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Master's Thesis
Concept of Operations for the Gateway and a Lunar Base

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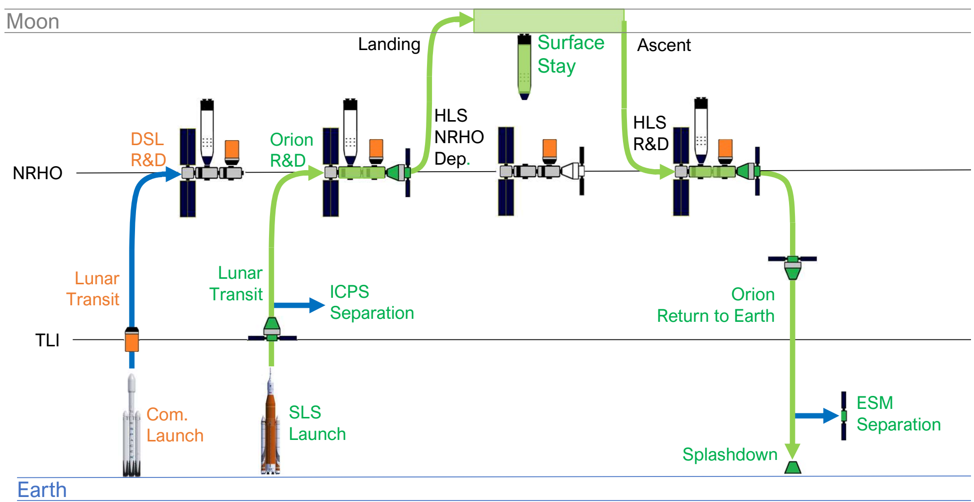

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Zusammenfassung

In naher Zukunft werden die Artemis-Missionen Menschen auf den Mond zurückbringen, mit dem Ziel dort zu bleiben. Um diese Mondpräsenz zu ermöglichen, wird eine Raumstation in der cis-lunaren Umlaufbahn, genannt Gateway, errichtet. Gateway wird als Forschungsplattform und Drehscheibe zwischen Erde und Mond fungieren. In dieser Arbeit wird ein Betriebskonzept, für die Phase nach dem Aufbau dieser Station, erstellt.
Zunächst wird der Stand der Technik in Bezug auf zukünftige Mondmissionen untersucht, um Randbedingungen zur Erstellung eines Missionskonzepts zu ermitteln. Noch offene Fragestellungen, wie die Wahl des Lebenserhaltungssystem des Gateways, die Nutzlastkapazität der Versorgungsraumschiffen oder das Lebenserhaltungssystem des Landemoduls, werden bewertet und die praktikabelste Option gewählt.
Um eine breitere Sichtweise über das Konzept zu erhalten, werden iterativ vier verschiedene Szenarien erstellt. Die vier Szenarien unterscheiden sich in ihrer Dauer und ihrem Lebenserhaltungssystem. Bei dem ersten Szenario handelt es sich um eine zeitlich begrenzte kampagnenartige Mission mit einem regenerativen Lebenserhaltungssystem. Das zweite Szenario ist von gleicher Dauer wie das erste, mit einer Mission im Kampagnenstil, verwendet aber ein nicht-regeneratives Lebenserhaltungssystem. Das dritte und vierte Szenario zielt darauf ab das ein permanent bemanntes Gateway zu ermöglichen. Die Lebenserhaltungssysteme werden ebenfalls alterniert, daher hat das dritte Szenario ein regeneratives und das vierte ein nicht regeneratives System. Alle Szenarien beinhalten eine identische Mondexkursion. Die Szenarien werden anhand ihrer Raumfahrtarchitektur, einer Abfolge der signifikantesten Ereignisse und einer Zeitlinie der operativen Aufgaben beschrieben.
Anschließend wird eine Analyse der erstellten Szenarien durchgeführt. Merkmale wie die verfügbaren Routine-Arbeitsstunden für wissenschaftliche Experimente, die benötigte Lebenserhaltungsmasse und die Anzahl der Raumflüge werden zwischen den vier Szenarien auf Missions- und Jahresbasis verglichen. Die Gateway-Szenarien mit kontinuierlicher Besatzung weisen die höchsten Routine-Arbeitsstunden auf. Für den regenerativen Fall stehen 2010 Stunden pro Jahr und Besatzungsmitglied zur Verfügung, was eine Versorgungsmasse von 4771 kg für das Lebenserhaltungssystem erfordert. Dies benötigt zwei Versorgungsflüge pro Jahr. Der nicht regenerative Fall erfordert die höchste Anzahl von vier Versorgungsflügen, um das Lebenserhaltungssystem mit 10647 kg zu versorgen. Zwei bemannte Missionen werden benötigt, um ein permanent bemanntes Gateway zu ermöglichen, dies macht zwei Mondausflüge pro Jahr möglich. In den Kampagnenszenarien wird eine Mission pro Jahr durchgeführt, sodass eine einzige Mundexkursion möglich ist. Die Stärken der Kampagnenszenarien liegen in der verfügbaren Nutzlast von mehr als 3000 kg sowohl für das regenerative als auch für das nicht regenerative Szenario durch einen einzigen Versorgungsflug. Beide Szenarien bieten 245 Stunden für Routine Arbeiten.
Abhängig vom Missionsziel ist das kontinuierliche Szenario oder das Kampagnenszenario von Vorteil. Diese Arbeit bietet einen fortgeschrittenen und fundierten Einblick in die Art und Weise, wie diese zukünftigen Missionen zu Gateway und dem Mond durchgeführt werden können.

Abstract

In the near future, the Artemis mission will return humans to the Moon to stay. A part of the plan to enable a sustainable Lunar presence is the development of a space station in Cis-Lunar orbit, called Gateway. Gateway will act as a research platform and hub between Earth and Moon. In this thesis, a concept of operations for the post assembly phase of this station is established.
First, the available vehicles and strategies for future Lunar missions are investigated by creating an outline of present plans and developments. From this, boundary conditions and constraints are defined. Topics vital to the creation of a mission concept, where a decision has not yet been made, are evaluated and the most reasonable option is selected. These topics include the Gateways life support system, the resupply vehicle payload capacity, and Lunar landing vehicles life support system.
This enabled the development of a concept for the operations of the spacecrafts and crews involved. To generate a broader view, four different scenarios are developed through an iterative process. The four scenarios differentiate in their duration and life support system. The first scenario describes a six weeks campaign style mission with a regenerative life support system. The second scenario is of the same duration as the first, but uses a non-regenerative life support system. The third and fourth scenario are designed to enable a permanently crewed Gateway, in contrast to the time limited campaign missions. Their life support systems are altered as well, creating the third scenario with a regenerative and the fourth with a non-regenerative system. All scenarios include an identical Lunar excursion of four weeks. The scenarios are presented through a spaceflight architecture and a sequence of events, describing the major events in a time proceeding manner. Followed by a timeline displaying the operational tasks arising throughout a mission. This describes how the missions in this concept are executed from an operational standpoint.
An analysis of the created scenarios is then conducted. Characteristics like the available routine working hours for scientific experiments, the required life support resupply mass, and the number of spaceflight are extracted and compared between the four scenarios on a mission and annual basis. The continuously crewed Gateway scenarios show the highest routine working hours. For the regenerative case 2010 hours per year and crew member are available, requiring a resupply mass of 4771 kg for the life support system. This makes two logistic flights per year necessary. The non-regenerative case requires the highest amount of four resupply flights to supply the life support system with 10647 kg. Two crewed missions are needed to enable the permanently crewed Gateway, making two Lunar excursions per year possible. In the campaign scenarios, one mission per year is conducted thus a single Lunar excursion is possible. The campaign scenarios strengths lie in the available cargo payload of more than 3000 kg for both the regenerative and non regenerative scenario, through a single resupply flight. Both scenarios provide 245 hours for routine work.
Depending on the mission's objective the continuous scenario or campaign scenario is advantageous. The thesis provides an advanced and reasonable insight into how these future missions to the Gateway and the Moon can be carried out.

Contents

List of Figures

List of Tables

Symbols and Formulas

Symbol	Unit	Description
d	day	Duration
F	N	Force
g_0	m/s^2	(Earth's) mean gravitational acceleration
I	Ns	Impulse
I_{sp}	s	Specific impulse
$m_{spacecraft}$	kg	Spacecraft mass
m_{inital}	kg	Initial spacecraft mass
m_{final}	kg	Final spacecraft mass
$m_{structure}$	kg	Structural mass
$m_{payload}$	kg	Payload mass
$m_{propulsion}$	kg	Propulsion mass
m_{ECLSS}	kg	ECLSS mass
$\dot{m}$	kg/s	Mass flow rate
n	-	Number of spaceflights
t	s	Time
V	m^3	Volume
v	m/s	Velocity
Δv	m/s	Delta-v budget
v_*	m/s	Effective exhaust velocity

Acronyms

ACLS	Advanced Closed-Loop System
ACS	Atmosphere Control System
ARS	Air Revitalization System
ASC	Ascent
ATV	Automated Transfer Vehicle
BLT	Ballistic Lunar Transfer
BPA	Brine Processing Assembly
CAMRAS	Carbon-dioxide and Moisture Removal Amine Swing-bed
CDRA	Carbon Dioxide Removal Assembly
CRA	Carbon Dioxide Reduction Assembly
CSA	Canadian Space Agency
DLR	German Aerospace Center
DRO	Distant Retrograde Orbit
DSA	Deep Space Antennas
DSL	Deep Space Logistics
DSN	Deep Space Network
ECLSS	Environmental Control and Life Support System
EI	Entry Interface
EL3	European Large Logistic Lander
EOP	Early Orbit Phase
ESA	European Space Agency
ESM	Equivalent System Mass
ESOC	European Space Operations Centre
ESPRIT	European System Providing Refueling, Infrastructure and Telecommunications
EVA	Extravehicular activity
EVR	Extravehicular Robotics
FDS	Fire Detection and Suppression System
HALO	Habitation and Logistics Outpost

HEOC	Human Exploration Operations Committee
HEPA	High Efficiency Particulate Air
HLS	Human Landing System
HTV	H-2 Transfer Vehicle
ICPS	Interim Cryogenic Propulsion Stage
I-HAB	International Habitat
ISP	Specific Impulse
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LEO	Lower Earth Orbit
LiOH	Lithium Hydroxide
LiSTOT	Life Support Trade Off Tool
LLO	Low Lunar Orbit
LOI	Lunar Orbit Insertion
LOP-G	Lunar Orbital Platform - Gateway
LRT	Institute of Astronautics
LTV	Lunar Terrain Vehicle
MCA	Multi-criteria Analysis
MCC	Mission Control Center
MCCH	Mission Control Center Houston
MMOD	Micro-Meteoroids and Orbital Debris
MPCV	Multipurpose Crew Vehicle
NASA	National Aeronautics and Space Administration
NRHO	Near Rectilinear Halo Orbit
OD	Orbit Determination
OGA	Oxygen Generation Assembly
OMM	Orbit Maintenance Maneuvers
PPE	Power and Propulsion Element
SCRA	Sabatier CO2 Reprocessing Assembly

SEP	Solar Electric Propulsion
SEPA	Solar Pressure Equilibrium Attitude
SI	International System of Units
SLS	Space Launch System
SOI	Sphere of Influence
SpaceX	Space Exploration Technologies Corporation
SSA	Source Selection Authority
SSTO	Single Stage to Orbit
TCCS	Trace Contaminant Control System
TCM	Trajectory Correction Maneuver
THC	Temperature and Humidity Control System
TLI	Trans Lunar Injection
TRL	Technology Readiness Level
UPA	Urine Processing Assembly
USOS	United States Orbital Segment
UTC	Universal Time Coordinated
V-HAB	Virtual Habitat
WPA	Water Processing Assembly
WRM	Water Recovery and Management System

1 Introduction

As we gaze into the skies above, we unmistakable recognize the most significant feature, our Moon. The brightest and by far largest object in our night skies. At a distance of 384 402 km, our natural satellite orbits Earth influencing and having shaped human life for thousands of years. In ancient history, the Moon was part of mystical stories and legends representing this distant and unknown world. In numerous cultures the Moon was even personified as a God. One of these was Artemis, Greek goddess of the wilderness, hunt and the Moon and twin sister to Apollo . Or the goddess Luna, in ancient Rome, where the word is still used in many languages found its Latin origin. Today the view has changed, empowered through exploration with the help of large telescopes, robotics missions and the first human landing on the 21st of July 1969, when Neil Armstrong set his foot on the surface of the Moon. But still, we have just scratched the surface of what lies beyond waiting for us to be discovered. Knowledge about our solar system, the origins of our Moon and the survival of mankind in deep space. The Moon marks the next big step in the progress of exploration. Where especially recent years have shown the vulnerability and fragility of our world. Curiosity and the drive to explore, to move forward can help us cope with disasters in the future. Either by providing solutions or alternatives. Space can provide this next frontier of exploration. (Dunbar, 2021)
Movies and recent developments in technologies might make it seem fairly easy to travel through the depth of space and the Moon. This image could not be more deceiving, as traveling to space, in particular deep space, requires technologies and materials to be operated at or even beyond their physical limits. This makes spaceflight extremely difficult by today's standards. Further, a mission to the Moon can not be conducted simply by jumping into a rocket and blasting off to space. It requires an immense amount of planning and preparation to enable life away from our home planet. Challenges emerging from the lack of oxygen, pressure, gravity, the impact of radiation, and many more need to be overcome. Even with a permanently crewed space station in Lower Earth Orbit (LEO) we are still far away from routine deep space missions. Technologies are still under development or being tested. Spacecrafts need to be capable of enduring a journey through space and bringing astronauts safely back to Earth. This also requires ground facilities and preparations for crew and personnel necessary to handle any situation that might arise throughout a mission. Some of these situations might not even result from a technical origin, but from other fields of science like chemistry, medicine, psychology or biology. This is making it necessary to include and understand these disciplines, as they either directly or indirectly impact the mission. Therefore, it involves a great effort to develop and conduct a crewed mission to the Moon. Through every mission new technologies are tested and experience is gathered. This allows pushing a little further every time. Consequently, going to the Moon and establishing a human presence in Cis-Lunar orbit and the surface of the Moon will happen through multiple steps each increasing the knowledge on how to survive in deep space. This is followed by the later goal of reaching Mars. (von Ehrenfried, 2020; NASA, 2020b)

As no man has ever spent a longer duration in deep space, a various number of questions arise that need to be answered before leaving Earth's Sphere of Influence (SOI). When considering future plans of traveling to Mars the technology should be sophisticated, tested and reliable. A single flight takes about six months and a return is not feasible within a two year period. System failures or outages are no option. The Moon provides the ideal testing ground close to Earth, which makes it an even more appealing destination in addition to scientific reasons. This, together with the intention of reaching the Lunar surface, led to the plan of developing a space station in Cis-Lunar orbit. It will allow to transfer today's knowledge gathered in the over 20 years of science and operation from the International Space Station (ISS) in LEO to deep space where mankind has never spent more than a week. The station will further allow the test of equipment and the conduction of research in this harsh environment while supporting missions to the surface of the Moon. The station's name is Gateway and will be built together by multiple space agencies from around the world similar to the ISS today. Agencies that agreed with the National Aeronautics and Space Administration (NASA) to contribute in this effort are the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA) and the Canadian Space Agency (CSA). Gateway will be assembled in the vicinity of the Moon within the mid-twenties and could already be supporting Artemis III on its way to land the next humans on the Moon. The station will then gradually grow to host more modules enabling a future joint deep space exploration. An Illustration of how the Gateway looks like as planed by today is given in Figure 1–1. Supply vehicles for logistics and the crewed Orion spacecraft are also visible docked to the Gateway. (Dunbar, 2021; NASA, 2020b)

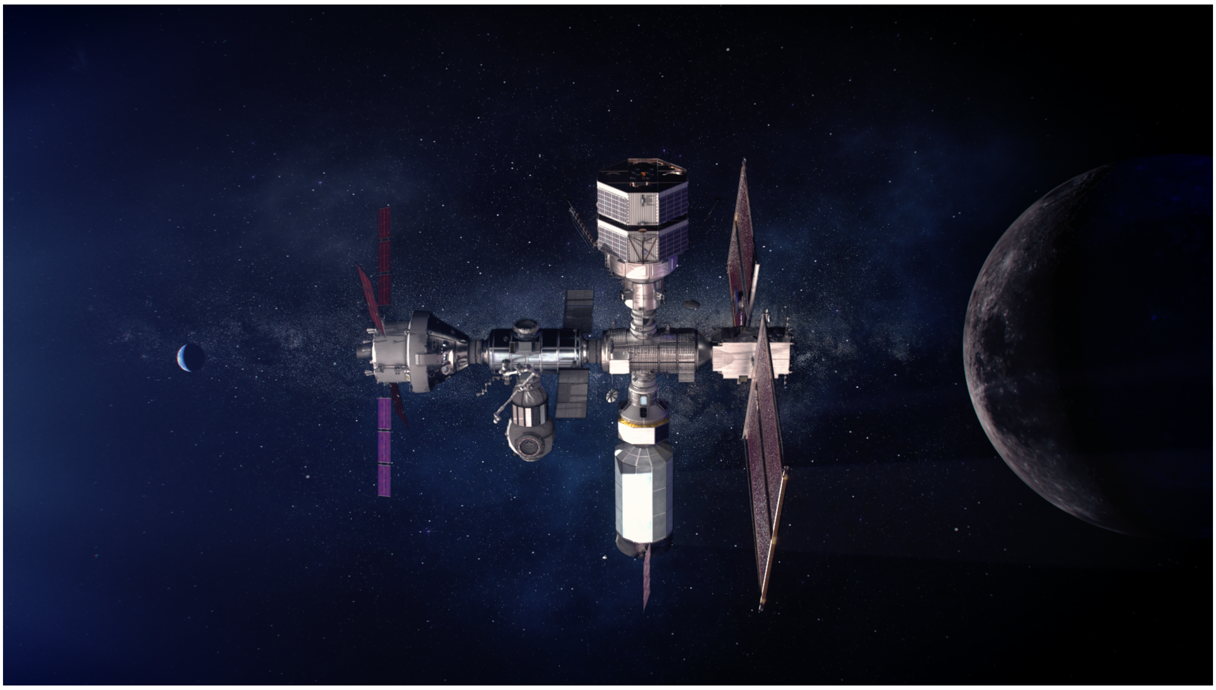


Fig. 1–1: Illustration of planned Gateway (Mars, 2021)

As plans for the station are getting more concrete, the choice of operational scenarios arise. These are of high importance, especially when considering that these future missions will not be robotic but manned spaceflights. In additional to the increased reliability vital factors like the life support systems need to be considered in these missions. Therefore, flight operation teams develop and evaluate mission scenarios. These scenarios can impact the design progress, as the vehicles and equipment are commonly designed specifically for a mission. As we are looking at a long-term operation and usage of the space station, a single mission scenario will not cover the entire lifetime. Different phases will see different mission scenarios and these need to be developed and discussed to create the best usage of the station for all parties involved. This might often be a difficult task especially on an international level, but nevertheless the outcome for research and cooperation is worth every effort.

The Gateway's present design enables a wide range of possible operational scenarios, as the lifetime is expected to last at least 15 years (Adamek, 2019, p. 26). In the early phase, during construction and verification of the space station, no long-term missions are likely to occur. Automated operations and an uncrewed station operation are likely to dominate. Also, the influence of the Lunar surface expeditions on the Gateways role must be considered. Depending on the available landing system, the Gateway might act as a hub or could be skipped entirely on the way to the surface. Later stages of operations for the Gateway could see long time crewed missions. In this thesis, different types of mission scenarios for the operation of the Gateway will be investigated. The scenarios are developed for a fully operational post-construction phase space station. The present state of technology and plans for the future Lunar exploration are therefore being considered.

1.1 Scope

The objective of this thesis is to identify and develop a mission concept for the Gateway in connection with a Lunar surface expedition. The scenarios will take place after the Gateway station is fully assembled and operational in Cis-Lunar space. It will focus on the application of the space station during this period. Based on this scenario, an operational timeline is created that allows an insight into the scenario's specific properties. Present technologies and concrete plans for the future are incorporated into the scenario to establish a wide application and meaningful concept.

In order to achieve this goal, the following questions are answered throughout the course of this thesis:

- What is the present state-of-the-art in the design of the Gateway and the plan for future Lunar missions?
- What are possible spaceflight architectures to deep space?
- What is a potential operational scenario? And further, how does a timeline including the expected tasks look?

- How do different key scenarios compare to each other including an alternation of the Environmental Control and Life Support System (ECLSS)? Key scenarios should be:
  - A continuous operation onboard Gateway, enabling a permanently crewed station.
  - A campaign mode operation to the Gateway.

  In both scenarios an excursion to the Lunar south pole is included in combination with a stay onboard the Gateway.

1.2 Structure and Approach

The thesis is structured in six chapters that creates a general picture of the developed concepts. Units are used after the International Bureau of Weights and Measures International System of Units (SI)-Brochure, given in (BIPM, 2019).

The first chapter provides the introduction to the topic and the scope of the thesis.

Chapter two provides the theoretical background. It describes the necessary components to enable the planned mission to the Moon. This includes the Gateway and other spacecrafts used as well as the available launchers. It describes their properties and, if already known, when they will be available and operational. The ECLSS and its purpose is provided and described by the present state of technology. The description is through the ISS system as it represents the state of the art in this area.

Chapter three provides the mission definition. NASA's plans and requirements are presented that are relevant for the creation of the concept. It specifically outlines limiting properties and already known requirements of the mission. Also the two ECLSS's, that are selected for the different scenarios, are introduced and described. In total, this leaves four distinct scenarios that are presented in this thesis.

Chapter four includes the presentation of the operational scenarios. The campaign and the continuous mission scenario are presented in both ECLSS variants. The scenarios spaceflight architectures are illustrated as well as their sequences of events and the resulting mission timelines.

Chapter five presents an analysis and discussion. It starts with mission defining and influencing factors, that can impact the scenarios drastically. These factors include the Deep Space Logistics (DSL) payload masses and ECLSS mass portions. Also the Human Landing System (HLS) capabilities and ECLSS masses are evaluated towards their impact. The chapter further includes the analysis of the presented concepts themselves where their quantitative properties are retried.

Chapter six, the final chapter, includes the conclusion and outlook towards future work.

2 Background

This chapter will provide the theoretical background and state-of-the-art for this thesis. It will describe the elements that are required and used in the near future to reach the Moon. Including ground infrastructures like communication facilities, control centers, and spaceflight segments like the Orion spacecraft or Gateway station. Their tasks and purposes will be stated and explained. Also, available launch vehicles and logistic spacecrafts, as well as the state of the art for life support systems, will be presented. At the end proposed Lunar base concepts will be given. Hereby, it needs to be considered that as long as the described systems are not built and used in service, they are subjected to change, especially when looking further into the future.

2.1 Spaceflight Operations

The term Spaceflight Operations has a broad variety of meanings in different contexts and through various periods of time, but in general, it spans the whole area of tasks related to the conduction of a mission in space. From mission planning, training, and control until the end of the mission's lifetime, including the disposal of the vehicle. A mission hereby is a major activity to achieve a goal, scientific, technological or engineering related (NASA, 2007, P. 185).

Every spaceflight has an excessive amount of staff and planning in the background, years before the actual launch of the mission until its decommission. Especially when it comes to human spaceflight missions, there is no room for errors and potential risks need to be identified and minimized to the largest extend feasible as early as possible. The crew onboard a spaceship is in nearly permanent contact to a Ground Control Center often referred to as the Mission Control Center (MCC) or Operations Center. There are various MCC's around the world as the famous Christopher C. Kraft Jr. Mission Control Center at NASA's Johnson Space Center in Houston, that was also known as Mission Control Center Houston (MCCH) and by the radio callsign 'Houston'.

The so called operations concept that is developed by the operations teams before the system is built, describes the overall scenario for the daily operation and control of a spacecraft and plays an important role in the development progress of the mission. It specifies who is responsible for what happens when and how during the mission (ESA, 2021c). To conduct this as successful as possible, the involved ground stations need to operate with the most time, cost and workload efficient schedule possible.

Tasks that arise include the designing, building and controlling of ground segments to establish contact with space vehicles during the mission in order to enable telemetry, tracking and command as well as data transfer for further processing and analysis. The planing of launch trajectories and orbits, the resulting launch windows and vehicles need to be determined and evaluated in detail. For long term missions a reasonable schedule for resupply logistics, backups or maintenance has to be considered carefully in order to achieve the main goal of conducting a safe and successful mission by reaching all mission objectives. (ESA, 2014)

To accomplish these goals the Pre-Phase A and Phase A of the program life cycle, see (NASA, 2007, pp. 17-41), include the development of a Concept of Operations. It describes the overall high-level concept of the system and how it will be used, based on a time sequence manner. Additionally, it gives an operational view and helps to develop architecture and requirements to achieve the systems goal. This stands in a light contrast to the Operations Concept, that mainly focuses on the interaction of the ground system and the flight system to ensure data transfer. (NASA, 2007, p. 51)

Automation in Spaceflight Automation has become a major point of interest in spaceflight operations. Already more than a decade ago the Automated Transfer Vehicle (ATV) has demonstrated automated docking manoevers at the ISS (Pinard et al., 2007). Automation is a welcome feature, to reduce the workload on the Astronauts and enable deep space missions.

Also crewed vehicles are now able to operate fully automated as the Dragon Spacecraft from Space X demonstrated. This will be a vital asset when looking towards operations at the Moon, as tasks like station assembly, maintenance and inspections can be conducted fully automated or partially automated with the support of an Earth based operator, that commands robotic arms or monitors the systems values. An early integration is therefore necessary to be considered in the development phase to make the system adaptable to robotics from the beginning (Rembala and Ower, 2009).

Automation can be on an internal or external level. Concerning internal automation, for instance for a closed system, the reduction of interactions might provide a great advantage. On the other side a closed automated system provides low flexibility and might not always provide the best option. External automation mostly refers to robotic arms or other robots, both internal and external of a pressurized habitat. Compared to humans they still lack in flexibility and accuracy, but the developments are evolving fast and routine or standard tasks can be supported through automation. This should be considered when designing the distribution of tasks for a crewed spaceflight as valuable crew time could be used for more complex tasks. (Messerschmid and Bertrand, 2013, pp. 452-464)

Automation has played an increasing role in crewed and uncrewed spaceflights in resent years and will do so in the future. For both, the space segment and the ground segment.

2.2 Deep Space Communication

To enable the monitoring and control of a Moon base or a station in the Lunar orbit, an essentially permanent up and down link is mandatory. Even with a high degree of automation, a communication link enabling data transfer is inevitable. A deep space communication network such as the European Estrack or NASA's Deep Space Network (DSN) can provide this service, not only for the Moon but also offer a communication link throughout the whole solar system. The Moons inclination requires ground stations on Earth to be located near the equator where they have the highest link visibility and pass duration. This enables keeping a stable connection independent of the Moon's position (Sabath and Nitsch, 2005).

To cover the entire sky a total of three antennas distributed around the globe are necessary. A brief introduction to the Estrack and DSN network are given in the following two sections. These antenna networks allow a continuous and uninterrupted connection to the Moon, vital for a crewed longtime mission.

2.2.1 Estrack

The European Estrack (ESA tracking) ground station network consists of a total of more than 20 antennas distributed around the globe, combining ESA owned and commercial ground stations. Out of these, three are 35 m diameter antennas enabling deep space signal transmission Deep Space Antennas (DSA). These antennas are located in New Norcia (Australia), Cebreros (Spain) and Malargüe (Argentina). The antennas are operated centrally from the European Space Operations Centre (ESOC) all year around. These antennas enable Europe's independent access to space and to hold telecommunication to spacecrafts and vehicles in deep space. (Doat et al., 2018; ESA, 2021b)

2.2.2 Deep Space Network

The DSN is operated by NASA's Jet Propulsion Laboratory (JPL) in Pasadena and is the worlds larges deep space telecommunication network at present. It consists of a total of three antennas that are shifted approximate 120 degrees around the globe and it is possible to control all three antennas from one of the sites allowing operation in the so called Follow the Sun concept, where a 24 hours a day operation is possible, but every operator only has to work during its local daytime. The stations are located in Canberra, operating the DSN from 22:00 Universal Time Coordinated (UTC) through 07:00 UTC , then handing over to the team in Madrid where the second Antenna is located. Operations in Madrid start at 06:00 UTC to 15:00 UTC, allowing a one hour overlap. The third operation center and antenna is positioned in Goldstone, California that continues operations from 14:00 UTC to 23:00 UTC. (Tzinis, 2021)

2.3 Gateway

The Deep Space Gateway, or short the Gateway, in the past also referred to as the Lunar Orbital Platform - Gateway (LOP-G), is a future space station in Cis-Lunar orbit enabling mankind to expand their presence further into our solar system. It will be humanities first deep space space station and have the capability to conduct deep space science as well as technology testing and verification beyond LEO, where the ISS is conducting research at the present moment. The station plays also a part in NASA's Artemis program where it contributes a crucial role in form of a habitation and logistics outpost along the way to the lunar surface. Analog to the ISS, it will consist of modules built by different international partners that will provide scientific as well as operational contributions. It will enable the space community to develop and test how a mission into deep space can be conducted and accomplished in a safe manner.

The preliminary plan is to man the Gateway for a minimum of 30 days continuously and provide enough habitation for this period and continuous propulsion. Otherwise the Gateway should be capable to endure an uncrewed period of three continuous years and be able to resume crewed operations thereafter (Adamek, 2019, P. 27). During the uncrewed period Gateway should be able to perform autonomous docking and undocking, as well as berthing and unberthing. The station is designed to accommodate from two to four crew members and the Orion spacecraft will act as a transport vehicle between the Earth and Gateway. This allows the use of the Orion's radiation shelters in case of an increased radiation event. On these missions signal delays can no longer be neglected and therefore real time operation can pose challenges. Where some will still be performed through voice commands and the crew, others especially safety relevant tasks will require automation. In order to achieve this, a higher level of automation for station keeping and the science experiments is required. Further, the station will allow remotely controlled robotics operations on board the Gateway and towards the Lunar surface. Enabling astronauts to stay at the Gateway, while controlling a robot in real time on the surface. It will also act as a supply, refueling and safety vessel for any Lunar surface mission. The gathered science and information will be vital to enable and conduct a safe mission to further distanced objects, for instance Mars. (Coderre et al., 2019)

The main purpose of Gateway will be to provide a deep space science platform, an exploration transportation hub, a technology proving ground and it will be able to act as a deep space communications relay. Acting as an transportation hub allows the storage of vehicles at the Gateway, where they can be refueled, repaired and outfitted for missions to the Lunar surface. Humans can also recover and prepare in a larger habitat and change from the Orion spacecraft to the HLS. In general, deep space operations will be demonstrated and the increased use of robotics and automation verified. Another vital aspect is the ability to act as a communications relay, through the Gateways Near Rectilinear Halo Orbit (NRHO) it can provide almost continuous signal cover of the Lunar south pole and relay the signal to Earth or allow robotic operations on the surface to be conducted from the Gateway, through a real time remote control link. (Duggan et al., 2019)

2.3.1 Elements

In the following paragraphs a more detailed overview of the planned Gateways structural elements will be given. The modules that make up the space station are listed, describing their main purpose and capabilities.

The Gateway, illustrated in Fig 2–1, will be a modular space station comparable to the ISS. It will weigh around 40 tonnes and will be assembled in stages and in the vicinity of the Moon. This assembly will be conducted primarily through automated docking. The modules are build by different nations based on a partnership between European Countries, the United States, Russia, Canada and Japan. It will have the capability of changing orbits through an independent propulsion and navigation system and is designed for 15 years of lifetime. After that, it will move to a Distant Retrograde Orbit (DRO) where it will remain stable for 100 years in an End-of-Life application. Each module is capable to store, receive and distribute power and control it's internal temperature and also allows the sharing of other resources for ECLSS in pressurized modules. In general, the modules should be designed for high reliability and minimal maintenance as well as the use of a modular hardware design. (Adamek, 2019)

The Gateways modules and their properties:

- **Power and Propulsion Element (PPE):** The first module that will be sent by NASA is the PPE providing a high-power, 50 kilowatt solar electric propulsion unit able to provide power and high-rate communications. The PPE should be launched by late 2022 on board of a SpaceX Falcon Heavy rocket and perform a one year flight demonstration, where the spacecraft will be fully owned and operated by Maxar Technologies. Afterwards, it will provide the key component upon which Gateway will be built, enabling attitude control and orbital transfer capabilities needed for Gateway. This is important for the maintenance of the standard Solar Pressure Equilibrium Attitude (SEPA) and other attitudes required for docking or berthing maneuvers. (Northon, 2020a)
- **Habitation and Logistics Outpost (HALO):** It will provide additional crew space and basic life support as well as command, control, and data handling capabilities and further energy storage, power distribution, thermal control, communications and tracking capabilities. HALO will also include docking ports for the Orion spacecraft and further modules. It is being developed by Northrop Grumman and will be managed by the Johnson Space Center in Houston. (Mars, 2021)
- **International Habitat (I-HAB):** The ESA was assigned to contribute the I-HAB that will contain vital contributions for life support subsystems and thermal loop pumps provided by JAXA. It will contribute a suitable environment for humans and also further docking ports and resources for scientific experiments that are accommodate inside and or outside I-HAB. Further it will contain external attachment points for the Gateway Robotic arm as well as internal attachment points for the Gateway Internal Robotic arm to perform simple un-crewed tasks. (ESA, 2020b)

- **Extravehicular Robotics (EVR):** CSA will developed the Canadarm3, an advanced robotic arm that can dock on the outside of Gateway. It can capture robotic spacecrafts and berth or unberth them and also assist in Extravehicular activity (EVA)'s or payload installations. (Potter, 2021)
- **European System Providing Refueling, Infrastructure and Telecommunications (ESPRIT):** Built by ESA, it will provide the Gateway with a window comparable to the ISS Cupola and enhanced communication as well as the possibility for refueling. (ESA, 2020d)
- **Airlock:** It will provide the capability to perform EVA's and accommodate suits and room for pre and post EVA preparations. (Adamek, 2019)

Figure 2–1 shows the concept design of the Gateway containing its various international modules as described in the paragraphs above. Further elements are for instance visiting vehicles like the DSL that will be supplying the Gateway already in advance of human arrivals with supply's and logistics. These should fly and dock automated. The HLS will perform surface missions to the Moon and for the development of this NASA has recently selected SpaceX, that are working on a single stage lander called the Starship that will most likely represent the HLS (Brown, 2021).

