Quantitative Modeling of Water Demand to Support a Continuous Human Presence on Mars

by

Yana Charoenboonvivat

B.S. Aerospace Engineering, Georgia Institute of Technology, 2021

Submitted to the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 2024

Authored by: Yana Charoenboonvivat
Department of Aeronautics and Astronautics
May 6, 2024

Certified by: Olivier L. de Weck
Apollo Program Professor, Thesis Supervisor

Accepted by: Jonathan P. How
R. C. Maclaurin Professor of Aeronautics and Astronautics
Chairman, Graduate Program Committee

Quantitative Modeling of Water Demand to Support a Continuous Human Presence on Mars

by

Yana Charoenboonvivat

Submitted to the Department of Aeronautics and Astronautics
on May 6, 2024 in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS

ABSTRACT

Establishing a continuous human presence on Mars is a crucial milestone in advancing human capabilities in space and is a high priority for the National Aeronautics and Space Administration. An important step toward establishing a continuous human presence on Mars is identifying landing sites suitable for human and scientific exploration. The quantity of water needed to sustain human life on Mars is a key driver in the selection of landing sites. However, minimal work beyond first-order water demand estimates has been completed to date.

To address this gap, this thesis quantitatively estimates how much water is needed to sustain a continuous human presence on Mars. Updates were made to a tool called HabNet, a MATLAB simulation tool that incorporates key mission parameters and outputs predictions of resource levels over time, to improve the accuracy and fidelity of water demand estimates. These updates involve creating additional Environmental Control and Life Support (ECLS) technologies and updating the crew model to reflect more recent data. The updated HabNet tool was then used to simulate five discrete cases that collectively represent a Mars surface campaign crew profile that shows increasing and continuous human presence.

Results from deterministic modeling of water demand showed that the net total water demand for 4, 8, 12, 16, and 20 crew members on a 790-day mission were 38,669 kg, 76,545 kg, 118,069 kg, 151,617 kg, and 193,134 kg, respectively. For each crew size, 63-65 % of water was needed for generating MAV propellant, 22-23 % of the water was needed for crops, and 12-15 % was needed for life support. Additionally, the water demand per crew member per day was found to fluctuate between 12.00 kg to 12.50 kg across the five cases. This thesis also demonstrated the ability to perform probabilistic modeling of water demand with HabNet using high-performance computing (HPC). A Monte Carlo simulation was completed using the MIT SuperCloud supercomputer for the same five discrete cases, which marked the first time HPC was used to produce HabNet simulation results. Gaussian and beta distributions were fitted to the water demand results from the Monte Carlo simulation. However, further work is still needed to determine which probability distribution best represents the data.

Opportunities for future work include improving the accuracy and fidelity of HabNet to make resource demand estimates and leveraging HPC for future analyses that may be computationally intensive.

Thesis supervisor: Olivier L. de Weck
Title: Apollo Program Professor

Acknowledgments

This thesis would not have been possible without the support of many people in my life.

Firstly, I would like to thank my advisor, Prof. Olivier 'Oli' de Weck, for his guidance and mentorship. Thank you for giving me the opportunity to be a part of your research group and for providing me with the insight and resources needed for me to pursue a research topic that I have thoroughly enjoyed working on. I deeply appreciate your unwavering support of my aspirations to continue pursuing a career at NASA Johnson Space Center (JSC) while seeking a graduate degree, an opportunity that has made me a better researcher and that I really do not take for granted. I look up to you as a role model for the qualities that a good advisor should have: someone who respects, supports, and pushes their students to do the best they can do during graduate school and beyond.

To Dr. Sydney Do, I would like to express my sincere appreciation for all your time, support, and mentorship. Thank you for your assistance and patience in helping me understand HabNet. Through reading your 600-page thesis (at least most of it), and having our weekly meetings, I have learned how to address technical challenges methodically and resolve them with confidence. The research process is naturally challenging, and I truly believe that working with you has helped prepare me for the rigor and intellectual challenge that I will encounter during my PhD and future career. You have made me a better researcher and engineer.

To my mentors and colleagues at NASA Johnson Space Center, I really appreciate the opportunity to be part of a wonderful community that is full of very intelligent and passionate people. My experiences at JSC have sparked my intrinsic motivation to push the boundaries in the field and contribute to leaving a legacy in the history of human space flight; this is one of the key reasons I was driven to pursue a graduate degree in the first place.

I would also like to thank my friends, lab mates, and staff in the AeroAstro department for making my first two years at MIT memorable. Nick, thank you for being a great friend through the highs and lows of my time here. To the board game gang: I look forward to more board game nights as we make it through graduate school. To the Thai community at MIT and in Boston: Thank you for making Boston feel like home away from home. I would also like to thank Mike for his help with using the MIT SuperCloud. Shokofeh and Fran – thank you for all your help in the past two years.

Finally, I would like to mention some important people who have supported me throughout this entire journey. Brian, thank you for all your kindness, care, and support. You have been my pillar, and I am grateful to have you in my life as a partner. To my parents: thank you for your eternal love and support. Thank you for all the sacrifices you have made for me to come to the U.S. to pursue my dreams and my future. Please give extra hugs to Campbell 'Bella' the cat for me.

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. 2141064. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation. The author acknowledges the MIT SuperCloud and Lincoln Laboratory Super-computing Center for providing HPC resources that have contributed to the research results reported within this paper/report.

Contents

List of Figures

List of Tables

Acronyms

BOR	=	Boil-Off Rate
BPC	=	Biomass Production Chamber
BVAD	=	Baseline Values and Assumptions Document
CCAA	=	Common Cabin Air Assembly
CDRA	=	Carbon Dioxide Removal Assembly
CHAPEA	=	Crew Health And Performance Exploration Analog
ECLS	=	Environmental Control and Life Support
ESA	=	European Space Agency
ESDMD	=	Exploration Systems Development Mission Directorate
EVA	=	Extravehicular Activity
EZ	=	Exploration Zones
ISRU	=	In-Site Resource Utilization
ISS	=	International Space Station
IVA	=	Intravehicular Activity
LEO	=	Low Earth Orbit
LHC	=	Latin Hypercube Sampling
MAV	=	Mars Ascent Vehicle
NASA	=	National Aeronautics and Space Administration
OGA	=	Oxygen Generation Assembly
ORA	=	Oxygen Removal Assembly
PDF	=	Probability Density Function
PCA	=	Pressure Control Assembly

RMSE	=	Root Mean Square Error
ROI	=	Regions Of Interest
SMD	=	Science Mission Directorate
SOMD	=	Space Operations and Mission Directorate
SWIM	=	Subsurface Water Ice Mapping on Mars
UPA	=	Urine Processing Assembly
WHC	=	Waste and Hygiene Compartment
WPA	=	Water Processing Assembly
WRS	=	Water Recovery System
WS	=	Water Sufficiency

Nomenclature

c	=	contingency factor
F	=	total water demand [kg]
LCH_4	=	Liquid Methane
LOX	=	Liquid Oxygen
$l_{LCH_4,t}$	=	level of LCH_4 at time t , $\frac{req_{LCH_4}}{T} + l_{LCH_4,t-1}(1 - BOR)$ [kg]
$l_{LOX,t}$	=	level of LOX at time t, $\frac{req_{LOX}}{T} + l_{LOX,t-1}(1 - BOR)$ [kg]
r_{LCH_4}	=	rate of LCH_4 production per day (factoring in the BOR) [kg/day]
r_{LOX}	=	rate of LOX production per day (factoring in the BOR) [kg/day]
req_{LCH_4}	=	required amount of LCH_4 [kg]
req_{LOX}	=	required amount of LOX[kg]
t	=	time [days]
T	=	mission duration [days]
W_A	=	Water available for extraction at a selected landing site
W_B	=	Water brought to Mars from Earth
W_D	=	Water Demand
x_i	=	parameter (water leakage rate/boil-off rate/air leakage rate)
η_{ISRU}	=	ISRU technology efficiency

Chapter 1

Introduction

1.1 Background and Motivation

Establishing a human presence on Mars is a vital stepping-stone for expanding human capabilities in space and is a high priority for NASA. According to the NASA Authorization Act of 2022, NASA "will make further progress on advancing the human exploration road-map to achieve human presence beyond low-Earth orbit to the surface of Mars" [1]. Mars provides an opportune location to expand scientific and human exploration not only because it is close by in the solar system but also because its formation and evolution are similar to Earth's. Mars is therefore a rich destination for searching for life beyond Earth, establishing a human presence beyond low-Earth orbit, and understanding the history of Earth and the solar system [2].

In past decades, robotic missions that have emerged from the Mars Exploration Program for NASA's Science Mission Directorate (SMD), including orbiters, landers, and rovers, have been critical to the knowledge of Mars. These robotic missions have been rooted in their ability to fulfill scientific objectives in astrobiology, climatology, and geology. Therefore, the process of planning, designing, building, and operating these missions has not been tailored toward the constraints of continuous human presence on the Martian surface. NASA's Space Operations and Mission Directorate (SOMD) and Exploration Systems Development Mission Directorate (ESDMD) provide a path to human presence on Mars. Starting in low-Earth orbit (LEO) and expanding to the Moon, the International Space Station (ISS) and the

Artemis program are helping to develop and mature key technologies needed for deep space human missions, including missions to Mars as outlined in NASA's Moon to Mars strategy [3]. Thus, establishing a continuous human presence on Mars is a coupled challenge between NASA's SMD, SOMD, and ESDMD that should enable feed-forward knowledge from Mars robotic missions to human exploration missions.

1.1.1 Determining Exploration Zones

Within this framework, there is a need to determine Exploration Zones (EZ), which are locations where humans can land, live, and work on Mars. Selecting EZs is critical since the nature of each EZ dictates key early decisions related to mission timeline and architecture, habitat architecture, and In-Situ Resource Utilization (ISRU) strategies. An EZ is defined to be a "collection of Regions of Interest (ROI) that are located within approximately 100km of a central landing site" (see Figure 1.1) [4]. ROIs are areas on the Martian surface that have high scientific interest for human exploration (science ROIs) and areas that may contain resources or the potential to develop capabilities necessary for sustainable human presence (resource ROIs). Each EZ contains a landing site, which can support safe landing based on a set of entry descent landing constraints, and a habitation site, which is an area that can facilitate the infrastructure for human presence [5]. Selecting candidate EZs is a multifaceted problem that involves understanding the supply and demand elements of Mars inhabitants and available Martian resources. Supply involves investigating resources available in the Martian environment that make it conducive to science exploration and safe and sustainable EZs, while demand characteristics include understanding the resources needed for human exploration missions. Understanding both the availability and demand of resources is crucial to ensure the optimal selection of EZs.

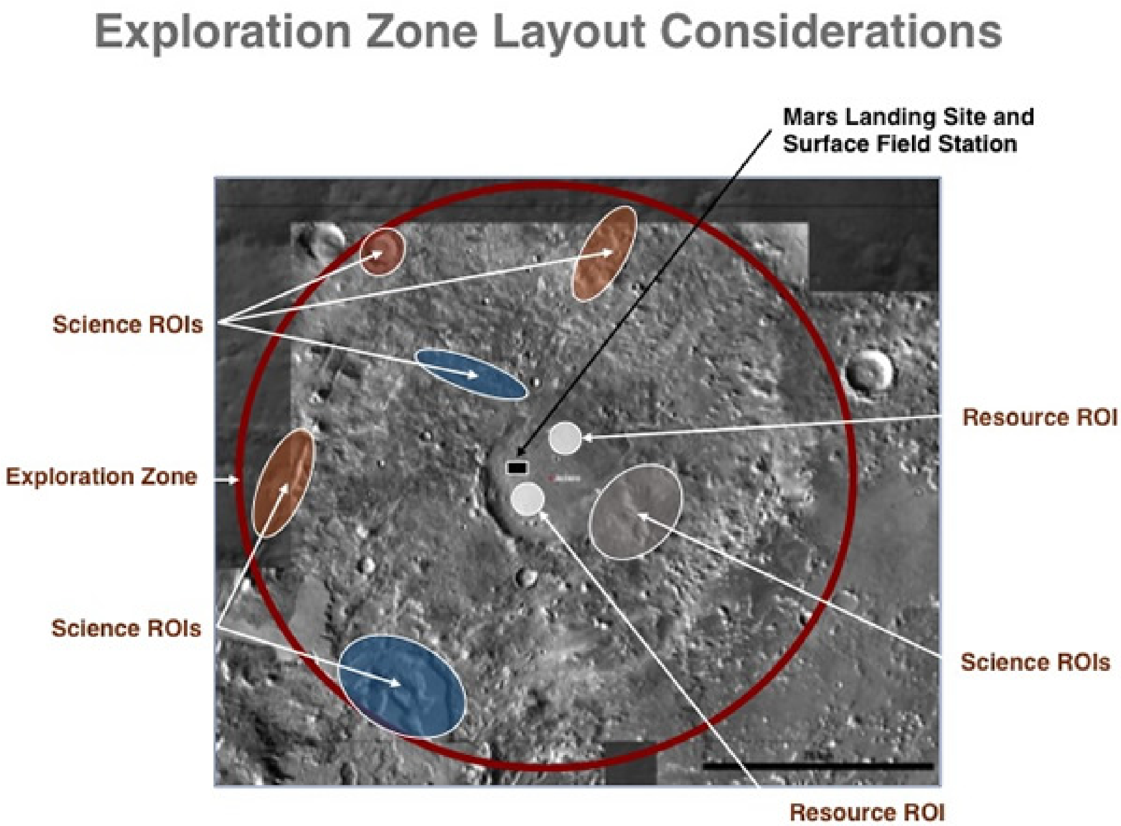


Figure 1.1: Labeled Exploration Zone on Mars showing science ROIs, resource ROIs, and Mars landing site and surface field Stations [4]

1.1.2 Water Demand and Supply on Mars

Water has always played a fundamental role in sustaining human life. On Earth, the availability of water for drinking, agriculture, and waste management made locations near bodies of water attractive and practical for early human settlements. Much like the crucial role that water plays for humans on Earth, the role of water in enabling a continuous human presence on Mars will be equally vital. On Mars, water will be essential for consumption, hygiene and health, science, and protecting crew and equipment from radiation. Water can also undergo electrolysis to produce hydrogen and oxygen: these byproducts can be processed to produce propellant needed for vehicles such as the Mars Ascent Vehicle (MAV) to enable the return of the crew to Earth [6]. Given the potential benefits of harnessing In-Situ Resource Utilization (ISRU) capabilities to source water locally, quantifying water demand to support a human presence on Mars complements ongoing studies to locate and quantify water availability. An example of such a study is the Subsurface Water Ice Mapping on Mars (SWIM) that identifies the location and nature of potential water resources on Mars (see Figure 1.2) [7]. Investigating water demand and supply on Mars will be valuable to NASA's SMD, SOMD, and ESDMD as part of the multi-year process of determining EZs and maturing Mars mission architectures to support continuous human presence.

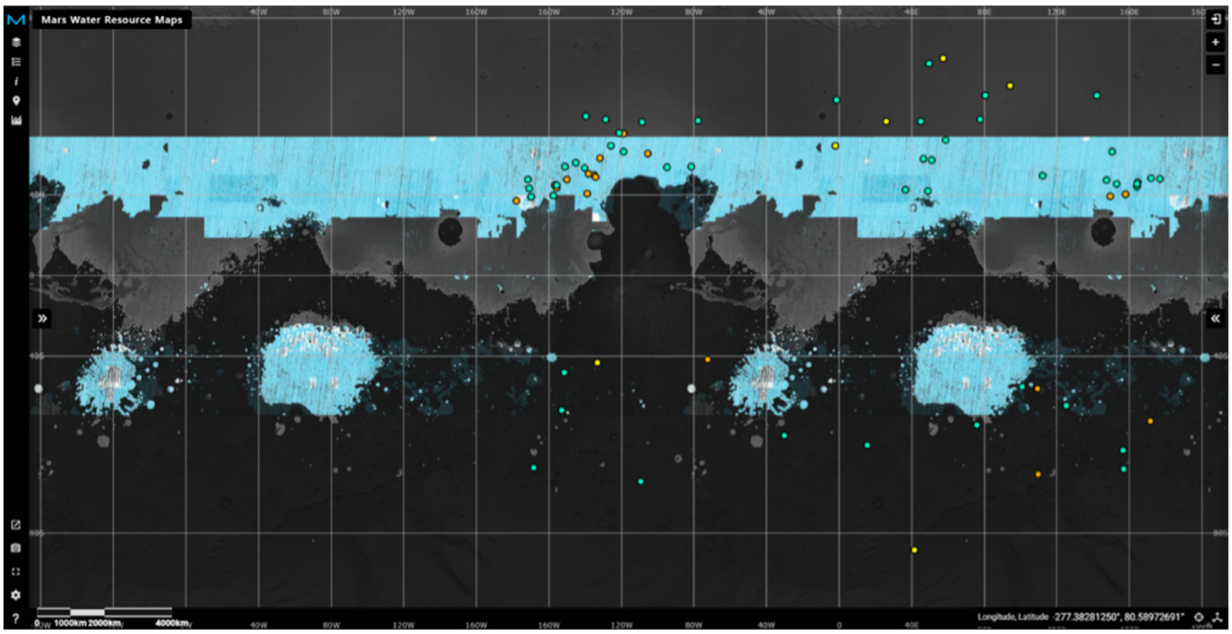


Figure 1.2: Mars water resource map from the SWIM project [7]

1.2 Thesis Statement and Outline

Considering the objective of sustaining a continuous human presence on Mars, the goal of this research is to address the fundamental question:

> *"How much water is needed to sustain a continuous human presence on Mars?"*

To address this research question, the remainder of this thesis is organized as follows. Chapter 2 is a literature review that primarily focuses on providing an overview of HabNet, an existing tool that can be used to quantify the amount of water needed to sustain a continuous human presence on Mars. The chapter also describes a baseline long-duration Environmental Control and Life Support (ECLS) system architecture that can facilitate long-duration stays on Mars.

Chapter 3 details the updates that were made to HabNet to better capture water demand elements. This involves creating new ECLS technology models and making updates to reflect more recent data. Modeling assumptions and limitations are outlined for each new ECLS technology modeled and verification test results are presented to confirm that the new and updated models function as intended. Chapter 3 also describes the HabNet simulation set-up that was used to obtain deterministic water demand estimates. This includes the selected Martian surface campaign crew profile, input parameters and variables for each simulation case, and ECLS technology running order. The simulation setup was verified by completing a unit test case that involved one crew member on a 2000-hour mission.

The fourth chapter presents and discusses the water demand estimates made using the methodology presented in Chapter 3 for crew sizes of 4, 8, 12, 16, and 20 members each on a 790-day mission. The results presented in Chapter 4 are based on a deterministic model of water demand. Chapter 5 demonstrates the ability to provide probabilistic models of water demand estimates for the cases simulated in Chapter 4 using High-Performance Computing (HPC). A sensitivity analysis was first conducted on three selected input parameters to investigate their impact on water demand. The sensitivity analysis provided an informed decision on which parameters were represented by probability distributions in the Monte Carlo simulation, which was completed using the MIT SuperCloud supercomputer.

Chapter 6 provides an overview of recent efforts to explore water availability on Mars. This overview was completed to help provide a more holistic perspective of water sufficiency for future human missions to Mars. A water sufficiency equation was also developed to provide a high-level understanding of key factors that impact crew water sufficiency.

Lastly, Chapter 7 concludes the thesis and outlines avenues for future research that can help plan and support mission architectures to support continuous human presence on Mars.

Chapter 2

Literature Review

To date, minimal work beyond first-order calculations has been completed toward quantitatively estimating water demand for a sustained human presence on Mars. Crew water usage data from LEO space stations such as the International Space Station (ISS) may provide the closest water demand estimate for sustained human presence on Mars given the similarity in constraints that space imposes on factors such as the environment, logistics, and crew habitation. However, the Martian surface environment is much different than that of LEO, rendering LEO space station crew water usage data inaccurate for Martian water demand estimates. While terrestrial Mars analog missions such as the Crew Health and Performance Exploration Analog (CHAPEA) mission, which involve human test subjects, can offer insights into water usage, they are resource-intensive and time-consuming [8]. Their mission durations span months to years, causing them to face constraints in their capability to explore aspects such as different crew profiles, habitat architecture, and environmental conditions. These constraints limit their capability to provide decision-makers and policymakers with the analysis needed to make key mission architectural decisions in a timely manner. To provide higher-order estimates of water demand to sustain a continuous human presence on Mars, the ability to model, simulate, and quantitatively estimate water demand through a simulated modeled platform becomes necessary.

2.1 HabNet

One such tool that can model and simulate water demand to sustain a continuous human presence on Mars is called HabNet, an integrated habitation and supportability architecting and analysis environment written in MATLAB [9]. This tool was first developed at the MIT Strategic Engineering Research Group by Sydney Do between 2013 and 2016 and has previously been used for various Mars one-way and return trip mission architectures [10]. HabNet consists of four modules: Habitation, ISRU sizing, Sparing, and Space Logistics [9]–[11]. The habitation module will be the core focus of this thesis since it uses key mission parameters such as the number of crew, mission duration, habitat layout, and Environmental Control and Life Support (ECLS) system architecture to predict required resources, such as water, over time. HabNet was selected to address the research question because of its ability to provide dynamic analysis at a medium fidelity with serial function evaluation times on the order of seconds to minutes. HabNet's computational speed, ability to model plant growth, and mid-fidelity dynamic analysis capabilities make it suitable for the intent of this study, which is to quantitatively estimate water demand for a sustained human presence on Mars [9]. Additionally, existing habitation and life support modeling tools are either computationally expensive, limited to steady state analysis, unable to model ECLS technologies necessary for long-duration missions, or constrained to integrated ECLS simulations within a flight module rather than a modular surface habitat [12].

2.1.1 Overview of the HabNet Habitation Module

Understanding the mechanics behind how the HabNet habitation module functions is key to understanding its capabilities and constraints, upgrades that may need to be implemented, and how HabNet can be used to run on various Mars mission architectures. Figure 2.1 provides a high-level visual representation of the code architecture that supports HabNet which consists of a main script that is comprised of three segments: initialization, record resource levels, and state update.

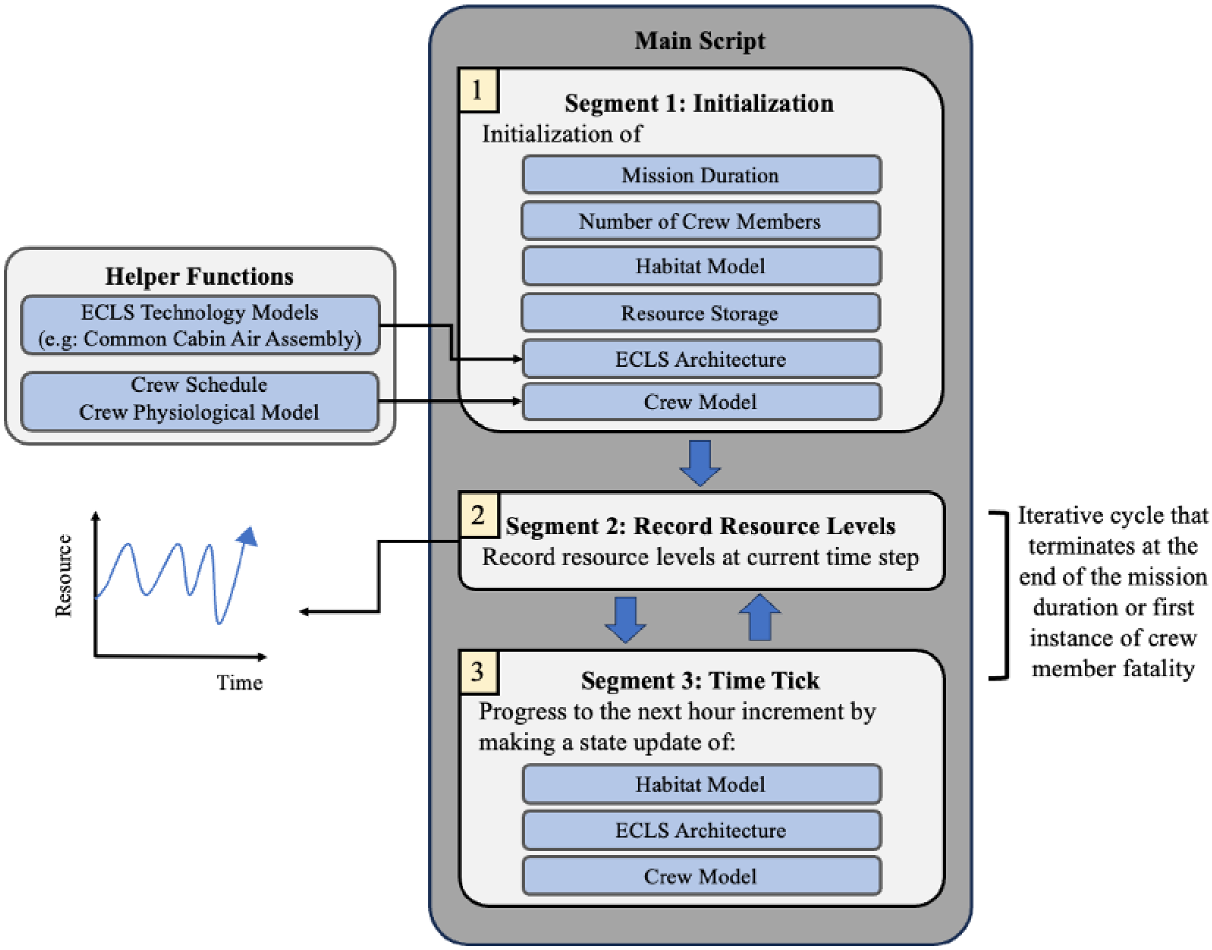


Figure 2.1: Overview of the HabNet habitation module architecture. Information was derived from [9]

2.1.2 Initialization

The initialization segment provides the habitation module with a modular capability whereby the user can define key mission variables and parameters according to the requirements of various mission architectures. These mission variables and parameters include mission duration, number of crew members in the mission, habitat model, resource storages, ECLS architecture, and crew model.

Habitat Model

Initializing the habitat model involves designing the configuration of a habitat. Figure 2.2 shows three examples of habitat layouts that can be designed in the HabNet habitation module; they range from a simple single-module pressurized core module to a more complex multi-module habitat. For each block in a habitat layout, the user can specify the target molar fraction of O_2, CO_2, water vapor, N_2, other gases, initial CO_2 concentration, hourly air leakage percentage rate, total targeted atmospheric pressure, O_2 fraction hypoxic limit, O_2 fire risk molar fraction, and volume.

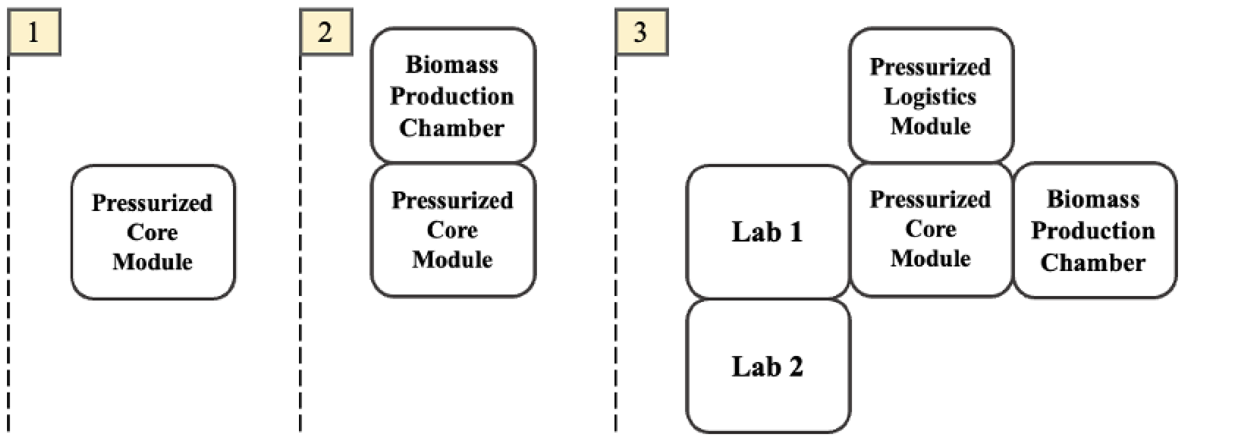


Figure 2.2: Three examples of habitat layouts composed of blocks

Resource Storage

Resource storage can be initialized internally to each block or external to the habitat by declaring the storage capacity and current level of different types of resources. Figure 2.3 provides an example of a habitat with initialized resource storages.

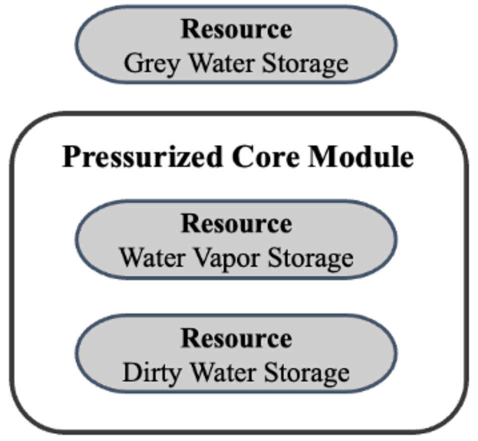


Figure 2.3: Example habitat layout with resource storages internal and external to the habitat

ECLS Architecture

ECLS is a system of technologies and processes that are centered on keeping the crew alive in a space habitat environment by controlling various aspects of the habitat such as air quality, water and food supply, and waste management. Designing an ECLS system involves strategically selecting a combination of different ECLS technologies to create a desired function. Some examples of ECLS technologies include the Pressure Control Assembly(PCA), Carbon Dioxide Removal Assembly(CDRA), and Water Processing Assembly(WPA). Within the scope of the HabNet habitation module, various ECLS technologies have been modeled by Do as "helper functions" that are called by the main script [9]. When these ECLS technology model functions are called, they process and transfer resources from one resource storage(s) to another. The user can specify which habitat block these ECLS technologies should belong in as well as which resource storage(s) they would like the ECLS technologies to transfer resources to and from. An example ECLS technology, Common Cabin Air Assembly (CCAA), that is implemented in the example habitat layout portrayed in Figure 2.3 can be found in Figure 2.4. Figure 2.4 depicts the CCAA taking in x moles of water vapor from the water vapor storage and processing it into y kg of grey water that is transferred to the grey water storage. The ECLS architecture is initialized in HabNet once all the necessary ECLS technology functions are called in the main script.

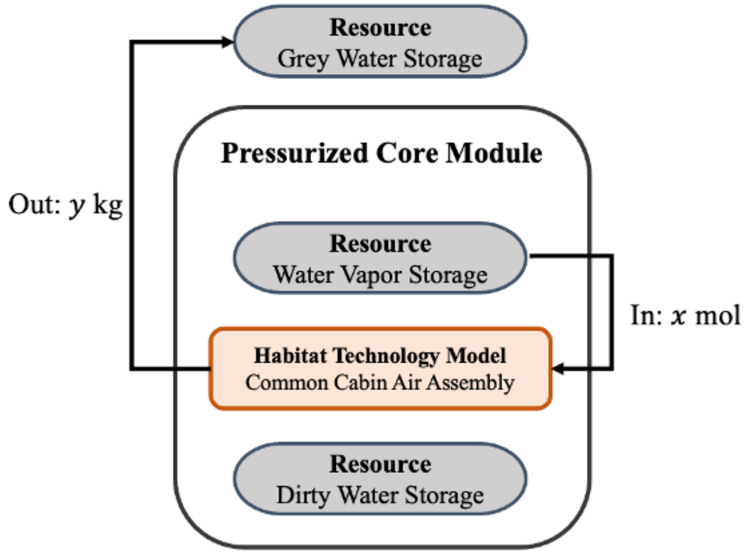


Figure 2.4: CCAA ECLS technology model implemented in the habitat layout shown in Figure 2.3

Crew Model

The capability to model human consumption and production of resources will be valuable for predicting crew survivability, which is necessary to characterize the trade space of future Mars mission architectures centered on human presence. The HabNet crew model consists of two portions that are dependent on each other: (1) A daily activity schedule for each crew member that increments in hours for the duration of the mission, and (2) A crew physiological model that indicates if crew member(s) are alive/dead and transfer resources to and from resource storages to simulate human consumption and production of resources [9]. Each activity in the crew member's daily activity schedule informs the crew's physiological model of how much resources are consumed/produced by the crew within that hour. Initializing the crew model involves designing a daily activity schedule for each crew member for the duration of the mission and instantiating the crew physiological model for each crew member. Figure 2.5 depicts a resource and data flow diagram of the crew model. It shows the crew schedule as an input to inform the crew physiological model of how much resources are consumed and produced by each crew member, and an indicator to determine whether the crew is dead or alive. Starvation, dehydration, and CO_2 poisoning are examples of conditions that can lead to crew fatality, which the crew model accounts for [9].

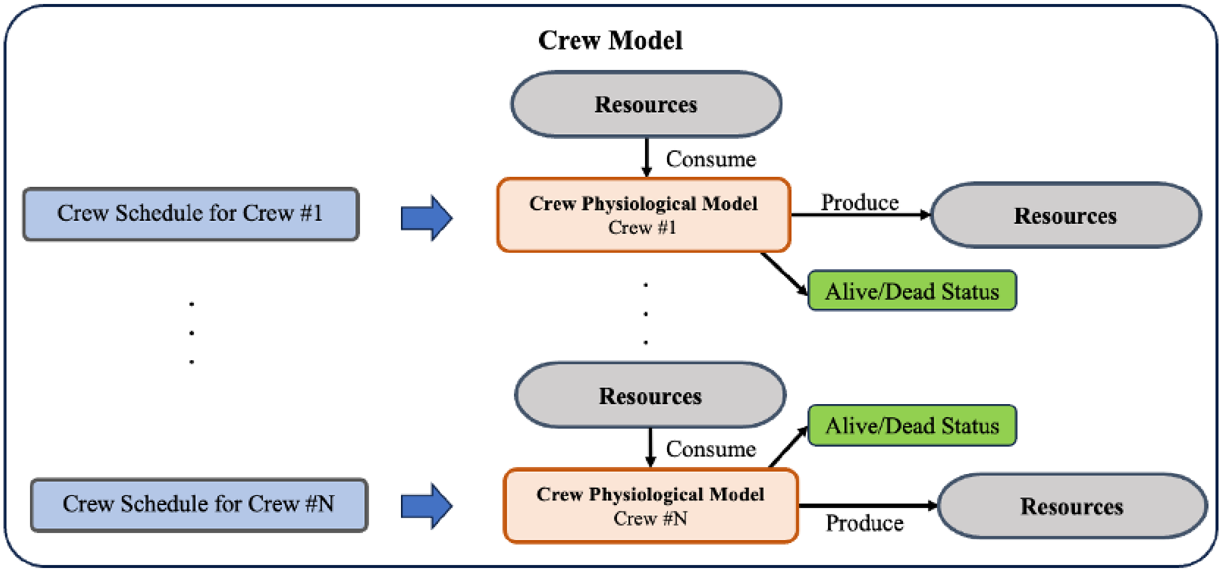


Figure 2.5: Crew model data and resource flow diagram

2.1.3 Record Resource Levels

In the second segment, resource levels are recorded. This segment records the current level of each initialized resource storage at the end of each time increment (1 hour) after instantiations of ECLS technologies and the crew model transfers resources to and from resource storages. Keeping track of resource levels throughout the mission duration is essential to verifying the simulation and ultimately assessing the water demand within the simulated mission architecture. Some key examples of resource levels tracked that are relevant to water demand estimation include dirty water, grey water, potable water, and water vapor. The definitions and examples of these four types of water within the scope of HabNet are provided in Table 2.1.

Table 2.1: Water types tracked in the HabNet habitation module

Water Type	Definition	Examples
Dirty Water	Biological wastewater or water that has come in contact with biological waste	Urine
Grey Water	Water that has been used domestically	Untreated output water from the laundry machine, showering, and CCAA
Potable Water	Water that is safe for human consumption	Drinking water
Water Vapor	Water in gaseous form	Product of crew/plant respiration or evaporated sweat

2.1.4 State Update

The state update segment progresses the ECLS technology models and crew model to the next time step (next hour) of the mission and enables the technologies to perform their functions. It is coupled with the second segment in which resource levels are recorded at the current time step after the ECLS technology models and crew model perform their functions.

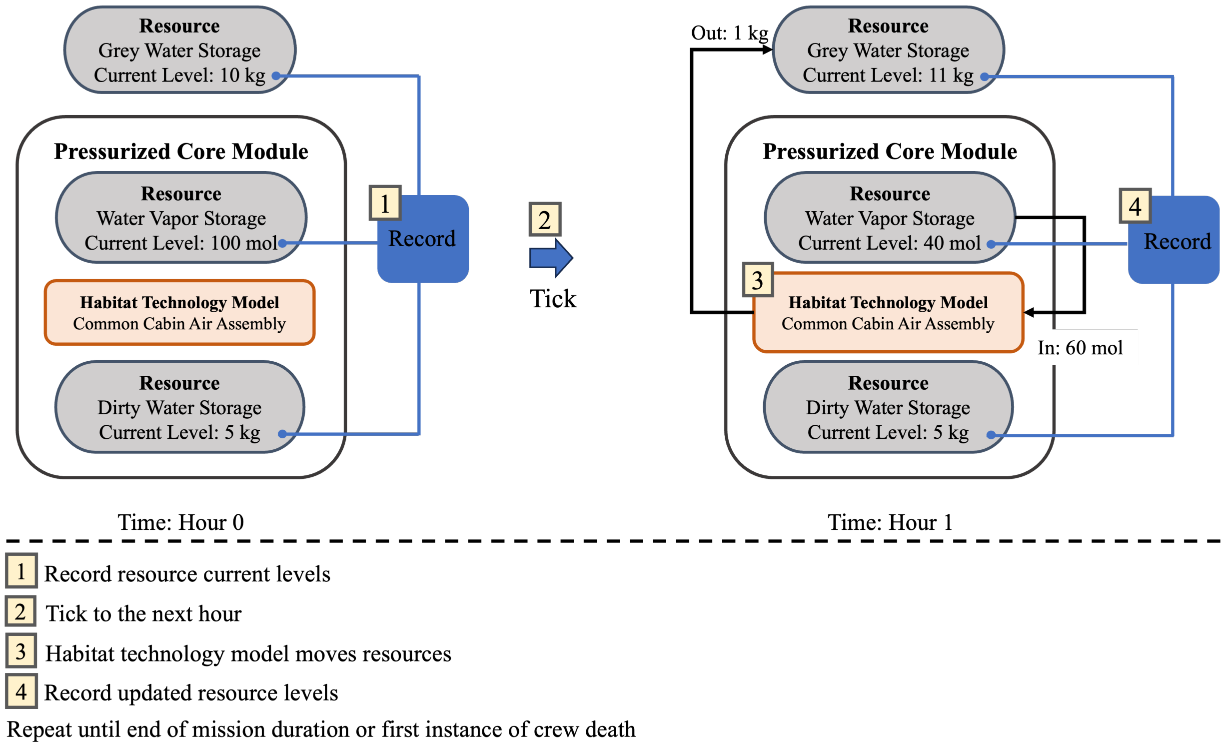


Figure 2.6: Interaction between segment two (record resource levels) and segment three (state update) of the HabNet habitation module

A demonstration of the interaction between the second and third segments, which builds upon the system shown in Figure 2.4, can be seen in Figure 2.6. It is of note that the system described in Figure 2.6 is not representative of a realistic habitat layout and ECLS system but its purpose is to capture how the HabNet habitation model functions. First, the current levels of grey water, dirty water, and water vapor are recorded. Then, the state update segment 'ticks' the ECLS technology model to the next hour. The CCAA takes in 60 moles of water vapor from the water vapor storage, leaving 40 moles left in storage. The CCAA then outputs 1 kg of water to grey water storage, which now has 11 kg of grey water. Updated resource levels are recorded and the main script cycles iteratively between the second and third segment and terminates at the end of the specified mission duration or at the first instance of crew member(s) death.

2.2 ECLS Architecture of Long Duration Missions

A baseline ECLS architecture for long-duration missions shown in Figure 2.7 was derived from an internal presentation provided by the NASA Jet Propulsion Laboratory [13]. The ECLS architecture shown is one of many possible architectures that can be implemented into HabNet to support long-duration missions for continuous human presence on Mars. The Mars habitation module is surrounded by potable water storage as a method of shielding the crew from deep space radiation, which is an important feature when humans venture farther beyond low-Earth orbit.

