an approach is, that the heat, humidity and trace gases could be removed by the equipment of the whole vehicle and therefore much less equipment is necessary. For example, for 100 passengers and the One Hour Shift Schedule, 11 CCAA instead of 21 for the deck-modus would be needed. As can be shown in 11.1.2, the handling and stability of such a system is very difficult. Because of this, and to stay more conservative the main focus for the following chapters is on a deck-mode for the IMV.

Below are the master table with all used components of the THC subsystem for Case4. This case is the basis for the following subchapters to maintain a clear overview.

Table 10-3: Installed components for the temperature and humidity control subsystem for Case4

Component	Mass [kg]	Volume [m³]	Units	Total component mass [kg]	Total component Volume [m³]
CHX	49.71	0.39	26	1,292.46	10.23
EIB	4.04	0.02	8	32.30	0.14
LS	0.64	0.00	33	20.96	0.02
Inlet Fan	25.31	0.13	21	531.51	2.73
TCCV	7.45	0.01	26	193.77	0.18
TS	0.26	0.00	59	15.52	0.08
WS	11.93	0.06	26	310.18	1.52
Intermodule fan	4.17	0.01	14	58.32	0.13
Intermodule valve	5.10	0.01	14	71.40	0.14
Tubes	1,742.00	20.52	1	1,742.00	20.52
CADDA	2.72	0.01	66	179.62	0.40
Diffusor	0.82	0.00	80	65.60	0.27
Total				**4,513.63**	**36.36**

The transient power demand of the THC subsystem for Case4 is given in Figure 10-2.

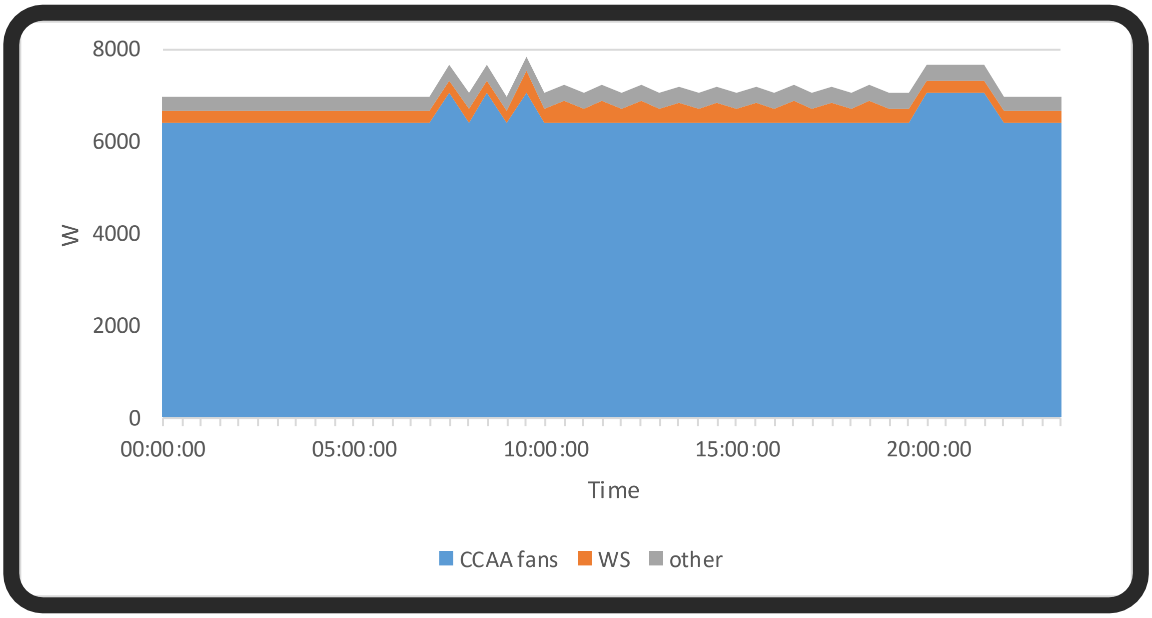

Figure 10-2: Total power demand of THC subsystem

10.2.1 Crew Quarters

Several different designs for the crew quarters (CQ) are considered and compared to each other. The design with the best trade-off between volume usability, ECLSS integration, and applicability are described below.

The general design of each crew quarter is similar to the common capsule hotels. This design has the advantage that it can also be used in partial gravity. General considerations for the design are:

- The vestibule shall have a width of at least 1 m and a height of at least 2 m, so they can be used in 0-g as well as in partial gravity
- Each CQ shall have at least the volume of the ISS CQ of 2.1 m^3 [115]

The layout of the crew quarter deck, shown in Figure 10-3, are divided into two rings with double rooms and a storage area in the middle and small personal bays on the outer circle. Because the Evolved-SpaceHab is considered to be a colonization ship, it is very likely that a part of the passengers consists of couples and therefore double rooms are preferable. Please note that the CQ on the left half of the shown deck in Figure 10-3 are hidden to better show the THC components.

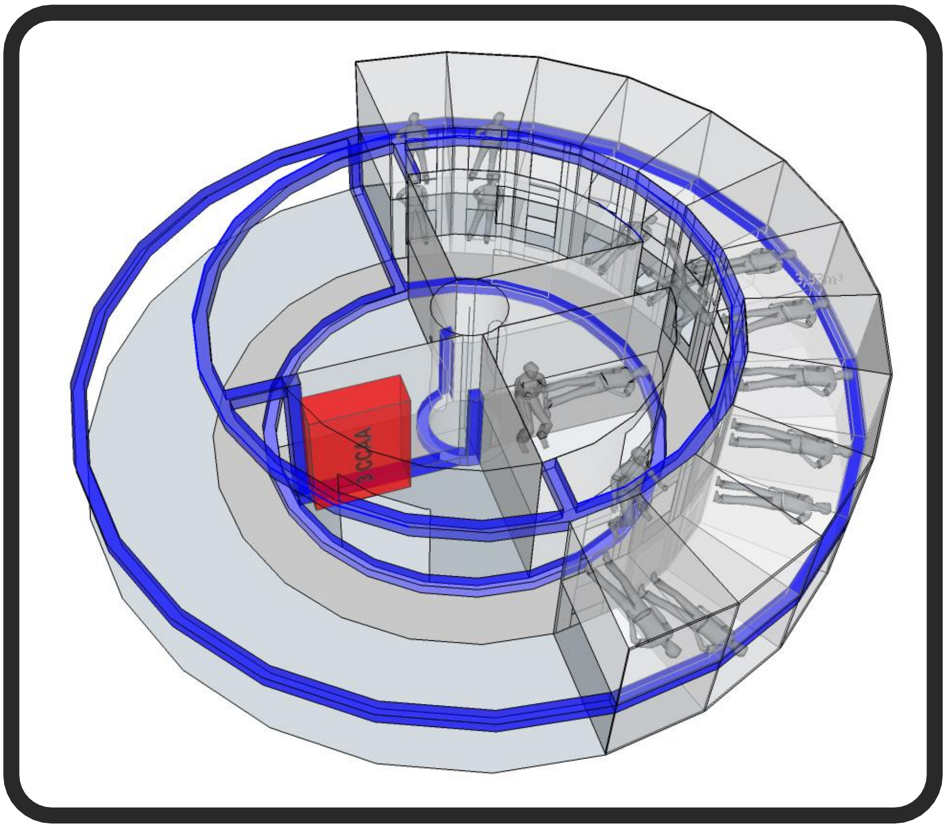

Figure 10-3: Temperature and humidity control on deck 8 and 7

The needed THC equipment for the passageways consists of bacteria filter elements (BFE) and diffusors incorporated into the ducts, marked blue in Figure 10-3. Overall 18 Diffusors (and corresponding BFE) are needed for an atmosphere exchange rate comparable to that on the ISS for both decks. Eq. (10-3) is used to determine the necessary number of diffusors.

$$n_{BFE} = \frac{V_{w/o,CQ}}{V_{LAB}} n_{BFE,LAB} \qquad \textbf{Eq. (10-3)}$$

with:

- n_{BFE} [-] - number of required BFE and Diffusor
- $V_{w/o,CQ}$ [m³] - pressurized volume of deck without CQ
- V_{LAB} [m³] - pressurized volume of ISS laboratory (106 m³ [38])
- $n_{BFE,LAB}$ [-] - number of BFE´s in ISS laboratory

Further, 3 CHX with the size and performance of the ones installed in the CCAA on ISS are needed for 100 passengers and the One Hour Shift Schedule, as seen in the red box in Figure 10-3. It is assumed that the same number of WS and TCCV are needed as CHX and only one electronic interface box (EIB) per deck. For more details about what differences the schedules have on the THC system, see also chapters 11.1.2 and 11.2.2. Besides metabolic heat and humidity, air borne heat load from equipment as well as humidity from the AR subsystem (10.3) has to be removed by the CHX. On ISS, the waste heat from electronics is 153 W per CQ [115]. If this value would be linear used, 15,300 W of additional heat, besides the metabolic heat of around 120 W CM^{-1} must be removed, which seems improbable. Instead, it is assumed that the waste heat from equipment is 30 W per CQ, consisting of the heat from the

THC system with overall 1,000 W (see Table 10-4) divided through the 100 CM, and additional 20 W per CM for personal equipment, like a tablet. Another factor that influences the required number of CHX is the additional humidity from the AR subsystem, since the selected solid amine water desorption process (see 10.3) produces a lot of humidity which is transported with the revitalized air. The mean assumed value for this is 0.7 kg h^{-1} (16.77 kg d^{-1})[29] for every deck of the Evolved-SpaceHab. The total transient heat and humidity load from equipment and human metabolism for the two decks can be seen in Figure 10-4.

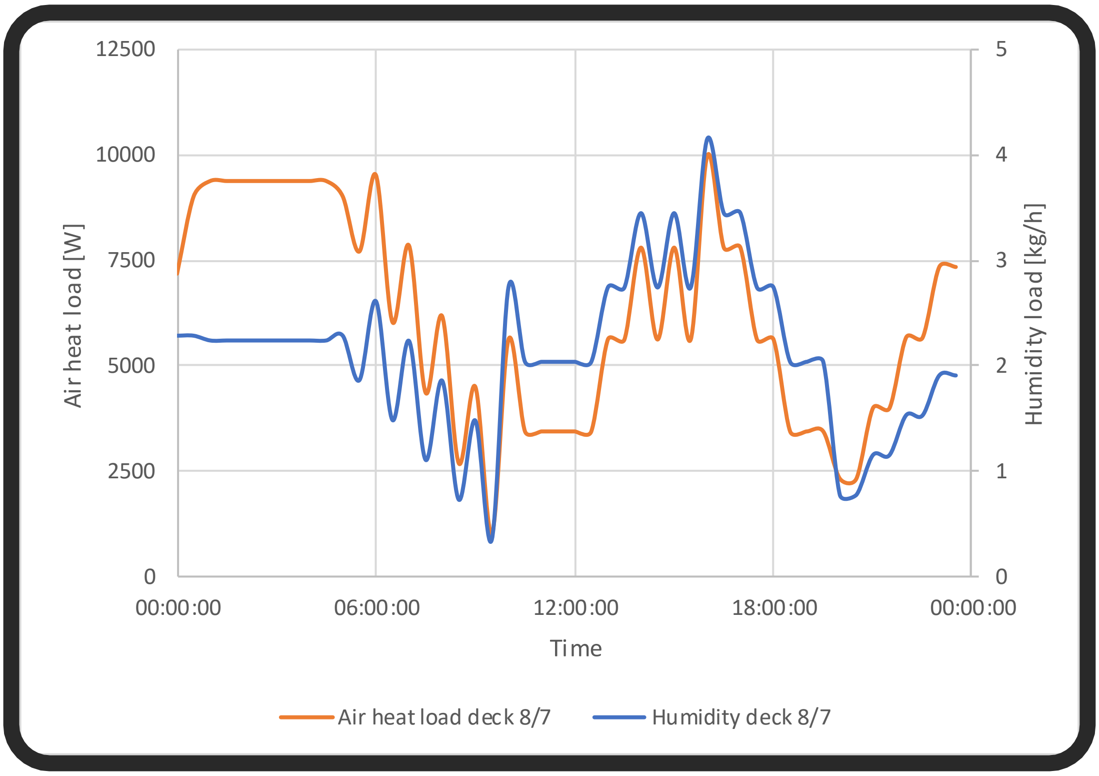

Figure 10-4: Air heat and humidity loads over 24 hours in decks 7 and 8 with 100 passengers and the one hour schedule

Not shown in Figure 10-3 are intermodular ventilation equipment and ducts. The size of the ducts depends on the assumed IMV loop. For a racetrack loop, the diameter of the ducts would be 313 mm, otherwise 119 mm. Besides the ducts are overall 4 IMV fan and valves.

The presented design has 48 small crew quarters per deck with a habitable volume of 3.04 m^3 each. This includes volume for sleep, recreation etc. and little stowage space. For comparison, the CQ on ISS have a stowage space of approximately 0.1 m^3 for personal items. The small CQ are shown in Figure 10-5, where the red box symbolizes the Bacteria Filter Assembly (BFE) and the Diffusor with the corresponding tubes in green and blue respectively. The needed volumes are 0.02 m^3 for the BFE and diffusor and an additional of 0.01 m^3 for the tubes. The BFE´s on ISS have normally a volume of 0.12 m^3 [38], but space in the CQ are much smaller and therefore it is assumed, that

[29] The difference between humidity in- and outflow of the ACLS is 2.5 kg d^{-1} [81]. Since the ACLS is sized for a crew of 3 [82], this value has to divided through 3. Furthermore, the assumed number of ACLS equivalent systems (101) has to be multiplied and this calculated humidity output has divided between 5 decks (LiSTOT does not separate between decks 7/8 and decks 1 to 3).

a downsized BFE with only 17 % of the volume and mass is needed in every CQ. This value is calculated by the average flow needed (see Eq. (10-3)). Volume for noise reduction is assumed to be 13% of the total volume [115], which would be a 7 cm thick acoustic blanket with a volume of 0.46 m^3. Combining two of this CQ to one double room, the resulting CQ would safe 0.17 m^3 for one acoustic blanket wall and would have a habitable volume of 6.25 m^3. The double quarters in the middle have a habitable volume of 6.52 m^3 each, excluding the volume of 0.06 m^3 for the ECLSS equipment and 0.98 m^3 for acoustic blankets. Therefore, for a maximum supposed crew of 100 people, 2 double rooms used by 4 people are considered. This leaves room for 106.45 m^3 of stowage, when assuming that two decks are used for the crew quarters and on both decks the outer circle is fully used for the small crew quarters. Alternatively, when considering radiation issues, this space in the middle can be converted to crew quarters and 28 small quarters are used for stowage, but then only 98.84 m^3 are available for stowage. If only considering available volume, crew quarters for up to 128 persons on two decks can be realized with this design. Nevertheless, the worst-case scenario of 100 people for the Evolved-SpaceHab is considered for the design of the ECLSS. The CQ-design with 40 people needs 36 small CQ and 2 double rooms, or 16 double rooms and 8 small CQ. For both design alternatives, stowage space of at least 310.64 m^3 would be available for the Evolved-SpaceHab. For the SpaceHab design, no additional stowage volume would be available, since deck 6 is 97.02 m^3 smaller than deck 7 or 8. The corresponding stowage space for 12 CM, assuming a personal CQ for every person, is 90.89 m^3 for the SpaceHab.

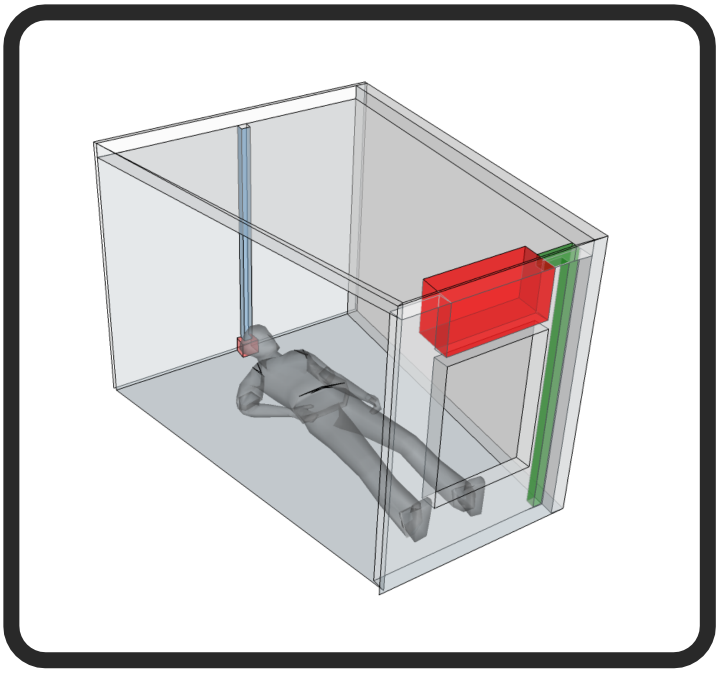

Figure 10-5: Temperature and humidity control in CQ

A breakdown of the required parameters for the THC equipment in the crew quarter decks 7 and 8 are given in Table 10-4 below.

Table 10-4: Properties of the temperature and humidity control subsystem with 100 passenger and 211 days (Case4) on decks 7 and 8 (crew quarters)

Component	Mass [kg]	Volume [m³]	Power [W]	Cooling[30] [W]	ESM [kg]
CCAA	250.56	3.57	1,230	282	939
Tubes[31]	678.53	8.46	0	0	1,420
IMV	121.07	0.27	3,128	718	276
Total	**1,374.09**	**12.29**	**4,358**	**1,000**	**2,634**

10.2.2 Medical Station and Lounge

The THC system for the medical station and the lounge consist of two duct rings, each one for return und supply of air to the incorporated CCAA´s. The considered layout is shown in Figure 10-6, where the rear section is the lounge with nearly 110 m³ of habitable volume, the front left room is assumed to be the medical station with around 50 m³ and the right section with the two required CCAA´s is a storage area with around 45 m³ pressurized volume.

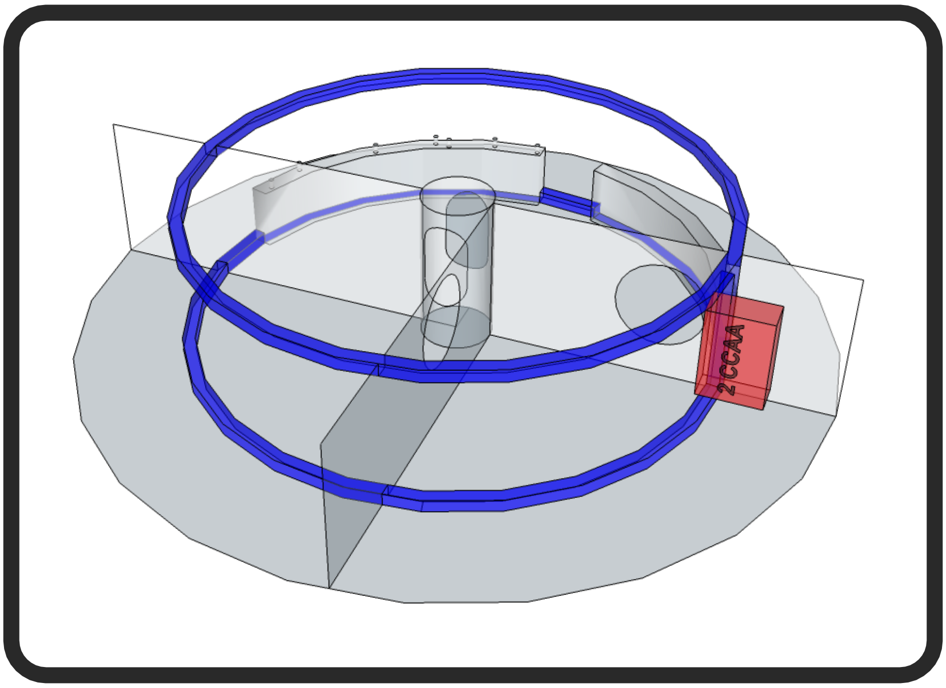

Figure 10-6: Temperature and humidity control on deck 6

The equipment air heat load in this deck is assumed to be 195 W from THC (see Table 10-5), as well around 305 W for medical gear and equipment like food preparation and refrigerators. Please note that the mentioned heat load only considers air heat load and that it is assumed that most equipment heat is removed by cold plates. When passengers are considered to be present, further 20 W CM^{-1} for personal equipment is considered as well as 80 W CM^{-1} for equipment like food rehydration or medical

[30] Assuming 23 % of power for THC equipment as airborne heat load. Nominal assumption with cold plates is 10 % [13]. Metabolic heat load is not included.
[31] Consist of the ducts and the diffusors. BFE´s are considered part of the AR subsystem (see 10.3)

devices. For the additional humidity load from ACLS, the same as described under 10.2.1 is applicable for this area. The transient total heat and humidity load on deck 6 over 24 hours from equipment and human metabolism can be seen in Figure 10-7.

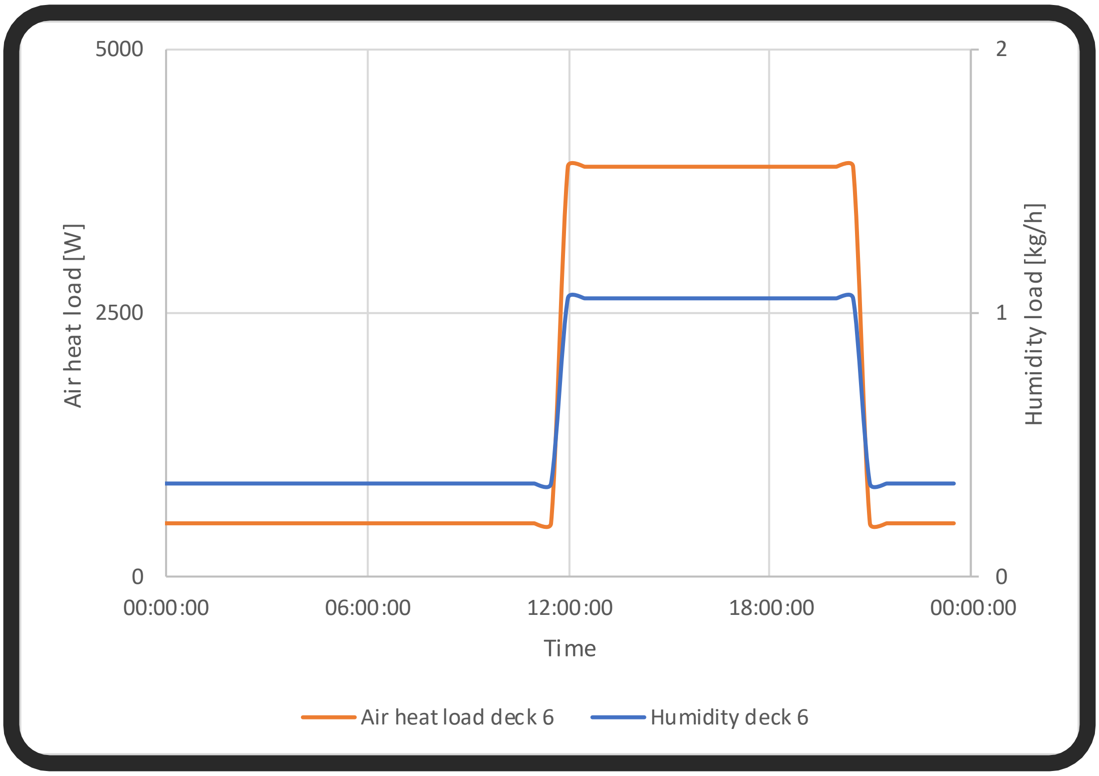

Figure 10-7: Air heat and humidity loads over 24 hours in deck 6 with 100 passengers and the one hour schedule

A breakdown of the required parameters for the THC equipment in the medical station and lounge on deck 6 are given in Table 10-5 below.

Table 10-5: Properties of the temperature and humidity control subsystem with 100 passenger and 211 days (Case4) on deck 6 (medical station and lounge)

Component	Mass [kg]	Volume [m³]	Power [W]	Cooling[32] [W]	ESM [kg]
CCAA	192.84	1.19	382	38	314
Tubes[33]	200.51	2.43	0	0	413
IMV	44.42	0.10	1,564	156	118
Total	**437.78**	**3.72**	**1,946**	**195**	**845**

10.2.3 Gym

The gym is the area with the by far highest requirements for the THC system. 9 CCAA are necessary to remove the metabolically heat and humidity of the passengers during exercise. The number of required CHX depends highly on the selected schedule. For

[32] Assuming 10 % of power for THC equipment as airborne heat load [13]. Metabolic heat load is not included.
[33] Consist of the ducts and the diffusors. BFE´s are considered part of the AR subsystem (see 10.3)

example, the highest needed number of CHX on this deck would be 18 for the Alternating Schedule with 80 passengers, of which up to 40 passengers at the same time doing workout. The layout of the THC system is given in Figure 10-8.

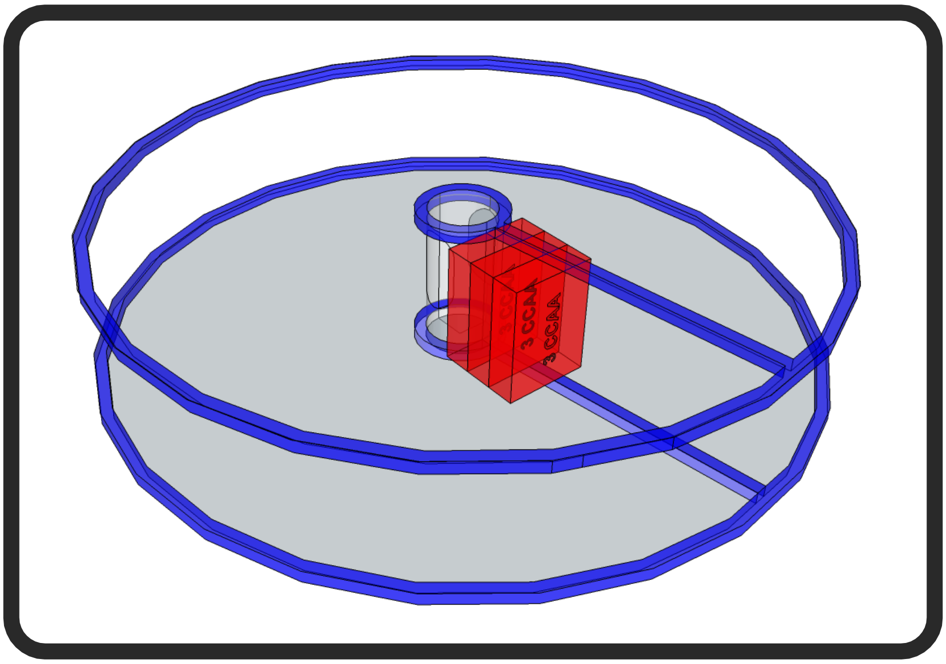

Figure 10-8: Temperature and humidity control on deck 5

The equipment air heat load in this deck is assumed to be 271 W from THC (see Table 10-6), as well as around 8,729 W for gym equipment and waste heat from ECLSS subsystems in the deck above. The total thermal load in deck 5 is calculated by Eq. (**10-4**), with $n_{CM,deck5,max}$ as the maximum number of crewmembers in this deck. For the one hour schedule, this is 20.

$$P_{th,deck5} = 425\, n_{CM,deck5,max} + 500 \qquad \textbf{Eq. (10-4)}$$

This high heat load is needed to maintain a balanced atmosphere with the highly fluctuating humidity loads in this level. When passengers are considered to be present, further 20 W CM^{-1} for personal equipment is considered. For the additional humidity load from ACLS, the same as described under 10.2.1 is applicable for this area. The transient total heat and humidity load on deck 5 over 24 hours for equipment and human metabolism can be seen in Figure 10-9.