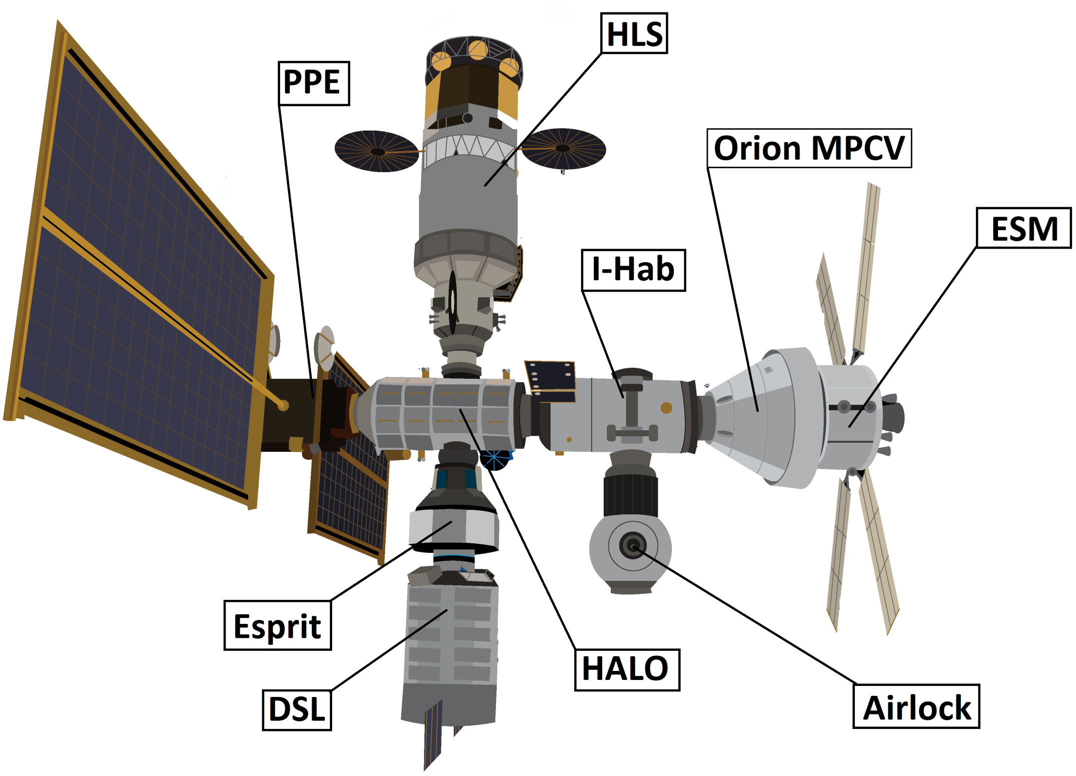


Fig. 2–1: Illustration of the Gateway, displaying the different modules in a possible structural configuration modified from (ESA, 2020d)

A further mayor contribution to the Gateway project will be the Orion Multipurpose Crew Vehicle (MPCV), often referred to as the Orion Spacecraft or simply Orion. As mentioned, it will used for the transfer from Earth and provide the vital radiation shelter. The Orions ECLSS includes a solid amine bed for CO_2 and H_2O control, as well as O_2 and N_2 tanks for pressure control and supply. Food is provided via prepacked food and a toilet with a collection container and urine venting facility is onboard, as well as water tanks (Burns et al., 2013, Table 1). This allows the support of a crew of four up to a period of at least 21 days. (Burns et al., 2013; ESA, 2020c)
The service module is provided by ESA and called the European Service Module. It provides propellant and life support systems tanks, solar arrays and thermal control capabilities. Orion is also designed to withstand impacts from Micro-Meteoroids and Orbital Debris (MMOD). It is scheduled to launch with the Artemis I for a round trip around the Moon by the end of 2021. The mission was previously called Exploration Mission 1 (EM-1) and is the first step towards the Moon, see Figure. 2–2. (Burns et al., 2013; Timmons et al., 2018)

The planned assembly of the Gateway in the vicinity of the Moon will take place over a course of multiple years and launchers like the Space Launch System (SLS) and the private sector will participate. The planned launches and their preliminary configuration concerning crews and launchers as well as the module sequence are given in Figure 2–2. This schedule has changed multiple times throughout recent years and is most likely going to be subjected to further changes, but as of today these are the planned assembly spaceflights to build the Gateway.

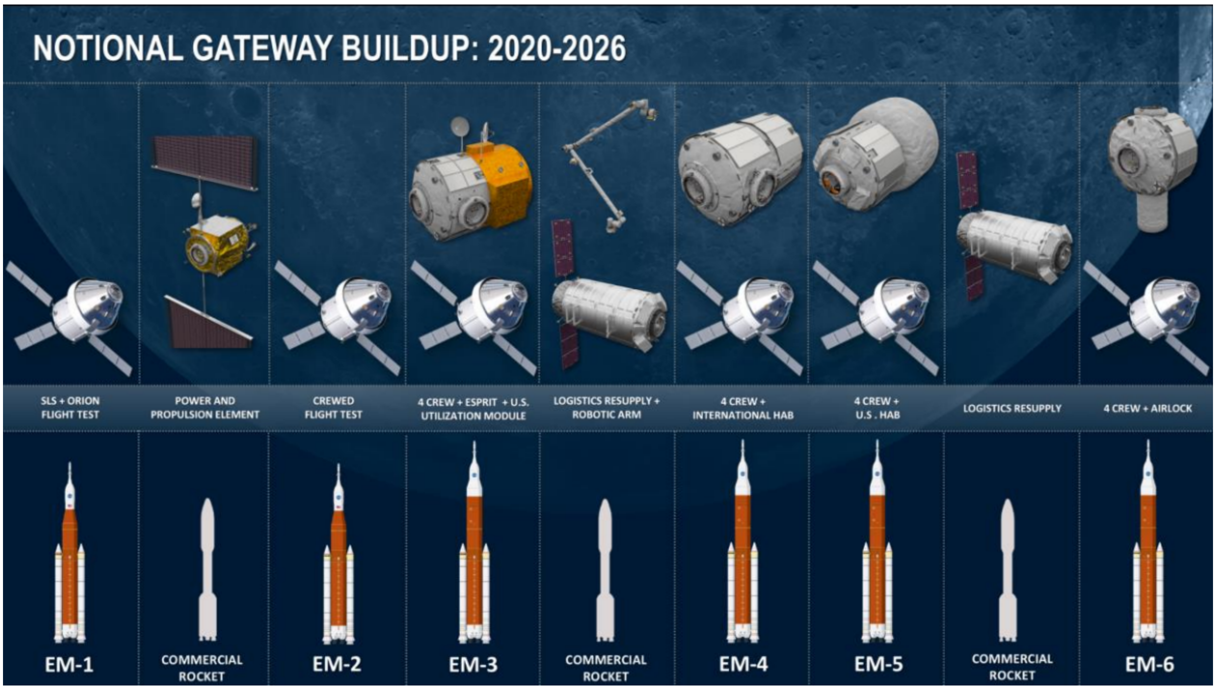


Fig. 2–2: Gateways launch and assembly sequence (Crusan et al., 2019, Figure 2.)

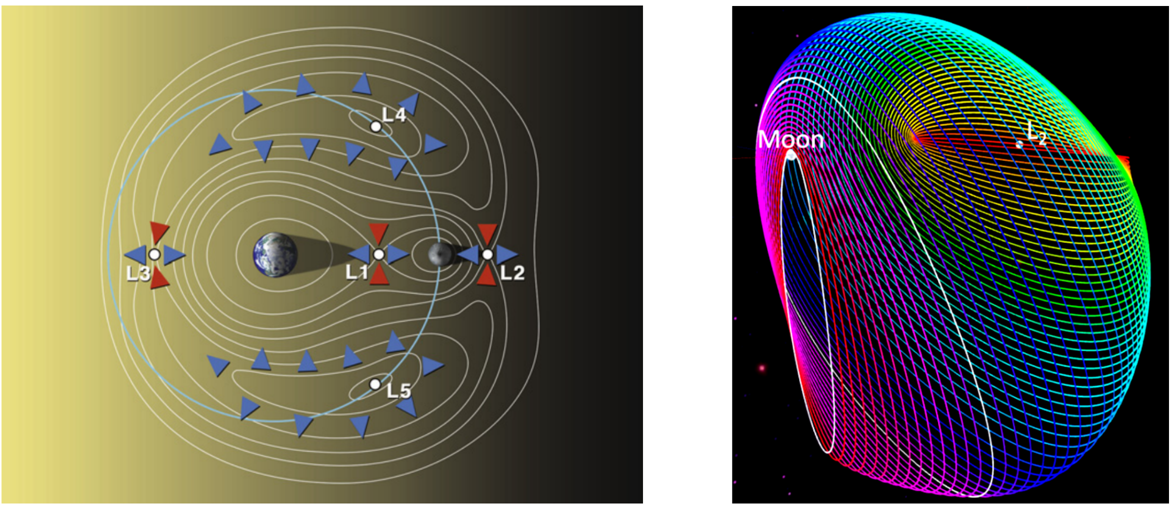
2.3.2 Orbit

For the Gateway a NRHO was chosen to be the most suitable and flexible orbit, not only to act as an intermediate point to the Moon, but also as a communications relay. It provides almost continuous signal cover of the Lunar south pole region and a continuous connection to Earth. The Δv, explained in detail in the following section 2.4, is favorable and also the transfer time from the orbit to the surface of the Moon is acceptable with a one way flight time of half a day. This reduces risks for crewed missions, and allows more crew time on the surface. The characteristics of the NRHO are given in Table 2–1. (Chavers et al., 2018)

Tab. 2–1: NRHO properties (Chavers et al., 2018)

Property	Value	Unit
Orbit period	7	days
Δ v from polar site	2730	$\frac{m}{s}$
ΔT from polar site	0.5	days
Δv from equatorial site	2898	$\frac{m}{s}$
ΔT from equatorial site	0.5	days
launch vehicle cost LEO to TLI	3.2	$\frac{km}{s}$
crew vehicle cost TLI to NRHO	0.45	$\frac{km}{s}$
BLT to NRHO	0.01	$\frac{km}{s}$

NRHOs are a subset of halo orbits and show nearly stable characteristics. They require little propellant for orbit maintenance. These so called Libration points, are gravitational equilibrium points in the Earth-Lunar system, literature often refers to them as



(a) (b)

Fig. 2–3: Earth-Moon libration points (a) from Burns et al. (2013, Fig. 1) and L2 horizontal Lyapunov orbit family (b) from (Zimovan et al., 2017, Fig. 2b)

Lagrange points. There exist five of these equilibrium points with LL_1 and LL_2 in the Lunar vicinity, see Figure 2–3 (a). The name 'LL' results from the fact that these equilibrium points also exist in the Sun Earth system and thus the first 'L' indicates that the Lunar libration points are considered. NRHO's are subset of halo orbits of these LL_1 and LL_2 points. The possible LL_2 horizontal Lyapunov orbits and their NRHO subset orbits are shown in Fig. 2–3 (b). The NRHO's bounds are marked with white lines.

Further advantages of the NRHO are that they can be reached from Earth through a relatively inexpensive transfer, as well as transfers from the NRHO to other cislunar orbits such as the Low Lunar Orbit (LLO) or a DRO can be conducted efficient. This allows Gateway for instance to conduct a round trip to the DRO within eleven months. (Burns et al., 2013) (Zimovan et al., 2017)

The planned NRHO is a LL_2 southern halo orbit with a 9:2 resonance towards the Lunar synodic period, shown in Figure 2–4. The station revolves the Moon nine times for every second period of the Lunar phase, each phase taking roughly 29.5 days. This gives a single orbit period of approximately 6.5 days and also enables the avoidance of eclipses due to Earth. The closest decent to the Lunar surface, at the north pole, will be 3200 km and the Apogee will have a distance of 70000 km above the south pole. This allows a long communication period between the Gateway and potential facilities at the south pole. Radio communication will only fail for a short period during the perigee when the Gateway passes over the north pole.
Due to solar pressure and the gravity gradient near the perigee the long-term operations require small Orbit Maintenance Maneuvers (OMM). These will be provided by the Solar Electric Propulsion (SEP) that can generate long and efficient maneuvers to keep the spacecraft in the desired orbit. Here the Orbit Determination (OD) plays a significant role to enable precise and minimal orbit maintenance. The Gateway OD will be provided via the Earth based DSN that will track the station. (Newman et al., 2018)

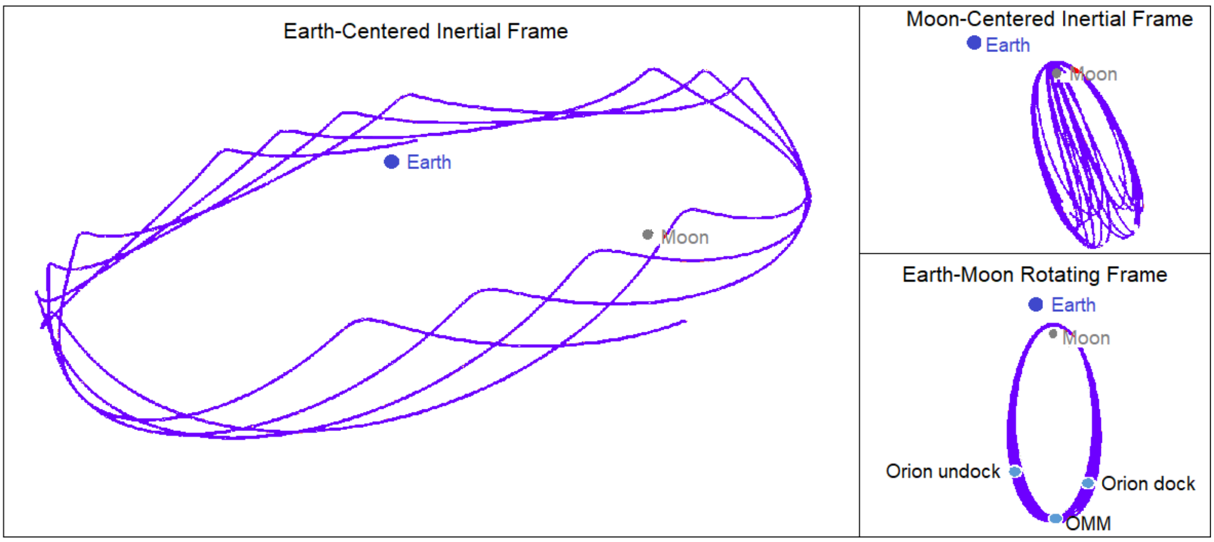


Fig. 2–4: 9:2 Lunar synodic resonant NRHO in three reference frames, modified from (Newman et al., 2018, Figure 1.)

The influence on the Gateways attitude and orbit stability, through the change in physical properties due to the visit of other spacecraft or connection of further modules needs to be considered, especially when a HLS the size of Starship is connected to Gateway. For this, the true anomaly, the position of the spacecraft within the orbit, and it's attitude need to be adapted and chosen carefully, so that the PPE is able to maintaining a stable orbit. These adjustments should be carried out at the apogee to reduce the risk of errors that create a more significant impact at the perigee. Without OMM the spacecraft is expected to leave the NRHO after 10 to 14 revolutions. Due to constrains from Orions tail-to-Sun requirement and the required attitudes for the Gateway during docking, special maneuvers need to be performed at suitable locations within the orbit to compensate for the change in physical properties and the docking perturbation. This is shown in Figure 2–4 on the bottom right and needs to be considered for launch windows not only for the Orion, but also for the HLS before descending to the Moon. (Newman et al., 2018)
During a noisy period on the Gateway, when a crew is on board, the OMM cost are increased due to venting processes that can result from CO_2 puffs and wastewater dumps, but also general increases in solar drag or influences through gravity on the lager station mass and volume add to an increase in orbit maintenance. (Newman et al., 2018)

2.4 Launch Vehicles

A rocket powered vehicle able to carry tons into space is referred to as a launch vehicle. They work after the basic principle of Newton's third law of motion stating: "for every action, there is an equal and opposite reaction". The engines, that are operating at the structural and material limit, eject a high mass flow towards Earth. For the Saturn V the mass flow rate was 12.5 tons per second creating a thrust of 33000 kN and through that pushing the rocket towards the skies (Walter, 2019).

At present, there are numerous space launch vehicles available, from small single-stage systems able to carry CubeSats into LEO to heavy-lift rockets that can send satellites weighing multiple tons beyond Earths SOI. These big rockets typically have multiple stages that are dropped as soon as the fuel is used up. Modern launchers are often equipped with solid rocket boosters for the first launch phase to accelerate the rocked as fast as possible. Because the goal of a launcher is to accelerate a spacecraft so it can overcome Earths gravity and reach the desired destination. Therefore structural weight is kept to the lowest point feasible to provide more weight for fuel and payload. In fact, for all chemical launchers, the weight of the fuel makes up the largest portion of 95% to even 99% of the vehicles lift-off weight. (Logsdon, 2019)
The goal of a launch vehicle is to accelerate the spacecraft it is caring to an orbital velocity. In the case of a Lunar mission, it might even accelerate the vehicle in a further burn, referred to as a TLI burn, to a velocity high enough to reach the Moons orbit of interest. This required velocity increase is referred to as "delta-v". To bring a spacecraft from Earth's orbit onto a translunar trajectory the Δv is in the area of 3.25 km/s. This is in addition to the acceleration required to reach LEO and can be provided by the launcher itself, to save fuel form the spacecraft. The mass different launchers can lift onto this Lunar trajectory is therefore often described via the TLI mass.

The principal equation describing this acceleration and the required propulsion mass is the Tsiolkovsky rocket equation, see equation 2–1. It describes the change in velocity in relation to the exhaust velocity multiplied by the logarithmic change in mass resulting from the used fuel. This ration is also called the propellant mass ratio (Benson, 2021a).

$$\Delta v = v_* ln \left(\frac{m_{inital}}{m_{final}} \right) \tag{2–1}$$

The characteristic quantity Δv describes the total change of velocity of the rocket and acts in the opposite direction of v_*, that describes the exhaust velocity and can vary slightly due to the change in pressure throughout the atmosphere. It is assumed constant for the ideal rocket equation. This Δv is used for the description of spacecraft maneuvers. (Walter, 2019)

A second parameter describing characteristics of a rocket is the so called Specific Impulse (ISP) labeled with (I_{SP}) in equation 2–2 and is given in seconds (Benson, 2021b). It gives information on the engine properties, explicitly the achievable impulse in relation to the exhaust propellant mass. Thus it describes the fuel efficiency of the engine.

Typically values range from 300 to 400 seconds for chemical engines, but can also reach values up to 6000 seconds for ion thrusters or electromagnetic engines (Walter, 2019, P. 19).

$$I_{SP} = \frac{F}{\dot{m}g_0} = \frac{I}{mg_0} = \frac{v_*}{g_0} \quad (2–2)$$

A preliminary study by Pütz et al. (2019) has gathered informations about available launch vehicles and their TLI payload, these values are displayed in Table 2–2 below, and also graphically visualized Figure 2–5. Information on the spacecrafts available at present, where also calculated in the paper by Pütz et al. (2019). Their payload values, as well as the ISP are given in Table 2–3. Their total masses are visualized in Figure 2–5 as well. The masses combine dry mass, fuel mass and payload mass of the vehicles. This shows which launcher is able to lift which spacecraft to a trans lunar trajectory. The spacecrafts fuel on board is calculated for a one way mission with a Δv of 340 m/s required to enter a stable NRHO (Parker and Born, 2008). It needs to be mentioned that a possible increase in fuel can significantly increase the payload of a factor three for some vehicles as shown in Pütz et al. (2019, Table 8.).

Tab. 2–2: Launch vehicle TLI values from Pütz et al. (2019, Table 7)

Launch vehicle	TLI Payload [kg]
Falcon 9 (Drone Ship Recovery)	3380
Atlas V (551)	6175
Ariane 64	8500
Falcon Heavy (recovery)	10300
Delta IV (Heavy)	10300
Falcon Heavy (expandable)	15190
SLS Block 1	26000
SLS Block 1B	37000
SLS Block 2	45000

Tab. 2–3: Spacecraft weight values from Pütz et al. (2019)

Spacecraft	Dry Mass [kg]	Fuel Mass [kg]	Payload [kg]	Payload +25% fuel [kg]	I_{SP} [s]
Cygnus	1923	800	2052	3046	300
Progress M	4050	900	504	1642	305
Dragon	4200	1290	678	1898	234
Dragon XL	-	-	5000	-	-
HTV	9068	2432	3016	6037	300
Orion	14197	8600	-	-	315

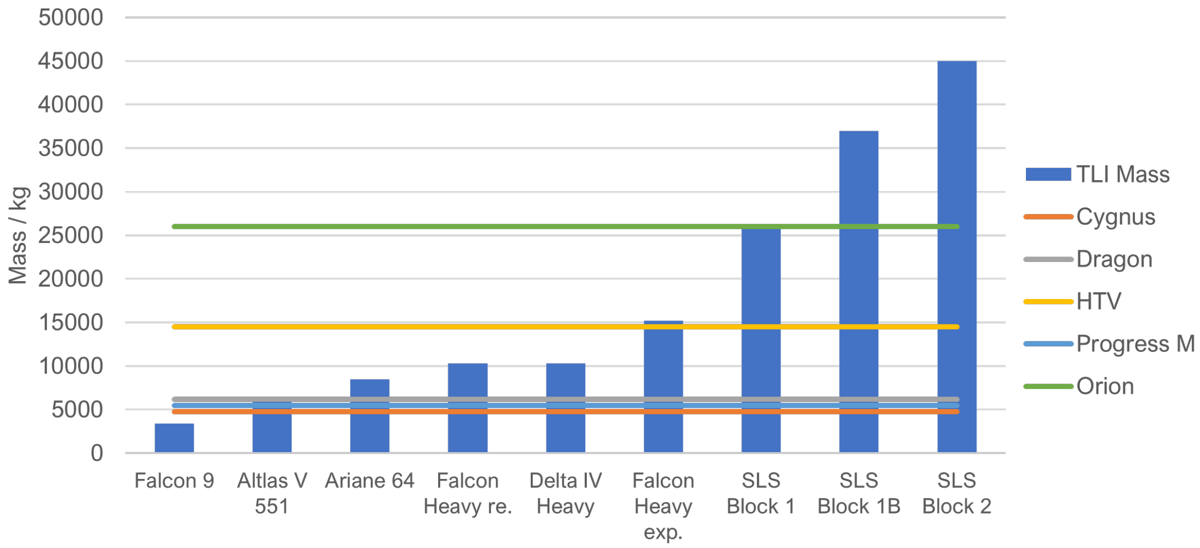


Fig. 2–5: TLI masses for different launch vehicles, indicating mass on the vertical axis. The total masses of selected spacecrafts are marked with horizontal colored lines.

As NASA has selected SpaceX to built a DSL spacecraft. SpaceX announced according to Clark (2020) that they will modify the existing Dragon spacecraft to provide a payload of 5000 kg to Gateway and call it Dragon XL. It is listed in Table 2–3 with the other spacecrafts for completeness. The Dragon XL should have the capability of being docked for six to twelve months and so far no return capability is considered by NASA. The vehicle is going to be be launched onboard a Falcon Heavy rocked. From this the total spacecraft launch mass is most likely not going to exceed the maximum of 15 290 kg of the Falcon Heavies launch capability including a TLI, when used as an expandable rocket.
Theoretically, it is also possible to refuel or dock multiple lighter spacecrafts in LEO and then perform the TLI but no system is in operation or planned to operate after this strategy in the near future. Therefore, this study focuses on the most feasible rockets that are going to be used and are capable of providing enough Δv to reach a Lunar orbit.

For the first crewed flights to the Gateway station or towards Moon in general the SLS will be the main focus, even though NASA already announced to launch the deep space logistics for the Gateway via private launch providers, like the Dragon XL. The SLS Block 1 Crew is planed to launch Orion around the Moon by the end of 2021 and is called Artemis 1. It will be the SLS's maiden flight and put Orion on a DRO as a uncrewed flight test demonstration and data gathering over the course of a four week mission, also for the European Service Module. (NASA, 2020b)

2.5 Life Support System

Space is a harsh and deadly environment. The radiation, weightlessness, temperature, pressure, and lack of oxygen make space an unforgivable place for humans. The human body is adapted to Earth's surface with an oxygen level of 21 % , a relative humidity between 30 % to 60 % and a well-being temperature in the low to mid twenty degrees Celsius. On top of that, the air pressure is one bar (10^5 Pa) and we are exposed to a permanent gravitational pull, further Earth's magnetosphere and atmosphere protect us from hazardous radiation and particles. All these characteristics are mandatory to support human life and we need to create these conditions artificially or provide alternatives, in order to survive in space.

From this, it can be seen that the task of creating a ECLSS is of central importance for human space explorations. Since the beginning of space flights, technology has advanced from supporting short-term missions over a period of a few hours up to the now continuous operation of the ISS for more than 20 years. There exist a range of different categories of life support systems like an open-loop, physiological, hybrid, regenerative or closed-loop system (Seedhouse, 2020, P.77). The selection of a system is dependent on multiple influencing factor that defines the mission from the duration, crew size, available launch vehicle, habitat size and leakage, resupply capability, Technology Readiness Level (TRL) and more. Especially concerning the TRL it has to be mentioned that a completely regenerative (closed loop) system is not available at present and represents a highly complex engineering task that involves not only technological but also biological aspects.

Before continuing into more detail, the main tasks of a life support system are listed here (Seedhouse, 2020, P. 78, Table 3.1):

- **Maintaining the atmosphere**, by monitoring and controlling partial pressure, temperature, humidity, contamination, atmosphere recycling and proper ventilation within the spacecraft.
- **Food**, to provide food or produce food on long duration missions.
- **Water management**, to recover and provide water as well as wastewater processing.
- **Waste management**, to store or process waste.
- **Crew safety**, to provide fire detection and suppression as well as radiation shielding.

One option is to bring all the required supplies along and hence use an open-loop life support system. When only considering oxygen a diver can be used as an example, caring oxygen with him in a tank and exhausting the used air into the ocean, the dive is hereby limited to the size of the tank, besides decompression effects. On the other side, all supplies could be recycled onboard the spacecraft and thereby creating a closed-loop system. In this case, no resupply is necessary and the system is able to recycle and clean all vital elements for life, like here on Earth. Due to the difficulty and complexity of such a system, there are partially closed-loop systems that are in between the two extremes of an open or closed-loop system. They enable high loop closures, but utilize chemical processes via a technical implementation and have the great advantage of controllability. These systems are either a physiochemical life support system, that creates some regenerative tasks via physical processes or a hybrid life support system combining a physiochemical and a biological regeneration process and thereby enables a high loop closure. (Seedhouse, 2020)

The advantage of a high loop closure becomes highlighted when taking the mission duration into account. As seen in Figure 2–6 the open-loop system has a continuous increase in mass over time, whereas the mass of a closed-loop system remains constant throughout time, but requires a higher initial mass. The determination of this cross-over point is vital in selecting the appropriate ECLSS also in relation to partially closed-loop systems like the hybrid or physiochemical life support system. Thus, depending on the mission duration different life support principles are more or less appealing. An important matter to be considered is the increase in complexity when looking at more sophisticated ECLSS that enable a higher loop closure, but also demand more crew time and spare parts. Especially at short mission duration, where crew time is already limited, a relatively lightweight open-loop system might after all be more favorable.

As seen on the vertical axis in Fig. 2–6 the equivalent mass is used to describe the transportation cost. This, often refereed to as the so called Equivalent System Mass (ESM), represents the sum of life support systems masses as well as the pressurized volume, power generation, required cooling and crew time multiplied by a mass equivalent factor. The ESM provides a mass-based quantification of the launch costs of a life support system. It is important to note that the ESM alone does not tell anything about safety, reliability or performance and therefore can not be used as a final metric.

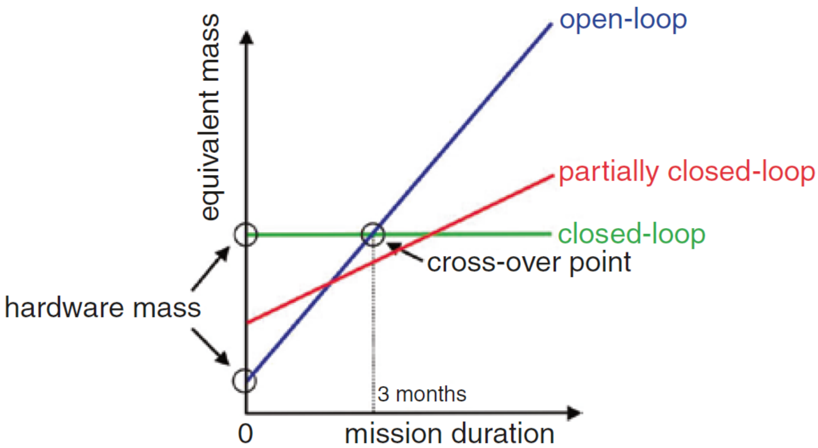


Fig. 2–6: Equivalent system mass in relation to mission duration, displaying an open-loop system in blue, a closed-loop system in green and a partially closed-loop system in red (Seedhouse, 2020, Figure 3.6)

2.5.1 Life Support Subsystems

The subsystems of the life support systems need to enable life for humans and thus we have to know the human metabolic rates to design an operative subsystem combination. The metabolic rates describe the needs of a human and hence give an insight on how much supplies need to be made available per day and crew member. Further, the produced waste must be processed or recycled. The standard values taken from NASA's Baseline Values and Assumptions Document (Anderson et al., 2018) are displayed in Table 2–4.

Tab. 2–4: Metabolic rates per crew members from Anderson et al. (2018)

Item	Value	Unit
Oxygen	0.82	kg per day
Carbon Dioxide	1.04	kg per day
Potable Water	2.52	kg per day
Hygiene Water	6.8	kg per day
Urine	1.6	kg per day
Sweat	1.92	kg per day
Food	1.51	kg per day
Heat	12	MJ per day

Due to the similarity between the Gateway and the ISS the life support system is expected to not vary much, also because the technology, onboard the ISS has proven its functionality and reliability over the last years. Making the use of the ISS's ECLSS subsystems a favorable option. The ISS is equipped with a physiochemical life support system that provides a 93 % loop-closure, excluding food supply (Seedhouse, 2020, p. 77). The subsystems on board the United States Orbital Segment (USOS) are described briefly below to give an insight into the basic functionality (Seedhouse, 2020, pp. 153-165)

- **Atmosphere Control System (ACS):** The main task is to maintain the interior partial pressure. This is done by monitoring the pressure levels and if necessary pumping nitrogen or oxygen throughout the modules.
- **Air Revitalization System (ARS):** Is responsible for the removal of carbon dioxide and the generation of oxygen as well as the control of trace contamination. Onboard the ISS these tasks are done by the Carbon Dioxide Removal Assembly (CDRA), the Oxygen Generation Assembly (OGA) and the Trace Contaminant Control System (TCCS). The CDRA utilizes a four-bed molecular sieve to absorb carbon dioxide from the incoming air. The so created CO_2 is then processed by the Carbon Dioxide Reduction Assembly (CRA) that creates water and methane via a Sabatier reaction. This is possible through the supply of hydrogen from the OGA that converts potable water into oxygen and hydrogen. A problem when

looking at the OGA record is the intensive maintenance work required due to failures, Seedhouse (2020, P.170) does therefore not recommend the ISS's OGA design to be used on long time deep space missions like Mars. Finally, the TCCS removes all trace chemical contaminants via chemical adsorption, thermal catalytic oxidation and physical adsorption.
Advancements have been made by the development of the Advanced Closed-Loop System (ACLS) that is being tested at the ISS. (Bockstahler et al., 2017)

- **Temperature and Humidity Control System (THC):** The primary task is to regulate the humidity and temperature via ventilation fans, heat exchangers and rotary liquid separators. The secondary task is to remove particles and microbes from the air through High Efficiency Particulate Air (HEPA) filters.
- **Fire Detection and Suppression System (FDS):** Its task is to detect fires via photoelectric detectors, provides breathing masks and carbon dioxide fire extinguishers.
- **Water Recovery and Management System (WRM):** Receives waste water from the crew as well as condensates and processes it to drinking water standards. The Urine Processing Assembly (UPA) together with the Brine Processing Assembly (BPA) enable a recovery of up to 98 % of water (Kelsey et al., 2018).

Figure 2–7 below shows these subsystems and how they interact with each other.