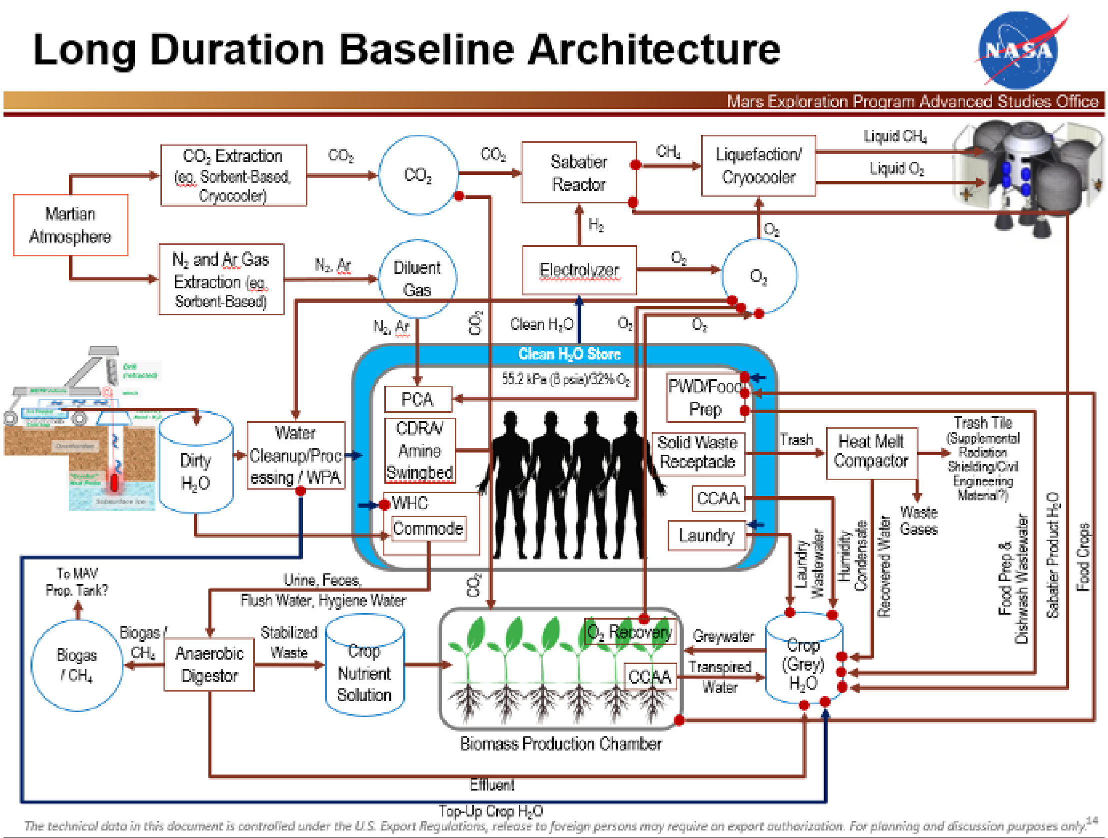


Figure 2.7: Long duration mission baseline ECLS architecture [13]

To integrate the presented baseline ECLS architecture into HabNet, updates to HabNet are required to account for ECLS technologies that have not been modeled. Table 2.2 outlines ECLS technologies found in Figure 2.7 that do not exist in HabNet.

Table 2.2: ECLS technologies found in the long duration baseline ECLS architecture that have not been modeled in HabNet

Technology	Description
Carbon dioxide, nitrogen, and argon extractor	Extracts carbon dioxide, nitrogen, and argon from the Martian atmosphere.
Heat Melt Compactor	Compacts trash into tiles, which could be used for supplemental radiation shielding and produces by-product water/gases [14].
Anaerobic digestor	Produces by-product CH4 (that may be used for MAV propellant) from human urine, feces, flush water, and hygiene water. By-product waste can also form a crop nutrient solution that is provided to the crops [15].
Potable Water Dispenser and Food Preparation Station	Dispenses potable water for crew consumption and takes in potable water for food preparation. By-product grey water is produced from food preparation.
Waste and Hygiene Compartment (WHC)	Transports crew wastewater/hygiene water within the habitat to external grey and dirty water storage tanks.
Laundry Machine	Clean crew member's clothes.
Mars Ascent Vehicle (MAV) and Cryocooler	The MAV is a vehicle designed to lift crew and cargo from the surface of Mars to dock with a Mars-Earth transportation vehicle. It helps return crew and cargo to Earth [6]. The cryocooler, which is integrated with the MAV, liquefies gaseous oxygen and methane to produce propellant for the MAV.
Water Electrolyzer for MAV propellant generation	Electrolyzes potable water into gaseous hydrogen and oxygen. Downstream the electrolyzer, oxygen is liquefied to produce oxidizer for the MAV and the hydrogen is fed into the Sabatier reactor to produce methane.
Sabatier Reactor for MAV propellant generation	Inputs carbon-dioxide and hydrogen to produce methane and water. By-product water is reclaimed and recycled while methane is liquefied to produce fuel for the MAV.

Chapter 3

Methodology

This chapter describes the methodology that was used to estimate water needed to sustain a continuous human presence on Mars. The methodology consists of four key parts. The first part involved making modifications to the baseline ECLS architecture described in Section 2.2. This helped to simplify the ECLS architecture implemented in HabNet and assist with water demand tracking. The subsequent part involved creating models of ECLS technologies not previously modeled in HabNet and verifying that these new models function as intended. The crew model was also updated to incorporate more recent data available. The third part entailed developing a simulation set-up in HabNet that was used to make water demand estimates, and the last part of the methodology verified that the simulation set-up operated as intended.

3.1 Modified Baseline ECLS Architecture

Modifications were made to the baseline ECLS architecture presented in Section 2.2 before being implemented into HabNet. These modifications, which included removing certain technologies in the baseline ECLS architecture and adding resource storages, were made to simplify the ECLS architecture, allow for a more conservative water demand estimate, and assist with tracking the three key pillars of water demand:

1. Life Support Water

2. Biomass Production Chamber (BPC) Water (i.e., Crop Water)

3. Water for MAV propellant generation

The modifications are documented below in Table 3.1.

Table 3.1: Modifications to the baseline ECLS architecture

Modification	**Explanation**
CO_2 extractor removed	An unlimited supply of carbon dioxide (either brought from Earth or extracted via ISRU on Mars) is assumed.
N_2 and Argon gas extractor removed	An unlimited supply of N_2 (either brought from Earth or extracted via ISRU on Mars) to support the Pressure Control Assembly is assumed. Argon is abstracted away since it is one of the least prevalent gases in the Martian atmosphere (∼2%) [16]
Heat melt compactor removed	The heat melt compactor reclaims water rather than uses water, so it is abstracted away to allow for a conservative water demand estimate.
Anaerobic digestor removed	The anaerobic digestor reclaims water rather than uses water so it is abstracted away to allow for a more conservative water demand estimate.
Potable water dispenser and food preparation station removed	The potable water dispenser and food preparation station is omitted and instead simplified to having crew consume water directly from the Mars habitat potable water storage and consume food directly from the Mars habitat food storage (food is either brought from Earth or transported from the BPC)
Grey water tank (BPC) added	A grey water tank is added to the BPC to track water demand for the crops in the BPC
Potable Water Tank (MAV Propellant) added	Separate grey water and potable water tanks are added to help track the water required to generate MAV propellant
Grey Water Tank (MAV Propellant) added	
WPA (MAV Propellant) added	A WPA is installed to recover water produced when generating MAV propellant

As a result of the modifications, a modified baseline long-duration ECLS architecture shown in Figure 3.1 was obtained and implemented into HabNet. Note that the coloring scheme shown in the key of Figure 3.1 will be used in block diagrams hereinafter.

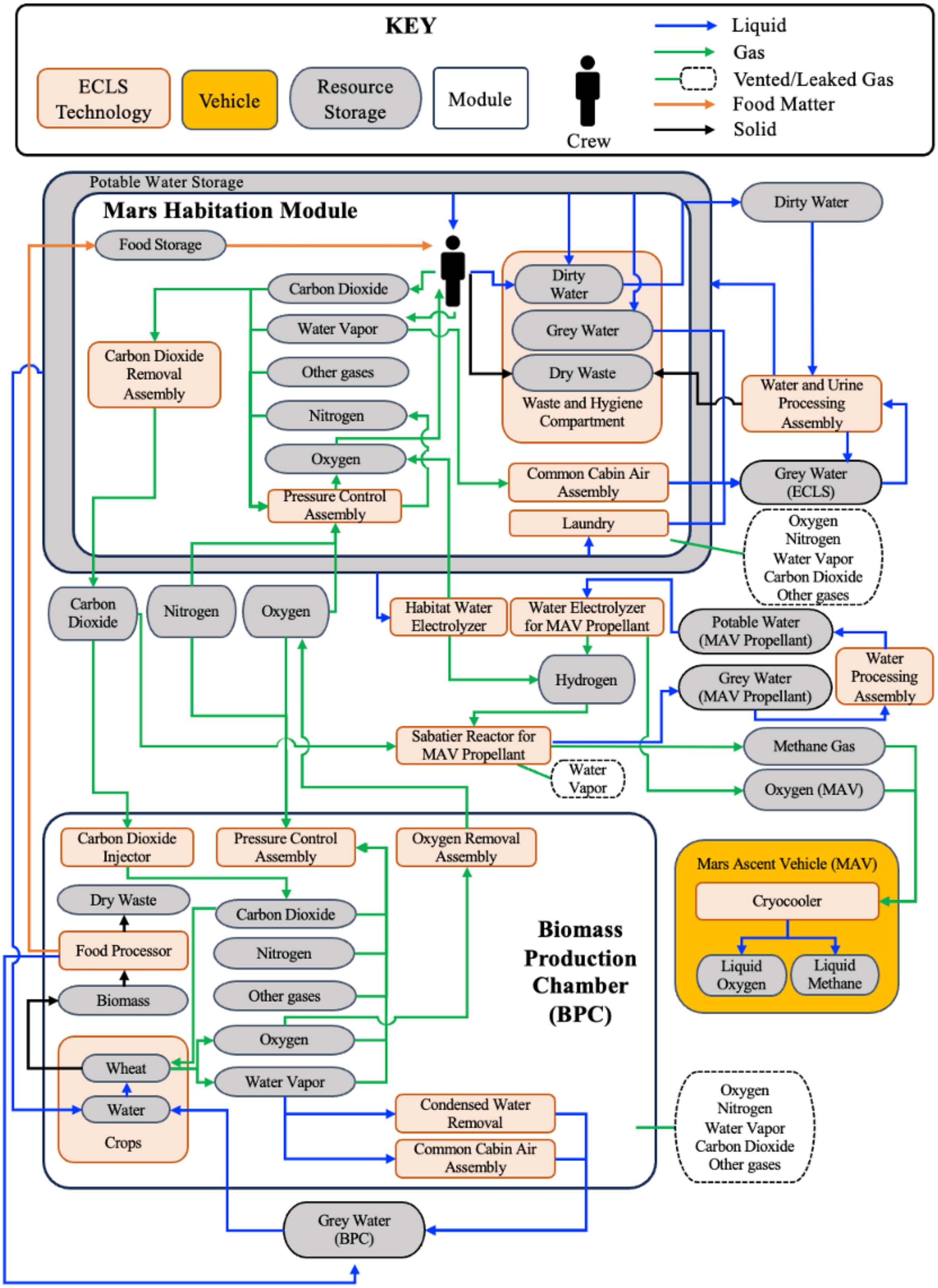


Figure 3.1: Modified baseline long-duration ECLS architecture.

At a high level, the modified baseline long-duration ECLS architecture presented in Figure 3.1 consists of three key water loops that are tracked: life support, BPC (crop water), and the MAV propellant loop. In the three water loops, the water/urine processing assembly (WPA/UPA) and common cabin air assembly (CCAA) facilitate water recovery.

3.1.1 Life Support Loop

Within the Mars habitation module where crew members live, life support equipment which includes the CDRA, habitat water electrolyzer, PCA, Waste and Hygiene Compartment (WHC), CCAA, and laundry machine work together to provide the crew with food, water, hygiene facilities, and habitable environmental conditions. The WPA/UPA and CCAA function to reclaim water in the life support loop.

3.1.2 BPC (Crop Water) Loop

The BPC module supports crew's food supply; it is where crops are grown and harvested to provide the crew with food. It is important to note that the BPC and Mars habitation module are modeled as two separate entities that do not physically interface. Crew will not need to enter the BPC to harvest crops and it is assumed that food is directly transported from the BPC to the Mars habitation module for crew to consume. Within the BPC, the Oxygen Removal Assembly (ORA), PCA, carbon dioxide injector, CCAA, and condensed water remover operate together to ensure that environmental conditions within the BPC can support crop growth. The crops and food processor work together to provide crew with food to consume during the mission. The "shelf stagger" feature is implemented in the BPC whereby a batch of crops is grown every day and harvested every day once the crops mature so that food production is continuous over the mission. Water reclamation in the BPC occurs primarily through the collection of water transpired by the plants that is then processed through the CCAA and used as a water source for the crops.

3.1.3 MAV Propellant Loop

The water electrolyzer and Sabatier reactor for MAV propellant, cryocooler, and MAV model work together to produce propellant (liquid oxygen and liquid methane) for the MAV. The water electrolyzer for MAV propellant transforms potable water into hydrogen and oxygen gases. Oxygen is then converted to LOX in the cryocooler, while hydrogen undergoes a reaction with carbon dioxide in the Sabatier reactor, resulting in the production of methane and grey water as byproducts. Methane is subsequently processed in the cryocooler to become LCH_4. The WPA reclaims water in the MAV propellant production loop, a notional capability that is introduced in this baseline long-duration ECLS architecture.

3.2 Updates to HabNet

Updates to the HabNet habitation module were deemed to be necessary to better capture water demand elements of an ECLS system. The ECLS architecture shown in Figure 3.1 consists of technologies that were not previously modeled in HabNet including the WHC, laundry machine, MAV and cryocooler, water electrolyzer for MAV propellant, and Sabatier reactor for MAV propellant. This section details the models of these new technologies, their assumptions, and verification tests to ensure that they function as intended. This section also details updates made to the crew model to reflect more recent data available. The remaining ECLS technologies were kept the same as originally constructed by Do and explanations of their functions and assumptions/limitations can be found in [9]. Several of the key ECLS technology models shown in Figure 3.1, including the CCAA, WPA/UPA, carbon dioxide removal assembly (CDRA), and pressure control assembly (PCA) are ISS derived [9]. Other technologies modeled, such as the oxygen removal assembly and carbon dioxide injector, are notional technologies.

3.2.1 Crew Model Update

The crew model implemented in the 2016 version of HabNet was rooted in a crew model developed by Goudarzi and Ting in 1999 and adopted within BioSim [17]. It determined crew resource demands based on gender, age, body mass, activity intensity, and metabolic rate and was based upon data that was over two decades old [9]. However, now that updated crew physiological data and understanding have become accessible, there emerged a need to improve the accuracy of HabNet's crew model by integrating the latest information available into HabNet. Since the water demand study focuses on ensuring sustainable continuous human presence on Mars, crew model updates are necessary because the crew are the main consumers and producers of resources, which is central to understanding crew survivability during a long-duration mission.

In the 2016 version of the crew model, the crew schedule comprised of five different types of activities that are qualitatively categorized by levels of intensity ranging from 1 (low intensity) to 5 (high intensity) as shown in Table 3.2 [9]. The intensity level of each activity planned in the crew schedule for each crew member informed the estimated heart rate of each crew member, which informed the respiratory quotient (moles of CO_2 exhaled for O_2 consumed) and caloric requirements [9]. Independent of the intensity level/activity were the water intake requirements. The 2016 crew model assumed that the crew consumed a fixed rate of 0.1667 liters of potable water per hour, 46.25% of which became urine, 17.5% of which became water vapor through respiration, and 36.25% of which turned into some form of grey water (e.g., liquid metabolic effluent, perspiration, etc.) [9]. While this allocation of crew water intake ensured the water-mass equilibrium of each crew member (i.e., water in is equal to water out), there was an opportunity to enhance the accuracy of the model.

Table 3.2: Crew activity and their intensity levels for the current HabNet tool [9]

Intensity	**Activity**
1	Sleep
2	Intravehicular Activities (IVA) (e.g., eating, housekeeping, and science experiments)
3	Light exercise
3-4	Extravehicular Activities (EVA)
5	Exercise

Increasing the accuracy of the crew model involved making modifications to two key components of the crew model: the crew schedule and crew physiology model. First, the portfolio of activities in the crew schedule was expanded to include aerobic exercise, resistive exercise, post-exercise recovery for the first, second, and third hours, sleep, and Intravehicular Activities (IVA). These activities, along with their associated water vapor output, liquid sweat rate, O_2 usage, CO_2 output, and dirty water produced, were taken from NASA's 2022 Life Support Baseline Values and Assumption Document (BVAD), as well as from an updated human metabolic model by Ewert, Downs, and Keener that incorporates a long exercise protocol suitable for long duration missions that surpass thirty days [18], [19]. Using information from the aforementioned sources, a generic 24-hour crew schedule was formulated and now integrates the new activities and crew resource production and consumption as outlined in Table 3.3. Note that values from Table 3 in [19] were processed to produce values in the 'Vapor Produced', 'O_2 Needed', 'CO_2 Output' and 'Potable Water Needed' columns. Values from Tables 4.20, 4.34, and 4.35 in [18] were processed to generate values in the 'Dirty Water Produced' column.

Table 3.3: 24-hour Crew schedule with activities and their resource consumption/production rates [18], [19]

Hour	**Duration (hr)**	**Activity**	**Vapor Produced (Mol/hr)**	**Dirty Water Produced (kg/hr)**	O_2 **Needed (Mol/hr)**	CO_2 **Output (Mol/ hr)**	**Potable Water Needed (kg/hr)**
1	0.5	Aerobic Exercise	43.337	0	3.846	3.660	0.781
2	1	Resistive Exercise	80.352	0	2.757	2.650	1.448
3	1	Recovery (Hour 1)	8.563	0	1.138	0.968	0.154
4	1	Recovery (Hour 2)	5.240	0	1.138	0.968	0.094
5	1	Recovery (Hour 3)	4.692	0	1.138	0.968	0.085
6-15	10	IVA	4.555	0	1.138	0.968	0.082
16	1	IVA (Personal Hygiene)	4.555	1.400	1.138	0.968	1.584
17-24	8	Sleep	3.699	0	0.713	0.617	0.066

Modeling Assumptions and Limitations

A couple of important notes regarding the content in Table 3.3 are highlighted. First, the vapor produced by the crew is assumed to encompass only water vapor produced through respiration and sweat water which is assumed to evaporate to the surrounding environment. The IVA activity from hours 6-15 includes laundry operations that are planned to occur once a week per crew member for one hour. The IVA activity involving toilet usage and personal hygiene triggers the waste and hygiene compartment model to operate, which manages wastewater from the crew. Furthermore, it is assumed that all personal hygiene and toilet usage functions, which include oral hygiene, showering, hand washing, urination, and defecation occur during the one-hour IVA activity dedicated to toilet usage/personal hygiene. Potable water needed is the sum of dirty water and vapor produced subtracted by food water content. Additionally, the values provided for vapor produced, O_2 needed, and CO_2 output are intentionally conservative; the data provided by Ewert, Downs, and Keener increment in 15-minute intervals, and the maximum values for water vapor output, liquid sweat rate, O_2 usage, and CO_2 output for the same activity were selected. To account for the slightly longer Martian sidereal day compared to that of Earth, crew resource consumption/production was scaled by 1.023, which is the ratio of minutes on a Mars sidereal day to minutes on an Earth sidereal day [20]. Other than the updates presented in section 3.2.1, the crew model was kept the same as originally coded and so other assumptions/limitations of the crew model related to crew food consumption, crew health, and dry waste production can be found in [9].

Verification of the Crew Model

Information from Table 3.3 was implemented into the crew schedule and crew physiology model of the crew model, which allowed crew resources to be taken/added to its relevant resource storage locations. To verify this new implementation of the crew model, a unit test was conducted using a single crew member who adheres to the 24-hour crew schedule presented in Table 3.3. The crew member was simulated to be in a single pressurized core module habitat with relevant resource storages and operated without any ECLS technology models. Within the scope of crew water resource production/consumption, the implemented crew model was verified using three criteria: (1) water mass balance (water in equals water out) of the crew member, (2) resources produced by the crew member (i.e., water vapor and dirty water) is equal to resources outputted by the crew member to the habitat resource storage, and (3) potable water consumed by the crew is equal to potable water depleted in the habitat. Figure 11 represents a flow diagram of the unit test simulation set-up whereby the crew member took in potable water, O_2, and food and outputted water vapor (in the form of evaporated sweat and respiration), CO_2, dry waste, and dirty water (in the form of urine water).

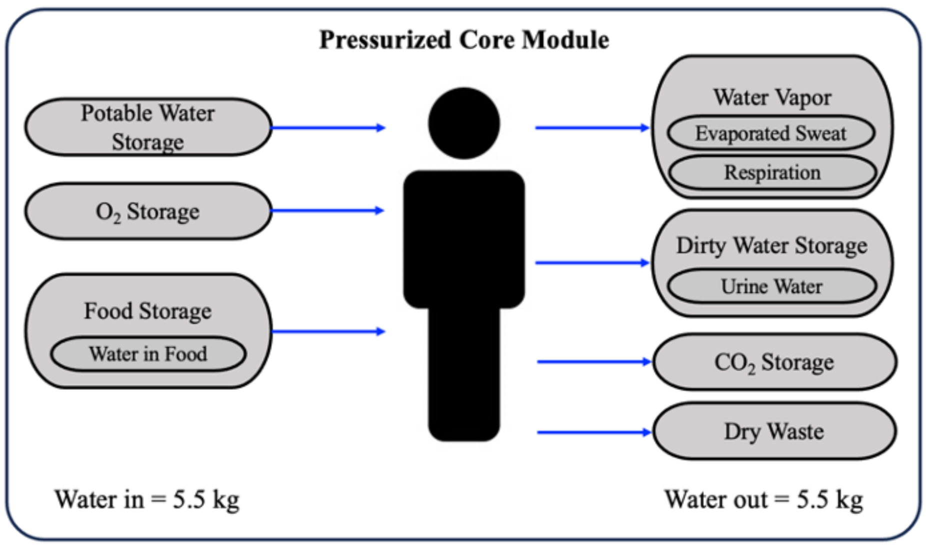


Figure 3.2: Resource flow diagram of a crew member inside a single pressurized core module habitat for 24 hours

From the test, a water mass balance in the crew model was confirmed; the crew consumed 5.5 kg of water and outputted 5.5 kg of water. This is approximately 20% more than the water mass input/output value of a crew member of the same mass and exercise protocol from a study completed by Ewert in 2019 where the crew member consumed and produced 4.53 kg of water daily [21]. This discrepancy was expected since the crew model used upper bound values for water vapor produced through respiration and sweat to ensure that water demand estimates erred on the side of being conservative. Creating conservative estimates of resource requirements early in the development process is important so that there is flexibility to accommodate for contingencies in subsequent developmental stages. In addition, Figure 3.3 through Figure 3.5 shows that that the model performed as intended. Figure 3.3 and Figure 3.4 show that the cumulative dirty water and water vapor produced is equal to the habitat dirty water storage and vapor storage level. Figure 3.5 shows that the potable water consumed by the crew is equal to the potable water depleted in the habitat; in other words, the water consumed and water remaining in the habitat potable water storage add up to the arbitrarily chosen initial value of 10 kg of potable water in the habitat.

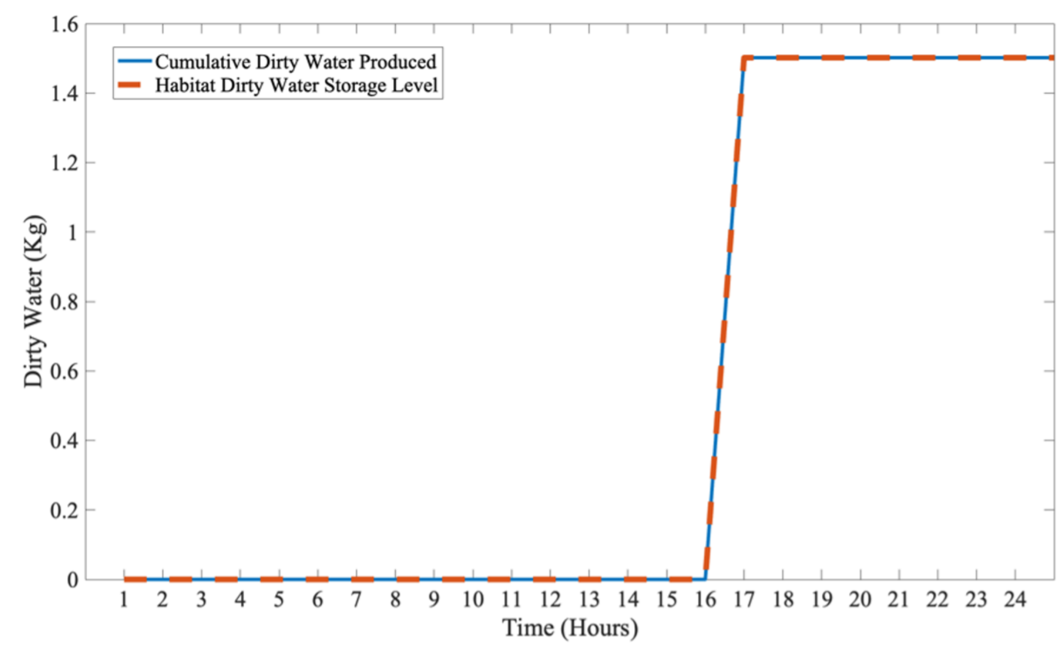


Figure 3.3: Dirty water level over time from running the crew model

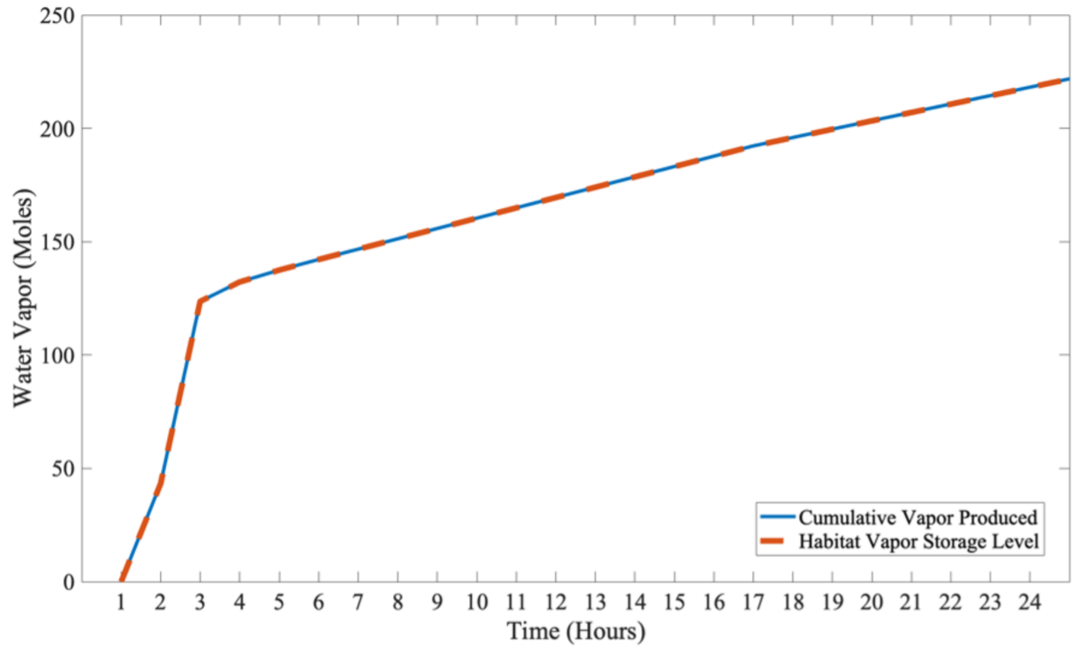


Figure 3.4: Water vapor level over time from running the crew model

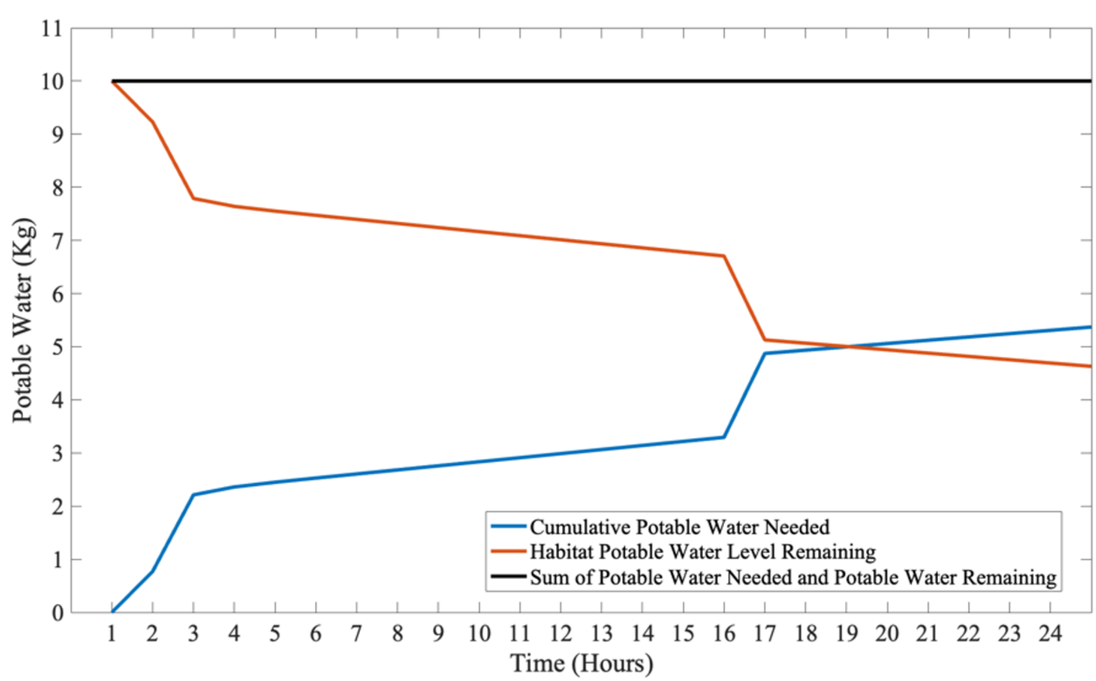


Figure 3.5: Potable water level over time from running the crew model

3.2.2 Validation of the Crew Model with ISS data

A first-pass validation of the updated crew model was performed using data from the ISS Water Recovery System (WRS). The data showed that "In the last year, 4474 L of potable water have been supplied to the US Segment potable bus by the WPA." It was assumed that "the last year" refers to the 2018-2019 year based on the publication date of [22], which approximately covers ISS Expeditions 57 to 61 [23]. Since the potable water generated by the WPA refers to the US segment potable bus, it was assumed that only US and European Space Agency astronauts are considered during Expeditions 57 to 61. On average, there were between 2-3 US and ESA astronauts onboard the ISS during each Expedition, suggesting that approximately 1491 L (lower bound) to 2237 L (upper bound) of water was produced by the WPA per crew member on the ISS [23].

HabNet was used to model the Node 3 'Tranquility' module of the ISS, where the WPA/UPA system is located, and was modified to include a Carbon Dioxide Removal Assembly (CDRA), Oxygen Generation Assembly (OGA), Pressure Control Assembly (PCA), Sabatier reactor, and WPA/UPA system [24]. A block diagram of the ECLS system is shown in Figure 3.6.

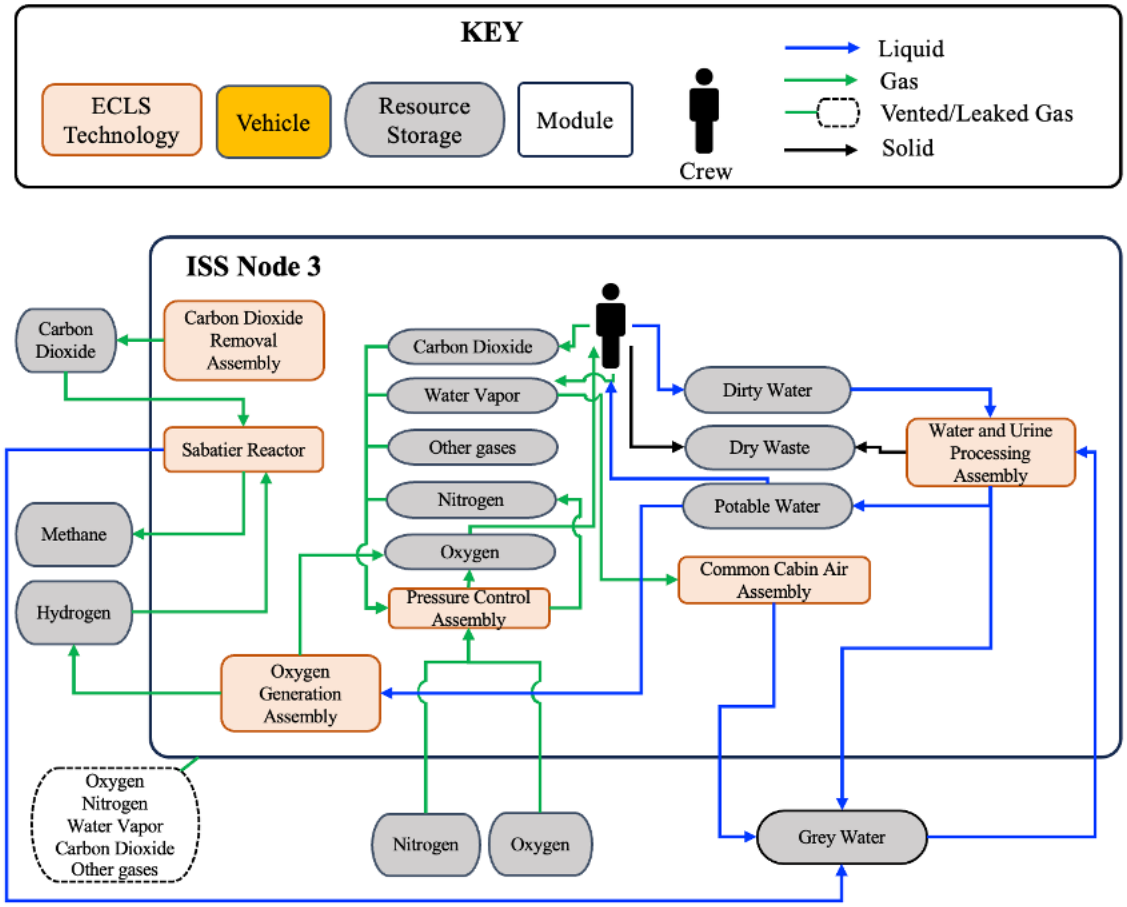


Figure 3.6: Block diagram showing the modeled ISS Node 3 ECLS architecture

The simulation was modeled for one crew member (modeled using the updated crew mode) on a one-year mission, and results showed that the WPA produced 1955 L of potable water over the one-year duration with one crew member. 1955 L is bounded by the upper and lower bounds of potable water generated by the WPA per crew member on the ISS in one year (1491 L and 2237 L respectively), which validates the updated crew model.

3.2.3 Waste and Hygiene Compartment

The waste and hygiene compartment functions to transport crew-generated wastewater into grey water and dirty water storage tanks, where the water will be reused or treated farther downstream. A resource flow diagram of the WHC is shown in Figure 3.7.

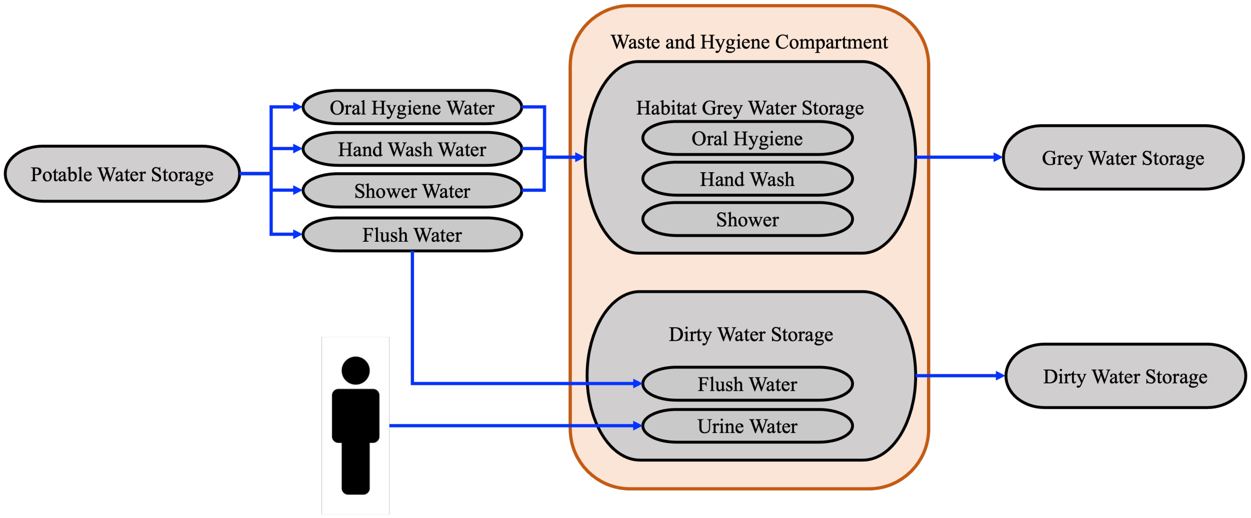


Figure 3.7: Resource flow diagram of the WHC

Potable water is used for personal hygiene functions which include oral hygiene, hand washing, shower, and toilet usage (flush water). Wastewater from oral hygiene, hand washing, and showering becomes grey water, and flush water is plumbed to the habitat's dirty water storage due to its contact with human excrement. Dirty water and grey water in the habitat are then transported to external dirty and grey water storage containment tanks for downstream processing or reuse. Values for the amount of oral hygiene water, hand wash water, shower water, and flush water needed per day were taken from NASA's 2022 Life Support BVAD and a twenty percent margin was added to each value for contingency as shown in Table 3.4 [18]. Note that values from Table 4-20 in [18] were processed to produce values in Table 3.4.

Table 3.4: Amount of water used per day per crew member for oral hygiene, hand wash, shower and flush water with a 20% margin [18]

Water Usage	**Amount per Day per Crew Member (kg)**
Oral Hygiene	0.552
Hand Wash	0.768
Shower Water	1.296
Flush Water	0.600

Modeling Assumptions and Limitations

Although flush water does not have to be potable water (water of a lower sanitation grade can be used), it was assumed that potable water is used as flush water to avoid bacterial accumulation in the WHC. It was also assumed that there is no flow rate limit on any of the water transfer processes (i.e., any amount of potable, grey, and dirty water can be transported per hour).

Modeling Assumptions and Limitations

To show that the WHC model performed as intended, a unit test was performed where the WHC model ran once during the twelfth hour of the day. It was isolated from other ECLS technologies and only interacted with potable, grey, and dirty water storage tanks. Figure 3.8 shows that the WHC functions as intended where the habitat potable water remaining after the twelfth hour of the day (6.784 kg) plus the external grey and dirty water levels (3.216 kg) that come from oral hygiene, hand wash, shower, and flushing, is equal to the initial value of 10 kg of potable water in the habitat (in other words, water mass is conserved within the WHC system). It is noted that because the crew model was not running in this test, the dirty water level excluded the mass of urine water.

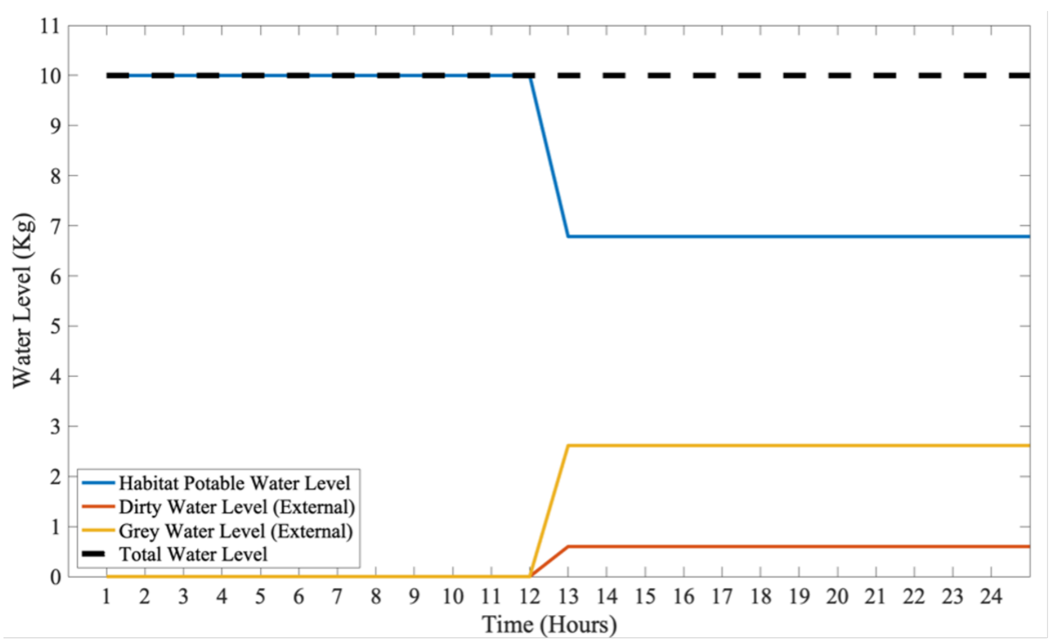


Figure 3.8: Dirty, grey, and habitat potable water levels from WHC operations

3.2.4 Laundry Machine Model

The laundry machine model functions to clean crew members' clothes throughout the mission and is abstracted to be a simplified model where it turns potable water into grey water as shown in Figure 3.9.