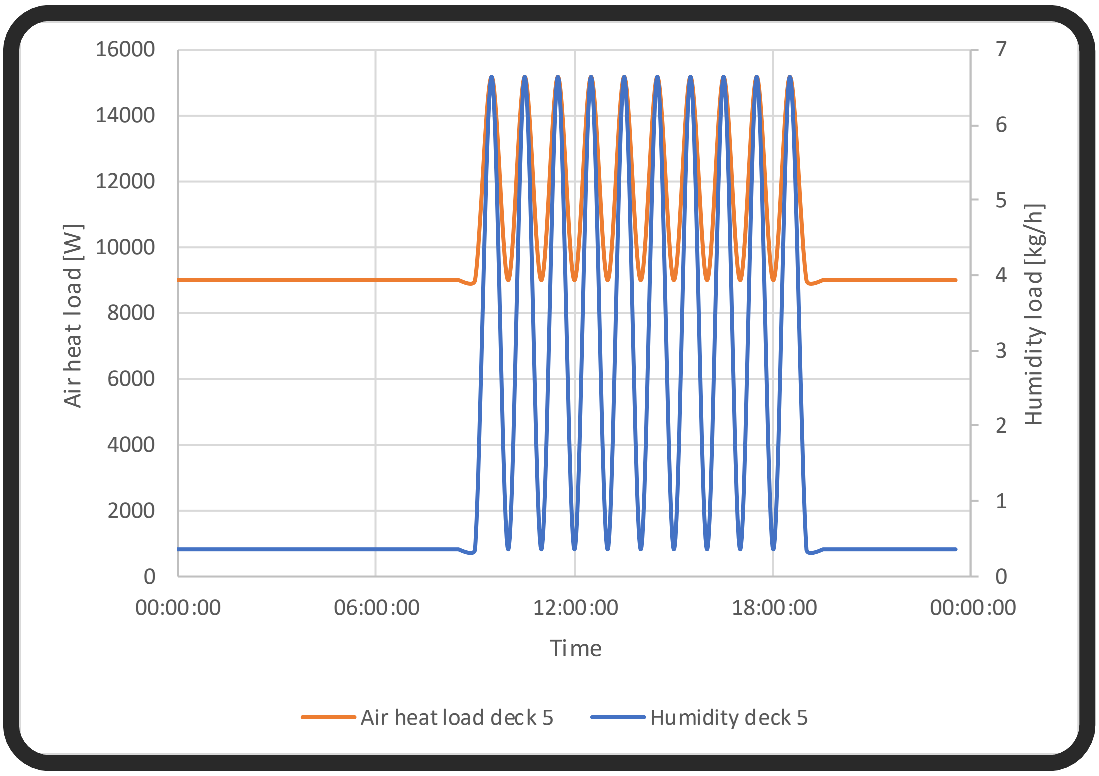

Figure 10-9: Air heat and humidity loads over 24 hours in deck 5 with 100 passengers and the one hour schedule

The required parameters for the THC equipment in the gym on deck 6 are given in Table 10-6 below.

Table 10-6: Properties of the temperature and humidity control subsystem with 100 passenger and 211 days (Case4) on deck 5 (gym)

Component	Mass [kg]	Volume [m³]	Power [W]	Cooling[34] [W]	ESM [kg]
CCAA	777.73	4.93	1,149	115	1,258
Tubes[35]	314.23	12.77	0	0	1,433
IMV	39.92	0.09	1,564	156	114
Total	**1,131.88**	**17.79**	**2,713**	**271**	**2,805**

10.2.4 Hygiene Facilities

The deck with the hygiene facilities houses the 5 showers and additional 3 commodes (see 3.2.2.6). Since the liquid flows are the highest of the ECLSS, the WRM is considered in this deck (see 10.4). The AR subsystem is also located on this level, because this deck is central and the interfaces to the other ECLSS subsystems benefits of the proximity. The layout of the THC system in this deck can be seen in Figure 10-10. The other subsystems are hidden for clarity.

[34] Assuming 10 % of power for equipment as airborne heat load [13]. Metabolic heat load is not included.
[35] Consist of the ducts and the diffusors. BFE´s are considered part of the AR subsystem (see 10.3)

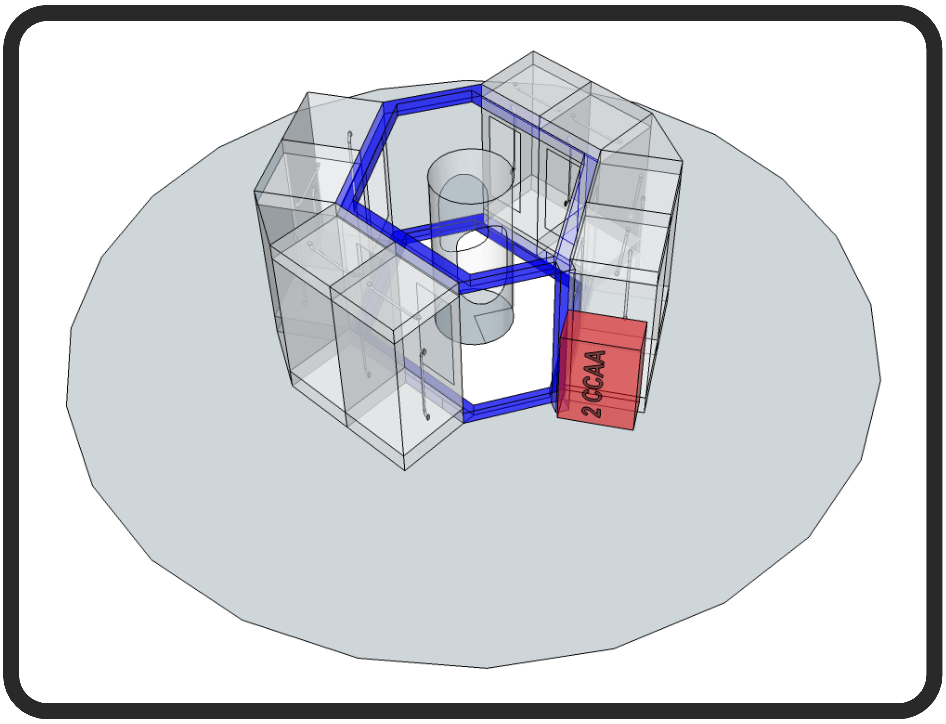

Figure 10-10: Temperature and humidity control on deck 4

The equipment air heat load in this deck is assumed to be 195 W from THC (see Table 10-7) and around 2,805 W waste heat from ECLSS subsystems. When passengers are considered to be present, further 20 W CM^{-1} for personal equipment is considered. For the additional humidity load from ACLS, the same as described under 10.2.1 is applicable for this area. Please note that humidity from shower is not considered in this calculation and it is assumed that all added humidity is removed by fans and CHX in the WRM subsystem. The transient total heat and humidity load on deck 4 over 24 hours for equipment and human metabolism can be seen in Figure 10-11.

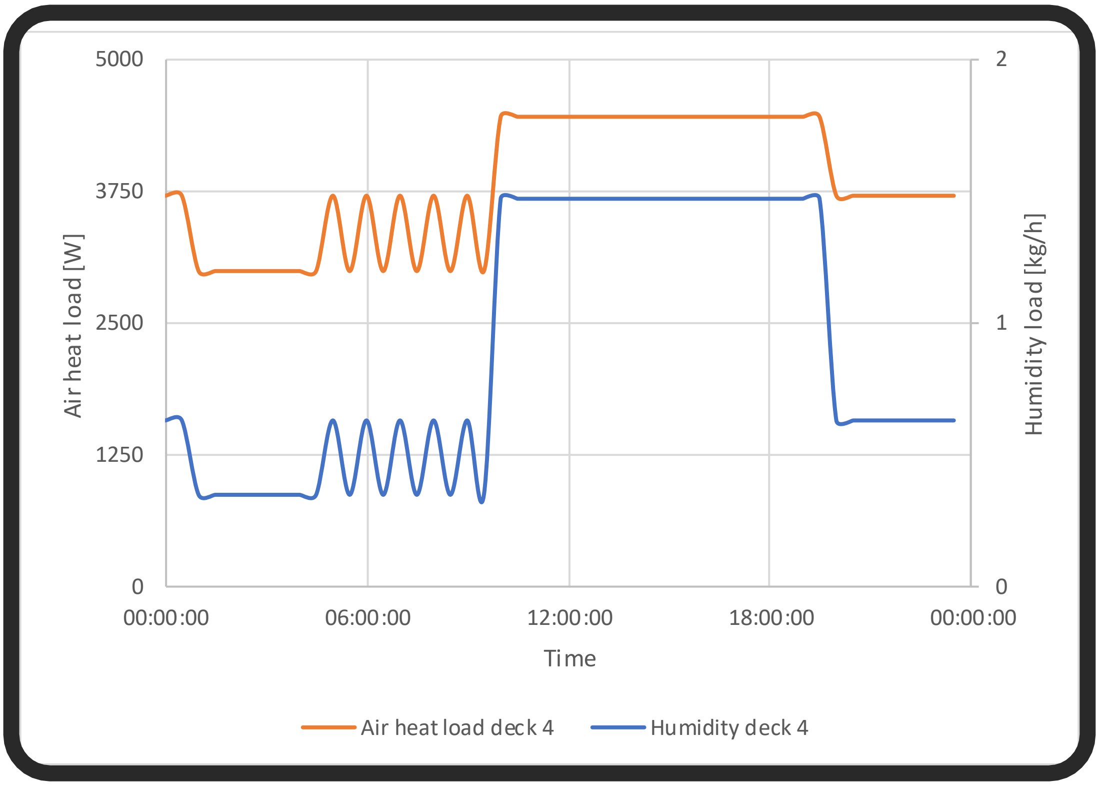

Figure 10-11: Air heat and humidity loads over 24 hours in deck 4 with 100 passengers and the one hour schedule

A breakdown of the required parameters for the THC equipment in the medical station and lounge on deck 6 are given in Table 10-7 below.

Table 10-7: Properties of the temperature and humidity control subsystem with 100 passenger and 211 days (Case4) on deck 4 (hygiene facilities)

Component	**Mass [kg]**	**Volume [m³]**	**Power [W]**	**Cooling[36] [W]**	**ESM [kg]**
CCAA	261.93	1.65	388	39	423
Tubes[37]	112.54	1.13	0	0	212
IMV	32.00	0.07	1,564	156	104
Total	**406.47**	**2.85**	**1,952**	**195**	**738**

10.2.5 Lecture Hall

The lecture hall goes over two levels in the Evolved-SpaceHab design, deck 2 and 3. Contrary to the original concept from SpaceX (see Figure 2-2), decks 2 and 3 are considered to be separated levels. Deck 3 is shown in Figure 10-12 with the THC components. Deck 2 has the same configuration just with a smaller diameter. Two CCAA are required to remove the metabolic heat and humidity of up to 30 passengers per deck.

[36] Assuming 10 % of power for equipment as airborne heat load [13]. Metabolic heat load is not included.
[37] Consist of the ducts and the diffusors. BFE´s are considered part of the AR subsystem (see 10.3)

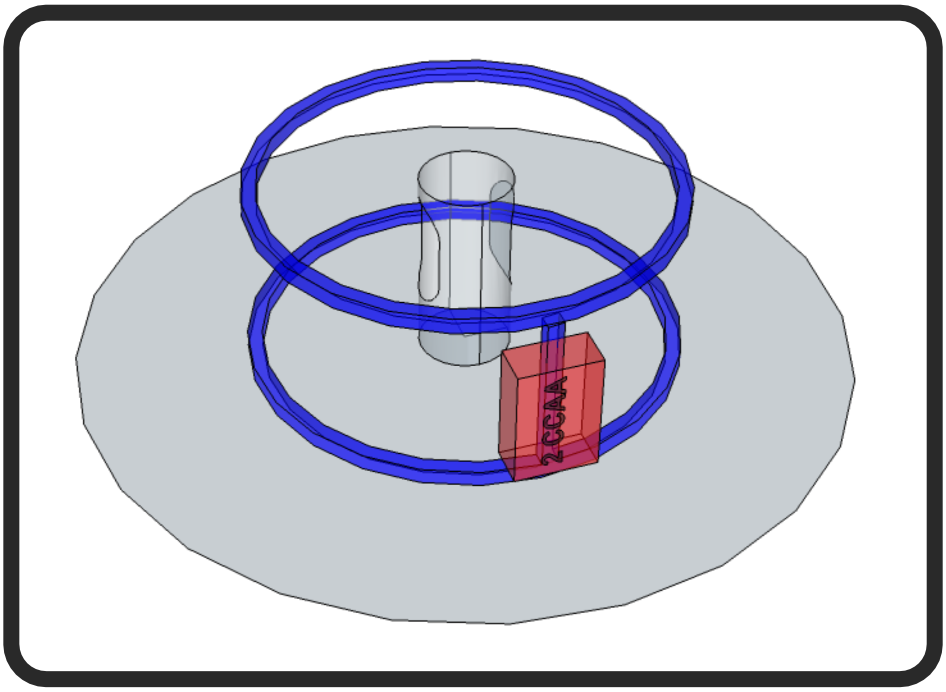

Figure 10-12: Temperature and humidity control on decks 2 and 3

The equipment air heat load in this deck is assumed to be 215 W from THC (see Table 10-8), as well around 3,645 W of equipment heat and waste heat from ECLSS subsystems from the deck below. The total thermal load in these two decks are calculated by Eq. (10-5). The maximum crew member size ($n_{CM,deck2and3,max}$) in these decks are 60 for the one hour schedule, divided over both decks.

$$P_{th,decks2and3} = 56\, n_{CM,deck2and3,max} + 500 \qquad \textbf{Eq. (10-5)}$$

When passengers are considered to be present, further 20 W CM^{-1} for personal equipment is considered. For the additional humidity load from ACLS, the same as described under 10.2.1 is applicable in this deck. The transient total heat and humidity load for the decks 1 to 3 over 24 hours can be seen in Figure 10-13, including equipment and human metabolism. Deck 1 is included in this figure, since decks 1 to 3 are merged together in the calculations in the Life Support Trade Off Tool. For the specify heat and humidity loads of deck 1, see chapter 10.2.6.

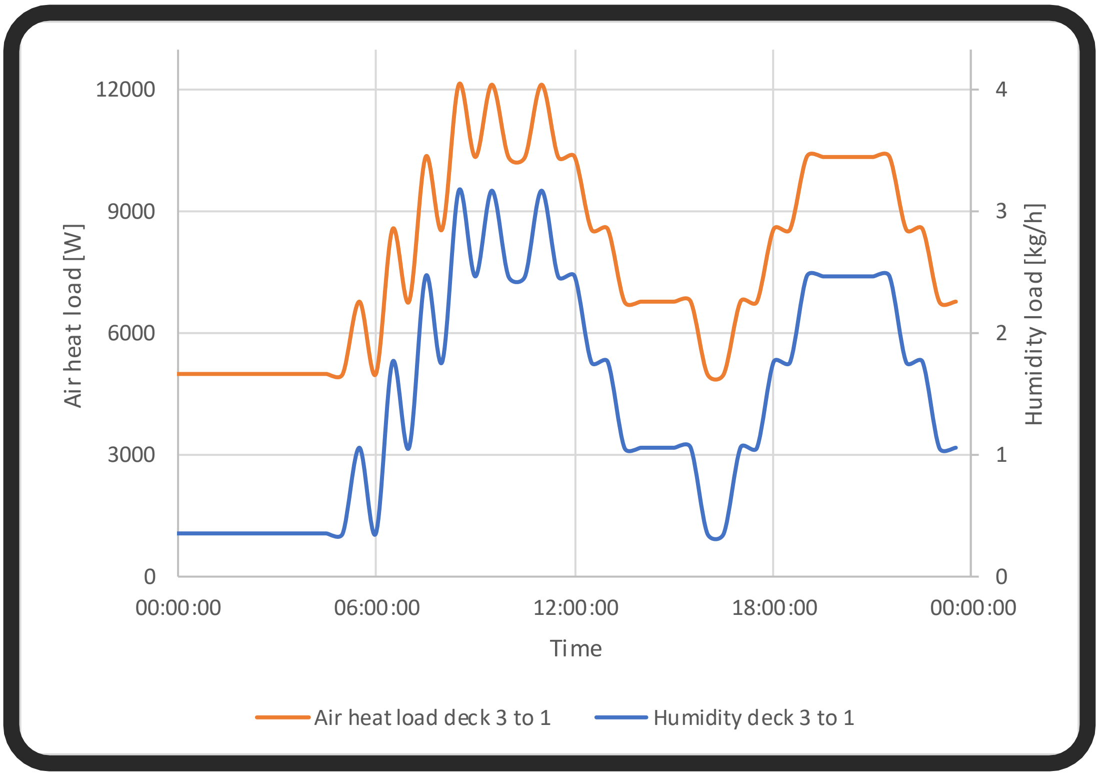

Figure 10-13: Air heat and humidity loads over 24 hours in decks 1 to 3 with 100 passengers and the one hour schedule

The required parameters for the THC equipment in the lecture hall on decks 2 and 3 are given in Table 10-8 below.

Table 10-8: Properties of the temperature and humidity control subsystem with 100 passenger and 211 days (Case4) on decks 2 and 3 (lecture hall)

Component	Mass [kg]	Volume [m³]	Power [W]	Cooling[38] [W]	ESM [kg]
CCAA	360.37	2.26	583	58	583
Tubes[39]	227.27	2.51	0	0	448
IMV	64.87	0.15	1,564	156	143
Total	**652.51**	**4.92**	**2,147**	**215**	**1,174**

10.2.6 Galley

The upper most deck is the galley with a conic shape. The THC subsystem for this area can be seen in Figure 10-14. There are 3 CCAA required to remove the heat and humidity from the air of this 112.09 m³ volume.

[38] Assuming 10 % of power for equipment as airborne heat load [13]. Metabolic heat load is not included.
[39] Consist of the ducts and the diffusors. BFE´s are considered part of the AR subsystem (see 10.3)

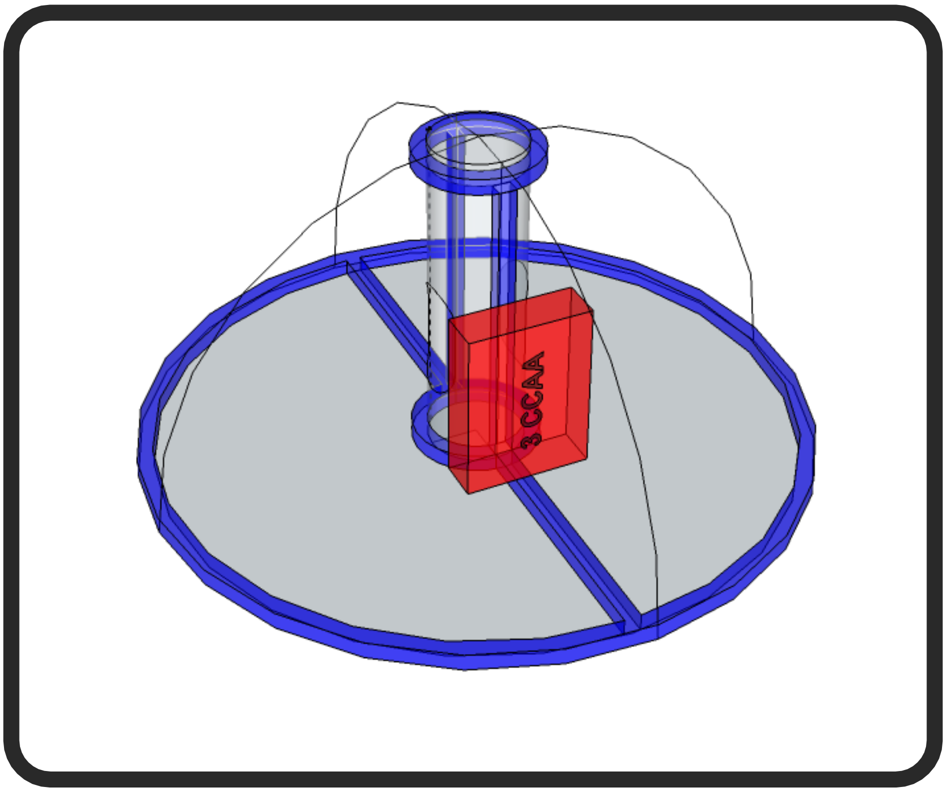

Figure 10-14: Temperature and humidity control on deck 1

The equipment air heat load in this deck is assumed to be 195 W from THC (see Table 10-9), as well as around 1,425 W of equipment heat like food rehydration. The total thermal load in this deck is calculated with the same equation as for decks 2 and 3 (Eq. (10-5)), with a maximum crewmember size of 20. When passengers are considered to be present, further 20 W CM^{-1} for personal equipment is considered. For the additional humidity load from ACLS, the same as described under 10.2.1 is applicable for this area. The transient total heat and humidity load for the decks 1 to 3 over 24 hours for equipment and human metabolism can be seen in Figure 10-13. As already mentioned, decks 1 to 3 are merged together in the calculations in the Life Support Trade Off Tool.

A breakdown of the TCH equipment in this space is listed in Table 10-9.

Table 10-9: Properties of the temperature and humidity control subsystem with 100 passenger and 211 days (Case4) on deck 1 (galley)

Component	Mass [kg]	Volume [m³]	Power [W]	Cooling[40] [W]	ESM [kg]
CCAA	261.93	1.65	388	39	423
Tubes[41]	220.16	2.48	0	0	438
IMV	43.79	0.10	1,564	156	118
Total	**525.88**	**4.24**	**1,952**	**195**	**979**

10.3 Final Design of Atmosphere Revitalization

The final design of the atmosphere revitalization (AR) system consists of the SAWD assembly for CO_2 removal, the SFWE assembly for oxygen generation, as well the Sabatier for CO_2 reduction. Additional equipment considered to the AR subsystem are two MCA for atmosphere monitoring, the TCCS for trace gas removal and BFE´s integrated into the ducts of the THC subsystem to remove airborne particles and bacteria.

The schematic of the developed AR subsystem for the Evolved-SpaceHab is given in Figure 10-15 below. The recycling, as well the storage system is shown. Please note that not all components of the AR subsystem are included for a better overview.

[40] Assuming 10 % of power for equipment as airborne heat load [13]. Metabolic heat load is not included.
[41] Consist of the ducts and the diffusors. BFE´s are considered part of the AR subsystem (see 10.3)

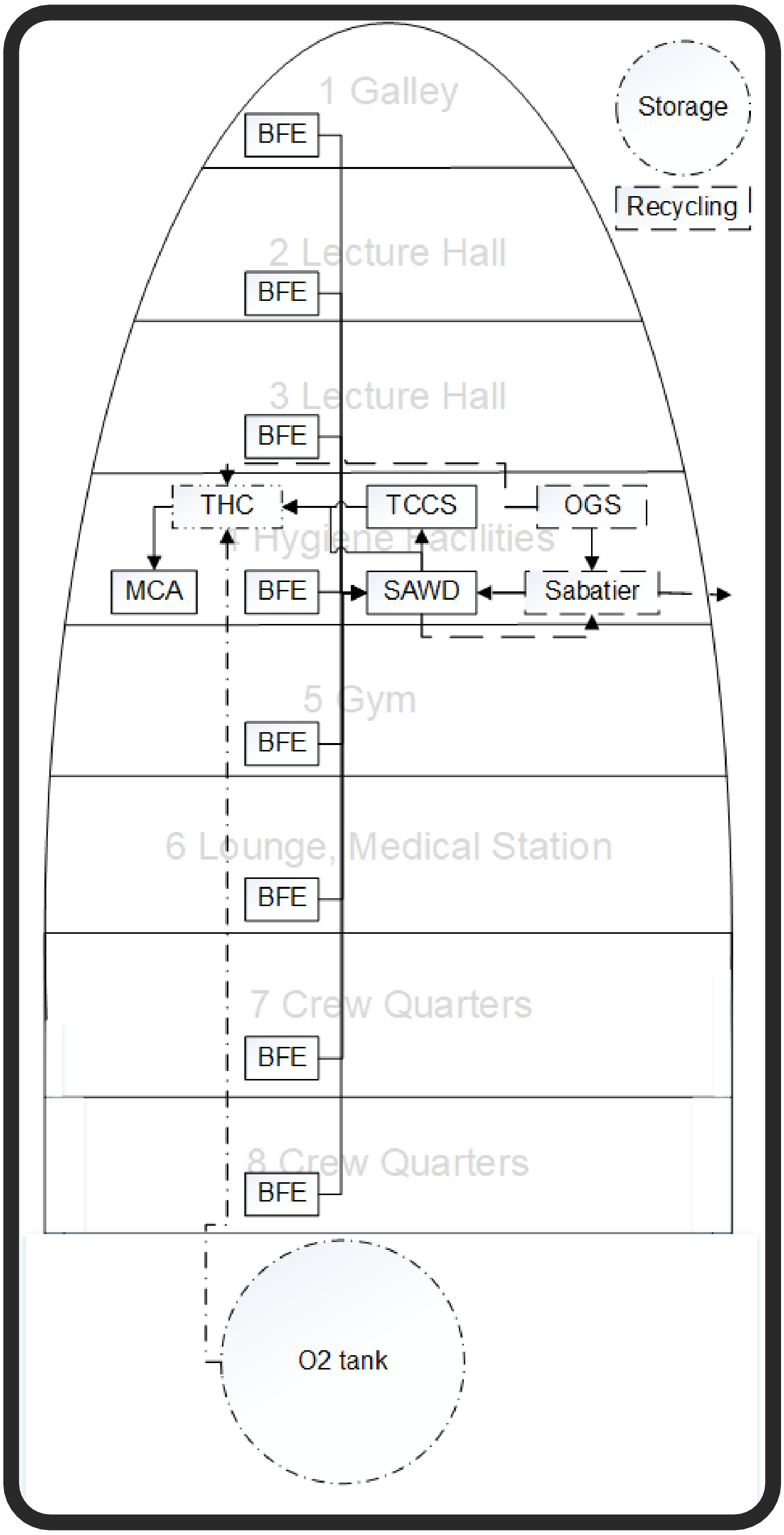

Figure 10-15: Schematic of the final AR design

In the following, the final properties of the water recovery and management system are presented for the trade cases one (Table 10-10) and four (Table 10-11). For both cases, the spares determined in 9.5.3 are included.

Table 10-10: Properties of the atmosphere revitalization system for 12 passengers and 88 days (Case1)

Parameter	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	ESM [kg]
TCCS	363.26	1.61	417	301	609
TCCS spares	59.25	012	0	0	75
BFE	1,635.53	7.55	0	0	2,674
MCA	109.50	0.51	88	88	216
MCA spares	45.63	0.08	0	0	57
SAWD	446.39	1.02	3,152	3,640	1,920
SAWD spares	892.78	2.04	0	0	1,174
Sabatier	622.64	0.20	3,087	6,350	2,038
Sabatier spares	1,245.27	0.39	0	0	1,299
SFWE	507.15	1.15	1,483	371	1,251
SFWE spares	1,014.30	1.92	0	0	1,278
Total	**6,941.68**	**16.58**	**8,225**	**10,749**	**12,593**

Table 10-11: Properties of the atmosphere revitalization system for 100 passengers and 211 days (Case4)

Parameter	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	ESM [kg]
TCCS	1,460.58	11.15	2,352	1,699	2,581
TCCS spares	77.34	0.16	0	0	91
BFE	2,558.19	11.81	0	0	3,594
MCA	109.50	0.51	88	88	190
MCA spares	67.73	0.12	0	0	78
SAWD	3,400.76	7.94	25,994	28,028	15,029
SAWD spares	10,202.28	23.82	0	0	12,290
Sabatier	5,124.77	1.61	25,462	52,915	16,737
Sabatier spares	15,374.30	4.82	0	0	15,796
SFWE	4,186.16	6.92	12,354	3,089	9,682
SFWE spares	12,558.49	24.83	0	0	14,736
Total	**55,120.08**	**93.67**	**66,250**	**85,817**	**90,804**

A mockup view of the AR subsystem for trade Case4 on deck 4 of the Evolved-SpaceHab can be seen in Figure 10-16. The assemblies are marked with different colors. Other ECLSS subsystems in this deck (THC, WRM) are not shown for clarity. There is also maintenance access considered, with a width of 0.76 m. The shown height of these access tunnels will be lower, since tubes, electric trays etc. not considered in this view.