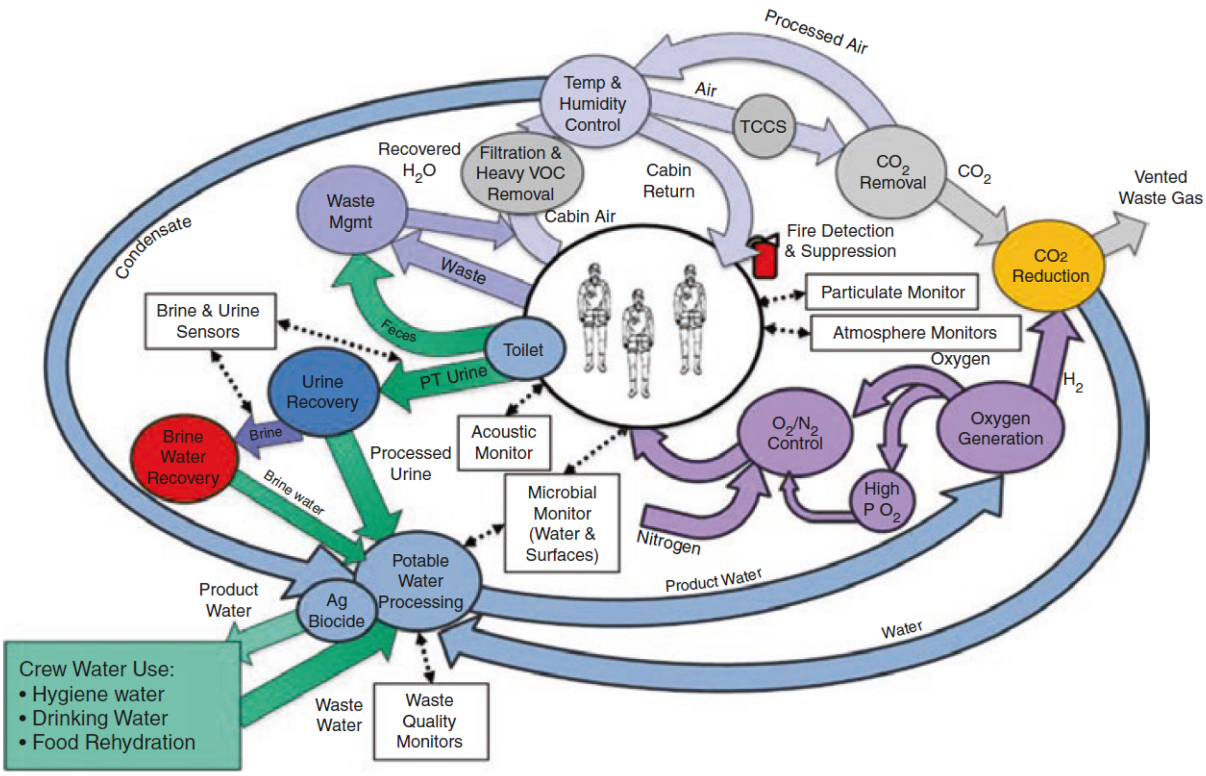


Fig. 2–7: Schematic ECLSS onboard the ISS. Displaying the interaction of the different subsystems. (Seedhouse, 2020, Figure 3.5)

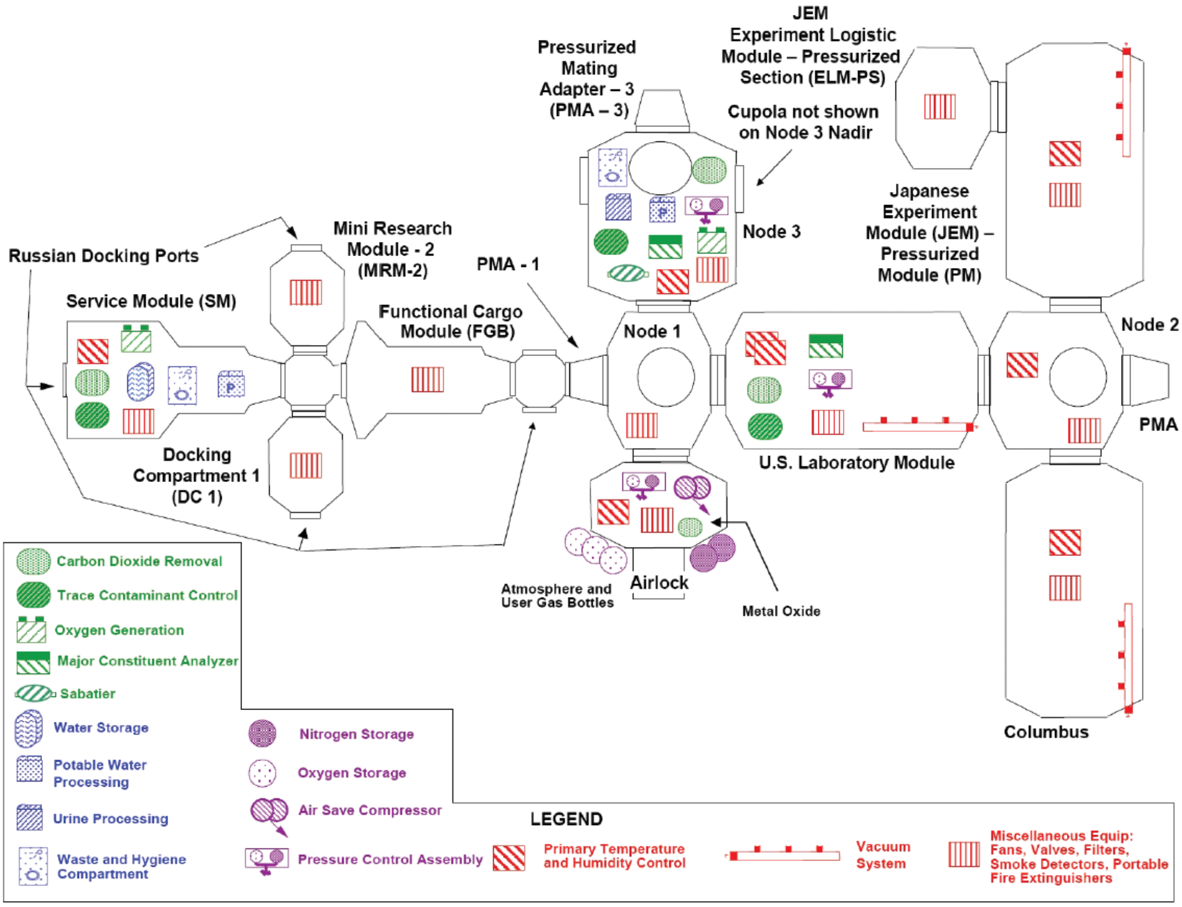


Fig. 2–8: Distribution of the ECLSS onboard the ISS (ESA, 2021a)

A further point is the structural distribution of these subsystems throughout the space station. As Figure 2–8 shows which subsystem is located where in the ISS. Due to the fact that the Gateway will be smaller, the number of systems will be reduced. Also the expected crew will be smaller than on the ISS. From this diagram it can be seen that some subsystems like the THC are installed in every module of the space station. Also vacuum systems for experiments and miscellaneous equipment including smoke detectors, fans and fire extinguishers are found throughout the station. While central subsystems for carbon dioxide removal like the Sabatier can be installed in a single module and are able to supply the entire station as long as proper ventilation is ensured. Nitrogen, located in external tanks, might become important for the Gateway when it is in an uncrewed mode, as modules can be purged with Nitrogen, if no crew is present, to reduce the risk of fire. Further Nitrogen is used for atmosphere control and experiments. (ESA, 2021a; Seedhouse, 2020, p. 156)

2.5.2 LiSTOT

As various options for life support subsystems exist and their properties change depending on mission duration, crew size, pressurized volume, exercise durations and more a trade-off tool was developed at the Institute of Astronautics (LRT) called Life Support Trade Off Tool (LiSTOT). With the help of LiSTOT an individualized ECLSS can be created and an ESM calculated as well as a Multi-criteria Analysis (MCA) can be performed. Most importantly, the required supply masses can be calculated , taking not only the required supply masses to satisfy human metabolics into account, but also known resupply values for maintenance work. Thus creating a concert and reliable statement about the total resupply mass over time. (Pütz and Schreck, 2018)

The steps required to create a proper life support system analysis are described in the LiSTOT User's Guide by Kaschubek et al. (2021) and summarized in the following. First of parameters like mission duration, crew size, pressurized volume, ECLSS type and a crew scheduled need to be defined. The crew scheduled describes the activity of the crew. Depending on what a human does, for instance sleeping in comparison to sport, the metabolic rate change. This influences the life support system. The different daily situations and their duration as well as an extract of the used metabolic factors are given in Table 2–5 below. Once all properties are selected a MCA can be performed. This step then expands the ESM by taking reliability, TRL and individualized attribute prioritization through weighting factors into account (Feigel, 2019). Then the complete ECLSS is assembled out of the individual subsystems providing the overall results.

From this the required resupply mass of the created ECLSS can be calculated. Including not only the required supply masses for the life support system to process and provide the required quantities, but also the maintenance masses.

Tab. 2–5: Extract from the metabolic factors used in LiSTOT (Anderson et al., 2018)

Item	Duration [h/day]	O_2 Consumption [kg/(CM h)]	CO_2 Production [kg/(CM h)]	Urine Water [kg/(CM h)]	Food Consumption [kg/(CM h)]	Heat Load [kJ/(CM h)]
Sleep	8.00	0.022	0.027	0.00	0.00	317.00
Post-Sleep	0.50	0.034	0.043	1.067	0.00	500.00
Pre-Sleep	1.00	0.034	0.043	0.533	0.00	500.00
Personal Hygiene	0.50	0.034	0.043	1.067	0.00	500.00
Work/Planning	6.50	0.034	0.043	0.00	0.00	500.00
Recreation	3.50	0.034	0.043	0.00	0.00	500.00
Pre-Exercise	0.25	0.236	0.299	0.00	0.00	1143.00
Exercise	0.25	0.236	0.299	0.00	0.00	2974.00
Post-Exercise	1.00	0.034	0.043	0.00	0.00	1174.75
Breakfast	0.50	0.034	0.043	0.00	1.007	500.00
Lunch	1.00	0.034	0.043	0.00	0.503	500.00
Dinner	1.00	0.034	0.043	0.00	0.503	500.00

2.6 Lunar Base

This section presents the plans and approaches towards the future planned Lunar bases. Investigations have shown that the location will be close to the south pole as resources like ice are available in the permanently shaded regions and crater rims are in almost permanent sunshine. Early missions will not include a permanent Lunar infrastructure and most likely use the HLS for habitation during short surface stays. Therefore the first subsection will focus on the possible concepts and plans for the landing system. Followed by the plans for the Artemis Base Camp that are in its early development at the moment. (NASA, 2020b, pp. 20-28)

2.6.1 Human Landing System

NASA's Source Selection Authority (SSA) has recently selected Space Exploration Technologies Corporation (SpaceX) to built the HLS Option A for the initial phase of the upcoming Artemis missions. The technical rating was rewarded as acceptable and the management as outstanding, reaching the highest score compared to the competitors Blue Orgin and Dynetics. (NASA, 2021)

Relevant for this thesis are landing systems beyond the initial phase. The concepts proposed for this phase at the moment are therefore introduced. During this sustainable phase surface stays should be in the range of 30 days and more, as well as the delivery of 1595 kg down to the surface and 1070 kg back up to the NRHO. When looking at the different approaches an one, two, or three element approach of the HLS is possible. All three are shown in Figure 2–9 including their docking procedures with the Gateway station. The single element approach represents today's Starship concept and is framed in red. Hereby a single vehicle performs landing and ascent. A two ele-

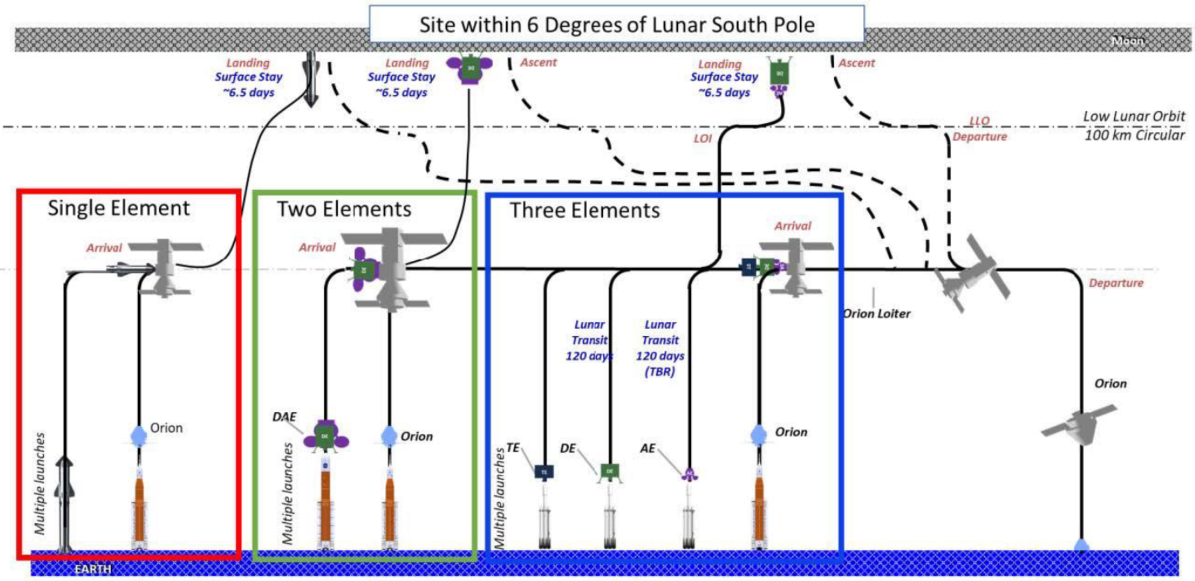


Fig. 2–9: Concepts for HLS operations in the sustaining phase (Watson-Morgan et al., 2021, P. 5, Fig. 3)

ment approach, colored in green uses a separate descent and ascent element, where the decent element can be left behind. The last option would be a three staged element like it is developed by Blue Orgin and is colored in blue. The crew would in all cases be transferred separately by an Orion spacecraft to the Gateway station. (Watson-Morgan et al., 2021)

Requirements for the HLS are listed by Chavers et al. (2020, Tab. 2). These include autonomous rendezvous with the Gateway and support a 8 h EVA. The mission reliability should be at 0.98 and be reusable by 2028. The HLS vehicle should then be able to perform five missions over a period of ten years. (Chavers et al., 2020)

2.6.2 Artemis Base Camp

For the first missions, the HLS is expected to serve as a habitat during the surface stay, whereas in a later progress a permanent habitat able to support a crew of four should be placed on the Moon. (NASA, 2020a)

The location of the base will be close to the south pole where various sights are under investigation, not only for their abundance of water ice, but also the availability of daylight. From the 1.54 degrees tilt of the Moon's axis, crater rims near the pole reach a long periods of light. Further aspects like the slope of the location or relevance of research locations close by. A recent study by (Kaschubek et al., 2021) has considered a variety of these points and found the Shackleton craters south east side and Mount Kocher as good locations for a future base.

In total NASA plans to deploy multiple elements to the surface of the Moon, like the Lunar Terrain Vehicle (LTV) an unpressurized rover followed by a habitable mobility platform, representing a pressurized rover. A Lunar habitation module with power systems and an in-situ resource utilization system. The base camp should then be able to support one to two month long missions. (NASA, 2020b, p. 27)

2.6.3 European Large Logistic Lander

To support the supply of the Lunar Base independent logistic flights will land on the Moon, so that the HLS is not forced to deliver all payloads. This would also allow the delivery of logistics, as the LTV, in advance. As NASA wants to commercialize logistic flights and is open for international cooperation the European Large Logistic Lander (EL3) could serve as one of these vehicles.
The EL3's system should be capable of deploying scientific or logistic payloads to the Moon. It is designed to be launched with the Ariane 6 launcher and supports different mission types. The spacecraft consist of a cargo segment, able to carry up to 1500 kg of payload mass. Below this will be the Payload Platform Element, providing power, thermal, night survival, communications and more depending on the required mission capability. The lowest element will be the Lander Descent Element. Currently, the EL3 is still in development and should finish phase A/B1 by the end of 2022 and conduct its first mission by 2027. (ESA, 2020a)

3 Mission Definition

There are numerous different scenarios and possibilities for how to get to Cis-Lunar space and the Lunar surface. Depending on the size and weight of the different spacecrafts, the amount of fuel available, the mission duration, the required return mass towards Earth, available launch vehicles, and many influencing factors more give a broad set of possibilities or limit these through adding colloquialism constraints. In order to identify the best feasible mission scenario to reach for the Moon a sophisticated knowledge of constraints and available technologies is essential.

The vehicles used for crews and logistics to get to Cis-Lunar space are going to be the Gateway station in NRHO, the Orion as crew transport from and to Earth as well as future Logistic modules like the Dragen XL or modified versions of existing vehicles like the Cygnus spacecraft. Further, multiple HLSs might be available from different manufactures. They could be based on different concepts creating various requirements for resupply and re-usability. Therefore the operation is heavily dependent on the chosen mission scenario. This chapter identifies the requirements and boundary conditions that are either already given through existing technologies or technology proposed for the planned missions. Announcements that were already made and spacecrafts developed are being considered.

3.1 Proposed Mission Outlines

After Artemis III, NASA is planning on further extending their Lunar presence onboard the Gateway and on the surface of the Moon at the so called Artemis Base. This would put the missions planned here towards the end and after the so called Phase 2 in the Lunar program as defined by the Human Exploration Operations Committee (HEOC) (von Ehrenfried, 2020). NASA has already announced the will to support up to 12 Artemis missions, where the Orion spacecraft should be used as a transport vehicle towards Cis-Lunar space (Northon, 2020b). The Gateway will be used throughout this missions as a hub and a research laboratory supporting multi-month stays and simulations for future Mars flights in a deep space environment. For these future missions NASA wants to send four crew members to the Gateway that can conduct operations at the station and or descent towards the surface. (NASA, 2020b, P.30)

In order to create a realistic and reasonable mission scenario the Gateway station as described in Chapter 2.3 is assumed operational and close to completion or already completed and thus providing mission vital elements like the PPE, ESPRIT and a habitat. Also the announced Dragon XL is assumed operational and able to bring 5000 kg of logistics to the Gateway (Clark, 2020). As a second DSL vehicle an upgraded Cygnus, indicated as Cygnus EX in this thesis, is used, able to carry 3000 kg to the Gateway. The weight of these three metric tons was selected as being a reasonable and doable, even with spacecrafts available today, see Table 2–3. It also represents a good average DSL payload capacity when looking at upcoming future logistic vehicles.

In general, there are many parameters that impact the mission, but several of these would not change the flight schedule as such and can be mitigated by including buffers and redundancies. Parameters influencing the mission concept are listed in the following and need to be considered before establishing a reasonable scenario.

- Crew size
- Mission duration
- Duration of lunar excursion
- DSL payload capacity
- Required ECLSS resupply
- HLS working principle (resupply/refueling)
- Lifetime and operational limits of vehicles
- Emergency equipment and backup supplies

Emergency equipment and supplies are not included in the general operation resupply scenario. They have to be already present at the Gateway station or brought to the station with the first logistic flight. These supplies need to be maintained or exchanged throughout the mission duration.

3.2 Mission Assumptions and Constrains

This section gives the necessary assumptions and constrains needed for the development of the mission concept. Boundary conditions like the crew size or vehicle volumes and launchers need to be known to make the design of an adequate ECLSS possible and thus create a planing scheduled for logistic flight and crewed missions. An overview over these assumptions and constraints are given in Table 3–1 at the end of this section.

The mission assumptions and constrains stated here, are mainly oriented on the state-of-the-art of planning and announcements regarding the future Gateway and Artemis missions as well as on physical and technical boundary conditions.

Crew Size: The number of humans onboard a spacecraft has a major impact on the mission in general and a direct impact on the vehicle's usability, the ECLSS, the available crew time for research or maintenance, and many other aspects. Also, psychological aspects need to be considered when looking at the duration especially with long term missions and the available size of the habitat. As the Orion spacecraft will be used to transfer humans from Earth to the Gateway, the maximum capacity is limited per crew to a total of four persons. This is due to the fact that the Orion will act as an emergency vessel if the mission needs to be aborted and further it was designed to provide vital radiation protection for a crew of four only.

Mission Duration: A further significant design parameter, defining the amount of resupplies necessary or the selection of the ECLSS, is the overall duration of the mission. The duration of crewed missions and the intervals between need to be known for planning, if the Gateway station is required to go into an autonomous mode or is permanently crewed. In the scope of this thesis, both the continuously crewed and the campaign mode will be analyzed. The duration for the campaign mode is set to be six weeks onboard Gateway close to the planned duration of early Artemis missions (Coderre et al., 2019, P.67). For the continuous mode, a single crew will stay half a year onboard the Gateway.

Maintainability: The next point that can have a major impact is that the selected technology needs to be functional with a minimum in maintenance and further it should be based on a modular design (Adamek, 2019). This also includes that operational procedures should be planed in the most sustainable and fail-safe design. Automation will play an important role especially with respect to monitoring systems and maintenance cycles. Therefore systems that have already achieved a high TRL are preferred in this environment over new and unproven systems.

Technical Limits: Other limiting factors are operation limits for spacecrafts like, the docking duration, or life time of parts, shadow periods for power systems or fuel volumes. Also the reusability and reactivation possibility needs to be considered when looking at the HLS or robotic systems.
For the Orion Spacecraft the operational lifetime was designed to be 21 days according to Timmons et al. (2018), whereas its docking duration is set to 180 days and can easily be extended to 1000 days described by Crusan et al. (2018).
The planed Dragon XL should also be able to endure a one year docking duration while carrying five metric tons to the Gateway station. But a return to Earth was not announced as of today. (Clark, 2020)
The Gateway itself will have a total of at least four docking ports, as described by Adamek (2019) and thus allow four simultaneous visits of vehicles. The crew supported by the station itself will be up to four crew members. Further details about Gateway are given in Chapter 2.3.

Lunar Excursion: Considering the Lunar excursion, an important design parameter is the duration. As resupply and flight schedules need to be established to enable a successful surface stay. Further, the HLS plays a major role as well as the facilities present on the surface. As the exact spacecraft and the used HLS system is not known for the post Artemis III era, a four week surface stay is assumed. It represents an intermediate value between the one week surface stays planned in the beginning and the up to two months stays that are planned for later Artemis missions (NASA, 2020b). For the scope of this thesis, different resupply values for a reusable HLS are considered, and designed by the means of the most reasonable ECLSS system based on Carbon-dioxide and Moisture Removal Amine Swing-bed (CAMRAS) requiring 27.16 kg per day for the entire four man crew.

Pre Mission Assumptions: The established mission timelines consider an fully operational Gateway where a preliminary supply flight already delivered emergency equipment. This means that food, watery oxygen and nitrogen is present at the station to enable a one month non-regenerative stay in the case of a system failure or other unexpected events. This provides the crew with backup and redundancies, and further allows to plan how standard operations look like.

DSL disposal: The disposal of the DSL assumed to be solved in a way that it does not concern the operation and conduction of the crewed missions. The vehicles undock and leave the Gateway to make room for the next logistic flight taking the non-reusable waste with them, section 5.1.2 provides possible options.

Emergency Equipment: Due to the importance of the life support system, a failure or resupply shortages has to be taken into consideration. From the beginning a non-regenerative supply for up to four weeks is to be provided as essential. This gives enough time to launch a further supply vehicle or abort the mission in a save manner. These additional resources need to be stored onboard Gateway and must be brought to the station in advance.

Further Constrains and Limitations: Other limitations originate from launchers or the ECLSS and are described in the Sections 2.4 and 2.5 respectively.

For a better overview all vital assumptions and constrain values are listed in table 3–1. These values are also used in the analysis and calculations. The ECLSS types are described in the following sections.

Tab. 3–1: Preliminary mission assumptions

Assumption or Constrain	Value/Description
Crew size per mission	4
Campaign mode period onboard Gateway	42 days
Continuous mode period onboard Gateway	196 days
Lunar excursion duration	42 days
Gateway's pressurized volume	125 m^3
Minimum number of airlocks on Gateway	4
DSL payload capacity	2000 to 5000 kg
Spacecraft operational lifetime	minimum 6 months
ECLSS Type 1 (regenerative)	ISS like
ECLSS Type 2 (non-regenerative)	CAMRAS based

3.3 Life Support System Selection

The ECLSS plays a major role when leaving Earth's protective environment. The systems must be reliable and resupply must be ensured to grantee an uninterrupted supply of oxygen and food to all crew members. Therefore, systems that have already reached a high TRL are being considered as usable for deep space missions. Further, the experience gathered with an already in use system represents an important asset when it comes to long time operations and the need for maintenance. The challenging distance and complexity inherent with reaching the Lunar Gateway leaves only little space for unexpected failures or major repairs.

For the scenarios considered in this thesis two different ECLSS where chosen. A non regenerative system working with a CAMRAS CO_2 removal cycle and a regenerative system like it is operational on the ISS today are being evaluated. These two system represent the two ends of the spectrum in possible live support systems that make sense in the near future on a Cis-Lunar station. One requires a high and the other a low resupply mass. The systems are described briefly in the following.

3.3.1 Regenerative System

As a more regenerative system a physiochemical system like onboad the ISS was chosen. This is due to the fact that the system is well studied and understood. Values for repairs and lifetime are known together with the benefit of a long time operation that showed strengths and weaknesses providing extensive experience with the ECLSS. Thus making it a very plausible and reasonable option to be used in a near future system also suitable for a long duration mission. This becomes especially valuable when looking at a permanently manned Gateway station that requires a high reliability and leaves little room for unexpected repairs requiring spare parts and tools.

The initial weight of the complete ECLSS hardware was calculated via LiSTOT to be 2603.17 kg. This includes all components as shown in Figure 3–1. The internal volume of the stations pressurized and habitable atmosphere for the calculation is 125 m^3, as assumed for the future Gateway. The calculations where performed for four crew members each performing two hour of exercise each day. The exercise is split in aerobic and restive exercise.
The ECLSS operates a MCA for atmosphere monitoring and a TCCS for trace contamination control. Besides that, the UPA and BPA process urine and reduce a minimal amount of lost water enabling long-duration missions without the need for water resupply (Garcia, 2021). The water extracted in the BPA unit is vented into the cabin providing humidity that is controlled via a condensing heat exchanger. The carbon dioxide (CO_2) is removed via a cycle consisting of a CDRA and a Sabatier CO2 Reprocessing Assembly (SCRA). Inside the SCRA CO_2 reacts with hydrogen (H_2) in the presence of ruthenium as a catalyst producing methane (CH_4) and water (H_2O). The hydrogen required for this process is produced via the OGA in an electrolysis that also provides oxygen for the crew. The oxygen is stored in a high pressure tank at ambient

temperature, before it is fed into the cabin. The Water Processing Assembly (WPA) is filtering and recycling all the gray water. The entire system is even producing a water surplus that is stored in a separate tank. This surplus water results from the addition of water to the entire cycle through food that is delivered to the station and non-regenerative. The surplus water can be used for experiments and provides leeway in case of a subsystem failure. It needs to be noted that the values for the components being exchanged between the subsystems displayed in Figure 3–1 indicate the usage and metabolics for a single crew member as they where calculated via LiSTOT.
Figure 3–1 shows schematically how the physiochemcial ECLSS works including the paths for different substances between the subsystems. The subsystems are each displayed in a box and include a rough description of its main purpose, except for the boxes Cabin, indicating the stations internal atmosphere, the box Crew indicated as a subsystem interacting with the cabin and other subsystems and the box Food that is non-regenerative and thus shows no incoming pointers.

The resupply necessary for this regenerative ECLSS requires a total of 12.17 kg/day for all four crew members to be brought to the station. Thereby the largest portion is made up by the resupply of food with a value 7.76 kg/day per day followed by clothing with a value of 1.37 kg/day. The stored waste also needs to be considered but it is unlikely that the storage capacity runs out before the next resupply flight arrives and allows a disposal via the DSL, but this needs to be considered in the mission timeline.

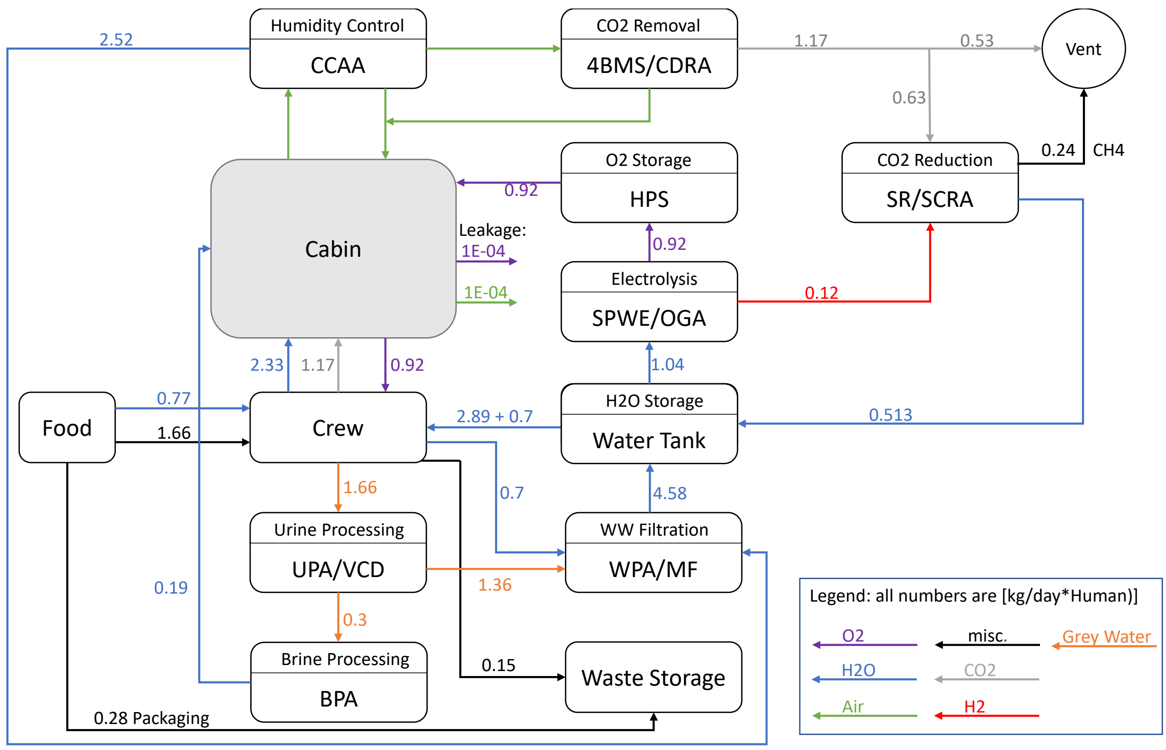


Fig. 3–1: Regenerative ECLSS schematics, displaying the subsystems and metabolic rates for a single crew member and day

3.3.2 Non-Regenerative System

As a non-regenerative system a CAMRAS based ECLSS was chosen. Besides carbon dioxide removal all components are provided from storage. This reduces the risk for a potential subsystem failure as substances vital for survival are not being regenerated but provided directly to the crew. Also the ECLSS structural weight, which can be of special interest when looking at short duration missions, can be lower.

The CAMRAS based system is shown schematically in Figure 3–2 and metabolic rates are indicated with colored pointers, also describing their flow direction. The values are again only for a single crew member. CAMRAS uses an amine swingbed that is regenerated by the vacuum of space. It absorbs the carbon dioxide as well as humidity from the cabins atmosphere and vents these unwanted compounds into space.

The total resupply mass necessary is 27.16 kg/day per day for all four crew members. Now water makes up the largest portion of 14.34 kg/day followed by food with 7.76 kg/day and oxygen with 3.68 kg/day. These values were calculated via LiSTOT.

CAMRAS will also provide life support for the Orion spacecraft and potentially on future lunar landing systems. Through Orion it can also act as a backup system for the Gateway provided enough food, water and oxygen is present.

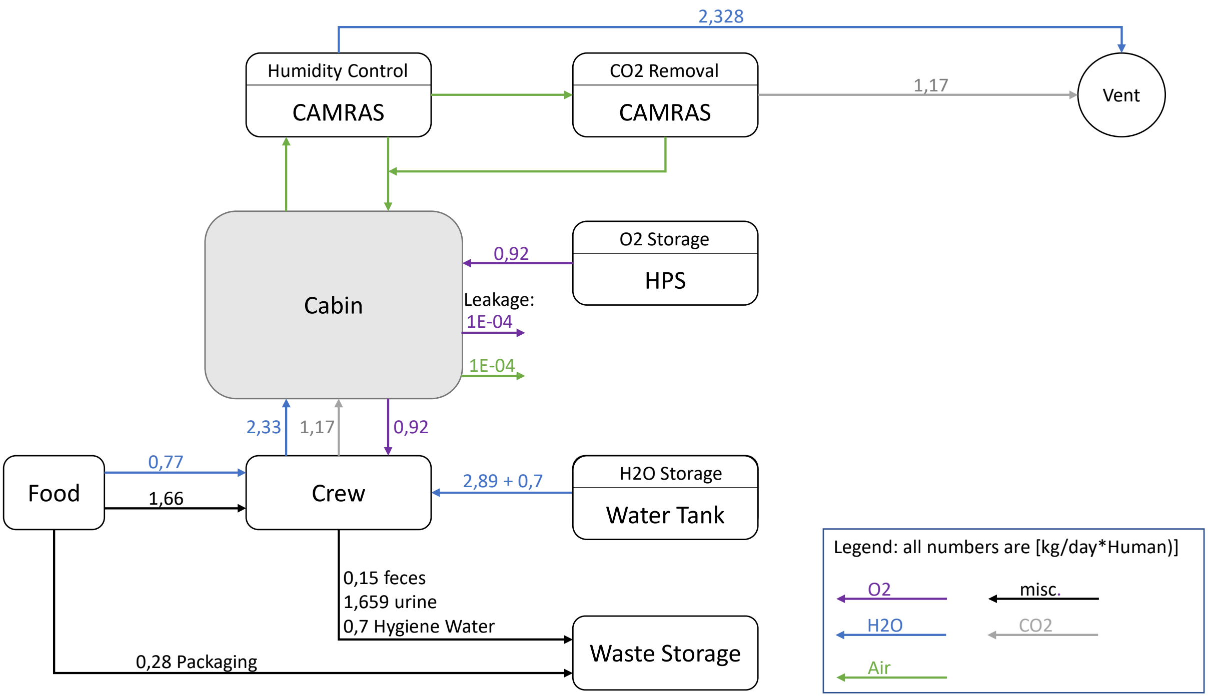


Fig. 3–2: Non-Regenerative ECLSS schematics, displaying the subsystems and metabolic rates for a single crew member and day

3.4 Design Reference Mission

The basic mission setup will comprise a stay onboard the Gateway as well as an excursion to the Lunar surface. This is in order to fulfill the mission goal of technology verification and testing as well as for deep space research and exploration especially when looking towards Mars. Further goals are the installation of a presence on the Moon while broadening commercial and international partnerships (von Ehrenfried, 2020, P.3). Therefore new technologies and commercial companies will play a vital role in the upcoming Lunar and Cis-Lunar missions.

Figure 3–3 shows the basic mission design, which will include the SLS as well as commercial launchers like the Falcon Heavy or Delta 4 Heavy. The Orion spacecraft will transfer humans, whereas Cygnus EX, developed by Northrop Grumman, or the Dragon XL, developed by Space X, will transport logistics to the Gateway. Also other vehicles like a variant of the Japanese H-2 Transfer Vehicle (HTV) could potentially fly logistic missions to Cis-Lunar space. Then the HLS needs to be brought to the station if it is not already present and docked at the Gateway. For the HLS Space X designed the Starship that can descent to the surface and return to orbit with a single stage. Refueling and stocking up supplies for the HLS can be conducted at the Gateway, whereas the Starship might not need this or be dependent on an extra refueling due to its size. For other HLS concepts and systems the refueling and reloading at the Gateway with logistics and supplies brought from Earth via the DSL might be of significant importance.

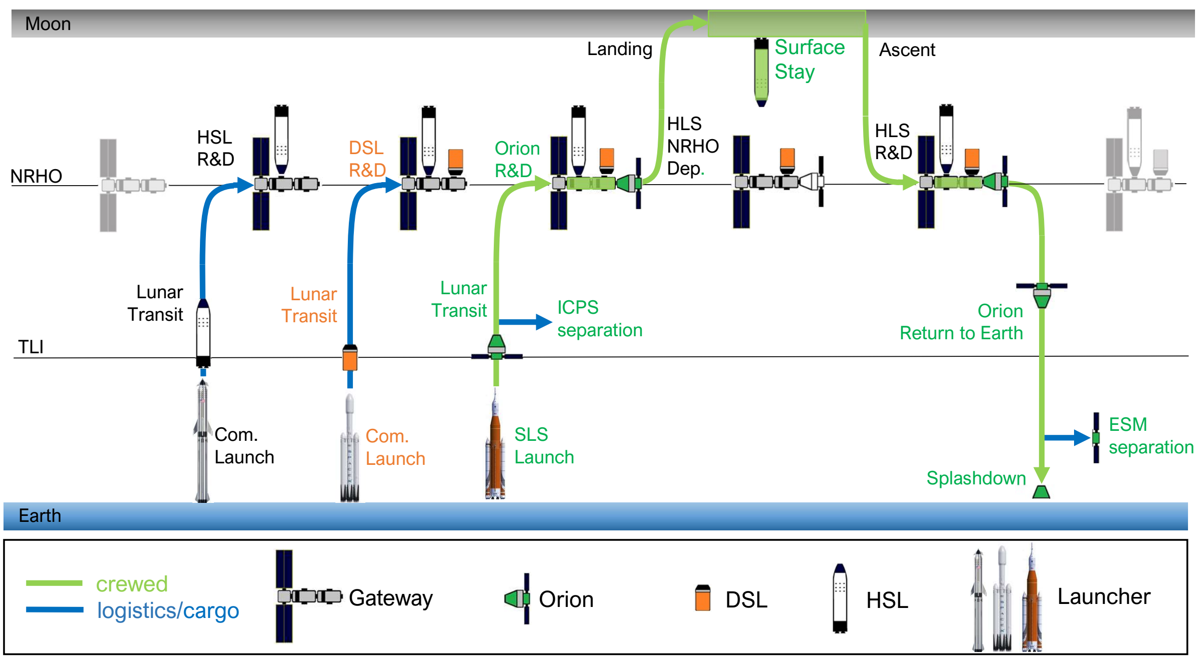


Fig. 3–3: Design Reference Mission, displaying the basic mission steps and their used vehicles

Once all logistics and mission vital elements are in place the Orion spacecraft will launch on top of a SLS rocket and deliver a crew of four to the Gateway. The crew can then conduct science at the Gateway or transfer to the HLS and descent to the Lunar surface. Orion will remain docked to the Gateway providing vital radiation shelter, extra living space and act as an emergency life vessel in case of a sudden return to Earth. At the end of the mission the crew will board Orion and return to Earth. This basic concept, displayed in Figure 3–3, indicates manned flights and stays with green lines and logistic or resupply flights, that are unmanned, in blue.