Figure 3.9: Resource flow diagram of the laundry model

Modeling Assumptions and Limitations

A 100% water return was assumed where wastewater from the laundry machine is transported to grey water storage and any moisture remaining on the washed clothes evaporates to the habitat environment and eventually gets processed by the common cabin air assembly (dehumidifier) into grey water. It was also assumed that each crew member would complete their laundry once a week, and this was encoded into the crews' schedule where the laundry machine is triggered once every seven days during an hour-long intravehicular activity. Each laundry load per crew member was assumed to use 24 gallons ($\sim$ 91 L) of water per load, which provides a 20% margin to the amount of water a standard washing machine uses per load [25].

Verification of the Laundry Model

A unit test with a single laundry machine for one load occurring at the twelfth hour of a day showed that the potable water depleted was equal to the grey water produced, verifying that the laundry model completed its intended function as shown in Figure 3.10.

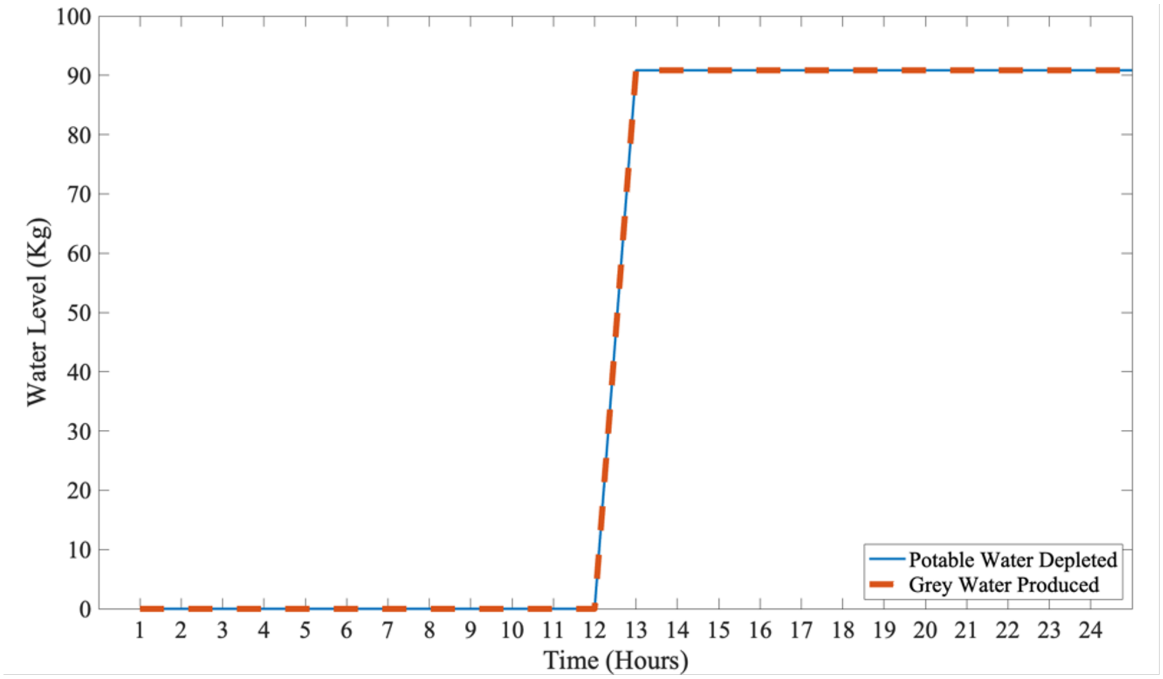


Figure 3.10: Potable water depleted and grey water produced for a laundry load occurring at the 12^{th} hour of the day

3.2.5 MAV and Cryocooler

The primary purpose of the MAV is to lift crew and cargo off the Martian surface and dock with a Mars-Earth transportation vehicle, facilitating the return of crew and cargo to Earth [6]. The MAV model uses cryogenic propellants (liquid oxygen (LOX) and liquid methane (LCH_4)) stored in cryogenic storage tanks that have an integrated cryocooler. As per the baseline long-duration ECLS architecture, gaseous oxygen and methane are fed into the cryocooler to be converted into LOX and LCH_4, which are stored in cryogenic storage tanks as shown in Figure 3.11.

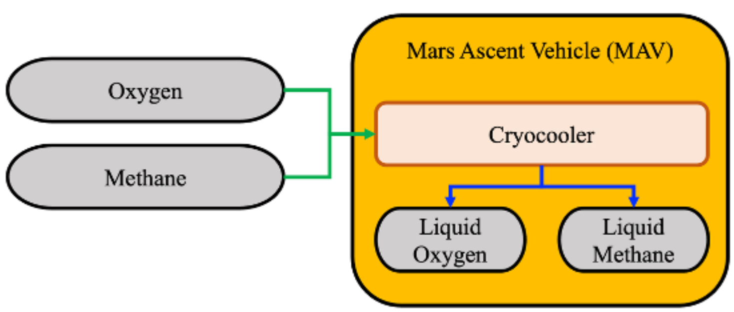


Figure 3.11: Resource flow diagram of the MAV and cryocooler model

At a high level, the MAV model outputs the amount of LCH_4 and LOX that is required to be produced per crew mission day such that there is enough propellant to lift crew and cargo off the surface of Mars by the end of the mission duration. Data taken from an internal JPL spreadsheet contains estimates of the necessary quantities of LOX and LCH_4 for a specified number of crew members on the mission, as shown in Figure 3.12, and were incorporated into the MAV model [26].

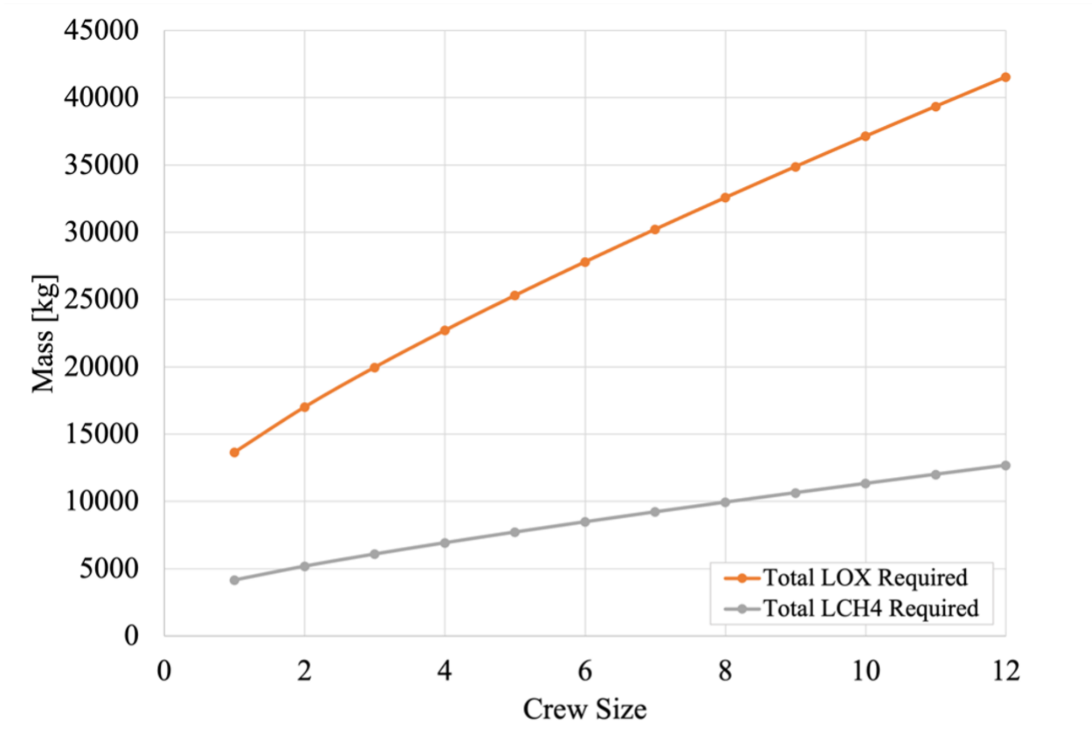


Figure 3.12: Plot of the LOX and LCH_4 mass required versus crew size. Note that the plot is altered from the original plot found in [26] to display relevant information and include formatting changes

The cryocooler and cryogenic storage tanks for LCH_4 and LOX were captured within the MAV model by incorporating a user input boil-off rate (BOR) parameter (%/day) for both the stored LOX and LCH_4.The MAV model uses the boil-off rates to calculate the amounts of LOX and LCH_4 that should be produced per day to ensure there is enough propellant at the end of the mission duration as per Figure 3.12. The amount of LCH_4 and LOX that is required to be produced per day is given by Equations 3.1 and 3.2.

$$r_{LCH_4} = \left(\frac{\sum_{t=1}^{T} l_{LCH_4,t} \times BOR}{req_{LCH_4} - \sum_{t=1}^{T} l_{LCH_4,t} \times BOR} \right) \frac{req_{LCH_4}}{T} \tag{3.1}$$

$$r_{LOX} = \left(\frac{\sum_{t=1}^{T} l_{BOR,t} \times BOR}{req_{LOX} - \sum_{t=1}^{T} l_{LOX,t} \times BOR} \right) \frac{req_{LOX}}{T} \tag{3.2}$$

where

r_{LCH_4}	=	rate of LCH_4 production per day (factoring in the BOR) [kg/day]
r_{LOX}	=	rate of LOX production per day (factoring in the BOR) [kg/day]
t	=	time [days]
req_{LCH_4}	=	required amount of LCH_4[kg] (per Figure 3.12)
req_{LOX}	=	required amount of LOX[kg] (per Figure 3.12)
$l_{LCH_4,t}$	=	level of LCH_4 at time t , $\frac{req_{LCH_4}}{T} + l_{LCH_4,t-1}(1 - BOR)$ [kg]
$l_{LOX,t}$	=	level of LOX at time t, $\frac{req_{LOX}}{T} + l_{LOX,t-1}(1 - BOR)$ [kg]
T	=	mission duration [days]
$l_{LCH_4,0}$	=	0
$l_{LOX,0}$	=	0

Modeling Assumptions and Limitations

The integrated MAV and cryocooler model assumed that the BOR is the only efficiency loss in the cryocooling process that turns gaseous oxygen and methane into LOX and LCH_4. Thermal efficiency, duty cycles, and power constraints were not factored into the MAV and cryocooler model. It was also assumed that the cryogenic propellant tanks can store any amount of LOX and LCH_4.

3.2.6 Water Electrolyzer for MAV Propellant

The water electrolyzer for the MAV propellant electrolyzes potable water into gaseous hydrogen and oxygen. The oxygen gas is then processed into LOX in the cryocooler while the hydrogen gas gets fed into the Sabatier reactor to react with carbon dioxide gas and produce methane gas which is then sent to the cryocooler to be turned into LCH_4. The block diagram in Figure 3.13 shows a resource flow diagram of the water electrolyzer for MAV propellant.

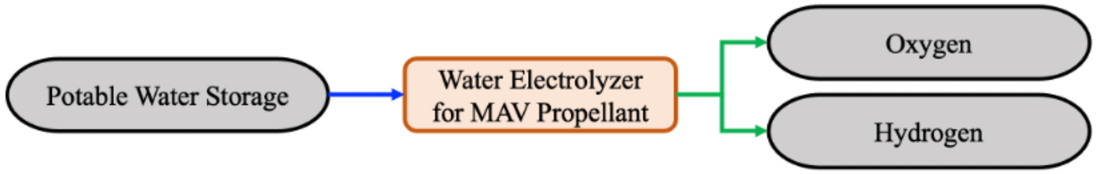


Figure 3.13: Block diagram showing the flow of inputs and outputs for the water electrolyzer for MAV propellant

The water electrolyzer for the MAV propellant model functions by taking in the amount of LOX and LCH_4 production required per day from the MAV model output and converting that to moles of water needed per hour to produce the required amount of LOX and LCH_4 based on the stoichiometric ratios shown in Equations 3.3 and 3.4. Water Electrolysis has the stoichiometric reaction shown in Equation 3.3.

$$2H_2O \rightarrow 2H_2 + O_2 \tag{3.3}$$

The Sabatier reaction has the stoichiometric reaction shown in Equation 3.4

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{3.4}$$

Based on Equations 3.3 and 3.4, it was inferred that two water molecules can yield one O2 molecule $(2:1)$ while two water molecules can yield 0.5 CH_4 molecules $(2:0.5)$. The molar oxidizer to fuel ratio (moles of LOX required to moles of LCH_4 required) for 1-12 crew members is $(1:1.64)$, meaning that hydrogen gas is the limiting reactant (i.e., the water required to be electrolyzed to produce enough MAV propellant is dependent on the amount of LCH_4 needed, and will result in an excess of LOX) [26]. The water electrolyzer then takes the amount of water from the potable water storage to produce the required amount of LCH_4 indicated by the MAV model output.

Modeling Assumptions and Limitations

It was assumed that the water electrolyzer for the MAV propellant could intake as much potable water as needed from the Mars habitation module and accommodate any oxygen production rate to ensure that enough LOX could be produced. A perfect stoichiometric reaction with no losses as shown in Equation 3.3 is also assumed. It is also assumed that there is no flow rate limit on any of the water/gas transfer processes.

3.2.7 Sabatier Reactor for MAV Propellant

The main function of the Sabatier reactor is to take in gaseous carbon dioxide and hydrogen to produce methane and water per the reaction shown in Equation 4. The output methane is fed into the cryocooler to be turned into LCH_4 for the MAV propellant and the output water is fed into the grey water storage as depicted in the block diagram shown in Figure 3.14.

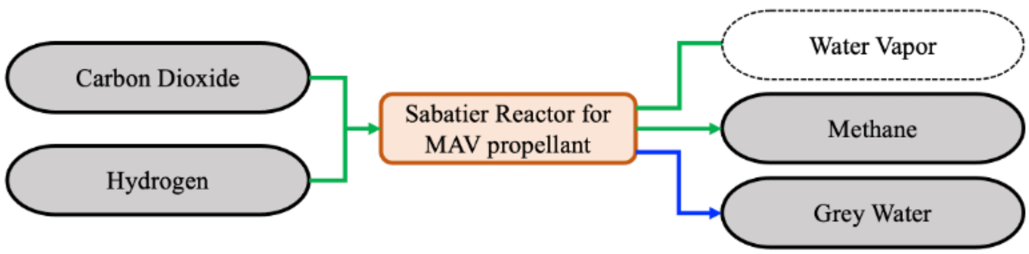


Figure 3.14: Block diagram showing the flow of inputs and outputs of the Sabatier reactor

Modeling Assumptions and Limitations

The Sabatier reactor was modeled such that it operated as soon as a 1:3.5 CO_2 to H_2 ratio was reached rather than a 1:4 CO_2 to H_2 ratio [27]. This was so that all the hydrogen in the storage tank could react as soon as possible since gaseous hydrogen is prone to leaking. In reality, some water product from the Sabatier reaction is lost as vapor. To account for this loss, the Sabatier reactor was modeled to include a user-inputted water conversion efficiency parameter that is currently approximated to be 0.9 (i.e., 0.9 of water produced gets reclaimed as grey water while 0.1 of water produced is vented away as water vapor) [28]. It was also assumed that the Sabatier reactor for the MAV propellant can intake as much carbon dioxide and hydrogen as needed and accommodate any methane production rate to ensure that enough LCH_4 can be produced by the end of the mission duration.

Verification of the MAV and Cryocooler, Water Electrolyzer for MAV propellant and Sabatier Reactor

To ensure that the MAV model, water electrolyzer for MAV propellant, and Sabatier reactor for MAV propellant all function as intended, a test was performed to see if the water electrolyzer for the MAV propellant and Sabatier reactor were both producing the expected amount of LOX and LCH_4 as outputted by the MAV model. This test ensured that the water electrolyzer for the MAV propellant was drawing the right amount of water needed to produce sufficient MAV propellant and that the stoichiometric reactions in both the Sabatier reactor and water electrolyzer had been implemented correctly. For a mission with one crew member on a 500-day mission and a LOX and LCH_4 boil-off rate of 0.1%/day, the results are as shown in Table 3.5.

Table 3.5: Table showing the expected LCH_4 and LOX production per hour based on the MAV model and the LCH_4 and LOX produced based on the Sabatier reactor and water electrolyzer output

Expected LCH_4 production per hour (MAV model output) [moles/hr]	LCH_4 production per hour (Sabatier reactor output) [moles/hr]	Expected LOX production per hour (MAV model output) [moles/hr]	LOX production per hour (Water electrolyzer output) [moles/hr]
27.56	27.56	45.24	55.13

The LCH_4 production per hour outputted by the Sabatier reactor is equal to the expected LCH_4 production per hour as outputted by the MAV model. The LOX production per hour outputted by the water electrolyzer is ∼10 moles/hour more than the expected LOX production per hour provided by the MAV model, which was expected as discussed in Section 3.2.6. To further verify that sufficient LCH_4 and LOX were being produced for MAV propellant, plots showing the LOX and LCH_4 levels over a 500-day mission for one crew member at a 0.1%/day boil-off rate are shown in Figure 3.15 and 3.16.

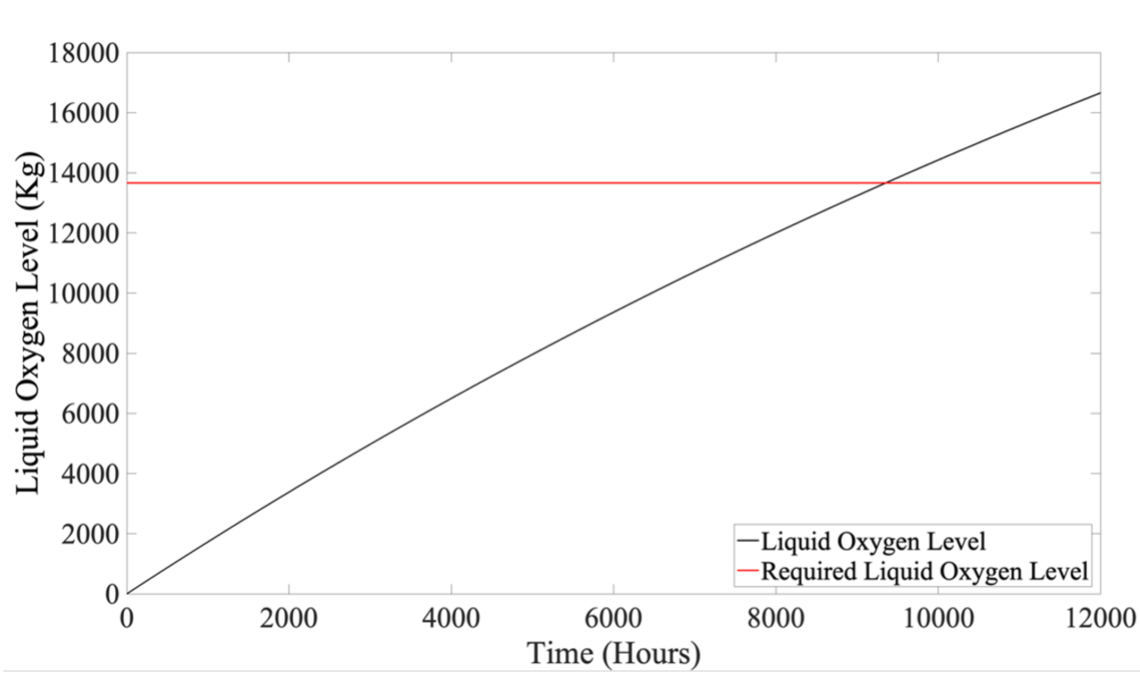


Figure 3.15: LOX level over time for a 500-day (12000 hr) mission for one crew member at a 0.1%/day boil-off rate

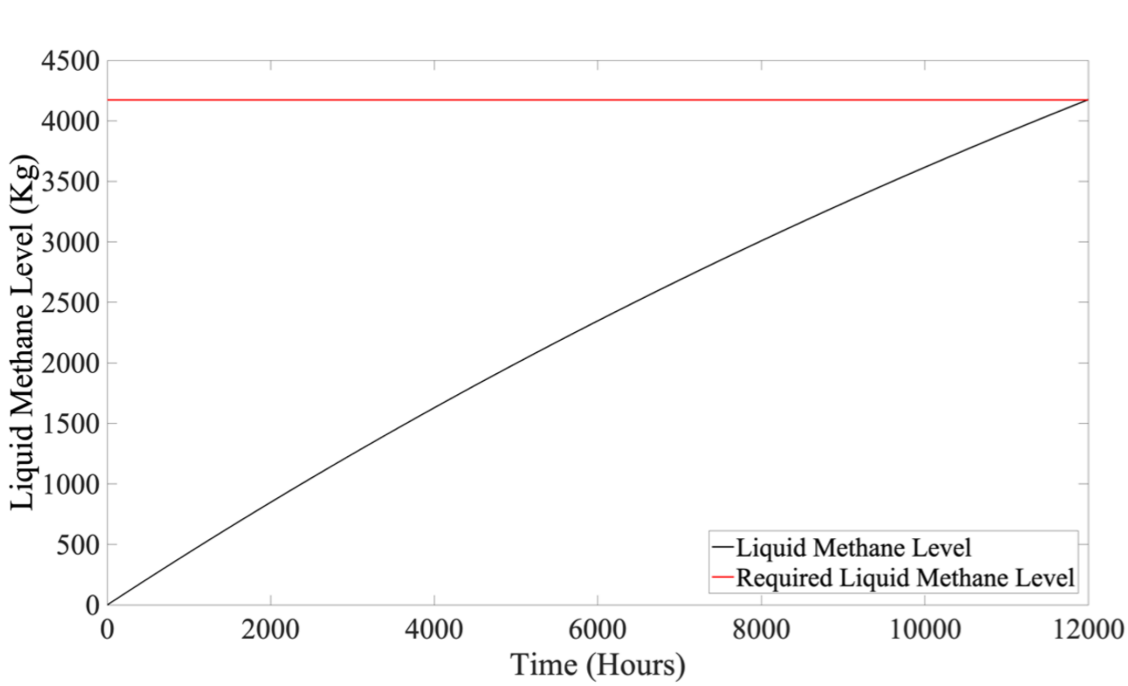


Figure 3.16: LCH_4 level over time for a 500-day (12000 hr) mission for one crew member at a 0.1%/day boil-off rate

Figure 3.15 shows that the amount of the LOX exceeds the required amount by the end of the mission and Figure 3.16 shows that the LCH_4 level reaches the required LCH_4 level by the end of the mission. These outcomes are both expected and indicate that the MAV model, water electrolyzer for MAV propellant, and Sabatier reactor for MAV propellant all collectively function to ensure that sufficient MAV propellant is produced by the end of the mission duration.

3.2.8 Summary of Updates to HabNet

Updates were made to the HabNet habitation module through modeling additional ECLS technology models and updating the crew model to reflect more recent data. The updates are summarized in Table 3.6.

Table 3.6: Summary of updates made to HabNet

Update	Explanation	Appendix
Crew Model	The crew schedule and crew physiological model were updated to reflect more recent data and enable the crew model to be modeled at a higher fidelity than what had been modeled by Do [9]. This can help improve the accuracy of water demand estimates. A water mass balance in the crew model was confirmed during verification as shown in Figure 3.3 to 3.5 and the crew model data was validated with ISS WPA data as described in Section 3.2.2.	A.1 A.2
Waste and Hygiene Compartment	A WHC was modeled to transport crew waste to grey and dirty water storage tanks where water can be reclaimed by the WPA. A water mass balance was confirmed during verification as show in Figure 3.8	A.3
Laundry	A laundry machine was modeled so that crew will have the capability to wash their clothes. It was assumed that ∼91L of potable water is used and turned into grey water per load. A water mass balance was confirmed during verification as shown in Figure 3.10.	A.4
MAV and Cryocooler	An integrated MAV and cryocooler model was created using data from an internal JPL spreadsheet [26]. It outputs the amount of LCH_4 and LOX that is required to be produced per crew mission day (factors in boil-off rates of LCH_4 and LOX) such that there is enough propellant to lift crew and cargo off the surface of Mars by the end of the mission duration. The output from the MAV and cryocooler model is used by the water electrolyzer for MAV propellant generation.	A.5
Water Electrolyzer for MAV propellant generation	The water electrolyzer for MAV propellant generation was modeled. It turns potable water into gaseous hydrogen and oxygen. The oxygen gas is processed into LOX while the hydrogen gas is fed into the Sabatier reactor.	A.6
Sabatier Reactor for MAV propellant generation	The Sabatier reactor for MAV propellant generation was modeled. It takes in gaseous hydrogen and carbon dioxide to produce methane gas, which is then processed in the cryocooler to be turned into LCH_4. An integrated verification test was performed for the MAV and cryocooler, water electrolyzer, and Sabatier for MAV propellant generation to show that the expected amount of LOX and LCH_4 is generated for a 500-day mission for one crew member. This is shown in Figure 3.15 and Figure 3.16.	A.7

3.3 Simulation Set-Up

This section describes the simulation set-up in HabNet that was used to predict the amount of water needed to sustain continuous human presence on Mars.

3.3.1 Martian Surface Campaign Crew Profile

A Martian surface campaign crew profile that captures increasing and continuous human presence is shown in Figure 3.17 and was the baseline crew profile used for water demand investigation. This crew profile is an extension of the NASA DRA5.0 recommended conjunction-class sortie mission [9]. In the Figure 3.17 profile, each successive crew of four (each denoted by a unique color) spends a progressively longer duration on the Martian surface until a predetermined steady-state population is achieved. The length of stay for each group of crew follows the rule that the nth group of crew remains on the surface for 790n+540 days until the $n+1^{th}$ crew group arrives. Subsequent crew groups after the n+1th remain on the Martian surface for 790(n+1) + 540 days in order to maintain the population [9]. These length-of-stay values assume that a conjunction class mission trajectory is used to transport four crew members for each mission. This results in a minimum period between each resupply (i.e., when a new group of crew arrives) that is approximately equal to the synodic period of Earth and Mars around the Sun (∼26 months or ∼790 days) [9]. The population ramp-up crew profile in Figure 3.17 was chosen because it facilitated the investigation of water demand requirements for space habitation capabilities that approach distant future "Earth Independence" capabilities (trajectory denoted by the blue arrow shown on Figure 3.18), which has yet to be explored.

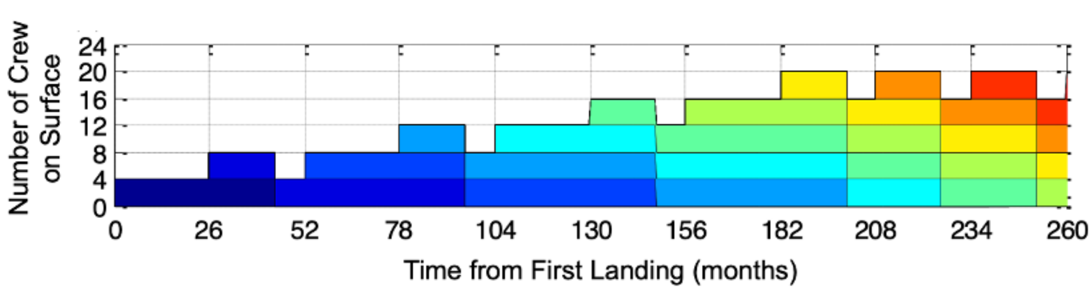


Figure 3.17: Mars surface campaign crew profile showing population ramp up [9]

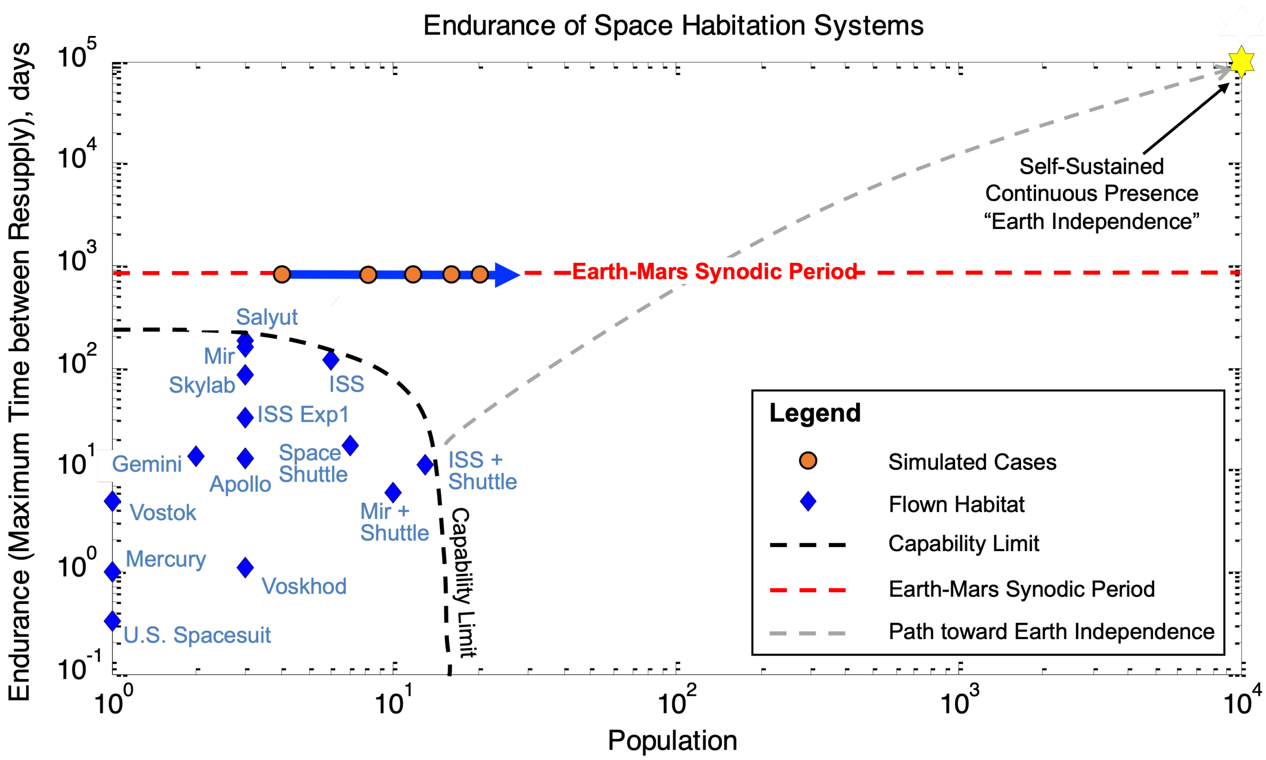


Figure 3.18: Evolution of Space Habitation Capabilities. Note that the image is altered from the original image found in [9]. The blue arrow represents space habitation capabilities within the scope of this paper that approach "Earth Independence" capabilities

To determine the water demand for the crew profile shown in Figure 3.17, five discrete cases that captured crew sizes of 4, 8, 12, 16, and 20 people were executed as documented in Table 3.7. These five discrete cases represent the annotated cases shown in Figure 3.18 and Figure 3.19, and were intentionally selected to enable the modeling of water demand for missions beyond the "capability limit" Pareto frontier shown in Figure 3.18 that humans astronauts have yet to venture beyond.

Table 3.7: Simulation cases

Case	Number of Crew	Duration
1	4	790 days
2	8	790 days
3	12	790 days
4	16	790 days
5	20	790 days

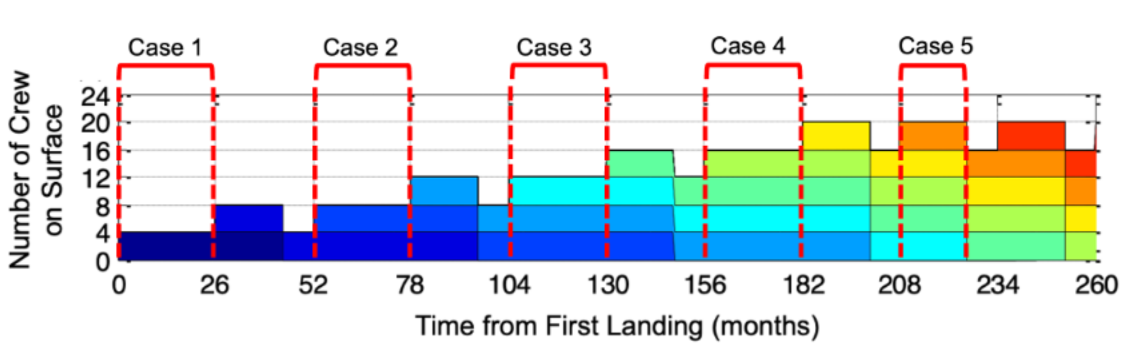


Figure 3.19: Simulation cases represented on the crew profile. Note that Case 5 was run for 26 months (790 days) rather than 540 days for consistency of the mission duration. The figure is altered from the original figure found in 3.17

It was assumed that a steady state population of 20 people was desired. The simulated cases do not capture the dynamics of resource levels in between the discrete cases presented; continuous simulation of the crew profile will be required and was left for future work. For consistency of the mission duration, Case 5 was executed for 26 months (790 days) rather than 540 days.

3.3.2 Input Parameters

The input parameters, which remained constant throughout all five cases, are presented in Tables 3.8 to 3.12. Based on Table 3.8 an unlimited initial supply of oxygen, nitrogen, carbon dioxide, grey water, potable water, and power was assumed. The simulation started with an unlimited amount of potable water (for the Mars Habitation Module and MAV propellant) and grey water (for the BPC) to allow water depletion to be monitored over time and enable the calculation of total water demand. For simplicity, only wheat was selected as the crop type for the crew to consume because wheat is the most calorically dense per square meter of crop growth area per day [9].

Table 3.8: Initial storages (resources brought from Earth or assumed to be readily available on Mars)

Input Parameter	Units	Value
Crop type	N/A	Wheat
Food	N/A	Twice the amount needed to sustain crew members for the mission duration
Oxygen	Moles	Unlimited
Nitrogen	Moles	Unlimited
Carbon Dioxide	Moles	Unlimited
Grey Water (BPC)	kg	Unlimited
Potable water (Mars Habitation Module)	kg	Unlimited
Potable water (MAV propellant)	kg	Unlimited
Power Available	W	Unlimited

Table 3.9 and Table 3.10 highlight air-related parameters inside the BPC and Mars Habitation Module. In HabNet, air composition is abstracted into categories of oxygen, nitrogen, carbon dioxide, water vapor, and other gases. The initial target levels of each of these gases are presented in Table 3.9 and Table 3.10. It is important to note that for the BPC, the target CO_2 molar fraction was set to 0.0012 because it was found to be the optimal concentration for maximizing photosynthesis rates in crops [29]. Oxygen fire risk molar fraction refers to the fraction of oxygen gas in the module that is considered a fire hazard. A key assumption made regarding the air tightness of the modules was a sustained leakage. For this work, it was assumed that there is a 0.05% air leakage rate per day [30]. The target relative humidity inside the Mars habitation module was also set to be 40%. This relative humidity level was selected because maintaining indoor relative humidity levels between 40-60% can help minimize adverse health effects [31]. Last, the target relative humidity inside the BPC was set to be 55%. This selection was made to support the ideal relative humidity for wheat, which is between 50% and 60% [32].

Table 3.9: Habitat module air parameters

Input Parameter	Units	Value
Daily air leakage rate	%	0.05 [30]
Total atmospheric pressure targeted	kPa	55.2 [33]
Target O_2 molar fraction	-	0.32 [33]
Target N_2 molar fraction	-	0.6656
Target CO_2 molar fraction	-	0.0004 [34]
Target water molar vapor fraction	-	0.004 [34]
Target other gases molar fraction	-	0.01 [34]
O_2 fire risk molar fraction	-	0.5 [9]
Target relative humidity	%	40 [31]

Table 3.10: BPC module air parameters

Input Parameter	Units	Value
Daily air leakage rate	%	0.05 [30]
Total atmospheric pressure targeted	kPa	55.2 [33]
Target O_2 molar fraction	-	0.32 [33]
Target N_2 molar fraction	-	0.6648
Target CO_2 molar fraction	-	0.0012 [34]
Target water molar vapor fraction	-	0.004 [34]
Target other gases molar fraction	-	0.01 [34]
O_2 fire risk molar fraction	-	0.5 [9]
Target relative humidity	%	55 [32]

Each crew member followed the generic crew schedule shown in Table 3.11 [35]. Every seventh day (once per week), each crew member would spend an hour cleaning laundry during the "Intravehicular Activity" crew member activity. It was assumed that each crew member is a 35-year-old male who weighs 85 kg. To prevent simultaneous use of facilities (e.g., WHC, laundry, exercise equipment), each additional crew member followed the same sequence of activities shown in Table 3.11, but shifted by an activity from the previous crew member.

Table 3.11: Crew schedule

Hour	**Duration (hr)**	**Crew Member Activity**
1	0.5	Exercise - Aerobic
2	1	Exercise - Resistive
3	1	Recovery - Hour 1
4	1	Recovery - Hour 2
5	1	Recovery - Hour 3
6-15	10	Intravehicular Activity (laundry module triggered once every 7^{th} day)
16	1	Intravehicular Activity (Toilet/Personal Hygiene)
17-24	8	Sleep

The BORs for LOX and LCH_4 are shown in Table 3.12 below.

Table 3.12: Boil-off rates for LOX and LCH_4

Fuel/Oxidizer	Boil Off Rate (%/day)
LCH_4	0.1
LOX	0.1

3.3.3 ECLS Technology Running Order

The various ECLS technologies were triggered in the order documented in Table 3.13. It was essential that the ECLS technologies were triggered in the presented order because each has downstream impacts on other ECLS technologies. For example, the PCA located in the BPC and Mars habitation module was triggered after all entities that move gases within the BPC and Mars habitation module (ORA, CDRA, Crops, CO2 Injector, CCAA, Condensed Water Remover, Crew) were triggered. This ensured that the modules were not under or over-pressured and that the oxygen level inside the modules was sufficient but not in excess. The CO_2 injector (which added CO2 into the BPC), CCAA, and condensed water remover (all in the BPC) all ran after the crops respired. This ensured that CO_2 levels and relative humidity values in the BPC reached target values by the end of each hour.

Table 3.13: Technology running order

Technology	Location
1. Mars Habitation Module (air leakage)	N/A
2. BPC Module (air leakage)	N/A
3. Habitat Water Electrolyzer	Mars Habitation Module
4. Water Electrolyzer for MAV Propellant	MAV Propellant Water Loop
5. Sabatier Reactor for MAV Propellant	MAV Propellant Water Loop
6. WPA	MAV Propellant Water Loop
7. ORA	BPC
8. CDRA	Mars Habitation Module
9. Laundry	Mars Habitation Module
10. WPA/UPA	Mars Habitation Module
11. Crops	BPC
12. CO_2 Injector	BPC
13. CCAA	BPC
14. Condensed Water Remover	BPC
15. Food Processor	BPC
16. Crew	Mars Habitation Module
17. CCAA	Mars Habitation Module
18. WHC	Mars Habitation Module
19. PCA	Mars Habitation Module
20. PCA	BPC

3.3.4 Input Variables

Table 3.14 below documents the input variables for each simulation case.

Table 3.14: Input variables for the simulation cases

<table>
<tr><th>Variable</th><th colspan="5">Value</th></tr>
<tr><th></th><th>Case 1</th><th>Case 2</th><th>Case 3</th><th>Case 4</th><th>Case 5</th></tr>
<tr><td>Number of Crew</td><td>4</td><td>8</td><td>12</td><td>16</td><td>20</td></tr>
<tr><td rowspan="2">Mars habitation module volume $[m^3]$</td><td>60</td><td>120</td><td>180</td><td>240</td><td>300</td></tr>
<tr><td colspan="5">Estimates of the Mars habitation module volume used the Celentano curve parametric function given by:

Habitable Volume $[m^3] = A(1 - e^{\frac{-duration}{B}}) \times N$

where the standard form uses $A = 5$ (tolerable), 10 (performance), 20 (optimum), $B = 20$ days, N is number of crew, duration is in days [36]. A was assumed to be 15 for all simulation cases.</td></tr>
<tr><td rowspan="2">BPC volume $[m^3]$</td><td>1000</td><td>1500</td><td>2000</td><td>2750</td><td>3250</td></tr>
<tr><td colspan="5">The BPC volume was sized to ensure that all crops stay alive throughout the mission duration. For larger crew sizes, more crops were needed to provide enough food for crew and therefore more CO_2 was required for crops to respire and stay alive. Larger volumes were therefore needed to accommodate more crops as seen in the increasing BPC volume.</td></tr>
<tr><td rowspan="2">Crop growth area $[m^2]$</td><td>156.685</td><td>313.370</td><td>470.056</td><td>626.741</td><td>783.426</td></tr>
<tr><td colspan="5">These were the crop growth areas required for different crew sizes to produce sufficient wheat crops to provide sufficient calories for crew members. Each crew member requires approximately ∼3773.3 calories per day as calculated in the crew model of HabNet based on crew age, gender, weight, and crew activity intensity [9]. This crop growth area ensures that the rate of food production is greater than or equal to the rate of food consumption (supports 100% of crew caloric needs).</td></tr>
<tr><td rowspan="2">Number of MAVs</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td colspan="5">It was assumed that each MAV could carry four crew members (consistent with the MAV design in [6]) so that the number of MAV seats readily available was equal to the crew size.</td></tr>
<tr><td rowspan="2">Number of CDRAs in the Mars habitation module</td><td>3</td><td>3</td><td>3</td><td>5</td><td>6</td></tr>
<tr><td colspan="5">The number of CDRA units was as many as required to ensure no crew members died of carbon dioxide poisoning. The current CDRA unit in HabNet was modeled after the ISS CDRA [9].</td></tr>
</table>

Number of WPA/UPA units for the life support loop	1	2	3	4	5
	An additional WPA/UPA system was brought and added to the Mars habitation module with each additional crew group of four. This ensured that the life support water loop water recovery rate (percentage of water output reclaimed) remained as close as possible to 93-94%, which is the water recovery rate on the ISS prior to the addition of the brine processing assembly (BPA) [37]. Given that the ISS serves an analog for the life support loop of the Mars habitation module – where MAV propellant production and food crop growth are absent – each simulation case aimed to achieve a water recovery rate closely aligned to that of the ISS.				
Number of CCAAs in the BPC	10	10	10	15	17
	The number of CCAA units in the BPC was such that the relative humidity inside the BPC stayed within ±10% of the target relative humidity of 55%.				
Number of CCAAs for the life support loop	1	1	1	2	2
	There were enough CCAA units to ensure that the relative humidity inside the Mars habitation module stayed within 30% to 60% (target relative humidity is 40%). 60% relative humidity was set to be the upper bound before another CCAA unit was added since 60% is stated to be the upper relative humidity bound to minimize adverse health effects [31].				
Number of WPAs for the MAV propellant loop	There were as many WPAs as needed to ensure that the WPA does not need to run every hour as a result of reaching full capacity. One WPA was needed for the MAV propellant loop for all five cases to achieve a water recovery rate of approximately 45% in the MAV propellant loop.				