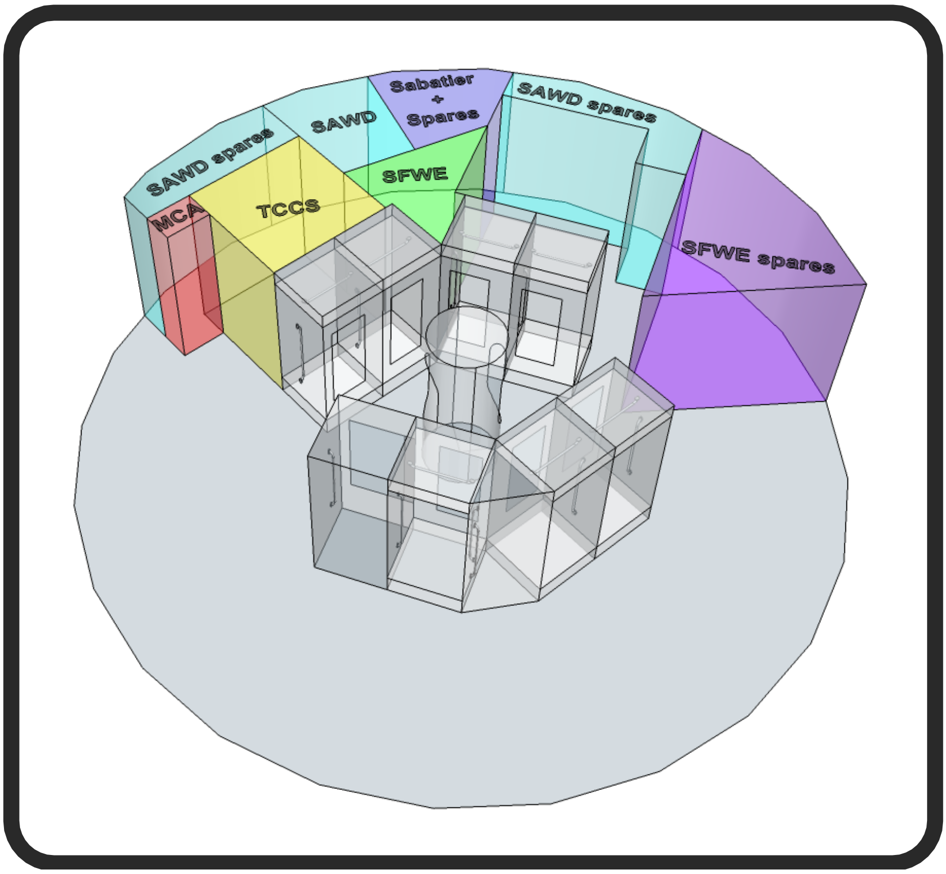

Figure 10-16: Mockup of the AR subsystem

10.4 Final Design of Water Recovery and Management

The water recovery and management (WRM) system consists of two water tanks (potable and waste), the distribution network tubes, a water quality monitoring assembly, and the vapor compression distillation (VCD) assembly for water recycling. The potable water tank is sized for a contingency consumables mass for one week and an additional working mass. This working mass is assumed to be normally at 68 %, or 1.7 days of consumption. For a hazard analysis, see 0. Waste water is collected in the waste water tank, which could hold up-to 3 days of accumulated waste waters. The nominal filling level is assumed to be one third and consists of humidity condensate, hygiene waste water, and urinal waste water. For a summary of the tank properties see Table 8-6. The working mass size and the nominal level of the tanks is chosen to compensate fluctuations and thus enable a constant operation of the WRM.

For the final design of the VCD, the urine processing assembly (UPA) on the ISS was used instead of the low TRL VCD used for comparison reasons in chapters 7 Trade Study and 8 Second Design Cycle. This was done since the UPA represents a flight-proven VCD system. The UPA has a mass of 291 kg, a volume of 0.52 m³, a power consumption of 315 W with an assumed cooling need of half of the power [63]. No consumables are contained within the UPA since the replacement of the recycle filter tank assembly with the advanced recycle filter tank assembly (ARFTA). Several changes on the design, proposed by [116], are considered, which leads to increased performance and reduced volume and power requirements. To increase the performance, a variable motor speed, the addition of a distillation assembly recuperative HX (+5 %), and a pressure control and pump assembly inlet HX in combination with the integration into the low temperature loop (+20 %) are considered. While it is presumed to implement these improvements and to stay conservative, a 20 % increase in performance is expected. The predicted size reduction of the distillation assembly is assumed to be nullified by the addition of the HX mentioned above. The greatest impact has the proposed reduction in power consumption of up to 50 % by changing the stationary bowl heater set point from 328 K to 317 K. For resizing, it is stated that the UPA is capable to process 8.45 kg of urine per day with a maximum load of 13.6 kg over an 18 hour period per day [117, p. 2]. With the mentioned 20 % increase in performance, the UPA is capable to process 10.14 kg urine per day. This value is used for the rescaling of the components. Besides the VCD, a post-treatment must be considered. On ISS, this is the WPA, which is a MF process. The WPA processes all waste waters, while the UPA only processes urine on ISS. Since the WRM design in this thesis is different from that of the ISS, some components of the WPA are used for post-treatment of the distillate. These components are listed in Table 10-12. For rescaling of this component, the process rate of 12.7 kg d^{-1} of the WPA is used.

Table 10-12: Properties of WPA components used for post-treatment of distillate water [63, p. 162]

Component	**Mass [kg]**	**Volume [m³]**	**MTBF [h]**
Catalytic Reactor	67.04	0.01	25,579
Gas Separator	39.15	0.07	84,008
Ion Exchange Bed	13.02	0.02	296,701
Microbial Check Valve	5.76	0.01	143,488
pH Adjuster	2.54	0.01	137,181
Pump Separator	31.34	0.09	42,398
Reactor Health Sensor	16.83	0.04	56,677
Sensor	4.81	0.01	143,664
Separator Filter	7.67	0.01	359,072
Start-up Filter	9.44	0.02	226,884
Water Delivery	47.54	0.10	64,561

A schematic for the developed WRM system is given in Figure 10-17. For a storage system, the waste water tank (WW), VCD, and PCQWM has to be excluded.

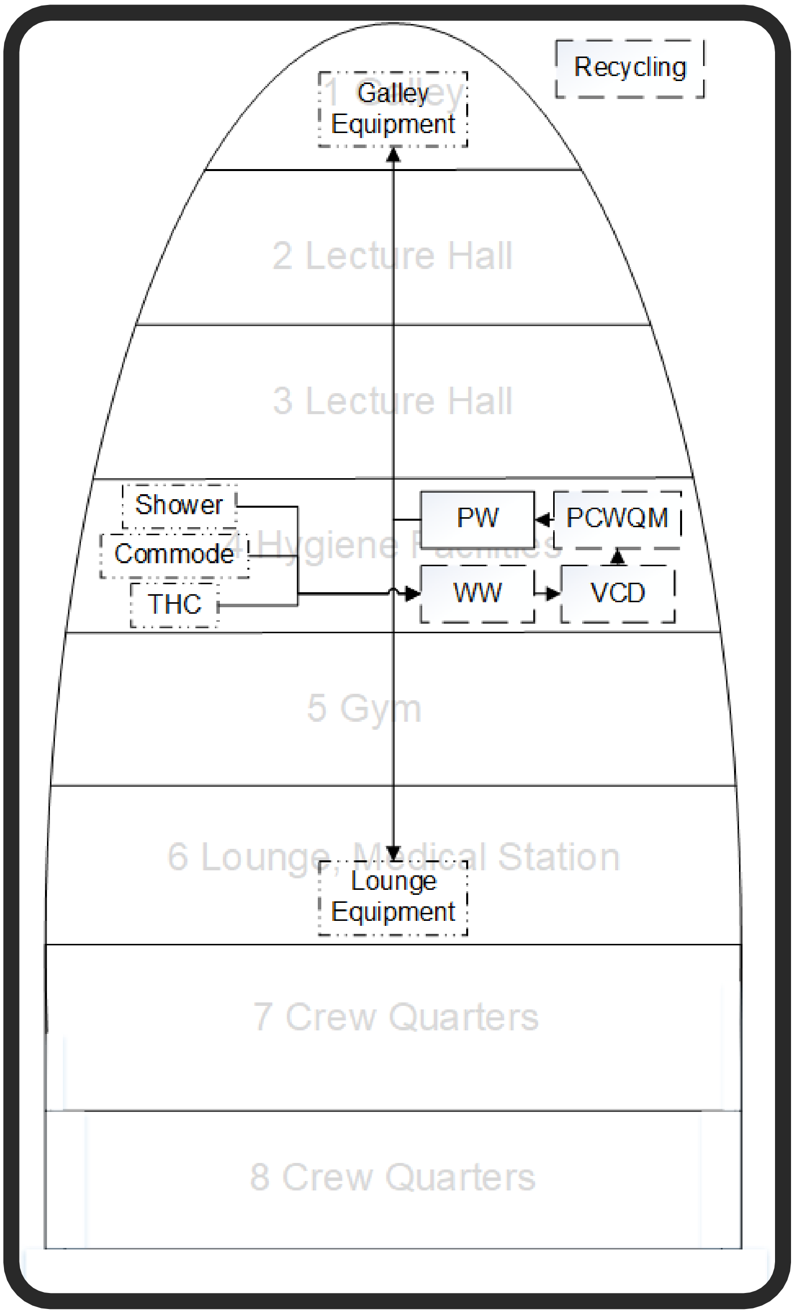

Figure 10-17: Schematic of the final WRM design

Now the final properties of the water recovery and management system are presented for the trade cases one (Table 10-13) and four (Table 10-14). For both cases, the spares determined in 0 are included.

Table 10-13: Properties of the water recovery and management system for 12 passengers and 88 days (Case1)

Parameter	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	ESM [kg]
PCWQM	76.00	0.10	60	60	89
PCWQM Spares	38.00	0.05			42
Tanks	60.31	2.23	10	10	257
VCD	3,300.87	4.96	3,230	1,942	3,919
VCD Spares	4,476.69	6.66			5,061
Tubes	13.89	0.01			15
Total	**7,965.77**	**14.02**	**3,300**	**2,012**	**9,383**

Table 10-14: Properties of the water recovery and management system for 100 passengers and 211 days (Case4)

Parameter	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]	ESM [kg]
PCWQM	76.00	0.10	60	60	89
PCWQM Spares	38.00	0.05			42
Tanks	251.56	18.60	10	10	1,883
VCD	27,507.25	41.32	26,914	16,182	32,660
VCD Spares	60,011.96	88.65			67,784
Tubes	13.89	0.01			15
Total	**87,898.66**	**148.73**	**26,984**	**16,252**	**102,474**

The recycled water mass by the VCD is shown in Figure 10-18. As can be seen, the recycled water mass grows exponential with longer trip times and larger crew size.

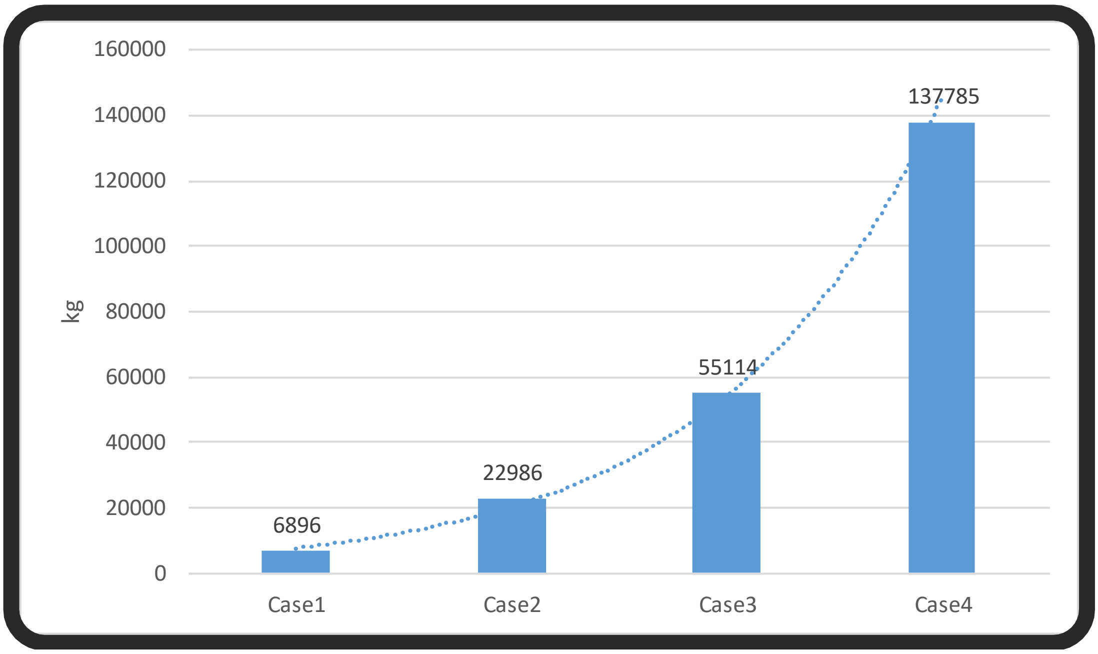

Figure 10-18: Recycled water mass for the considered trade cases

As can be seen in Figure 10-19, the trend for mass and volume saving is comparable to the exponential growth discovered in Figure 10-18. It is shown in Figure 10-20, that a recycling system for 100 passengers is always superior over a storage system when comparing mass or volume. The mass and volume step after 130 days for the VCD-system originates from more needed spares for the VCD, which adds nearly 20,000 kg and 33 m³ of spare mass and volume.

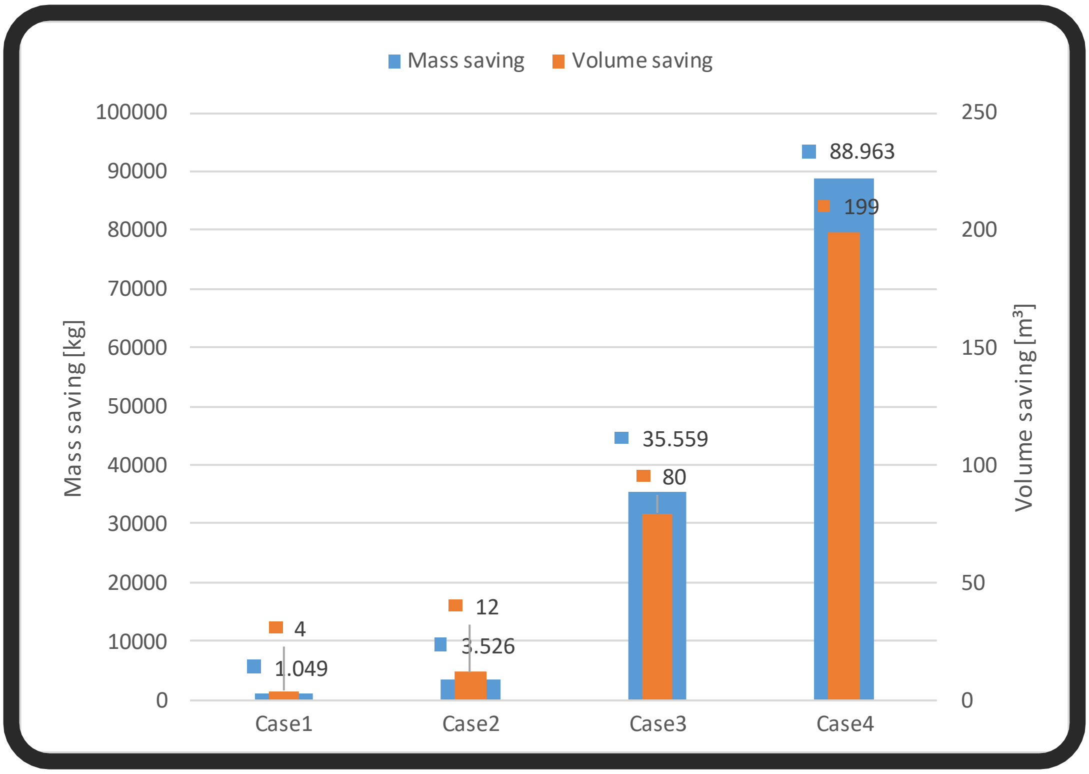

Figure 10-19: Mass and volume savings of the considered trade cases in comparison to a baseline storage system

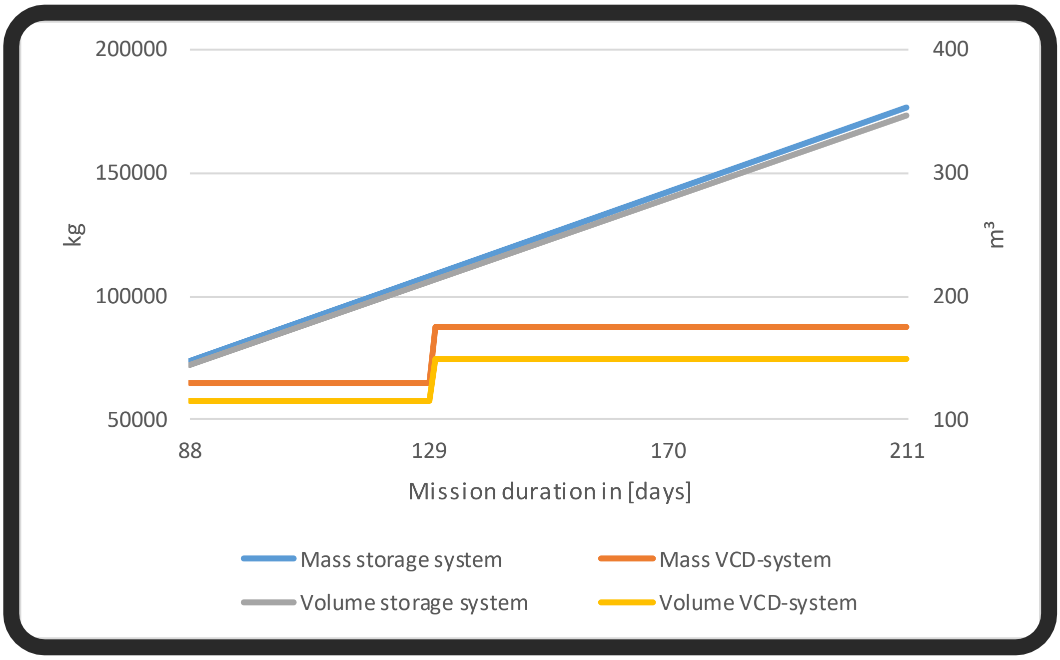

Figure 10-20: Required mass and volume for a storage and recycling water system over time for 100 people

The last object to consider is how much power is necessary to warm up the consumable water, since heating of water is relatively energy intensive and past designs of manned spacecraft's showed that a lot of power is required [118].

The different considered consumable water sources are potable water for drinking and food rehydration, and hygiene water for shower and grooming. In the following, only the scenario with 100 passengers is considered because this is the worst-case scenario. The considered temperatures of the water before consumption and the quantity for one day are listed in Table 10-15. A low water supply temperature for cold drinks is something that was not considered in past vehicles, but is highly appreciated for psychological reasons [118]. The required power for heating or cooling of the water can be calculated with Eq. (9-3). This calculation is assuming no heat losses through pipes and an efficiency of 100 %. The storage temperature of the potable and hygiene water is considered to be at ambient temperature of around 22.0 °C (195.13 K). A transient analysis over one day with the One Hour Shift Schedule (see 3.2.3.2) is shown in Figure 10-21. It can be seen, that the peaks for power and water consumption are after wake-up times, since it is considered by the schedule that shower is handled during a relatively short time. With an additional insulated tank, this power requirement could potentially be spread over the day, but because it is only 600 W, which is small in comparison to other subsystems, this is neglected.

$$\dot{Q} = c_{water}\, m_{th}\, \Delta T \qquad \textbf{Eq. (10-6)}$$

with:

- $\dot{Q}$ [J] - required energy
- c_{water} [Wh kg^{-1} K^{-1}] - specific heat capacity of water (1.163)
- m_{th} [kg] - mass to heat or cool
- ΔT [K] - temperature difference

Table 10-15: Temperature, mass, and required power for consumable waters for 100 passengers

Parameter	**Average temperature [°C]** [42]	**Quantity per day [kg]**	**Required power [kWh day^{-1}]**
Shower	38.90	142.86	2.81
Grooming	38.90	40.00	0.79
Drinking	7.00	200.00	-3.49
Rehydration	73.85	50.00	3.01

[42] Water rehydration temperature for cold drinks is 2 to 7 °C, for rehydration of food it is between 68.3 to 79.4 °C, and for personal hygiene it is between 29.4 and 46.1 °C [9, p. 367, 17, p. 9].

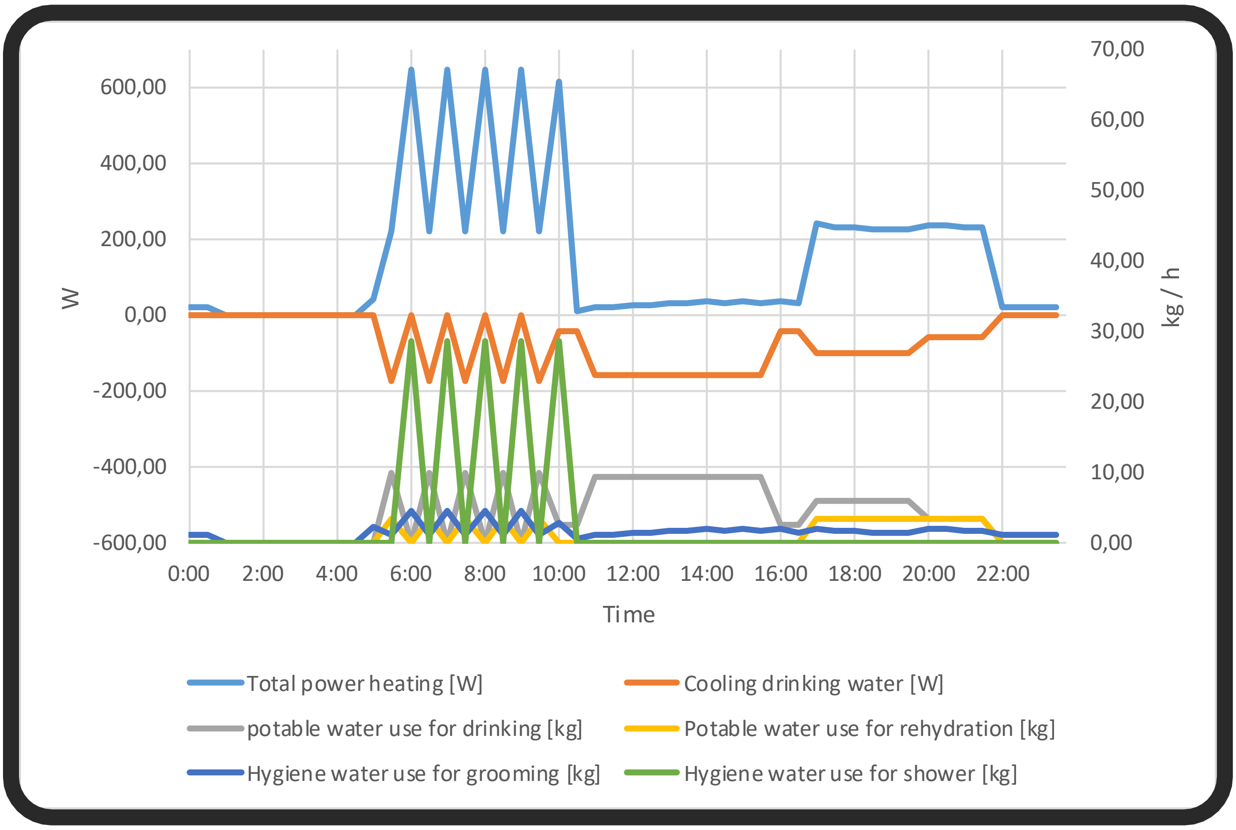

Figure 10-21: Transient power and mass need for the different consumable water sources over one day for the one hour schedule and 100 people

A mockup view of the WRM system for trade Case4 on deck 4 of the SpaceHab can be seen in Figure 10-22. The blue marked elements stand for potable water systems, yellow ones for waste water systems, and the red element is the VCD assembly including spares. Other ECLSS subsystems in this deck (ACS, THC, AR) are not shown for clarity. Not shown as well are the water pipes, since with 1.27 cm diameter they are very small and the purpose of this mockup is to see the general volume constraints. There is also maintenance access considered, with a width of 0.76 m. The shown height of these access tunnels will be lower, since tubes, electric trays etc. are not considered in this view.

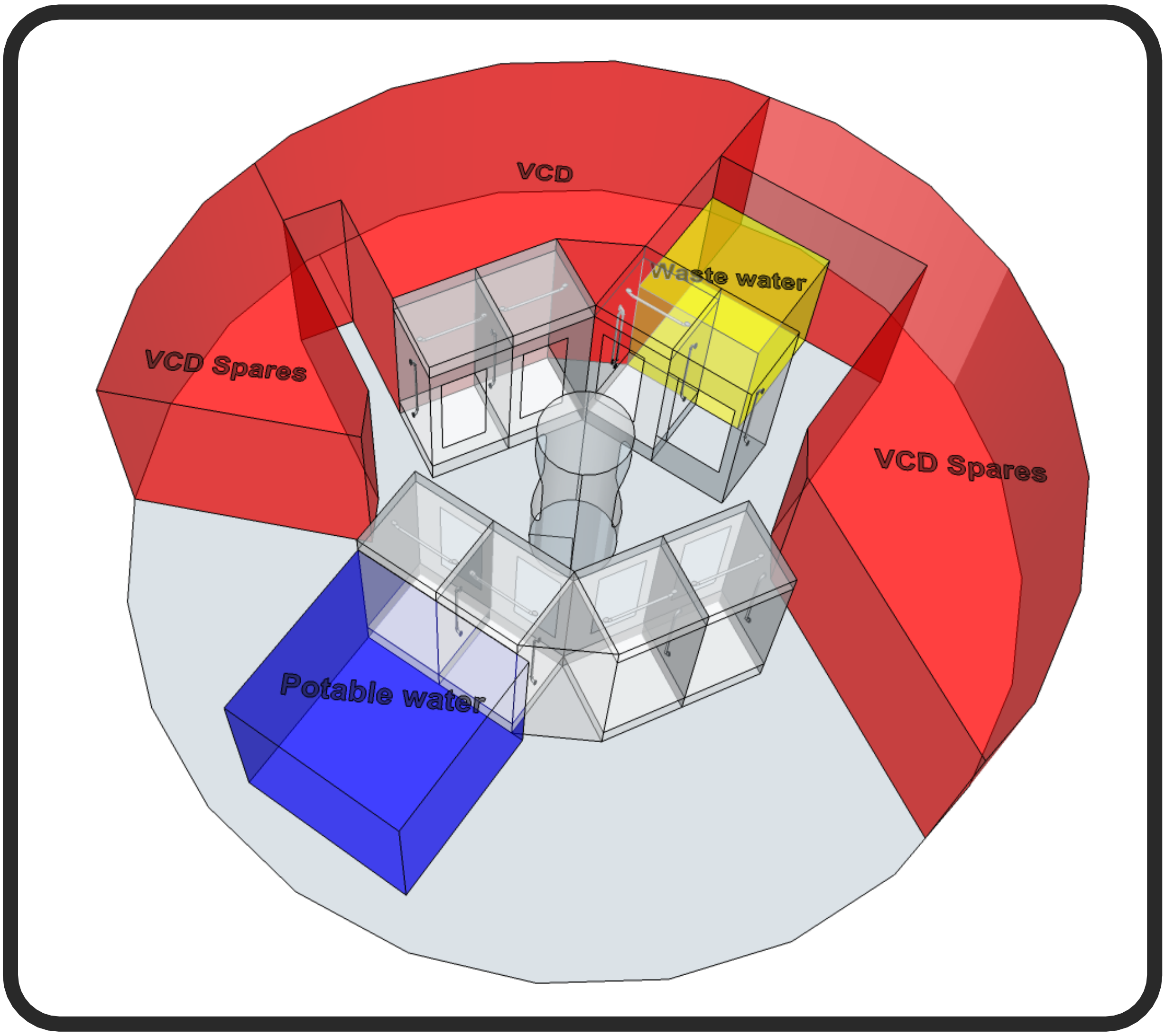

Figure 10-22: Mockup of the WRM system

10.5 Overview

The following chapters provide an overview of the complete ECLSS for the different trade cases, defined in Table 3-2. For all systems described in the following sections, the One Hour Shift Schedule and a recycling system is considered, with the exception of Case4, where a storage system is analyzed additionally.