In order to access the impacts of a continuous operations of the Gateway in comparison to a short term crewed operation these two different mission scenarios, also referred to as modes, are developed. The modes are called the continuous and the campaign mode. They differ in their duration. In case of the campaign mode a short duration of six weeks, a 42 days stay at Gateway is planned. For the rest of the time Gateway will be in an automated standby operation. In the continuous mode a six month crew rotation onboard of the Gateway is implemented, thus an automated Gateway operation is not needed. For both missions a Lunar excursion of four weeks is considered, and takes place prior to the stay on the Gateway because Astronauts might have difficulties adapting to the minimal gravity on the Moon after staying in weightlessness for six months. A further driving design parameter is the selected ECLSS that influences the need for resupply flights. Both previously described ECLSS systems, the regenerative ISS system and the non-regenerative CAMRAS based system, are used for developing four different mission scenarios. On overview of all four scenarios is listed in Table 3–2. The duration only indicates the time spent on board of the Gateway and excludes the four weeks on the lunar surface, where the HLS is providing the crew with life support.

Tab. 3–2: Selected mission modes and ECLSS together with their daily resupply masses, duration and required total resupply mass for the Gateway per mission

Mission Mode	ECLSS Type	Resupply mass [kg/day]	Duration [day]	Total resupply mass [kg]
continuous mode	regenerative	12.17	196	2385.32
	non-regenerative	27.16	196	5323.36
campaign mode	regenerative	12.17	42	511.14
	non-regenerative	27.16	42	1140.72

4 Mission Concept

The mission concept presented in this chapter describes the operational tasks required to enable the success of a mission. A mission refers to a crewed spaceflight to the Moon, beginning with the launch of the crew from Earth until they return. Vital aspects like logistic flights that are required to enable the mission are also considered. In total two major mission concept modes are given. The continuous mode, where a crew is permanently present onboard Gateway and in contrast the campaign mode, where a single crew visits the Gateway for a limited period of time. Both modes include a four week Lunar surface excursion that is identical in all missions presented. An alternation of the life support systems, one more and one less regenerative, is also being considered and displayed, giving a total of four different mission concepts.
First, a description of the methods used to display and describe the concepts, is given. Three major representations were chosen to create an understanding and insight of the proposed missions, followed by the presentation of the different mission modes.

4.1 Description of Methods

In this section the methods used to present the missions and their progression are described. Starting with the general Spaceflight Architecture, to give an initial insight on the multiple spacecrafts used. This is followed by the sequence of events and the more detailed Timeline of the mission.

4.1.1 Spaceflight Architecture

The Spaceflight Architectures objective is to give an overview on the vehicles and elements used throughout the progression of the mission. The diagram used to display this architecture is designed in a way that allows a distinct and conclusive identification of the spacecrafts, their orbits and docking or undocking sequence. Time intervals are not explicitly given, but the mission advances from left to right.

In Figure 4–1 an illustration of a fictive spaceflight architecture is given, where all elements are labeled and described through blue boxes. The purpose of this diagram is solely to show the used logic behind the Spaceflight Architecture. The main features are the Earth at the bottom and the Moon at the top of the diagram indicating these two reference bodies. Orbits are displayed as lines in certain distances to each other. In this case the NRHO is displayed closer to the Lunar surface to indicate its proximity. The spacecrafts that reach or are in this orbit are pictured on top of the orbit line. The different spacecrafts have unique primary colors and their event descriptions are in accordance to the spacecraft's color. The short cut 'R&D' stands for rendezvous and docking, other shortcuts mainly refer to the elements used like the SLS or ESM.

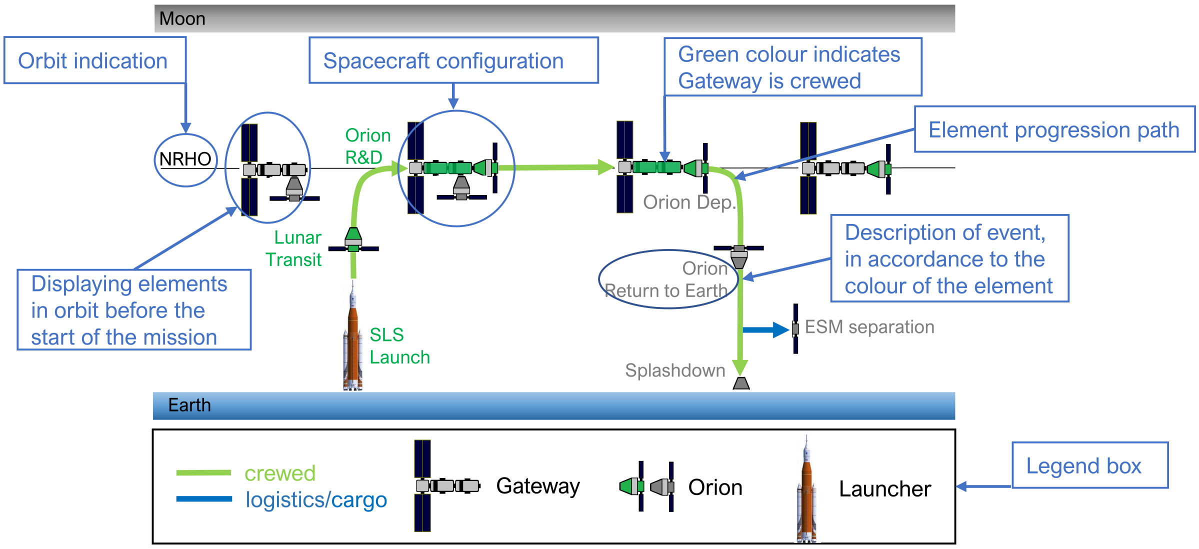


Fig. 4–1: Description of the flight architecture diagram

The element's progression path is colored in green or blue depending on a crewed or uncrewed element. This also holds true for the Gateway station that is colored in green when a crew is onboard the station. Further, at the bottom of the diagram is a legend box located to help identify all elements used throughout the mission.

4.1.2 Sequence of Events

The sequence of events gives an overview on the required crewed and logistic flights to enable the success of the mission. Further, it gives an insight on the number of crew members involved and the docking port in use at the Gateway station. The docking duration and resupply intervals are selected carefully in accordance to the used ECLSS and spacecrafts payload capabilities. Also influencing factors such as launchers available and spacecraft flexibility is taken into account for this sequence of events to generate a favorable redundancy and hence increasing the probability of mission success. Besides these factors, boundary conditions concerning the Gateway station and the Orion spacecraft are considered in accordance with the descriptions from the previous Chapters.

The diagram describing the sequence of events, is given in Figure 4–2 and built as follows. The top section gives the indication of the mission duration through the weeks that are listed in the second row below. Every time a mission starts a red line can be seen in the week row. The numbering of the weeks is bound to the start of Mission 1 and continues in an incrementing manner from there. The column on the left describes the used vehicles and is split into three sections where the upper section lists the HLS and Orion and their number of crew members onboard throughout the mission. For Gateway it also indicates when the mission is in an automated uncrewed mode. Below the Gateway a row labeled 'Port Usage' can be seen that shows the numbers of ports

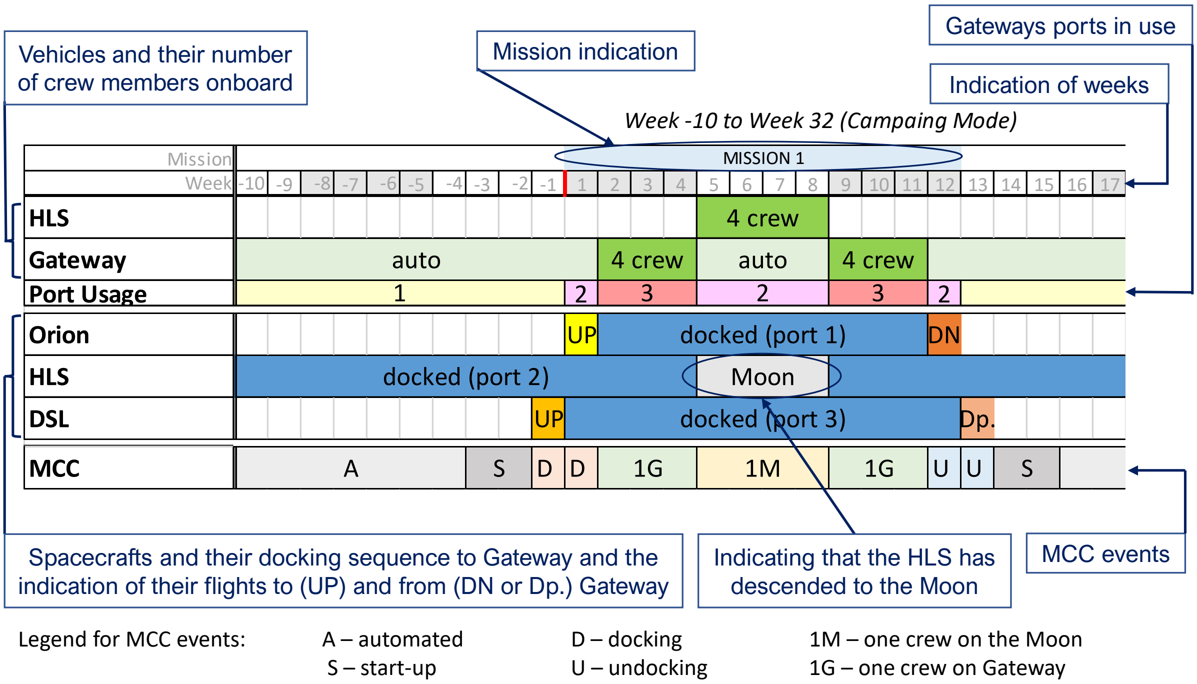


Fig. 4–2: Description diagram for the sequence of events

occupied throughout the weeks. The major section below lists the Orion, the HLS and the DSL and gives the docking sequence of these elements towards the Gateway station. Therefore the HLS is listed here again, because when it is not used for a Lunar mission it is assumed to be docked to Gateway. For the DSL it needs to be mentioned that when different spacecrafts are used the name of the used spacecraft will be listed instead. The last section labeled with MCC gives a basic overview on the different major activities for the ground control and described in a legend at the bottom of Figure 4–2. The major events and shortcuts used throughout the Sequences of Events are labeled in the following way:

- 'UP', indicating a flight from Earth towards the Gateway
- 'DN', indicating a flight from the Gateway back to Earth
- 'Dp.', indicating the disposal of a logistics spacecraft
- 'docked (port number)', indicating that a spacecraft is docked during these weeks at the Gateways port given in brackets
- '4 crew', for the Gateway and the HLS the number of crew members on board is displayed

The time steps used in the sequence of events are one week, allowing to display the period of more than one and a half years of operations. The maximal mission duration for the continuous mode is 33 weeks per mission and thus the presentation of one and a half years becomes necessary to show the overlaps crew handovers.

4.1.3 Timeline

The timelines given in the following chapters are a chronological arrangement of events of what will take place throughout the mission. They refer to a single crew and their tasks in the expected order of their occurrence and show the operational tasks that are necessary to conduct a successful mission. Further, they indicate where routine crew time for science and experiments is available, besides the operational tasks that are required to ensure the progress and success of the mission.

The timeline gives each day of the mission. A legend and description for the buildup of the timeline is given in Figure 4–3. The days are split in 24 possible sections, representing a 24 hour day. The resolution for events and tasks goes down to one hour and always refers to the entire crew. Implicating that a crew is assigned the same task. A crew is expected to consists out of four crew members. A more detailed or individual assignment of tasks does not make sense at the present state of progress in mission planing. Due to this fact the exact distribution of tasks within the crew members will vary and the sequence of tasks given will not be identical for all crew members. The spotlight lies on the overall hours spent throughout a day and these will be identical for all four crew members. Thus the timeline, even though it is planned for the entire crew, can be read as the time spent by a single astronaut. For example, when the crew is assigned two hours of exercise and seven hours of work, not all four crew members will exercise simultaneously and then work, but exercise evenly distributed throughout the day and spend the rest of the time at work. At the end of the day all four crew members will have spent the same amount of time on the assigned work, but not necessarily at the designated time slot.
In general tasks are assigned in a way that allows this flexible distribution of crew members towards the tasks and often include buffer throughout the day as only seven hours of work are assigned specifically where possible.

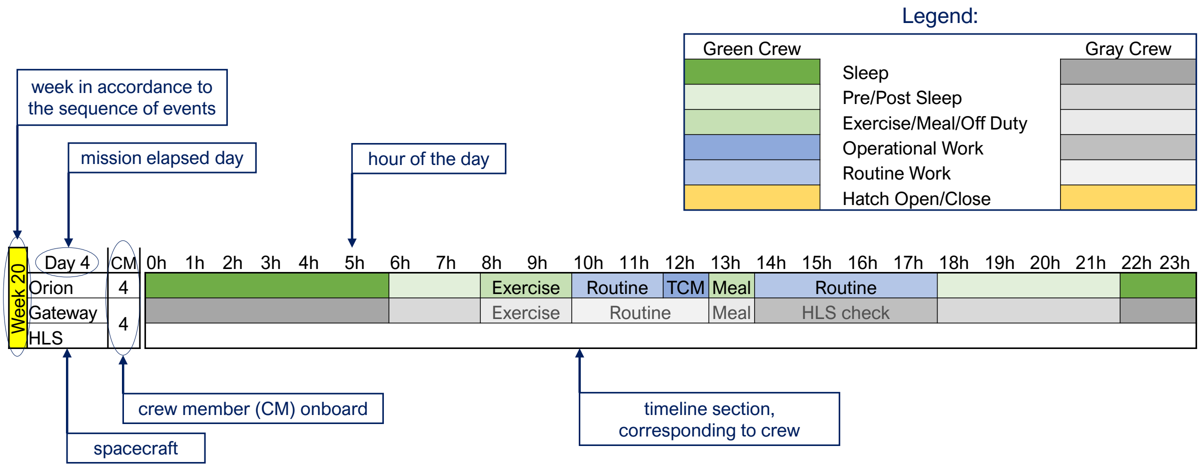


Fig. 4–3: Legend for the timeline, showing the used colors and their corresponding tasks for both, the Green and the Gray Crew as well as explaining the different rows and columns.

For the representation of the various tasks, different colors are used and shown in the legend located in the upper right corner of Figure 4–3. The differentiation in the Green and Gray Crew comes from the circumstance that in the Continuous Mode during some weeks two crews are in space and for a total of two weeks both crews are onboard the Gateway. To better identify and separate the crews different colors are used, highlighting the Green Crew as the crew that is followed through the mission. Therefore, the Gray Crews tasks are differentiated through different gray tones, whereas the Green Crew shows more variety. The leisure or recreational tasks are separated through different green tones for the Green Crew and are divided in the main groups of sleeping, pre- or post-sleep times as well as exercise, meal and off duty time. Work is indicated in a blue color tone, where operational work gets a more intense tone than routine work. One last major color is yellow, used to indicate when hatches are opened or closed, due to the fact that this always involves both crews on either side of the hatch. The color is identical for both crews.

The left block of the timeline shows the corresponding week and mission day also shows three lines for the spacecrafts of interests. The column 'CM' indicates the crew members onboard each spaceship. When a spaceship is docked a single number spanning the relevant rows is given, and thus indicating that the number of crew members are onboard both spacecrafts with the hatch open.

The timeline section directly corresponds to the crews and the line chosen correlates to the most relevant spaceship for the crew at that time. Throughout the mission it can be seen that the crews change the rows within the section, when a hatch is opened or closed. This happens in accordance to the crew changing the spacecraft and thus aims to feature the vehicle of main interest.

4.2 Campaign Mode

In the campaign mode, the goal is to fly a single mission to the Gateway and the Moon within a year. During the rest of the year the Gateway is in an automated and uncrewed mode. In this scenario the HLS is assumed operational in a reusable manner and thus docked to the Gateway. The crew will consist of a total of four astronauts and all four will descent towards the surface during the four week long Lunar excursion. This makes a three week stay onboard the Gateway before and after the excursion necessary. The total mission duration including the flights from and back to Earth will then be 12 weeks.

4.2.1 Spaceflight Architecture

The flights required to make the Campaign Mode possible are shown in the Spaceflight Architecture diagram in Figure 4–4. The Gateway can be seen already in the NRHO with the docked HLS before the launch of any vehicle. Also displayed is the TLI indicating which spacecraft is send to the NRHO.

Before the crew can launch, the logistics have to reach the Gateway with the DSL spacecraft and provide the required ECLSS equipment and payload. The Orion spacecraft with a crew of four will launch from Earth to the NRHO and dock there with the Gateway, indicated with the green line. The Gateway is now crewed and gets a green color in Figure 4–4.

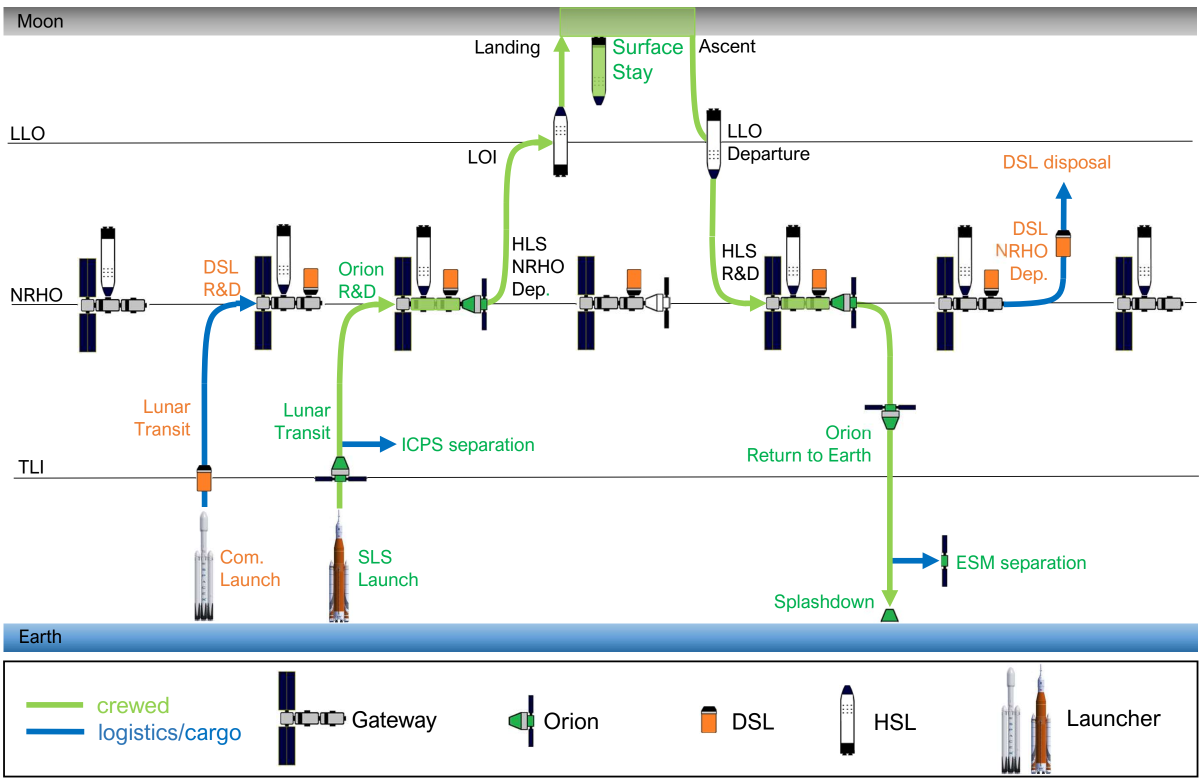


Fig. 4–4: Flight architecture of the campaign mode

The Lunar excursion takes place thereafter while the Orion remains docked to the uncrewed Gateway. The HLS performs a Lunar Orbit Insertion (LOI) and remain there until the landing is initiated. It stays on the surface for four weeks with the crew onboard and therefore the HLS can be seen marked in green during this period. Then the HLS returns to the Gateway and the crew is onboard the Gateway with the still docked Orion and DSL. After three weeks the crew returns to Earth onboard their Orion spacecraft and thereafter the DSL will be disposed, while the Gateway and the HLS remain in the NRHO until the next campaign towards the Moon is launched.

To enable the mission the Gateways ECLSS requires a total resupply mass of 1140.72 kg for the non-regenerative system and 511.14 kg for the regenerative system. This makes a single DSL flight sufficient for both cases of the Campaign Mode, as the Dragon XL is expected to be able to carry 5000 kg and the Cygnus XL 3000 kg. The logistics flight will depart prior to the crew in an automated manner and be already present at the Gateway before the crew arrives. It is also possible to load the DSL with supplies for the Lunar excursion specifically for this mission. Cargo volume can also be used for fuel for the HLS if the system is designed for it. Depending on the Lunar excursion further supply flights are possible, also direct supplies to the Lunar surface could be an option, but for the sole purpose of this mission, a single logistic flight is sufficient. This logistic flight is very likely to be conducted by a commercial launcher and will reach the Gateway fully autonomously.

4.2.2 Sequence of Events

The single launch campaign to the Gateway and down towards the Lunar surface will require the Gateway to be in an automated standby mode during the unmanned period and be reactivated to an active mode before the crew arrives. During the Lunar excursion, the Gateway will be in a standby mode with increased automation. The stay onboard Gateway will be six weeks in total giving the crew three weeks prior to the descent and three weeks afterwards. This should give the crew enough time to conduct all necessary tasks to enable a Lunar excursion to the surface, while using Gateway as a hub. The HLS is assumed to be already docked at Gateway and is used for the descent to the surface, as well as acting as a habitat on the surface during the four week stay. The HLS also acts as an ascent module from the Moon. The sequence of events given is designed independently from the used HLS due to the high uncertainty concerning the used vehicle and concept at present.

Figure 4–5 shows a 33 week schedule on how a campaign mode mission would look like. The numbering of the weeks starts with the launch of the crewed Orion. But to show the automated mode of Gateway indicated with 'auto' ten weeks before and after the actual mission are also displayed. This also enables the display of the vital logistic flight prior to the launch of the crewed mission, and disposal after the 12 week duration of the mission. The crewed mission duration includes one week of flight towards the Gateway, indicated in yellow with UP and one week for the return flight indicated with

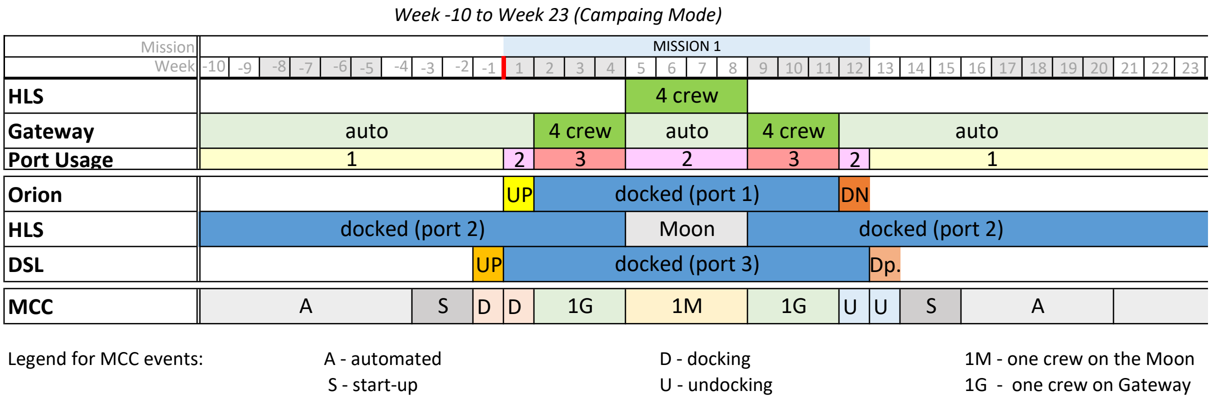


Fig. 4–5: Sequence of events for the campaign mission mode, displaying the section for the crew members onboard with the Gateways port usage on top. The section indicating the docked spacecrafts and their docking and unlocking sequence in correspondence to the weeks in the center, and the MCC's events in the bottom.

an orange DN. The transfer flight itself only takes about five days, but in the schedule a week is reserved. This provides buffer in case of any delays caused for instance by bad weather. The DSL reaches the station before the Orion and its crew and leaves after they have already returned to Earth. This reduces work load and stress, as the DSL docks and undocks automatically without crew assistance and thus is performed before and after the crewed mission. The crew then only needs to unload and later load the spacecraft and prepare it for undocking. The arrival of the DSL prior to the crew is vital to ensure all supplies are already at the Gateway. An earlier launch of the DSL than one week in advance is therefore also plausible.

4.2.3 Timeline

In this subsection the timeline for the campaign mode will be given. It correlates to the missions sequence of event that can be seen in Figure 4–5. The crewed mission starts in week 1 and lasts for a total of 12 weeks until week 12. Due to the short duration, no difference between the regenerative or non-regenerative ECLSS arises, concerning the required logistic flights, but the amount of available payload would be deceased in a non-regenerative case. The working hours that result from the different weeks are listed in the Appendix Table A3 for detail. The EVAs are a part of the routine working hours whilst onboard the Gateway and are more of an indication of the possibility to conduct EVAs.

4.2.3.1 Week 1 of the Campaign Mode: Orion Launch

Week 1 for the campaign mode starts with the launch of the Orion spacecraft towards the uncrewed Gateway. Due to the fact that only a single crew is present, only one row of the timeline is occupied.
From ground control the space station is already activated from a standby mode to an operational mode two weeks in advance to ensure that the Gateway's ECLSS is operational when the crew arrives.

Day 1, as shown in Figure 4–6, of the mission begins with the launch of the orion and the ascent phase, labeled with 'ASC' for ascent. Thereafter follows the Early Orbit Phase (EOP) where checkouts and inspections are conducted as well as the designated Orbit for the following TLI is reached. After that, the Orion is en-rout towards the Moon and the Interim Cryogenic Propulsion Stage (ICPS) that performed the TLI burn can be separated. The crew now has time for a meal and will perform Trajectory Correction Maneuver (TCM)s as well as an inspection of the spacecraft. Days 2 and 3 follow an identical plan with six hours of routine, two hours of exercise and one hour reserved for TCMs. Day 4 is then an off-duty day where the crew should relax and recharge before reaching the NRHO on day 5. In the morning of day 5 the orbit insertion takes place followed by the docking preparation. After the meal the rendezvous is conducted. When the leak check is complete the crew is done for the day, depending on the ECLSS startup of the Gateway the crew can already transfer to the station. On day 6 they need to complete the startup of the space station. For this a total of 12 hours per crew member is reserved and may also include maintenance work if necessary to ensure and undisturbed operation throughout the coming weeks.
During this first days on Gateway, the Orion capsule remains activated in case a major malfunction that require the Orion to take over the primary life support for all four crew members. This will most likely result in an abortion of the mission and a return to Earth. In general the Orion acts as a life vessel to enable the return to Earth when needed, but when docked to the Gateway the space station will take care of the primary ECLSS.

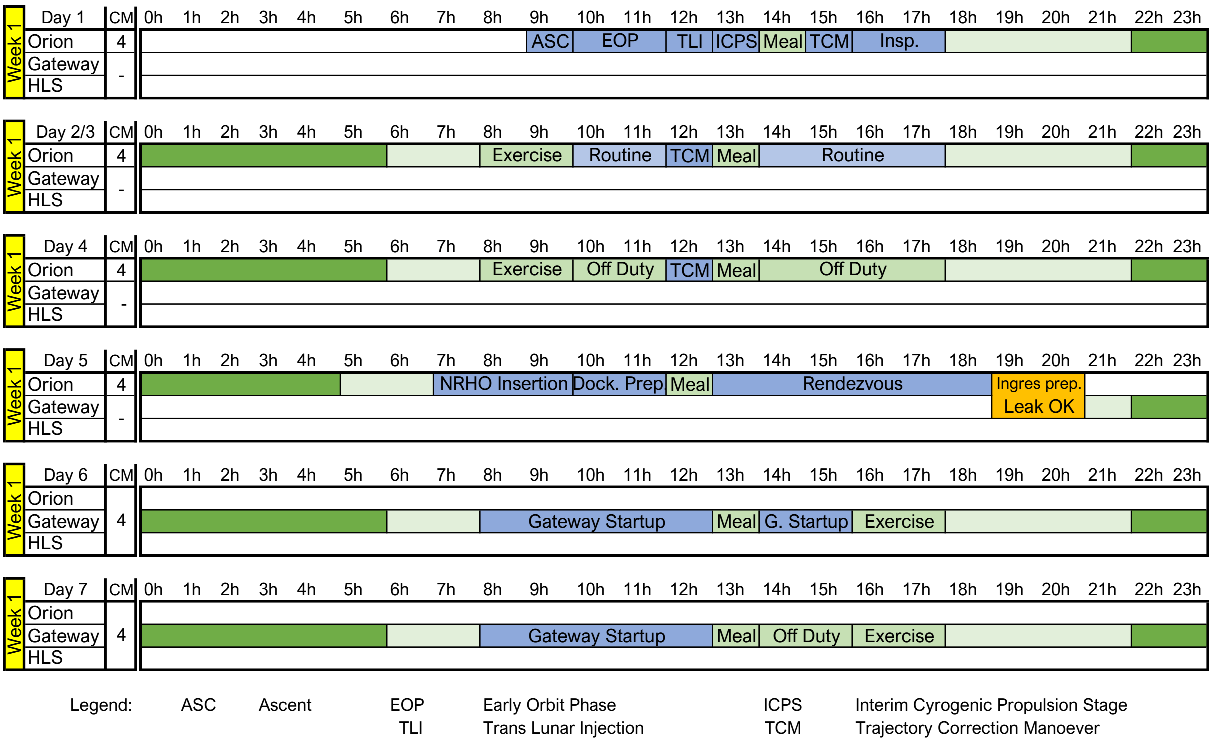


Fig. 4–6: Campaign mode timeline week 1, Orion Launch

4.2.3.2 Week 2 of the Campaign Mode: Gateway Arrival

Now that the crew has arrived at the Gateway and the station is completely operational the focus of week 2, as shown in Figure 4–7, lies on unloading and storing payloads from the Orion as well as the previously docked DSL. In the beginning of the week the crew will transfer all payload from the Orion Spacecraft to the Gateway. This also includes possible unpressurized equipment that needs to be unloaded via the robotic arm. Also, cargo or equipment that needs to be transferred or stored to the HLS, that is already docked to the Gateway. The HLS has either arrived at the Gateway a few weeks earlier through an automated flight or is docked to the Gateway since the last crew used it for their lunar descent. For this transfer task the complete working time of day 1 and a major portion of day 2 is used. Day 2 ends with the weekly medical conferences. On day 3 the crew is off duty in the morning and has time for housekeeping in the afternoon. This can also include minor maintenance work that was not complete during the Gateway startup. On day 11 the crew is off duty, and has time to recover and unwind. Day 12 has time to unload the docked DSL. It was docked to the station automatically in advance and has food, experiments, repair parts and other payload onboard. It can also have unpressurized equipment that needs to be unloaded with the robotic arm, therefore day 13 is reserved for the same purpose of unloading the DSL spacecraft as well and is identical to day 12.
Day 11 is a routine day that can also act as a buffer day in case the launch is delayed or other complications during the Gateway startup may move the timeline.

Fig. 4–7: Campaign Mode timeline week 2, Gateway Arrival

4.2.3.3 Week 3 of the Campaign Mode: Gateway Operations

Week 3 is shown in Figure 4–8, where on the first day, day 15, the HLS is operational from its start two weeks prior of the Lunar excursion to ensure it is fully functional. Therefore, its systems are monitored as long as it is docked to Gateway and does not act as a primary habitat. The rest of the day the crew can perform routine work as on day 26 that ends with the weekly medical conference. This week contains more buffer than the previously intense weeks, where a launch delay would move the entire scheduled backwards. Day 17 starts as a off duty day and includes the housekeeping in the afternoon. Days 18 and 19 present routine days that could also include EVA's. This is indicated on day 19 and depending on the conduction of an EVA the routine working hours will be 27 or 33 hours in this week due to the increased time required for pre- and post-EVA preparations. The EVA's at the Gateway can be due to repair or installation work outside the station that cannot be conducted via robotic operations or experimental setups that need to be installed by hand. In the case an EVA takes place, a maximum of two crew members would leave the station while the others support the EVA from the inside. Day 20 provides more time for routine work, and in the afternoon the HLS, that is now up and running for six days, is checked for anomalies or system failures. Day 21 is an off-duty day for the crew.