3.4 Simulation Set-Up Verification

To verify that the integrated simulation set-up outlined in Section 3.3 is functional, an integrated 'unit-test' case was completed for a mission involving one crew member on a 2000-hour mission. The input parameters and technology running order documented in Table 3.8 through Table 3.12 were used and the input variables implemented in this unit-test case are shown in Table 3.15.

Table 3.15: Input variables for a 2000-hour test case with one crew member

Variable	**Value**
Number of Crew	1
Mars Habitation Module volume [m^3]	60
BPC volume [m^3]	1000
Crop growth area [m^2]	79
Number of CDRAs in the Mars habitation module	3
Number of WPA/UPA units for the life support loop	1
Number of CCAAs in the BPC	10
Number of CCAAs for the life support loop	1
Number of WPAs for the MAV propellant loop	1

Key resource levels and atmospheric conditions in the Mars habitation module (MarsHab) and BPC were tracked over time. Results indicated that the integrated simulation operated as expected. Behaviors in the hydrogen, grey water, LOX, and LCH_4 levels suggest that the MAV propellant loop was functioning as intended. Water reclamation capabilities were verified in the life support loop. Furthermore, the dynamics of gases and pressure in the MarHab and BPC indicate that both the PCA and CCAA were able to perform their functions in the integrated simulation environment. Food levels in the MarsHab and dry waste accumulation in the BPC suggested that the BPC system was able to support plant growth and feed crew. In all, these observations from the unit-test case confirmed that the simulation set-up outlined in Section 3.3 can be applied for longer-duration missions and larger crew sizes. The detailed verification can be found in Appendix B.

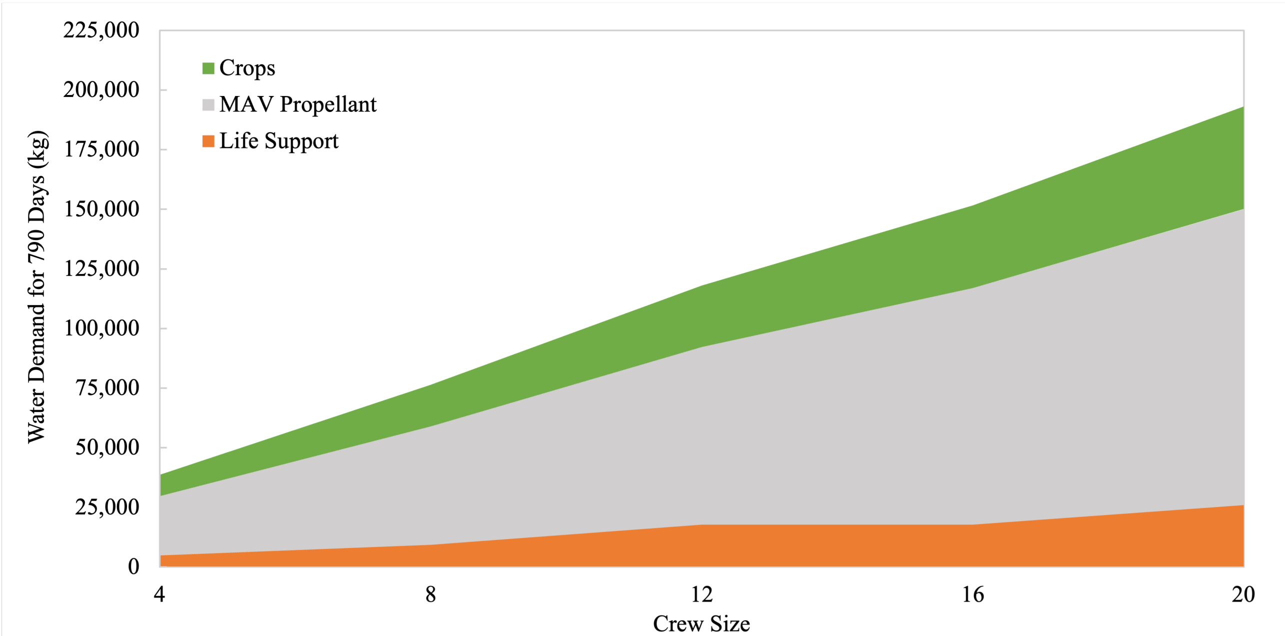
Chapter 4

Deterministic Modeling of Water Demand

This chapter presents results from executing the five simulation cases documented in Table 3.7 that used the ECLS architecture shown in Figure 3.12 and the input parameters, variables, and technology running order documented in Section 3.3. The results for water demand were interpreted and bench-marked against water used by an average American household. Limitations to the water demand estimates are discussed, along with improvements that could be made to increase the accuracy of the presented water demand results.

4.1 Results

Figure 4.1 presents the water demand for 790 days for crew sizes of 4, 8, 12, 16, and 20 people along with the net water demand per crew member per day. Results show that across all crew sizes, 63-65% of water is needed for generating MAV propellant, 22-23% of the water is needed for crops, and 12-15% is needed for life support.



Crew Size	4	8	12	16	20
Total Water Demand [kg]	38,669	76,545	118,069	151,617	193,134
Water Demand per Crew Member per Day [kg/Crew Member/Day]	12.24	12.10	12.45	12.00	12.22

Figure 4.1: Water demand for 790 days for crew sizes of 4, 8, 12, 16, and 20 and the corresponding water demand per crew member per day

The water recovery rates across all the cases are documented in Table 4.1 for the life support and MAV propellant water loop. It should be noted that the water recovery rate of the life support loop across all five cases deviated no more than 2% from that of the ISS prior to the installation of the BPA (93-94%) [37]. Note that the BPC water recovery rate is not quantified because the design of the water recovery system in the BPC water loop (i.e., the number of CCAAs in the BPC) was intended to let the BPC achieve the target relative humidity (55±10%) rather than a predetermined and consistent water recovery rate.

Table 4.1: Water recovery rate for the life support water loop and MAV propellant water loop

Crew Size	Life Support Water Recovery Rate [%]	MAV Propellant Water Recovery Rate [%]
4	93.47	44.94
8	93.73	44.97
12	91.74	44.97
16	93.63	44.98
20	92.45	44.98

4.2 Discussion

The water demand for each crew member per day fluctuates between 12.00 to 12.45 kg across the five cases. These results do not reflect the expected benefit of economies of scale, where the water demand per crew member per day decreases with a larger crew size. An intuitive explanation for this is that the crew schedule was not optimized for sharing resources as the crew size increased. For example, each crew member completed laundry once a week without sharing loads. In addition, the CCAA and WPA/UPA technologies in the Mars habitation and BPC modules were modeled based on systems that exist on the ISS that are not optimized for larger crew sizes [9].

By comparing the average US household water consumption rates to those used by the Martian crew members, some key insights were gained. Benchmarking the water demand estimates against the average American household water usage highlighted the impact of incorporating water recovery capabilities in the ECLS architecture for long-duration missions. According to the US Environmental Protection Agency, the average American family (between 3-4 people) uses over 300 gallons of water per day ($\sim$ 360 kg per person per day) for indoor and outdoor activities such as showering, laundry, and watering lawns [38]. This equates to $\sim$ 900,000 kg over 790 days at an assumed 0% water recovery rate. Comparatively, four crew members require 4.31% of that used by the average American family over 790 days. Even with a crew size of 20, the water demand is only 21.53% of that used by the average American family in 790 days. These water demand estimates may seem unexpectedly low, but a key consideration that must be made is the use of water recovery methodologies. The average US household can be considered inefficient in their use of water whereas Martian use is more efficient through the implementation of water recovery technologies. It is asserted that this difference is a major source of disparity between Martian and Earth-based (average US household) water consumption rates. This difference is also highlighted as a critical factor in accurately modeling water demand and recovery needs for long-term Martian missions.

While water reclamation technologies have the potential to reduce the amount of water that will need to be extracted from the Martian surface or brought to Mars, they can also introduce operational and integration complexities to the ECLS system. Implementing water reclamation technologies can also add to the launch mass needed for parts, spares, and maintenance capabilities. Determining water required to sustain continuous human presence on Mars can therefore be seen as a trade-off between many factors including but not limited to the ECLS system water recovery rate, launch mass, ECLS system complexity, and ISRU capabilities.

4.3 Limitations and Future Work

The water demand estimates presented in this paper have associated limitations and areas for further work. Specifically, improvements to the simulation set-up, BPC module, Mars habitation module, and crew logistics are addressed.

4.3.1 Simulation Set-Up

The five discrete cases summarized in Table 3.7 were simulated to determine the water demand of the crew profile shown in Figure 3.17. However, these discrete cases do not capture the dynamics of resource levels between the cases and thus necessitate continuous simulations of the crew profile. Performing continuous simulations in the future can help capture water demands at a higher fidelity. This includes modeling mission architectural elements such as changing crew sizes, the addition of ECLS technologies or modules throughout the mission, and resupply capabilities.

In addition, the simulation set-up assumed that there was an unlimited supply of power, oxygen, nitrogen, and carbon dioxide. These supplies are either assumed to be readily available for use on Mars or brought to Mars from Earth, which is not realistic. Further literature review needs to be conducted to understand the availability and capabilities to extract these resources on Mars as the limited resources can pose constraints that impact water demand. For example, power constraints can impact the duty cycle of various ECLS technologies (e.g., CCAA, WPA/UPA, and water electrolyzer for the MAV propellant), which can impact the water recovery rate and water demand. Furthermore, water leakage, extravehicular activities, and reserved water needed for radiation shielding were not modeled. All three may contribute to increased water demands to compensate for leaked water, cooling spacesuits, and supplying additional water to protect the crew from radiation.

4.3.2 BPC Module

As seen in Table 3.14, the BPC volume expanded as crew size increased to ensure that there was sufficient CO_2 to support more crops to feed more crew members. This suggests that the BPC volume can expand over time, which can pose logistical and operational challenges if implemented. An approach to fixing this issue could be to add smaller identical BPC modules to accommodate more crops. This strategy, rather than increasing the volume of a single BPC module, can also provide the crop growth system with redundancy.

Another limitation of the BPC module is that wheat was the only crop grown inside the BPC. While wheat provides sufficient calories for crew members to perform their activities, wheat does not have all the macro-nutrients necessary for a nutritious diet or to support critical bodily processes such as growth, development, and metabolic activities. Future simulations can incorporate other crop types already modeled in HabNet such as tomatoes, beans, and rice.

In addition, the number of CCAAs installed in the BPC was aimed at ensuring the relative humidity remained within the desired bounds of 55±10%. An avenue for further exploration could be to size the number of CCAAs in the BPC to maximize the water recovery rate in the BPC, minimize power usage, and reduce system mass while still maintaining the desired relative humidity inside the BPC.

4.3.3 Mars Habitation Module

Estimates for the Mars habitation module volume for each crew size were based on the Celentano curve parametric function. However, there are known limitations with Celentano curves. The test conducted by Celentano et al., upon which the Celentano curves are predicated, had a maximum duration of seven days [39]. Data for habitable volume beyond the seven-day time frame were extrapolated and may be inaccurate for durations as long as 790 days [39]. While the Celentano curve habitable volume estimate may initially suffice, future iterations of the simulation will need to implement a more robust habitable volume estimation scheme.

4.3.4 Crew Logistics

In the cases simulated, each additional crew member's schedule was shifted by an activity from the previous crew member's schedule. Although the shifted schedules aided in preventing the simultaneous use of equipment between crew members, the schedules may prove impractical for cohabiting crew members. For example, some crew members may be asleep while others are exercising, potentially causing disruption for those who are trying to sleep. To address this issue, an optimal redesign of the crew schedule can help align sleep times for all crew members while ensuring that they can still avoid simultaneous use of facilities and equipment.

Furthermore, it was assumed that the number of MAV seats, with each MAV capable of transporting four crew members, matched the total number of crew in the mission. This provided the option for crew members to depart from the Martian surface at any time but was contingent upon the availability of 15 MAVs. With the current MAV model's capability of estimating LOX and LCH_4 requirements for a MAV that can hold up to 12 crew members, there is an opportunity to further investigate other crew return architectures. This exploration may prove beneficial in better understanding water demands for sustaining continuous human presence on Mars.

Chapter 5

Probabilistic Modeling of Water Demand

The purpose of this chapter is to demonstrate the ability to provide probabilistic water demand estimates for the cases simulated in Chapter 4 using High-Performance Computing (HPC). To accomplish this, three input parameters were selected for investigation into how they impact water demand. The parameters of interest include:

1. Water Leakage Rate [%]

2. LOX and LCH_4 Boil-Off-Rates [%/day]

3. Air Leakage Rate [%/day]

These parameters were selected based on heuristic reasoning, which posits that water demand is notably sensitive to resource losses within the system. Specifically, water leakage contributes to a depletion of the system's water supply, subsequently leading to an increase in water demand. Additionally, the boil-off of LOX and LCH_4 results in the loss of MAV propellant, necessitating supplementary water to facilitate the production of the required propellant quantity. Furthermore, air leaks lead to a dissipation of air, which includes water vapor, into the Martian environment, necessitating additional water to compensate for the incurred loss. A sensitivity analysis was first conducted to quantitatively evaluate the extent to which each of the three input parameters impacts the total water demand (the sum of water required for life support, MAV propellant generation, and crops). The results of the sensitivity analysis provided an informed decision on which parameters were to be represented by probability distributions in the Monte Carlo simulation, which was then conducted for each of the five cases outlined in Table 3.7 using the MIT SuperCloud supercomputer. This marked the first time HabNet leveraged HPC to obtain results and can support future studies that may require computationally intensive uses of HabNet.

5.1 Sensitivity Analysis

A sensitivity analysis was performed on Case 1 (4 crew members on a 790-day mission, with the simulation set-up documented in Section 3.3) for the water leakage rate, boil-off rate, and air leakage rate. It was presumed that the outcome of the sensitivity analysis conducted on Case 1 could extend to larger crew sizes in Cases 2 through 5, rendering it unnecessary to repeat the analysis for these subsequent cases. The selection of lower and upper bounds for each parameter was informed by relevant literature and is documented in Table 5.1.

Table 5.1: Lower and upper bounds for water leakage rate, boil-off rate, and air leakage rate used in the sensitivity analysis

Parameter	Lower Bound	Upper Bound
Water Leakage Rate [%]	0	25
Boil-off Rate [%/day]	0	0.5
Air Leakage Rate [%/day]	0.01	0.09

As reported in [40], the average water loss across 43 cities surveyed on Earth in 2012 was found to be 21%. Under the presumption that a water system designed for the Martian environment is expected to be less prone to leaks compared to Earth-based systems, attributed to the relative scarcity of water and newness of water systems on Mars, the upper bound water leakage rate was set to 25%. The lower bound for water leakage was set to 0%, which is consistent with the assumption made in Chapter 4. The boil-off rate lower bound of 0%/day assumes zero-boil off (ZBO), a cryogenic fluid management technology capability that NASA is working toward [41], while the upper bound boil-off rate of 0.5%/day is based on commercially available Earth-based cryogenic tanks [42]. The upper and lower bounds for air leakage were taken from Table 4-1 of NASA's 2022 Baseline Value and Assumptions Document [18].

5.1.1 Water Leakage Rate

Water leakage was implemented into the simulation as the loss of grey and potable water flowing through the system. Water leakage was assumed to only impact flowing grey water and potable water in the simulation. This was because the flow of dirty water was presumed to fall under the domain of a sewage system, and such consideration was deemed to be outside the scope of the current analysis. Water leakage was incorporated into all ECLS technology models that involve the transfer of potable or grey water. The laundry machine model can be used to illustrate the implementation of water leakage. As illustrated in Figure 3.9, the laundry machine takes in a fixed amount of water from the potable water storage and outputs the same amount to the grey water storage. Assuming the water leakage rate is $X\%$, and that the water required by the laundry machine is y per load, then the amount of water taken out of the potable water storage is:

$$(1 + X\%)y \tag{5.1}$$

and the amount of water added to the grey water storage is:

$$(1 - X\%)y \tag{5.2}$$

Equation 5.1 shows more water being taken out of the potable water storage than is required by the laundry machine to compensate for the potable water leakage. Equation 5.2 shows less water being added to the grey water store than is taken in by the laundry machine to account for grey water leakage.

Figure 5.1 presents a plot of the total water demand versus water leakage rate for 4 crew members on a 790-day mission. It can be observed that the difference in total water demand between the upper and lower bound water leakage rate is approximately 2.03×10^5 kg.

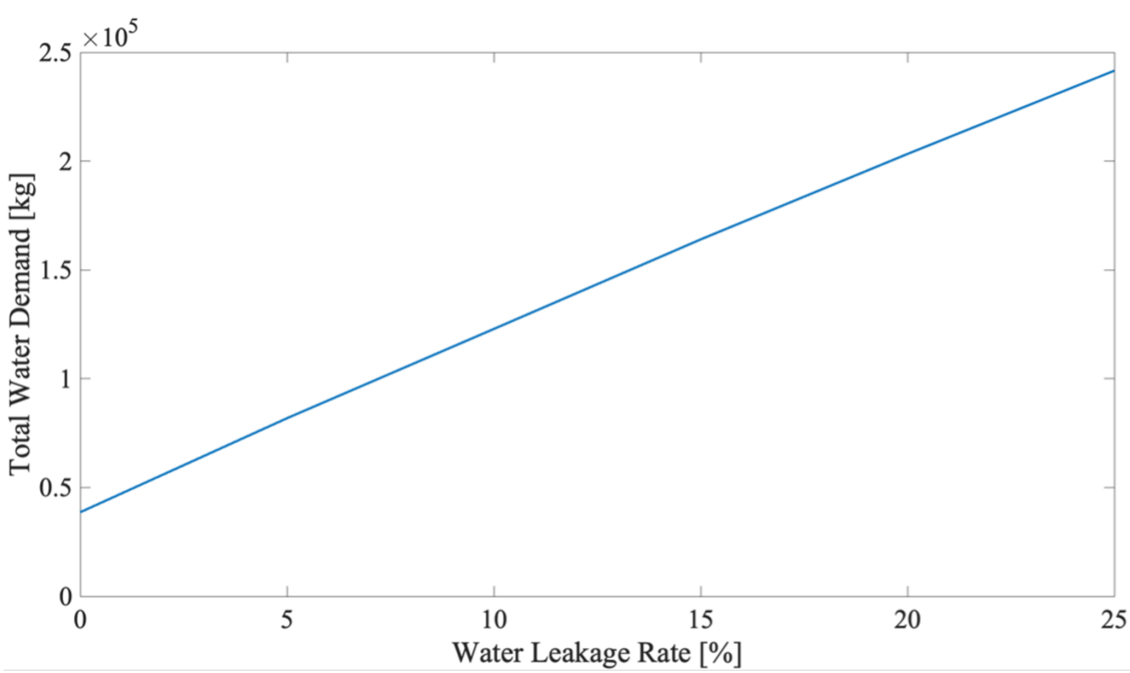


Figure 5.1: Plot showing the total water demand versus water leakage rate for four crew members on a 790-day mission

5.1.2 Boil-off Rate

Figure 5.2 presents a plot of the total water demand versus boil-off rate for four crew members on a 790-day mission. It was assumed that the boil-off rate for LOX and LCH_4 was the same. The difference in total water demand between the upper and lower bound boil-off rate is approximately 5.22×10^4 kg.

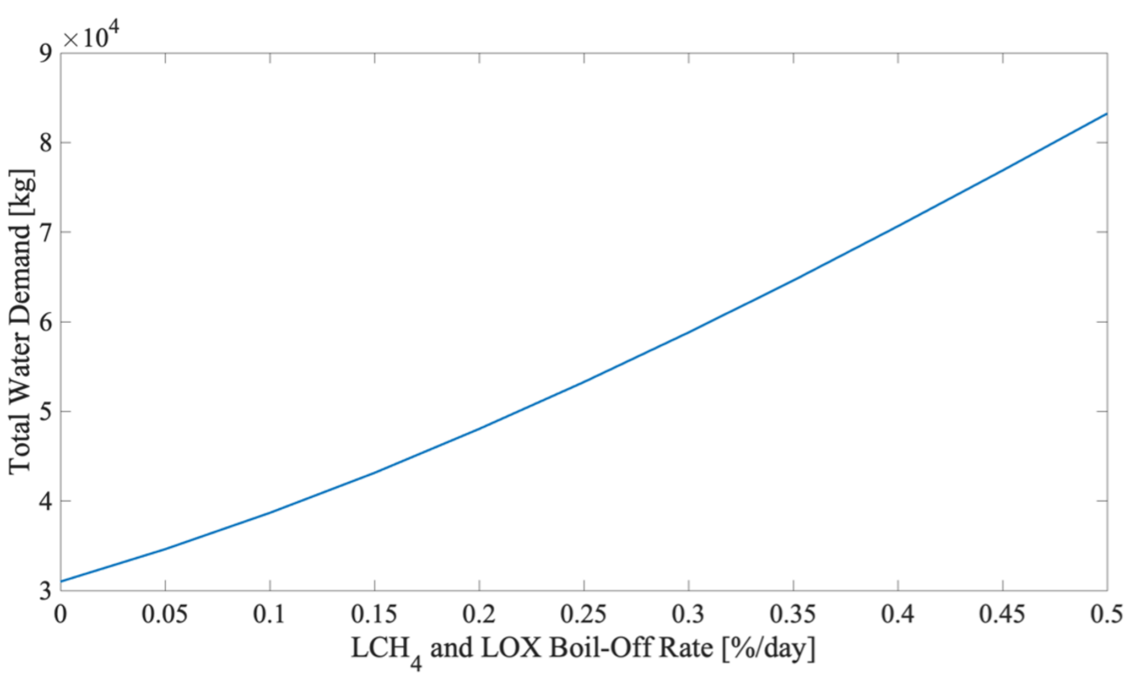


Figure 5.2: Plot showing the total water demand versus boil-off rate for four crew members on a 790-day mission

5.1.3 Air Leakage

Figure 5.3 presents a plot of the total water demand versus air leakage rate in the Mars habitation module and biomass production chamber for four crew members on a 790-day mission. Note that the difference in total water demand between the upper and lower bound air leakage rate is < 6 kg.

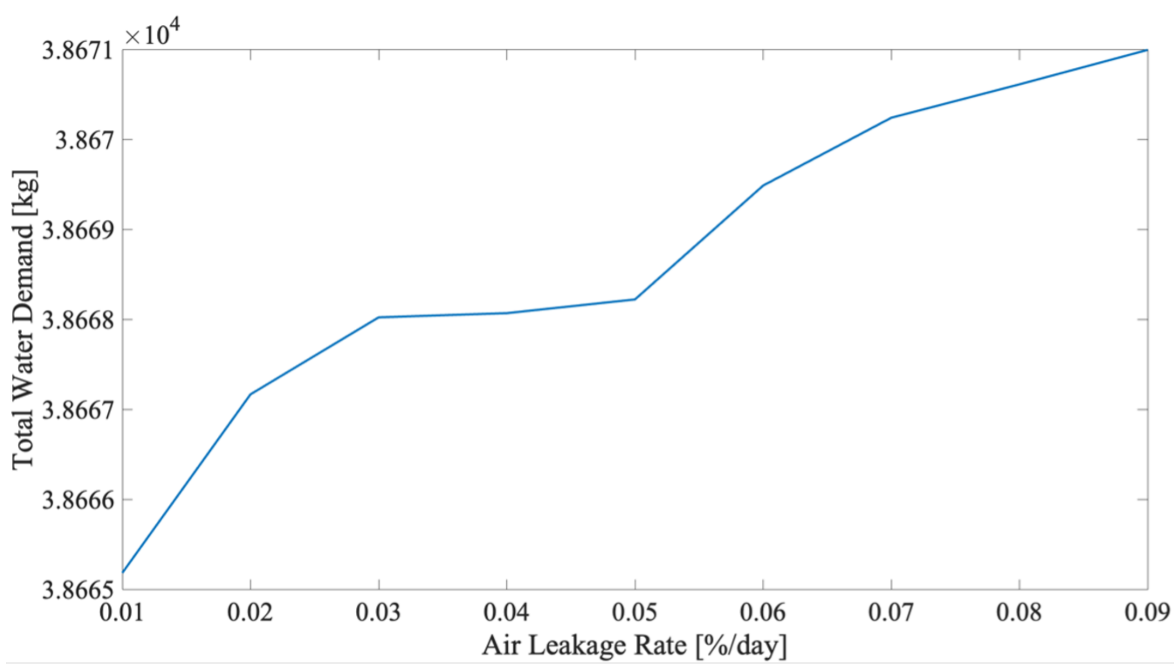


Figure 5.3: Plot showing the total water demand versus air leakage rate in the Mars habitation module and BPC for four crew members on a 790-day mission

5.1.4 Normalized Derivative

Calculating the normalized partial derivative of water demand with respect to each parameter can provide valuable insight into how a percentage change in water leakage rate, boil-off rate, and air leakage rate impacts the percentage change in total water demand. The normalized derivative can then be used to determine a rank order of which parameter total water demand is most sensitive to; the higher the normalized partial derivative, the more sensitive total water demand is to that parameter. The normalized derivative was calculated using Equation 5.3.

$$\frac{\Delta F/F}{\Delta x_i/x_i} \approx \frac{x_{i,0} + \frac{\Delta x_i}{2}}{F(x_{i,0} + \frac{\Delta x_i}{2})|_{x_0}} \cdot \frac{\partial F}{\partial x_i}|_{x_0} \approx \frac{x_{i,0} + \frac{\Delta x_i}{2}}{F(x_{i,0} + \frac{\Delta x_i}{2})|_{x_0}} \cdot \frac{F(x_{i,0} + \Delta x_i) - F(x_{i,0})}{\Delta x_i} \tag{5.3}$$

Where

$$
\begin{aligned}
F &= \text{total water demand [kg]} \\
x_i &= \text{parameter (water leakage rate/boil-off rate/air leakage rate)} \\
x_0 &= \text{baseline parameter values} \\
& \quad x_{waterLeakRate,0} = 0\% \\
& \quad x_{boilOffRate,0} = 0.1\%/\text{day} \\
& \quad x_{airLeakageRate,0} = 0.05\%/\text{day} \\
&= (x_{waterLeakRate,0},\ x_{boilOffRate,0},\ x_{airLeakageRate,0}) = (0,\ 0.1,\ 0.05)
\end{aligned}
$$

Note that the partial derivative shown in Equation 5.3 is approximated using the forward difference formula because subsequent data is available for all three parameters at the baseline parameter values. The normalized partial derivative is evaluated at x_0. Table 5.2 shows the normalized partial derivative of total water demand with respect to each parameter.

Table 5.2: Normalized partial derivative of total water demand with respect to each parameter

Parameter	**Normalized Partial Derivative**
Water Leakage Rate	3.584×10^{-1}
Boil-Off Rate	2.723×10^{-1}
Air Leakage Rate	1.799×10^{-4}

5.1.5 Sensitivity Analysis Summary

The normalized partial derivative of water demand with respect to each parameter and the difference in total water demand between the upper and lower parameter bounds are summarized in Table 5.3.

Table 5.3: Normalized partial derivative and difference in total water demand between the upper and lower parameter bounds

Parameter	**Normalized Partial Derivative**	**Difference in total water demand between the upper and lower parameter bounds [kg]**
Water Leakage Rate [%]	3.584×10^{-1}	2.03×10^{5}
Boil-off Rate [%/day]	2.723×10^{-1}	5.22×10^{4}
Air Leakage Rate [%/day]	1.799×10^{-4}	<6

From the results shown in Table 5.3, the total water demand appears to be most sensitive to water leakage rate, followed by boil-off rate, then air leakage rate. The difference in total water demand between the upper and lower bounds of water leakage rate and boil-off rate is on the order of magnitude of 10 to 100 metric tons of water while the difference is less than 6 kg of water for air leakage rate. Air leakage rate likely has a low impact on total water demand because water vapor takes up a very small percentage of the air content ($\sim 0.4\%$) that is leaked.

Based on the results of the sensitivity analysis, a decision was made to exclude the air leakage rate from the Monte Carlo simulation and represent only the water leakage rate and boil-off rate with a probability distribution.

5.2 Monte Carlo Simulation

5.2.1 Monte Carlo Simulation Set-Up on the MIT SuperCloud

A Monte Carlo simulation was performed for each of the cases presented in Table 3.7 with the simulation set-up documented in Section 3.3. Values for boil-off rate and water leakage rate were randomly sampled from uniform probability distributions with lower and upper bounds shown in Table 5.1. The solution space for each case was sampled with 2000 experiments and utilized parallel computing on the MIT SuperCloud through 8 computing nodes each with 48 cores (total of 384 computing cores) [43]. For reference, Figure 5.4 is a block diagram that illustrates how the Monte Carlo simulation was executed for a sample case (Case 1 with four crew members).

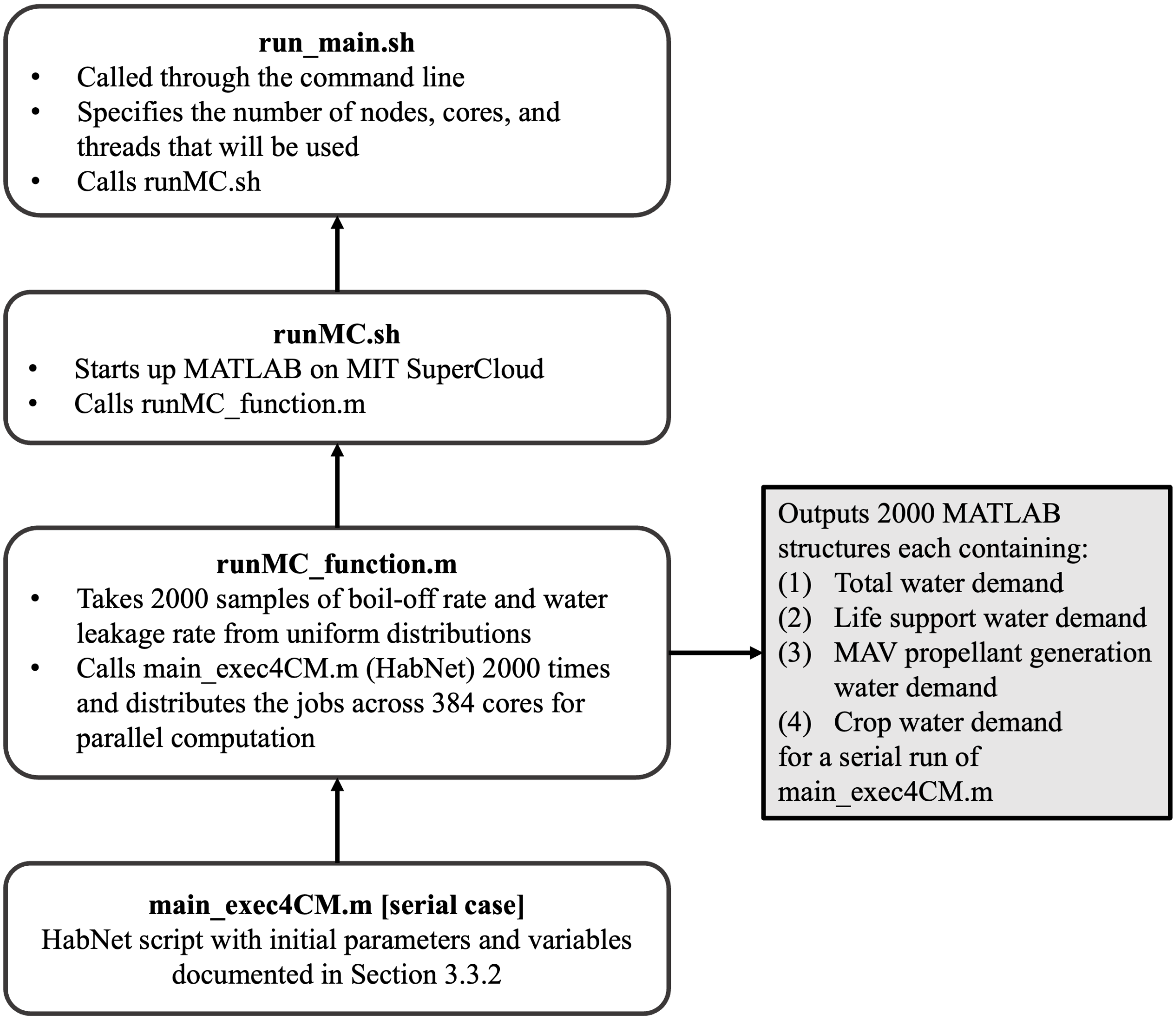


Figure 5.4: Block diagram illustrating how a Monte Carlo simulation is executed on the MIT SuperCloud

At a high level, the run_main.sh shell script specifies the number of nodes, cores per node, and threads that will be used and calls runMC.sh, which starts up MATLAB on the MIT SuperCloud and calls runMC_function.m. The runMC_function.m MATLAB script takes 2000 random samples of boil-off rate and water leakage rate from uniform distributions. It then calls main_exec4CM.m, the serial HabNet script with initial parameters and variables specified in Sections 3.3.2 and 3.3.4, 2000 times and distributes the jobs across 384 cores for parallel computation. The output of the Monte Carlo simulation includes 2000 MATLAB structures each containing the total water demand, life support water demand, MAV propellant generation water demand, and crop water demand. Appendix C includes all four scripts that were used to execute the Monte Carlo simulation for Case 1 (4 crew members) as an example. Note that since the crew model was written such that there is a one in a million chance of crew dying under nominal circumstances, water demand results from experiments that end in crew death were omitted.