10.5.1 Overview for Case1

The total mass of the ECLSS subsystems for Case1 is 24,389.40 kg. This includes all consumables like water and food. Figure 10-23 shows the shares of the subsystems to this mass.

The required volume for Case1 is 59.26 m³. As can be seen in Figure 10-24, the ACS system has only a volume of 0.8 m³, since only the volume in the crew compartment is considered and the tanks with a volume of 4.7 m³ are outside the pressurized volume.

The AR subsystem has by far the highest power requirement as shown in Figure 10-25. **The total necessary power for the SpaceHab and 12 passengers is 15.32 kW.**

The cooling requirement, shown in Figure 10-26, of the THC system includes metabolic heat of the crew as well the airborne heat load from the equipment, which is assumed to 10 % of the total cooling requirement [13]. Therefore, 10 % of the cooling requirement of the other subsystems are subtracted to prevent double counting. **The total cooling requirement for Case1 is 21.55 kW.**

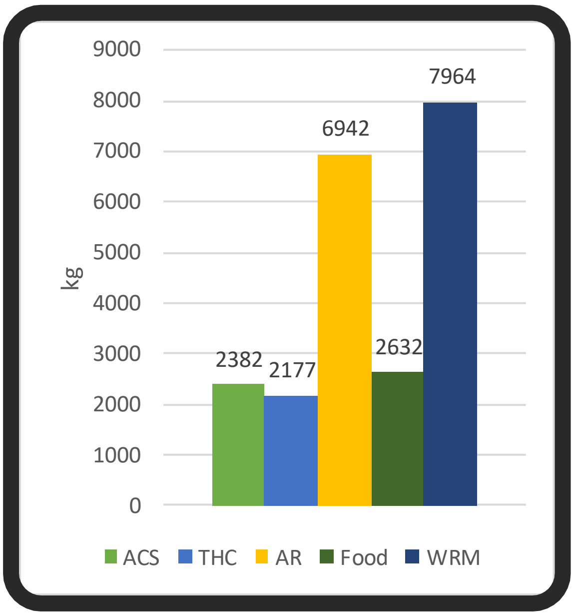

Figure 10-23: Mass of the different subsystems for Case1

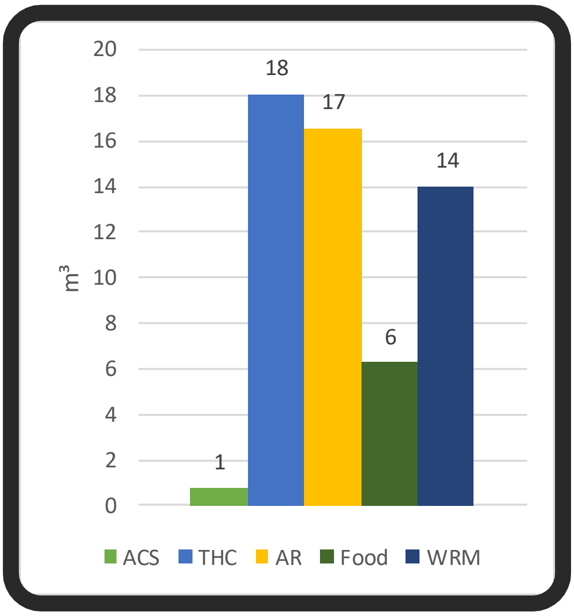

Figure 10-24: Volume of the different subsystems for Case1

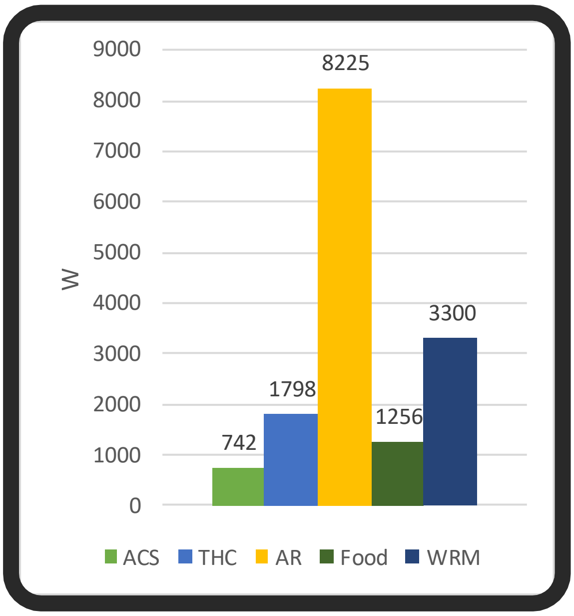

Figure 10-25: Power requirements of the different subsystem for Case1

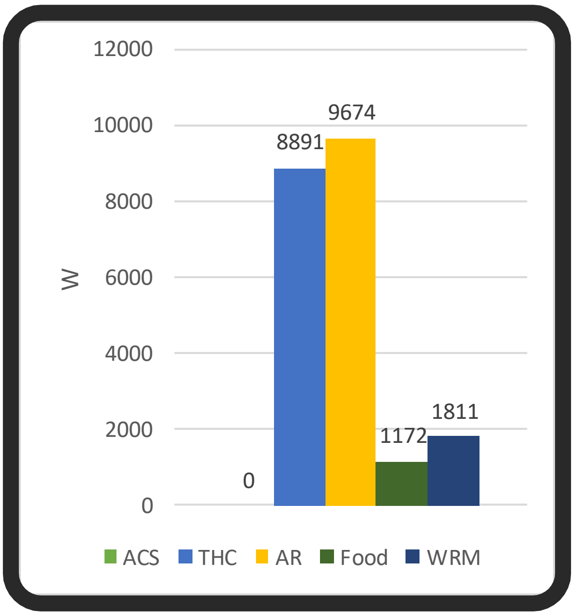

Figure 10-26: Cooling requirements of the different subsystems for Case1

10.5.2 Overview for Case2

As specified in Table 3-2, Case2 has the same duration and volume as Case1 but 40 passengers instead of 12. While the mass of the ACS and THC subsystems growth only marginal, as can be seen in Figure 10-27, the other systems require considerable more mass for the additional passengers. **The total mass for Case2 is 57,775.82 kg**.

The same behavior as for the mass can be seen (Figure 10-28) for the volume. **121.32 m³ are necessary to house all required ECLSS systems for 40 passengers in the SpaceHab.**

The required power of the subsystems can be seen in Figure 10-29. **The sum of all power consumption for Case2 is 44.35 kW.**

The total heat dissipation for Case2 is 51.97 kW. The shares for the subsystems can be seen in Figure 10-30.

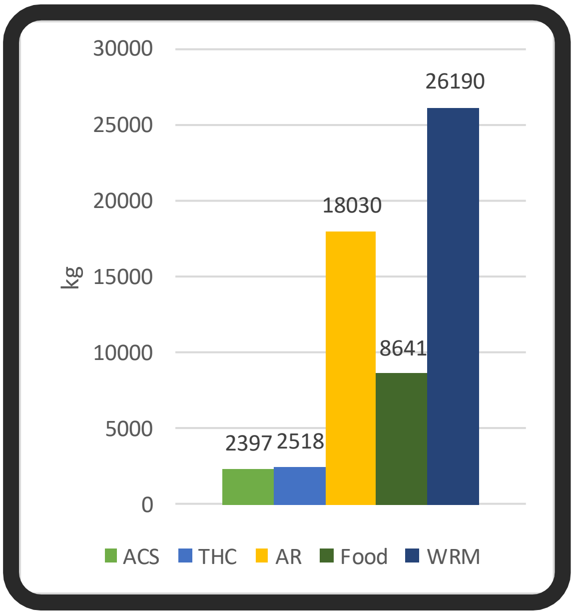

Figure 10-27: Mass of the different subsystems for Case2

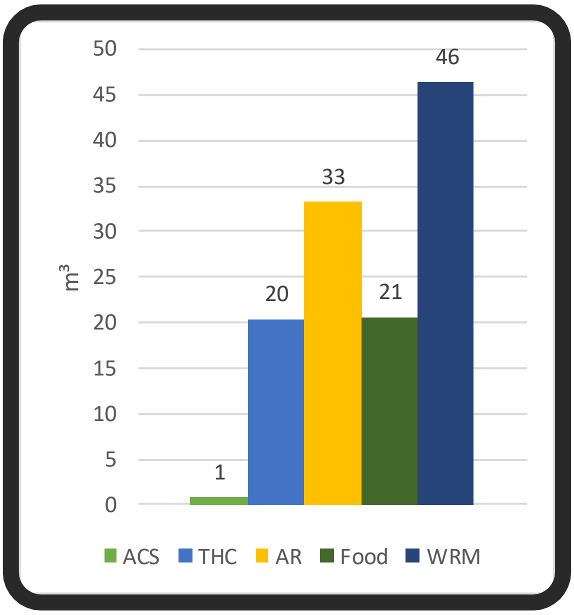

Figure 10-28: Volume of the different subsystems for Case2

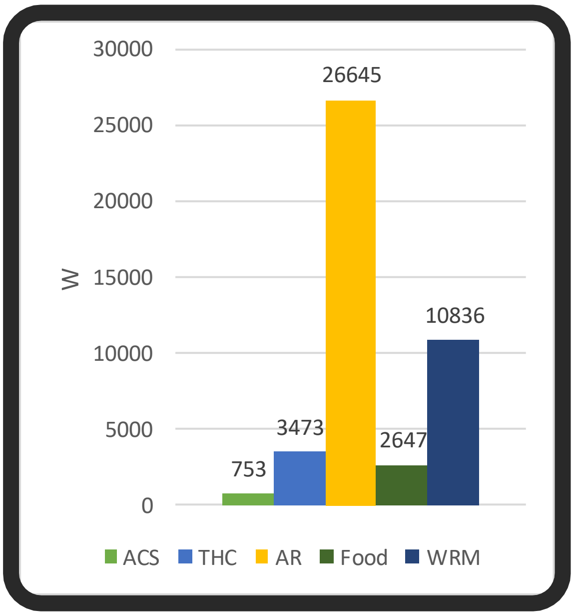

Figure 10-29: Power requirements of the different subsystem for Case2

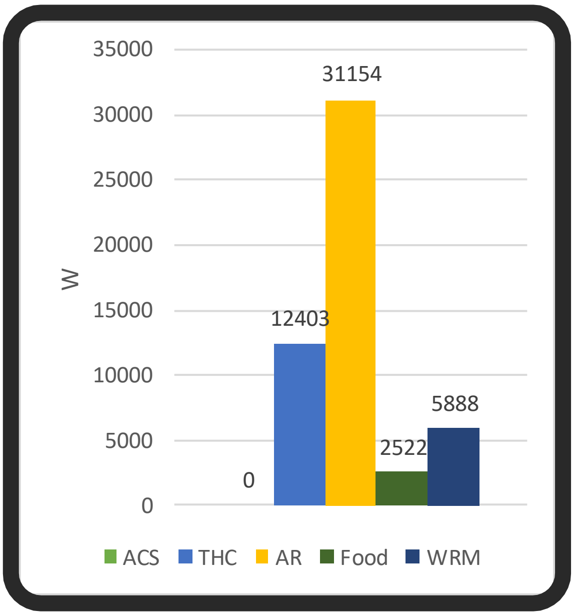

Figure 10-30: Cooling requirements of the different subsystems for Case2

10.5.3 Overview for Case3

As can be seen in Figure 10-31, the mass of the food growths most. The mass increase of the AR and WRM system is mostly due to more required spares for the longer duration of this case. The ACS and THC increase comes from the inclusion of the additional two decks. **The total mass of the ECLSS system for Case3 is 87,352.94 kg.**

The size of the food is more than doubled (Figure 10-32), since this system increases linear with mission length. **A volume of 185.38 m³ is necessary for 40 passengers and a mission duration of 211 days.**

The power (Figure 10-33) and cooling (Figure 10-34) requirements for the subsystems AR and WRM stay the same as Case2, since only spares are added. **Therefore, the total power and cooling increases slightly for Case3 to 46.36 kW and 56.82 kW respectively.**

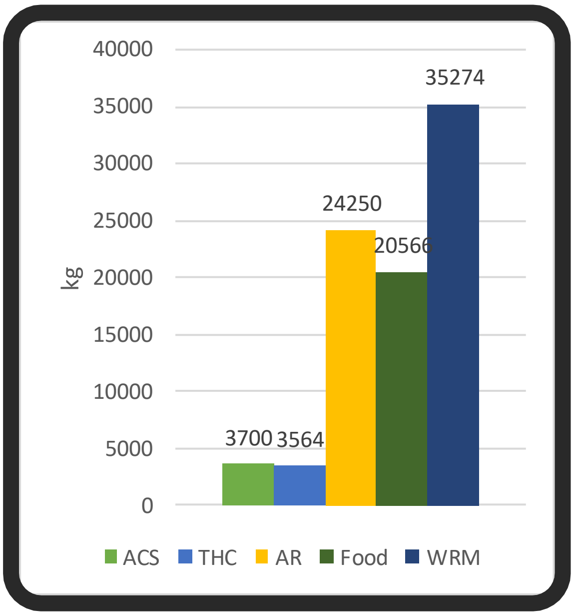

Figure 10-31: Mass of the different subsystems for Case3

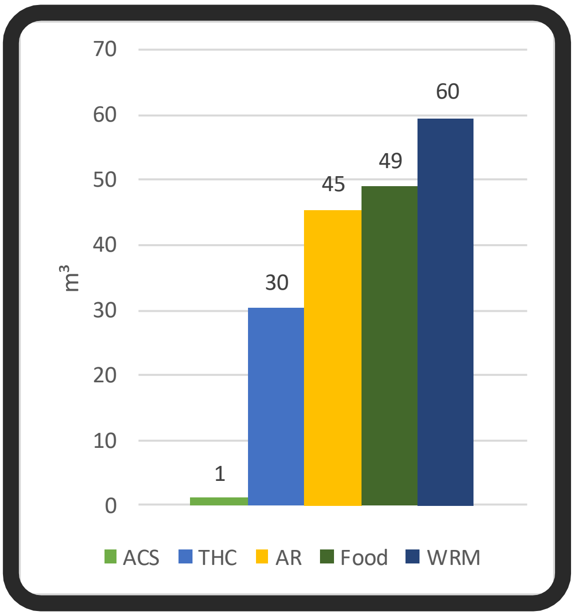

Figure 10-32: Volume of the different subsystems for Case3

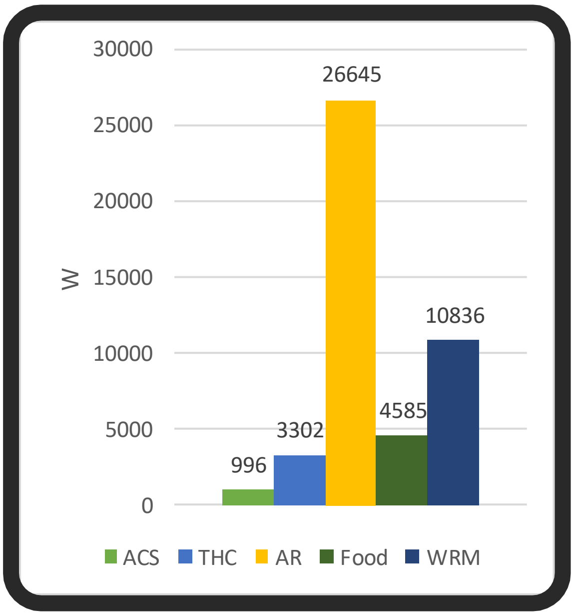

Figure 10-33: Power requirements of the different subsystem for Case3

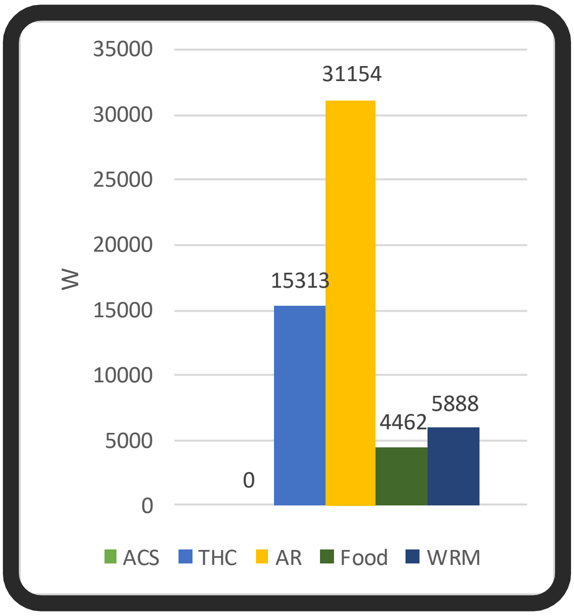

Figure 10-34: Cooling requirements of the different subsystems for Case3

10.5.4 Overview for Case4

10.5.4.1 Recycling System

The total mass for the final design of a recycling system for Case4 is 202,701.10 kg. The masses for the ECLSS subsystems are shown in Figure 10-35.

As can be seen in Figure 10-36, the WRM subsystem needs the most volume, since it has the most spares. **The total volume required for the recycling system for Case4 is 402,90 m³.**

The AR subsystem alone requires 66.25 kW power as can be seen in Figure 10-37, which is only slightly under the maximum allowed power consumption of 69.28 kW, as specified in requirement 4.1.c. **The total required power for Case4 is 111.43 kW**, which is more than the generated power through the solar cells of 86.6 kW (see chapter 2.1 for more details). Even when no exercise is considered (Emergency Schedule), the power requirement would be 93.96 kW. Therefore, the proposed system would not be feasible. The only possibility to reduce the power extensive is a storage system. Such a system needs only 46.68 kW because no Sabatier and SFWE are included, which account for 57 % of the required power for the AR subsystem. Additional, the WRM system consists only of tanks and needs minimal power for pumps and consumable water heating. The storage system for Case4 is described in chapter 10.5.4.2. Because such a system requires 115,804.74 kg more mass and occupies 198.86 m³ more volume, it is highly recommended to install additional solar arrays with a total power capability of 321.68 kW in LEO. If the initial assumption (see chapter 2.1) that the stated power capability of 200 kW is not in LEO and instead in Mars orbit, the recycling system would be feasible without modifications.

The AR subsystem would require nearly 165 % of the available heat rejection capability, as can be seen in Figure 10-38. **The total required cooling for 100 passengers in the Evolved-SpaceHab is 131.60 kW.** This means, for a feasible recycling system, the heat rejection capability must be increased too. It should be noted, that SpaceX has not stated what the heat rejection capability is and therefore the described system could be feasible without modifications.

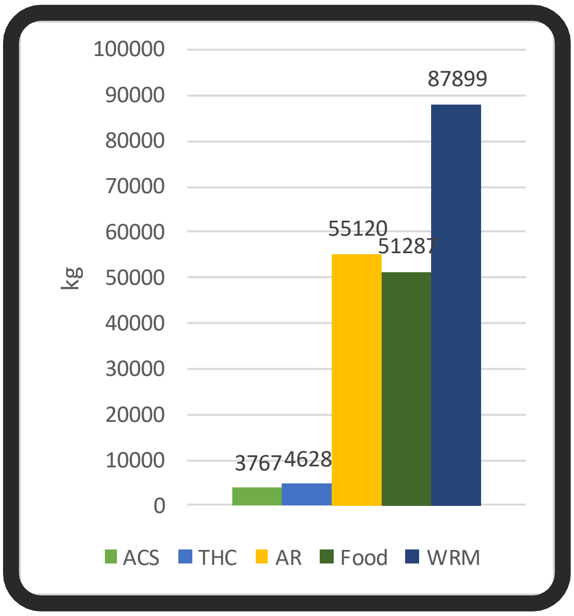

Figure 10-35: Mass of the different subsystems for Case4 in a recycling system

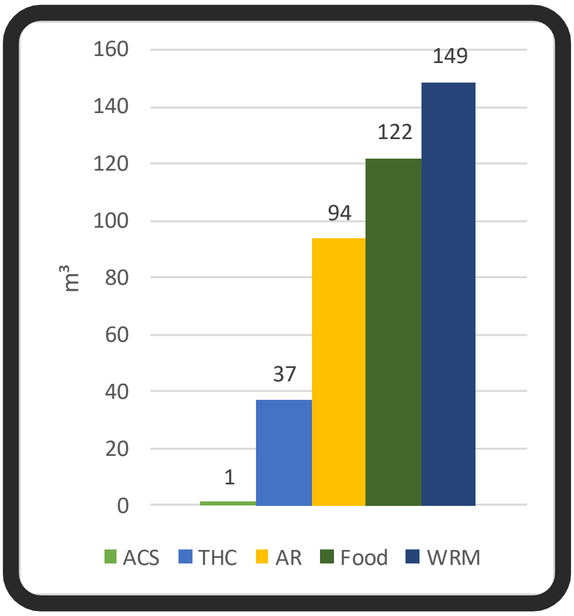

Figure 10-36: Volume of the different subsystems for Case4 in a recycling system

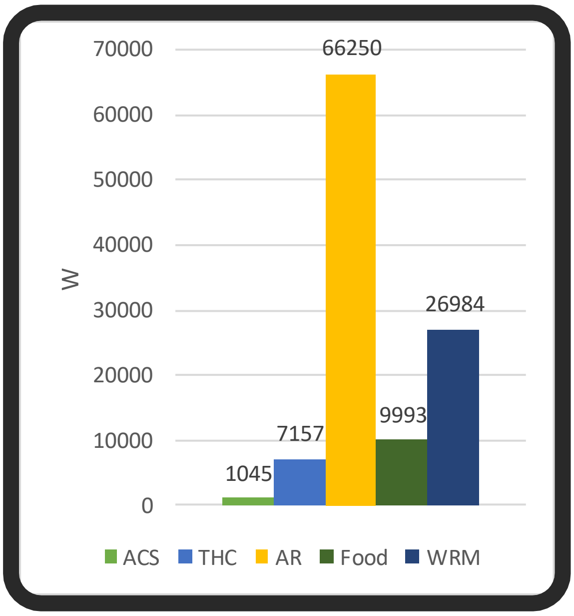

Figure 10-37: Power requirements of the different subsystem for Case4 in a recycling system

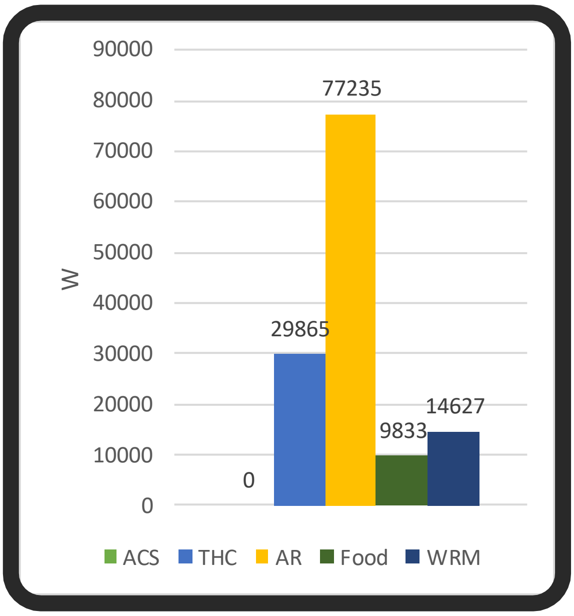

Figure 10-38: Cooling requirements of the different subsystems for Case4 in a recycling system

10.5.4.2 Storage System

A storage system is considered for Case4, since a recycling system requires too much power (see above). While such a system is highly reliable and has much less power and cooling requirements, it requires considerably more mass and volume. **The total mass required for Case4 is 318,505.84 kg.** As can be seen in Figure 10-39, the most mass is necessary for stored water in the WRM subsystem.

The most volume is occupied by the WRM subsystem (Figure 10-40). **The total required volume for a storage system is 601,76 m³.** Therefore, the lower two decks would be required alone for consumables.

The required power of the AR system is approximately 60 % less than for a recycling system and the power for the WRM is negligible (Figure 10-41). This saves much power and results in a **total power requirement of 46.72 kW for the storage system of Case4.**

Cooling need is also reduced to around 66.53 kW for the storage system of Case4. As can be seen in Figure 10-42, the highest cooling is now required for the THC system.