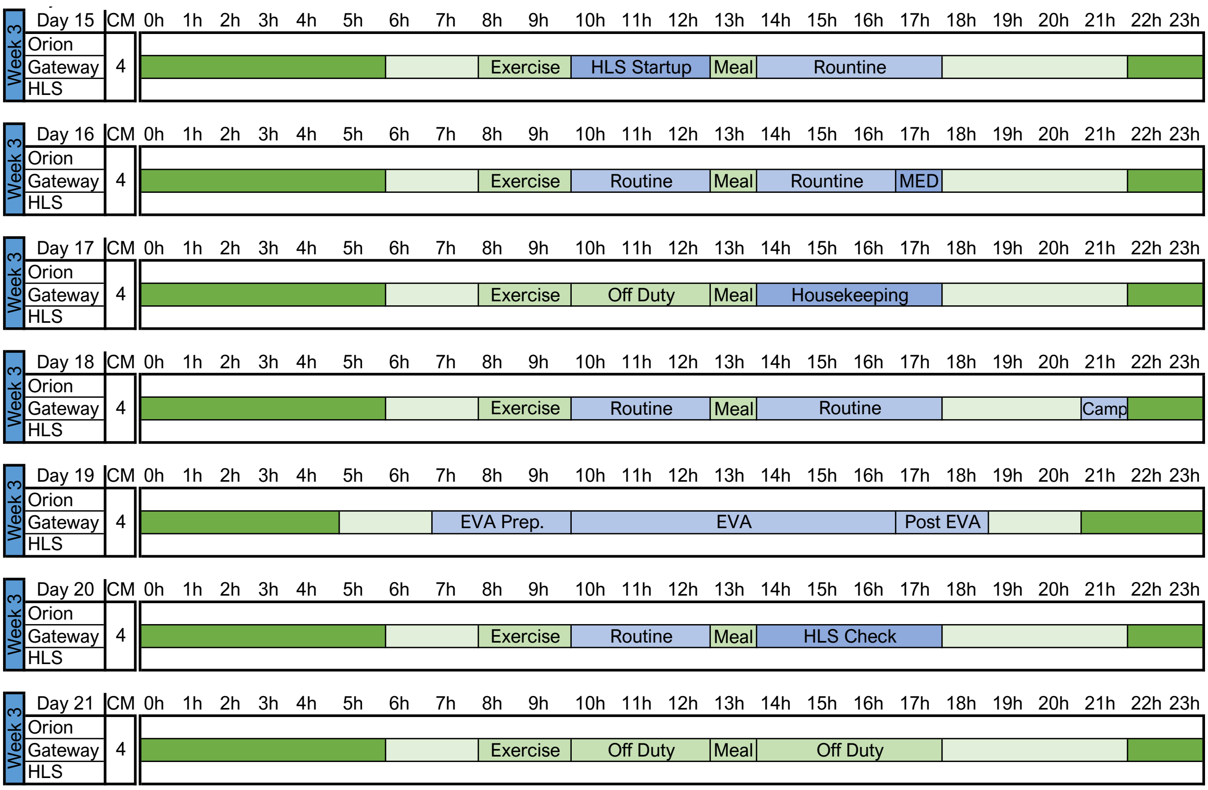


Fig. 4–8: Campaign mode timeline week 3, Gateway Operations

4.2.3.4 Week 4 of the Campaign Mode: Lunar Preparation

In week 4, shown in Figure 4–9, the preparation of the HLS for the Lunar excursion lies in the main focus. On day 22 the HLS is prepared for the four weeks surface stay. This includes maintenance work and repairs. Day 23 acts as a buffer and routine day and on day 24 the lunar preparation includes crew preparation, and equipment as well as other required setups for the excursion. In the afternoon the medical conference takes place and day 25 is off duty except for the housekeeping in the afternoon. Day 26 is then a general off duty day. On day 27 the transfer of payload and equipment to the HLS, that was not moved already earlier during lunar preparation or the unloading of the Orion is now moved into the HLS. This could again include unpressurized payloads that are brought to the Lunar surface.
Due to the fact that in this scenario the entire crew is descending to the surface of the Moon, some of the Gateways systems need to be put to standby again on day 28. This would not be necessary if crew members stay behind on the Gateway as it is planed for the first missions, but reduces the available crew time on the surface.
At this point HLS is up and running and fully functional since the lunar preparation was complete and thus after the Gateway is configured for the crew to leave the hatch is closed at the end of day 28 with the crew onboard the HLS. Thereafter the HLS will remain docked through the night.

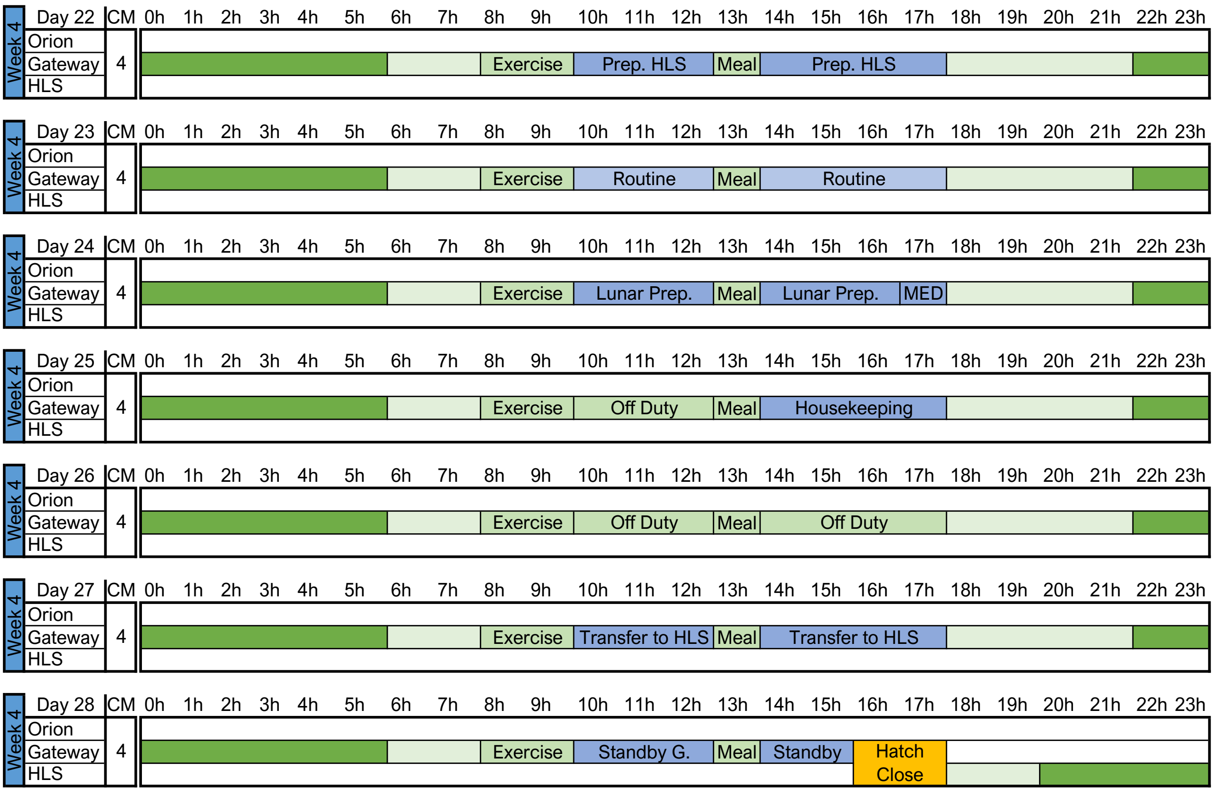


Fig. 4–9: Campaign mode timeline week 4, Lunar Preparation

4.2.3.5 Week 5 to 8 of the Campaign Mode: Lunar Excursion

The Lunar excursion takes place in week 5 to week 8. The crew will undock on day 29 and depart the NRHO down to LLO the where they will conduct the LOI after a 12 hour transfer. During the transfer the crew will conduct some inspections and TCMs. There is also time for routine work and otherwise the crew is off duty. The HLS will remain in the LLO over night and conduct the landing on the next day on the afternoon after the cabin stow and descent. In the evening the crew will start preparing for their fist Lunar EVA. The routine on the Lunar surface from day 32 to day 53 will focus on the EVAs and therefore Figure 4–11 will demonstrate how this week might look to all four crew members as they will not all conduct an EVA every day.
The general crew view for the Lunar excursion is identical in the Continuous Mode weeks 23 to 26 found in Figures 4–22, 4–23 and 4–24 respectively.
The beginning of week 5 and the end of week 8 is given in Figure 4–10 below to clarify the transitions at the beginning and the end of the Lunar excursion. The pink line marks the cut in the timeline, where the crew will perform two and a half weeks of EVAs. Day 54 marks the end of the routine Lunar surface stay and includes a spacecraft inspection in the afternoon. Day 55 starts with the launch preparations and the ascent in the evening. The flight back to the NRHO will be performed through the night and on day 56 the HLS will rendezvous with the Gateway again.

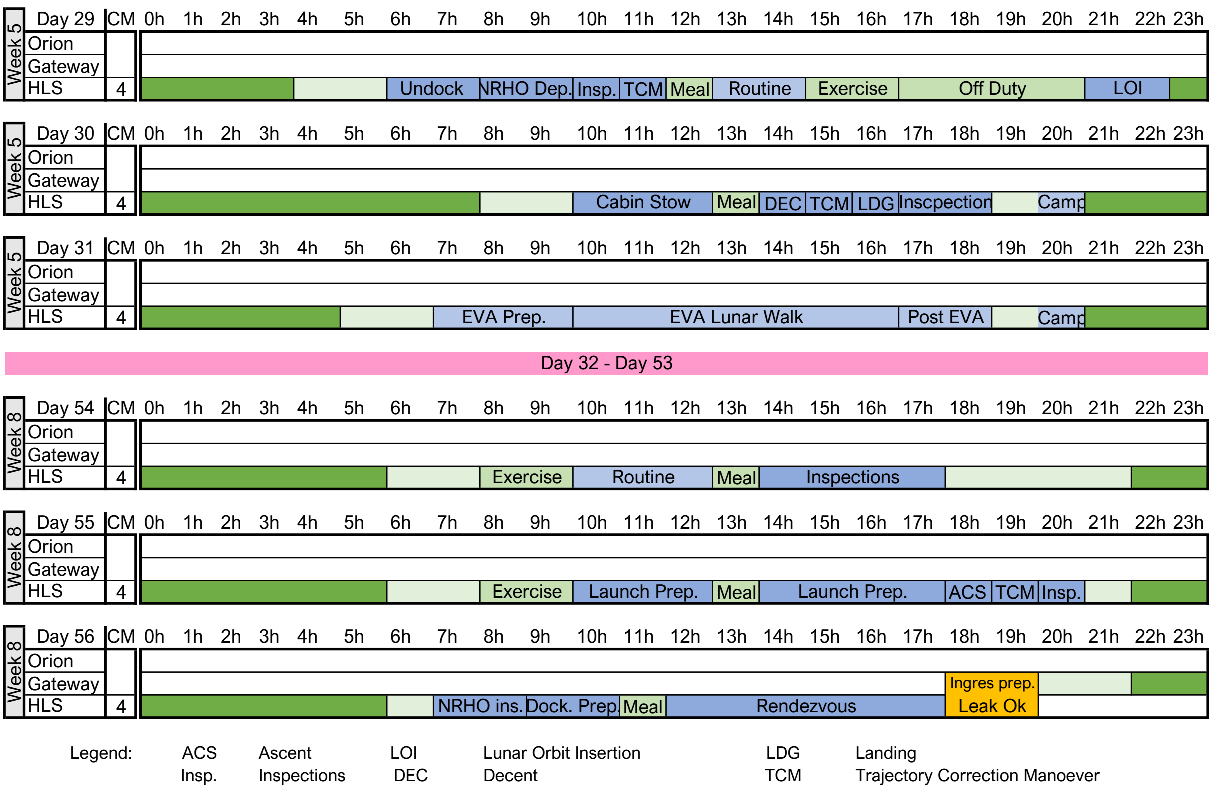


Fig. 4–10: Campaign mode timeline week 5 to 8, Lunar Excursion

During the Lunar excursion the priority in work will lie on the exploration and science on the Moon specially in the form of EVAs. To show how a routine week on the surface of the Moon could look like Figure 4–11 shows days 36 to 41 for all four crew members explicitly.

The scheduled is chosen in a way that the maximal working hour for a single Astronaut does not surpass the routine working time of 40 hours. Together with five hours of Operational work like housekeeping, it will end at a tight 45 hour working week. Therefore, an extra off duty day is inserted for each crew member. In the proposed EVA overview a maximum of two EVAs per crew member are conducted with a break of at least two days in between. Two Astronauts will go on an EVA together while one of the other two is supporting the EVA. The fourth Astronaut is off duty. Day 38 is reserved for cleaning of the EVA equipment as the harsh Lunar environment poses a thread to the suites especially the fine grained Lunar Regolith. On days 39 and 40 the scheduled from the previous days is repeated, where two and two Astronauts will go on an EVA while the other can support or are off duty. The weekend is reserved for off duty time and housekeeping as well as the medical conferences.

Fig. 4–11: Week 6 during the Lunar excursion, displaying the EVAs per crew member

4.2.3.6 Week 9 of the Campaign Mode: Return to Gateway

In week 9, as shown in Figure 4–12, the crew has returned from their surface excursion. The docking maneuver, performed on the last day of week 8, is shown in 4–10. The Gateway station that was in standby mode, needs to be reactivated. This is expected to require a full day until all systems are fully operational and the Gateway can provide the primary ECLSS. For this task day 57 is reserved. The next day, day 58, the transfer of payload, samples and equipment from the HLS to the Gateway or directly to the Orion can take place. Also unpressurized samples or cargo can be transferred via the robotic arm. In the afternoon the medical conferences are held for the crew members. Day 59 is off duty in the morning and includes four hours of housekeeping in the afternoon, this housekeeping will mainly focus on the HLS that is now going to be unloaded and shut down. Day 60 is an off duty day for the crew before on day 61 the HLS is unloaded completely. After this, on day 62, the HLS is checked and maintained before being shut down or moved to an inactive state while docked to Gateway for the next months. The pressurized volume of the deactivated HLS can still be used, depending on the size of the used lander otherwise the hatch could be closed or the HLS kept operational to provide ECLSS for its pressurized space. Day 63 indicates time for routine work and acts as a general buffer day for the works this week or a delayed lunar launch.

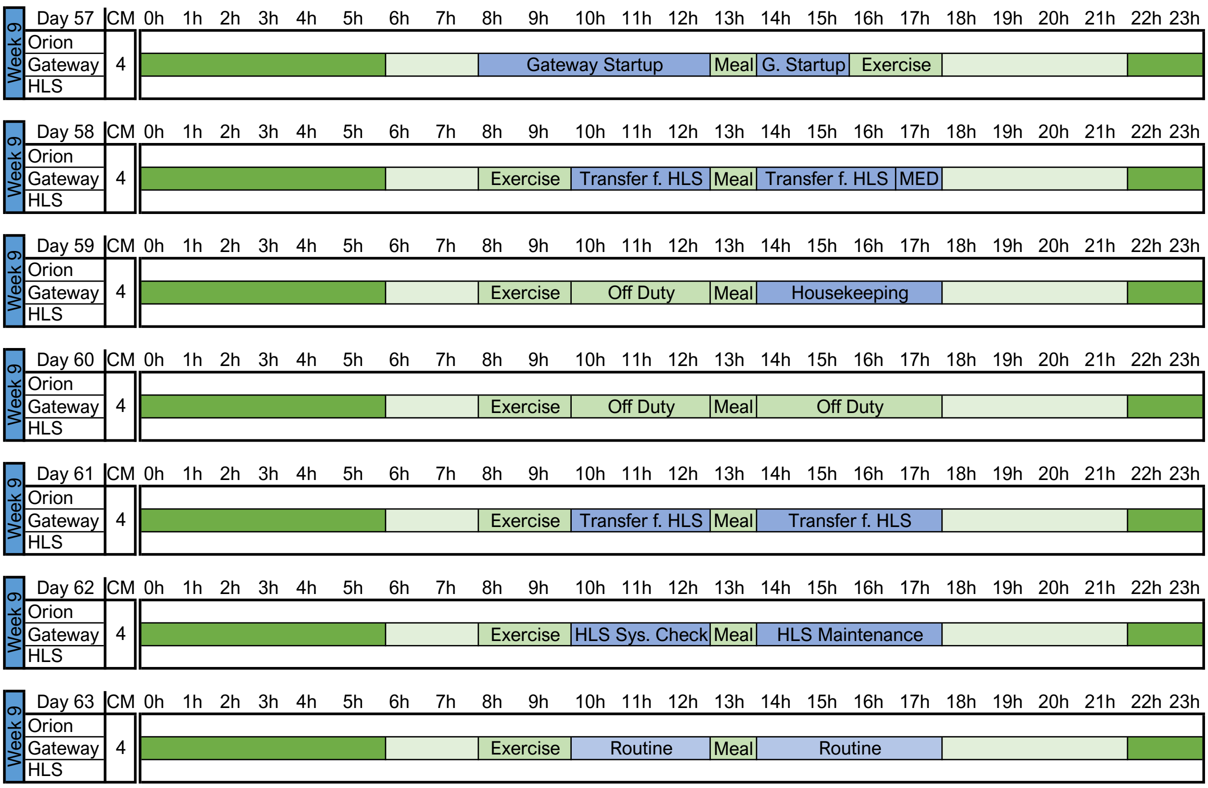


Fig. 4–12: Campaign mode timeline week 9, Return to Gateway

4.2.3.7 Week 10 of the Campaign Mode: Routine

Week 10, seen in Figure 4–13, is a routine week onboard the Gateway allowing EVA's. This week is in some sense comparable to the weeks 29 to 44 in the Continuous Mode, where operational work is kept at a minimum to conduct science experiments.
In general, this week sees no days that are acting as buffer or reduce the routine time in an other way. Housekeeping and minor maintenance will take place on day 66 in the afternoon, after the morning was already off duty. The medical conference will be the night before on day 65.
The EVA indicated on day 68 is to show the possibility and will not be done by every crew member. Also the day of the EVA is not fix and it is feasible that different crew members conduct different space walks on different days throughout the week. But when considering one crew member alone in the schedule, a single spacewalk already is adding up to a total of 40 routine working hours and therefore seems plausible. If the same crew member needs to perform multiple EVA's he might require a further off duty day to keep the workload at a feasible level.
Due to a slight shift in the scheduled of working days from the previous weeks the off duty days are moved apart to counteract the circumstance of a longer than five day working period. Therefore, the second off duty day in this week is on day 70.

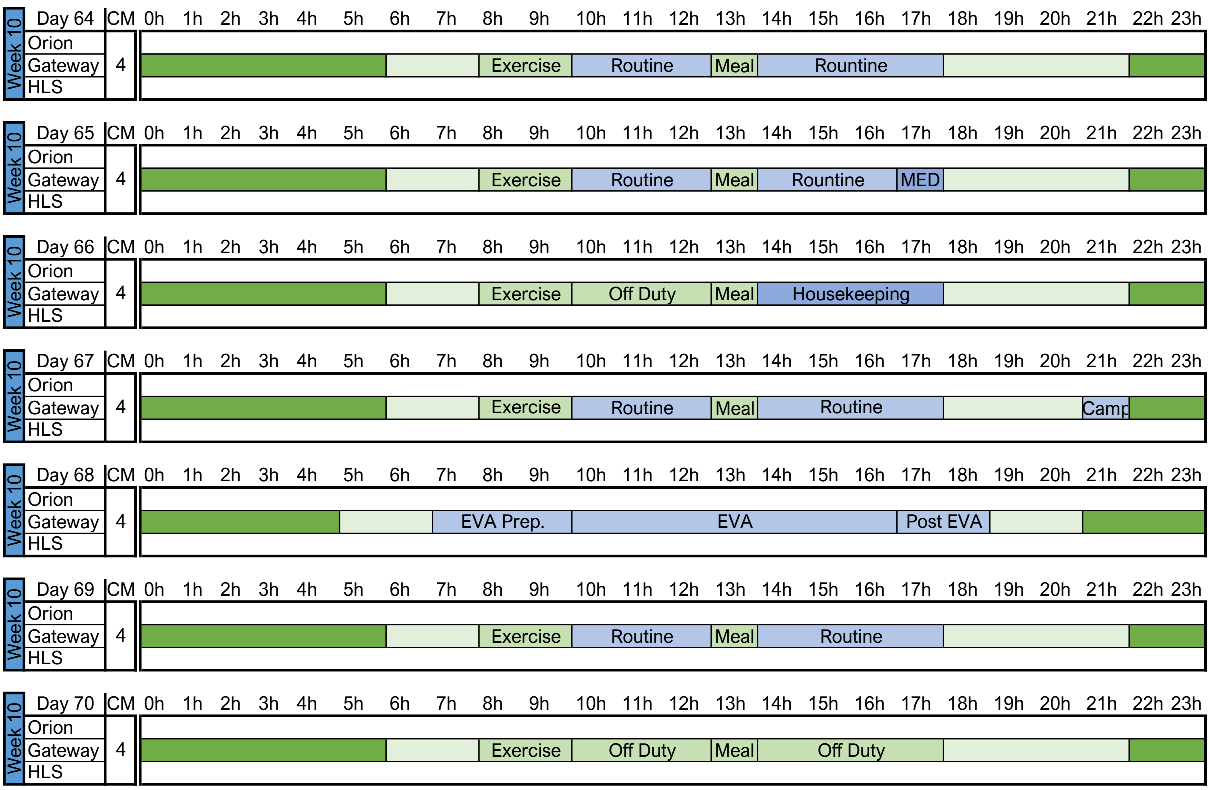


Fig. 4–13: Campaign mode timeline week 10, Routine

4.2.3.8 Week 11 of the Campaign Mode: Gateway Shutdown

In week 11, seen in Figure 4–14, the crew prepares for their return to Earth. Starting with the loading of the DSL on days 71 and 72. The DSL was docked for the entire stay of the crew and its pressurized volume was available throughout the entire mission. The hatch is closed at the end of day 72, but the DSL will not undock until week 13, when the crew has already left. This is to reduce extra work and distraction of the crew that has already a tight schedule to follow. With the hatch closed and all systems set, the DSL will undock automatically and be disposed, in accordance to the selected disposal variant.

Days 73 and 74 are off duty except for the weekly housekeeping on day 73 in the afternoon. Day 75 is reserved for a general Gateway check and to perform routine or necessary maintenance of the station prior to leaving. On day 75, the Orion is being loaded and payload is transferred to the Orion. Also the Orion is prepared for the return flight to Earth. The payload might include payload brought from the Lunar surface. In the end of day 76 the medical conference takes place.

Day 77 marks the end of the mission onboard Gateway. The station is shutdown and configured for remote operations before the hatch to the Orion spacecraft is closed. This is indicated in the timetable with 'Shutdown G.'. The complete shutdown or standby operation will be conducted throughout the following weeks from Earth. After that the Gateway will be controlled from a MCC in an automated mode from Earth.

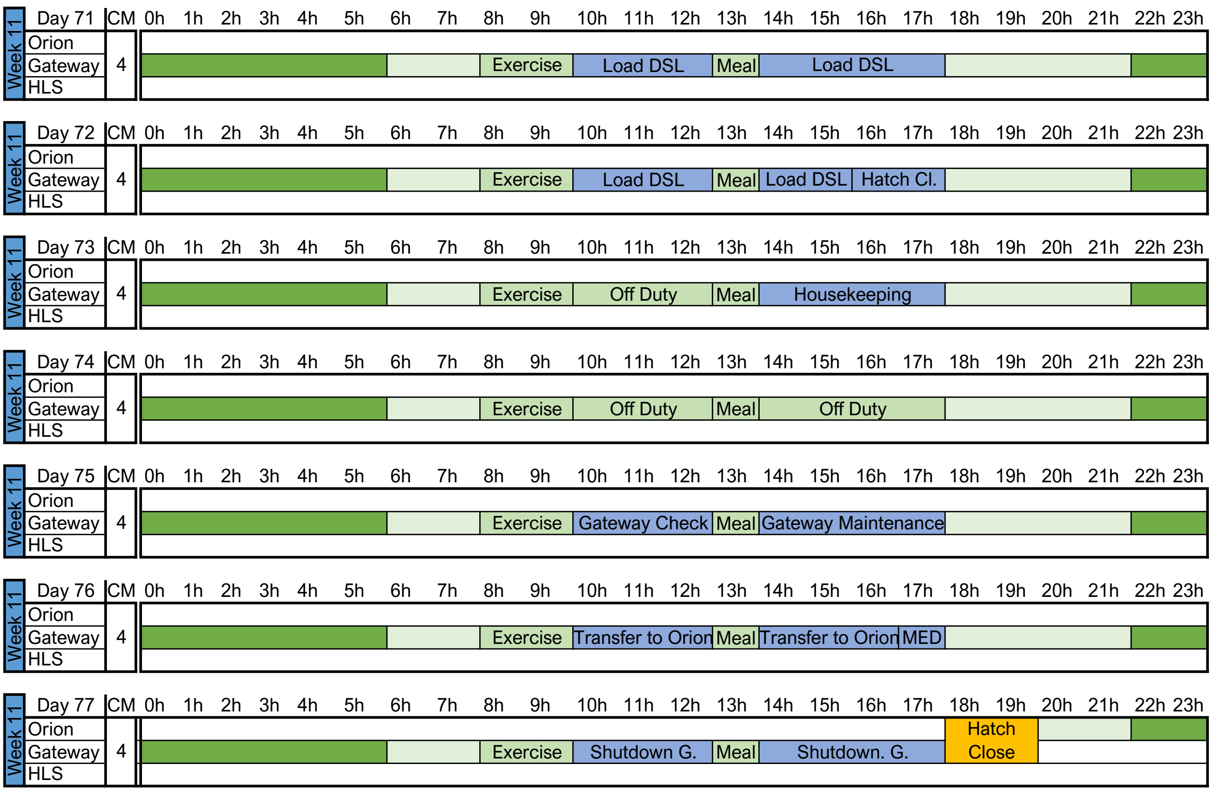


Fig. 4–14: Campaign mode timeline week 11, Gateway Shutdown

4.2.3.9 Week 12 of the Campaign Mode: Orion Return

Week 12, seen in Figure 4–15, is very similar to the return flight for the continuous mode, except for the off duty day on day 79. Other than the the Orion will undock and depart the NRHO on a return trajectory towards Earth requiring TCM's. The days 80 and 81 give some time for routine experiments, that are doable onboard the Orion with the medical conference on day 81 in the evening. Day 82 starts as a routine day and then requires the cabin stow in the afternoon. The crew will then go to bed and prepare for reentry and landing the next morning. After the ESM separation the Orion will enter the entry interface and end their twelve week mission with the splashdown of the Orion spacecraft somewhere in the ocean.

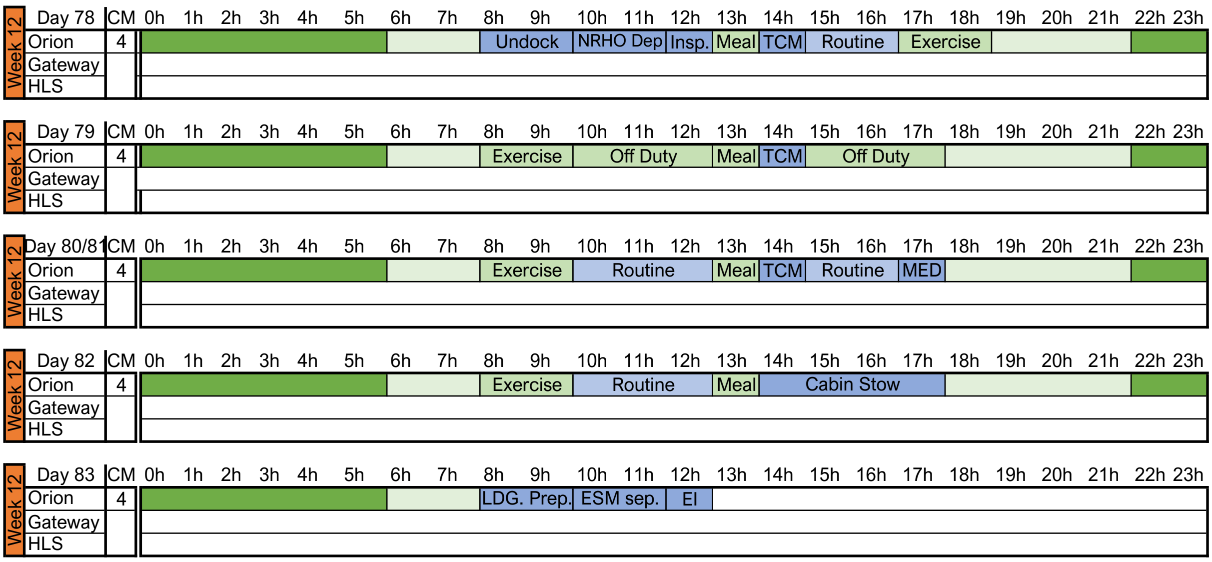


Fig. 4–15: Campaign mode timeline week 12, Orion Return

4.3 Continuous Mode

In the continuous mode the goal is to have a permanent human presence onboard the Gateway. This neglects the need for automated periods and enables significantly more crew time for science and technical exploration as well as enabling long time experiments necessary for Mars transits. Also transitions from non-automated to automated operations are obsolescence as well as the need for a complete automation of the station. Through this, operations can be realized very similar to the ISS. In the continuous mode the total stay on Gateway will be 196 days per crew and the descent towards the Lunar surface will be four weeks. Therefore, the stay on the Gateway will be half a year, 26 weeks, and an additional week before and after the surface excursion adding up to the 196 days, or 28 weeks, in total. During these two weeks the crew on Gateway will consist of eight crew members creating an overlap between the two missions.

4.3.1 Spaceflight Architecture

To establish a permanent presence in Cis-Lunar orbit a continuous supply in logistics is required, as well as crewed flights every six months. Due to the fact that every mission requires the same basic supply, the flight intervals are repeated after six months. Therefore, the architectures given in the following present the flights taking place during a single crewed mission.

For the regenerative ECLSS a total payload of 2385.32 kg is required to keep the life support system operational. This is enough for a 28 week stay onboard Gateway including the 26 week where the crew is alone and the two weeks where two crews are onboard. For the Lunar excursion a total of 760.84 kg is required for four crew members on a CAMRAS based ECLSS. For the supply of the Gateway alone the Cygnus XL spacecraft would be sufficient and a single Dragon XL can also bring enough supply to restock the HLS. It is assumed that the logistic spacecrafts are altered for every mission to add more redundancy and also ensure the resupply for the Lunar excursions.

The Spaceflight Architecture for the continuous mode missions with a regenerative ECLSS is displayed in Figure 4–16. The Gateway located in NRHO is crewed throughout the entire time and thus marked with a green color. On the left the Gateway can be seen with the HLS docked, as well as a DSL marked in yellow and a gray Orion spacecraft. Now a Orion spacecraft launches with a SLS rocked from Earth and docks to the Gateway, adding four crew members to the station, therefore the green color is intensified. Until the crew that just arrived descents to the Lunar surface four vehicles are docked to the Gateway. During the surface stay the crew will live onboard the HLS. Therefore it is marked in green as well. The crew that stayed behind on Gateway will remain there until the return of the crew from the surface. Then they will return back to Earth, with their gray Orion. Now the crew that arrived with the green Orion and then descended to the Moon will stay for 26 weeks onboard the station. The previously docked DSL will be disposed indicated with a blue line in Figure 4–16. The blue line refers to uncrewed or logistic flight, also stage separations and the ESM disposal be-

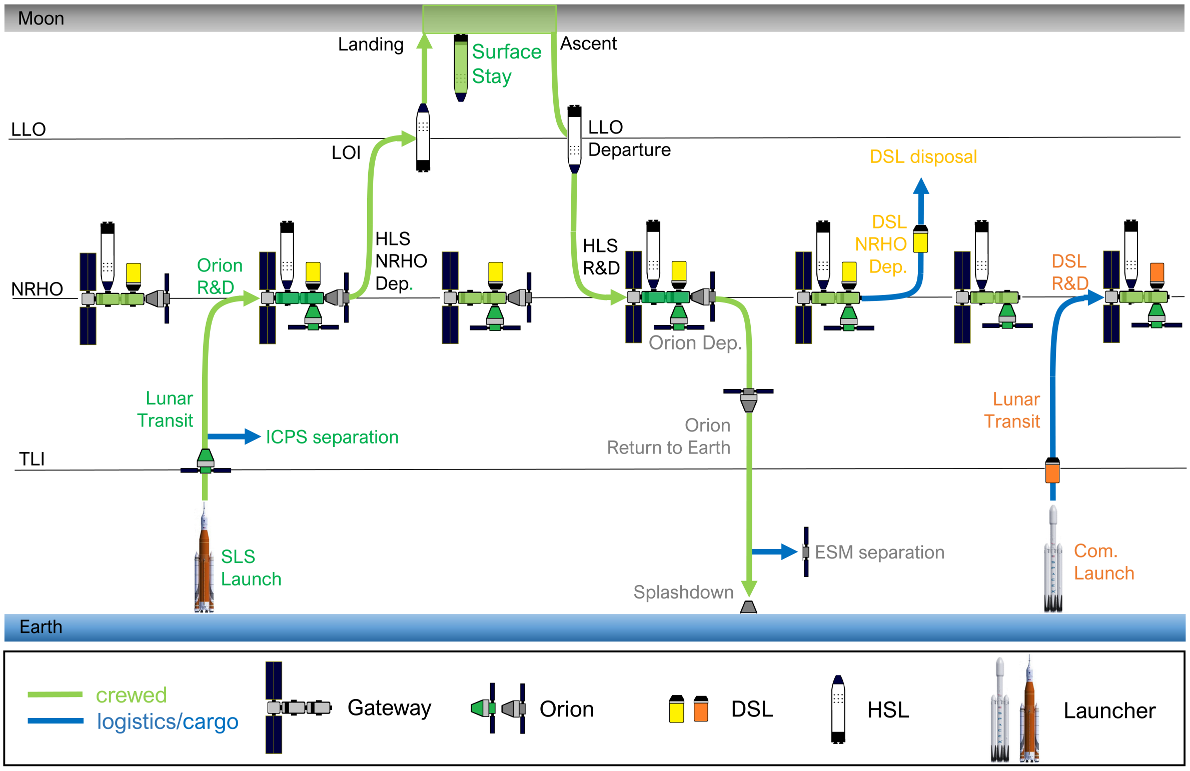


Fig. 4–16: Flight architecture for the continuous mode with a regenerative ECLSS

fore entry is colored in blue. After the yellow DSL was disposed, a second DSL vehicle will be send to the Gateway providing supplies. This vehicle is marked in orange and will remain docked to the Gateway. The architecture will now repeat itself as long as the operation of the Gateway in the regenerative continuous mode is conducted.

In the non-regenerative case, the mission requires one logistics flight more. The Spaceflight Architecture is given in Figure 4–17. The required mass for the operation of the ECLSS for a crewed mission is 5324.36 kg. This makes a second DSL flights necessary. Besides the blue DSL spacecraft, the architecture is comparable to the regenerative case. A crew is present at the beginning and stays onboard Gateway with a gray colored Orion spacecraft, that also acts as their life vessel in case of an emergency. The next crew arrives with the green Orion and descents to the surface of the Moon after docking to the Gateway and transferring to the HLS. Once the crew returns from their surface expedition the crew that was present on Gateway from the beginning will return to Earth with their Orion and leave the Gateway to the new crew. Then the logistic flights will take place and thereafter the entire sequence repeats itself enabling an uninterrupted crewed Gateway.