5.2.2 Histograms and Statistical Results

Histograms of the water demand for the five cases are shown in Figure 5.5 through Figure 5.9

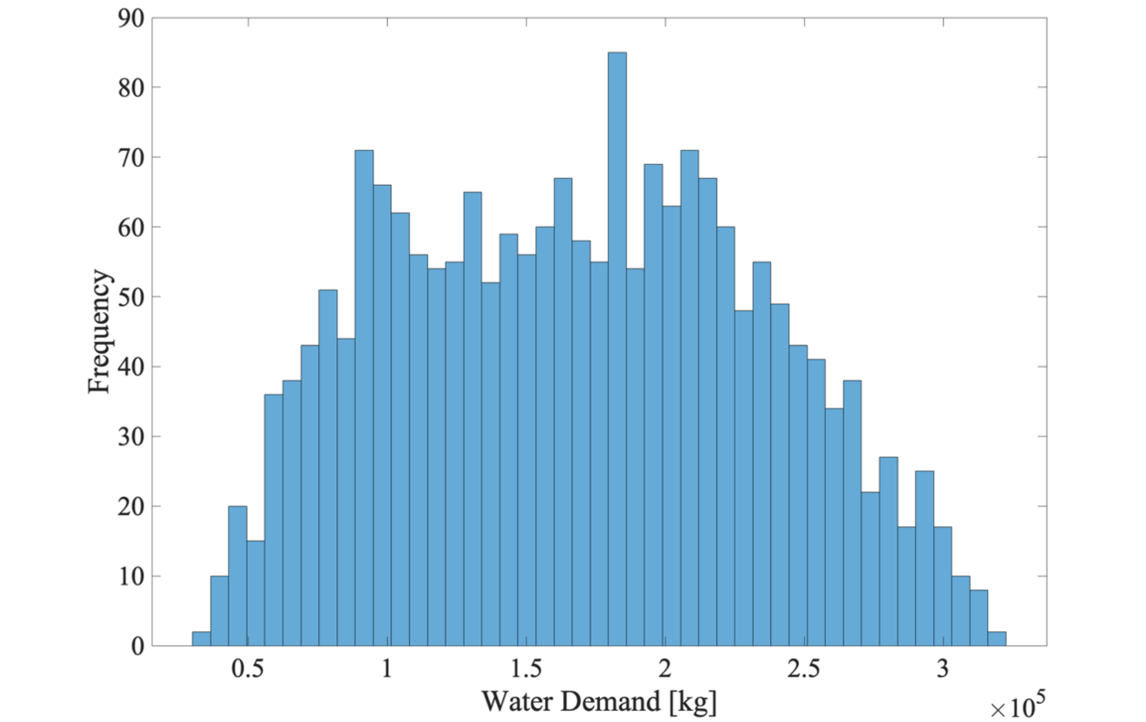


Figure 5.5: Water demand histogram for 4 crew members on a 790-day mission

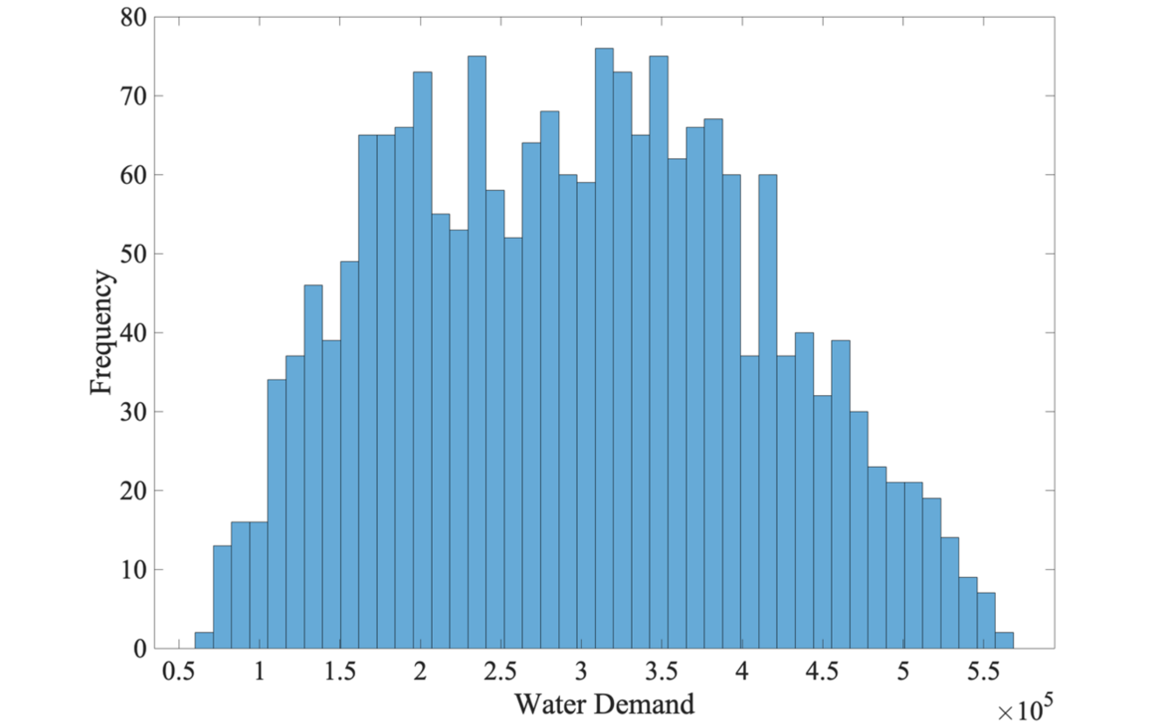


Figure 5.6: Water demand histogram for 8 crew members on a 790-day mission

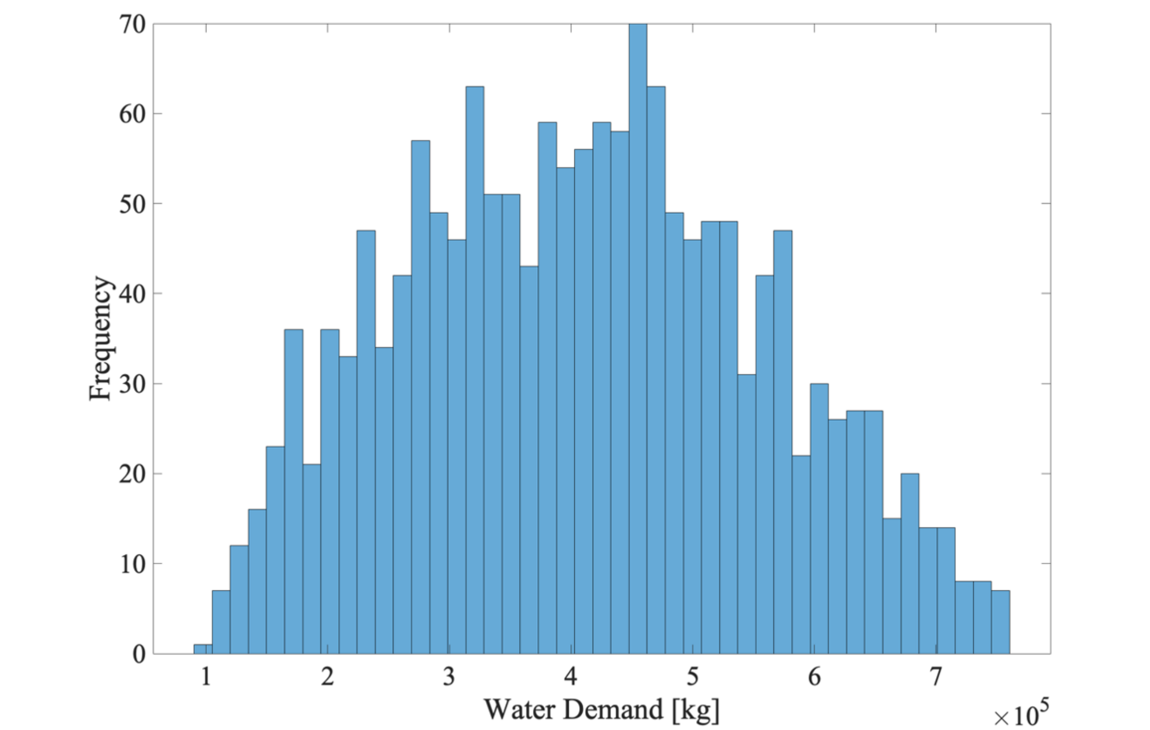


Figure 5.7: Water demand histogram for 12 crew members on a 790-day mission

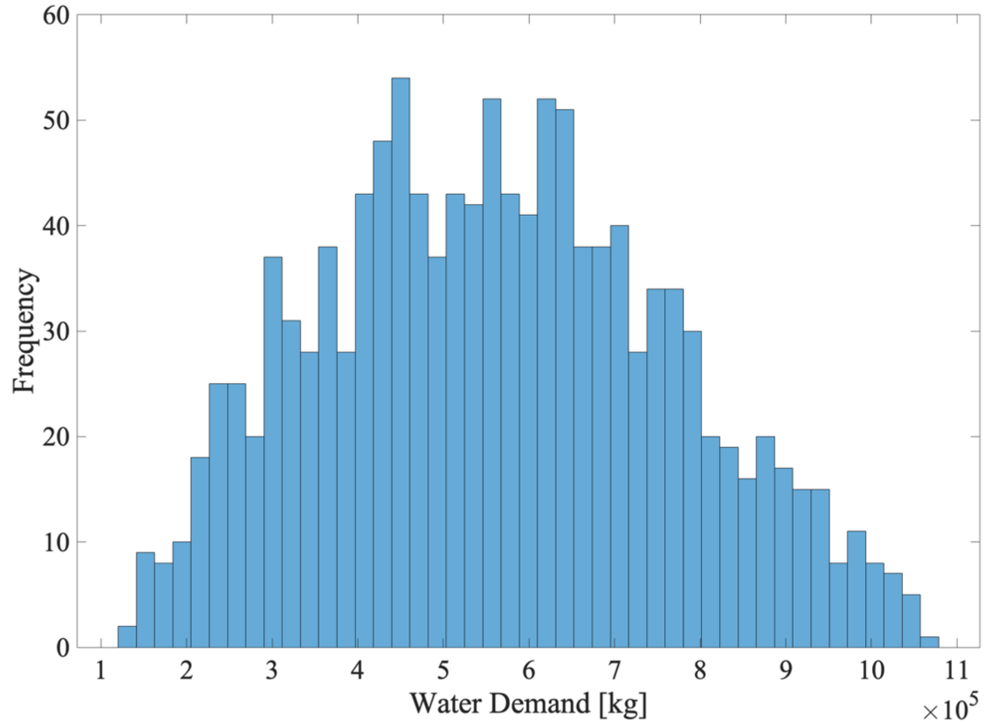


Figure 5.8: Water demand histogram for 16 crew members on a 790-day mission

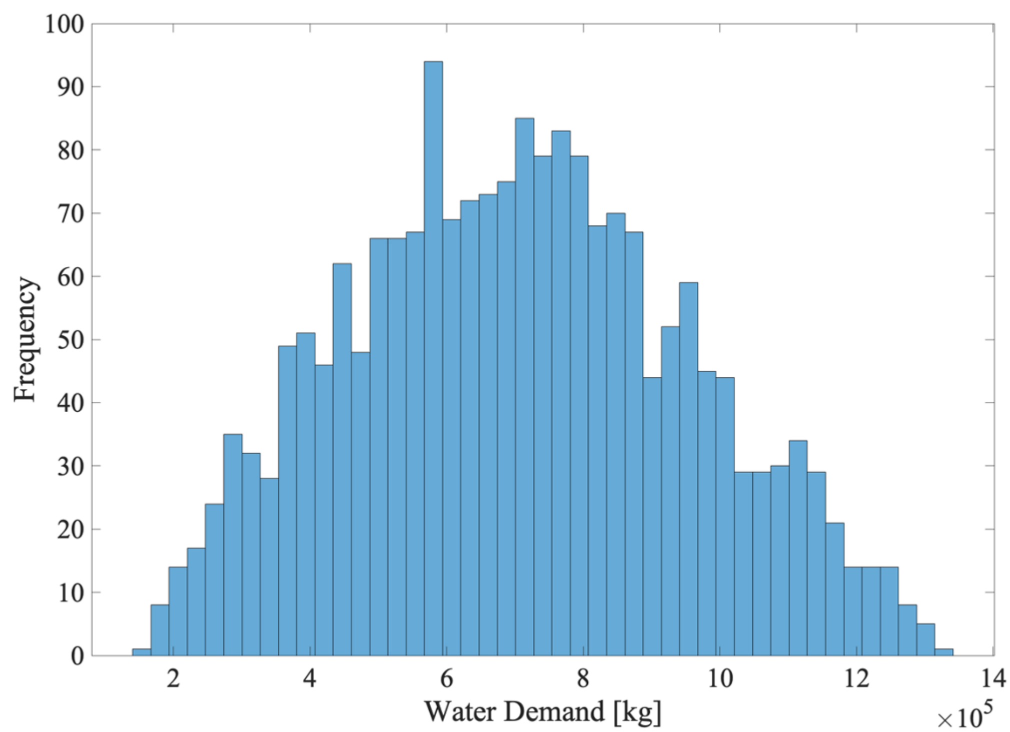


Figure 5.9: Water demand histogram for 20 crew members on a 790-day mission

Statistical results for each Monte Carlo simulation case are presented in Table 5.4 as shown below.

Table 5.4: Statistical values for water demand from the Monte Carlo simulation

Statistical Value for Water Demand	**Case 1 (4 Crew)**	**Case 2 (8 Crew)**	**Case 3 (12 Crew)**	**Case 4 (16 Crew)**	**Case 5 (20 Crew)**
Mean [kg]	168,170	296,391	410,303	562,397	704,666
Standard Deviation [kg]	65,999	111,800	147,080	204,351	248,217
Skewness	0.085	0.127	0.125	0.175	0.132

5.2.3 Discussion

Gaussian Distribution Fitting

Visual observation of the histograms presented in Figure 5.5 through Figure 5.9 indicates that the total water demand distribution across all crew sizes appears to be right skewed. This is further corroborated by the positive skewness values shown in Table 5.4, which suggests that the total water demand distribution is not Gaussian.

Overlaying normal distributions onto the histograms (see Figure 5.10) verifies that the total water demand distribution is not Gaussian because the left tails of the normal distributions indicate negative total water demand, which is not realistic. One key factor that may be contributing to the right-skewed nature of the total water demand is the exponential relationship between the total water demand and boil-off rate shown in Figure 5.2. Higher boil-off rates result in higher total water demand, causing the probability to taper off more slowly for higher total water demands.

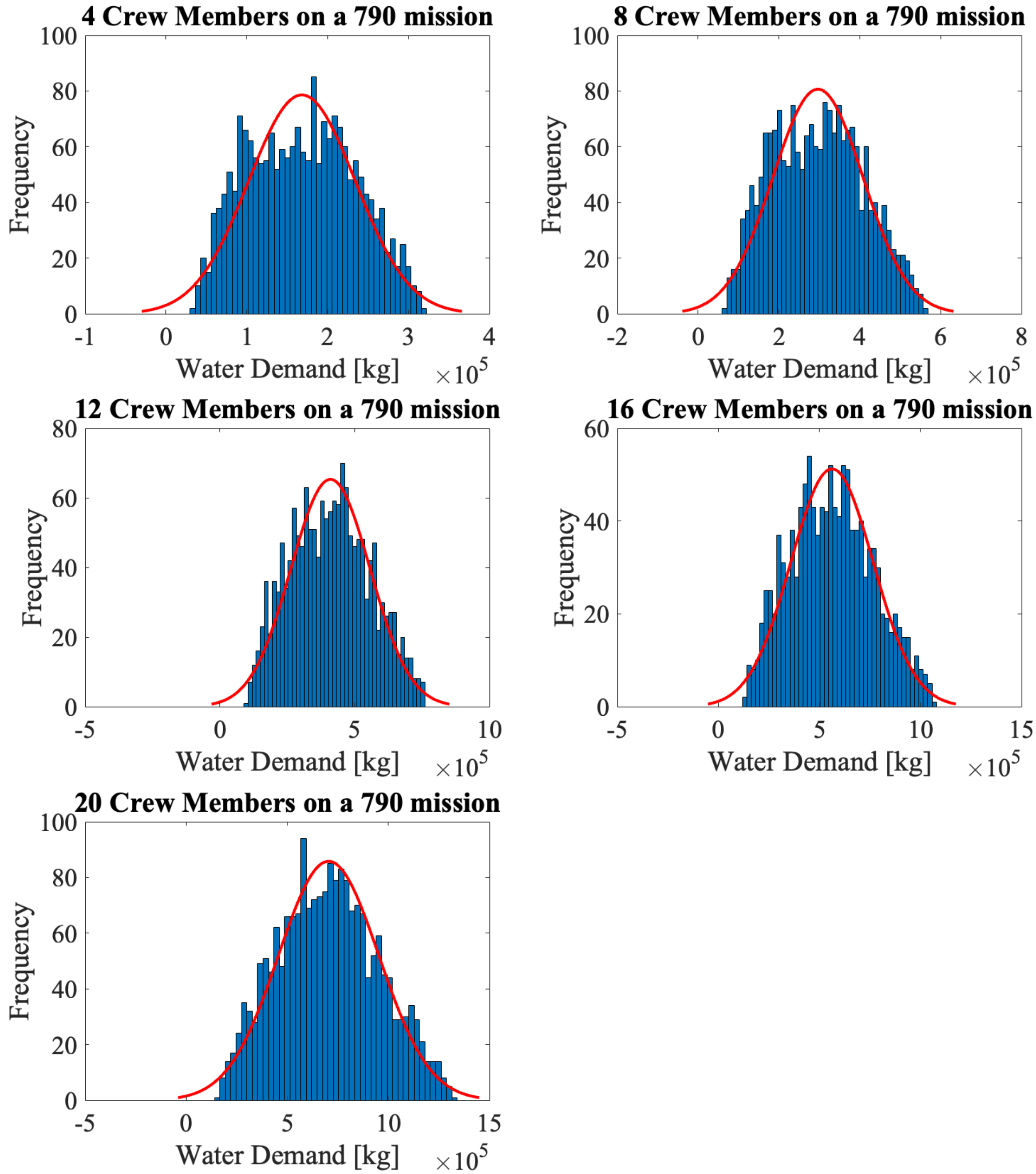


Figure 5.10: Normal distribution (red) fitted to total water demand histograms for crew sizes of 4, 8, 12, 16, and 20 crew members each on a 790-day mission

Beta Distribution Fitting

Because the Gaussian distributions shown in Figure 5.10 did not provide a realistic representation of the water demand distributions, a choice was made to fit a beta distribution to the data sets. A beta distribution is a continuous probability model, represented by two positive parameters α and β, that is suitable for modeling random variables within a finite interval. This makes it fit for modeling water demand, since water demand is constrained within an upper and lower limit of possible values. The script used to fit and plot beta distributions to the data sets can be found in Appendix D. Fitting the beta distribution comprised of two key steps:

1. Normalizing water demand data between 0 and 1.

2. Finding values of α and β that minimize the Root Mean Square Error (RMSE) between the beta distribution and the normalized water demand histogram for each crew size. The bin size of the water demand distribution, RMSE, and values of α and β that minimize the RMSE are shown in Table 5.5.

Table 5.5: Table showing the bin size of the water demand distribution, RMSE, and values of α and β that minimize the RMSE for each crew size

Crew Size	α	β	**Number of Bins**	**RMSE**
4	1.6	1.9	50	0.3835
8	1.6	2.1	45	0.3825
12	1.6	1.9	50	0.3928
16	1.5	1.8	50	0.4663
20	1.5	1.8	45	0.4920

Results from fitting beta distributions to the normalized water demand histograms can be found in Figure 5.11. It is worth noting that the beta distributions exhibit positive skewness, which is consistent with the positive skewness values shown in Table 5.4.

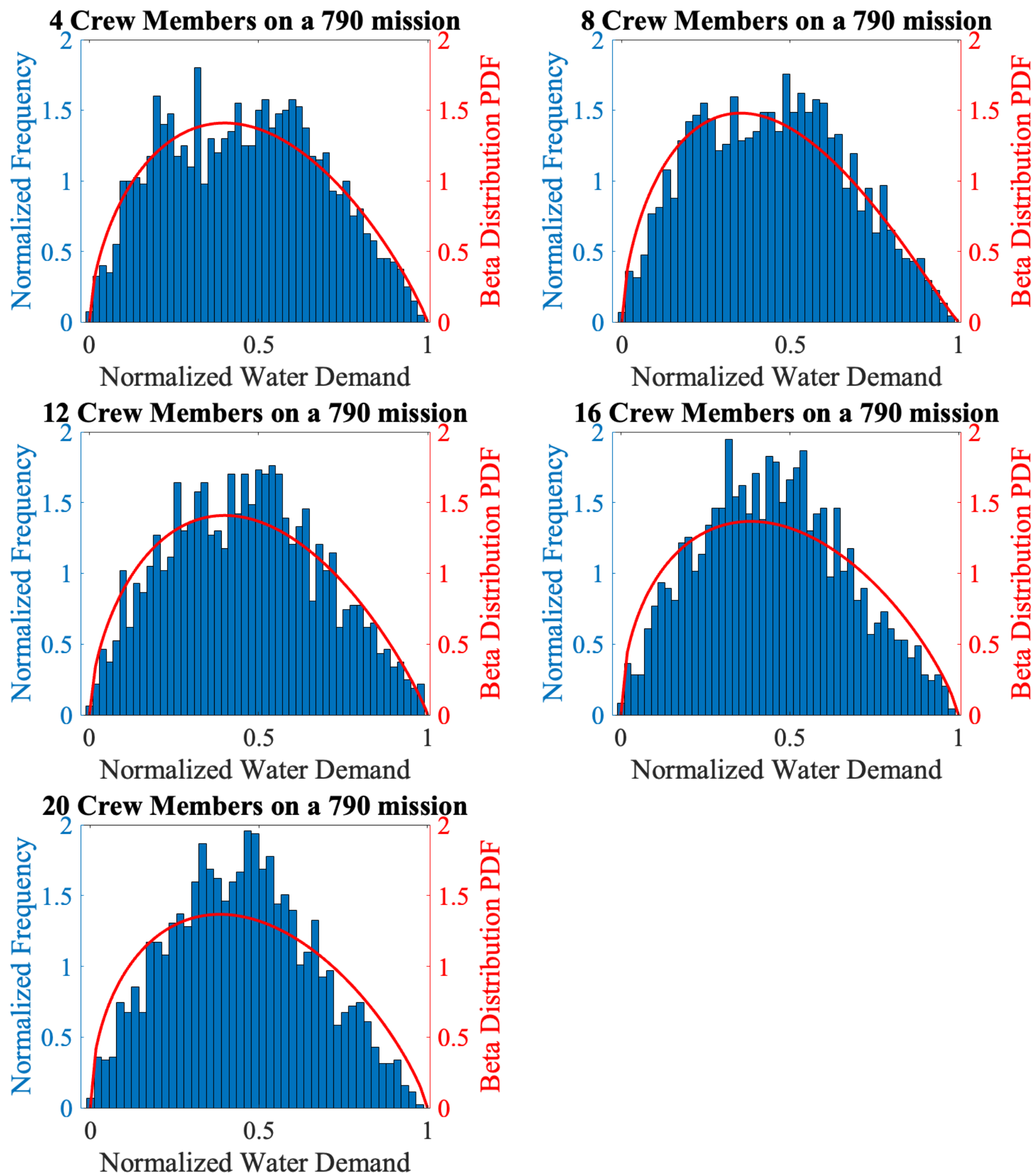


Figure 5.11: Beta distribution probability density function fitted to the normalized total water demand histogram for crew sizes of 4, 8, 12, 16, and 20 each on a 790-day mission.

Mean Water Demand per Crew Member versus Crew Size

A plot showing the calculated mean water demand per crew member versus crew size is shown in Figure 5.12. The trend line shown in Figure 5.12 reflects the expected benefits of economies of scale (i.e., reduced mean total water demand per crew member) when the crew size increases from 4 to 12 crew members but shows diseconomies of scale when the crew size grows from 12 to 20 crew members. A possible explanation for this trend is that several key HabNet ECLS technologies that affect total water demand (CCAA and WPA/UPA) were modeled based on systems utilized on the ISS. Historically, the ISS has accommodated a maximum of 13 astronauts at one time [44]. This suggests that the modeled ECLS technologies may have inefficiencies for larger crew sizes, explaining the observed diseconomies of scale behavior for crew sizes larger than 12.

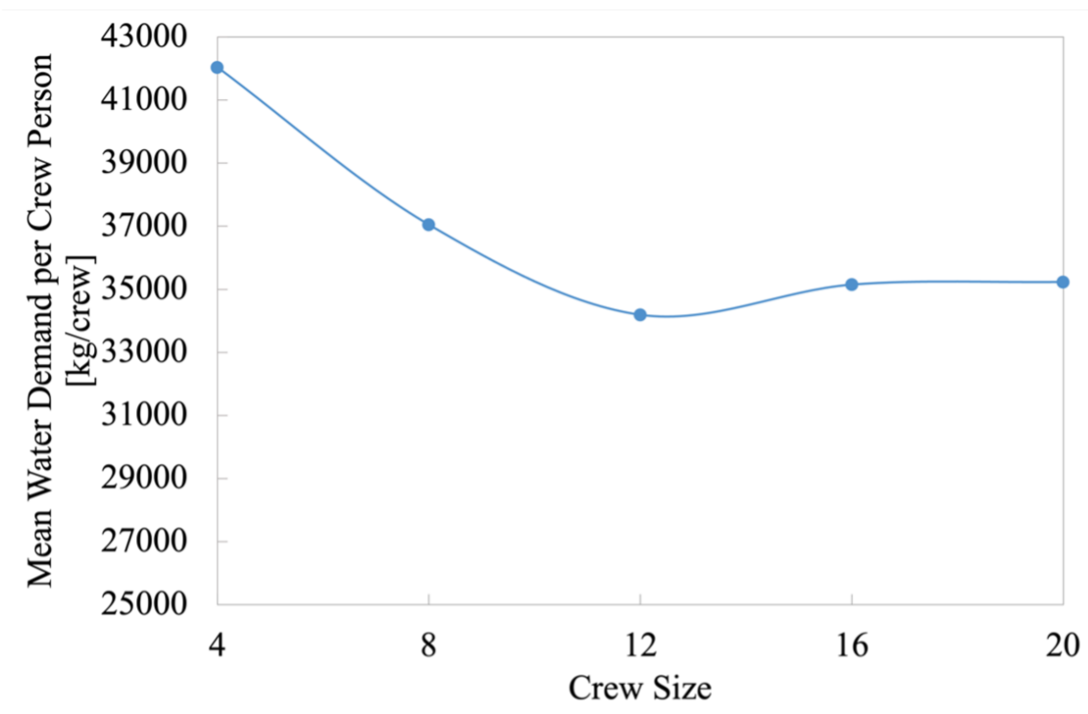


Figure 5.12: Mean total water demand per crew person versus crew size

5.3 Limitations and Future Work

Limitations associated with the completed analysis are mainly related to the number of experiments in the Monte Carlo simulation and sampling technique of the selected parameters (boil-off rate and water leakage rate).

Specifically, the solution space for each case was sampled using 2000 experiments in the Monte Carlo simulation. The number of experiments was heuristically selected with the primary intent of demonstrating the ability to leverage parallel computing on MIT SuperCloud and performing enough experiments for the results to show a probabilistic distribution. In Monte Carlo simulations, determining when enough experiments have been conducted typically relies on achieving convergence, which is the point at which statistical properties of the simulation stabilize within an acceptable tolerance (i.e. additional iterations are unlikely to change the results). Before determining which probability distribution best represents the total water demand data, it is important to achieve convergence in the Monte Carlo simulation (e.g., achieving a stabilized mean total water demand within a $\pm 10\%$ tolerance) to decide when enough experiments have been conducted. This will provide increased confidence in the probability distribution of total water demand and pave the way for future studies in probabilistic system failure and risk management analysis for human missions to Mars.

Additionally, there are limitations associated with randomly sampling boil-off rate and water leakage rate. These limitations include sampling bias, sampling inefficiency, and sample clustering. Other sampling techniques, such as Latin Hypercube Sampling (LHS), can help resolve the limitations incurred by random sampling and improve the accuracy and reliability of the Monte Carlo simulation results [45]. Furthermore, LHS provides a systematic way of sampling high dimensional spaces (i.e. many parameters), which will be beneficial for future Monte Carlo simulations that involve sampling more than just two parameters [46].

Chapter 6

Water Availability on Mars

Selecting candidate EZs, as discussed in Section 1.1.1, is a multifaceted problem that requires considering both the availability and demand for resources on Mars. In this respect, it is ideal for the analysis of water availability and demand to occur concurrently. This will help ensure the optimal selection of EZs and advance the goal of sustaining a continuous human presence on Mars. Therefore, a crucial question that complements the water demand estimates made in this study is:

"What is the availability of water on Mars?"

The purpose of this chapter is to provide a summary of recent efforts that have tackled the question of water availability and its location on Mars. Focus was placed on the Mars SWIM (Subsurface Water Ice Mapping) project, which was formed in 2018 as a result of NASA-commissioned studies in 2017 to further refine the selection of landing sites on Mars [47]. Harnessing knowledge from existing literature on water availability and the water demand predictions made in this thesis, an attempt was made to develop a "Water Sufficiency" equation. This equation aims to provide a high-level abstraction of key factors that contribute to assessing whether the crew will have sufficient water on Mars. A demonstration of the WS equation was also performed to showcase how the equation can be used and how its results may be interpreted.

6.1 Subsurface Water Ice Mapping (SWIM Project)

Predictions suggest that accessible subsurface water-ice on Mars likely originated from deposited water vapor in the Martian atmosphere. Recent claims propose that emerging technologies could potentially access these subsurface water-ice sources, particularly those in the upper few meters of the Martian surface [47]. These water-ice sources are believed to remain stable from the polar regions down to the upper-mid latitudes [47], hinting at the substantial potential for scientific exploration and ISRU. In the past, the search for non-polar water-ice resources has faced limitations due to the lack of remote-sensing data and the narrow focus of subsurface water-ice studies on isolated Martian regions rather than broader areas [48], [49].

The goal of the SWIM project is to utilize existing remote-sensing data to provide the community with a water-ice map of Mars [47]. It is an improvement to prior attempts at searching for non-polar subsurface water-ice because the SWIM project methodology involves synthesizing data from five independent remote-sensing techniques to generate a subsurface water-ice map. This map covers northern mid-latitudes from the equator to ±60°N and spans the entire range of longitudes. The lower-latitude and lower-elevation region captured within the specified longitude and latitude ranges was intentionally selected because it addresses two important considerations that are critical for planning human missions:

1. Lower elevations are favorable for descent and landing systems due to higher atmospheric pressures. Landing-zone properties need to satisfy the engineering thresholds of descent and landing systems, which may rely on parachutes for speed reduction to touch down on the Martian surface [47].

2. Lower latitudes are favorable due to higher insolation and temperatures [47]. This ensures that landing sites can support surface operations that depend on solar power and higher temperatures for electronics/instruments to function.

6.1.1 Ice Consistency and the SWIM Equations

The five remote sensing techniques used in the SWIM project used to detect subsurface water-ice, along with the Mars orbiters and instruments used to collect the relevant data, are summarized in Table 6.1. Further information on how these instruments indicate the potential presence of water-ice can be found in [50].

Table 6.1: Summary of the water-ice characterization techniques and the corresponding Mars orbiters and instruments used to collect relevant data [47]

Water Ice Characterization Technique	Orbiter	Instrument
Neutron detection (N)	Mars Odyssey	Neutron spectrometer
Thermal analysis (T)	Mars Global Surveyor	Thermal Emission Spectrometer
	Mars Odyssey	Thermal Emission Imaging System
Geomorphic mapping (G)	Mars Reconnaissance Orbiter	Context Camera (CTX)
Radar Surface Analysis (RS)	Mars Reconnaissance Orbiter	Shallow Radar (SHARAD)
Radar Subsurface Dielectric Analysis (RD)		

To synthesize the data gathered using the five remote-sensing techniques listed in Table 6.1, the collected data is converted into quantitative values that represent ice consistency. This 'ice consistency' parameter is defined as follows:

Ice consistency (C): "A parameter that tabulates the degree to which each technique supports or refutes the presence of near-surface ice." [47]

Ice consistency falls between the range of -1 and +1 where -1 indicates complete inconsistency with ice, 1 indicates complete consistency with ice, and 0 suggests that data is inconclusive or missing [47]. To calculate the "composite" ice consistency, C_i, the SWIM equation was developed to combine the ice consistency values from each remote sensing technique as shown in Equation 6.1 [47].

$$C_i = \frac{C_N + C_T + C_G + C_{RS} + C_{RD}}{5} \tag{6.1}$$

Note that the subscripts indicate which remote sensing technique (denoted in Table 6.1) the ice consistency values represent. The ice consistency range for the thermal analysis and geomorphic mapping technique (C_G and C_T) is currently limited between 0 and 1, thus C_i can be interpreted as follows [50]:

$C_i = 1$	:	All remote sensing techniques support the presence of water-ice.
C_i = -3/5	:	All remote sensing techniques refute the presence of water-ice (excludes C_T and C_G)
C_i >0.2	:	At least one remote sensing technique supports the presence of water-ice
C_i >0.5	:	The majority of remote sensing techniques support the presence of water-ice

In the second phase of the SWIM project, efforts were made to improve the SWIM equation presented in Equation 6.1 [50]. Because the different remote sensing techniques probe different depth zones, these updated SWIM equations (see Equations 6.2, 6.3, 6.4) incorporate weighting factors, s, to better represent water-ice consistency at different subsurface depths (<1 m, 1-5 m, and >5 m). Note that the subscripts "GS" and "GD" represent "shallow-geomorphic" and "deep-geomorphic" respectively.

$$C_i[< 1m] = \frac{s_N C_N + s_T C_T + s_{GS} C_{GS} + s_{RS} C_{RS}}{s_N + s_T + s_{GS} + s_{RS}} \tag{6.2}$$

$$C_i[1 - 5m] = \frac{s_{GS} C_{GS} + s_{RS} C_{RS} + s_{RD} C_{RD}}{s_{GS} + s_{RS} + s_{RD}} \tag{6.3}$$

$$C_i[> 5m] = \frac{s_{GD} C_{GD} + s_{RD} C_{RD}}{S_{GD} + S_{RD}} \tag{6.4}$$

Further details on the formulation of the weighting factors can be found in [50]. It is important to note that C_i does not confirm the quantity, distribution, or presence of ice. C_i is a quantitative indication of whether the data collected indicates water-ice consistency and does not represent the probability of water-ice presence. A Bayesian statistical analysis framework has been proposed and demonstrated on a single location on Mars (a location near an ice crater with a thermal inertia of 1500± 500 tiu) to help capture measurement uncertainty and produce a set of probability distribution functions that indicate the “most likely concentration of water ice" at the location [50]. If this Bayesian statistical analysis is applied to every point on Mars, a probability map for water-ice on Mars can then be generated. However, the Bayesian approach is an ongoing area of research that requires further testing before the results can be used for mission planning or decision-making [50].

6.1.2 SWIM Water-Ice Maps

Subsurface water-ice maps produced by the SWIM project (current as of 2021) at different depth zones are shown in Figure 6.1 through Figure 6.4. Regions with deeper blue shades (higher water-ice consistency) are indicative of regions that may be of interest for future robotic missions to probe.

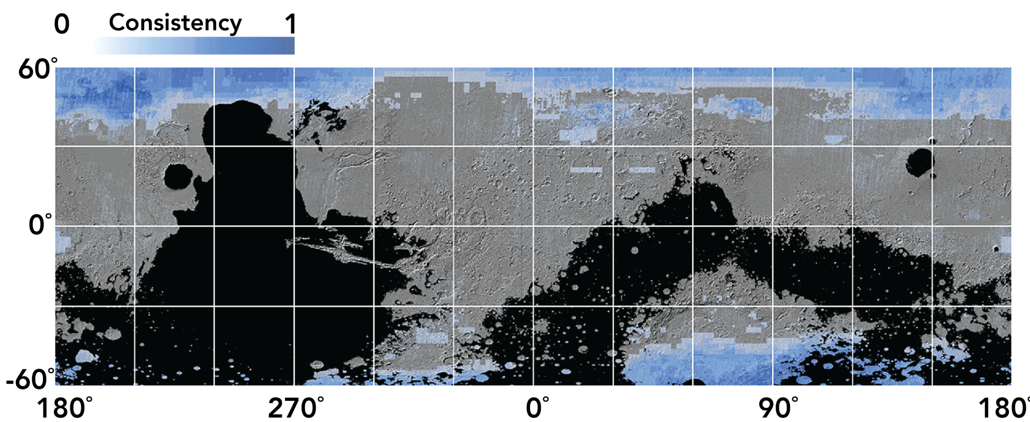


Figure 6.1: Water-ice map produced using the original SWIM equation [51]

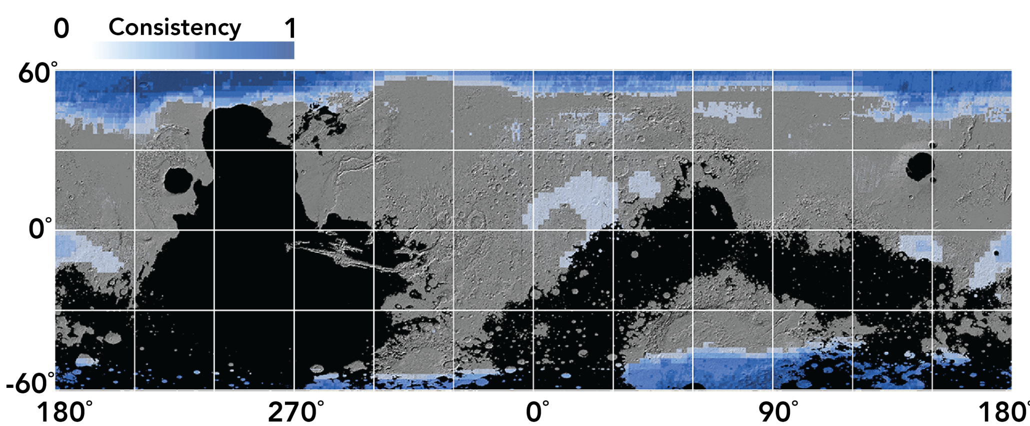


Figure 6.2: Water-ice map at a subsurface depth of <1 m [51]

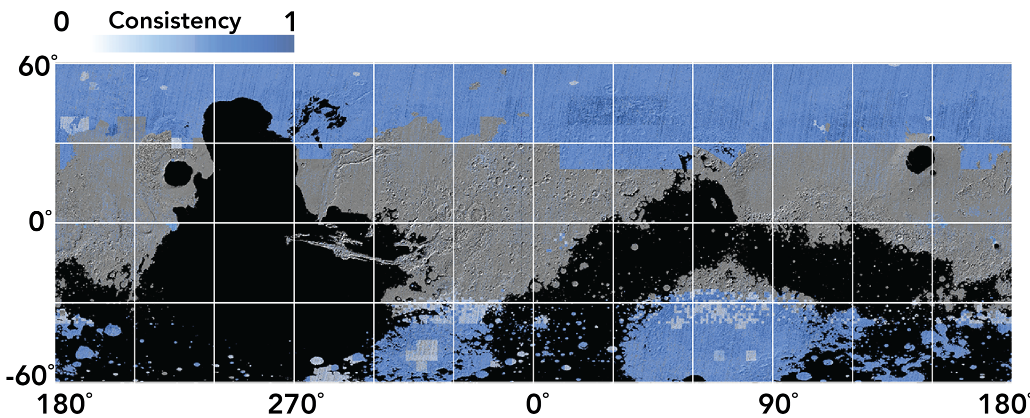


Figure 6.3: Water-ice map at a subsurface depth of 1-5 m [51]

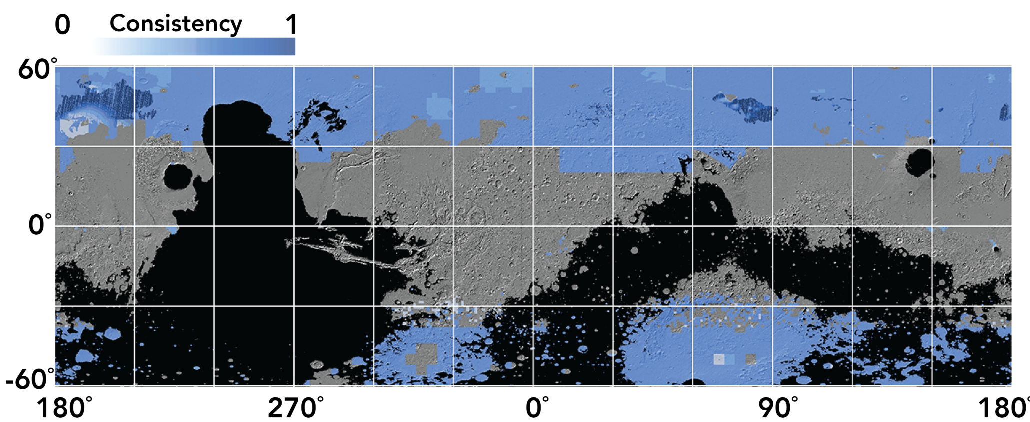


Figure 6.4: Water-ice map at a subsurface depth of >5 m [51]

6.2 Water Sufficiency (WS) Equation

A simplified abstraction of water sufficiency is presented in Equation 6.5 and is referred to as the WS equation hereinafter. The left-hand side term represents the amount of water produced locally on Mars and the right-hand side term represents the net water demand. Satisfying the WS equation indicates that the crew has sufficient water to survive and fulfill mission requirements.

$$W_A \eta_{ISRU} c_A = (W_D - W_B) c_D \tag{6.5}$$

where

W_A	=	Water available for extraction at a selected landing site
η_{ISRU}	=	ISRU technology efficiency. It is An efficiency factor that captures how much of the available water on Mars that the water ISRU technologies can extract. With our current understanding of subsurface water ice, η_{ISRU} will likely be highly dependent on factors such as water-ice depth, purity of the ice, power available for the equipment etc.
W_D	=	Water demand. This parameter was the main focus of this thesis.
W_B	=	Water brought to Mars from Earth.
c_A	=	Contingency factor to account for over-estimation of water available or water ISRU extraction capabilities.
c_D	=	Contingency factor to account for under-estimation of water needed or water that can be extracted.

The WS equation was formulated with four primary motivations:

1. To provide a high-level abstraction of key factors that contribute to water sufficiency for human missions to Mars.

2. Provide a framework to determine whether the amount of water produced locally on Mars equates to the net water demand (i.e., will crew have sufficient water on Mars?) once more data becomes available.

3. To place the water demand estimates made in this thesis in the context of a broader area of investigation related to water resource management on Mars.

4. To highlight the complex nature of Mars mission planning and the abundance of research that needs to be completed to help propel the early phases of conceptual Mars mission planning.

It is important to note that the WS equation is subject to further refinement and is at most a first-order representation of water sufficiency for human missions to Mars.

6.2.1 Pillars of Water Sufficiency

Utilizing the proposed WS equation for a preliminary assessment of water sufficiency necessitates adequate knowledge of the "pillars" of water sufficiency (W_A, η_{ISRU}, W_D, and W_B). Below is a summary of the current understanding and knowledge gaps of these pillars.

Water Availability (W_A)

The literature review conducted in Section 6.1 on the SWIM project study highlights the necessity for further investigation to obtain a quantitative estimate of water availability on Mars. While the water-ice consistency maps presented in Figure 6.1 through Figure 6.4 indicate progress toward understanding non-polar water ice on Mars, there are still critical knowledge gaps related to the composition, spatial distribution, and accessibility of these subsurface water-ice sources for future human Martian missions [52]. According to Putzig et al., "Ultimately, it would be best to obtain actual ground truth at a prospective human landing site using a landed robotic mission with a drilling system capable of reaching ice within a few meters of the surface" [50].

Water ISRU Technology (η_{ISRU})

NASA's Lunar Surface Innovation Initiative (LSII) lists ISRU as one of the six key capabilities that it is actively engaged in advancing [53]. An example of a planned mission that supports this key capability is the Polar Resources Ice Mining Experiment-1 (PRIME-1), which will carry a drill to the lunar surface and demonstrate the feasibility of ISRU [53]. It is scheduled to launch in late 2024 via a Falcon 9 [54]. Other terrestrial proof-of-concept experiments for extracting water from lunar and Martian regolith have also been completed in the past [55], [56]. Water ISRU technologies for both the Moon and Mars are currently still in the early stages of development, and their capability to extract water relies on understanding the characteristics of subsurface water-ice such as purity, depth, and quantity.

Water Demand (W_D)

The work in this thesis culminated in the deterministic and probabilistic modeling of water demand to sustain a continuous human presence on Mars (Chapters 4 and 5). There are key limitations and assumptions associated with the results (as documented in sections 4.3 and 5.3) as well as areas for future work which will be outlined in Section 7.2. Addressing these shortcomings can help increase the fidelity and accuracy of water demand estimates necessary for conducting a future water sufficiency assessment.

Water Brought to Mars from Earth (W_B)

The amount of water that can be brought to Mars from Earth is bounded by launch vehicle payload capacity and space logistics. Currently, SpaceX's Starship is known to be the most powerful launch vehicle developed and is claimed to have a payload capacity of 100 to 150 metric tons [57]. Delivering water (and other resources) to Mars prompts a variety of questions and considerations. Should water be delivered through higher cadence launches on lower payload capacity launch vehicles or through fewer launches on higher payload capacity launch vehicles? Can water be lost or evaporated during transit to Mars and if so, how much? These are open questions that remain to be tackled.

6.2.2 Demonstration of the WS Equation

An attempt was made to demonstrate the use of the WS equation for a mission where the assumed parameters used are documented in Table 6.2.

Table 6.2: Assumed values of the WS equation parameters used to demonstrate the use of the WS equation

Parameter	Assumed Value	Rationale
η_{ISRU}	0.1	Given that water ISRU technology is still in its early stages of development, an optimistic water ISRU efficiency of 0.1 is assumed.
W_D	168,170 kg	This value was taken from Table 5.4 and represents the mean amount of water needed for a crew size of 4 people on a 790-day mission when factoring in MAV propellant boil-off rates and water leakage.
W_B	150,000 kg	SpaceX states that Starship has a payload capacity of 100-150 metric tons [57]. It is assumed that Starship can transport 150t of water to Mars through a single launch to Mars.
c_A	0.5	c_A<1 is assumed for a conservative water sufficiency assessment.
c_D	1.5	c_D>1 is assumed for a conservative water sufficiency assessment.

Using the WS equation and assumed values tabulated in Table 6.2, W_A is calculated:

$$W_A = 545,100 \text{ kg}$$

The results from this demonstration of the WS equation indicate that achieving water sufficiency for 4 crew members on a 790-day mission requires the landing site to have 545,100 kg of water available for extraction. Should future studies discover this amount of water does not exist on Mars, efforts will need to be made to improve many aspects of the mission such as developing water reclamation capabilities in the ECLS system to drive down W_D, improving launch vehicle payload capabilities to increase W_B, and developing water ISRU technologies that can extract more water from subsurface water-ice to increase η_{ISRU}. It should be emphasized that this interpretation of the results is contingent upon the assumptions made in Table 6.2. The purpose of this demonstration was to illustrate how the WS equation can be used and how the results may be interpreted because similar analyses may need to be completed in the future when more data becomes available.