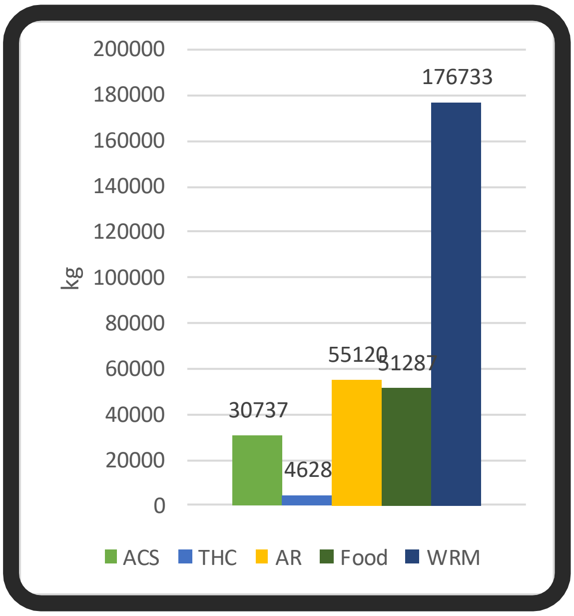

Figure 10-39: Mass of the different subsystems for Case4 in a storage system

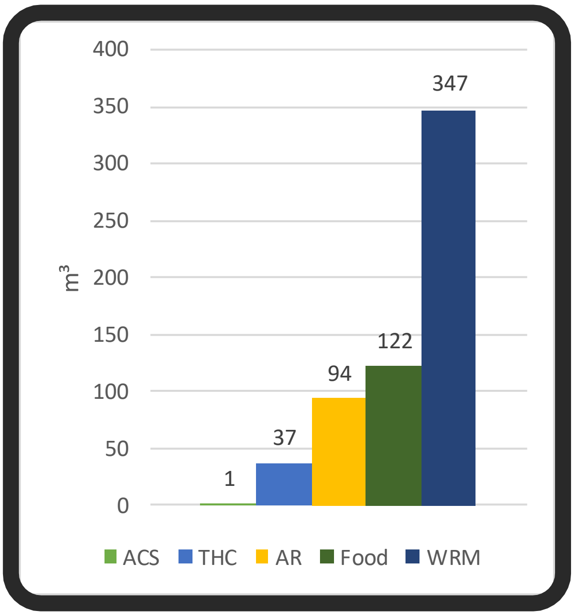

Figure 10-40: Volume of the different subsystems for Case4 in a storage system

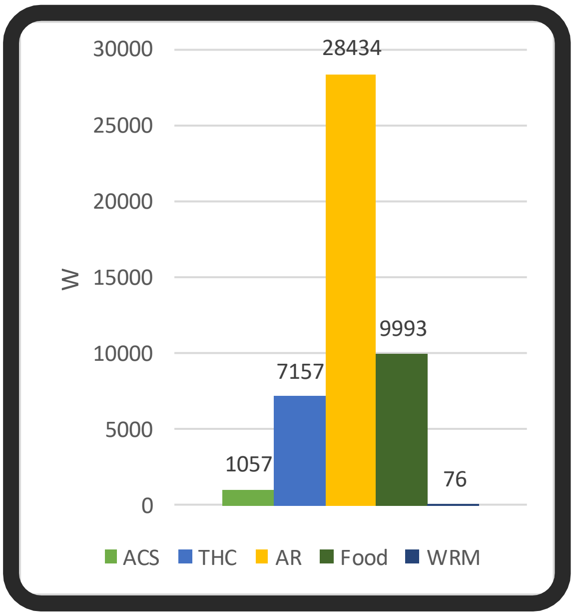

Figure 10-41: Power requirements of the different subsystems for Case4 in a storage system

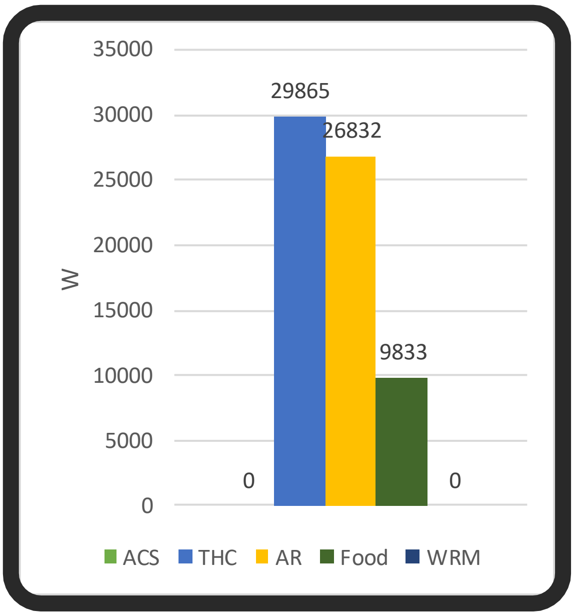

Figure 10-42: Cooling requirements of the different subsystems for Case4 in a storage system

10.6 Hazard Analysis

In the following, a hazard analysis for every subsystem is presented. This analysis can be used to determine the maximum allowable time to reestablish the operativeness after a failure of the appropriate subsystem.

10.6.1 Atmosphere Control and Supply

The limiting factor for O_2 in the atmosphere is 15.9 kPa during a 28-day emergency as stated in requirement 4.2.1.e. When no oxygen supply through tanks or the AR subsystem is considered, the time to hazard can be calculated with Eq. (10-7) to 6.95 days for a crew of 12 or 2.09 days for a crew of 40 and the SpaceHab design. For the Evolved-SpaceHab design, the hazard times is 3.27 days for 40 crewmembers and 1.31 day for 100 crewmembers. These calculations are based on a nominal schedule. Since it is unlikely that exercise is performed in such an emergency, the times can be stretched up-to 8.91 days for the best-case and 1.68 days for the worst-case scenario.

$$t_{O_2,hazard} = \frac{m_{atmo} - m_{needed}}{\dot{m}_{consumption}} \qquad \textbf{Eq. (10-7)}$$

$$m_{needed} = \frac{M_{O_2}\, p_{required}\, V}{R\, T} \qquad \textbf{Eq. (10-8)}$$

with:

- t_{hazard} [days] - time to hazard
- m_{atmo} [kg] - O_2 mass in atmosphere
- m_{needed} [kg] - minimal O_2 mass needed for required partial pressure
- $\dot{m}_{consumption}$ [kg day^{-1}] - daily O_2 consumption mass (depends on schedule)
- M_{O_2} [g mol^{-1}] - molar mass of oxygen (31.9988)
- $p_{required}$ [Pa] - minimum required partial pressure
- V [m^3] - volume of SpaceHab
- R [J Kmol^{-1}] - gas constant (8.314472)
- T [K] - temperature (295.15 K assumed)

Table 10-16: Hazard analysis for atmosphere control and supply

Time to hazard in days	Case1	Case2	Case3	Case4
nominal	6.95	2.09	3.27	1.31
emergency	8.91	2.67	4.19	1.68

10.6.2 Temperature and Humidity Control

The THC subsystem is one of the most critical subsystem, since the times to hazard are very short [96]. The critical parameter for the THC system is temperature. There are at least two CCAA in every deck. In the most critical area, deck 5, 9 CCAA are installed. If one of them fails, no major consequences besides a slightly higher temperature is expected. A reduction of the exercise task could compensate this, since this task has a high heat output. A failure of 4 of them would produce a major hazard, since 5 are not enough to compensate the assumed heat production in this deck. The stated values in Table 10-17 shows how many CCAAs could fail before a hazard is emerging. Please note that the system is calculated to minimum mass and volume, and therefore even one failure has to be compensated by a switch of schedule or any other operational action.

Table 10-17: Hazard analysis for temperature and humidity control

Deck	Number of failed CCAAs before hazard emerging
1 to 3	1
4	0
5	3
6	1
7 & 8	0

A more detailed analysis for a time to hazard considering the temperature and the dew point is necessary. But since the components of the THC are very reliable, as can be seen in the reliability analysis (9.5.2), it is unlikely that the THC system will cause a major hazard.

10.6.3 Atmosphere Revitalization

The limiting factor for the CO_2 partial pressure ($p_{CO_2,max}$) is 0.9066 kPa (6.8 mmHg) for under 24 hours as stated in requirement 4.2.3.a. The time to reach this partial pressure can be calculated by Eq. (10-9). For the mean CO_2 production mass ($\dot{m}_{production}$), the one hour schedule is assumed. These values depend highly on the schedule, the time of day where the AR system has a failure, and the current CO_2 level. With the mentioned assumptions, the time to hazard for the different trade case are given in Table 10-18.

$$t_{CO_2,hazard} = \frac{m_{CO_2,max} - m_{CO_2,atmo}}{\dot{m}_{production}} \qquad \textbf{Eq. (10-9)}$$

$$m_{CO_2,max} = \frac{M_{CO_2}\, p_{CO_2,max}\, V}{R\, T} \qquad \textbf{Eq. (10-10)}$$

with:

- $t_{CO_2,hazard}$ [days] - time to hazard
- $m_{CO_2,atmo}$ [kg] - CO_2 mass in atmosphere (nominal p_{CO2} is 0.267 Pa)
- $m_{CO_2,max}$ [kg] - maximum CO2 mass in atmosphere
- $\dot{m}_{production}$ [kg day^{-1}] - mean CO_2 production mass (depends on schedule)
- M_{CO_2} [g mol^{-1}] - molar mass of CO_2 (44.01)
- $p_{CO_2,max}$ [Pa] - maximum allowable CO_2 partial pressure
- V [m^3] - volume of SpaceHab
- R [J Kmol^{-1}] - gas constant (8.314472)
- T [K] - temperature (295.15 K assumed)

Table 10-18: Hazard analysis for atmosphere revitalization subsystem

	Case1	Case2	Case3	Case4
Time to hazard [h]	21.47	6.44	10.11	4.04

10.6.4 Water Recovery and Management

The potable water tank includes a contingency water mass for 7 days plus a working mass of up-to 3 days of consumption. The nominal fill level is at 68 %, or 1.7 days of consumption. In the event of a VCD malfunction, 7 days could be bypassed in the worst-case when no working mass is assumed. The best-case with a full tank, consisting of contingency and working mass, 10 days of water consumption are provided. When the VCD cannot be repaired, the consumption water has to be rationed, which means the potable water should only be used for drinking and food rehydration with a reduced rate of 2.05 kg $CM\text{-}d^{-1}$ besides the needed water for the OGA and CCA in the ACLS system (see also 10.6.3). With these assumptions, the time can be stretched to 7.6 days for the worst-case, or 11.8 days for the best-case with a full tank. A summary of this analysis can be found in Table 10-19 below.

Table 10-19: Hazard analysis for water recovery and management

Time to hazard in days	Nominal consumption rate	Reduced consumption rate
contingency	7	7.6
full tank	10	11.8

11 Verification

For the design of this thesis, a spreadsheet tool was developed, called Life Support Trade Off Tool (LiSTOT), which uses a mix between static values and transient calculations. The Tool is described in detail in appendix 14A. Before the design of the SpaceHab can be verified, it must be ensured, that the calculations in LiSTOT are correct. For the subsystems, THC and AR, the Virtual Habitat (V-HAB) is used, which is a proved and validated dynamic life support simulation tool developed at TUM, which is further described in the next chapter. This dynamic simulation tool was considered for verification, since the air systems are the most dynamic ones. The WRM system was not considered for a full dynamic simulation, since the WRM subsystem is relatively inert.

11.1 Virtual-Habitat (V-Hab)

As already mentioned, V-HAB is a dynamic life support simulation tool developed since 2006 at the institute of aeronautics at TUM [8]. The main features are the dynamic, modular, bottom up modelling of LSS and a human model with crew schedule. The tool is object oriented programmed in MATLAB® and is constantly enhanced. A big library of LSS technologies is included which can be individually adjusted.

V-HAB consists of 5 modules: a crew module, physico/chemical module, biological module, and the infrastructure module. The crew module contains a dynamic physiological model of the human body. The physico/chemical and the biological modules contains the corresponding technologies of these domains. The last one, the infrastructure module tie all other modules together and is described in the following.

The backbone of V-HAB is the infrastructure module. With the help of this framework, the different elements of the simulation are interconnected. It further provides classes for monitoring parameters during the simulation and includes a simulation timer that can set a variable time step of each simulation entity. A model of a technology is made up of several parts. One of these basic parts are the stores, which contain one or several phases. Stores are the representation of a tank.

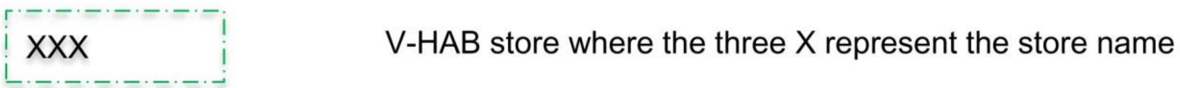

Figure 11-1: V-HAB store [119, p. 26]

The phases can be solid, liquid or gaseous state and contains all matter. No other components in V-HAB can hold mass.

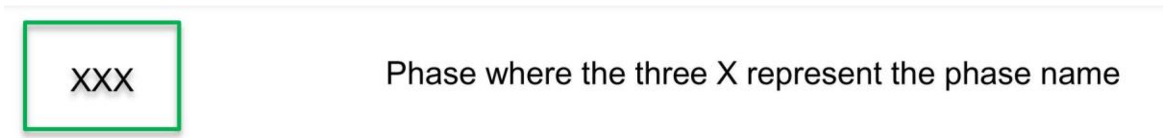

Figure 11-2: V-HAB phase [119, p. 26]

To move matter between two phases in a store, so called phase-to-phase (P2P) processors can be used. For example, to simulate evaporation, the P2P is used to transfer mass from a water phase to a vapor phase. This processor can also be used to model chemical reactions.

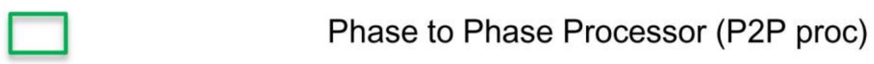

Figure 11-3: V-HAB p2p [119, p. 26]

When only the manipulation of one phase is considered, a manipulator (M) must be used. These can be used to simulate chemical reactions or heating/cooling of the phase.

Figure 11-4: V-HAB manipulator [119, p. 26]

Different stores can be connected by a branch. This symbolize the plumbing of system through which the matter flows.

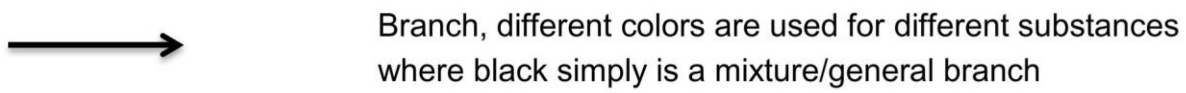

Figure 11-5: V-HAB branch [119, p. 26]

To connect a Brach and a phase in the store, an extract/merge processor is needed as interface. This processor extract the mass of one phase and puts it into the other phase.

Figure 11-6: V-HAB exme [119, p. 26]

Another type of processor is the flow-to-flow (F2F) processor which is used to change properties of a matter flow in branch, like increasing the pressure and temperature to simulate a fan.

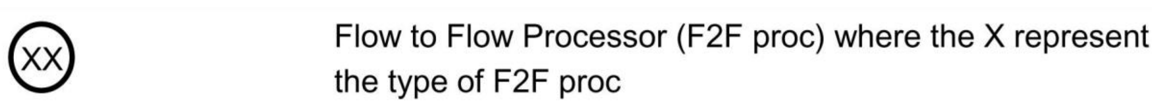

Figure 11-7: V-HAB f2f [119, p. 26]

The above described matter flow branches can be assigned to a solver. Several different solvers are available, like linear, iterative, or manual solvers. The two types used in this thesis are the manual solver and the residual solver. With the manual solver, fixed flow rates can be set, which makes it very fast. The residual solver is used to calculate the necessary flow rate to keep the mass of a phase constant.

V-HAB has several simplification and limitations, since it is only a model of the reality. Some of these are:

- All stores are ideally stirred containers
- If not modeled specifically, all processes are adiabatic
- Flows from one phase to the other are instantaneous

- Sweat produced by human evaporates immediately and completely
- Branches cannot contain mass

11.1.1 SpaceHab V-Hab Model

The ISS model with ACLS was developed in [119] and the SpaceHab model developed in this thesis used the previous model as a foundation to build upon. For information about the V-HAB ACLS model, please refer to [119]. The focus in this chapter is about the necessary rework of this model.

The modeled modules of the ISS where used to simulate the different decks of the SpaceHab. To differ between the SpaceHab and the Evolved-SpaceHab, just two decks where not simulated. Also, other ECLSS components like 4BMS or OGA are removed, since they are no longer considered. To ease the trade process, several parameters can be committed with the execution command:

- Crew size between 1 and 200
- Schedule (6 different are available, see 3.2.3)
- Mission duration
- IMV loop (deck-mode or racetrack, see 10.2)
- SpaceHab or Evolved-SpaceHab design

With these parameters, up to 4800 different possible systems could be simulated.

11.1.1.1 Schedule and Human Model

There is already a daily schedule built into the previous model. This model sets the starting times of the different tasks for the assumed 6 crew members individual and transfers the specific crew member during runtime into one of the simulated module stores, based on the current task. For a more detailed description about the human model, please refer to [119, 42–43, 97-98]. To accommodate the different considered schedules, outlined in chapter 3.2.3, a more dynamic approach has to be developed. First, it is determined into how many groups the crew members should be separated. Normally, this is specified through the schedule, but for very small sizes, it is possible that fewer groups as specified in the schedule are necessary. For example, 4 crew members could not be separated into 5 groups for the one hour shift schedule, instead there will be 4 groups. Depending on the chosen schedule, the starting times of the tasks are applied. In a follow-on procedure, the shifts of the groups are determined and applied, so that every group has different starting times of the tasks.

11.1.1.2 Thermal Humidity Control

The THC system from the previous model where used, since the considered system for the SpaceHab is the same system as used on the ISS and this is already implemented in the model. For a detailed description of the CCAA model in V-HAB see [119, pp. 80-83]. The difference between the new and the previous model is that the number of CCAAs is dynamically changed depending on the input parameters. With the help of LiSTOT, the necessary number of CCAA in every deck can be determined. An export function in LiSTOT generates a csv file. This file is a big matrix in which every line stands for a specific system. Overall 2700 distinct systems are generated. In the column of this matrix is the information about the number of the CCAA in every deck, as well sizing information about the CCA, CRA, and OGS. The first 3 columns have information about the schedule, the number of passengers, as well as the used system design. With this information, the program can determine how many CCAAs should be generated in the decks. The general schematic of the CCAA in V-HAB is given in Figure 11-8 below.

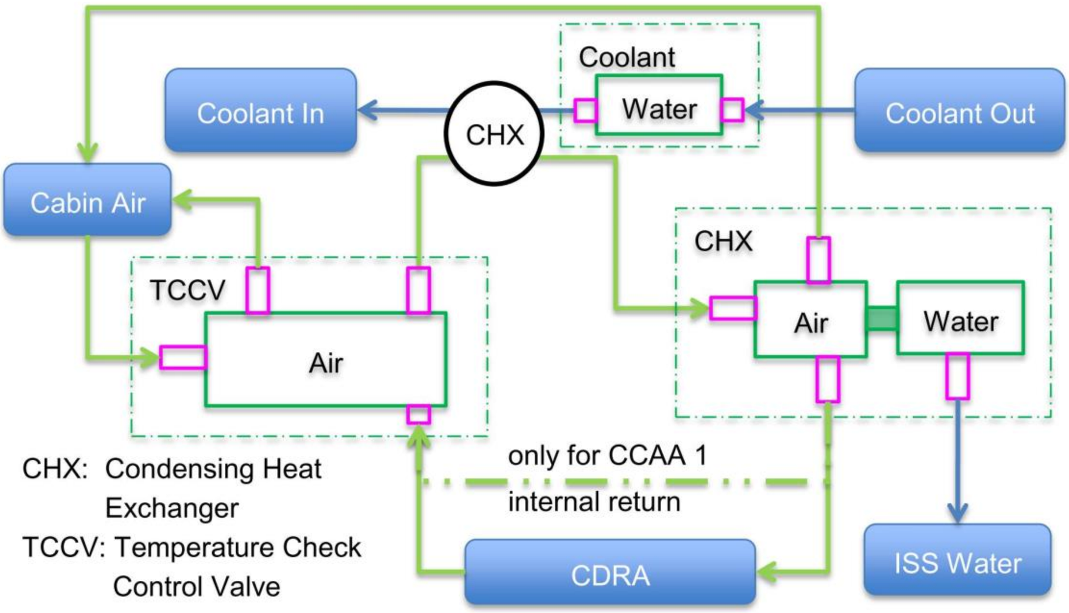

Figure 11-8: V-HAB CCAA schematic [119, p. 80]

For the thermal simulation of the SpaceHab, the already implemented crew and payload sensible thermal load is enhanced. The crew heat load now consists off the metabolic load and a heat load from personal or used equipment. Besides this, an assumed equipment heat load is applied, even when no passenger is currently on this deck. For the assumed equipment heat load, please see chapter 10.2.

Since the passenger size in the decks vary considerable, it was necessary to include an automatic switch-off-on logic for the CCAA to prevent the deck atmosphere from becoming too cold. Therefore, the CCAA in a deck is switch off when the temperature is below 291.65 K (18.5 °C) and it is turned back online when the temperature exceeds this value.

A new implemented hatch simulation connects every deck. Since no diffusion solver is available in V-HAB yet and to make the simulation as fast as possible, a manual solver was used. The function in Eq. (11-1) mimics a diffusion flow through the hatch. Note that this is only a first guess, but it was considered as sufficient since no excessive flows are expected to flow through such a hatch in comparison to the IMV system. The quadratic function below has a maximum of 2.898 kg h^{-1} at pressure difference of $1{*}e^4$ Pa. This flow rate is assumed to be the maximum flow through the hatch to keep the flow velocity under 3 m s^{-1}.

$$\dot{m}_{flow} = \frac{\dot{m}_{flow,old}\, d + A_{flow}\, \Delta p^2 + B_{flow}\, \Delta p}{d+1} \qquad \textbf{Eq. (11-1)}$$

with:

- $\dot{m}_{flow}$ [kg s^{-1}] - mass flow rate through the hatch
- $\dot{m}_{flow,old}$ [kg s^{-1}] - mass flow rate through the hatch from last time step
- d [-] - damping constant (must be greater 1; 1.5 used)
- A_{flow} [s^3 m^2 kg^{-1}] - first constant ($\frac{7}{1.32*10^{12}}$)
- B_{flow} [m s] - second constant ($\frac{1813}{6.6*10^{8}}$)
- Δp [Pa] - pressure difference between two connected decks

The IMV system is completely rewritten with now two options. For the racetrack option, a IMV system is simulated, where air flows from the top deck (deck 1) through every deck till the lowest deck and then back to the top deck. The nominal volume flow through the IMV on ISS is 120 cfm. For the SpaceHab, this flowrate had to be sized, based on the number of passengers (n_{CM}). For this, a linear function is used (Eq. (**11-2**)) to determine a flow-factor (f_{FF}) which is then applied to the original flow rate. The linear function below is 1 for 3 passengers and 12 for 100 passengers.

$$f_{FF} = \frac{n_{CM}\,11}{97} + \frac{64}{97} \qquad \textbf{Eq. (11-2)}$$

The other option consists of two buffer tanks for the ACLS system, which is separately connected to every deck. The first buffer tank is used for the inflow and the second one for the outflow. Because a manual solver is used, the flow rate into the buffer tank and the different decks must first be determined. An equal flow rate over all decks was shown to be not feasible, since the CO_2 level in some decks would then exceed the SMAC limits. The maximum inflow into ACLS is 0.122 kg s^{-1} multiplied with a sizing factor which depends on the size of the crew. To this maximum inflow, a normalized ratio factor is applied which depends on the partial CO_2 pressure of the deck. For the outflow, the same ratio factor is used and applied to the maximum outflow of ACLS which is the sum CCA outflow and the OGS airflow.

11.1.1.3 ACLS for Atmosphere Revitalization

The ACLS system consist of the carbon dioxide concentration assembly (CCA) for CO_2 removal, the carbon dioxide reprocessing assembly (CRA) for CO_2 reduction, and the oxygen generation assembly (OGS) which is an electrolyze to produce H_2 for the CRA and O_2 for breathing. The simulated ACLS model is integrated as one integrated subsystem which safes simulation time and makes it easier to integrate into a parent system. The components of the system are described in chapter 6.3 and a schematic of the implemented V-HAB model from [119] is given in Figure 11-9 below. The shown connections in this figure that come from or lead to the outside are the interfaces of the ACLS subsystem to the parent system. The rework of this system consists of a resizing of the different stores, HX, and flowrates. This approach was chosen to minimize the impact on simulation time. If several different ACLS subsystems would be simulated all included stores, branches and processor would have multiplied. Since the ACLS subsystem is the most simulation time consuming component, this would lead to unfeasible simulation durations. Depending on the input parameters, the program determines the required resizing information from the csv file. Every store and flow of manual branches is increased linear, based on this information. As the mass of the astrine is a result of the CO_2 capacity, the maximum necessary capacity must first be determined. This is done with the help of the calculateMaxDesorbedMass function in class AbsorberProc. This class is a slight adjusted version of the original class to make it possible to calculate the maximum desorption mass ($m_{CO_2 capacity,max}$) and therefore to resize the necessary astrine mass. The final mass of the astrine ($m_{Astrine}$) in every bed can then be calculated with Eq. (11-3), where 0.07 stands for the adsorption capacity of astrine at 2 mmHg CO_2 in the air and a safety margin of 33 % is applied.

$$m_{Astrine} = \frac{m_{CO_2 capacity,max}}{0.07} \, 1.33 \qquad \textbf{Eq. (11-3)}$$

Other important changes are, that ACLS uses a low temperature loop (LTL) with 277.55 K (4.4 °C) instead of the original 290.15 K (17 °C), which makes the integrated CHX much more effective and removes more humidity from the outgoing air.

Also changed is the cooling of the Sabatier reactor (CRA). The original model assumes air cooling. This has shown to be not feasible for an up-sized system, since it would heat up the atmosphere considerably. Instead it is cooled by a HX, connected to the LTL.

The original OGA control logic is based on the O_2 percentage in the atmosphere. This could lead to an ever-increasing pressure, for example the temperature is increased, the total pressure rises and therefore the portion of the oxygen in the air is lowered. In this situation, the old OGA logic produces more oxygen and therefore the total pressure rises even higher and with it the temperature. This could lead to an ever-growing situation. Therefore, the new logic is based on the partial pressure which has shown good stability.

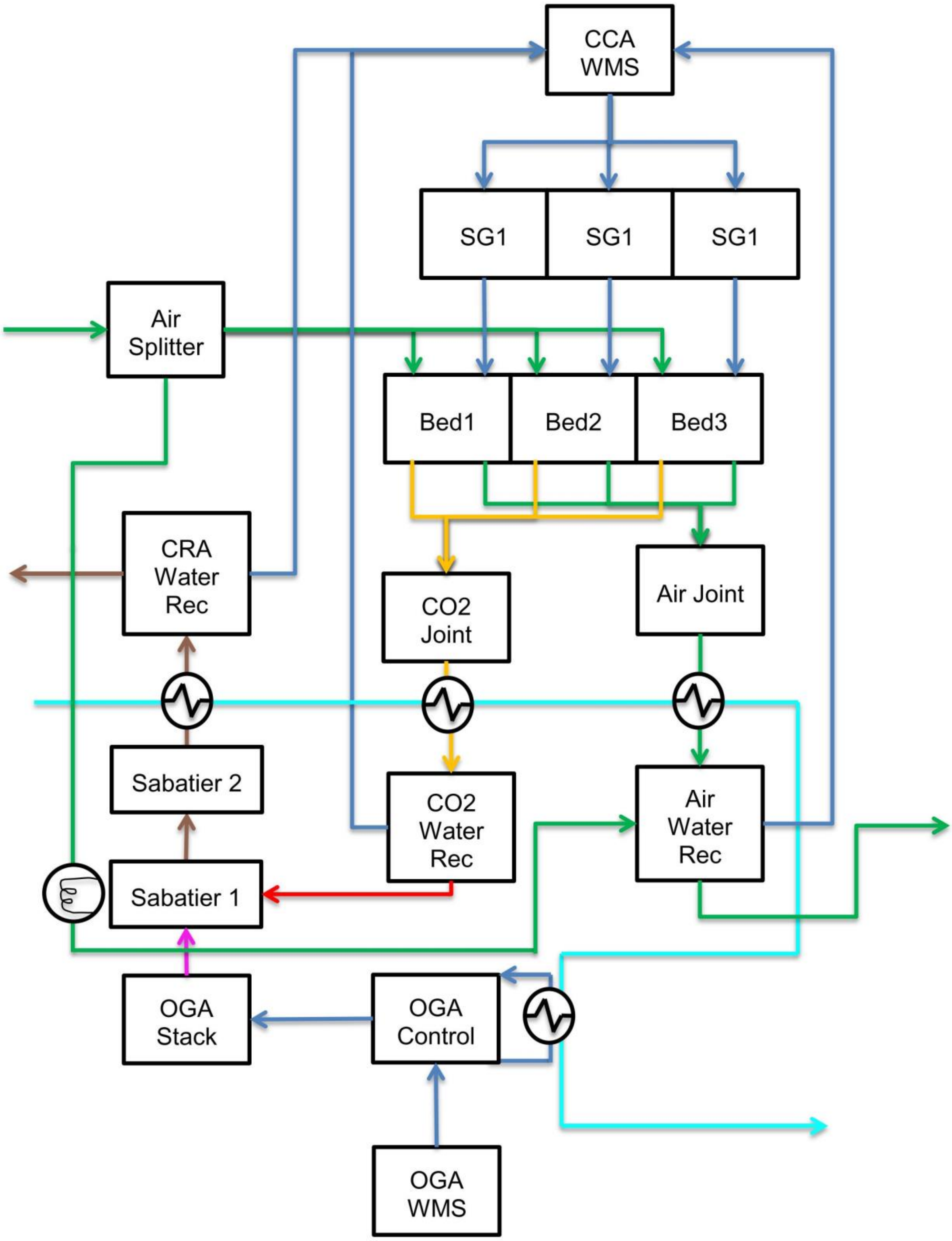

Figure 11-9: V-HAB ACLS functional block diagram [119, p. 50]

11.1.2 Simulation Results

The results of the V-HAB model where used to refine the LiSTOT calculations and vice versa, since the development is an iterative approach.