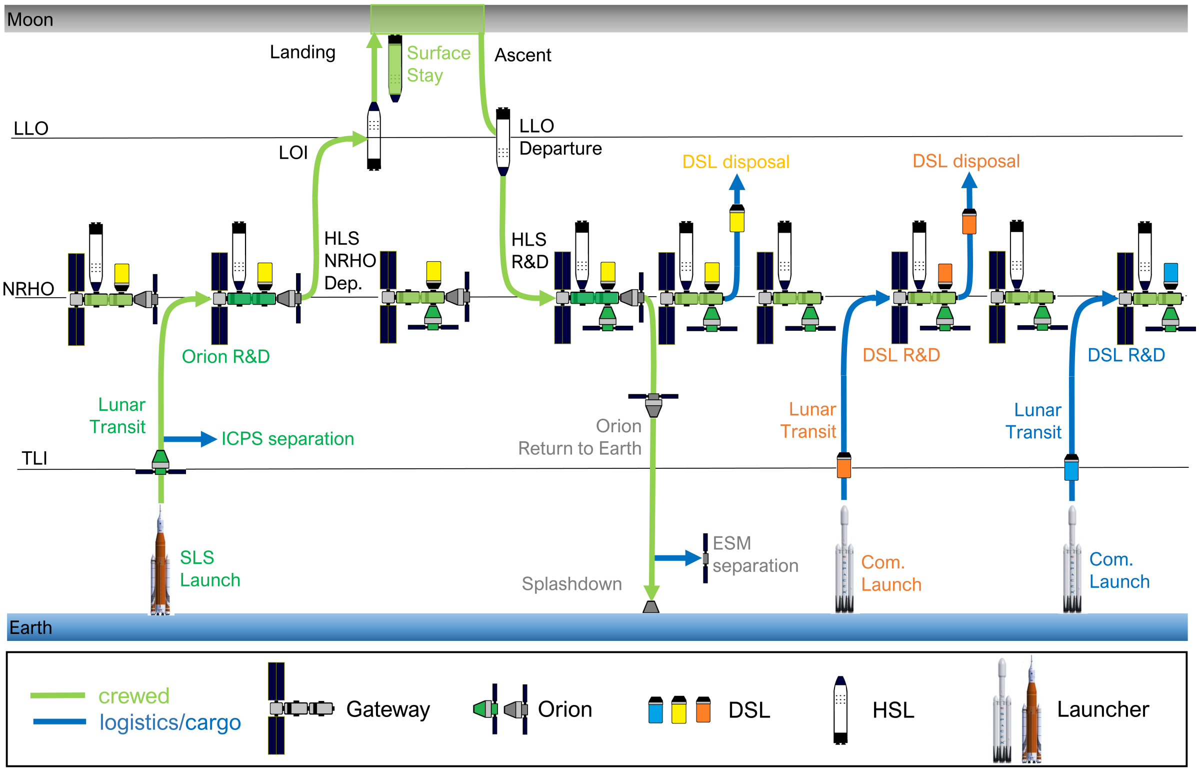


Fig. 4–17: Flight architecture for the continuous mode with a non-regenerative ECLSS

4.3.2 Sequence of Events

For the continuous mode the sequence of events spans a relative wide time span to generate a comprehensive picture on the course of events. Multiple crewed missions will be indicated to show the overlapping periods where two crews are onboard Gateway. The weeks are numbered chronological beginning with week 1 at the start of 'Mission 1'. This first mission does not include a Lunar excursion as it represents the start of the permanently crewed space station and thus has now overlapping crew in advance. Therefore, the regular long time crew rotation starts with 'Mission 2' in week 21 and repeats itself in a 26 week cycle.

In Figure 4–18 a one and a half year period of the continuous mode is shown. During this time a total of three missions are completed and the fourth one just started as indicated in the top row. The diagrams top section is indicating the crew members onboard either the HLS or the Gateway. They are colored in either green or gray in accordance to the arrival of their Orion spacecraft. This colors also coincide with the designated crews of the timeline in the following section. The Gateways docking ports are indicated just below the crew member row and are used in a way that only during the time when two crews are onboard all four ports are occupied while otherwise one port is always available in case of any delays or emergencies. This allows a docking period of 25 weeks for the DSL in the regenerative mode, where only one supply flight per mission is required. Through that the pressurized space of the cargo spacecraft can be used and docking or undocking is planned in weeks with now crew arrivals to reduce stress and workload. Even though the Dragon XL could supply the crew for the period of a year it was decided to use two different logistic vehicles to ensure a higher redundancy and also allow the transport of cargo. Further, the Cygnus alone would not be able to supply the station for an entire year. Therefore a logistic flight arrives at the Gateway always a week before the next crew arrival providing equipment and life support goods. The crews always arrive with an Orion spacecraft that acts as a life vessel and remains docked to Gateway during the entire time of the mission. The internal ECLSS is designed to last at least three weeks and thus provides enough redundancy, because the Orion is only used for a period of 10 days in these missions, five days for each transfer to and from Earth. The last row in the diagram for the sequence of events in Figure 4–18 show the different main activities relevant to the MCC.

For the non-regenerative ECLSS based on CAMRAS an additional resupply flight per mission is necessary. This reduces the docking time of the DSL to about eleven weeks before it is disposed and a new logistics vehicle arrives. This is displayed in Figure 4–19, showing the sequence of events for the non-regenerative continuous mode. Besides the additional resupply flights, the non-regenerative sequence of events was developed identical to the regenerative case, providing a four week Lunar excursion and a total of 28 weeks onboard the Gateway. From an operational perspective this increases the work for unloading and loading of two more logistic vehicles, also the docking and undocking is likely to be monitored by the crew. Due to this, the non-regenerative mode has an increase in operational working hours and reduction in routine working time.

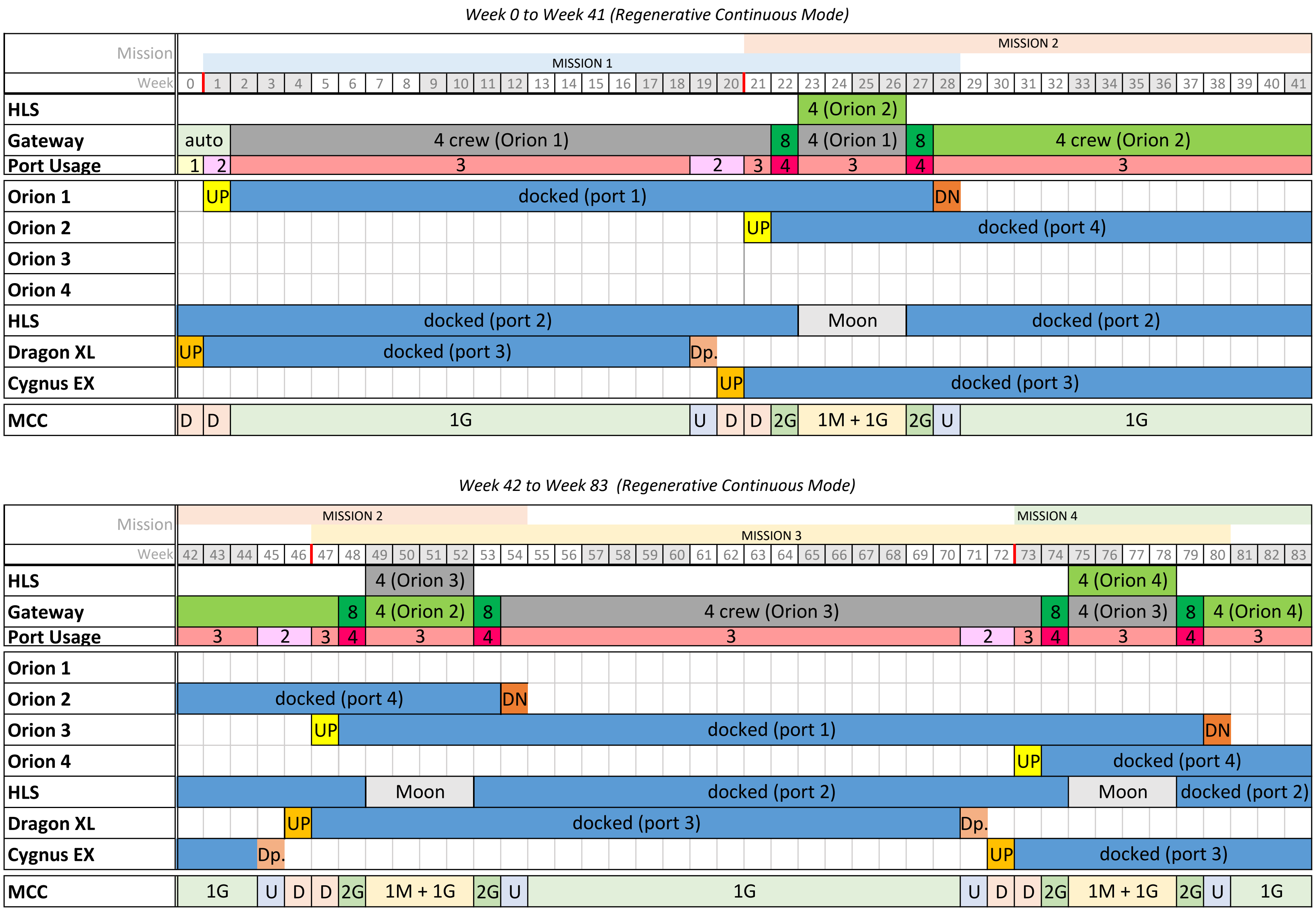


Fig. 4–18: Sequence of events for the continuous mission mode with a regenerative ECLSS. Displaying a period of 84 weeks spitted into two diagrams where each consist of a top section indicating the crew members onboard the HLS and the Gateway. The vehicles used, their docking duration and flights in the central section and the MCC's main activity at the bottom.

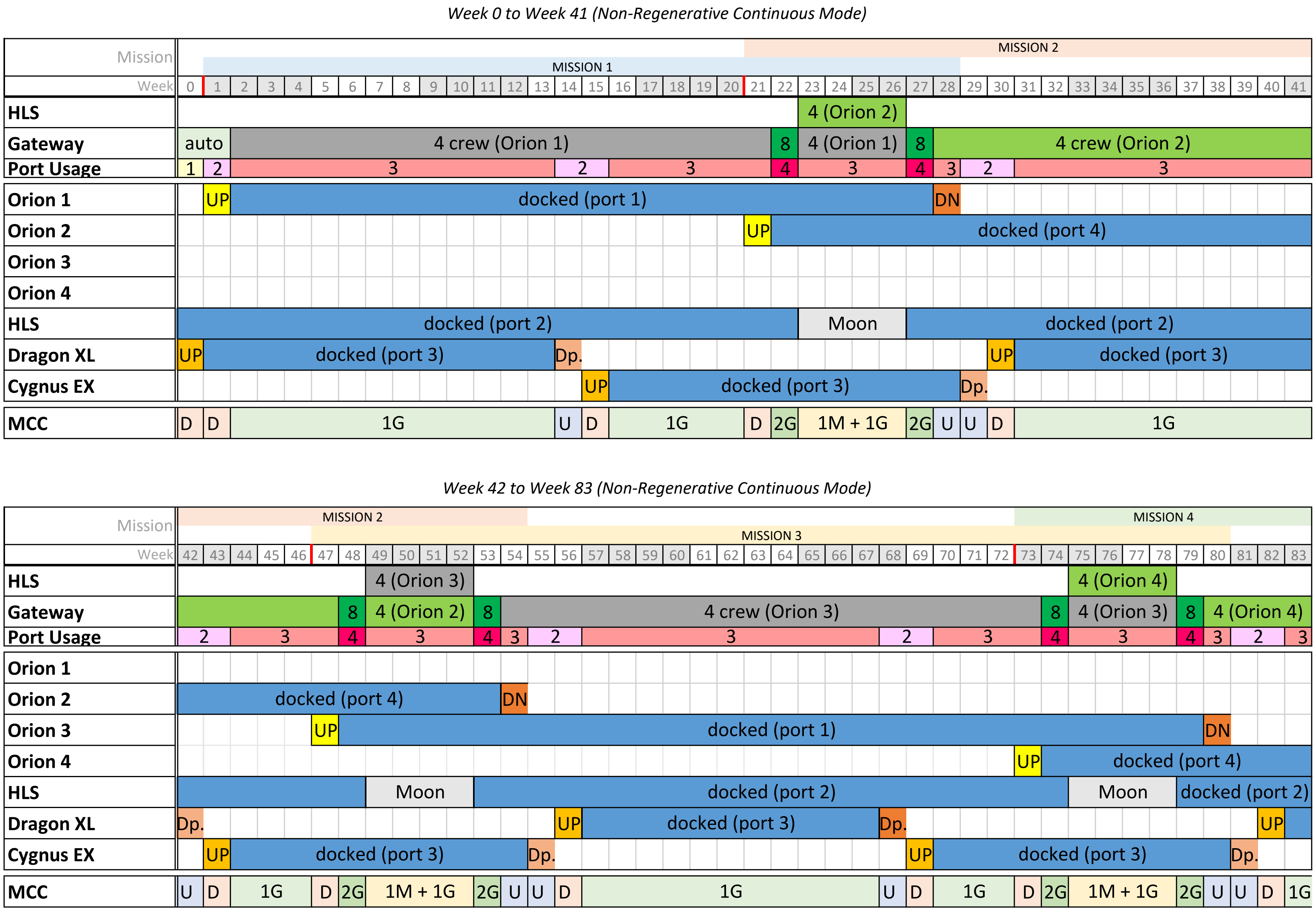


Fig. 4–19: Sequence of events for the continuous mission mode with a non-regenerative ECLSS. Displaying a period of 84 weeks spitted into two diagrams where each consist of a top section indicating the crew members onboard the HLS and the Gateway. The vehicles used, their docking duration and flights in the central section and the MCC's main activity at the bottom.

4.3.3 Timeline

In the following pages the timeline for the regenerative continuous mode will be given. The mission described in detail is labeled as 'MISSION 2' in Figure 4–18 and starts from week 21 until week 54, spanning a total of 33 weeks in mission duration. Thereby including four weeks on the surface of the Moon at the beginning of the mission. The timeline is almost identical to the non-regenerative mode except there is an additional DSL supply flight required. Therefore, only the regenerative case is described in detail. For the non-regenerative mode week 45 and week 46 where the DSL undocks and the new DSL docks, would be repeated at an earlier stage, during week 29 and 30. This would reduce the time available for routine work during these two weeks, but has no more significant impact.

Further, the timeline shows week 21 to week 46, because after this 26 weeks have passed, the crew from 'Mission 3' will launch. The tasks from week 47 on are the same as for week 20 with the difference that the Green Crew will perform the duties of the Gray Crew. Concrete this leads to the repetition of the timeline after week 46.

The working hours that result from the different weeks, corresponding to the sequence of events are in the Supplementary Tables Appendix A. The table gives a detailed insight on the working hours required for operational tasks, like housekeeping, maintain dance or transfer of payload and the hours available for routine work.
EVA's indicated during Gateway operations, are a part of the routine working hours while onboard the Gateway and are more of an indication of the possibility to conduct EVA's during the time of week 29 to 44 than a definite event and may not be required.

4.3.3.1 Week 21 of the Regenerative Continuous Mode: Orion Launch

In the first week of 'Mission 2', the crew for this mission, from now on referred to as the Green Crew, launches from Earth onboard an Orion Spacecraft. This corresponds to the yellow UP box in week 20 of the general mission sequence of events in Figure 4–18.

On day 1, as seen in Figure 4–20, the ascent, indicated with Ascent (ASC), takes place followed by the EOP, where perigee raise and initial Orion checkouts are conducted. Once all requirements are met to safely leave towards the Moon, the TLI burn is initiated and thereafter the ICPS is separated and disposed. When the Orion is enrout, it gives the crew a break to take the meal before they need to conduct a TCM. The exact timing of this maneuver is here not defined yet and is dependent on many flight parameters, but will not allow other actives to be conducted simultaneously and therefore one hour is reserved in the timeline. The first day ends with a general inspection of the spacecraft for the Green Crew.

The Gray Crew, that is onboard Gateway during this time, is conducting their routine everyday exercise and scientific work and will start up the HLS that is docked to Gateway. It is also assumed that it was docked during the past months and depending on the HLS used it might require refueling. During this startup the HLS's internal ECLSS will be activated, and all computers awaken if they were in a standby configuration. Thus the startup is performed two weeks in advance of the actual utilization of the vehicle to have time to solve any encountered disturbances or problems.
Days 2 and 3 are identical. During the transfer further TCM's might be necessary, otherwise the crew is available for routine work and needs to start a daily routine of exercise due to the lack of gravity.
For the Green Crew nothing changes on day 4. The Gray Crew will check if the startup of the HLS was successful and conduct necessary maintenance and repairs.
On day 5 Orion will enter the NRHO and the crew will prepare for the docking maneuver. After meal, the rendezvous will take place followed by the leak check. This requires the attention of the crew onboard Orion as well as the Gateway and thus is marked in the yellow box for both crews in the timeline. Once the hatch is opened the Gray Crew will welcome the Green Crew onboard and thereafter the day comes to an end.
Day 6 will have time conduct housekeeping onboard Orion for the Green Crew and the Gray Crew will do the same on Gateway, both crews will be off duty for the rest of the week on day 7.

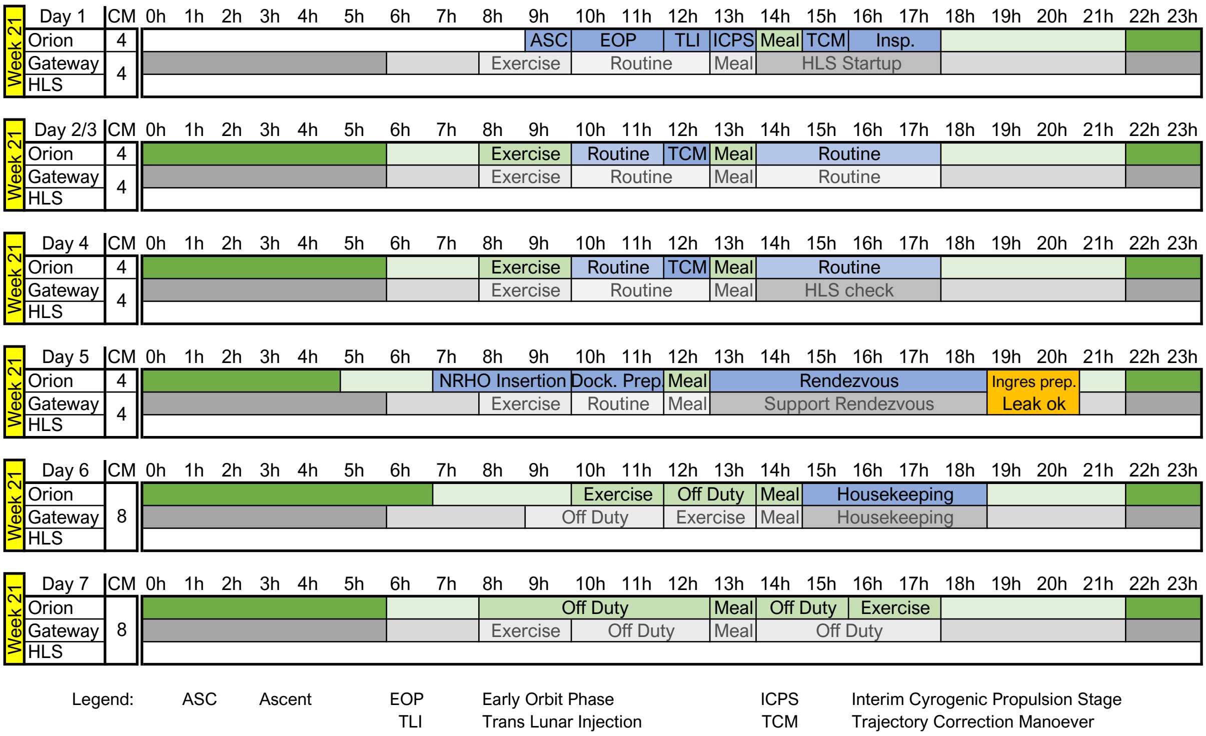


Fig. 4–20: Regenerative continuous mode timeline week 21, Orion Launch

4.3.3.2 Week 22 of the Regenerative Continuous Mode: Transition

In the second week, as shown in Figure 4–21, the Green Crew as well as the Gray Crew will participate in the unloading of the Orion on day 8 followed by the weekly medical conference in the afternoon. While the Gray Crew will resume routine operations, the Green Crew will finish the payload transfer and stow all parts necessary before heading into the HLS module and preparing it for the one month excursion towards the Lunar surface. For this they will also have day 10 giving a total of two days for the spacecraft preparation, that should already be up and running since a week by this time. The preparation includes minor maintenance that was not yet conducted and the stowing of the equipment brought from Earth. The Gray Crew will conduct routine work during day 10, 11 and 12. Also for the Green Crew the afternoons on day 9 and day 10 are reserved for routine work and serve as a buffer in case the transfer of payloads or preparation of the HLS require more time. Day 12 will be an early off duty day for the Green Crew, because by the end of the week they will start their descent towards the Lunar surface. In the morning, they will conduct their Housekeeping with a primary focus in the Orion spacecraft that is now docked to the Gateway and in a standby operation. On day 13 both crews are off duty, but the Gray Crew will conduct housekeeping in the afternoon. Day 14 is off duty for the Gray Crew until the hatch is closed, and the Green Crew will conduct their final preparation before moving into the HLS and closing the hatch before going to bed. In this timeline the Green Grew will sleep in the HLS already with the hatch closed, but the vehicle still docked to the station.

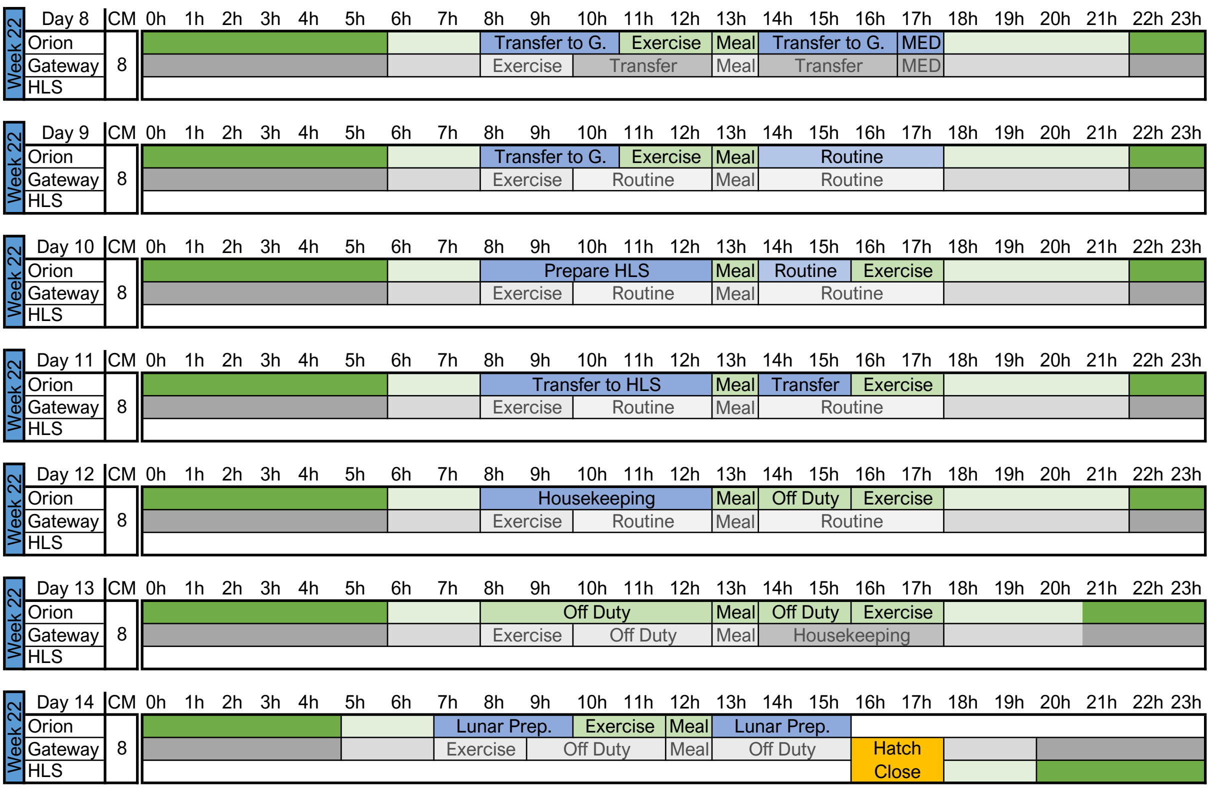


Fig. 4–21: Regenerative continuous mode timeline week 22, Transition

4.3.3.3 Week 23 of the Regenerative Continuous Mode: Lunar Arrival

In this week, as shown in Figure 4–22, the surface excursions begin, starting with the undocking of the HLS from the Gateway followed by the NRHO Departure, a brief inspections and necessary trajectory corrections, TCM's. The Gray Crew onboard Gateway is conducting support tasks during this time and resumes routine after lunch when the HLS has safely left the vicinity of the Gateway station. The same holds true for the Green Crew that is also given some off duty time until the LOI in the evening of day 15 is over and both crews go to rest. The transfer from the NRHO to the LLO takes about 12h and was chosen to be conducted while the crew is awake.
On day 16 in the morning the Green Crew prepares for landing and stows everything in the HLS. After lunch the descent is initiated and the landing conducted. There is also a TCM planned while on descent from the LLO to the surface. Once the HLS landed successfully the crew needs to perform an inspection. The entire descent phase is monitored and supported from the Gateway as required. Before going to rest, the Green Crew performs a camp phase as preparation for the lunar EVA the next day.
Days 17 and 18 present Lunar EVA walks that are supported from the Gateway. It is likely that not all crew members are involved in the conduct of an EVA simultaneously, so two crew members might perform one on day 17 and the other two on day 18 as two EVAs in a row may be possible but a non-EVA day inbetween should be considered.
Day 19 is a routine day for both crews ending with the medical conference and day 20 and 21 are off duty days with one afternoon reserved for housekeeping.

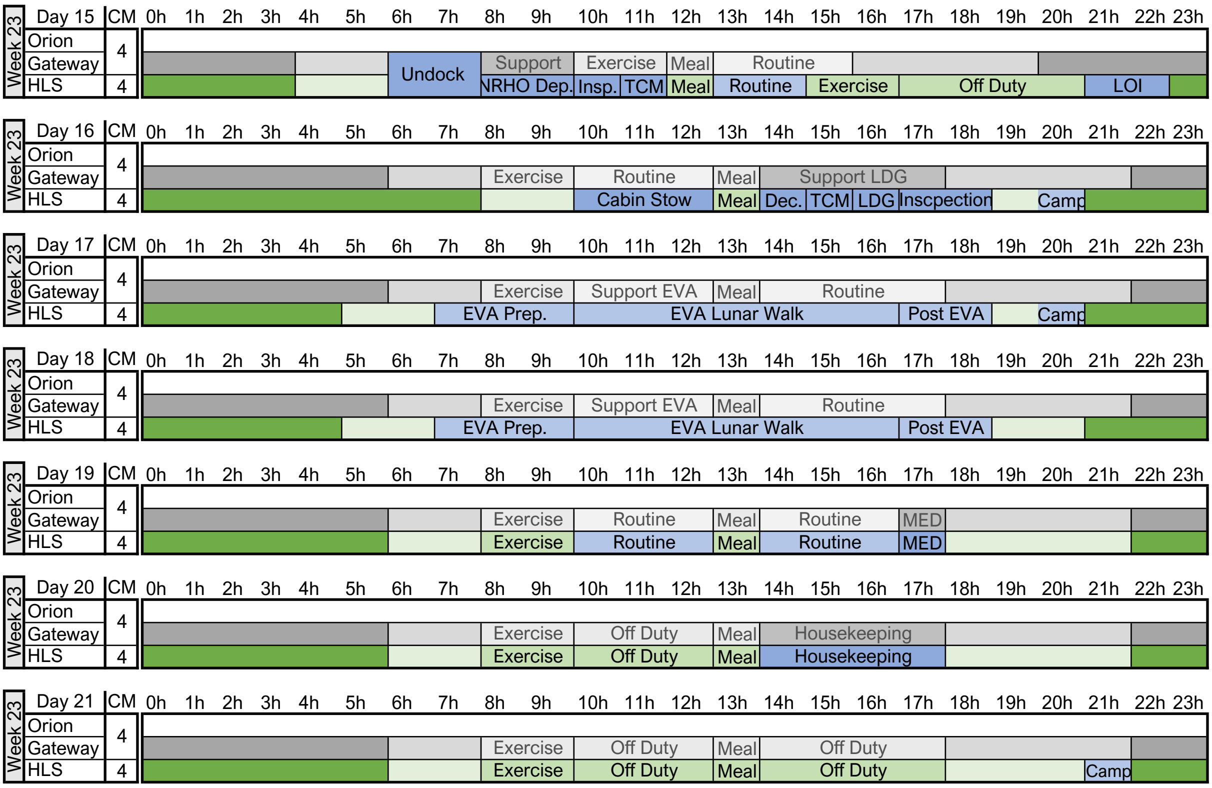


Fig. 4–22: Regenerative continuous mode timeline week 23, Lunar Arrival

4.3.3.4 Week 24 and 25 of the Regenerative Continuous Mode: Lunar Excursion

Week 24 and 25 are identical and displayed in Figure 4–23. They represent the surface operation weeks on the Moon. Surface walks are the central task for these weeks.
Figure 4–23 gives the scheduled for a single crew member. To keep the working hours at a feasible level three EVAs per crew member are conducted. Each seven hour EVA includes six hours of preparation, suit clothing and cleaning. The distribution of the surface walks will be throughout the week and every crew member will have a slightly different schedule from the others as indicated in Figure 4–11. Two Astronauts perform an EVA simultaneously. Through this the total amount of work done per crew member will be identical, but the distribution throughout the week will vary.
During the one day of routine on day 24 the crew could also perform robotic tasks or experiments onboard the HLS in Lunar gravity. Also the routine day can be used for additional EVA equipment cleaning and preparation. One day, here days 27 and 34, include four hours of Housekeeping in the HLS module.
For the Gray Crew the same logic is applied as in week 23 that they can support the EVA's from the Gateway if required or conduct routine work in Orbit. The support hours are therefore also added to the routine working hours of the Gray Crew. Support could also be in the form of robotics that are controlled from the Gateway station.

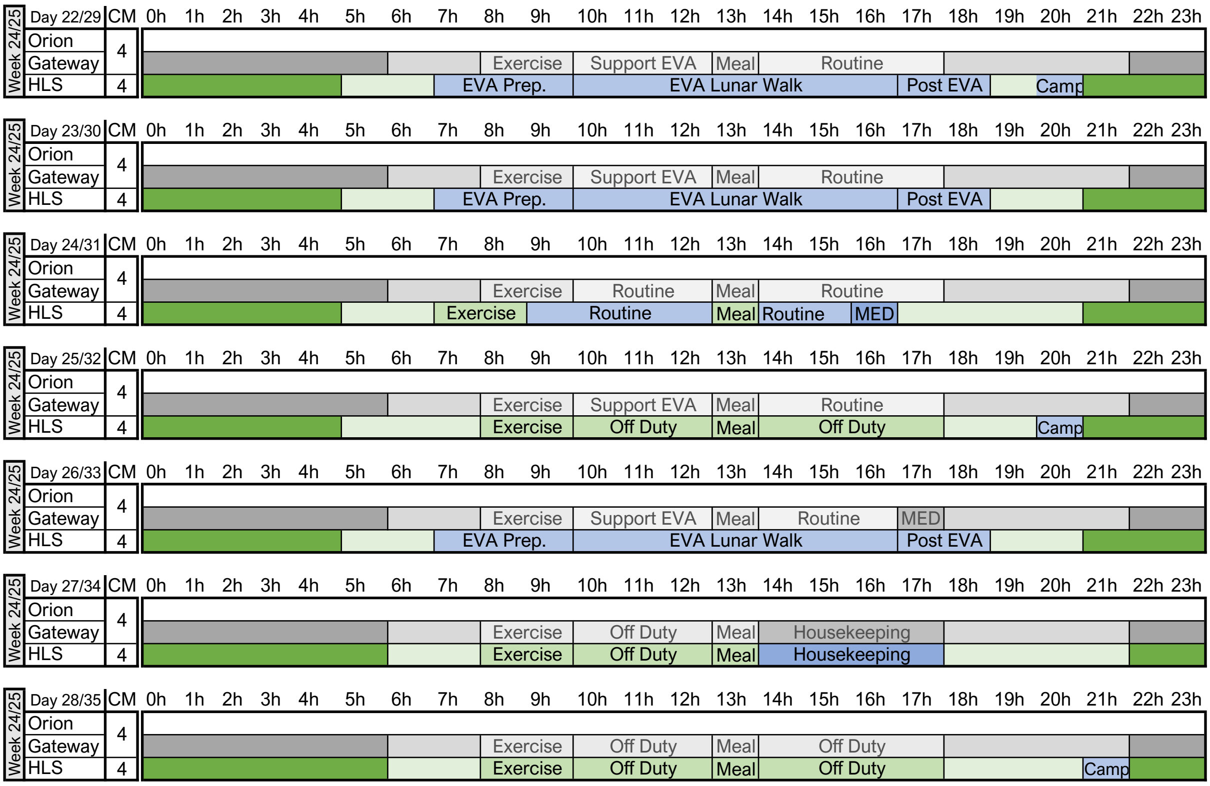


Fig. 4–23: Regenerative continuous mode timeline week 24 and 25, Lunar Excursion

4.3.3.5 Week 26 of the Regenerative Continuous Mode: Lunar Ascent

In week 26, as shown in Figure 4–24 the Green Crew will return from the surface of the Moon back to the Gateway station, where the Gray Crew is present at the moment.
The first days (36 and 37) will be similar to the days in week 23 and 24, containing EVA's that can be assisted from the Gateway. Besides the assistant work, the Gray Crew will perform routine work until days 39 and 40, where the off duty days are advanced and thus the housekeeping and medical conference. The Green Crew will perform this already on day 38 and have time on day 40 for some final routine work and then start with the spacecraft inspections and preparations for launch. These duties will continue on day 41 until the launch in the evening. After the ascent and some trajectory corrections, the spacecraft is inspected for possible damages from the launch. During these inspections they are already en-route to the NRHO and the crew will go to bed thereafter. The Gray Crew onboard Gateway is able to support the launch directly if necessary and will perform routine work otherwise.
The flight back to Gateway takes place during the night in comparison to the descent on day 15, where the 12 hour flight was during the day. Both options are possible and indicated in this time plan. On day 42 and the rendezvous and docking takes place. Here both crews attention is required until the leak check is complete and the hatch between the HLS and the Gateway is opened again. The HLS will remain docked until the next Lunar mission.