Chapter 7

Conclusions and Future Work

7.1 Conclusion

The main objective of this thesis was to make progress toward answering the question "How much water is needed to sustain a continuous human presence on Mars?". HabNet was identified as a tool suitable for answering this research question, and updates were made to HabNet to better capture water demand elements. These updates included modeling new ECLS technologies and incorporating more recent data into the crew model to enable more accurate water demand estimation. Each new ECLS technology model, including the updated crew model, was verified to ensure that it functions as intended.

Using the updated version of HabNet, five discrete simulation cases which collectively represent a continuous human presence Martian surface campaign crew profile were performed. It was found that the net total water demand for 4, 8, 12, 16, and 20 crew members on a 790-day mission were 38,669 kg, 76,545 kg, 118,069 kg, 151,617 kg, and 193,134 kg, respectively. For each crew size, 63-65% of water was needed for generating MAV propellant, 22-23% of the water was needed for crops, and 12-15% was needed for life support. These simulation cases implemented a long-duration ECLS architecture with water-recovery capabilities. Additionally, the water demand per crew member per day was found to fluctuate between 12.00 kg to 12.50 kg across the five cases.

This work also demonstrated the ability to provide probabilistic models of water demand for the five discrete simulation cases using High-Performance Computing (HPC). A sensitivity analysis was first performed on three selected input parameters (water leakage rate, MAV propellant boil-off rate, habitat air leakage rate) to investigate their impact on water demand. Results from the sensitivity analysis showed that water demand was most sensitive to water leakage rate, followed by MAV propellant boil-off rate, then air leakage rate. This rank order was based on the normalized partial derivative of water demand with respect to water leakage rate, boil-off rate, and air leakage rate for a baseline case with four crew members on a 790-day mission. The normalized partial derivatives were 3.584×10^{-1}, 2.723×10^{-1}, and 1.799×10^{-4} respectively and were evaluated at the 'baseline' point of 0% water leakage rate, 0.1% boil-off rate, and 0.05% air leakage rate. Because the air leakage rate had a relatively low impact on total water demand, only the water leakage rate and boil-off rate were represented by uniform probability distributions in the Monte Carlo simulation. The Monte Carlo simulation was completed on the MIT SuperCloud, marking the first time HabNet leveraged super-computing capabilities to output results. Gaussian and beta distributions were fitted to the water demand results from the Monte Carlo simulation. The Gaussian distribution did not appear to represent the water demand distributions realistically, and further work will need to be completed to address the limitations associated with the Monte Carlo simulation.

While there are limitations associated with both the deterministic and probabilistic model for water demand estimation using HabNet, this thesis provided water demand estimates that have the fidelity that surpassed first-order calculations completed in the past. This work presented a framework grounded in engineering principles to quantify water demand, which contributes to enabling continuous human presence on Mars.

7.2 Future Work

In addition to addressing the limitations and future work presented in Section 4.3 and Section 5.3 related to the deterministic and probabilistic modeling of water demand, the work presented in this thesis offers many avenues for future work. The identified areas for future work can help increase the accuracy, validity, and fidelity of HabNet to model other Martian mission architectures for trade space analysis.

7.2.1 Integrating a Martian Climate Model into HabNet

A Mars climate model, such as that available on the Mars Climate Database with information such as the temperature, gas composition, and surface H_2O ice layer at different locations on Mars, should be integrated into HabNet to address current limitations with the HabNet simulation set-up [58], [59]. Rather than assuming that an unlimited supply of carbon dioxide, nitrogen, water, and oxygen is available for use, HabNet will be able to refer to the climate model to determine the abundance of different gases in the atmosphere at specified locations, times, and altitudes on Mars. This feature can be advantageous for future trade-off analysis that determines which resources and what quantity of resources should be extracted from the Martian environment, produced on Mars, or brought from Earth. Implementing a temperature profile of Mars can also assist with the design and analysis of ECLS technology duty cycles due to the limited availability of power and fluctuating power requirements to heat or cool various hardware elements based on environmental temperature. Integrating a Mars climate model into HabNet can be considered a high priority due to the downstream impacts that it will have on the fidelity, validity, and accuracy of estimating resource demands in HabNet.

7.2.2 Power Demand Estimation

Like how HabNet was updated and used to make water demand estimates in this study, HabNet should also be applied to estimate power demand for Martian missions. The current HabNet simulation set-up assumes that there is access to unlimited power, implying that the modeled ECLS technologies are operating at the highest power setting available and are operational for the entirety of the mission. In reality, power availability will be constrained, impacting the design of ECLS technologies' duty cycles and when to operate ECLS technologies at lower power settings. This will cause downstream impacts on resource demand estimations, including water and power demand estimates.

Implementing an ECLS technology duty cycle/power setting design feature that inputs power available to provide power demand estimates will be a valuable area of future development for HabNet. This new capability will enable HabNet to inform crew survivability with the provided power constraints and ultimately indicate if a change in power availability is necessary for the mission to succeed. Understanding the impact of power availability on mission success will be informative to NASA's Fission Surface Power (FSP) program, which is currently working toward demonstrating surface fission power on the lunar surface and translating these into power requirements for initial human Mars exploration campaigns [60], [61]. Should results indicate a need to adjust power availability to optimize for mission success, the design of these surface fission reactors or mission architecture may need to evolve accordingly.

7.2.3 Modeling additional ECLS Technologies

To improve the accuracy and fidelity of making resource demand estimates in HabNet, ECLS technologies presented in Figure 3.1 that were not developed within this thesis can be modeled, verified, and validated for use in future HabNet simulations. These include the carbon dioxide, nitrogen, and argon extractor, heat melt compactor, anaerobic digestor, potable water dispenser and food preparation station. Descriptions of these technologies can be found in Table 2.2.

7.2.4 Validating HabNet with Mars Analog Mission Data

To further validate HabNet beyond comparing output data with ISS data and telemetry, HabNet output data should be compared against Mars analog mission data. An example of such a mission is the first Crew Health and Performance Exploration Analog (CHAPEA). The mission began on June 25^{th} 2023 with four crew members and is scheduled to be completed on July 6^{th} 2024 [8]. HabNet can be used to model and simulate the CHAPEA mission, including the plants that have been grown and harvested since the mission began. The output data from HabNet can then be compared with CHAPEA data for validation.

7.2.5 Updating Hypoxia and Hyperoxia conditions for Crew

Updated information on hypoxia, "normoxia", and hyperoxia conditions for crew based on habitat pressure (shown in Figure 7.1) can be integrated into HabNet to improve the fidelity and accuracy of resource demand estimation and crew survivability. This update would be implemented in the pressure control assembly model that is used inside the habitation module, which injects or vents gases to ensure that the habitat is not over or under pressure and that the oxygen level inside the habitat is sufficient but not in excess for the crew. The "normoxia" curve shown in Figure 7.1 can be parameterized to represent the target oxygen percentage in the habitation module and can be bounded by the parameterized hypoxia and hyperoxia curves outlined in green.

Including the pressure versus percent O_2 parameterized curves rather than providing a fixed target oxygen percentage will provide a more accurate model of gas flow in and out of the habitat. This enhanced fidelity can lead to more accurate estimations of resource demands and provide better predictions of crew survivability.

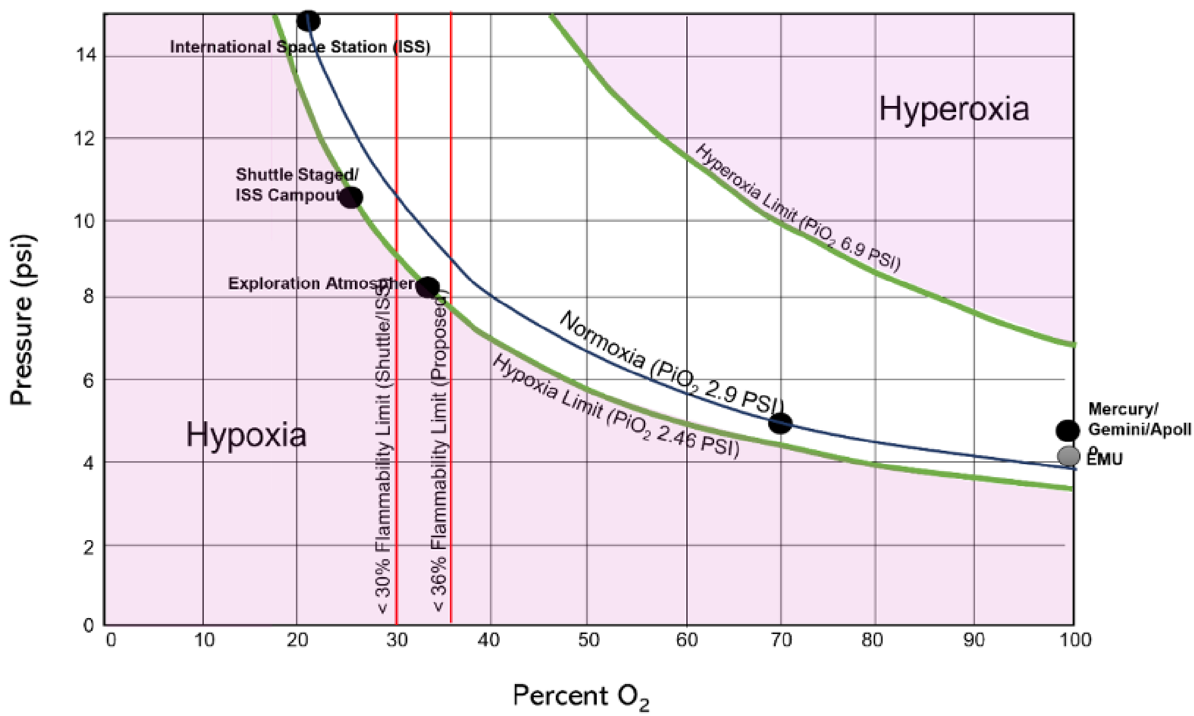


Figure 7.1: Plot showing the pressure versus percent O_2 of the cabin atmosphere with limits for hypoxia and hyperoxia [62]

7.2.6 Expanded Sensitivity Analysis

The sensitivity analysis presented in Section 5.1 was completed with the intent of quantifying how much of an impact each of the three heuristically selected parameters (water leakage rate, water boil-off rate, and habitat air leakage rate) had on the total water demand. After implementing the improvements outlined in Section 7.2.1 through 7.2.5, it would be beneficial to conduct a water and power demand sensitivity analysis with all the parameters listed in Table 3.8 through Table 3.12. This expanded sensitivity analysis can facilitate progress toward addressing a key question: for a given mission architecture, which parameter(s) is total water demand and power demand most sensitive to, and by how much? Findings from this expanded sensitivity analysis can provide valuable insight into the design of the mission timeline, logistics, and ISRU strategies toward sustaining a continuous human presence on Mars.

7.2.7 Closing the MAV Propellant Water Loop

As outlined in Section 3.1.3, the ability to reclaim ∼45% of water in the MAV propellant generation water loop is a notional capability that was introduced to the baseline long-duration ECLS architecture implemented in HabNet. Leveraging the expertise of ECLS specialists to apply the knowledge of achieving over 98% water recovery on the ISS for enhancing water recovery rates in the MAV propellant generation water loop can be beneficial. This is valuable because most of the total water demand is attributed to MAV propellant generation (∼63-65%, as shown in Chapter 4), thus achieving higher water recovery rates can lead to less total water demand.

7.2.8 Leveraging the use of HPC with HabNet

Chapter 5 demonstrated the capability to perform HabNet simulations using HPC. This will enable computationally intensive uses of HabNet for future work including:

1. Simulating missions lasting longer than 26 months, extending possibly to decades, with the use of GPUs available in the MIT Super-computing system. This will enable

the simulation of long-duration continuous mission profiles such as that presented in Figure 3.17.

2. Leveraging parallel computing capabilities to conduct expanded sensitivity analyses such as that outlined in Section 7.2.6.

3. Enhancing the robustness of the Monte Carlo simulation by achieving convergence. This may involve running Monte Carlo simulations with more than 2000 experiments and observing when the statistical properties of total water demand stabilize.

Appendix A

Code Listing: Updates to HabNet

A.1 ActivityImpl.m

```
% Yana Charoenboonvivat | 4/14/2024
classdef ActivityImpl %< handle
    properties
        ID
        Name
        Location
        Intensity
        Duration
        VaporProduced
        DirtyWaterProduced
        O2Needed
        CO2Output
        PotableWaterNeeded
    end

    methods
        function obj = ActivityImpl(ID,location,duration)
            if nargin > 0
                obj.ID = ID;
                obj.Duration = duration;
                obj.Location = location;
                if obj.ID == 1
                    obj.Name = 'Exercise - Aerobic';
                    obj.Intensity = 5;
                    obj.VaporProduced = 43.3272; %moles/hour (sweat included)
                    obj.DirtyWaterProduced = 0; %kg/hour
                    obj.O2Needed = 3.8462; %moles/hour
                    obj.CO2Output = 3.6595; %moles/hour
                    obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
                elseif obj.ID == 2
                    obj.Name = 'Exercise - Resistive';
                    obj.Intensity = 5;
                    obj.VaporProduced = 80.3523; %moles/hour (sweat included)
                    obj.DirtyWaterProduced = 0; %kg/hour
                    obj.O2Needed = 2.7569; %moles/hour
                    obj.CO2Output = 2.6500; %moles/hour
                    obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
                elseif obj.ID == 3
                    obj.Name = 'Recovery - 1st hour';
                    obj.Intensity = 2;
                    obj.VaporProduced = 8.5627; %moles/hour
                    obj.DirtyWaterProduced = 0; %kg/hour
                    obj.O2Needed = 1.1375; %moles/hour
                    obj.CO2Output = 0.9675; %moles/hour
                    obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
                elseif obj.ID == 4
                    obj.Name = 'Recovery - 2nd hour';
                    obj.Intensity = 2;
                    obj.VaporProduced = 5.2404; %moles/hour
                    obj.DirtyWaterProduced = 0; %kg/hour
                    obj.O2Needed = 1.1375; %moles/hour
                    obj.CO2Output = 0.9675; %moles/hour
                    obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
                elseif obj.ID == 5
```

```
                obj.Name = 'Recovery - 3rd hour';
                obj.Intensity = 2;
                obj.VaporProduced = 4.6924; %moles/hour
                obj.DirtyWaterProduced = 0; %kg/hour
                obj.O2Needed = 1.1375; %moles/hour
                obj.CO2Output = 0.9675; %moles/hour
                obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
            elseif obj.ID == 6
                obj.Name = 'IVA';
                obj.Intensity = 2;
                obj.VaporProduced = 4.5554; %moles/hour
                obj.DirtyWaterProduced = 0; %kg/hour
                obj.O2Needed = 1.1375; %moles/hour
                obj.CO2Output = 0.9675; %moles/hour
                obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
            elseif obj.ID == 7
                obj.Name = 'Personal Hygiene and Toilet';
                obj.Intensity = 2;
                obj.VaporProduced = 4.5554; %moles/hour
                obj.DirtyWaterProduced = 1.4000; %kg/day (but count as hour because↙
1hr of this activity per day)
                obj.O2Needed = 1.1375; %moles/hour
                obj.CO2Output = 0.9675; %moles/hour
                obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
            elseif obj.ID == 8
                obj.Name = 'Sleep';
                obj.Intensity = 1;
                obj.VaporProduced = 3.6991; %moles/hour
                obj.DirtyWaterProduced = 0; %kg/day
                obj.O2Needed = 0.7133; %moles/hour
                obj.CO2Output = 0.6169; %moles/hour
                obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
            elseif obj.ID == 9
                obj.Name = 'Laundry';
                obj.Intensity = 2;
                obj.VaporProduced = 4.5554; %moles/hour
                obj.DirtyWaterProduced = 0; %kg/day
                obj.O2Needed = 1.1375; %moles/hour
                obj.CO2Output = 0.9675; %moles/hour
                obj.PotableWaterNeeded  = obj.VaporProduced*0.01802 + obj.↙
DirtyWaterProduced;
            end
        end
    end
end
end
```

A.2 crewScheduler_new.m

```
% Yana Charoenboonvivat | 4/14/2024
function [crewSchedule,activityIndexVec] = crewScheduler_new(missionDurationInHours,↙
location)
    numberofDays = missionDurationInHours/24;
    standardDaySchedule =[ActivityImpl(1,location,1),ActivityImpl(2,location,1),↙
ActivityImpl(3,location,1),ActivityImpl(4,location,1),ActivityImpl(5,location,1),↙
ActivityImpl(6,location,10),ActivityImpl(7,location,1),ActivityImpl(8,location,8)];
    laundryDays = 1:6:numberofDays;
    laundryDays = laundryDays(2:end);
    laundryDaySchedule =[ActivityImpl(1,location,1),ActivityImpl(2,location,1),↙
ActivityImpl(3,location,1),ActivityImpl(4,location,1),ActivityImpl(5,location,1),↙
ActivityImpl(6,location,9),ActivityImpl(7,location,1),ActivityImpl(8,location,8),↙
ActivityImpl(9,location,1)];

    crewSchedule = [];
    for i = 1:1:numberofDays
        if any(i == laundryDays)
            crewSchedule = [crewSchedule laundryDaySchedule];
        else
            crewSchedule = [crewSchedule standardDaySchedule];
        end
    end
end
```

A.3 WHC.m

```
% Yana Charoenboonvivat | 4/14/2024
classdef WHC < handle
    properties
        Environment
        greyWaterStore_outside
        dirtyWaterStore_outside
        crew
        externalStoreList_s
        habitatStoreList_s
        externalStoreList
        habitatStoreList
        BPCStoreList
        BPCStoreList_s
        astro
    end

    properties (SetAccess = private)
        flushWater = 0.6; %KG
        oralHygiene =  0.552; %KG
        showerWater = 1.296; %KG
        handWash = 0.768; %KG
    end

    methods
        function obj = WHC(astro,environment,greyWaterStore_outside,↙
dirtyWaterStore_outside,ExternalStoreList,HabitatStoreList,BPCStoreList,↙
ExternalStoreList_s, HabitatStoreList_s,BPCStoreList_s)
            obj.Environment = environment;
            obj.greyWaterStore_outside = greyWaterStore_outside;
            obj.dirtyWaterStore_outside = dirtyWaterStore_outside;
            obj.externalStoreList_s = ExternalStoreList_s;
            obj.habitatStoreList_s = HabitatStoreList_s;
            obj.externalStoreList = ExternalStoreList;
            obj.habitatStoreList = HabitatStoreList;
            obj.BPCStoreList = BPCStoreList;
            obj.BPCStoreList_s = BPCStoreList_s;
            obj.astro = astro;
        end

        function tick(obj,track,waterLeak)
            if track == 1
                E_vec_before = []; H_vec_before = []; BPC_vec_before = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_before = [E_vec_before; obj.externalStoreList{i}.currentLevel];
                end

                for j = 1:1:length(obj.habitatStoreList)
                    H_vec_before = [H_vec_before; obj.habitatStoreList{j}.currentLevel];
                end

                for k = 1:1:length(obj.BPCStoreList)
                    BPC_vec_before = [BPC_vec_before; obj.BPCStoreList{k}.currentLevel];
                end
            end

            if obj.Environment.DirtyWaterStore.currentLevel > obj.flushWater
                obj.Environment.GreyWaterStore.add(obj.oralHygiene + obj.showerWater +↙
obj.handWash);
```

```
                obj.Environment.PotableWaterStore.take((obj.oralHygiene + obj.showerWater↙
+ obj.handWash + obj.flushWater)*(1+waterLeak));
                obj.Environment.DirtyWaterStore.add(obj.flushWater);
                obj.greyWaterStore_outside.add((obj.Environment.GreyWaterStore.↙
currentLevel)*(1-waterLeak));
                obj.Environment.GreyWaterStore.take(obj.Environment.GreyWaterStore.↙
currentLevel);
                obj.dirtyWaterStore_outside.add(obj.Environment.DirtyWaterStore.↙
currentLevel);
                obj.Environment.DirtyWaterStore.take(obj.Environment.DirtyWaterStore.↙
currentLevel);
            end

            if track == 1
                E_vec_after = []; H_vec_after = []; BPC_vec_after = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_after = [E_vec_after; obj.externalStoreList{i}.currentLevel];
                end

                for j = 1:1:length(obj.habitatStoreList)
                    H_vec_after = [H_vec_after; obj.habitatStoreList{j}.currentLevel];
                end

                for k = 1:1:length(obj.BPCStoreList)
                    BPC_vec_after = [BPC_vec_after; obj.BPCStoreList{k}.currentLevel];
                end

                delta = round([E_vec_after;H_vec_after;BPC_vec_after]-[E_vec_before;↙
H_vec_before;BPC_vec_before],16);
                resourceList = [obj.externalStoreList_s; obj.habitatStoreList_s; obj.↙
BPCStoreList_s];
                indexMask = delta ~= 0;
                fileID1 = fopen('d:WHC.txt','a');
                resourceChanged = resourceList(indexMask);
                quantity = delta(indexMask);
                tick = [obj.Environment.tickcount].*ones(length(quantity),1);
                T1 = table(tick,resourceChanged,quantity);
                writetable(T1,'d:WHC.txt','Delimiter','|', 'WriteMode','append')
                fclose(fileID1);
            end
        end
    end
end
```

A.4 laundryOps.m

```
% Yana Charoenboonvivat | 4/14/2024
classdef laundryOps < handle
    properties
        Environment
        LaundryWaterOutput
        externalStoreList_s
        habitatStoreList_s
        externalStoreList
        habitatStoreList
        BPCStoreList
        BPCStoreList_s
    end

    properties (SetAccess = private)
        potableWater_perload = 24*3.785;
        astro
    end

    methods
        function obj = laundryOps(astro,environment,LaundryWaterOutput,ExternalStoreList,↙
HabitatStoreList,BPCStoreList,ExternalStoreList_s, HabitatStoreList_s,BPCStoreList_s)
            obj.Environment = environment;
            obj.LaundryWaterOutput = LaundryWaterOutput;
            obj.externalStoreList_s = ExternalStoreList_s;
            obj.habitatStoreList_s = HabitatStoreList_s;
            obj.externalStoreList = ExternalStoreList;
            obj.habitatStoreList = HabitatStoreList;
            obj.BPCStoreList = BPCStoreList;
            obj.BPCStoreList_s = BPCStoreList_s;
            obj.astro = astro;
        end

        function tick(obj,track,waterLeak)
            if track == 1
                E_vec_before = []; H_vec_before = []; BPC_vec_before = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_before = [E_vec_before; obj.externalStoreList{i}.currentLevel];
                end

                for j = 1:1:length(obj.habitatStoreList)
                    H_vec_before = [H_vec_before; obj.habitatStoreList{j}.currentLevel];
                end

                for k = 1:1:length(obj.BPCStoreList)
                    BPC_vec_before = [BPC_vec_before; obj.BPCStoreList{k}.currentLevel];
                end
            end
            for i = 1:length(obj.astro)
                if obj.astro(i).CurrentActivity.ID == 9
                    obj.Environment.PotableWaterStore.take((1+waterLeak)*obj.↙
potableWater_perload);
                    obj.LaundryWaterOutput.add((1-waterLeak)*obj.potableWater_perload);
                end
            end
            if track == 1
                E_vec_after = []; H_vec_after = []; BPC_vec_after = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_after = [E_vec_after; obj.externalStoreList{i}.currentLevel];
```

```
                end

                for j = 1:1:length(obj.habitatStoreList)
                    H_vec_after = [H_vec_after; obj.habitatStoreList{j}.currentLevel];
                end

                for k = 1:1:length(obj.BPCStoreList)
                    BPC_vec_after = [BPC_vec_after; obj.BPCStoreList{k}.currentLevel];
                end

                delta = round([E_vec_after;H_vec_after;BPC_vec_after]-[E_vec_before;↙
H_vec_before;BPC_vec_before],16);
                resourceList = [obj.externalStoreList_s; obj.habitatStoreList_s; obj.↙
BPCStoreList_s];
                indexMask = delta ~= 0;
                fileID1 = fopen('d:laundry - laundryOps.txt','a');
                resourceChanged = resourceList(indexMask);
                quantity = delta(indexMask);
                tick = [obj.Environment.tickcount].*ones(length(quantity),1);
                T1 = table(tick,resourceChanged,quantity);
                writetable(T1,'d:laundry - laundryOps.txt','Delimiter','|',↙
'WriteMode','append')
                fclose(fileID1);

            end
        end
    end
end
```

A.5 MAV_cryocooler.m

```
% Yana Charoenboonvivat | 4/14/2024
classdef MAV_cryocooler < handle
    properties
        missionDurationDays
        numberOfCrew
        boilOffRateLOX
        boilOffRateCH4
        LOXdayProdRate
        LCH4dayProdRate
        LCH4LostCumulative
        LOXLostCumulative
        LOXdayReqProdRate
        LCH4dayReqProdRate
        crewSizevsLOXreq
        crewSizevsLCH4req
    end

    methods
        %% Constructor
        function obj = MAV_cryocooler(numberOfCrew, missionDurationInHours,↙
boilOffRateLOX,boilOffRateCH4)
            obj.missionDurationDays = missionDurationInHours/24;
            obj.numberOfCrew = numberOfCrew;
            obj.boilOffRateLOX = boilOffRateLOX/100;
            obj.boilOffRateCH4 = boilOffRateCH4/100;
            obj.crewSizevsLOXreq =↙
[13662,17021,19977,22717,25316,27813,30231,32586,34888,37147,39367,41553];%values in kg
            obj.crewSizevsLCH4req =↙
[4173,5199,6101,6938,7732,8494,9233,9952,10655,11345,12023,12691]; %values in kg
            obj.LOXdayProdRate = obj.crewSizevsLOXreq(obj.numberOfCrew)/obj.↙
missionDurationDays;
            LOXLevel = 0;
            obj.LOXLostCumulative = 0;
            i = 0;
            while i < obj.missionDurationDays
                LOXLevel = LOXLevel*(1-obj.boilOffRateLOX) + obj.LOXdayProdRate;
                LOXLost = LOXLevel*obj.boilOffRateLOX;
                obj.LOXLostCumulative = obj.LOXLostCumulative + LOXLost;
                i = i+1;
            end

           LOXpercentageProdIncrease = obj.LOXLostCumulative/(obj.crewSizevsLOXreq(obj.↙
numberOfCrew) - obj.LOXLostCumulative);
           obj.LOXdayReqProdRate = obj.LOXdayProdRate*(1+LOXpercentageProdIncrease);

           obj.LCH4dayProdRate = obj.crewSizevsLCH4req(obj.numberOfCrew)/obj.↙
missionDurationDays;
           LCH4Level = 0;
           obj.LCH4LostCumulative = 0;
           j = 0;
            while j < obj.missionDurationDays
                LCH4Level = LCH4Level*(1-obj.boilOffRateCH4) + obj.LCH4dayProdRate;
                LCH4Lost = LCH4Level*obj.boilOffRateCH4;
                obj.LCH4LostCumulative = obj.LCH4LostCumulative + LCH4Lost;
                j = j+1;
            end

           LCH4percentageProdIncrease = obj.LCH4LostCumulative/(obj.crewSizevsLCH4req↙

(obj.numberOfCrew) - obj.LCH4LostCumulative);
           obj.LCH4dayReqProdRate = obj.LCH4dayProdRate*(1+LCH4percentageProdIncrease);
        end
    end
end
```

A.6 WaterElectrolyzerforMAVprop.m

```
% Modified by Yana Charoenboonvivat on 4/14/2024 from ISSOGAwithRSA.m by Sydney Do
classdef WaterElectrolyzerforMAVprop < handle
    properties
        Environment
        PowerConsumerDefinition
        PotableWaterConsumerDefinition
        O2ProducerDefinition
        H2ProducerDefinition
        Error = 0
        LOXrequiredPerDay
        LOXrequiredPerHour
        LCH4requiredPerDay
        LCH4requiredPerHour
        externalStoreList
        habitatStoreList
        externalStoreList_s
        habitatStoreList_s
        BPCStoreList
        BPCStoreList_s
        molesOfWaterRequired
        molesOfWaterRequiredOxygenLim
        molesOfWaterRequiredMethaneLim
    end


    methods
        function obj = WaterElectrolyzerforMAVprop(WaterSourceLocation,Environment,↙
LOXdayReqProdRate,LCH4dayReqProdRate,O2output,H2output, ExternalStoreList,↙
HabitatStoreList,BPCStoreList,ExternalStoreList_s, HabitatStoreList_s,BPCStoreList_s)
            obj.Environment = Environment;
            obj.externalStoreList = ExternalStoreList;
            obj.habitatStoreList = HabitatStoreList;
            obj.externalStoreList_s = ExternalStoreList_s;
            obj.habitatStoreList_s = HabitatStoreList_s;
            obj.BPCStoreList = BPCStoreList;
            obj.BPCStoreList_s = BPCStoreList_s;
            obj.PotableWaterConsumerDefinition = WaterSourceLocation;
            obj.O2ProducerDefinition = O2output;
            obj.H2ProducerDefinition = H2output;
            obj.LOXrequiredPerDay = LOXdayReqProdRate; % kg/day
            obj.LCH4requiredPerDay = LCH4dayReqProdRate; %kg/day
        end

        function [molesOfO2Produced,action] = tick(obj,track,waterLeak)
            if track == 1
                E_vec_before = []; H_vec_before = []; BPC_vec_before = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_before = [E_vec_before; obj.externalStoreList{i}.currentLevel];
                end

                for j = 1:1:length(obj.habitatStoreList)
                    H_vec_before = [H_vec_before; obj.habitatStoreList{j}.currentLevel];
                end

                for k = 1:1:length(obj.BPCStoreList)
                    BPC_vec_before = [BPC_vec_before; obj.BPCStoreList{k}.currentLevel];
                end
            end
```

```
            if obj.Error == 0

                obj.LOXrequiredPerHour = (obj.LOXrequiredPerDay/24);
                O2requiredPerHourMoles = obj.LOXrequiredPerHour * 31.251171918947;
                obj.molesOfWaterRequiredOxygenLim = 2*O2requiredPerHourMoles;

                obj.LCH4requiredPerHour = obj.LCH4requiredPerDay/24;
                CH4requiredPerHoursMoles = obj.LCH4requiredPerHour * 62.33442;
                obj.molesOfWaterRequiredMethaneLim = CH4requiredPerHoursMoles*4;

                if obj.molesOfWaterRequiredMethaneLim == obj.↙
molesOfWaterRequiredOxygenLim
                    obj.molesOfWaterRequired = obj.molesOfWaterRequiredOxygenLim;
                else
                    obj.molesOfWaterRequired = max(obj.molesOfWaterRequiredOxygenLim,obj.↙
molesOfWaterRequiredMethaneLim);
                end
                litersOfWaterRequired = obj.molesOfWaterRequired*18.015279999999997/1000;
                litersOfH2OConsumed = obj.PotableWaterConsumerDefinition.take↙
(litersOfWaterRequired*(1+waterLeak));
                molesOfH2OConsumed = ((litersOfH2OConsumed * 1000) / 18.015279999999997)/↙
(1+waterLeak);
                obj.O2ProducerDefinition.add(molesOfH2OConsumed/2);
                obj.H2ProducerDefinition.add(molesOfH2OConsumed);

            else
                molesOfO2Produced = 0;
                return

            end

            if track == 1
                E_vec_after = []; H_vec_after = []; BPC_vec_after = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_after = [E_vec_after; obj.externalStoreList{i}.currentLevel];
                end

                for j = 1:1:length(obj.habitatStoreList)
                    H_vec_after = [H_vec_after; obj.habitatStoreList{j}.currentLevel];
                end

                for k = 1:1:length(obj.BPCStoreList)
                    BPC_vec_after = [BPC_vec_after; obj.BPCStoreList{k}.currentLevel];
                end

                delta = round([E_vec_after;H_vec_after;BPC_vec_after]-[E_vec_before;↙
H_vec_before;BPC_vec_before],16);
                resourceList = [obj.externalStoreList_s; obj.habitatStoreList_s; obj.↙
BPCStoreList_s];
                indexMask = delta ~= 0;
                fileID1 = fopen('d:waterElectrolyzerMAV - OGAforMAV.txt','a');
                resourceChanged = resourceList(indexMask);
                quantity = delta(indexMask);
                tick = [obj.Environment.tickcount].*ones(length(quantity),1);
                T1 = table(tick,resourceChanged,quantity);
                writetable(T1,'d:waterElectrolyzerMAV - OGAforMAV.txt','Delimiter','|',↙
'WriteMode','append')
```

```
                fclose(fileID1);

            end
        end
    end

end
```

A.7 SabatierforMAVprop.m

```
% Modified by Yana Charoenboonvivat on 4/14/2024 from ISSCRSImpl.m by Sydney Do
classdef SabatierforMAVprop < handle
    properties
        % Consumer/Producer Definitions
        CO2ConsumerDefinition
        H2ConsumerDefinition
        PowerConsumerDefinition
        GreyWaterProducerDefinition
        MethaneProducerDefinition
        CO2Accumulator
        CompressorError = 0
        ReactorError = 0
        SeparatorError = 0;
        CO2Vented = 0
        WaterVaporVented = 0
        CompressorOperation = zeros(2,1)
        CompressorPowerConsumed = 0
        ReactorPowerConsumed = 0
        CondensorPowerConsumed = 0
        externalStoreList
        habitatStoreList
        externalStoreList_s
        habitatStoreList_s
        BPCStoreList
        BPCStoreList_s
        Environment
    end

    properties (Access = private)
        ReactionH2CO2ratio = 3.5
        idealGasConstant = 8.314; % J/K/mol
        ReactorWaterConversionEfficiency = 0.9
    end

    methods
        function obj = SabatierforMAVprop(Environment,H2Source,CO2Source,WaterOutput,↙
CH4Output,PowerSource,ExternalStoreList,HabitatStoreList,BPCStoreList,↙
ExternalStoreList_s, HabitatStoreList_s,BPCStoreList_s)
            obj.externalStoreList = ExternalStoreList;
            obj.habitatStoreList = HabitatStoreList;
            obj.externalStoreList_s = ExternalStoreList_s;
            obj.habitatStoreList_s = HabitatStoreList_s;
            obj.BPCStoreList = BPCStoreList;
            obj.BPCStoreList_s = BPCStoreList_s;
            obj.CO2ConsumerDefinition = CO2Source;
            obj.H2ConsumerDefinition = H2Source;
            obj.PowerConsumerDefinition = PowerSource;
            obj.GreyWaterProducerDefinition = WaterOutput;
            obj.MethaneProducerDefinition = CH4Output;
            obj.Environment = Environment;
        end

        function currentH2OProduced = tick(obj,track,waterLeak)
            if track == 1
                E_vec_before = []; H_vec_before = []; BPC_vec_before = [];
                for i = 1:1:length(obj.externalStoreList)
                    E_vec_before = [E_vec_before; obj.externalStoreList{i}.currentLevel];
                end
```

```
            for j = 1:1:length(obj.habitatStoreList)
                H_vec_before = [H_vec_before; obj.habitatStoreList{j}.currentLevel];
            end

            for k = 1:1:length(obj.BPCStoreList)
                BPC_vec_before = [BPC_vec_before; obj.BPCStoreList{k}.currentLevel];
            end
        end


        if obj.CompressorError == 0 && obj.ReactorError == 0 && obj.SeparatorError ==↙
0
            if obj.H2ConsumerDefinition.currentLevel > 0
                H2MolestoReact = obj.H2ConsumerDefinition.take(obj.↙
H2ConsumerDefinition.currentLevel);
                CO2MolestoReact = obj.CO2ConsumerDefinition.take(1/obj.↙
ReactionH2CO2ratio*H2MolestoReact);
                currentH2OProduced = obj.GreyWaterProducerDefinition.add↙
((H2MolestoReact/2 * obj.ReactorWaterConversionEfficiency *(2*1.008+15.999)/1000)*(1-↙
waterLeak));
                obj.WaterVaporVented = obj.WaterVaporVented + H2MolestoReact/2 * (1-↙
obj.ReactorWaterConversionEfficiency);
                obj.CO2Vented = obj.CO2Vented + (CO2MolestoReact-H2MolestoReact/4);
                obj.MethaneProducerDefinition.add(H2MolestoReact/4);

            end

        else
            currentH2OProduced = 0;
            return

        end

        if track == 1
            E_vec_after = []; H_vec_after = []; BPC_vec_after = [];
            for i = 1:1:length(obj.externalStoreList)
                E_vec_after = [E_vec_after; obj.externalStoreList{i}.currentLevel];
            end

            for j = 1:1:length(obj.habitatStoreList)
                H_vec_after = [H_vec_after; obj.habitatStoreList{j}.currentLevel];
            end

            for k = 1:1:length(obj.BPCStoreList)
                BPC_vec_after = [BPC_vec_after; obj.BPCStoreList{k}.currentLevel];
            end

            delta = round([E_vec_after;H_vec_after;BPC_vec_after]-[E_vec_before;↙
H_vec_before;BPC_vec_before],16);
            resourceList = [obj.externalStoreList_s; obj.habitatStoreList_s; obj.↙
BPCStoreList_s];
            indexMask = delta ~= 0;
            fileID1 = fopen('d:sabatierReactorMAV - SabatierforMAVprop.txt','a');
            resourceChanged = resourceList(indexMask);
            quantity = delta(indexMask);
            tick = [obj.Environment.tickcount].*ones(length(quantity),1);
            T1 = table(tick,resourceChanged,quantity);




            writetable(T1,'d:sabatierReactorMAV - SabatierforMAVprop.↙
txt','Delimiter','|', 'WriteMode','append')
            fclose(fileID1);
        end
    end
end

end
```

Appendix B

Simulation Set-Up Verification

Figure B.1 shows that no hydrogen remained in the hydrogen storage tank throughout the 2000-hour mission. This indicates that all hydrogen generated via electrolysis was successfully transferred to the Sabatier reactor to produce methane for the MAV propellant. No hydrogen was expected to be left in the hydrogen tank because hydrogen was found to be a limiting reactant in the production of MAV propellant (as explained in Section 3.2.6). Additionally, Figure B.2 and Figure B.3 indicate that sufficient LOX and LCH_4 was produced for one crew member. Figure B.4 shows that the WPA in the MAV propellant loop processed grey water to generate potable water when the water level in the grey water storage tank exceeded the WPA tank capacity of ∼45 L. Overall, these behaviors in the hydrogen, grey water, LOX, and LCH_4 levels suggest that the MAV propellant production loop was operating as intended.

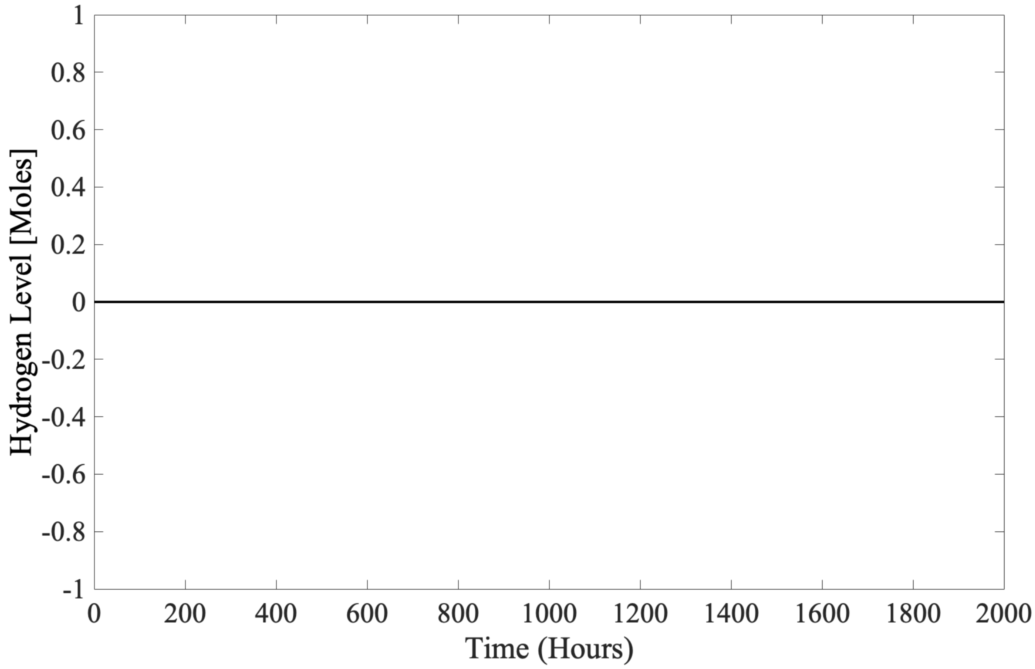


Figure B.1: Hydrogen level over time for a 2000-hour mission with one crew member.