Overall 32 simulations with variable parameters where done and verified. The variables where:

- Crew size of 12, 40, or 100
- SpaceHab or Evolved-SpaceHab design
- Used Schedule (6 different ones are considered, see 3.2.3)
- IMV loop (deck-mode or racetrack, see 10.2)
- Simulation time

The simulation time is constraint, since the simfactor is 4.9 for 12 crewmembers and 3.5 for 100 CM. This means, that for the simulated 14 days of a system with 100 CM, MATLAB needs 4 days of computation time. The used computer has an Intel® Core™ i5-4460 Quad-Core CPU with 3.20 GHz, 16 GB DDR3 RAM, and a SSD hard drive. Therefore, the simulation time was normally restricted to 7 days, or 3 days for the racetrack simulations. Longer simulations have shown, that these times are enough to reach a daily repeating behavior or to see a trend. For the 100 CM system, the limited RAM prevents the plotting of times longer than 10 days, therefore a maximum of 10 days is used for this system.

In the following chapters, the results from these simulations are presented. First the considered system for the Final Design (chapter 10) is verified. Second, a short general survey about the differences that the schedules have on the atmosphere is given. In the final step, it is shown, that some schedules are not feasible, even when considering the crew member reduction due to volume constraints (see 3.2.3).

11.1.2.1 Final Design Verification

The simulation of the final design with 100 passengers on the Evolved-SpaceHab design were constraint to 10 days for the reasons mentioned above. The One Hour Shift Schedule (3.2.3.2) was used for the verification. Both IMV loops were verified, while the total simulation time of the racetrack loop was reduced to 3 days. The trends of the different loops are comparable, while the racetrack loop fluctuates more, as can be seen Figure 11-12.

As can be seen in Figure 11-10 the total pressure is within the specified boundaries most of the time. In the morning, between 8:00 and 12:00 a.m., the total pressure is up to 1.5 kPa too high in the crew quarters for around 30 minutes and a bit lower on the other decks. This is caused by relatively high temperatures (see Figure 11-14), rising partial pressures (see Figure 11-11 and Figure 11-12), as well a high relative humidity (see Figure 11-16). During this time, the metabolic produced CO_2 and humidity as well the consumed O_2 begin to increase, and the THC subsystem needs some time react on this. This can be seen on the following times till 7 p.m. (19:00), where the metabolic values are still the same, but the total pressure is falling. The requirement of 102.7 kPa maximum total pressure (4.2.1.a) is adapted from ISS requirements where it is limited due to the aluminum pressure shell. For a final conclusion on the maximum allowable total pressure for the SpaceHab, it has to be considered that the pressure shell material is composite, which has normally a much higher strength.

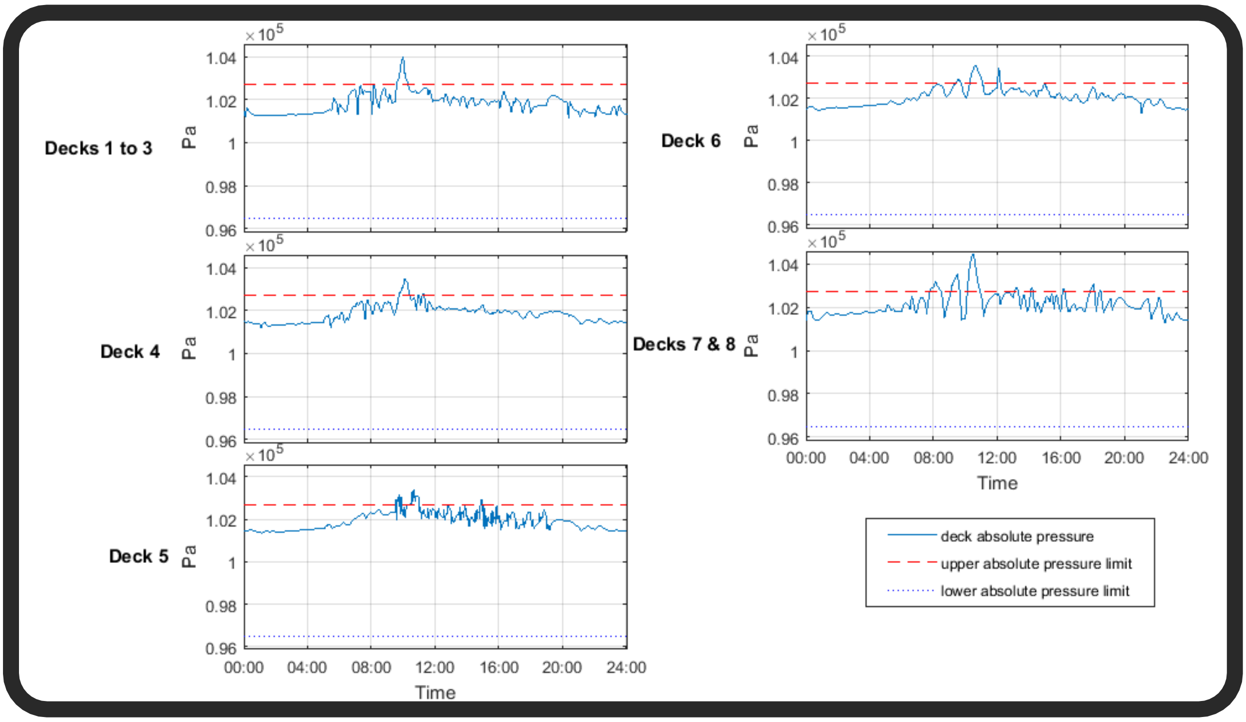

Figure 11-10: Verification plot of the total pressure for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over one day

The partial O_2 pressure is always within the boundaries of 19.5 to 23.1 kPa, with a mean level of around 21.3 kPa. During sleep times, the pressure rises and declines during the day. The highest fluctuation can be seen during exercise times in deck 5, as expected.

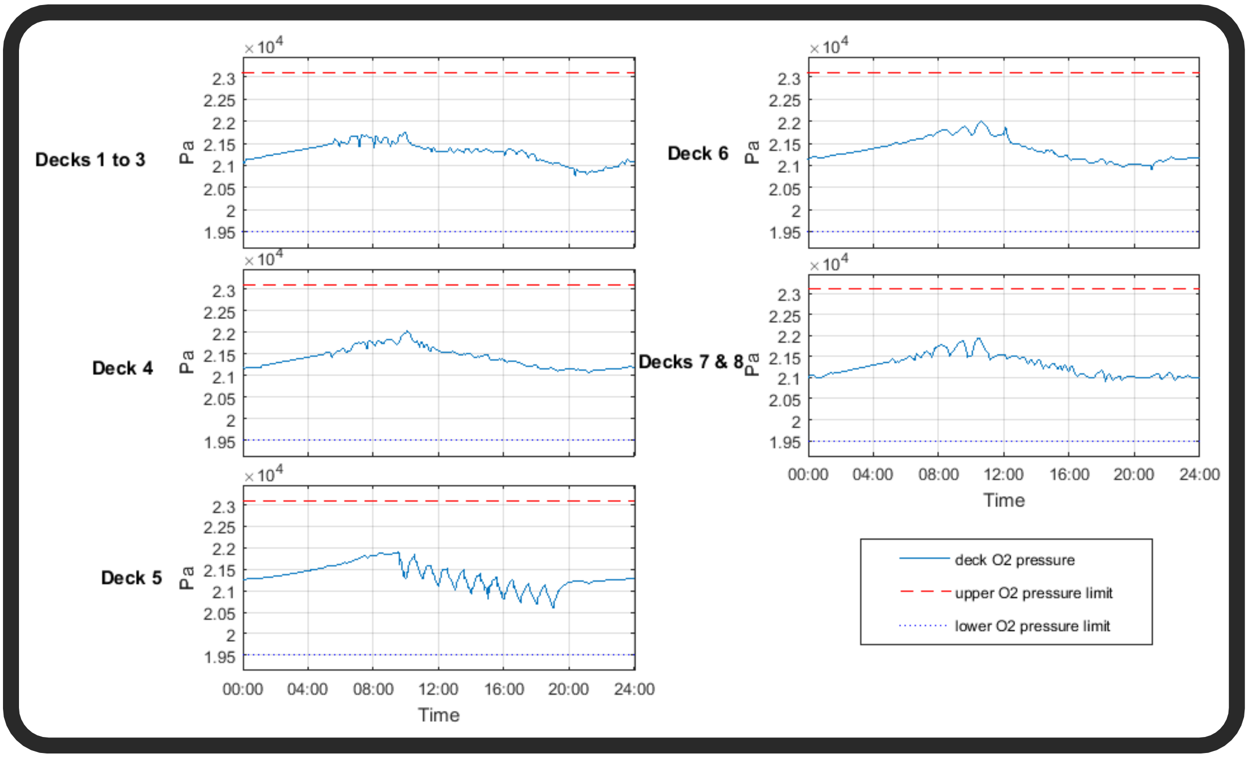

Figure 11-11: Verification plot of the partial oxygen pressure for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over one day

The partial CO_2 pressure is of special interest, because the CO_2 removal is the most dynamic component in the ECLSS. As can be seen in Figure 11-12, the nominal level rises during activity times, especially during workout. The blue line is the IMV deck-loop and the orange line is the racetrack loop. The highest level for the deck-loop is reached after the last workout session at 7 p.m. (19:00) with just around the pressure limit of 700 Pa. This shows the robustness of the calculated system in LiSTOT. The mean partial CO_2 pressure over the whole day is around 200 Pa. Interestingly, the highest peak for the racetrack loop is not in deck 5 but instead in the crew quarter decks 7 and 8. This is caused by the fact that the produced CO_2 during workout flows into the upper decks through the IMV. Overall it can be seen, that the CO_2 partial pressure is more uniform over the decks as in the deck-loop case. To show that no mentionable differences for a simulation over several days occur, the partial CO_2 pressure plot over 10 days is shown in Figure 11-13.

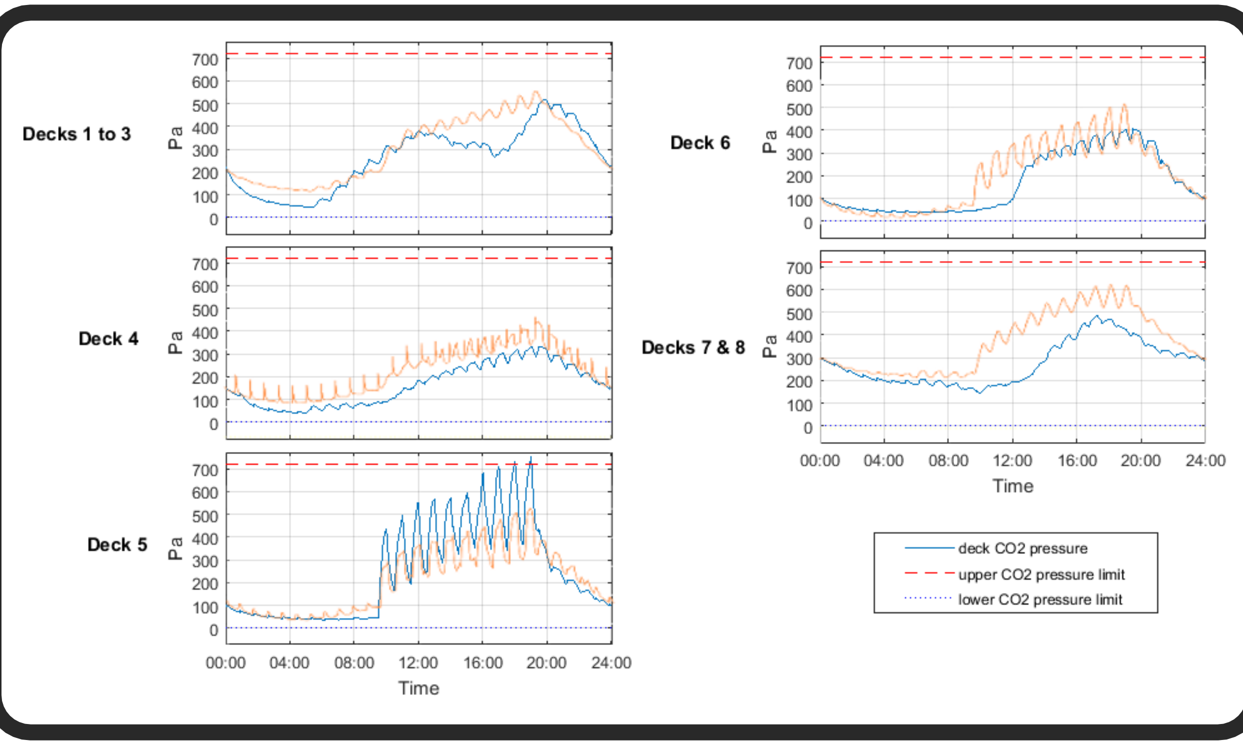

Figure 11-12: Verification plot of the partial carbon dioxide pressure for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over one day

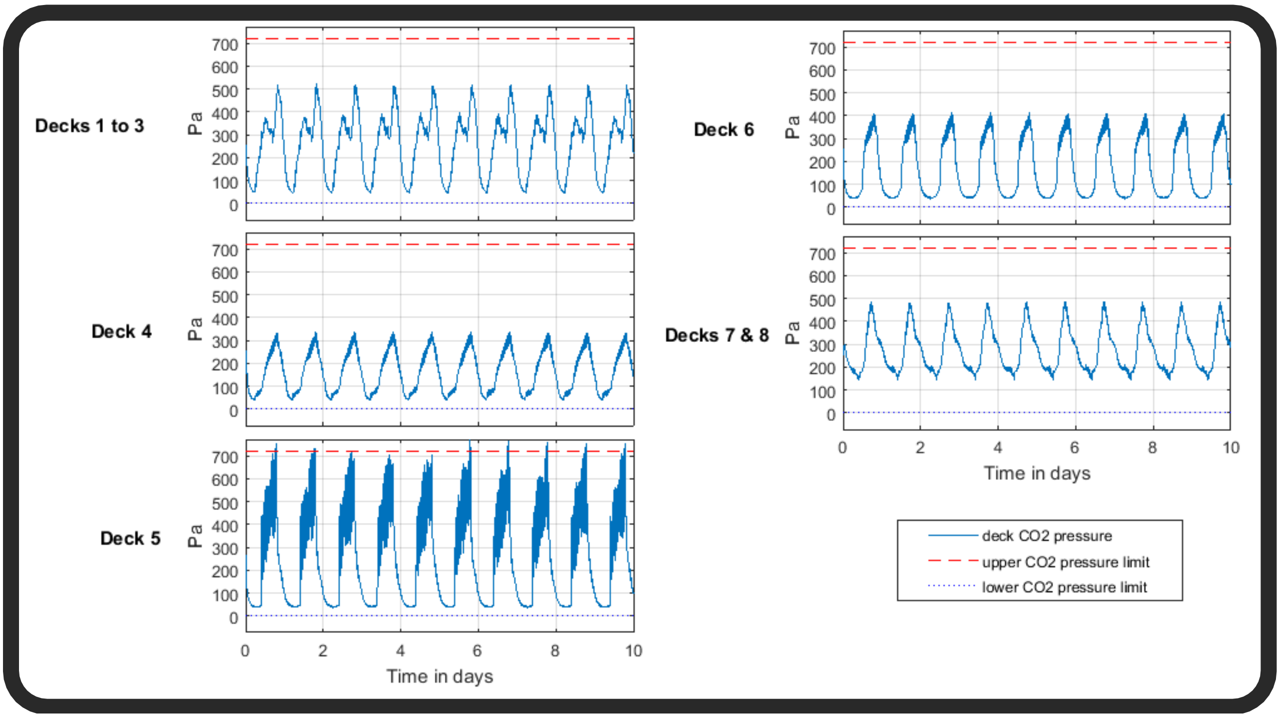

Figure 11-13: Verification plot of the partial carbon dioxide pressure for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over ten days

The temperature and dew point plot is shown in Figure 11-14. Besides some very brief peaks of the temperature, which are negligible, the temperature stays within the boundaries of 291.5 to 299.8 K (18.35 – 26.65 °C). The requirement to stay within 1.1 K (4.2.2.a.iii) of the selected temperature of 295.15 K (22 °C) is not manageable. Especially on decks 1 to 3 and 7 to 8, the temperature fluctuates by 2 K around the selected temperature. This is partially because these two areas are not simulated as separate decks. Instead, deck 1, 2, and 3 are assumed to be one big volume of 454.58 m³ with a crew size of up to 80 people. For the decks 7 and 8, the combined volume is 620.48 m³ with up to 100 people. The measured dew point is relatively high during activity times. For the crew quarters, it is even slightly above the upper boundary of 288.7 K. Again, this could be caused by the chosen simulation structure. The dew point on deck 6 always stays on an elevated level, because the relative humidity in this level is not removed by the CCAAs (see Figure 11-16). This is because the temperature is relatively low during times without a present crew on the deck and therefore the CCAAs are working at minimum. For a clearer difference of the distance between the dew point and the temperature, see Figure 11-15. This distance is important, since it marks the safety margin to prevent condensation in the cabin.

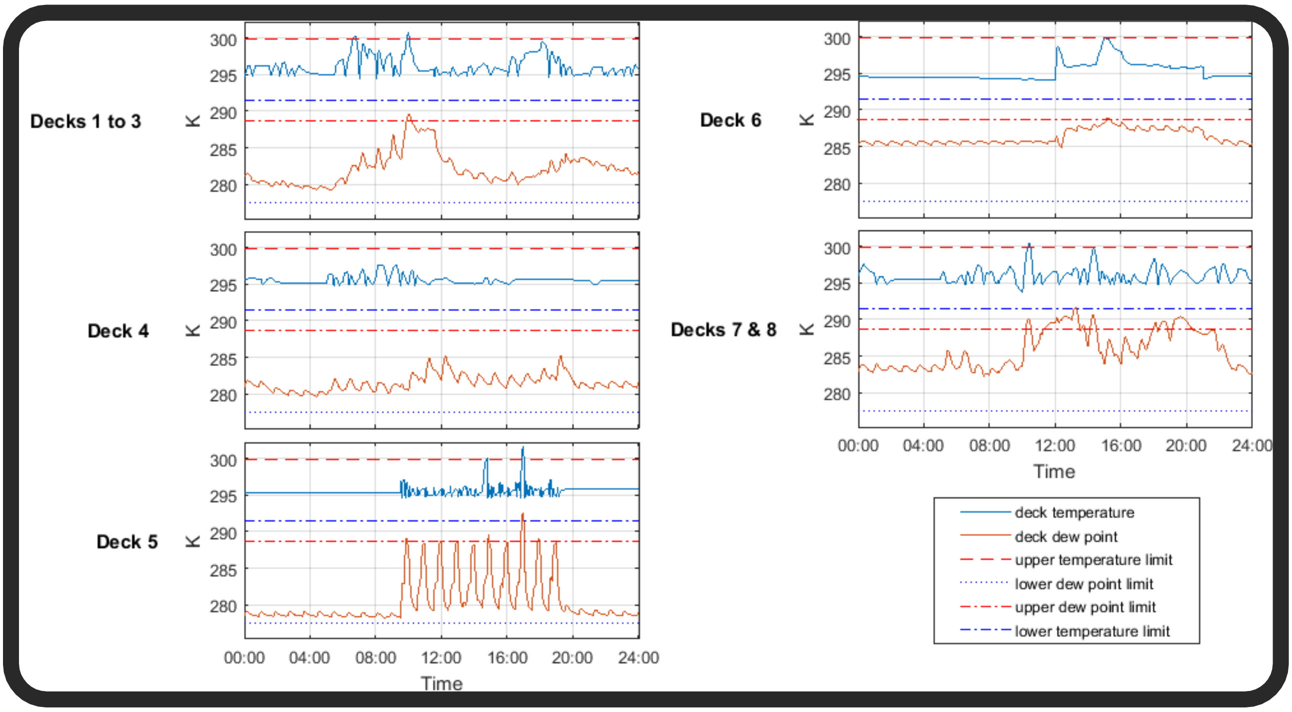

Figure 11-14: Verification plot of the temperature and dew point for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over one day

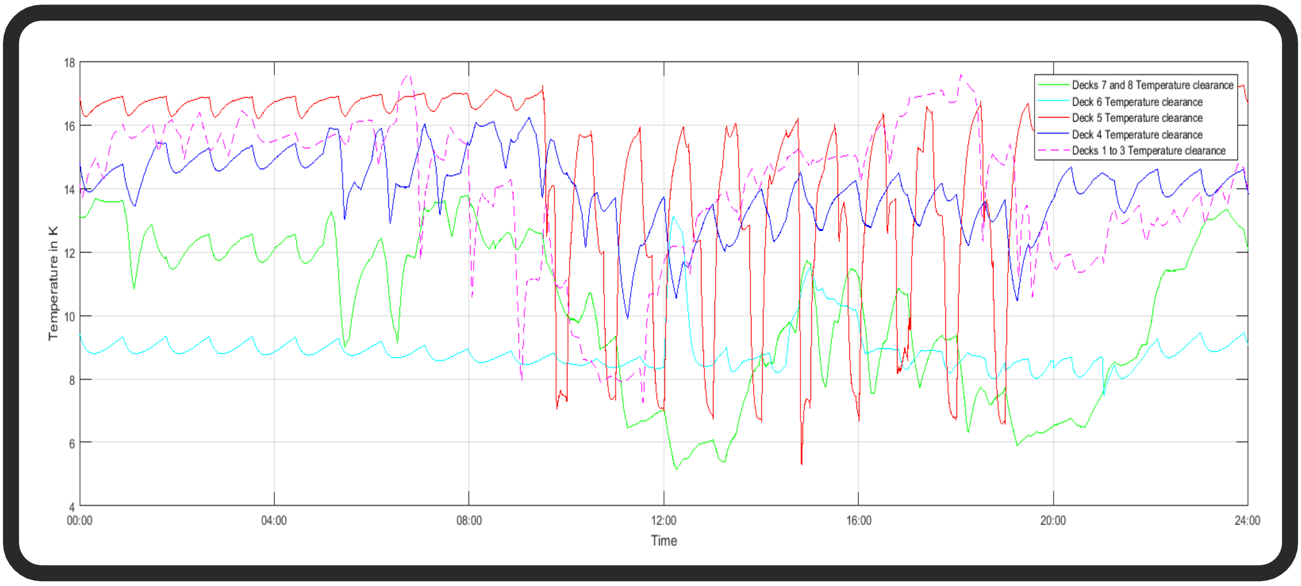

Figure 11-15: Clearance between dew point and temperature for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over one day

As can be seen in Figure 11-16, the relative humidity (RH) stays below the upper boundary of 70 %. The short peaks on deck 7/8 at around 12:00 are insignificant. Besides deck 6, the mean RH is around 42 % and therefore on a good level.

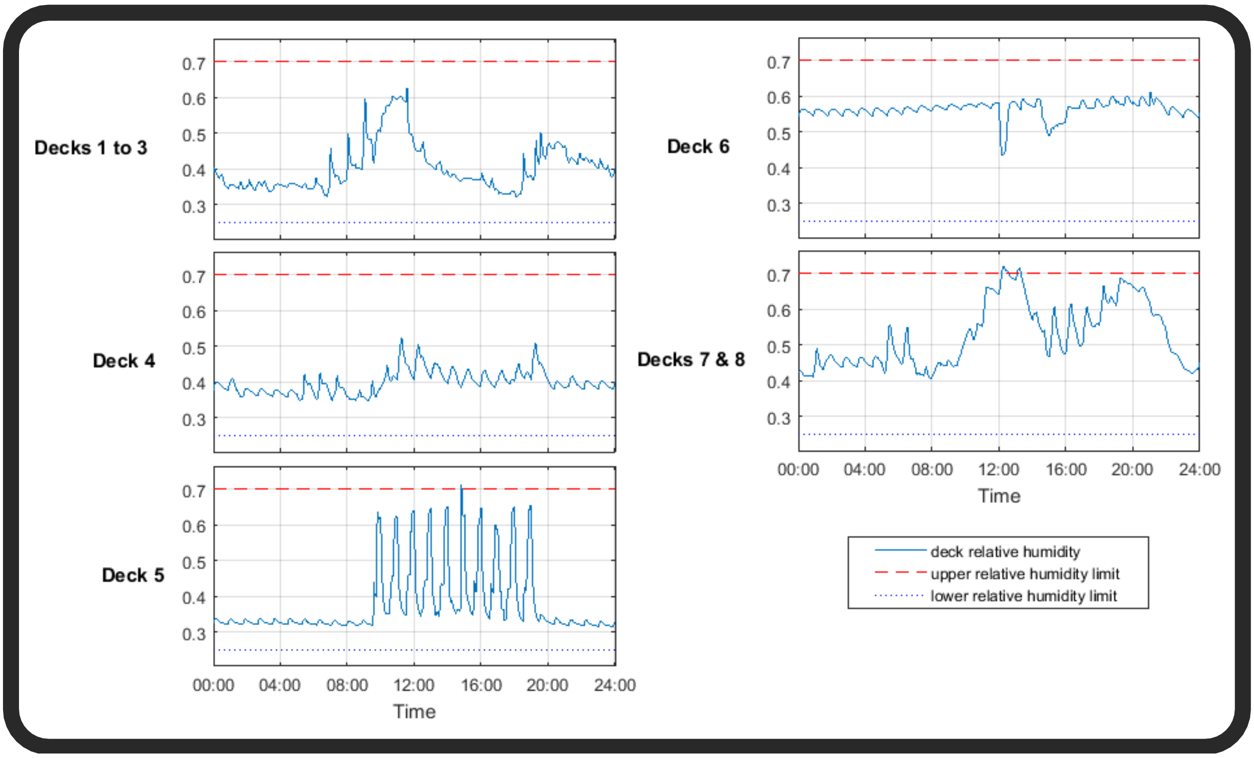

Figure 11-16: Verification plot of the relative humidity for Evolved-SpaceHab, 100 passengers, and one hour shift schedule over one day

As the verification of the simulation results in this section has shown, the atmospheric part of the designed ECLSS through LiSTOT is feasible.

11.1.2.2 Schedule Comparision and Verification

Now the impact of the different schedules on the cabin atmosphere is analyzed and compared. For this investigation, the SpaceHab design is chosen, since the volume is considerably smaller than the Evolved-SpaceHab and therefore changes are more dynamic since the volume buffer is smaller. The crew size of all schedules is 40, instead of the Crowd Schedule and the Emergency Schedule, which has a limitation of 20 passengers for the SpaceHab design (see 3.2.3.6). These two schedules are marked as dash-dotted lines in the following plots.

As can be seen in Figure 11-17, the temperature of the Eight-Hour Shift Schedule is above the upper limit of 299.8 K (26.65 °C) several times on decks 1 to 3. Since these decks have limitations as described in the section before and the peaks are of very brief periods this is no major concern. Additionally, it must be considered that exercise is done on deck 3 and therefore the variation in temperature could be higher. Of concern are the very low temperatures for the Crowd Schedule and the Emergency Schedule on deck 6, especially as the dew point in this time frame (10 a.m. to 11 a.m.) is also very high. The dew point of the Alternating Schedule is the highest oscillating one. It exceeds the upper dew point boundary on decks 1 to 3 and deck 6 several times. There are no active passengers considered on deck 5 for the SpaceHab design and therefore only minor changes of temperature or dew point are observable.