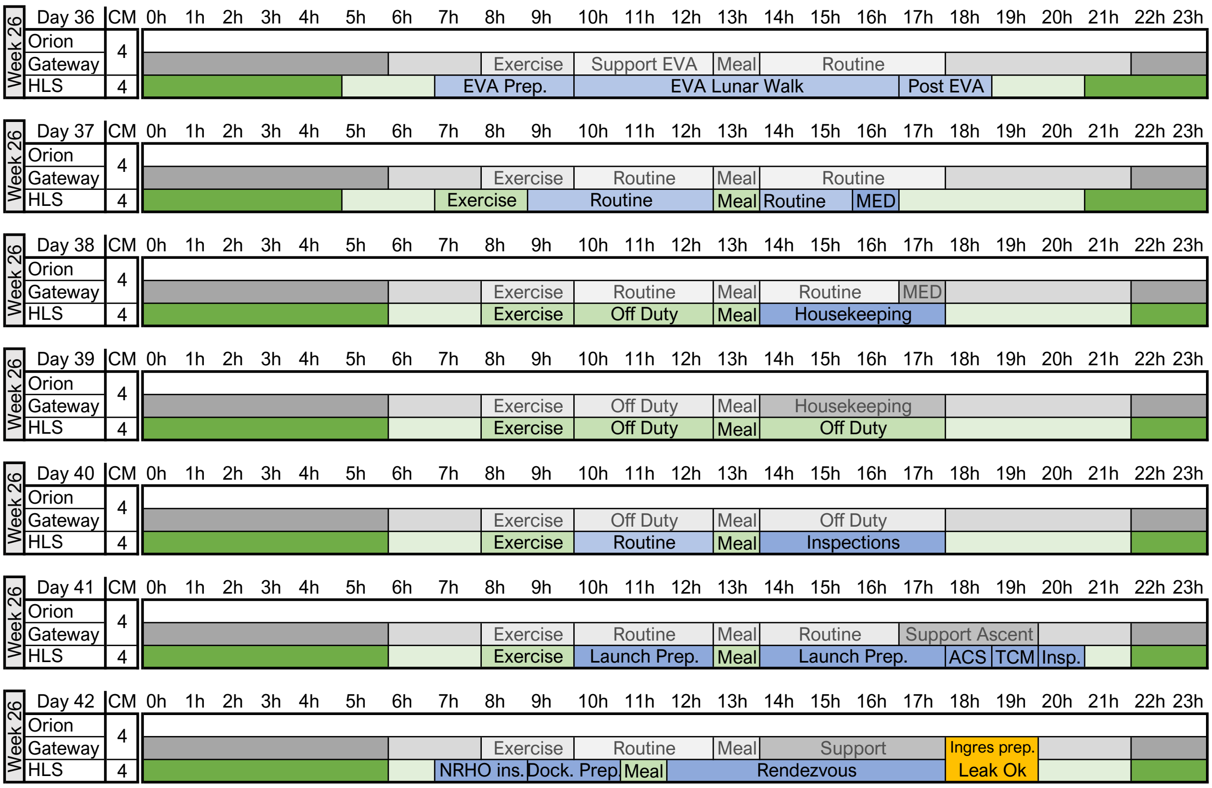


Fig. 4–24: Regenerative continuous mode timeline week 26, Lunar Ascent

4.3.3.6 Week 27 of the Regenerative Continuous Mode: Gateway Arrival

In week 27, as shown in Figure 4–25 the HLS has returned to the Gateway station and is docked again. This means that all eight crew members are now in the same space, consisting of the Gateways habitats and pressurized modules, the HLS, the Gray Crews Orion capsule and the Green Crews Orion capsule. The first two days the HLS is unloaded and cargo moved to the Orion or the Gateway. For this not all eight crew members onboard are necessary at all time. Thus the timetable indicates only one crew, the Green Crew, to perform the transfer, while the Gray Crew has time for routine work. The day 44 ends with the medical conference for both crews, and the Green Crew is off duty on day 45 and 46 after five intense days including the lunar ascent. The Green Crew will perform their housekeeping on the HLS parallel with the housekeeping of the Gray Crew on Gateway in the afternoon of day 46. Day 47 is the second off duty day for the Gray Crew and represents the first routine day for the Green Crew on Gateway, it also acts as a buffer day for unfinished transfer work. On day 48, the Gray Crew will perform a system check on Gateway, where they test all equipment and perform routine maintenance. The Green Crew will also do the same on the HLS. The last day of week 26, the Green Crew will have time to conduct routine work or prepare samples and cargo brought from the surface of the Moon that are transferred to Earth with the next leaving Orion. The Gray Crew transfers payload to their Orion spacecraft, that will return to Earth, where the Green Crew could assist if necessary.

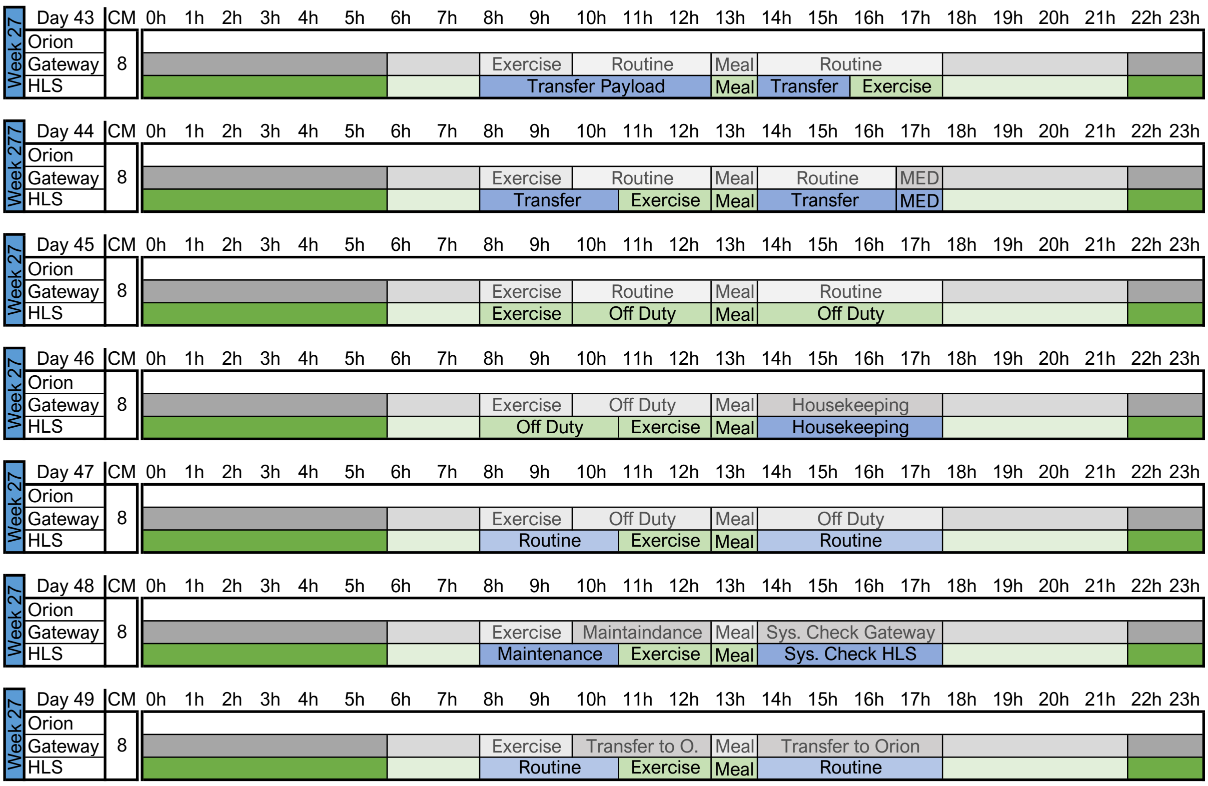


Fig. 4–25: Regenerative continuous mode timeline week 27, Gateway Arrival

4.3.3.7 Week 28 of the Regenerative Continuous Mode: Orion Return

In week 28, as shown in Figure 4–26, the Gray Crew will return to Earth. On day 50 both crews will participate in the transfer of payloads to the Orion and after the meal the crew handover of the Gateway station takes place. The Green Crew will now remain on Gateway for six months, whereas the Gray Crew will return to Earth.
In the evening the hatch between the Orion and Gateway is closed. At this point it needs to be mentioned that in total two Orions where docked. Each crew arrived with one Orion, but because when docked to Gateway they act more like a module of Gateway. Only one Orion is shown in the timeline, because at no time both Orions are being crewed. On day 51, the Orion with the Gray Crew will undock and perform the NRHO departure followed by an inspections and TCM's. The leftover time can be spent with routine work. Onboard Gateway the Green Crew has time to shut down the HLS and transfer all controls to the Gateway in order to convert it more or less into a further Gateway module. Day 52 will be off duty for both crews except, for TCM's for the Gray Crew. Day 53 will be routine for both crews except a medical conference for the Gray Crew and day 54 is a routine day for the Green Crew and the Gray Crew in the morning, but the pre-landing cabin stow in the afternoon. On day 55 is the landing for the Gray Crew, starting with landing preparations, the ESM separation followed by the Entry Interface (EI) and the splashdown. Now the Green Crew remains alone and performs routine work with a medical conference in the evening on day 55 and a day off on day 56, where they will also conduct the weekly housekeeping.

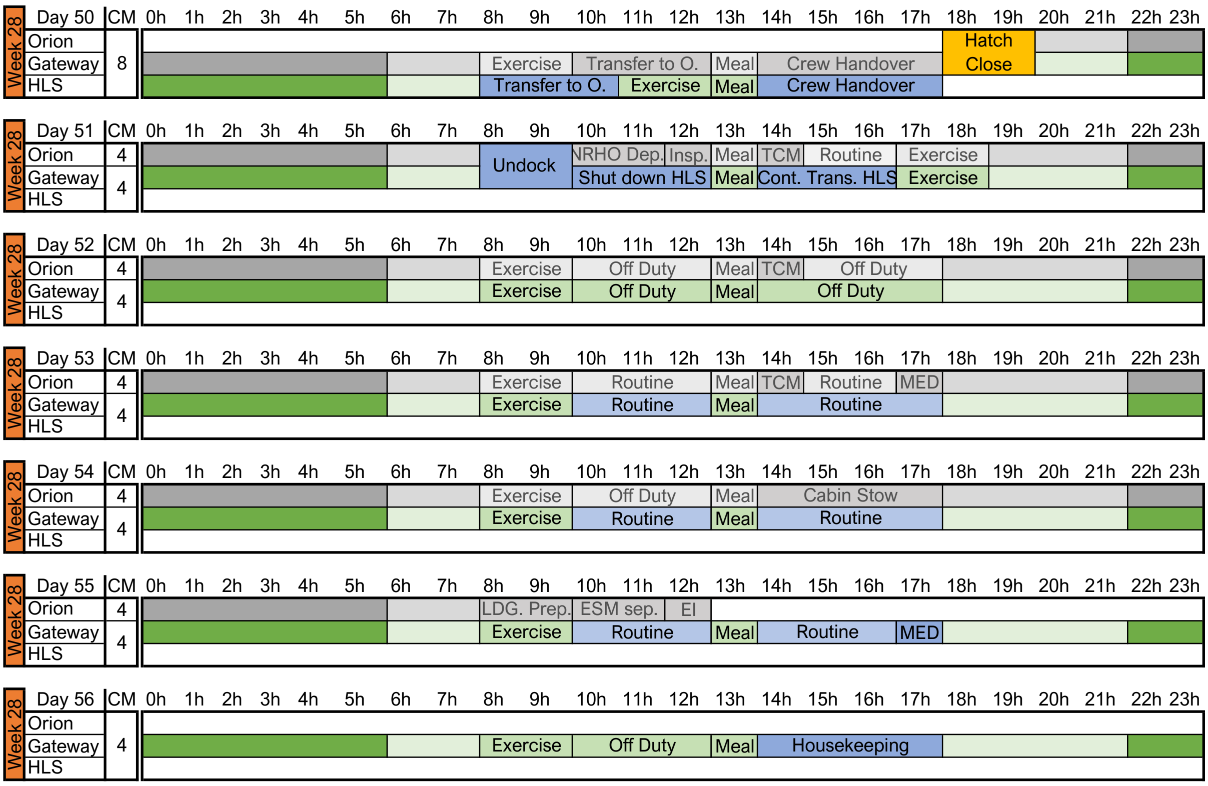


Fig. 4–26: Regenerative continuous mode timeline week 28, Orion Return

4.3.3.8 Week 29 to 44 of the Regenerative Continuous Mode: Routine

In week 29 to 43 ,the crew will stay on Gateway and have time to perform routine work that could also include optional EVA's. As most activities outside the pressurized habitats will be automated or robotic, most weeks, or even all, will not include an EVA. The layout of how a typical week on the Gateway during these period of 15 weeks could look like is given here in Figure 4–27, where the EVA is indicated to represent the option.
For the non-regenerative continuous mode, week 29 would be used for the undocking of the DSL as seen in week 45 and in week 30 the docking of the new DSL would take place as described in week 46 in the regenerative case. They would repeat themselves after 11 weeks so the next undcking would be in week 42 and docking in week 43 as seen in the sequence of events for the non-regenerative case in Figure 4–19.
The days are labeled using roman numerals due to the fact that not a specific day is assigned to this work. The working time can fluctuate from 35 to 40 hours of routine work depending on the amounts of EVA's, because they increase working times significantly. Again, not all crew members will perform EVA's and most definitely not every week. The time plan below should just give an insight on how a routine week on Gateway could look like for a specific crew member. On day V in the afternoon the medical conference will take place and housekeeping or maintenance work on day VI in the afternoon. It can be seen that two days are planned to be off duty days in order to give the crew time to regenerate.

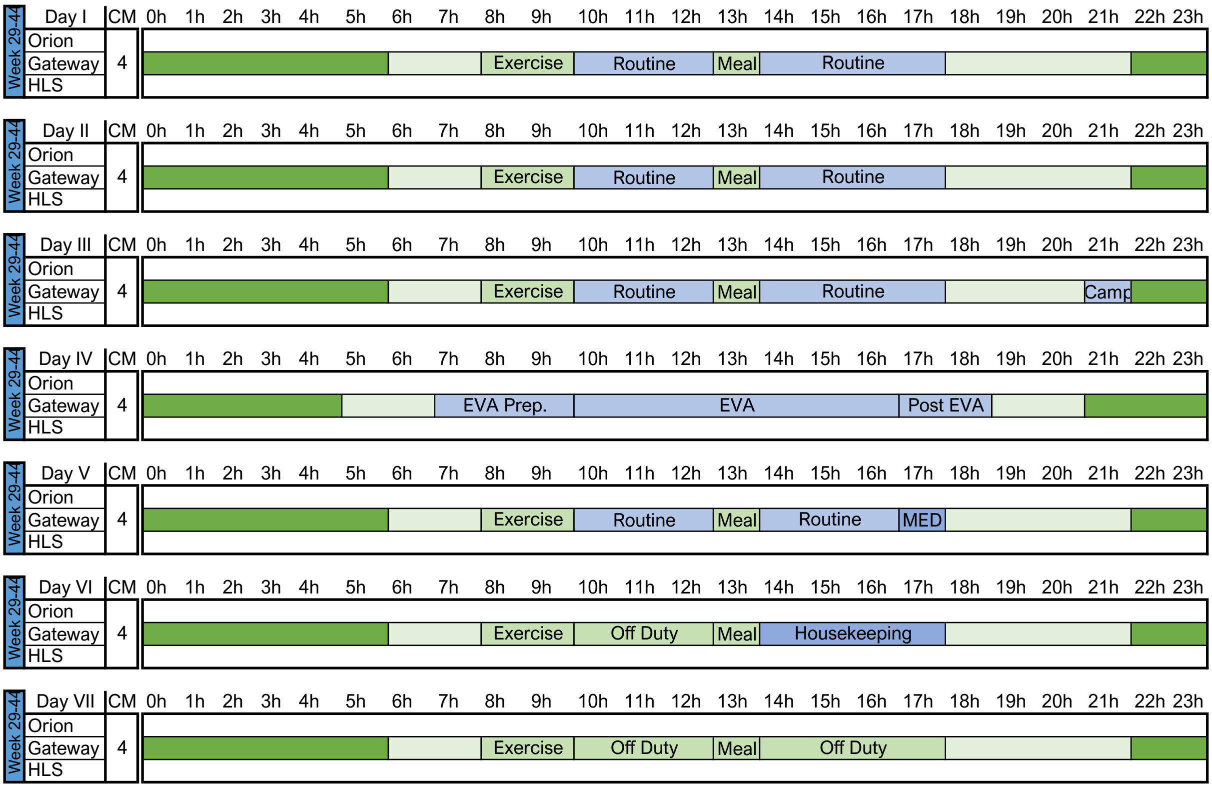


Fig. 4–27: Regenerative continuous mode timeline week 29 to 44, Routine

4.3.3.9 Week 45 of the Regenerative Continuous Mode: DSL Disposal

In week 45 the DSL, that was docked since week 19, before the arrival of the Green Crew, leaves the Gateway station. In this case, it is a Cygnus XL spacecraft that was docked for 26 weeks. This holds true for the regenerative case, were in the non-regenerative case it would have been eleven weeks. The pressurized space was available to the station during this time, and the DSL acted as a module being part of the Gateway.
Depending on the disposal option, the DSL can be loaded with trash or return items back to Earth before it is being undocked on day 108. For this transfer of payload two days of work are reserved on day 106 and 107. On day 108 in the morning the DSL's hatch is closed and the undocking is monitored.The Undocking will be performed automated as well as the flight of the DSL vehicle itself. The crew will spend the rest of the week like the general weeks before with routine work, a medical conference on day 110 in the afternoon and housekeeping on day 111. They will have an off duty day on day 112.

It is possible that the DSL might not require these specific two days for the loading of cargo like waste or other payloads, but that it might happen successively throughout the mission. Nevertheless, a total of two days is a reasonable duration, after a 26 week period, to prepare the DSL for its disposal.

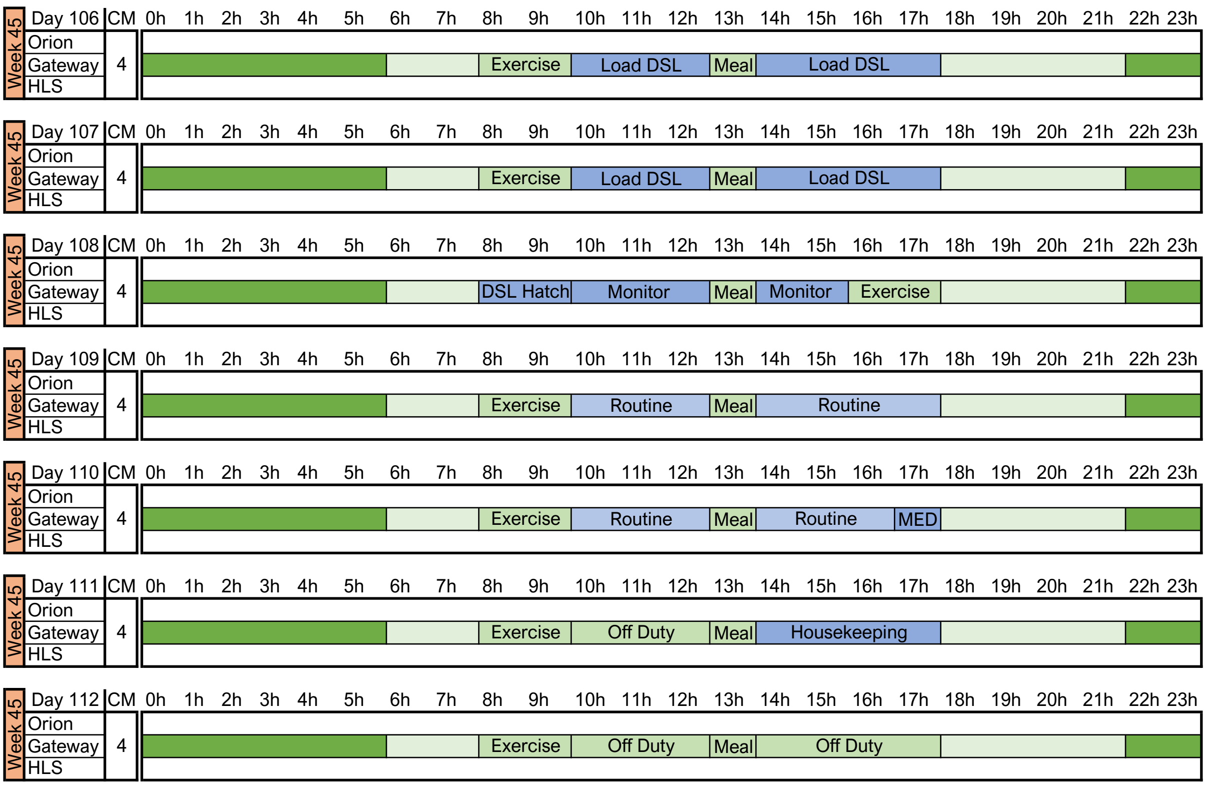


Fig. 4–28: Regenerative continuous mode timeline week 45, DSL Disposal

4.3.3.10 Week 46 of the Regenerative Continuous Mode: DSL Docking

In week 46, as shown in Figure 4–29, the next DSL arrives and brings supplies for the coming weeks. In the regenerative case, the DSL supplies the crew for the entire duration of the stay. In this case it would provide the essential supplies for the 'Mission 3' that would arrive the following week. Further, the spacecraft used will now be a Dragon XL and thus provide redundancy by using different DSL suppliers. The cargo and payload transported by the DSL could also include fuel to refuel the HLS if required or equipment for Lunar excursions.
After day 113 and 114 being routine work days, the docking is monitored on day 115 until the leak check is ok and the hatch opened. The DSL arrived fully automated from Earth. The days 116 and 117 are then reserved for unloading and storing away of the payloads pressurized and unpressurized with the help of the robotic arm. As before the working week ends with the medical conference and the housekeeping and maintenance on day 118. Thereafter, the crew is off duty.

In week 47, the new crew launches towards the Gateway and thus the timeline starts to repeat itself like in week 21 except that the Green Crew will now perform the Gray Crews tasks. Therefore, they are not described again, but can be seen in the descriptions of week 21 to week 28 as the Gray Crew.

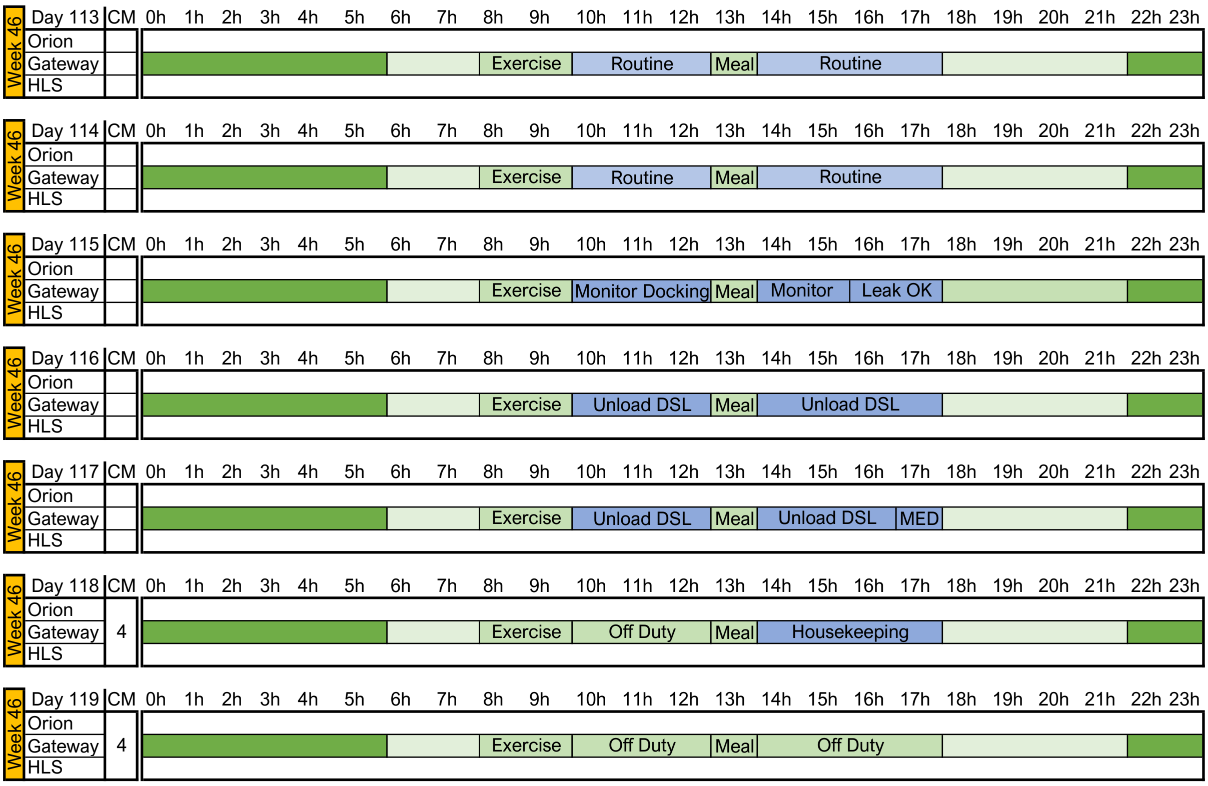


Fig. 4–29: Regenerative continuous mode timeline week 46, DSL Docking

5 Analysis and Discussion

In this chapter the concepts presented will be analyzed and defining quantities retrieved. Starting with the evaluation of vital properties, which can influence the presented concepts and their timelines. Characteristics like the size and number of logistic flights are analyzed regarding their payload margins and redundancy. Followed by the Lunar excursion resupply mass and duration. This impacts the complete concept and is therefore studied towards its stability. Finally, an investigation on all four different modes, the regenerative and non-regenerative campaign, and continuous missions, will be conducted. Hereby the quantitative properties are retrieved and displayed to each other.

5.1 Deep Space Logistic

The term deep space logistics refers to the uncrewed spaceflights to the Gateway or the Moon transporting supplies and equipment to these outposts. Typically these flights are conducted in advance of a crewed mission or throughout the operations if required. In this section a closer look towards the frequency of these flights in accordance to the developed mission concepts will be taken. Especially when looking at the permanently crewed continuous mode.

To successfully conduct the missions additional logistic flights to the Orion spacecraft transporting the crew are inevitable. This results from the limited cargo space available in the crew vehicle Orion, which can not supply the Gateway for the required period or bring the 761 kg of supply mass required for the Lunar excursion on the HLS. For the analysis presented here the payload capacity of the Orion is neglected and not considered. It is assumed that it will be used for the supply of the transfer flights and act as a minor buffer in case of an emergency event. A separate logistic flight also increases mission flexibility and makes an independent launch of the DSL from the human-rated spacecraft possible.

First off the spaceflight intervals depending on the mission mode and available spacecraft are evaluated. Thereafter some possible disposal options for the DSL vehicles are considered as they can also influence the mission concept, especially when looking at longtime operations in Cis-Lunar orbit.

5.1.1 Spaceflight Intervals

When considering the flight intervals to supply the Gateway station with the essential ECLSS resupplies, one is interested in the minimal amount of flights that would enable the success of the mission. Further evaluating how much payload can be brought in addition. The additional payload could be for scientific purposes, technology demonstrations, EVA equipment, or as essential like fuel required for station keeping or Nitrogen for purges.

The mass calculated with LiSTOT is assumed to represent the minimal required supply mass, see Section 3.3 for the computation. It takes maintenance mass and water resupply into consideration and thus provides a good first estimate of the necessary masses for the operations during a long period. From there potential additional payload capacities are evaluated in combination with an alternation of the performed number of spaceflights.
The evaluation will mainly focus on the continuous mode, because the campaign mode only needs a resupply of 1901 kg in a CAMRAS based scenario including the Lunar excursion and thus leaves a sufficient safety margin even for this worst case. The margin towards the Cygnus EX would still be above 1000 kg , as a capacity of 3000 kg was assumed and this is the smallest DSL considered.

To analyze the number of logistic flights necessary the supply for a single mission is evaluated. For the continuous mode the duration of a single crew onboard the Gateway is 28 weeks, including two weeks overlap where two crews are present. This adds up to a total of 196 days per mission, where the regenerative system requires 12.17 kg/day and the non-regenerative system 27.16 kg/day. These numbers are valid for a crew of four. The proportion of the ECLSS mass onboard the DSL is then varied towards the total payload capacity. This allows to calculate the number of logistic flights required as shown in equation 5–1.

$$n = \frac{m_{ECLSS} \cdot d}{m_{spacecraft} \cdot p_{\%}} \qquad (5\text{–}1)$$

n . . . . number of flights
m_{ECLSS} . . . . .total mass for the ECLSS required in a day
d . . . . number of mission days
$m_{spacecraft}$ . . . mass of the selected spacecraft
$p_{\%}$ . . . . percent value of spacecraft mass available for ECLSS

The number of flights were evaluated for a range of p within [1 100]. The masses for the spacecrafts where calculated with 2052 kg for the Cygnus, 3000 kg for the Cygnus EX and the Dragon XL was assumed to be able of caring 5000 kg to the NRHO. The results are plotted in Figure 5–1 for the regenerative ECLSS on the top and the non-regenerative CAMRAS based ECLSS below. The diagram can be understood as showing the percent of mass used by the ECLSS onboard the spacecraft and the consequential number of spacecrafts, and thus flights, required. For the Dragon XL as well as for the Cygnus XL a single resupply flight is sufficient to supply the Gateway station for a single mission. This is marked with P1, for a single Dragon XL flight and P2 for a single Cygnus EX flight. For the Dragon XL the spacecraft would still be half empty even with the entire ECLSS payload mass of 2386 kg on board it would only make up 47 % of the total payload capacity. For the Cygnus XL 21 % of the 3000 kg payload mass would be available. When today's Cygnus is used a single flight would not be sufficient to provide the required supplies for life support to the Gateway with a single flight. This can be identified as even when 100 % of the spacecrafts mass would be used for the ECLSS it still would require more than a single flight.

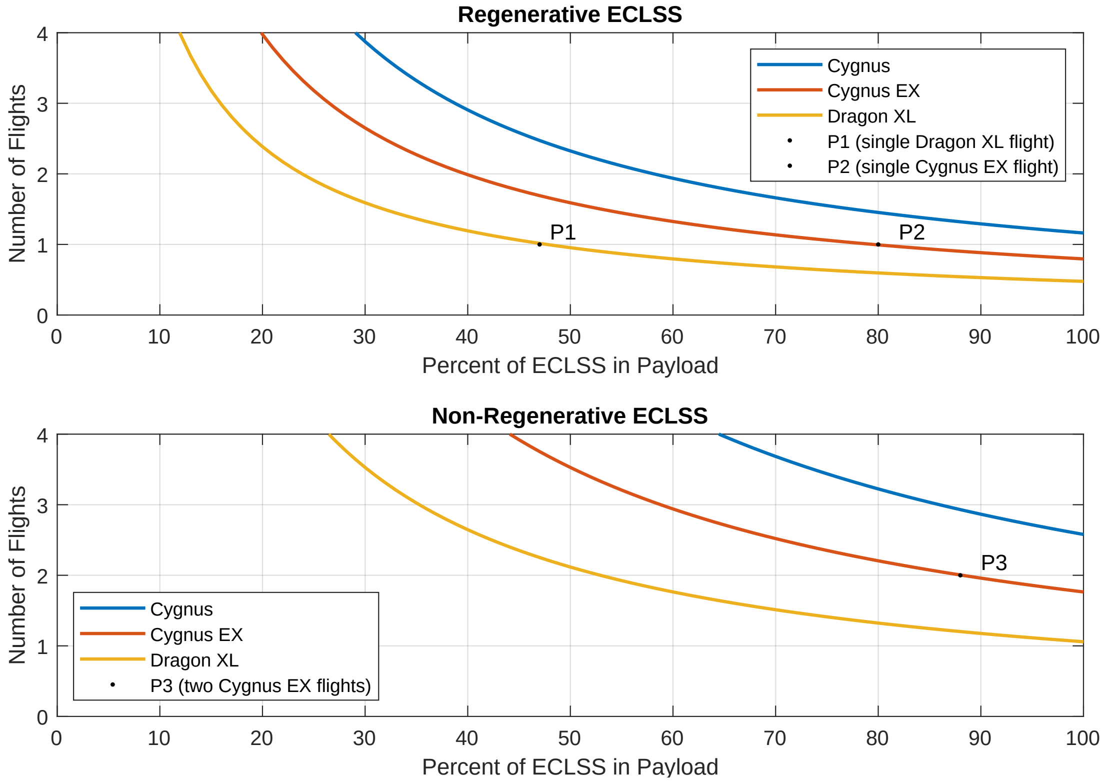


Fig. 5–1: Logistic supply flights in relation to the ECLSS mass on board the vehicle. The lines mark how much percent of the spacecrafts available payload is used for the ECLSS mass required for a single mission of 28 weeks. Displaying the regenerative ECLSS on the top and the non-regenerative system below.

This also holds true for the non-regenerative case where none of the examined spacecrafts fulfills the criteria of transporting 5324 kg in a single flight. Therefore a second flight becomes inevitable, where for the Cygnus EX the margin remains extremely small with only 12 % payload available in total throughout two flights, marked with P3 in the diagram. This would require an additional logistics flight to provide the life support mass for the Lunar excursion.
When looking at the optimal flight numbers and intervals, that leave a sufficient amount of payload available for the Lunar excursion and Gateway operation, it makes sense to consider a one year period and thus two crewed missions. This also makes the numbers better comparable to the campaign mode that only launches a single crew each year. Therefore Figure 5–2 shows the required flights for a supply of the Gateway for an one year period. Again the three spacecrafts Cygnus, Cygnus EX and Dragon XL are displayed. The percentage of the spacecrafts mass used for the Gateways ECLSS is calculated via equation 5–1 but now for a total of 392 days instead of 196 days. The calculation uses 392 days instead of 364, due to the crew overlap. Through this additional four weeks need to be supplied per crew, resulting in a total of 56 crew weeks.

For the regenerative ECLSS, shown in Figure 5–2 on the top, a total of 4772 kg is required to enable the continuous supply of the Gateway station for a full year. This could be done by a single Dragon XL flight, that is 95 % loaded marked with P4.