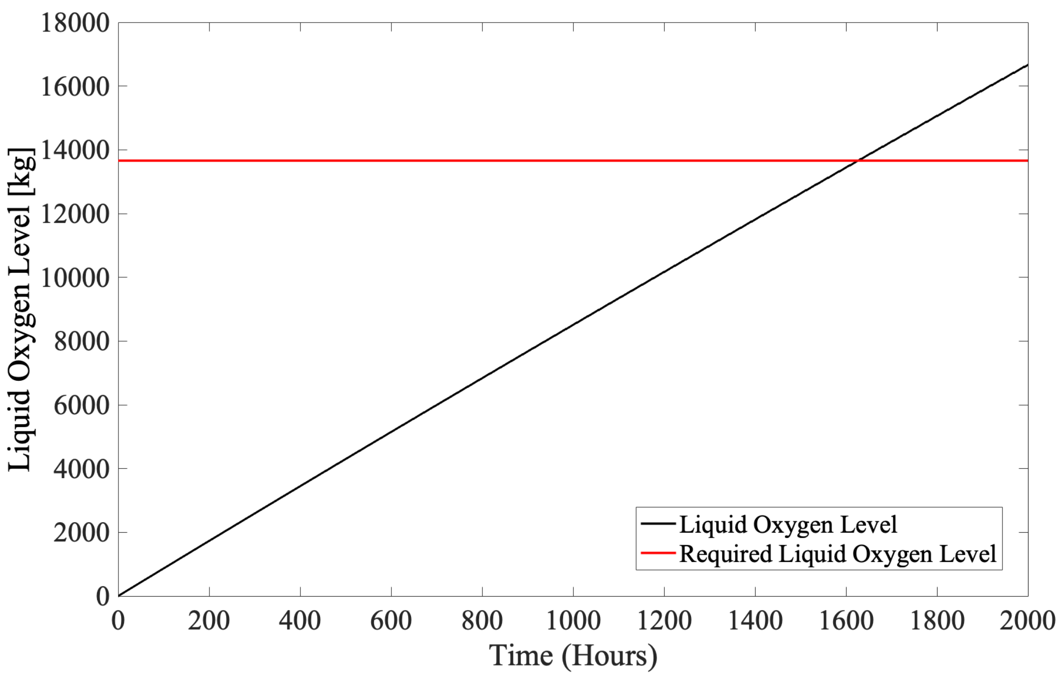


Figure B.2: *LOX* level over time for a 2000-hour mission with one crew member.

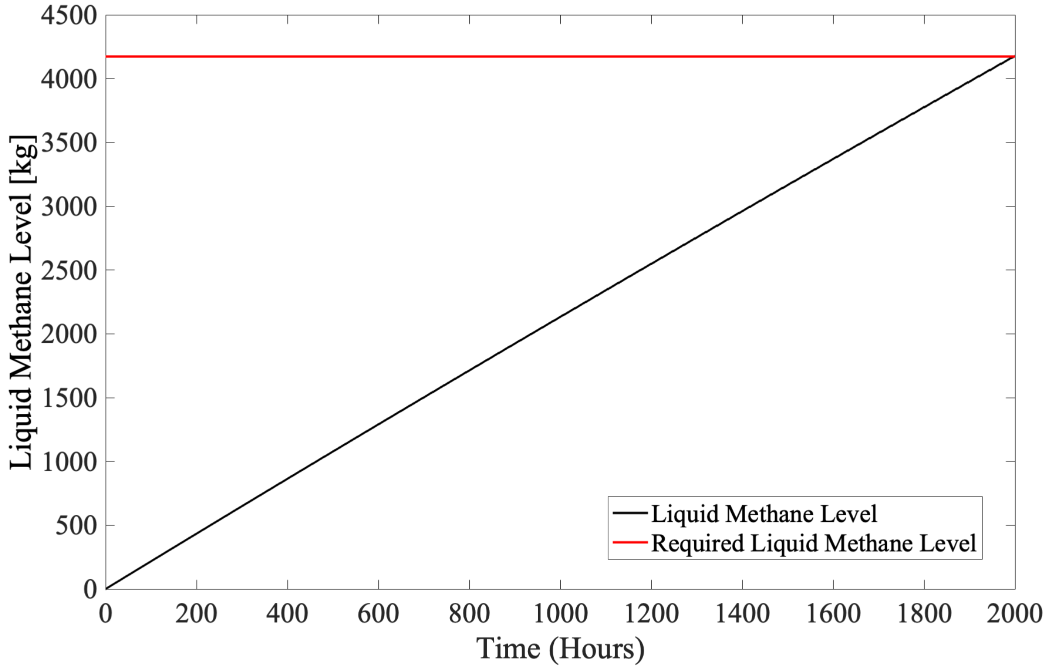


Figure B.3: LCH_4 level over time for a 2000-hour mission with one crew member.

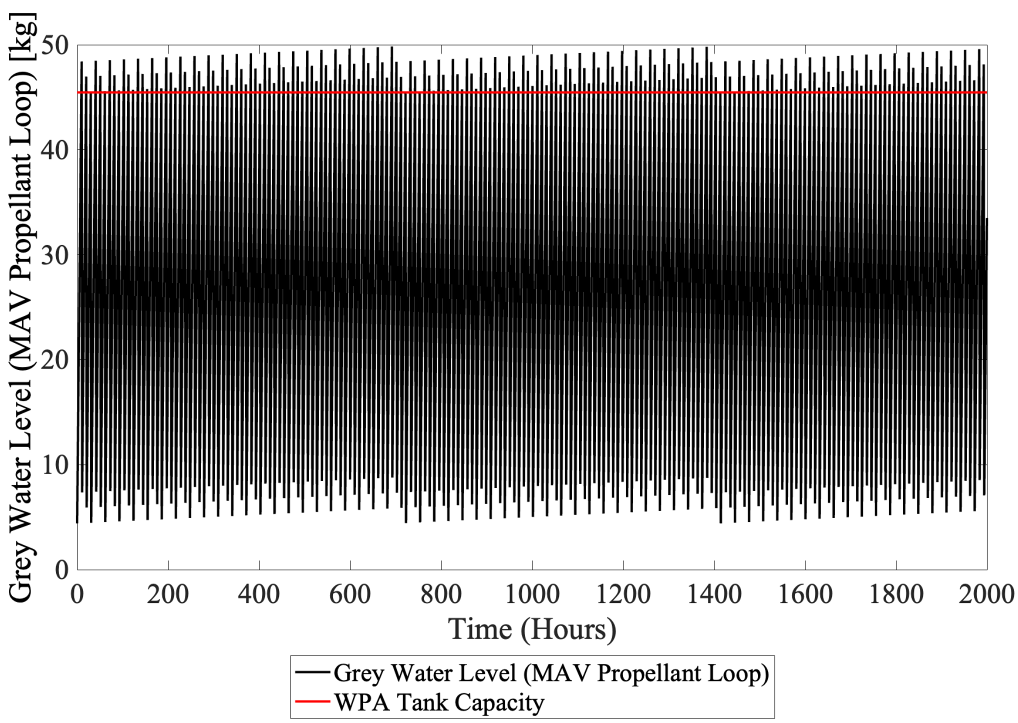


Figure B.4: Grey water level in the MAV propellant loop for a 2000-hour mission with one crew member.

The absence of grey water and dirty water in the MarsHab (see Figure B.5 and Figure B.6) suggests that the WHC successfully transferred crew waste/hygiene water to the external grey water and dirty water tanks. Figure B.7 shows that the UPA was able to process urine (dirty water) to generate grey water when the dirty water level in the dirty water storage tank exceeded the UPA tank capacity of ∼8 L. Furthermore, Figure B.8 shows that the WPA in the life support loop processed grey water to produce potable water when the water level in the grey water storage tank exceeded the WPA tank capacity of ∼45 L. These are all expected behaviors of the UPA and WPA, verifying the water reclamation capabilities of the life support loop in the integrated simulation.

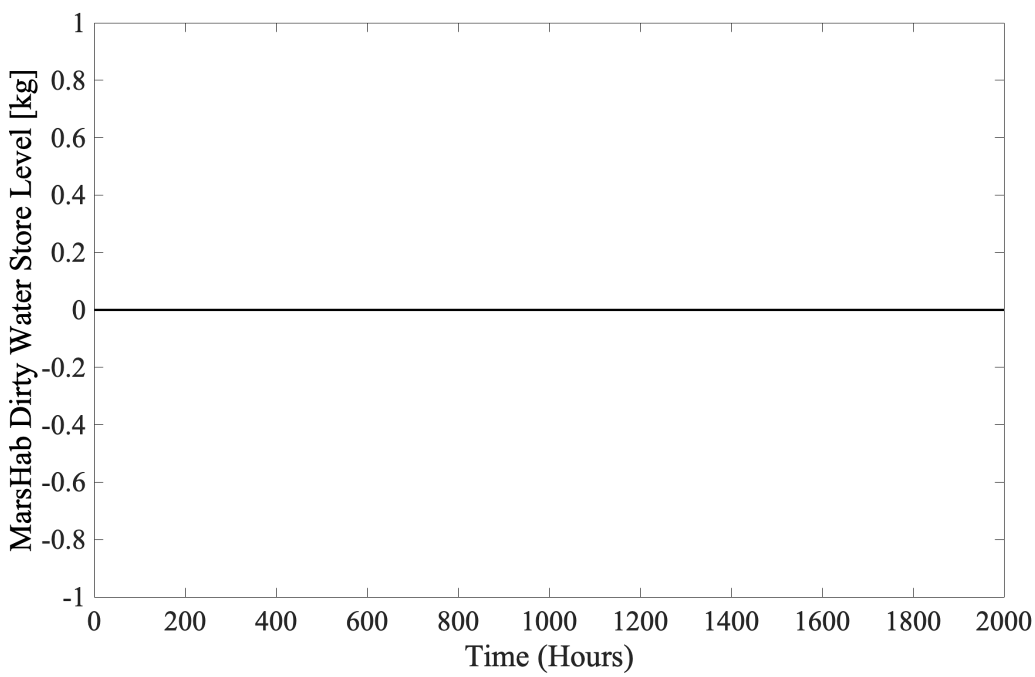


Figure B.5: Dirty water level in the MarsHab over time for a 2000-hour mission with one crew member.

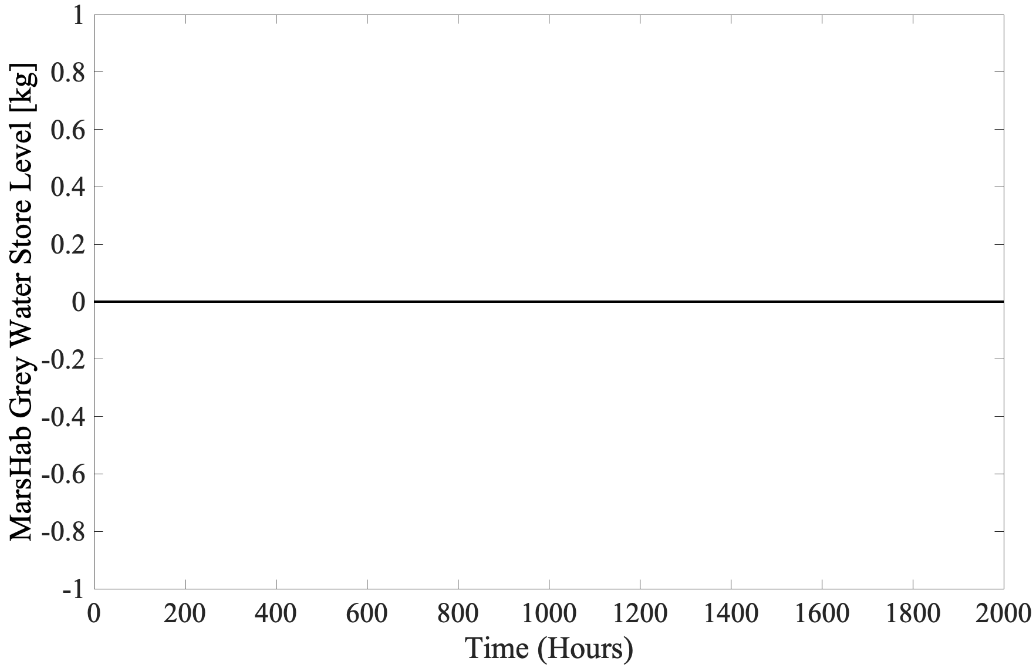


Figure B.6: Grey water level in the MarsHab over time for a 2000-hour mission with one crew member.

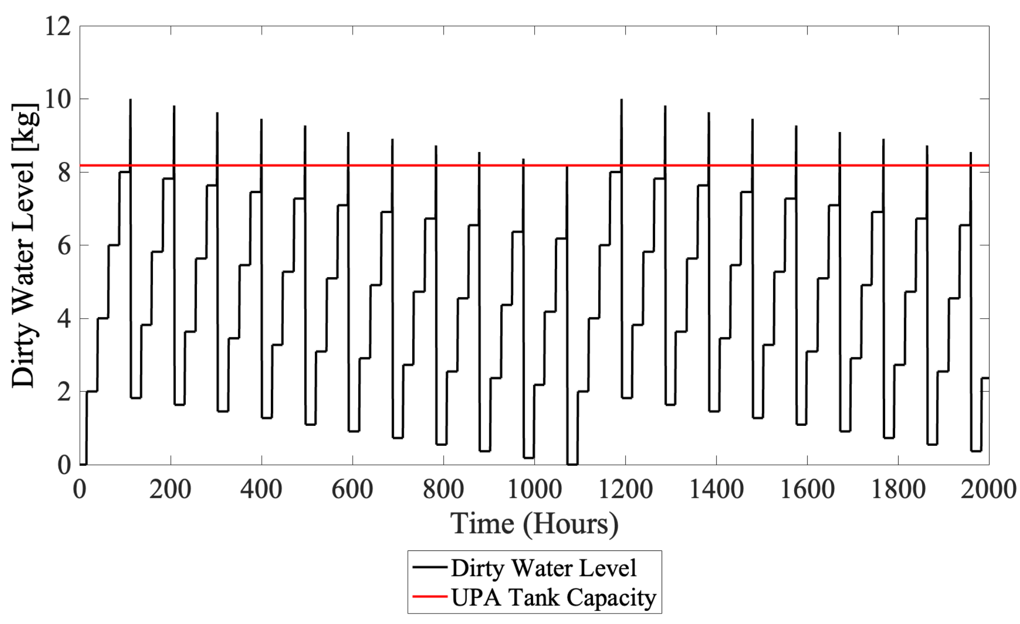


Figure B.7: Dirty water level over time for a 2000-hour mission with one crew member.

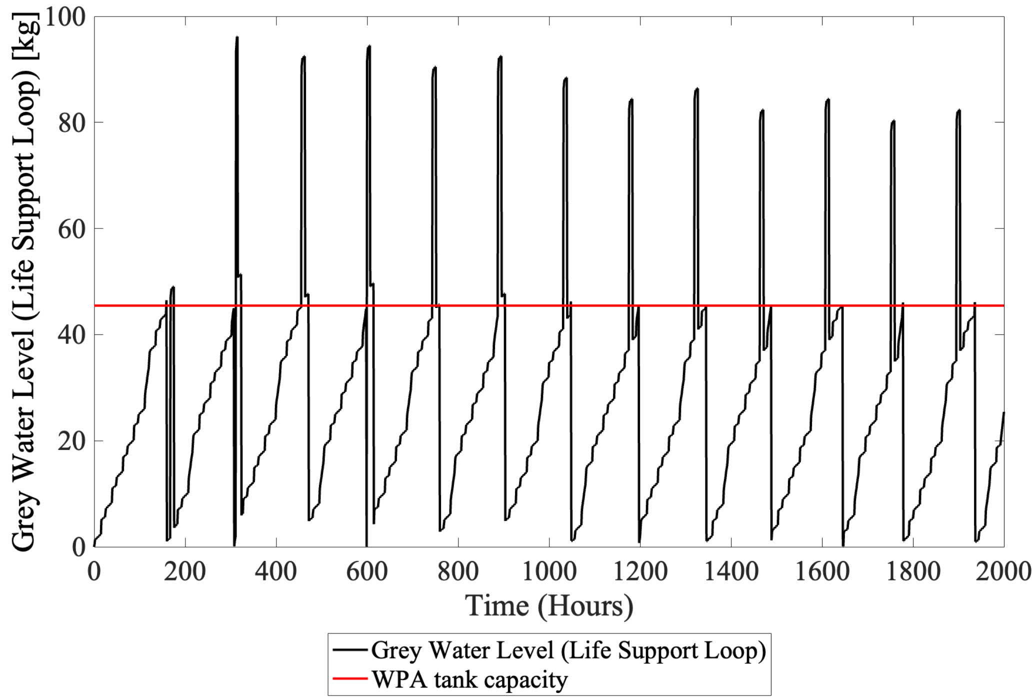


Figure B.8: Grey water level in the life support loop for a 2000-hour mission with one crew member.

During the 2000-hour mission, the MarsHab experienced under-pressure conditions around hours 925, 1285, and 1645. To correct for the under-pressure conditions, the PCA in the life support loop injected nitrogen into the MarsHab, which increased the overall nitrogen level inside the MarsHab and decreased the nitrogen level in the external tank. This correction for under-pressure can be observed in Figure B.9 and Figure B.10 where the MarsHab nitrogen level spiked and the nitrogen level in the external tank dropped at around hours 925, 1285, and 1645 in Figure B.11. However, injecting nitrogen into the MarsHab caused the concentration of oxygen to fall below the acceptable minimum threshold. This triggered the PCA to inject oxygen into the MarsHab (which allowed the partial pressure of oxygen to remain above the minimum oxygen partial pressure allowed as shown in Figure B.12) but resulted in over-pressure conditions in the subsequent hour (see Figure B.11 for pressure spikes above the pressure bounding box threshold). Over-pressure conditions caused the PCA to vent gases inside the MarsHab to the external environment and explain why the level of other gases inside the MarsHab dropped at around the same time as shown in Figure B.13.

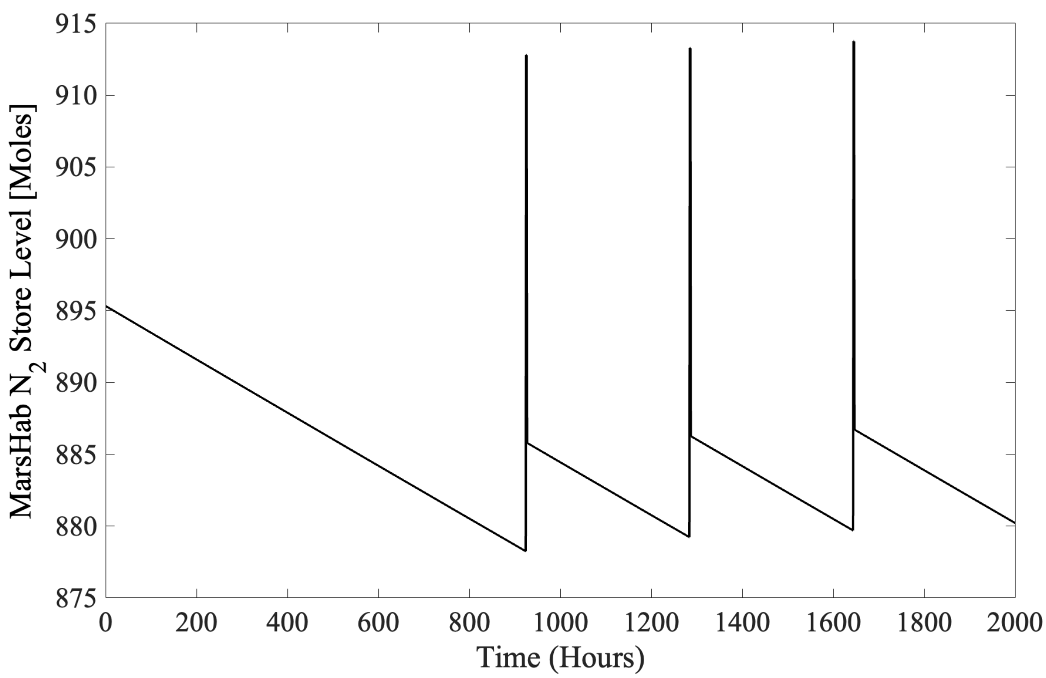


Figure B.9: Nitrogen level in the MarsHab over time for a 2000-hour mission with one crew member.

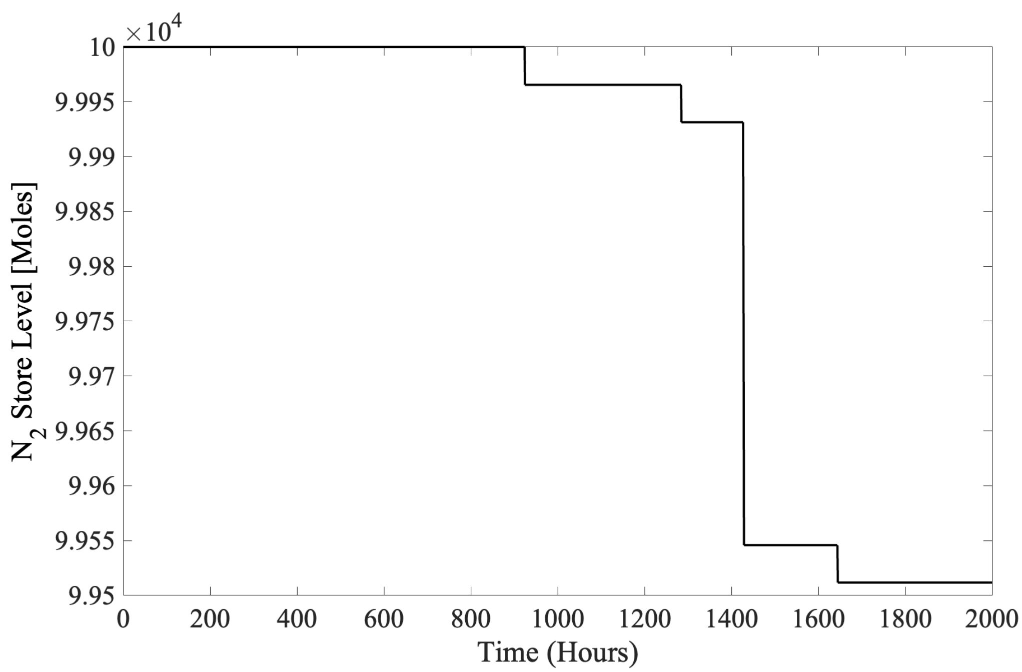


Figure B.10: Nitrogen level over time for a 2000-hour mission with one crew member.

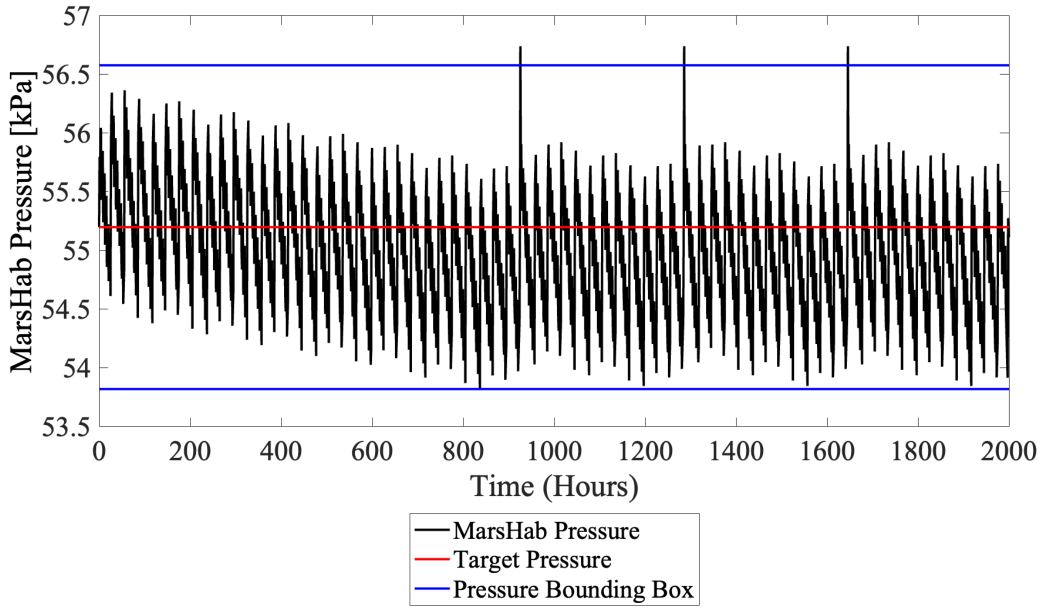


Figure B.11: MarsHab pressure over time for a 2000-hour mission with one crew member.

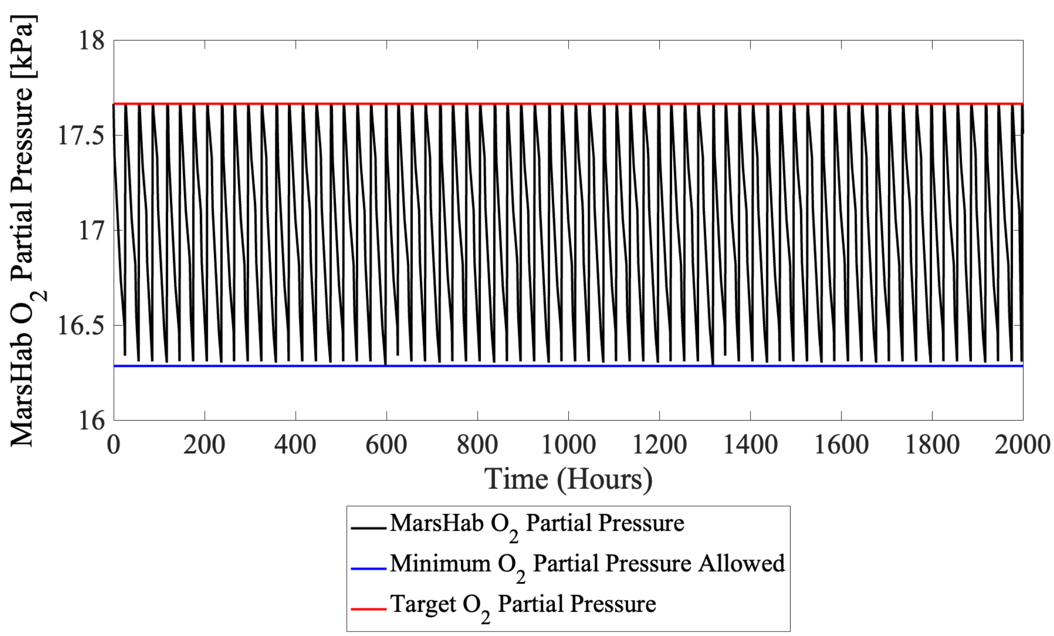


Figure B.12: Oxygen partial pressure in the MarsHab over time for a 2000-hour mission with one crew member.

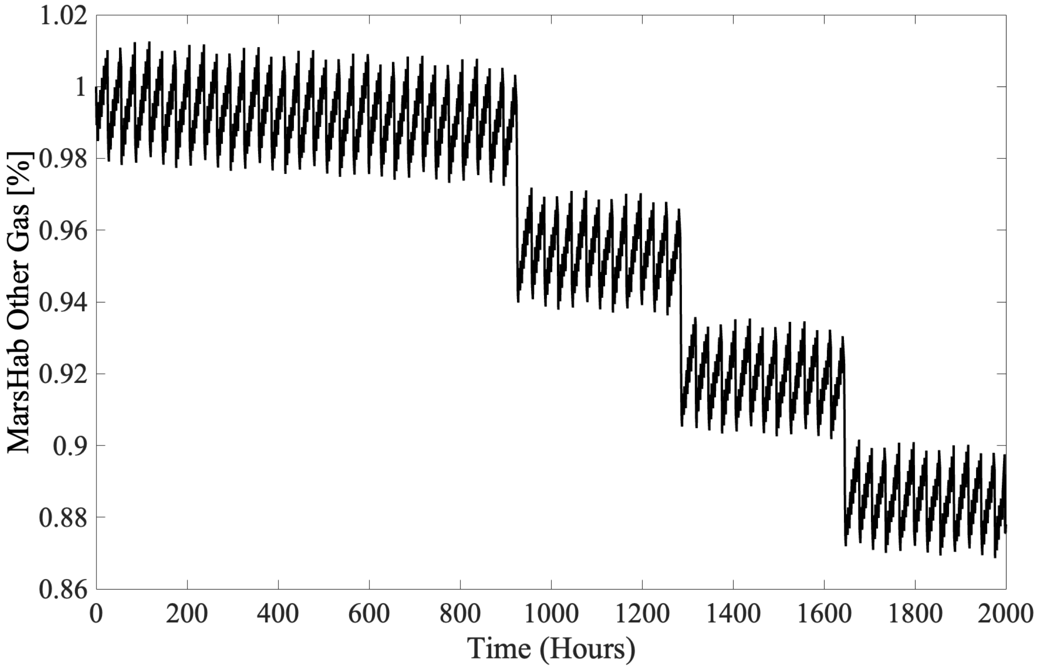


Figure B.13: Level of other gases in the MarsHab over time for a 2000-hour mission with one crew member.

At around the 1425^{th} hour, the BPC also experienced an under-pressure condition (see Figure B.14), triggering the PCA to inject nitrogen into the BPC. This resulted in the dip in nitrogen level and increase in BPC nitrogen level at around hour 1425 shown in Figure B.10 and in Figure B.15 respectively.

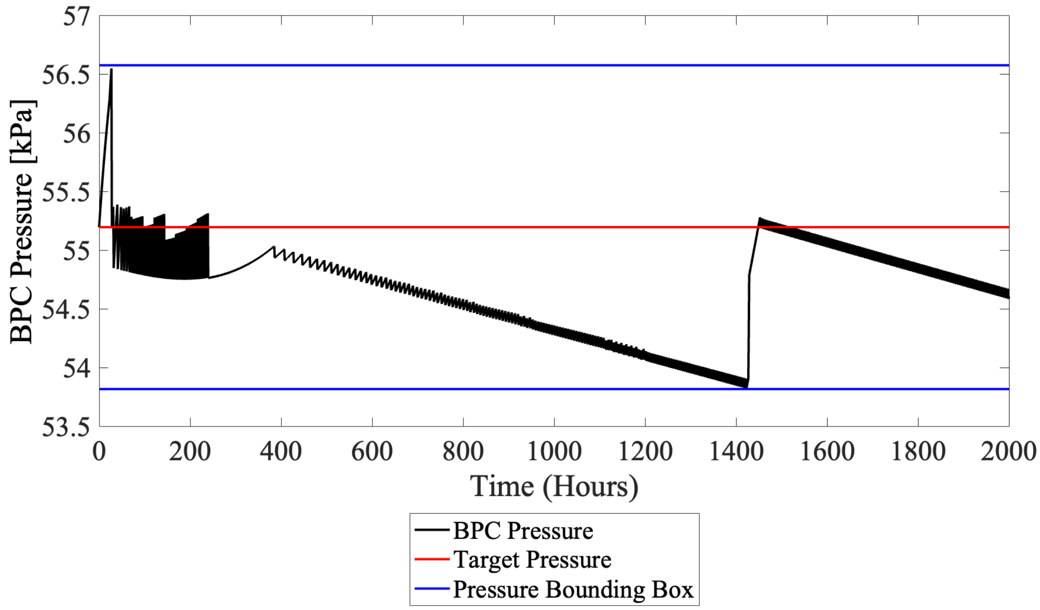


Figure B.14: BPC pressure over time for a 2000-hour mission with one crew member.

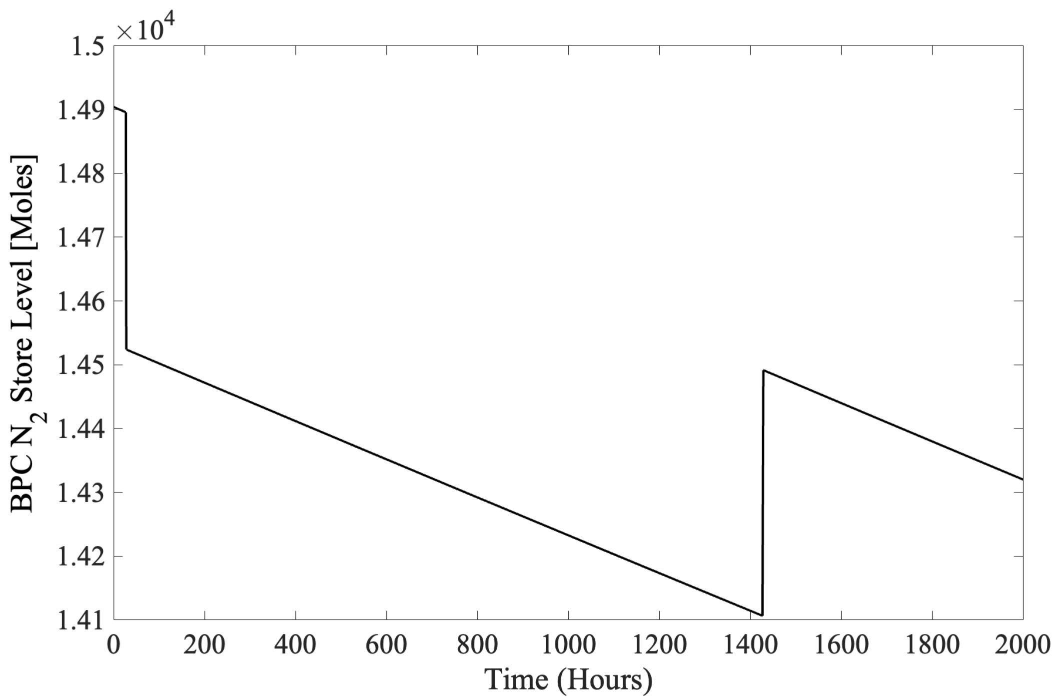


Figure B.15: Nitrogen level in the BPC over time for a 2000-hour mission with one crew member.

The dynamics of gases and pressure in the MarsHab and BPC observed in Figure B.9

through Figure B.15 indicate that the PCA is operating as expected in the integrated environment. Dry waste accumulation in the BPC, which is a by-product of operating the food processor, is seen to occur in Figure B.16 when the crops have matured (i.e., are ready to be harvested and processed for crew consumption). Crop maturity also coincided with when food levels in the MarsHab started to increase (see Figure B.17), which indicates that the BPC system was able to support plant growth and provide the crew with food.

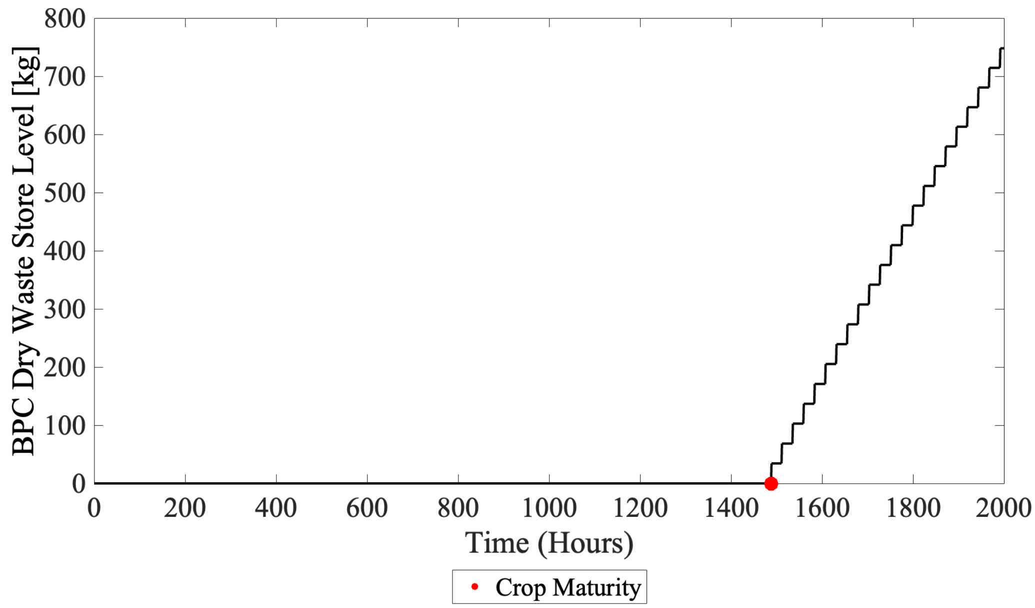


Figure B.16: Dry waste in the BPC over time for a 2000-hour mission with one crew member.

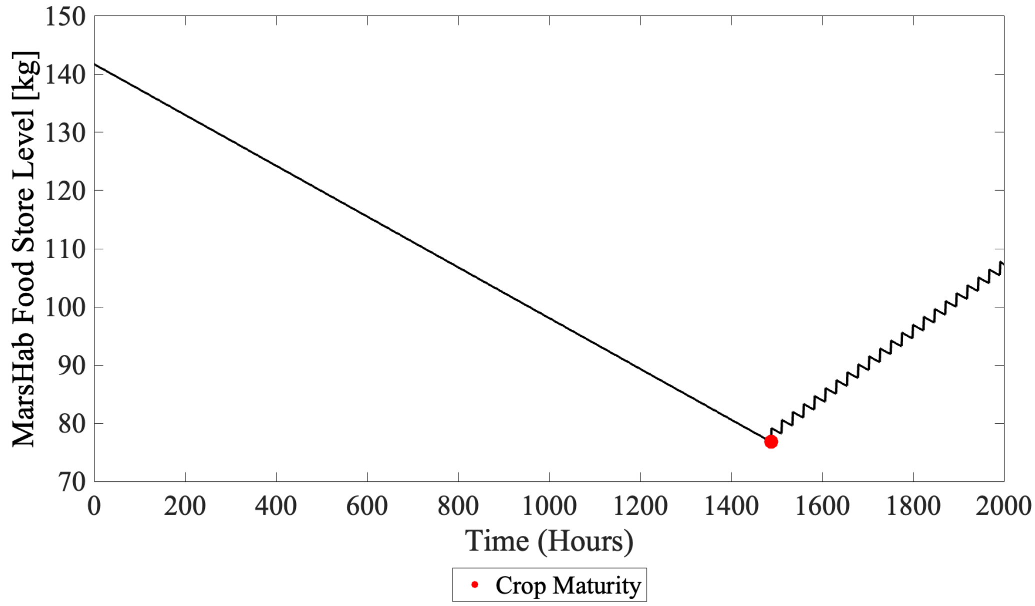


Figure B.17: Food level in the MarsHab over time for a 2000-hour mission with one crew member.

The relative humidity inside the MarsHab and BPC were observed to oscillate between ±10% of the 40% and 55% targeted relative humidity (see Figure B.18 and Figure B.19). This provides verification that the CCAA is operating as anticipated in the integrated simulation.

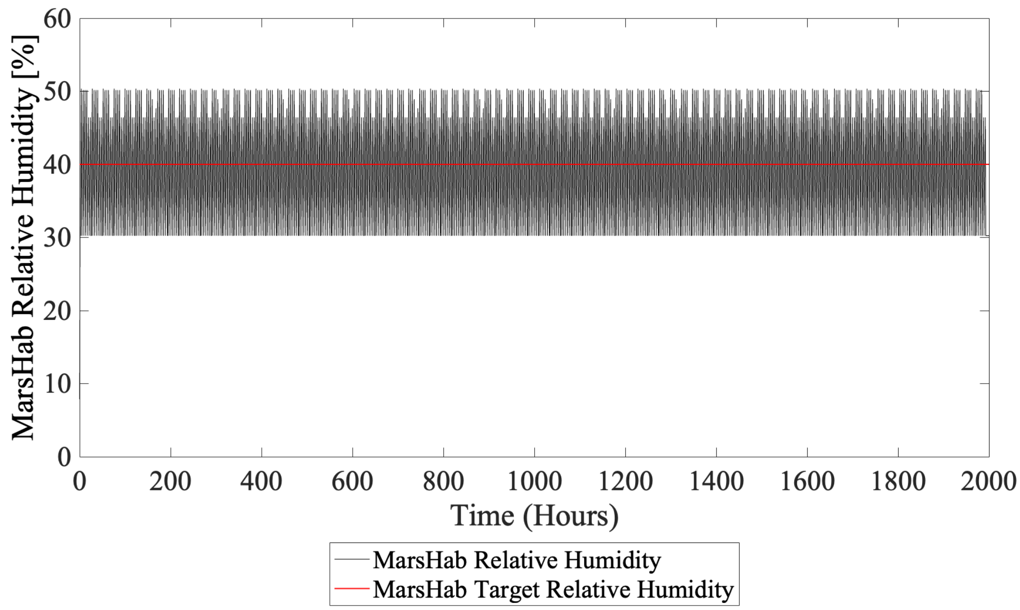


Figure B.18: Relative humidity in the MarsHab over time for a 2000-hour mission with one crew member.