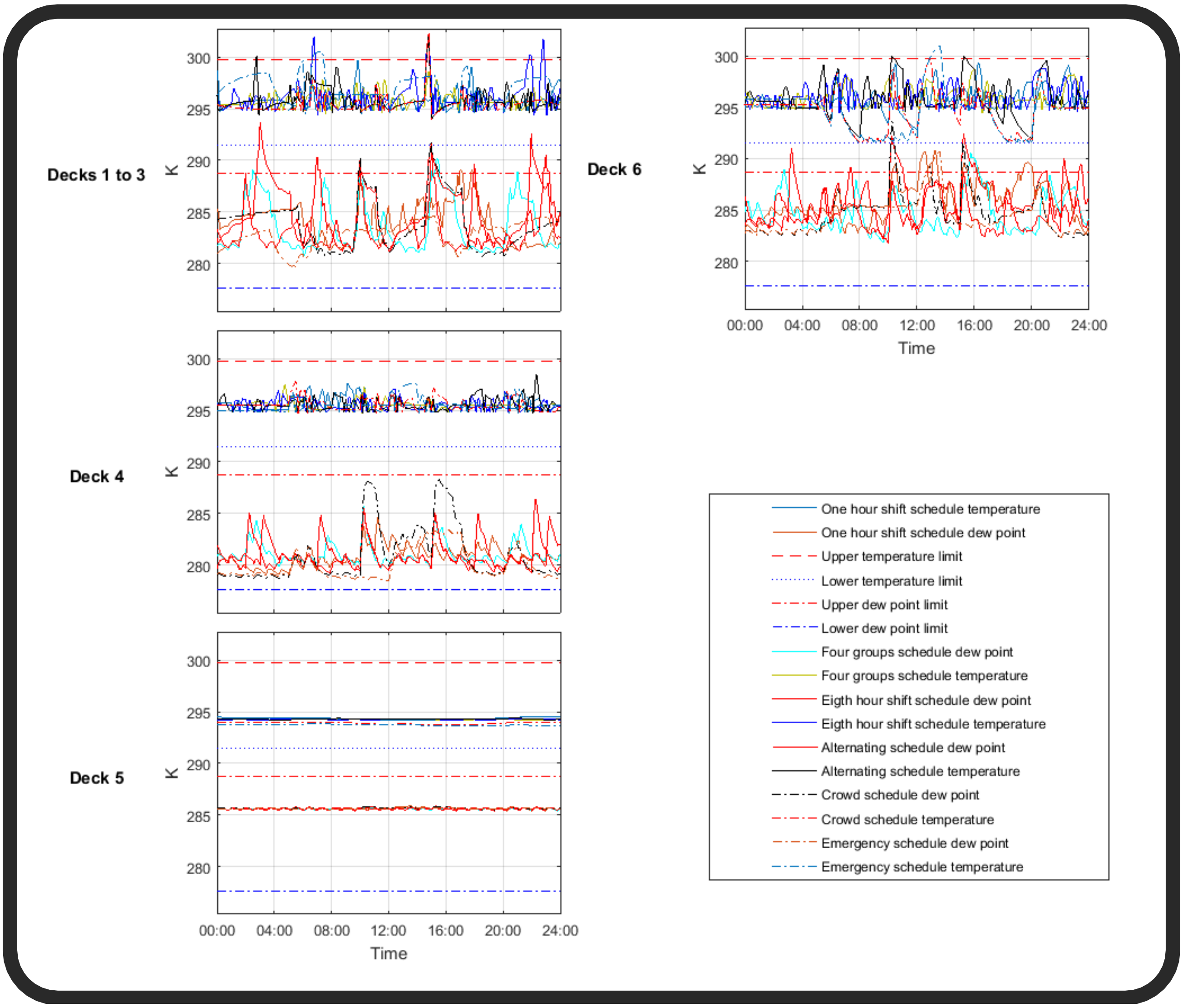

Figure 11-17: Comparison plot of temperature and dew point between the schedules

The same behavior as for the dew point can be seen for the relative humidity in Figure 11-18. The Alternating Schedule has the worst performance as it exceeds the limits several times for short durations. Likewise, the crowd schedule is often near the boundary with one major exceeding on deck 1 to 3.

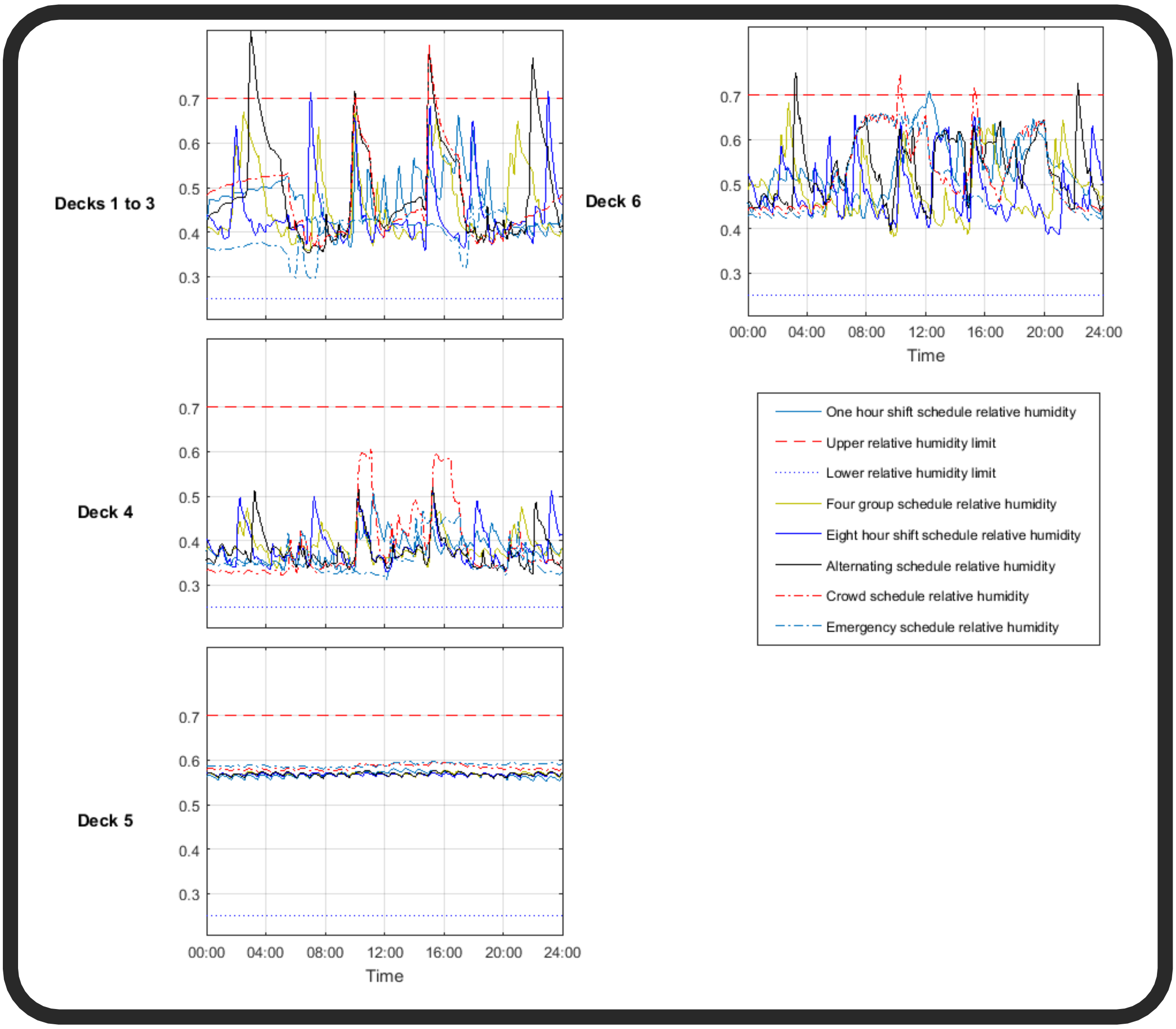

Figure 11-18: Comparison plot of relative humidity between the schedules

All schedules are within the O_2 partial pressure boundaries as can be seen in Figure 11-19.

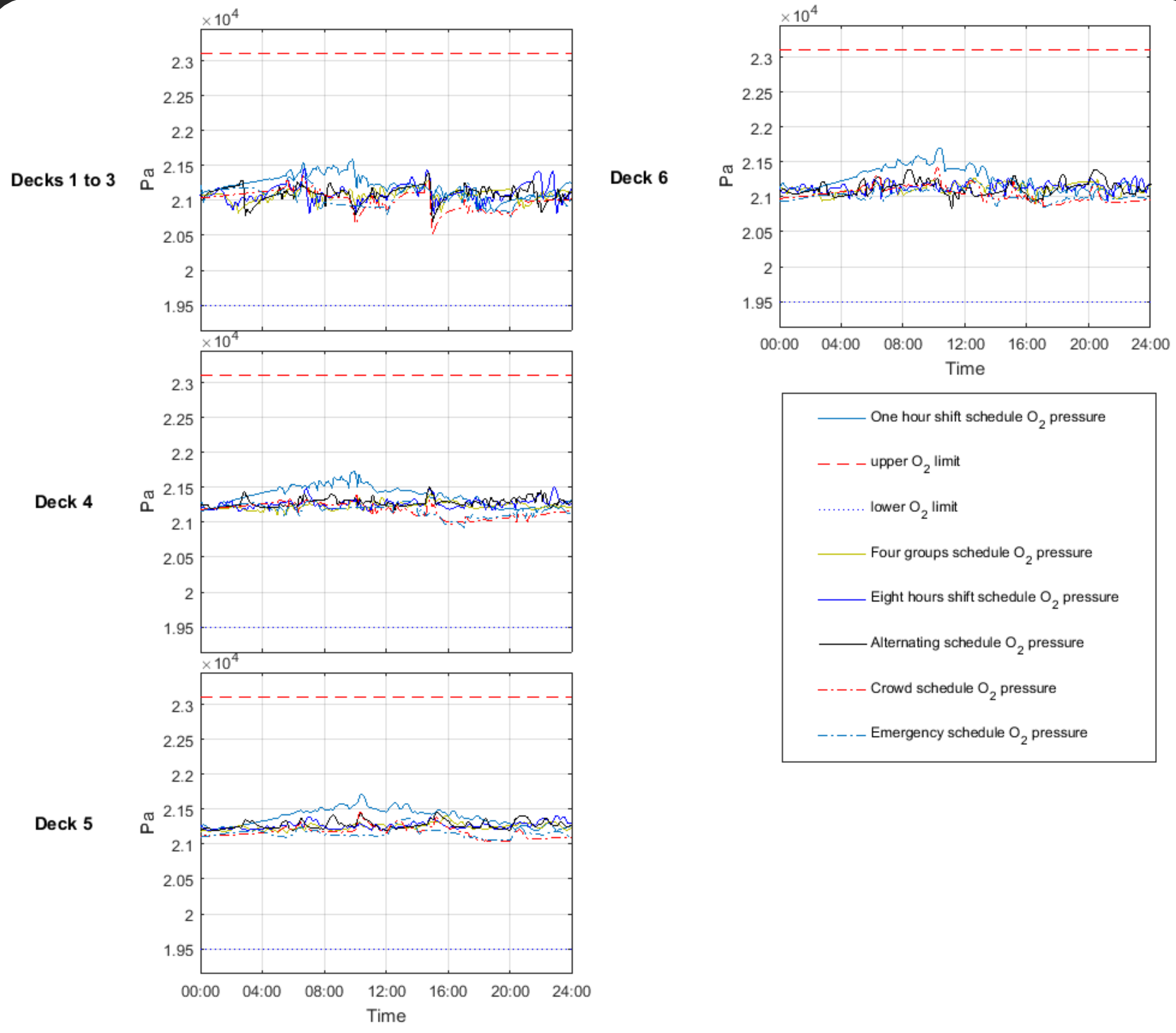

Figure 11-19: Comparison plot of partial O_2 pressure between the schedules

As can be seen in Figure 11-20, all schedules are below the boundary for the partial pressure of CO_2. The schedules with the highest peaks are the Crowd Schedule and the One Hour Shift Schedule at around 500 Pa for very short periods during workout. It can be said that all schedules fulfill the requirements for the CO_2 scrubbing.

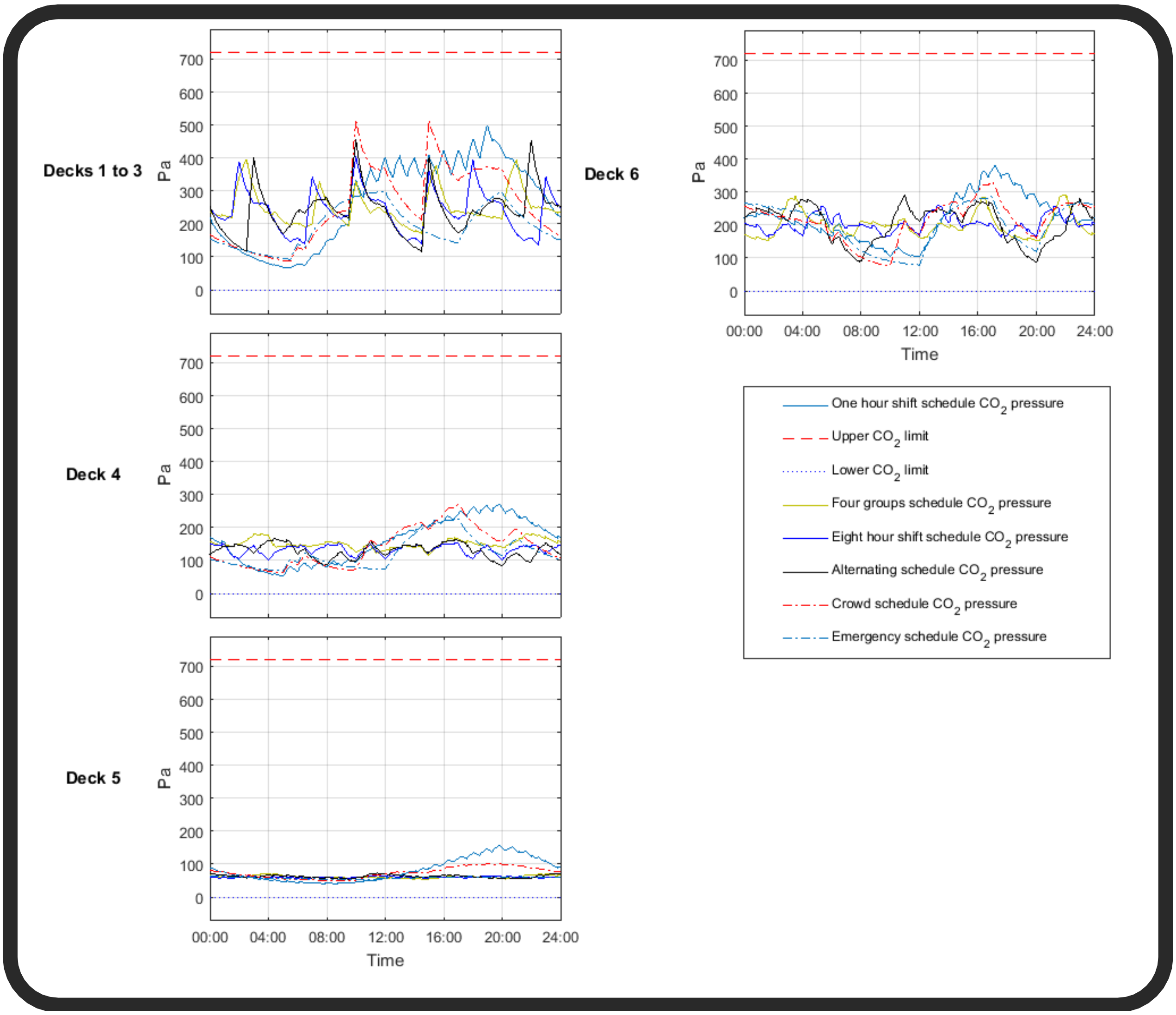

Figure 11-20: Comparison plot of partial CO_2 pressure between the schedules

As can be seen by this analysis, the Alternating Schedule and Crowd Schedule should not be considered as feasible schedules because their impact on the ECLSS ae too large. For example, the number of CHX is the same for the One Hour Shift Schedule, the Alternating Schedule, as well for the Crowd Schedule, but the last one has only half as many passengers as the other ones.

11.1.2.3 Water use of the Carbon Dioxide Concentration Assembly

The water consumption of the Carbon Dioxide Concentration Assembly (CCA) of the advanced closed loop system (ACLS) was measured during the simulations.

The water content over 10 days in the water management subsystem (WMS) tank of the ACLS for the One Hour Shift Schedule and 100 crew members can be seen in Figure 11-21. The original size of the store is assumed by [119] to 0.01 m^3 and is resized for 100 CM to 0.29 m^3 to accommodate 290 kg water. This water is used by the 3 CCA beds to scrub CO_2. When the tank is below 50 % of the original level, it is refilled within 100 seconds until it contains 95 % of the initial mass. This happen about every 63 hours for the analyzed system. It can also be seen in Figure 11-21, that the water is not removed linear since humidity from the air is also used. The higher gradients are during sleep times when less metabolic humidity is produced. The schedule is very important for this process. As can be seen in Figure 11-22, the water level is oscillating over several days and requires no refill even after one week.

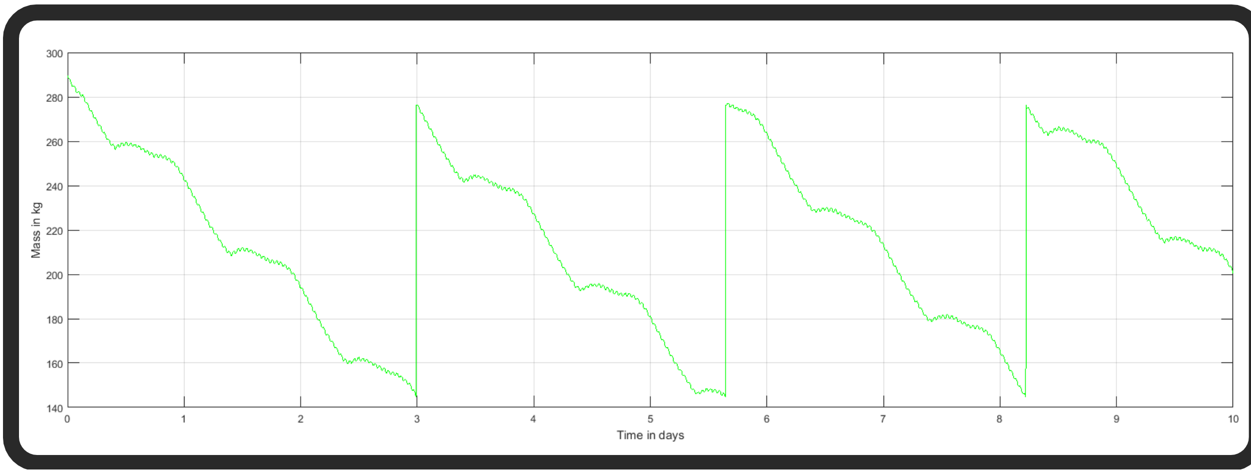

Figure 11-21: WMS tank water content over 10 days for one hour schedule and 100 CM

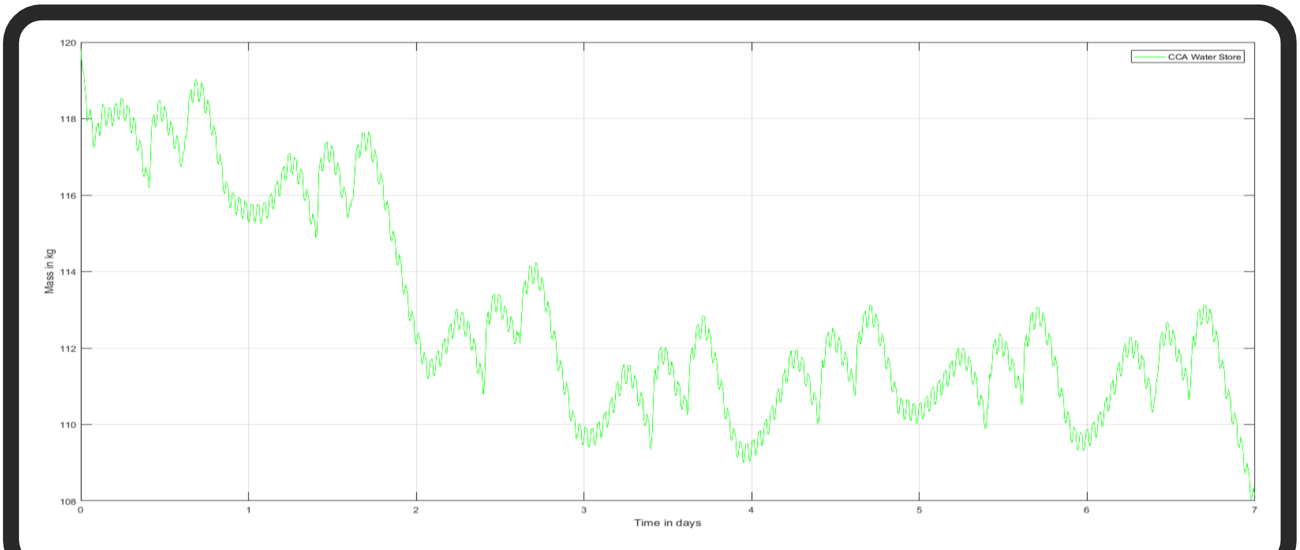

Figure 11-22: WMS tank water content over one week for crowding schedule and 40 CM

The measured WMS consumption rates for different crew sizes and schedules are listed in Table 11-1. For values with a relational operator, no refill was done till the end of the simulation time and therefore the consumption rate must be estimated. This analysis revealed, that schedules that have exercise times more distributed over the day needs much less water. For example, the one hour shift schedule distributes the workout time over 9 hours while the 8-hour shift schedule has the workout evenly distributed over the day.

Table 11-1: Measured WMS consumption rates over different schedules and crew sizes

Schedule	SpaceHab 12 CM	SpaceHab 40/20 CM	Evolved-SpaceHab 40/30 CM	Evolved-SpaceHab 100 CM
One hour shift	0.3462	0.9267	0.756	2.0635
8 hour shift	-	0.6814	0.375	-
Alternating	-	-	0.5093	-
Crowd	-	<0.18	<0.38	-
Emergency	-	0.3144	<0.34	-

11.1.2.4 Carbon Dioxide Reduction Venting Rate

While there is a built-in air and water safe capability in the ACLS, some air (N_2, O_2, and H_2O) is still vented after the carbon dioxide reduction assembly (CRA). In the following table, the total vented masses for the trade cases are presented. Since it was not possible to simulate the full 88, respectively 211 days, an extrapolation of the simulated 14 days must be used. A linear approximation of the measured value is applied. The results are shown in Table 11-2 below. As can be seen, there is a considerable mass loss though the CRA venting, especially for 40 and 100 crew member size system. The ratio of water mass loss due to CO_2 venting for Case1 is around 8 %, while for 40 CM it is a tremendous 56 % and even 74 % for 100 CM. The original CRA is developed for a crew of 3 and only sizing factors where applied. Therefore, these values should only be used with care. Please see also chapter 12.2 for a discussion about this.

Table 11-2: Extrapolated venting rates of CRA for the trade cases

	N2	O2	H2	CO2	H2O	CH4
Case1	28.10	8.52	8.88	617.70	47.54	228.77
Case2	80.84	25.47	37.32	2,024.73	1,143.80	756.46
Case3	196.10	25.47	36.41	2,024.16	1,143.92	765.30
Case4	463.85	149.69	211.93	12,238.13	9,069.20	4,430.00

11.2 Design Verification

The purpose of this chapter is the clear presentation, that the requirements stated in chapter 4 Requirements and Constraints are satisfied.

11.2.1 Atmosphere Control and Supply Verification

The ACS subsystem has to fulfill 12 requirements and 5 constraints outlined below. As can be seen, all are satisfied.

Table 11-3: Atmosphere control and supply verification matrix

Requirement	Status	Reference
4.2.1.a Control Atmosphere Total Pressure	fulfilled[43]	10.1, 10.6.1
4.2.1.b Relieve Overpressure	fulfilled[43]	10.1
4.2.1.c Manage Leakage	fulfilled[43]	Figure 10-1
4.2.1.d Add Metabolically Inert Gas to Atmosphere	fulfilled[43]	10.1
4.2.1.e Control Oxygen Partial Pressure	fulfilled[43]	10.1
4.2.1.f.i & 4.2.1.f.ii Add Oxygen to Atmosphere	fulfilled[43]	10.1
4.3.1.a Detect Rapid Decompression	fulfilled[43]	10.1
4.3.1.b Recover from Rapid Decompression	fulfilled[43,44,44]	10.1, Table 10-1, Table 10-2
4.4.1.a Supply Inert Gas	fulfilled[43,45]	10.1
4.4.1.b Store Inert Gas	fulfilled[44, 44]	Table 10-1, Table 10-2
4.4.1.c Supply Oxygen	fulfilled[43]	10.1
4.4.1.d Store Oxygen	fulfilled[44]	Table 10-1, Table 10-2
4.1.d Power Consumption	considered	Table 10-1, Table 10-2
4.1.f Thermal Heat Production	considered	Table 10-1, Table 10-2
4.1.m Reliability	considered	Table 9-9
4.1.t Volume	considered	Table 10-1, Table 10-2
4.1.v Mass	considered	Table 10-1, Table 10-2

[43] PCAs used for monitoring and control of total and partial pressures as well for supply of O_2 and N_2.
[44] Storage tanks are sized to provide enough O_2 and N_2 for one repressurization as well leakage.
[45] NIAs used supply N_2 for equipment.

11.2.2 Temperature and Humidity Control Verification

The THC subsystem has to fulfill 9 requirements and 5 constraints as can be seen in the breakdown of the following table.

Table 11-4: Temperature and humidity control verification matrix

Requirement	Status	Reference
4.2.2.a.i to 4.2.2.a.iii Control Atmospheric Temperature	fulfilled[46,47]	6.2.2
4.2.2.b Remove or Add Sensible Heat	fulfilled[46]	6.2.2, Table 10-3
4.2.2.c.i & 4.2.2.c.ii Control Atmospheric Humidity	fulfilled[46]	6.2.2
4.2.2.d Remove or Add Moisture	fulfilled[46]	6.2.2, Table 10-3
4.2.2.e Ventilation Velocities in the Crew Habitable Volume	fulfilled[48]	Table 10-3
4.2.2.f Exchange Atmosphere between Modules	fulfilled[49]	Table 10-3
4.4.2.b.i to 4.4.2.b.iii Accept Thermal Energy	fulfilled[46,47]	6.2.2
4.4.2.c Reject (Dispose of) Excess Thermal Energy	fulfilled[50]	6.2.2
4.4.2.d Reuse Thermal Energy	not considered	
4.1.d Power Consumption	considered	Figure 10-2, 10.5
4.1.f Thermal Heat Production	considered	10.5
4.1.m Reliability	considered	Table 9-10
4.1.t Volume	considered	10.5
4.1.v Mass	considered	10.5

[46] CHX are used to remove heat and humidity form the atmosphere.
[47] Cold plates are used to provide cooling of equipment. Since this not part of the ECLSS, it not further analyzed.
[48] Diffusor and BFE are used for ventilation. No detailed analysis of the cabin velocities where done.
[49] The integrated IMV system exchange air between the different decks.
[50] The CCAA has a cooling fluid interface to the low temperature loop subsystem.

11.2.3 Atmosphere Revitalization Verification

As can be seen in Table 11-5, the 10 requirements and 5 constraints for the AR subsystem are fulfilled or considered respectively.

Table 11-5: Atmosphere revitalization verification matrix

Requirement	Status	Reference
4.2.3.a Control Partial Pressures of Atmospheric Contaminants	fulfilled[51,52]	6.3.7, 6.3.17, Table 10-10, Table 10-11
4.2.3.b Remove Gaseous Atmospheric Contaminants	fulfilled[51,53]	6.3.7, 6.3.20, Table 9-11, Table 10-10, Table 10-11
4.2.3.c Control Airborne Particulates	fulfilled[54]	8.3, Table 10-10, Table 10-11
4.2.3.d Remove Airborne Particulates	fulfilled[54]	8.3, Table 10-10, Table 10-11
4.2.3.e Control Microbes	fulfilled[54]	8.3, Table 10-10, Table 10-11
4.2.3.f Remove Airborne Microbes	fulfilled[54]	8.3, Table 10-10, Table 10-11
4.3.2.a Detect Hazardous Atmosphere	fulfilled[55]	8.3, Table 9-11, Table 10-10, Table 10-11
4.3.2.b Recover from Hazardous Atmosphere	fulfilled[51,53]	6.3.7, 6.3.20, Table 9-11, Table 10-10, Table 10-11
4.4.3.a (Re)generate Oxygen	fulfilled[52]	6.3.17, Table 10-10, Table 10-11
4.4.3.b Process Gaseous Wastes	fulfilled[56]	6.3.11, Table 10-10, Table 10-11
4.1.d Power Consumption	considered	10.5
4.1.f Thermal Heat Production	considered	10.5
4.1.m Reliability	considered	9.5.3
4.1.t Volume	considered	10.5
4.1.v Mass	considered	10.5

[51] SAWD is considered to remove CO_2 from the atmosphere.
[52] SFWE is considered to electrolyze water and replenish O_2.
[53] TCCS is considered to remove gaseous contaminants like ammonia.
[54] BFE are used to filter the air and remove particulates and airborne microbes.
[55] MCA is considered to measure the contents of the atmosphere.
[56] Sabatier is considered to process removed CO_2.

11.2.4 Water Recovery and Management Verification

Overall 7 requirements and 5 constraints relating to the WRM subsystem has to fulfilled.

Table 11-6: Water recovery and Management verification matrix

Requirement	Status	Reference
4.2.4.a Control Water Quality	fulfilled[57]	6.4.9
4.4.4.a Supply Water	fulfilled	Table 10-15
4.4.4.b.i to 4.4.4.b.iv Store Water	fulfilled	Table 9-14, Table 10-13, 0
4.4.4.e Accept Wastewater	fulfilled[58]	10.4
4.4.4.f Transport Wastewater	fulfilled	Table 10-13, Table 10-14
4.4.4.g Store Wastewater	fulfilled[58]	Table 10-13, Table 10-14
4.4.4.h.i to 4.4.4.h.iii Process Wastewater	fulfilled[58]	Table 10-13, Table 10-14
4.1.d Power Consumption	considered	Figure 10-21
4.1.f Thermal Heat Production	considered	Figure 10-21, Table 10-14
4.1.m Reliability	considered	0
4.1.t Volume	considered	Table 10-13, Table 10-14
4.1.v Mass	considered	Table 10-13, Table 10-14

11.2.5 Overall Concept

In the section above, the requirements and constraints of the different ECLSS subsystems where verified. In this chapter, the overall concept is verified against the top-level constraints (see chapter 4.1) and is feasibility is shown. As the baseline system, trade Case4 is used, since all other cases have lower values and are therefore within the constraints.

As already shown in chapter 10.5.4, only a storage system has a low enough power requirement to be feasible for the mentioned case. A storage system on the other hand has a low enough power requirement to be feasible, but requires considerably more mass and volume. Therefore, both concepts are outlined in the following.

11.2.5.1 Recycling System

The values of chapter 10.5.4 are shown in the table below. Additional, parameters for crew safety and accommodation should be included to validate the feasibility of the complete concept. A breakdown of all considered parameters are listed in Table 11-7 below.

[57] There were no detailed calculations of the water impurities considered, since this would exceed the scope of this thesis. Instead silver is assumed as biocide in the water storage and a quality control assembly was included in the design.

[58] Wastewater is considered to be disposed for the storage system to save mass and volume.

Table 11-7: Properties for the overall recycling concept

Parameter	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]
THC	4,627.90	37.22	7,157	29,865
ACS	3,767.12	1.17	1,045	0
AR	55,120.08	93.67	66,250	77,235
WRM	87,898.66	148.73	26,984	14,664
Total ECLSS	**151,413.76**	**280.79**	**101,436**	**121,764**
Potable breathing apparatus	454.00	20.90		
Emergency suits	181.00	0.40		
Total crew safety	**635.00**	**21.30**		
Crew alone	7,500.00	9.92[59]		
Consumables[60]	17,545.30	76.84		
Food & equipment	51,287.34	122.11	9,993	9,833
Exp. clothes	6,643.32	27.43		
Survival kits	1,361.00			
Workout equ.	0,00[61]	69.56		
Recreation equ.[62]	2,500.00	108.76		
Sleep accommodations	900.00			
Shower		19.36		
Total crew accommodation	**87,736.96**	**414.62**	**9,993**	**9,833**
Total	**232,285.72**	**706.79**	**111,429**	**131,597**

As can be seen in the table above, 151,413 kg of ECLSS mass is required for a crew of 100 during a 211-day trip, excluding food. With food, the necessary mass is 202,700 kg, which is lower than the maximum allowable 337.500 kg specified by requirement 4.1.v. When crew safety and accommodation equipment is also considered, the total payload is 232,285 kg which is less than the maximum allowable

[59] Assuming worst-case 95th male with 0.0992 m³ [9, p. 73]

[60] This includes urine pretreatment chemicals, fecal collection mittens, toilet paper, gloves, personal hygiene Kit, hygiene consumables, grey or duct tape, trash bags, wipes for housekeeping, and health care consumables.

[61] No data about mass for the exercise equipment where found.

[62] This includes stowage for personal stuff as well recreation equipment like games, books etc.

payload of 450,000 kg and even under the 300,000-kg payload mark. Therefore, no loading in LEO would be necessary.

The allowable ECLSS volume is 570.33 m³ (4.1.t). As the ECLSS volume including food is only 402.9 m³, the requirement is fulfilled.

Requirements 4.1.c and 4.1.e states, that the maximum allowable power and thermal consumption is 69.28 kW and 100 kW respectively. As described in chapter 10.5.4, it is recommended to increase these capabilities to make the concept feasible and safe mass and volume when comparing to a storage system.

As can be seen in Table 11-7, around 232 t are the minimal necessary mass for a passenger size of 100 people. Therefore, up to 218 t are remaining for other payloads.

Since the occupied space is 706.79 m³, around 1003.97 m³ of pressurized volume is left. This would be 10.04 m³ CM^{-1}, assuming that no additional space is required for other equipment or additional payload, which is very unlikely. See also Table 3-11 for a comprehensive overview of habitable volume in the different decks.

The presented concept is sized to include maximum payload and requires therefore the maximum travel time. When a shorter trip is desired, which is recommended, and less payload mass allowable, much mass and volume could be saved. As stated in Table 2-3, the mean mission duration for a total payload of 200 t is 112 days. Such a short duration reduces the required food mass to 27,291.74 kg. The overall mass would be 161,684.11 kg which means 38,315.89 kg are still available for other payloads. The occupied volume could also be reduced to 550.01 m³ and hence additional 156.78 m³ would be available.

11.2.5.2 Storage System

As been for the recycling system, additional parameters for crew safety and accommodation are included to validate the feasibility of the complete concept. Table 11-8 shows all parameters of the considered subsystems.

Table 11-8: Properties for the overall storage concept

Parameter	Mass [kg]	Volume [m³]	Power [W]	Cooling [W]
THC	4,627.90	37.22	7,157	29,865
ACS	30,737.13	1.30	1,057	0
AR	17,876.36	55.49	28,434	26,832
WRM	176,733.39	347.46	76	0
Total ECLSS	**229,974.79**	**441.47**	**36,724**	**56,697**
Potable breathing apparatus	454.00	20.90		
Emergency suits	181.00	0.40		
Total crew safety	**635.00**	**21.30**		
Crew alone	7,500.00	9.92[59]		
Consumables[60]	17,545.30	76.84		
Food & equipment	51,287.34	122.11	9,993	9,833
Exp. clothes	6,643.32	27.43		
Survival kits	1,361.00			
Workout equ.	0,0061[61]	69.56		
Recreation equ.[62]	2,500.00	108.76		
Sleep accommodations	900.00			
Shower		19.36		
Total crew accommodation	**87,736.96**	**414.62**	**9,993**	**9,833**
Total	**318,346.75**	**877.39**	**46,717**	**66,530**

For ECLSS equipment and Food, 281,262 kg is required for a crew of 100 during a 211-day trip. This is lower than the maximum allowable 337.500 kg specified by requirement 4.1.v.

Requirements 4.1.t specifies, that the ECLSS volume has to be under 570.33 m³. As the necessary food and ECLSS volume is 563.58 m³, the requirement is scratched fulfilled.

The maximum allowable power and thermal consumption (defined by requirements 4.1.c and 4.1.e) is 69.28 kW and 100 kW respectively. Since the power consumption is 46.72 kW and the thermal heat rejection 66.53 kW, both values are well within the requirements.

Around 318 t are the minimal necessary mass for a passenger size of 100 people (see Table 11-8). Therefore 132 t are remaining for other payloads, when assuming the maximum allowable payload mass of 450 t at LEO are used.

Since the occupied space is 877.39 m^3, around 833.37 m^3 of pressurized volume is left. This would be 8.33 m^3 CM^{-1}, assuming that no additional space is required for other equipment or additional payload, which is very unlikely.

22.56 kW of power is still available. But it must be considered that the value in Table 11-8 above did not include power for exercise equipment or the shower, since no data where available.

As already stated in 11.2.5.1, much mass and volume could be saved when considering short trip times for the sake of less payload. When assuming the mean trip time of 112 days for a 200-t payload (see Table 2-3), the total required mass for a storage system would be reduced to 164,301 kg and the necessary volume would be 560.73 m^3. This is comparable to the recycling system with 161,684 kg and 550.01 m^3, but with considerable less power and thermal requirements. For the shortest considered duration of 88 days, the storage system mass would actually be 463.42 kg less.

12 Discussion

12.1 Summary

Since the extent of this study includes many areas, the summary will be separated into subchapters. The main objective of this thesis could be answered and an optimized ECLSS systems for several trade cases was derived and modelled. Furthermore, a comprehensive tool was developed to make decent trade-offs and support the design of an ECLSS. The results from this tool were validated with a state-of-the-art dynamic simulation tool (V-HAB).

12.1.1 Habitat Layout

The obtainable information about the SpaceHab was studied in detail to identify the constraints for the further analysis. A detailed investigation of necessary space and the arrangement of functional areas was done on the basis of a task analysis. With this, several possible crew schedules were developed to measure the impact on the ECLSS in distinct zones.

12.1.2 Life Support Trade Off Tool (LiSTOT)

A spreadsheet tool was developed to assist with the trade-off study. This tool was separated into different modules. The requirements engineering module manages the constraints and requirements for the overall design, as well as for the different subsystems. In the database module, all necessary information about ECLSS technologies are saved as well as data about human metabolism. The crew schedules are also part of this module. The last developed module is the trade study module, which gathers all information from the other two modules to make a decision about an optimized life support system. The tool is programmed in a generic approach as far as possible to allow the analyzation of other systems as well.

12.1.3 Multi-step Trade Analysis

With the help of LiSTOT, a trade analysis was performed which included several steps. In the first step, two analysis methods (ESM and multi-criteria-method) were used and compared to each other. The results were verified with a detailed sensitivity analysis. The subsequent refining step allowed the decision of the optimal architecture of the selected technologies from the first step. The selected metric for this second step was ESM. A detailed system design followed to calculate required components and make necessary decisions on operational aspects. This contains a transient calculation of flows, power etc. in ½ hour increments over one day.

12.1.4 Final Design

The verification of the whole system has shown that only a storage system is feasible within the given constraints. The most limiting factor is the available power. With a relaxation of the power and thermal constraints, high mass and volume savings could be achieved for longer trip times and crew sizes.

12.2 Conclusion

The analysis demonstrates, that the proposed ITS is feasible. This feasibility is based on several assumptions. First and foremost, the considered ECLSS systems are developed mainly for small crews. The assumptions made for the rescale factors, which uses mostly a linear scaling may be incorrect. For example, life support systems for larger submarines with comparable crew sizes are considerable smaller. But since it is not certain whether these technologies would be applicable for a 0-g environment, they are not considered in this thesis.

The reliability of the subsystems is based on the assumption, that every failure can be identified and located in time, and that the component can be easily replaced with a spare. Additionally, it is assumed that the spare is within the constant part of their lifetime, but since reliability is normally a bathtub curve function, the probability that the component fails at begin of operation is higher. Further there is no uncertainty in the given MTBF values assumed. All these assumptions lead to the conclusion that, while sufficient for a preliminary analysis, the reliability of the designed system should be used with care.

The presented final systems, especially the recycling systems, uses lots of spares. While desired in the constraints, no commonality of components and parts is considered. It is believed that such an approach would reduce the mass and volume of the spares dramatically.

The chosen approach to consider only storage or recycling for every system may not results in the best selection. For example, while the consideration for a storage system on the AR system reduces the power extensively, the storage of enough consumption water makes the system very heavy. If only the WRM system would be considered to be a recycling system, the mass of the overall system would be dramatically lower.

While the assumption for the equipment cooling on the different decks is feasible for a system with lots of passengers, it is too high for smaller designs since less ECLSS equipment is necessary. This means the THC system is oversized for such small systems. But because the THC system is the smallest subsystem (1.7 % of mass and 6.6 % of volume), the impact on the complete system is not extensive.

The simulated CRA venting rates in V-HAB seem very high. The original ACLS system was developed for a crew of 3 with many assumptions. The used linear scaling functions could therefore be wrong and another approach must be used.

13 Future Work

As already mentioned in the chapter before, a mix between storage and recycling subsystems should be incorporated in the analysis to evaluate the impact on the final design and the feasibility of the SpaceHab.

The reliability analysis is based on many assumptions, similar systems and, if no data was available, only on assumed redundancy. More data about the considered components is needed to perform a decent analysis. Further, the reliability approach should be extended to include commonality.

The radiation shield estimation is very preliminary and requires a reevaluation once additional data is available. Additionally, it should be analyzed how the crew could be better protected against radiation and an analysis should be made on the amount of received radioactivity through the wall and shields.

In the following, the future work is separated into the developed tool and the simulation model to make distinctions more obvious.

13.1 LiSTOT

While LiSTOT is generally generically programmed to be usable for different vehicles, the detailed layout of the subsystems THC and AR are currently relatively specific. A more dynamic behavior should be included to make trade-offs scalable to every considered system.

LiSTOT´s database has currently 348 distinct entries for assemblies and components with up to 10 different values from several sources for every entry. This database has to be constantly updated. Further it should be analyzed how the trade value entries could be better sized.

An enhanced interface of the requirements module to the other modules is desirable to be able to see results on changed requirements in real time. Currently, this is only done for the top-level constraints.

The database module has currently some worksheets that depend on the trade analysis module. For example, the baseline worksheet presents the results from the storage system trade-off. Therefore, a major overhaul of LiSTOT is highly desirable.

At the moment, the data for V-HAB is generated by a VBA script and manually converted to a csv-file. It should be evaluated if a better interface to V-HAB or a more automatic approach is necessary.

13.2 V-HAB Model

Besides the regenerable system (ACLS), a storage system is implemented in the developed V-HAB model, but currently not executable due to bugs in the model. This should be fixed if a simulation of this system is of interest.

The mentioned high venting rates of the CRA have to be reevaluated. There could be a bug in the system or a wrong assumption on the scaling parameters.

The simulation speed is relatively low. The code should be optimized to enable a simulation over the full considered mission duration.

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A Life Support Trade Off Tool (LiSTOT)

While dynamic simulation tools like V-HAB (see chapter 11.1 for more details) calculating parameters of a system, like O_2 or CO_2 levels, very precisely, they require much computation time to simulate a complete system for the considered mission duration. Furthermore, the programming of all subsystems is very complex and time consuming. Because of this reasons, a spreadsheet tool was programmed, named Life Support Trade Off Tool (LiSTOT). The main purpose of this tool is a practical and fast comparison of different trade cases through the trade study module (A.4) by changing several mission parameters. The result is based on the specifications in the requirements module (A.2) and the database (A.3).

A.1 Simplifications

Several simplifications are necessary due to limitations in a spreadsheet program as well as to enable a quick calculation. Besides the simplifications described in chapter 5, the following are applied:

- Mean metabolic values from BVAD are applied for the schedule.
- Tasks will be precisely followed by the crewmembers and every day has the same sequence.
- ½ hour increments over 24 hours are used for calculations.
- Since only one day is simulated, it is assumed that every day begins with the same initial parameters.
- Produced humidity, heat, and CO_2 is removed within one increment (½ hour) when enough systems are installed.
- The temperature and pressure in the crew compartment is assumed to be constant.
- For calculations like the hazard analysis, the ideal gas law is applied.
- Constant rates for waste generation, food consumption etc. are assumed.

A.2 Requirements Module

The requirements module allows the easy handling of all requirements and constraints. It consists of 5 worksheets. The 'TOP-Level' worksheet handles all constraints, like maximum heat rejection capability and has 25 entries overall (see chapter 4.1). Functions for the subsystems are divided into control, respond, and provision functions and are listed in the corresponding worksheets (see chapters 4.2 to 4.4). The sources for requirements are listed in worksheet 'references' with a distinct ID, the title of the source, the author, and the year of publication. This worksheet is also included in all other modules.

Besides the stated requirement, columns with metadata are included, mainly derived from [19], as outlined below.

Table 13-1: Metadata for requirements

Element	Function
Id	Unique identification number for sorting and tracking.
Description/ Function	A short, comprehensive title of the constraint, function, or requirement.
Rationale	Additional information on the specific requirement to clarify the intent.
Traced from	Gives information about the parent requirement since all requirements are hierarchically arranged.
Verification method	States what method of verification is used (e.g. simulation, calculation, etc.).
Verification level	Defines the hierarchically level of the requirement (e.g. system, subsystem, assembly, or component).
Source	When a requirement is derived from a source, the ID of this source is stated here. All sources are listed in worksheet references.
Notes	Room for additional notes when necessary.
Value	Only in worksheet 'TOP-Level' at the moment. A number which specifies a constraint. This value can be used in other modules.
Type	Only in worksheet 'TOP-Level'. Specifies the type of function (linear or quadratic) which is used by the Multi-Criteria-Method.
Subsystem	Not used in worksheet 'TOP-Level'. A drop-down field to select the corresponding subsystem (e.g. ACS, THC, AR, WRM, WM, or CA)
Needed performance	Not used in worksheet 'TOP-Level'. Gives information about necessary performance of a specific requirement (e.g. heat removal). This field uses data from other modules to calculate the presented information.
TechnologyX	Not used in worksheet 'TOP-Level'. The X stands for a consecutively number, where every number has its own column. Lists all technologies from the database module that could fulfill the requirement. Only for information purposes at the moment.

A.3 Database Module

In the database module, all values used in the other modules are saved. One of the main worksheets is 'technologies'. This worksheet is comprised of a large table with all necessary data of overall 346 entries in 59 columns. An excerpt of this worksheet can be seen in Figure 13-1. Other data, like metabolic values, are stored in separate worksheets. There are 17 worksheets in total.

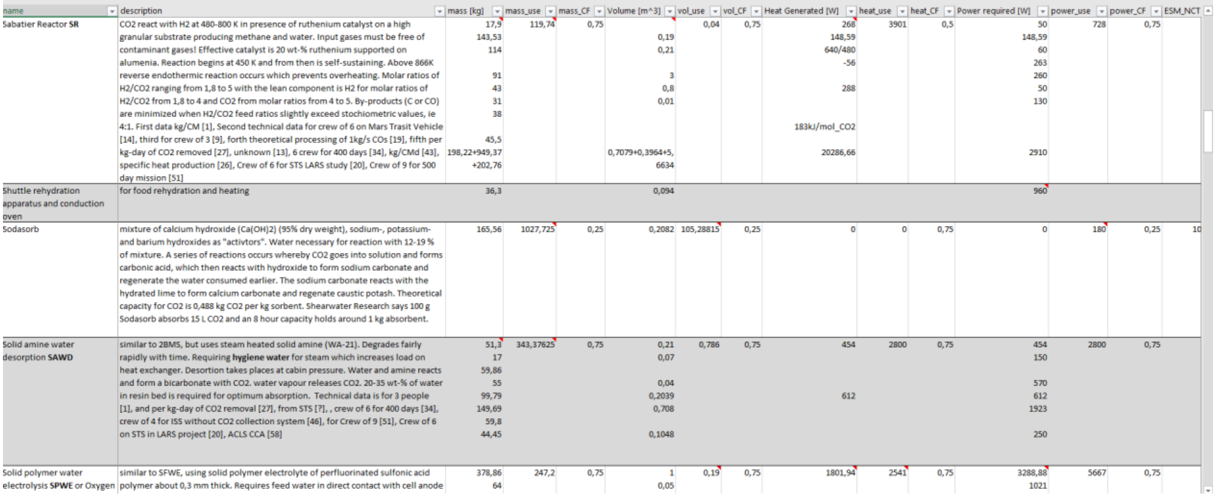

Figure 13-1: Screenshot from worksheet technologies in LiSTOT

Some worksheets include calculations based on selections made in the trade study module. One of these worksheets is 'schedule'. This worksheet is by far the most complex in this module and calculates metabolic inputs and outputs of the system. An excerpt of this worksheet can be seen in Figure 13-2.

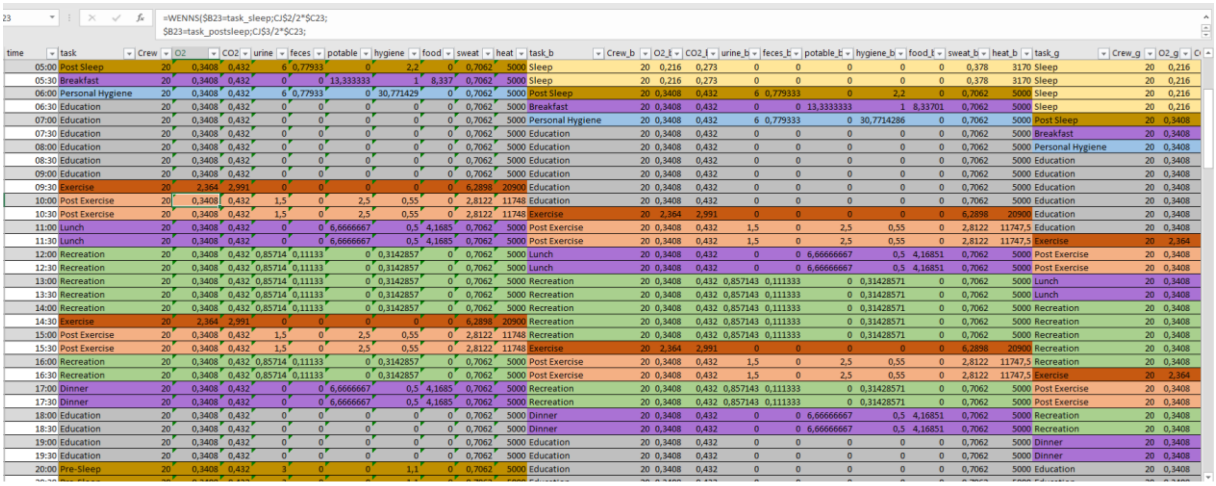

Figure 13-2: Screenshot from worksheet schedule in LiSTOT

A.4 Trade Study Module

The trade study module is the main module of LiSTOT. This module controls and processes all information stored in the other two modules. With the help of the worksheets 'MCM' and 'Subsystem_Trades', a trade analysis of the different functions can be made, based on ESM and the Multi-Criteria-Method (see chapter 7). The different ECLSS subsystems are then further refined in the corresponding worksheets. Most formulas in these worksheets are refined by findings from the dynamic simulation in V-HAB. In the worksheet 'TradeMaster' (see Figure 13-3), the variables listed in Table 13-2 can be altered to make different trade cases. Several diagrams in this worksheet (see Figure 13-3) shows the results on variable changes immediately.

Table 13-2: Trade study variables

Variable	Description
Crew size	Integer which defines the number of crew members to consider.
Mission duration	Integer which defines the length of the trip in days.
Hab volume	This is the sum of the volumes of the different considered decks, defined in the system-specification tables on the right.
Payload mass	Integer, that defines the maximum payload mass in kg. Used for sizing the TCCS.
Schedule #	Defines, which schedule should be used: • 1 - one hour shift schedule • 2 - 4 groups schedule • 3 - 8 hour shift schedule • 4 - alternating schedule • 5 - crowding schedule • 6 - emergency schedule
System size	Currently, SMALL (SpaceHab) and BIG (Evolved-SpaceHab) system sizes are implemented. This information is used in the subsystem worksheets to determine which system-specification table should be used.
ESM factors	The different ESM factors can be changed, to directly see the impact of altered values.
Loop closure	Defines the level of loop closure of the ECLSS, excluding food. Options are: • Storage – all supplies are stored • Partial – some recycling is considered • Full – as much as possible recycling (currently Sabatier) • ISS – systems of the space station
THC type	The options are RaceTrack or Deck.
Use ACLS	This defines, if the additional humidity from the ACLS subsystem should be considered in the THC calculations.

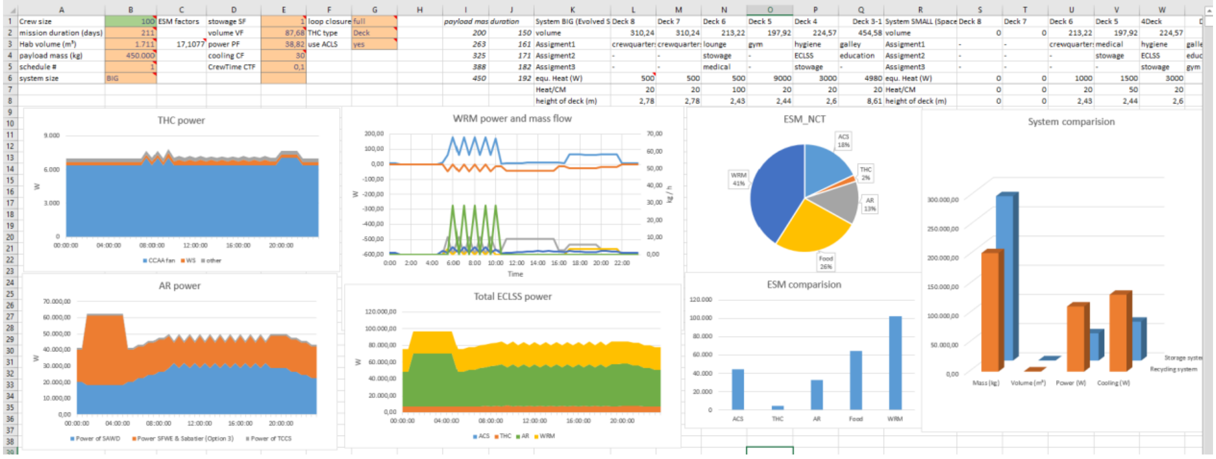

Figure 13-3: Screenshot form worksheet ‘TradeMaster’ in LiSTOT