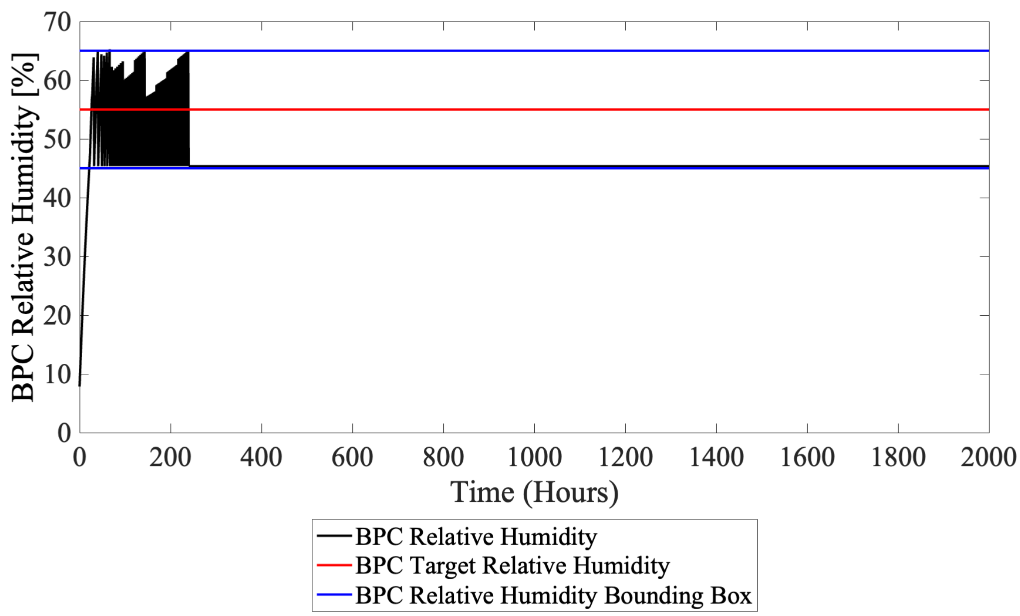


Figure B.19: Relative humidity in the BPC over time for a 2000-hour mission with one crew member.

Appendix C

Code Listing: Monte Carlo Simulation

C.1 run_main.sh

```
# Save the start date and time to a variable
start_date=$(date)

# Run the script
LLsub ./runMC.sh [8,48,1]

#Get the stop date and time
end_date=$(date)

#Find the elapsed time to complete the script
start=$(date -d "$start_date" +%s)
end_time=$(date -d "$end_date" +%s)
elapsed=$((end_time-start))
```

C.2 run_MC.sh

```
#!/bin/bash

# Slurm sbatch options

matlab2023b -nodisplay -batch "runMC_function( $LLSUB_RANK , $LLSUB_SIZE );
exit"
```

C.3 runMC_function.sh

```
function runMC_function( LLSUB_RANK, LLSUB_SIZE)
    taskid = LLSUB_RANK;
    num_tasks = LLSUB_SIZE;
    addpath('/home/gridsan/yanac/integratedTest-LongDurationArchitecture/')
    for i = 1:2000
        BOR(i) = unifrnd(0,0.5);
        waterLeak(i) = unifrnd(0,0.25);
    end
    MC_array = [BOR;waterLeak];
    tasks = 1:2000;
    my_tasks = tasks(taskid+1:num_tasks:length(tasks));
    for i = 1:length(my_tasks)
        [BPCWater,ECLSWater,MAVWater,TotalWaterReq] = main_exec4CM(MC_array(2,my_tasks↙
(i)),MC_array(1,my_tasks(i)));
        MC_4CM.TotalWater = TotalWaterReq;
        MC_4CM.ECLSWater = ECLSWater;
        MC_4CM.MAVWater = MAVWater;
        MC_4CM.BPCWater = BPCWater;
        BOR_name = num2str(MC_array(1,my_tasks(i)));
        WaterLeak_name = num2str(MC_array(2,my_tasks(i)));
        filename = ['./data2000/MC_4M_struct',BOR_name(3:end),'_',WaterLeak_name(3:↙
end),'.mat'];
        save(filename,'-struct','MC_4CM');
    end
end
```

C.4 main_exec4CM.m

```
function [BPCWater,ECLSWater,MAVWater,TotalWaterReq] = main_exec4CM(waterLeak,BOR)
    addpath('/home/gridsan/yanac/integratedTest-LongDurationArchitecture/');
    %% Initialize Key Mission Parameters
    missionDurationInHours = 790*24;
    missionDurationInDays = missionDurationInHours/24;
    habitatVolumeComfortness = 15;
    numberOfCrew = 4;
    missionDurationInWeeks = ceil(missionDurationInHours/24/7);
    fractionOfFoodLocallyGrown = 1;

    %% Initialize Stores External to the Habitat and BPC
    O2Store = StoreImpl('O2 Store','Environmental',1000000000,100000);
    O2StoreMAV = StoreImpl('O2 Store MAV','Environmental',1000000000,0);
    CO2Store = StoreImpl('CO2 Store','Environmental',1000000000,1000000);
    N2Store = StoreImpl('N2 Store', 'Environmental',1000000000,100000);
    H2Store = StoreImpl('H2 Store', 'Environmental',1000000,0);
    CH4Store = StoreImpl('CH4Store','Environmental',100000,0);
    MainPowerStore = StoreImpl('Power','Material',10^1000,10^1000);
    DirtyWaterStore_outside = StoreImpl('Dirty Water Store Outside','Material',↙
1000000000,0);
    GreyWaterStore_outside = StoreImpl('Grey Water Store Outside', 'Material',↙
1000000000,0);
    GreyWaterStore_BPC = StoreImpl('Grey Water Store BPC', 'Material',↙
1000000000,300000);
    GreyWaterStore_MAV = StoreImpl('Grey Water Store MAV','Material',1000000000,0);
    PotableWaterStore_MAV = StoreImpl('Potable Water Store MAV','Material',↙
1000000000,100000);

    %% Initialize Stores for the Habitat and BPC
    CarriedFood = Wheat;
    AvgCaloriesPerCrewPerson = 3040.1;
    StockedDaysOfFood = 2*ceil(missionDurationInHours/24);
    CarriedCalories = numberOfCrew*AvgCaloriesPerCrewPerson*StockedDaysOfFood;
    CarriedTotalMass = CarriedCalories/CarriedFood.CaloriesPerKilogram;
    initialfood = FoodMatter(Wheat,CarriedTotalMass,CarriedFood.↙
EdibleFreshBasisWaterContent*CarriedTotalMass); % xmlFoodStoreLevel is declared within↙
the createFoodStore method within SimulationInitializer.java
    CarriedFoodStore = FoodStoreImpl(CarriedTotalMass,initialfood);
    PotableWaterStore = StoreImpl('Potable Water Store', 'Material', 3000000, 300000);
    GreyWaterStore = StoreImpl('Grey H2O','Material',1000000,0);
    DirtyWaterStore = StoreImpl('Dirty H2O','Material',1000000,0);
    DryWasteStore = StoreImpl('Dry Waste','Material',1000000,0);
    BPCDryWasteStore = StoreImpl('BPC Dry Waste','Material',1000000,0);
    SolidWasteStore = StoreImpl('Solid Waste Store','Material', 1000000,0);
    BiomassStore = BiomassStoreImpl(100000);

    %% Initialize Air Parameters for the Habitat and BPC
    dailyLeakagePercentage = 0.05;
    hourlyLeakagePercentage = 100*(1-(1-dailyLeakagePercentage/100)^(1/24));
    TotalAtmPressureTargeted = 55.2;
    o2fireRiskMolarFraction = 0.5;
    volume = habitatVolumeComfortness*(1-(exp(1)^(-missionDurationInDays/20)))↙
*1000*numberOfCrew;
    TargetCO2MolarFraction = 0.0004;
    TargetN2MolarFraction =  (1-0.32-0.0004-0.01-0.004);
    TargetWaterFraction = 0.004;
    TargetOtherFraction = 0.01;
    TargetO2MolarFraction = 0.32;
```

```
    targetCO2conc = 1200*1E-6;
    BPCvolume = 1000*1000;

    MarsHab = SimEnvironmentImpl('Mars Habitat', TotalAtmPressureTargeted,volume,↙
TargetO2MolarFraction,TargetCO2MolarFraction,TargetN2MolarFraction,↙
TargetWaterFraction,...
        TargetOtherFraction, hourlyLeakagePercentage, PotableWaterStore, GreyWaterStore,↙
DirtyWaterStore, DryWasteStore, CarriedFoodStore, o2fireRiskMolarFraction,↙
SolidWasteStore);

    BPC = BPCSimEnvironmentImpl('Biomass Production Chamber',TotalAtmPressureTargeted,↙
BPCvolume,TargetO2MolarFraction,targetCO2conc,(1-0.32-targetCO2conc-TargetOtherFraction-↙
TargetWaterFraction),TargetWaterFraction,TargetOtherFraction,hourlyLeakagePercentage,↙
PotableWaterStore,GreyWaterStore,...
        DirtyWaterStore,BPCDryWasteStore,CarriedFoodStore,o2fireRiskMolarFraction,↙
SolidWasteStore);

    %% Initialize MAV
    mav = MAV_OLD(numberOfCrew, missionDurationInHours,BOR,BOR);

    %% Initialize Crew Schedule

    crewSchedule = crewScheduler_new(missionDurationInHours,MarsHab);

    %% Initialize Crew Persons
    astro1 = CrewPersonImpl3('Crew 1',35,82,'Male',crewSchedule,externalStoreList,↙
marsHabStoreList, BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
    astro2 = CrewPersonImpl3('Crew 2',35,82,'Male',circshift(crewSchedule,1),↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);
    astro3 = CrewPersonImpl3('Crew 3',35,82,'Male',circshift(crewSchedule,2),↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);
    astro4 = CrewPersonImpl3('Crew 4',35,82,'Male',circshift(crewSchedule,3),↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);

    %% Initialize PCA (Pressure Control Assembly)
    MarsHabPCA = ISSinjectorImpl(TotalAtmPressureTargeted,TargetO2MolarFraction,O2Store,↙
N2Store, MarsHab,'PCA',externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s); % Assume Oxygen
    MarsHabPCA.UpperPPO2PercentageLimit = o2fireRiskMolarFraction;

    %% Initialize CCAA (Common Cabin Air Assembly)
    MarsHabCCAA = ISSDehumidifierImpl(MarsHab,GreyWaterStore_outside,MainPowerStore,↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);

    %% Initialize CDRA (Carbon Dioxide Removal Assembly)
    MarsHabCDRA1 = ISSVCCRLinearImpl(MarsHab, MarsHab,MarsHab,CO2Store,↙
MainPowerStore,'Nominal',externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
    MarsHabCDRA2 = ISSVCCRLinearImpl(MarsHab, MarsHab,MarsHab,CO2Store,↙
MainPowerStore,'Nominal',externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
    MarsHabCDRA3 = ISSVCCRLinearImpl(MarsHab, MarsHab,MarsHab,CO2Store,↙
MainPowerStore,'Nominal',externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
```

```
    %% Initialize Laundry Machine
    MarsHablaundry = laundryOps([astro1 astro2 astro3 astro4], MarsHab,↙
GreyWaterStore_outside,externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize WHC (Waste and Hygiene Compartment)
    MarsHabwhc = WHC(astro1, MarsHab, GreyWaterStore_outside, DirtyWaterStore_outside,↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);

    %% Initialize WPA/UPA
    MarsHabwpaupa = ISSWaterRSLinearImplValidateWithISS(MarsHab,DirtyWaterStore_outside,↙
GreyWaterStore_outside,GreyWaterStore_outside, MarsHab.DryWasteStore,MarsHab.↙
PotableWaterStore, MainPowerStore,externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
    MAVwpaupa = MAVISSWaterRSLinearImplValidateWithISS(MarsHab,GreyWaterStore_MAV,↙
MarsHab.DryWasteStore,PotableWaterStore_MAV, MainPowerStore,externalStoreList,↙
marsHabStoreList, BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize Water Electrolyzers for the Habitation Module and MAV Prop Generation
    HwaterElectrolyzer = ISSOGAwithRSA(TotalAtmPressureTargeted,TargetO2MolarFraction,↙
MarsHab,MarsHab.PotableWaterStore,MainPowerStore,H2Store,externalStoreList,↙
marsHabStoreList, BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
    MAVwaterElectrolyzer = OGAforMAVprop(PotableWaterStore_MAV, MarsHab, mav.↙
LOXdayReqProdRate,mav.LCH4dayReqProdRate,O2StoreMAV,H2Store,externalStoreList,↙
marsHabStoreList, BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize Sabatier Reactor for MAV Prop Generation
    MAVsabatierReactor = SabatierforMAVprop(MarsHab,H2Store,CO2Store,GreyWaterStore_MAV,↙
CH4Store,MainPowerStore,externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize Wheat Crop Growth
    growthFactor = numberOfCrew/4;
    WheatShelf = ShelfImpl3(CarriedFood,156.685,BPC,GreyWaterStore_BPC,MarsHab.↙
PotableWaterStore,MainPowerStore,BiomassStore,0,externalStoreList, marsHabStoreList,↙
BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize Staggered Shelves
    WheatShelves = ShelfStagger(WheatShelf,WheatShelf.Crop.TimeAtCropMaturity,0,↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);

    %% Initialize FoodProcessor (raw biomass --> edible food)
    FoodProcessor = FoodProcessorImpl(BPC,externalStoreList, marsHabStoreList,↙
BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);
    FoodProcessor.BiomassConsumerDefinition = ResourceUseDefinitionImpl(BiomassStore,↙
1000,1000);
    FoodProcessor.PowerConsumerDefinition = ResourceUseDefinitionImpl(MainPowerStore,↙
1000,1000);
    FoodProcessor.FoodProducerDefinition = ResourceUseDefinitionImpl(MarsHab.FoodStore,↙
1000,1000);
    FoodProcessor.WaterProducerDefinition = ResourceUseDefinitionImpl(GreyWaterStore_BPC,↙
1000,1000);
    FoodProcessor.DryWasteProducerDefinition = ResourceUseDefinitionImpl(BPC.↙
DryWasteStore,1000,1000);
```

```
    %% Initialize BPC PCA
    BPCPCA = BPCISSinjectorImpl(TotalAtmPressureTargeted,TargetO2MolarFraction,O2Store,↙
N2Store,BPC,'PCA',externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);
    BPCPCA.UpperPPO2PercentageLimit = o2fireRiskMolarFraction;

    %% Initialize BPC CCAA
    BPCCCAA = BPCISSDehumidifierImpl(BPC,GreyWaterStore_BPC,MainPowerStore,↙
externalStoreList, marsHabStoreList, BPCStoreList, externalStoreList_s,↙
marsHabStoreList_s, BPCStoreList_s);

    %% Initialize BPC ORA (Oxygen Removal Assembly)
    BPCORA = O2extractor(BPC,TotalAtmPressureTargeted,TargetO2MolarFraction,↙
O2Store,'Molar Fraction',externalStoreList, marsHabStoreList, BPCStoreList,↙
externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize BPC CO2 Injector
    BPCco2Injector = CO2Injector(BPC,CO2Store,targetCO2conc,CO2Store,externalStoreList,↙
marsHabStoreList, BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initialize Condensed Water Removal System
    BPCWaterExtractor = CondensedWaterRemover(BPC,GreyWaterStore_BPC,externalStoreList,↙
marsHabStoreList, BPCStoreList, externalStoreList_s, marsHabStoreList_s, BPCStoreList_s);

    %% Initiate Time Loop
    MarsHabPCAaction = zeros(4,1);
    BPCPCAaction = zeros(4,1);
    waterElectrolyzeraction = zeros(1,1);
    simtime = missionDurationInHours;

    for i = 1:simtime+1
        % Exit time loop and return 0 water demand if any crew member is
        % dead
        if astro1.alive == 0 || astro2.alive == 0|| astro3.alive ==0 || astro4.alive ==0
            BPCWater = 0; MAVWater = 0; ECLSWater = 0; TotalWaterReq = 0;
            return
        end

        % Store water levels (State update)
        greywaterlevel_bpc(i) = GreyWaterStore_BPC.currentLevel;
        potablewaterlevel_mav(i) = PotableWaterStore_MAV.currentLevel;
        MarsHabpotablewaterlevel(i) = MarsHab.PotableWaterStore.currentLevel;

        % Progress to the next hour (Time Tick)
        MarsHab.tick(0);
        BPC.tick(0);
        [waterElectrolyzeraction(:,i+1)] = HwaterElectrolyzer.tick↙
(waterElectrolyzeraction(:,i),0);
        MAVwaterElectrolyzer.tick(0,waterLeak);
        MAVsabatierReactor.tick(0,waterLeak);
        MAVwpaupa.tick(0,waterLeak);
        BPCORA.tick(0);
        MarsHabCDRA1.tick(0,0);
        MarsHabCDRA2.tick(0,0);
        MarsHabCDRA3.tick(0,0);
        MarsHablaundry.tick(0,waterLeak);
        MarsHabwpaupa.tick(0,waterLeak);
        WheatShelves.tick(waterLeak);
```

```
        BPCco2Injector.tick(0);
        BPCCCAAoutput(i) = BPCCCAA.tick(0,waterLeak);
        BPCWaterExtractor.tick(0,waterLeak);
        FoodProcessor.tick(0,waterLeak);
        astro1.tick(0);
        astro2.tick(0);
        astro3.tick(0);
        astro4.tick(0);
        MarsHabCCAAoutput(i) = MarsHabCCAA.tick(0,waterLeak);
        MarsHabwhc.tick(0,waterLeak);
        [MarsHabPCAaction(:,i+1)] = MarsHabPCA.tick(MarsHabPCAaction(:,i),0);
        [BPCPCAaction(:,i+1)] = BPCPCA.tick(BPCPCAaction(:,i),0);
    end

    %% Water Demand Calculation
    BPCWater = max(greywaterlevel_bpc)- min(greywaterlevel_bpc);
    MAVWater = potablewaterlevel_mav(1) - potablewaterlevel_mav(end);
    ECLSWater= MarsHabpotablewaterlevel(1) - MarsHabpotablewaterlevel(end);
    TotalWaterReq = BPCWater + MAVWater + ECLSWater;
end
```

Appendix D

Code Listing: Beta Distribution Fitting

```
%% Yana Charoenboonvivat | 5/4/2024
%% Fit Beta Distribution to Data
[x_4,a_4,b_4,y_4,M_4,H_4,n_4] = betadist(MC_2000_stat4CM.totalWaterVec,50);
[x_8,a_8,b_8,y_8,M_8,H_8,n_8] = betadist(MC_2000_stat8CM.totalWaterVec,45);
[x_12,a_12,b_12,y_12,M_12,H_12,n_12] = betadist(MC_2000_stat12CM.totalWaterVec,50);
[x_16,a_16,b_16,y_16,M_16,H_16,n_16] = betadist(MC_2000_stat16CM.totalWaterVec,50);
[x_20,a_20,b_20,y_20,M_20,H_20,n_20] = betadist(MC_2000_stat20CM.totalWaterVec,45);

%% Plot
figure
x0=10;
y0=10;
width=850;
height=1300;
set(gcf,'position',[x0,y0,width,height])

subplot(3,2,1)
title('4 Crew Members on a 790 mission')
ax = gca;
yyaxis left
bar(0:(1/n_4):1-(1/n_4),(H_4.Values/length(x_4))*n_4,1)
ylim([0,2])
ylabel('Normalized Frequency','Color',[0 0.4470 0.7410])
xlabel('Normalized Water Demand')
ax.YColor = [0 0.4470 0.7410];
yyaxis right
[B,I] = sort(x_4);
plot(sort(x_4),y_4(I),'r',LineWidth=2)
ylim([0,2])
ylabel('Beta Distribution PDF','Color', "red")
ax.YColor = "red";
set(ax,'FontSize',18)
set(ax, 'FontName', 'Times New Roman')

subplot(3,2,2)
title('8 Crew Members on a 790 mission')
ax = gca;
yyaxis left
bar(0:(1/n_8):1-(1/n_8),(H_8.Values/length(x_8))*n_8,1)
ylim([0,2])
ylabel('Normalized Frequency','Color',[0 0.4470 0.7410])
xlabel('Normalized Water Demand')
ax.YColor = [0 0.4470 0.7410];
yyaxis right
[B,I] = sort(x_8);
plot(sort(x_8),y_8(I),'r',LineWidth=2)
ylim([0,2])
ylabel('Beta Distribution PDF','Color', "red")
ax.YColor = "red";
set(ax,'FontSize',18)
set(ax, 'FontName', 'Times New Roman')

subplot(3,2,3)
title('12 Crew Members on a 790 mission')
ax = gca;
yyaxis left
bar(0:(1/n_12):1-(1/n_12),(H_12.Values/length(x_12))*n_12,1)
ylim([0,2])
```

```
ylabel('Normalized Frequency','Color',[0 0.4470 0.7410])
xlabel('Normalized Water Demand')
ax.YColor = [0 0.4470 0.7410];
yyaxis right
[B,I] = sort(x_12);
plot(sort(x_12),y_12(I),'r',LineWidth=2)
ylim([0,2])
ylabel('Beta Distribution PDF','Color', "red")
ax.YColor = "red";
set(ax,'FontSize',18)
set(ax, 'FontName', 'Times New Roman')

subplot(3,2,4)
title('16 Crew Members on a 790 mission')
ax = gca;
yyaxis left
bar(0:(1/n_16):1-(1/n_16),(H_16.Values/length(x_16))*n_16,1)
ylim([0,2])
ylabel('Normalized Frequency','Color',[0 0.4470 0.7410])
xlabel('Normalized Water Demand')
ax.YColor = [0 0.4470 0.7410];
yyaxis right
[B,I] = sort(x_16);
plot(sort(x_16),y_16(I),'r',LineWidth=2)
ylim([0,2])
ylabel('Beta Distribution PDF','Color', "red")
ax.YColor = "red";
set(ax,'FontSize',18)
set(ax, 'FontName', 'Times New Roman')

subplot(3,2,5)
title('20 Crew Members on a 790 mission')
ax = gca;
yyaxis left
% histogram(x_20,45,"FaceColor",[0 0.4470 0.7410],"FaceAlpha",1)
bar(0:(1/n_20):1-(1/n_20),(H_20.Values/length(x_20))*n_20,1)
ylim([0,2])
ylabel('Normalized Frequency','Color',[0 0.4470 0.7410])
xlabel('Normalized Water Demand')
ax.YColor = [0 0.4470 0.7410];
yyaxis right
[B,I] = sort(x_20);
plot(sort(x_20),y_20(I),'r',LineWidth=2)
ylabel('Beta Distribution PDF','Color', "red")
ylim([0,2])
ax.YColor = "red";
set(ax,'FontSize',18)
set(ax, 'FontName', 'Times New Roman')

%% betadist: Function to fit a beta distribution to the dataset by minimizing the %Root↙
Mean Square Error
function [x, alpha, beta,y,M,H,n] = betadist(input,n)
    x = rescale(input);
    figure
    H = histogram(x,n);
    H_Values = H.Values;
    V = [];
    for b = 1:0.1:6
```

```
        for a = 1:0.1:6
            y = betapdf(x,a,b);
            e_rms = rmse(y(1:(length(x)/n):length(x)),((H_Values/length(x))*n)');
            vec = [a b e_rms];
            V = [V;vec];
        end
    end
    [M,I] = min(V(:,3));
    alpha = V(I,1);
    beta = V(I,2);
    y = betapdf(x,alpha,beta);
end
```

References

[1] *U.S. Senate Committee on Commerce, Science, & Transportation",* Mar. 2024. URL: https://www.commerce.senate.gov/services/files/CFC99CC6-CE84-4B1A-8BBF-8D2E84BD7965 (visited on 03/15/2023).

[2] National Aeronautics and Space Administration, *NASA's Journey to Mars - NASA*, en-US, Dec. 2014. URL: https://www.nasa.gov/image-article/nasas-journey-mars/ (visited on 03/08/2024).

[3] National Aeronautics and Space Administration, *NASA's Moon to Mars Strategy and Objectives Development.* URL: https://www.nasa.gov/wp-content/uploads/2023/04/m2m_strategy_and_objectives_development.pdf (visited on 04/10/2024).

[4] Lunar and Planetary Institute, *First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars will be conducted October 27-30, 2015, in Houston, Texas.* URL: https://www.hou.usra.edu/meetings/explorationzone2015/ (visited on 03/08/2024).

[5] B. Bussey and R. Davis, *Human Landing Sites Study (HLS2) Overview*, en.

[6] T. P. Polsgrove, T. K. Percy, M. Rucker, and H. D. Thomas, "Update to Mars Ascent Vehicle Design for Human Exploration," in *2019 IEEE Aerospace Conference*, ISSN: 1095-323X, Mar. 2019, pp. 1–15. DOI: 10.1109/AERO.2019.8741709. URL: https://ieeexplore.ieee.org/abstract/document/8741709 (visited on 03/08/2024).

[7] *Mars Water Resource Maps - MWR.* URL: https://ammos.nasa.gov/marswatermaps/?mission=MWR (visited on 03/08/2024).

[8] National Aeronautics and Space Administration, *Crew Health and Performance Exploration Analog*, en-US, Mar. 2024. URL: https://www.nasa.gov/humans-in-space/chapea/ (visited on 04/10/2024).

[9] S. Do, "Towards Earth independence - tradespace exploration of long-duration crewed Mars surface system architectures," eng, Accepted: 2016-12-05T19:10:21Z, Thesis, Massachusetts Institute of Technology, 2016. URL: https://dspace.mit.edu/handle/1721.1/105554 (visited on 03/08/2024).

[10] S. Do, A. Owens, K. Ho, S. Schreiner, and O. de Weck, "An independent assessment of the technical feasibility of the Mars One mission plan – Updated analysis," *Acta Astronautica*, vol. 120, pp. 192–228, Mar. 2016, ISSN: 0094-5765. DOI: 10.1016/j.actaastro.2015.11.025. URL: https://www.sciencedirect.com/science/article/pii/S0094576515004294 (visited on 03/08/2024).

[11] S. Do, A. Owens, and O. de Weck, "HabNet – An Integrated Habitation and Supportability Architecting and Analysis Environment."

[12] J. Chambliss, I. Stambaugh, and M. Moore, "Resource Tracking Model Updates and Trade Studies," NTRS Author Affiliations: NASA Johnson Space Center, L-3 Communications Corp. NTRS Report/Patent Number: ICES-2016-434 NTRS Document ID: 20160005447 NTRS Research Center: Johnson Space Center (JSC), Vienna, Jul. 2016. URL: https://ntrs.nasa.gov/citations/20160005447 (visited on 03/08/2024).

[13] S. Do and T. Ishimatsu, *Water Demand Study Status Meeting*, (Internal Briefing (Unpublished)), NASA Jet Propulsion Laboratory, Jan. 2021.

[14] J. Parodi, S. Trieu, J. Young, G. Pace, K. R. Martin, T. M. J. Richardson, and J. M. Lee, "Performances of the Heat Melt Compactor System in Various Operational Scenarios," NTRS Author Affiliations: Bionetics (United States), Logyx LLC, Wyle (United States), Ames Research Center NTRS Report/Patent Number: ICES-2020-326 NTRS Document ID: 20205004360 NTRS Research Center: Ames Research Center (ARC), Virtual, Jul. 2020. URL: https://ntrs.nasa.gov/citations/20205004360 (visited on 04/12/2024).

[15] US EPA, *How Does Anaerobic Digestion Work?* en, Overviews and Factsheets, Mar. 2019. URL: https://www.epa.gov/agstar/how-does-anaerobic-digestion-work (visited on 04/12/2024).

[16] D. Williams, *Mars Fact Sheet*, Jan. 2024. URL: https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html (visited on 03/08/2024).

[17] S. Goudarzi and K. C. Ting, "Top Level Modeling of Crew Component of ALSS," English, SAE International, Warrendale, PA, SAE Technical Paper 1999-01-2042, Jul. 1999, ISSN: 0148-7191, 2688-3627. DOI: 10.4271/1999-01-2042. URL: https://www.sae.org/publications/technical-papers/content/1999-01-2042/ (visited on 03/08/2024).

[18] M. K. Ewert, T. T. Chen, and C. D. Powell, "Life Support Baseline Values and Assumptions Document," en, *Life Support*,

[19] M. K. Ewert, M. E. Downs, and J. F. Keener, "Developing a Daily Metabolic Rate Profile for Human Exploration Missions," NTRS Author Affiliations: Johnson Space Center, Jacobs Technology, Inc. NTRS Document ID: 20205010692 NTRS Research Center: Johnson Space Center (JSC), Virtual. URL: https://ntrs.nasa.gov/citations/20205010692 (visited on 03/08/2024).

[20] National Aeronautics and Space Administration, *Mars Facts*, en. URL: https://science.nasa.gov/mars/facts/ (visited on 03/08/2024).

[21] M. K. Ewert and C. Stromgren, "Astronaut Mass Balance for Long Duration Missions," NTRS Author Affiliations: NASA Johnson Space Center, Binera NTRS Report/Patent Number: ICES-2019-126 NTRS Document ID: 20190027563 NTRS Research Center: Johnson Space Center (JSC), Boston, MA, Jul. 2019. URL: https://ntrs.nasa.gov/citations/20190027563 (visited on 03/08/2024).

[22] L. Carter, J. Williamson, C. A. Brown, J. Bazley, D. Gazda, R. Schaezler, F. Thomas, and S. Molina, "Status of ISS Water Management and Recovery," en,

[23] *List of International Space Station expeditions*, en, Page Version ID: 1217360043, Apr. 2024. URL: https://en.wikipedia.org/w/index.php?title=List_of_International_Space_Station_expeditions&oldid=1217360043 (visited on 04/05/2024).

[24] Eurpoean Space Agency, *Environment Control and Life Support System (ECLSS)*, English. URL: http://wsn.spaceflight.esa.int/docs/Factsheets/30%20ECLSS%20LR.pdf (visited on 04/05/2024).

[25] Whirlpool, *How Much Water Does a Washing Machine Use?* en-US. URL: https://www.whirlpool.com/blog/washers-and-dryers/he-washing-machine-water-usage.html (visited on 03/08/2024).

[26] T. Ishimatsu, *MAV Model*, (Internal (Unpublished)).

[27] F. F. Jeng, S. Lafuse, F. D. Smith, S.-D. Lu, J. C. Knox, M. L. Campbell, T. D. Scull, and S. Green, "Analyses of the Integration of Carbon Dioxide Removal Assembly, Compressor, Accumulator and Sabatier Carbon Dioxide Reduction Assembly," English, SAE International, Warrendale, PA, SAE Technical Paper 2004-01-2496, Jul. 2004, ISSN: 0148-7191, 2688-3627. DOI: 10.4271/2004-01-2496. URL: https://www.sae.org/publications/technical-papers/content/2004-01-2496/ (visited on 03/08/2024).

[28] J. C. Knox, M. Campbell, K. Murdoch, L. A. Miller, and F. Jeng, "Integrated Test and Evaluation of a 4-Bed Molecular Sieve (4BMS) Carbon Dioxide Removal System (CDRA), Mechanical Compressor Engineering Development Unit (EDU), and Sabatier Engineering Development Unit (EDU)," English, SAE International, Warrendale, PA, SAE Technical Paper 2005-01-2864, Jul. 2005, ISSN: 0148-7191, 2688-3627. DOI: 10.4271/2005-01-2864. URL: https://www.sae.org/publications/technical-papers/content/2005-01-2864/ (visited on 03/08/2024).

[29] G. of Ontario, *Supplemental carbon dioxide in greenhouses*, en, Jul. 2022. URL: http://www.ontario.ca/page/supplemental-carbon-dioxide-greenhouses (visited on 03/08/2024).

[30] M. S. Anderson, M. K. Ewert, and J. F. Keener, *Life Support Baseline Values and Assumptions Document*, en.

[31] A. V. Arundel, E. M. Sterling, J. H. Biggin, and T. D. Sterling, "Indirect health effects of relative humidity in indoor environments.," *Environmental Health Perspectives*, vol. 65, pp. 351–361, Mar. 1986, ISSN: 0091-6765. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1474709/ (visited on 03/08/2024).

[32] M. Bravo, *Ideal conditions for wheat quality. What does this mean?* en-US, May 2022. URL: https://plant-pest-advisory.rutgers.edu/ideal-conditions-for-wheat-quality-what-does-this-mean/ (visited on 03/08/2024).

[33] National Aeronautics and Space Administration, "Recommendations for Exploration: Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group," NASA Exploration Atmospheres Working Group, NASA Johnson Space Center, Houston, Tech. Rep., 2010. URL: https://www.nasa.gov/wp-content/uploads/2023/03/henninger-8.2-34-atm-tp216134-2010.pdf.

[34] D. Ward, *Composition of the atmosphere*. URL: http://www.atmo.arizona.edu/students/courselinks/fall16/atmo336/lectures/sec1/composition.html (visited on 03/08/2024).

[35] Y. Charoenboonvivat, O. L. De Weck, and S. Do, "Enhancing HabNet to Support Water Demand Estimates for Human and Scientific Exploration of Mars," in *ASCEND 2023*, ser. ASCEND, American Institute of Aeronautics and Astronautics, Oct. 2023. DOI: 10.2514/6.2023-4760. URL: https://arc.aiaa.org/doi/10.2514/6.2023-4760 (visited on 03/08/2024).

[36] J. Celentano, D. Amorelli, and G. Freeman, "ESTABLISHING A HABITABILITY INDEX FOR SPACE STATIONS AND PLANETARY BASES," en, in *Manned Space Laboratory Conference*, Los Angeles,CA,U.S.A.: American Institute of Aeronautics and Astronautics, May 1963. DOI: 10.2514/6.1963-139. URL: http://arc.aiaa.org/doi/10.2514/6.1963-139 (visited on 04/04/2024).

[37] M. Gaskill, *NASA Achieves Water Recovery Milestone on International Space Station*, en-US, Aug. 2023. URL: https://www.nasa.gov/missions/station/iss-research/nasa-achieves-water-recovery-milestone-on-international-space-station/ (visited on 03/08/2024).

[38] US EPA, *How We Use Water*, en, Overviews and Factsheets, Jan. 2017. URL: https://www.epa.gov/watersense/how-we-use-water (visited on 03/08/2024).

[39] C. Stromgren, C. Burke, J. Cho, M. A. Rucker, and M. Garcia-Robles, "Defining the Required Net Habitable Volume for Long-Duration Exploration Missions," in *ASCEND 2020*, ser. ASCEND, American Institute of Aeronautics and Astronautics, Nov. 2020. DOI: 10.2514/6.2020-4032. URL: https://arc.aiaa.org/doi/10.2514/6.2020-4032 (visited on 03/08/2024).

[40] OECD, "Water Governance in Cities," Paris, Tech. Rep., 2016. URL: https://read.oecd-ilibrary.org/governance/water-governance-in-cities_9789264251090-en (visited on 03/08/2024).

[41] National Aeronautics and Space Administration, *Zero-Boil-Off Tank Experiments to Enable Long-Duration Space Exploration*, en. URL: https://science.nasa.gov/science-research/science-enabling-technology/zero-boil-off-tank-experiments-to-enable-long-duration-space-exploration/ (visited on 04/05/2024).

[42] S. E. Technologies, *Liquid Oxygen (LOX) Systems for Ozone Generation*, en-US. URL: https://spartanwatertreatment.com/ozone-generator-lox-systems/ (visited on 03/08/2024).

[43] A. Reuther, J. Kepner, C. Byun, *et al.*, "Interactive Supercomputing on 40,000 Cores for Machine Learning and Data Analysis," in *2018 IEEE High Performance extreme Computing Conference (HPEC)*, ISSN: 2377-6943, Sep. 2018, pp. 1–6. DOI: 10.1109/HPEC.2018.8547629. URL: https://ieeexplore.ieee.org/document/8547629 (visited on 04/09/2024).

[44] National Aeronautics and Space Administration, *International Space Station Astronaut Record Holders*, en-US, Section: Humans in Space, Sep. 2023. URL: https://www.nasa.gov/international-space-station/space-station-astronaut-record-holders/ (visited on 04/14/2024).

[45] M. D. McKay, R. J. Beckman, and W. J. Conover, "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," *Technometrics*, vol. 21, no. 2, pp. 239–245, 1979, Publisher: [Taylor & Francis, Ltd., American Statistical Association, American Society for Quality], ISSN: 0040-1706. DOI: 10.2307/1268522. URL: https://www.jstor.org/stable/1268522 (visited on 04/14/2024).

[46] J. Menčík, "Latin Hypercube Sampling," en, in *Concise Reliability for Engineers*, IntechOpen, Apr. 2016, ISBN: 978-953-51-2278-4. DOI: 10.5772/62370. URL: https://www.intechopen.com/chapters/50120 (visited on 04/14/2024).

[47] G. A. Morgan, N. E. Putzig, M. R. Perry, *et al.*, "Availability of subsurface water-ice resources in the northern mid-latitudes of Mars," en, *Nature Astronomy*, vol. 5, no. 3, pp. 230–236, Mar. 2021, Publisher: Nature Publishing Group, ISSN: 2397-3366. DOI: 10.1038/s41550-020-01290-z. URL: https://www.nature.com/articles/s41550-020-01290-z (visited on 05/01/2024).

[48] D. M. H. Baker and J. W. Head, "Extensive Middle Amazonian mantling of debris aprons and plains in Deuteronilus Mensae, Mars: Implications for the record of mid-latitude glaciation," *Icarus*, vol. 260, pp. 269–288, Nov. 2015, ISSN: 0019-1035. DOI: 10.1016/j.icarus.2015.06.036. URL: https://www.sciencedirect.com/science/article/pii/S0019103515002882 (visited on 05/01/2024).

[49] A. V. Pathare, W. C. Feldman, T. H. Prettyman, and S. Maurice, "Driven by excess? Climatic implications of new global mapping of near-surface water-equivalent hydrogen on Mars," en, *Icarus*, vol. 301, pp. 97–116, Feb. 2018, ISSN: 00191035. DOI: 10.1016/j.icarus.2017.09.031. URL: https://linkinghub.elsevier.com/retrieve/pii/S0019103517303664 (visited on 05/01/2024).

[50] N. E. Putzig, G. A. Morgan, H. G. Sizemore, *et al.*, "Ice Resource Mapping on Mars," en, in *Handbook of Space Resources*, V. Badescu, K. Zacny, and Y. Bar-Cohen, Eds., Cham: Springer International Publishing, 2023, pp. 583–616, ISBN: 978-3-030-97913-3. DOI: 10.1007/978-3-030-97913-3_16. URL: https://doi.org/10.1007/978-3-030-97913-3_16 (visited on 05/01/2024).

[51] T. P. S. Institute, *Subsurface Water Ice Mapping*. URL: https://swim.psi.edu/SWIM2Products.php (visited on 05/01/2024).

[52] A. Bramson, C. Andres, J. Bapst, *et al.*, "Mid-Latitude Ice on Mars: A Science Target for Planetary Climate Histories and an Exploration Target for In Situ Resources," en, *Bulletin of the AAS*, vol. 53, no. 4, Mar. 2021. DOI: 10.3847/25c2cfeb.cc90422d. URL: https://baas.aas.org/pub/2021n4i115 (visited on 05/01/2024).

[53] National Aeronautics and Space Administration, *NASA's Lunar Surface Innovation Initiative - NASA*, en-US. URL: https://www.nasa.gov/space-technology-mission-directorate/lunar-surface-innovation-initiative/ (visited on 05/01/2024).

[54] National Aeronautics and Space Administration, *Intuitive Machines 2 (PRIME 1)*. URL: https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=PRIME-1 (visited on 05/01/2024).

[55] Y. Liu, C. Wang, Y. Pang, *et al.*, "Water extraction from icy lunar regolith by drilling-based thermal method in a pilot-scale unit," *Acta Astronautica*, vol. 202, pp. 386–399, Jan. 2023, ADS Bibcode: 2023AcAau.202..386L, ISSN: 0094-5765. DOI: 10.1016/j.actaastro.2022.11.002. URL: https://ui.adsabs.harvard.edu/abs/2023AcAau.202..386L (visited on 05/01/2024).

[56] D. L. Linne and J. E. Kleinhenz, "Extraction and Capture of Water from Martian Regolith Experimental Proof-of-Concept," en, in *8th Symposium on Space Resource Utilization*, San Diego, California, USA: American Institute of Aeronautics and Astronautics, Jan. 2016, ISBN: 978-1-62410-391-9. DOI: 10.2514/6.2016-0226. URL: http://arc.aiaa.org/doi/10.2514/6.2016-0226 (visited on 05/01/2024).

[57] SpaceX, *SpaceX - Starship*. URL: https://www.spacex.com/vehicles/starship/ (visited on 05/01/2024).

[58] F. Forget, F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand, M. Collins, S. R. Lewis, P. L. Read, and J.-P. Huot, "Improved general circulation models of the Martian atmosphere from the surface to above 80 km," *Journal of Geophysical Research*, vol. 104, pp. 24 155–24 176, Oct. 1999, ADS Bibcode: 1999JGR...10424155F, ISSN: 0148-0227. DOI: 10.1029/1999JE001025. URL: https://ui.adsabs.harvard.edu/abs/1999JGR...10424155F (visited on 05/01/2024).

[59] E. Millour, F. Forget, A. Spiga, M. Vals, V. Zakharov, L. Montabone, F. Lefèvre, F. Montmessin, and P. L. Read, "THE MARS CLIMATE DATABASE (VERSION 5.3)," en, 2018.

[60] National Aeronautics and Space Administration, *Fission Surface Power*, en-US, Section: Technology Demonstration Missions Program. URL: https://www.nasa.gov/tdm/fission-surface-power/ (visited on 04/12/2024).

[61] M. A. Rucker, *Surface Power for Mars*, Dec. 2016. URL: https://ntrs.nasa.gov/api/citations/20160014032/downloads/20160014032.pdf.

[62] National Aeronautics and Space Administration, *Environmental Control & Life Support System (ECLSS): Human-Centered Approach*, en.