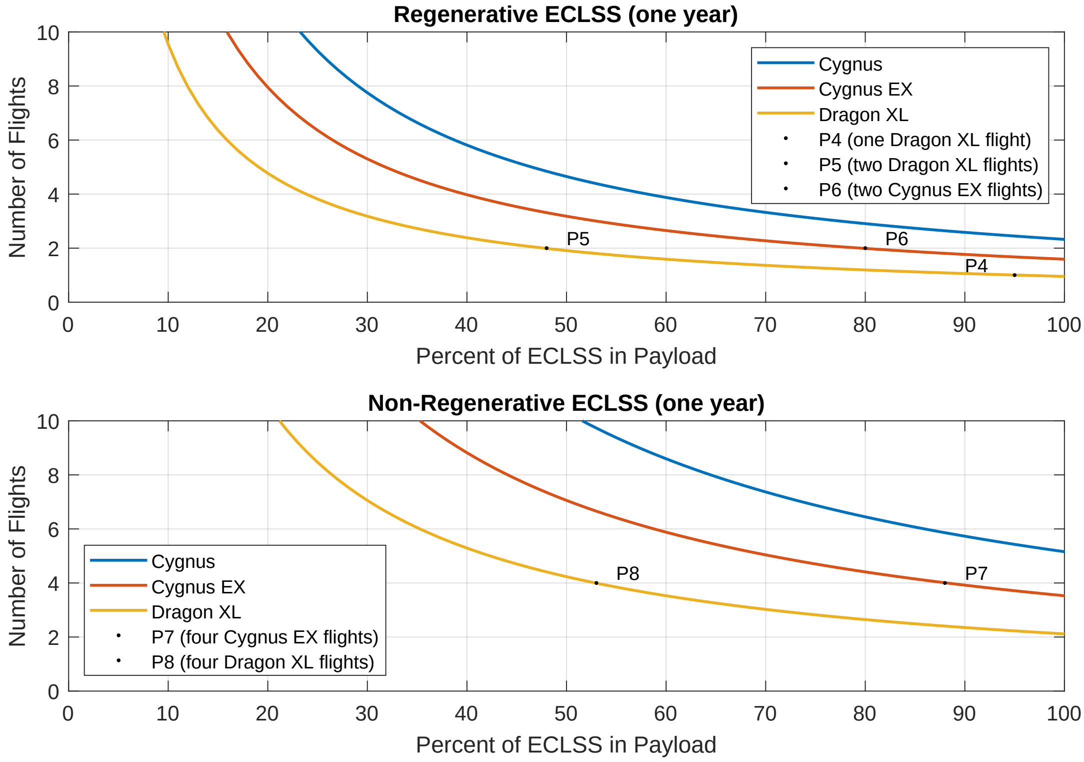


Fig. 5–2: Logistic supply flights in relation to the ECLSS mass on board the vehicle. The lines mark how much percent of the spacecrafts available payload is used for the ECLSS mass required for 52 weeks of operation. Displaying the regenerative ECLSS on the top and the non-regenerative system below.

For the Cygnus EX already 1.59 flights would be required and for today's Cygnus a total of 2.32 logistic flights per year would be necessary to supply the ECLSS alone. Hence considering two logistic flights become certainly more attractive, as the curve remains relative flat in the area above the 50 % payload share of ECLSS. For the Dragon XL a second logistics flight would reduce the portion of ECLSS goods to 48 %, see P5, providing almost 2500 kg of additional payload per flight. For the Cygnus EX a second flight would reduce the required life support mass to 80 %, marked with P6, per flight and thus would also provide 600 kg of payload. Unfortunately for today's Cygnus, two flights are still not enough and an absolute number of three flights are necessary in this case. From Figure 5–2 it can also be seen that reducing the ECLSS share below 30 % increases the required flights in an almost exponential manner.
For the non-regenerative life support the curve does not flatten as much as for the regenerative case and none of the spacecrafts are able to supply the Gateway with a single flight, or even two spaceflights per year. For the Cygnus EX a total of four flights per year is the minimum number of flight required with only 12 % of payload to spare, see P7. Four flights would allow the Dragon XL to fly with 47 % payload available besides life support marked at P8 in Figure 5–15.

An evaluation of the different options for the combination of the DSL spacecrafts is given in Table 5–1 showing the payload available with respect to the number and com-

Tab. 5–1: Possible resupply logistic flights per year and the available payload mass for a permanently crewed Gateway

ECLSS Mode (supply mass)	Resupply Sequence	Flights	Additional Payload [kg]
regenerative (4771 kg)	1 Dragon XL	1	230
	1 Cygnus EX, 1 Cygnus	2	282
	1 Dragon XL, 1 Cygnus	2	2282
	1 Dragon XL, 1 Cygnus EX	2	3230
	2 Dragon XL	2	5230
non-regenerative (10 647 kg)	3 Dragon XL	3	4353
	2 Dragon XL, 1 Cygnus	3	1403
	2 Dragon XL, 1 Cygnus EX	3	2353
	2 Dragon XL, 2 Cygnus EX	4	5353

bination of spaceflights. Important to note is that to successfully conduct the presented missions an additional 761 kg per Lunar excursion needs to be brought to the Cis-Lunar orbit and then transferred to the HLS. This excludes the fuel required for the descent and ascent. In total for the continuous mode two excursions are conducted in a year making a total of 1522 kg necessary to be transferred. This only leaves the option for a supply via two flights. For the non-regenerative mode it even requires a minimum of three flights.
A further paramter is the flight redundancy that comes with the operation of different spacecrafts, as the probability for a loss of a launcher or the outage of a DSL vehicle type is reduced. For instance, when the Dragon XL is grounded or can not launch in the designated time an other type of spacecraft like the Cygnus EX could launch instead. This redundancy is of high value as a gap in the supply chain can lead to the abortion of the mission and operations in Cis-Lunar space. Therefore the option of launching a single spacecraft per year is discarded also because the additional payload does not enable the transfer required for the Lunar excursion.
Other options like the combination of two different spacecrafts therefore offers the best choice even though two Dragon XL could carry more payload, but creates the dependency on a single vehicle type. For the regenerative case a combination of the Dragon XL in alternation with the Cygnus EX would provide a payload of 3230 kg throughout the year and enables the transfer of all ECLSS supplies required for the Lunar excursion, plus an extra capacity of 1708 kg that can be used to transfer additional cargo to the Gateway.

For the non-regenerative case multiple flights are required in any case and thus the same logic applies, that combining different types of spacecrafts provides a reasonable and good choice. The option of launching two Dragon XL and one Cygnus would already provide a payload capacity of 830 kg when subtracting the masses for the Lunar excursion. Otherwise a second Cygnus EX flight would even increase this to a value of 3831 kg and a total of two supply flight during each crewed mission.

5.1.2 Vehicle Disposal

In the schedules presented the DSL spacecrafts no longer used are being disposed before the arrival of the next vehicle. As this leads to the problem of where to store these disposed spacecrafts, once they have fulfilled their duty of transporting payloads to the Gateway, three options are listed here. Especially when looking at a permanently crewed Gateway, as the supply flights alone require two or even four spacecrafts a year a buildup of vehicles could provide a problem. Due to the possibility of refueling the HLS additional flights get to the NRHO and this soon leads to a congested orbit. Therefore this chapter gives a brief overview of possible disposal scenarios where also the option of returning goods, and payloads to Earth is evaluated. An in-depth analysis is not performed as this would be beyond the scope of this thesis.

5.1.2.1 Deorbit on Moon

The probably simplest solution is the controlled deorbit of the vehicle onto the surface of the Moon, as no landing burn is required and the spacecraft can simply be crashed at a designated location. Problems that can result from this are derbies and planetary contamination that can, especially when organic material is dumped, lead to violations of the planetary protection program (Meltzer, 2012). If due to special pre-processing steps the option for dumping the trash on the Lunar surface is an option, the landing site needs to be selected carefully. This is to protect the surroundings and to not destroy later research ground. This evaluation is difficult to be conducted at present day and therefore this option seems unlikely for near future operations.

5.1.2.2 Disposal Orbit

Another option is to fly the no longer required DSL vehicles to a different orbit, where they can be stored. This requires a highly stable orbit, as most disposed vehicles will not be observed or able to perform evasive maneuvers as their available fuel tanks will be empty. The orbit should also not require a large burn to be reached from the NRHO as this fuel needs to be extra transported from Earth. An orbit that might fulfill these requirements is the DRO. The Δv required to reach the DRO from the NRHO is only a total of 56 m/s, considering that flight time does not play a vital role, as the transfer would take a total of 335 days (Lantoine, 2017).
Further the DRO shows a very high orbital stability as it is considered for the Gateways End-of Life orbit where it should remain stable for 100 years (Adamek, 2019, P.25). The orbit was also considered to store captured asteroids due to the high stability as solar gravity is to be the only impending force, especially when looking at orbits the size of 60 000 km to 68 000 km (Bezrouk and Parker, 2014). Leading to the next problem, comparable to orbits surrounding Earth today, that at one point in the future the Orbits become congested and space could become rare. But for near future missions this option is very plausible.

5.1.2.3 Return to Earth

The last option considered is the return back to Earth, representing the most costly method when looking at the Δv that needs to be overcome by bringing extra fuel for the return flight. The spacecraft can then be landed or burn up in Earths atmosphere as today's ISS logistic vehicles do. The landing option allows the return of goods to Earth, but requires a heat shield in addition and the proper entry interface to be met. The complexity and fuel requirement for the landing option of the DSL is even higher than a return to Earth and burn up in the atmosphere.

The Δv between Earths LLO and the NRHO lies approximately at 3.2 km/s and atmospheric breaking can be utilized. As for the logistic flights time is of no factor the return to Earth could also be powered by SEP, as the Smart-1 mission has already demonstrated through a transfer from Earth to the Moon (Racca et al., 2002). This could solve the problem of caring the fuel required for the transfer, but requires the use of a different engine, thus changing the flight duration also for the flight to the Moon.

An additional approach offers the combination of the mentioned systems. As the delivery of supplies to the NRHO will most likely not be launched years in advance and thus a SEP engine for a DSL vehicle seems unlikely. An option is to first store the used vehicles in the DRO. And then use a single DSL with additional fuel reserves, or a transfer vehicle powered through SEP, that transport the vehicles stored in orbit back to Earth. This deep space trash disposal train like option can also be performed later in time. It allows the return of elements that might burn up in the atmosphere while other elements reenter and land on Earth.

5.2 Gateway ECLSS Limitations

The Gateways ECLSS for the regenerative case was designed after the present day ISS ECLSS as it has proven its long-time service and reached a high TRL in all systems. This is important when considering long term missions as the required maintenance intervals and operation lifetimes are well understood. The system for the Gateway was designed to support up to four astronauts, but before and after the Lunar excursion two crews are present onboard the Gateway. This increases the total number of people onboard the station to eight astronauts and therefore the ECLSS must be able to cope with the increased load or otherwise the HLS or Orion might have to cover for additional life support tasks.

To examine critical weeks, simulations were run with Virtual Habitat (V-HAB) by Daniel Kaschubek to evaluate if additional life support systems are required to back the Gateways systems. For the simulation the Gateways volume was assumed to be 125 m^3 and the astronauts are assumed to perform two hours of sport each day distributed between 08:00 in the morning and 17:00 in the evening. The workout includes a 30 minutes aerobic exercise delivering 3847 kJ/h (696 W) and one hour resistive exercise averaging at 1251 kJ/h (348 W) for a medium fit person (Ewert et al., 2021). The simulation was run for a total of 14 days where in the first four days only a single crew consisting of four crew members was present. The ten days thereafter were simulated with a total of eight crew members and a ten day period. This already represents the extreme case, that might appear due to unexpected delays as the crews are not planned to spend more than eight days simultaneously onboard Gateway.

Figure 5–3 shows the humidity levels for the Orion on the left, the Gateway in the center and the HLS module on the right. For the Orion and HLS a volume of 20 m^3 each was assumed. The arrival of the second crew can be identified clearly in all three images

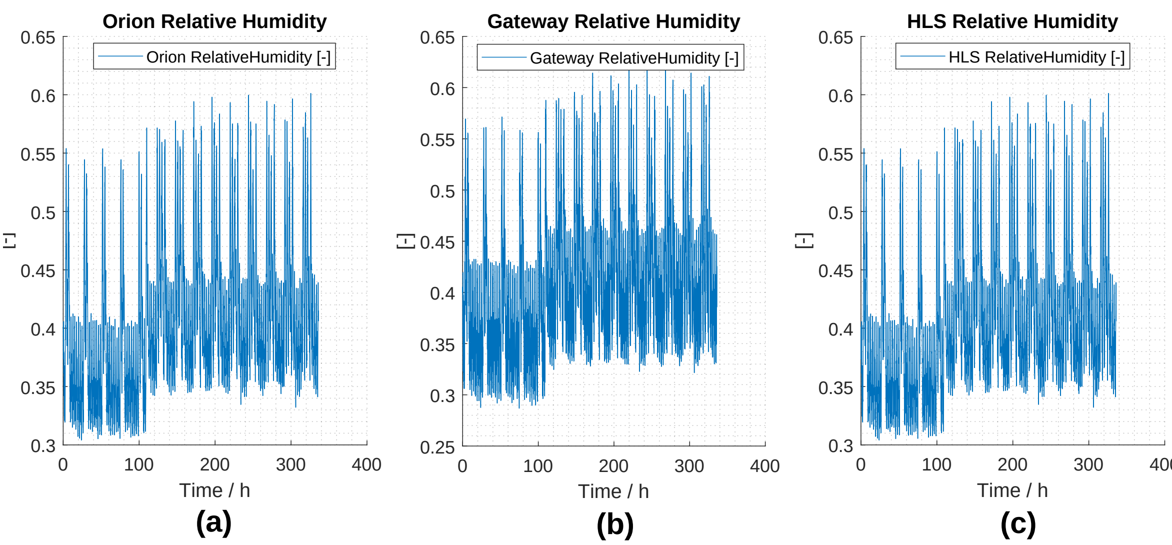


Fig. 5–3: V-HAB simulation for relative humidity in the Orion on the left in (a), the Gateway in the center in (b), and HLS on the right in (c)

of Figure 5–3 as a jump in the relative humidity mean value. Also the explicit training sessions result in a peaks in humidity that can be identified. In total the value does not exceed the 60% in relative humidity and if it remains well below 75% and only peaks shortly during the workout session in the Gateway element (NASA, 2014, P. 362). As these numbers are well within the limits no further steps are required to control the relative humidity.

Concerning carbon-dioxide levels are increasing quite significantly as it can be seen in Figure 5–4. During routine operations onboard the Gateway with four crew members levels fluctuate between 300 Pa to 400 Pa but with the arrival of four more crew members on the fifth day the CDRA can not push the partial pressure back down. This results in the effect that when eight crew members are present the concentration peaks at just above 900 Pa seen at 137 h in the diagrams. The levels for carbon-dioxide concentrations are all following the same trend throughout all three elements. Even though the value drops as the crew is sleeping it remains above a value of 700 Pa and thus enters a sub-optimal region. The limit recommend by NASA for a period longer than seven days is 5.5 mmHg corresponding to about 707 Pa (NASA, 2014, P. 349).

The carbon-dioxide removal should be increased to reduce the concentration in the atmosphere especially during the day as it peaks at values above 1000 Pa partial pressure. The Orions or HLSs CAMRAS could support the Gateway during this critical week, as prior to the descent to the Moon the HLS is operational anyways and could continue operation as it return to the Gateway after the Lunar excursion. Also the Orion returning the crew back to Earth could be activated a week earlier to checkout all systems and power up its CAMRAS. The system could then be operated alongside the Gateways CDRA and reduce the carbon-dioxide level throughout the station and the docked elements.

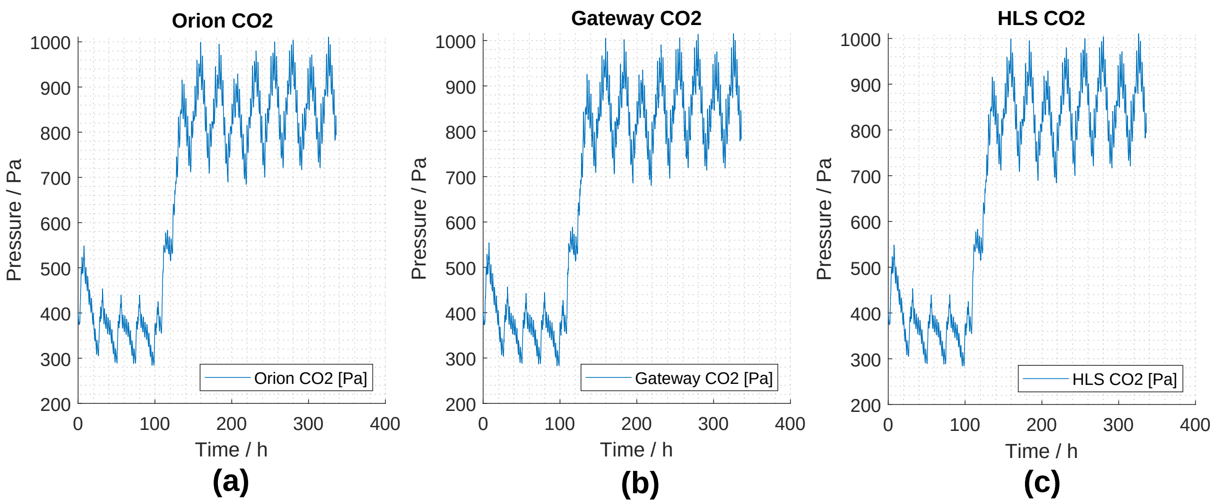


Fig. 5–4: V-HAB simulation for carbon-dioxide levels in the Orion on the left in (a), the Gateway in the center in (b), and HLS on the right in (c)

Concerning the oxygen concentration in the atmosphere the values must remain between certain borders due to the risk for hypoxia or hyperoxia. The oxygen levels descent gradually until leveling at around 1,95·10^4 Pa in all three elements, as shown inFigure 5–5. The Gateway shows a slightly stronger fluctuation in the oxygen partial pressure compared to the docked elements. Recommended limits for the partial pressure of oxygen lie between 139 mmHg and 178 mmHg which is an equivalent to 1,85·10^4Pa to 2,37·10^4Pa (NASA, 2014, P. 345). Therefore no further oxygen supply is required as the values remain within the limits. The descent of the curve in the first four days, where only four crew members are present results from the fact that the OGA operates after a set value and adjusts to that value over time. Once the system has reached this value it is perfectly capable to maintain it even for a crew of eight.

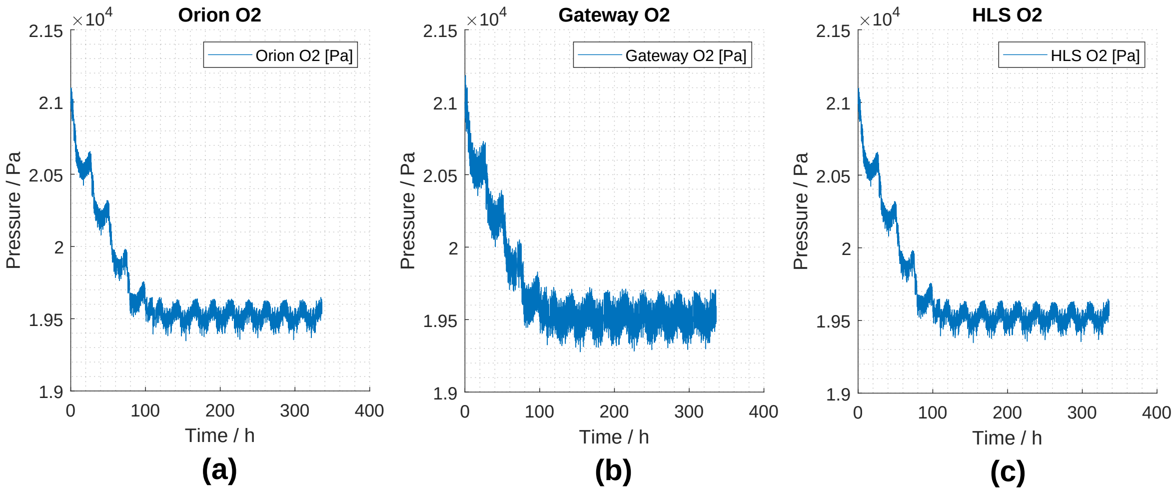


Fig. 5–5: V-HAB simulation for oxygen levels in the Orion on the left in (a), the Gateway in the center in (b), and HLS on the right in (c)

Conclusively the simulations show that humidity and Oxygen levels are remaining within limits. For these no additional system is required to supply eight crew members. The carbon-dioxide levels though are above limits and need to be reduced during the week where two crews are onboard Gateway.

5.3 Lunar Excursion

This section exhibits characteristics of the Lunar excursion focused on supply logistics. The concepts presented assumes the HLS present and docked to the Gateway and to act as a habitat on the surface of the Moon. On this basis, the properties of the HLS can change the proposed mission concepts, as masses for ECLSS or fuel needs to be brought to the NRHO. This can be done either by the regular DSL flights or can require additional flights. Therefore different options are evaluated here to establish an overview of the possibilities in combination with the Gateway concept presented.

5.3.1 ECLSS Payload

The payload required by the HLS's ECLSS during the Lunar exploration plays an important role as it influences the available payloads on the DSL flights. This mass needs to be brought from Earth in addition to the Gateways ECLSS supply. As the exact realization of the HLS is not known at the present moment the used life support system is also unknown. Therefore three reasonable systems are used for the calculation of the required resupply masses. The ECLSS selected are a regenerative system comparable to the ISS today, a CAMRAS based system and a conservative Lithium Hydroxide (LiOH) based system.

As the duration for the Lunar excursion was set to four weeks in all modes the resupply for a period of 28 days is evaluated. Figure 5–6 shows the behavior of the three different ECLSS systems in their required supply mass with respect to the duration of the operation. A red dashed horizontal line marks the planned 28 days. For the LiOH, indicated with a blue line, a value of 40 kg per day for all four crew members was used. This value is computed from the 7.76 kg of food and 1.37 kg of clothing calculated via

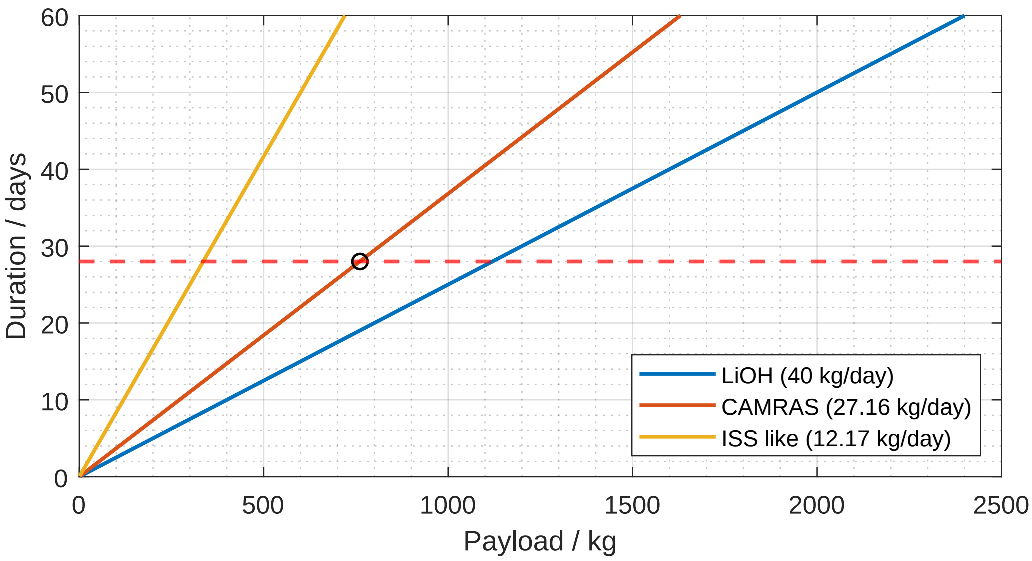


Fig. 5–6: Duration of surface excursion compared to life support payload, displaying three different ECLSS systems, a ISS based, CAMRAS system or a LiOH life support system used for the lander. The horizontal dashed line marks the 28 days line.

LiSTOT combined with the 31.52 kg for LiOH, water and oxygen taken from (Jones, 2017, Table 2.). It represents the worst case assumption resulting in a total mass of 1120 kg after 28 days. For the CAMRAS, indicated in red, this results in 761 kg supply mass and a regenerative system, marked in yellow, would only require 341 kg for the period of four weeks.

Due to the fact that the HLS will not be operated in a permanent manner but only for four weeks at the time and then be shut down or automated, the CAMRAS system was selected in the concepts developed here as being a feasibly ECLSS. This leads to an additional 761 kg that need to be delivered with the DSL to the Gateway station and then be transferred to the docked HLS. This point where 28 days intersect with the CAMRAS supply mass curve is marked in Figure 5–6.

5.3.2 HLS Fuel Required

An important parameter is the required fuel for the HLS, depending on the concept used the HLS might be refueled at the Gateway. This is part of the idea of reusing the same spacecraft again. Depending on the concept this would require a tanker, additional payload or a landing segments to be delivered to the station. In order to get an estimate for the fuel required an analysis is conducted in this subsection.

The Δv required for the Lunar excursion from the Gateway, located in the NRHO, is given by NASA (2019, P. 41) and adds to a total of 5665 m/s. This includes the descent as well as the ascent, as displayed in Figure 5–7 where the $\Delta v's$ form the burns from the NRHO departure to the surface and back are displayed. Some TCM are as low as 5 m/s and therefore barley visible, as the largest portion is made up by the landing requiring a total of 2060 m/s and the ascent burn of 1860 m/s. The LOI also requires approximately 650 m/s and the LLO departure 670 m/s. These $\Delta v's$ are required to reach the surface of the Moon and return to the Gateway.

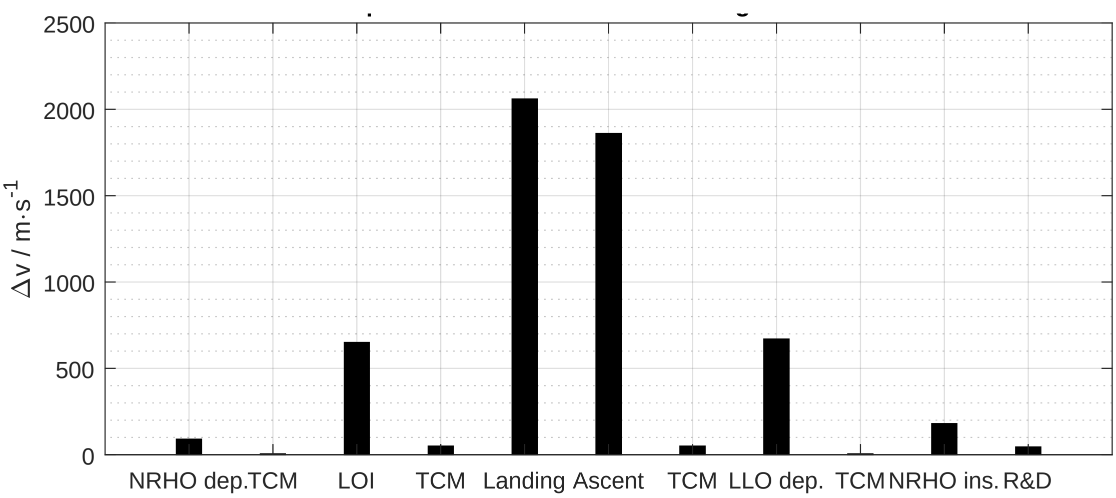


Fig. 5–7: Delta v required for descent and ascent to conduct the Lunar excursion from the NRHO in the order of the required maneuvers

With the Tsiolkovsky equation (eq. 2–1) an initial evaluation for the required fuel for each maneuver can be calculated and provide a basic sense for the HLSs fuel consumption. These values depend on the used engine and the total weight of the system and as these are only roughly known, the calculation as such must be treated as an estimate.

Rearranging the ideal rocket equation leads to the calculation of the initial mass towards the final mass and is shown in equation 5–2. This mass ratio gives information about the fuel used by the spacecraft. As the final mass subtracted from the initial mass gives the fuel consumed during the maneuver. The parameter v_* represents the exhaust velocity of the rocket engine.

$$\frac{m_{initial}}{m_{final}} = e^{\frac{\Delta v}{v_*}} \tag{5–2}$$

As this ideal equation calculates the mass ratio for a single staged rocket directly the relationship with respect to the required velocity is plotted in Figure 5–8. For a single staged spacecraft, referred to as Single Stage to Orbit (SSTO), the entire structure descents and later returns to orbit, without dropping any tanks or leaving elements behind. As this is the concept of the Space X Starship, recently selected by NASA, see Brown (2021), the vacuum ISP of 378 s was selected. This is the latest value for the raptor engine, see (Dodd, 2021, 03:40), most likely being used for the Starship. Figure 5–8 marks the required 5665 m/s with a red circle leaving a mass ratio of 21.7 %. This would require a fuel mass of 437 t of fuel when the Starship reaches the weight of 120 t , excluding additional payloads.

As the maximal payload delivered to NRHO with the DSL is 5000 kg and so far the maximal TLI payload is at 45 t for the SLS Block 2 a supply of 437 t of fuel via the considered vehicles seems unlikely. Therefore a refueling of the HLS via Gateway is not possible and not included in the concepts presented.

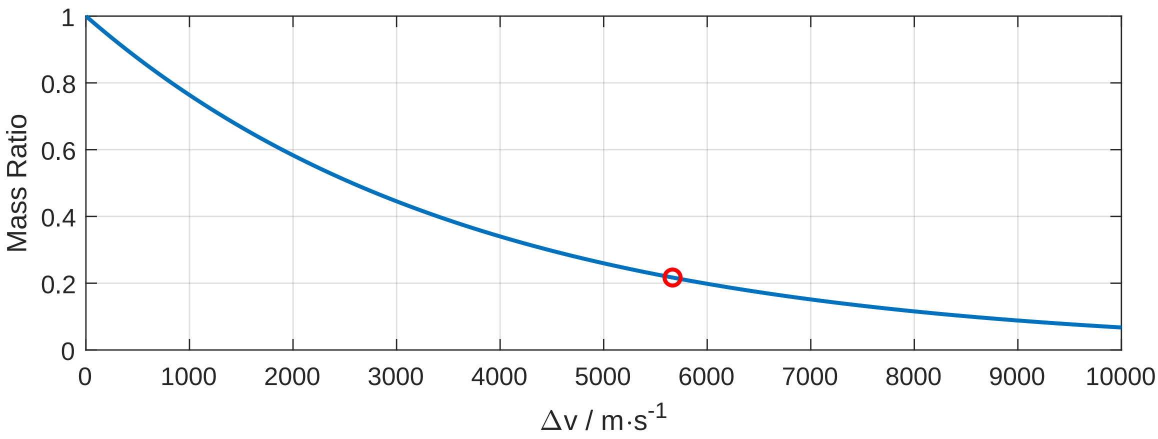


Fig. 5–8: Mass ratio for a SSTO using an ISP of 378 s**, marking the required** 5665 m/s **with a red circle**

Further rearranging of the Tsiolkovsky equation (eq. 2–1) and splitting the masses into the structural, payload and propulsion part allows to solve for the relationship between the payload and the initial mass. The equation in 5–3 holds true for the single stage approach and gives the mass relation.

$$\frac{m_{payload}}{m_{inital}} = (1 + \frac{m_{structure}}{m_{propulsion}}) \cdot e^{\frac{-\Delta v}{v_*}} - \frac{m_{structure}}{m_{propulsion}} \qquad (5–3)$$

When alternating the propulsion mass as well as the structural mass the available payload can be computed. This was done for a SSTO and the results are displayed in Figure 5–9. The structural and fuel masses are alternated between a value of zero to 120 t and zero to 500 t. All values can be read in tons and the diagram gives the relation between the masses for the required Δv of 5665 m/s and an ISP of 378 s. The diagrams origin is on the left and the horizontal axes describe an increase in structural and propulsion mass. An increase in payload mass leads to either an increasing of fuel mass or a decrease in structural mass. As these are the theoretical ideal values the diagram also indicates the possibility of high payloads and minimal structural weight, even though in reality this is not constructible.
The red lines intersecting in the left section of Figure 5–9 indicate 20 t of structural and 100 t of fuel mass. The structural mass was selected as a example also for the following two stage approach. It leaves about 7.7 t of payload for a SSTO.The intersection is marked with a red square. The cyan line on the right marks 120 t of structural weight, assumed as structural weight for the SpaceX Starship (SpaceX, 2020). It can be identified that the minimal fuel required is 433 t, marked with a cyan square, and depending on the payload this value is increased. The green square close to the origin marks the 5 t of fuel that can brought to the Gateway by a DSL used in this concept, it would enable a mass of 1386 kg to be brought to the surface and back, this includes structural as well as payload mass.

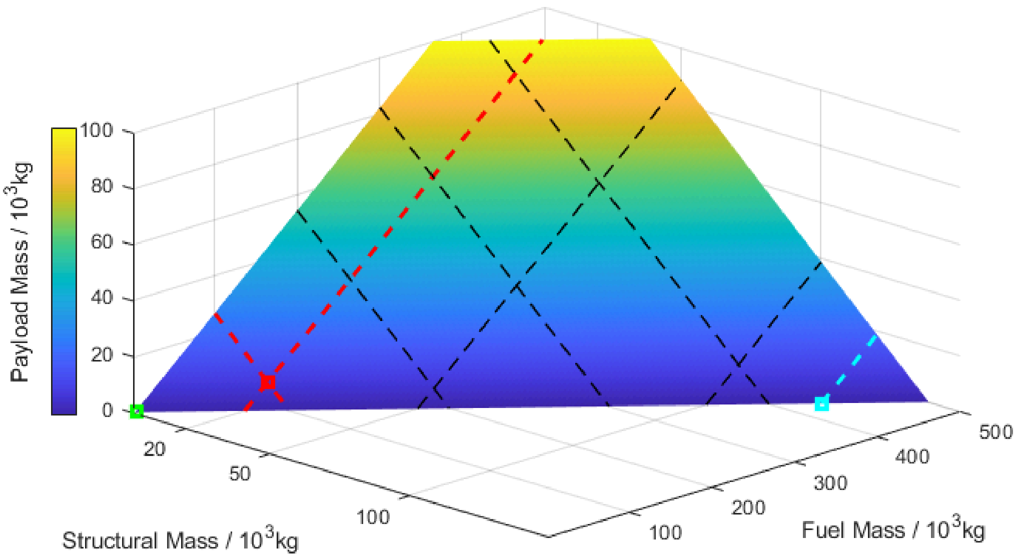


Fig. 5–9: Structural, payload and fuel masses for a SSTO using an ISP of 378 s **and** 5665 m/s

A further method beside the single staged approach is to use a multiple stage system. For analysis the fuel to final mass was plotted for the ascent and descent from the NRHO are displayed in Figure 5–10. In order to allow a separate contemplation the two stages are displayed separately, the ascent stage on the top and the descent stage in the bottom of Figure 5–10. The vertical red dashed line indicates a theoretical spacecraft mass of 20 t leading to a required fuel of 22.67 t and thus a total weight of 42.67 t for the ascent stage. This mass needs to be delivered to the surface and thus acts as the minimal final mass for the descent stage. Value is marked with a vertical red dashed line in the diagram (b) for the descent stage. This value does not consider the weight of the descent stage itself, and thus the values in reality is definitely larger. The used engines ISP was altered to visualize impact of the engine used. The blue line represents a vacuum ISP of 378 s, the red a value of 350 s and the yellow line resembles an ISP of 300 s. It can be seen that the change in the engines properties can influence the propulsion mass required quite significantly with up to 30 % difference between an ISP of 378 s towards the ISP of 300 s.
This analysis shows as well that a supply of fuel for the HLS via the DSL flights of this concept are not feasible and an additional independent supply of fuel for the HLS will be indispensable to make use of the reutilization of the HLS.

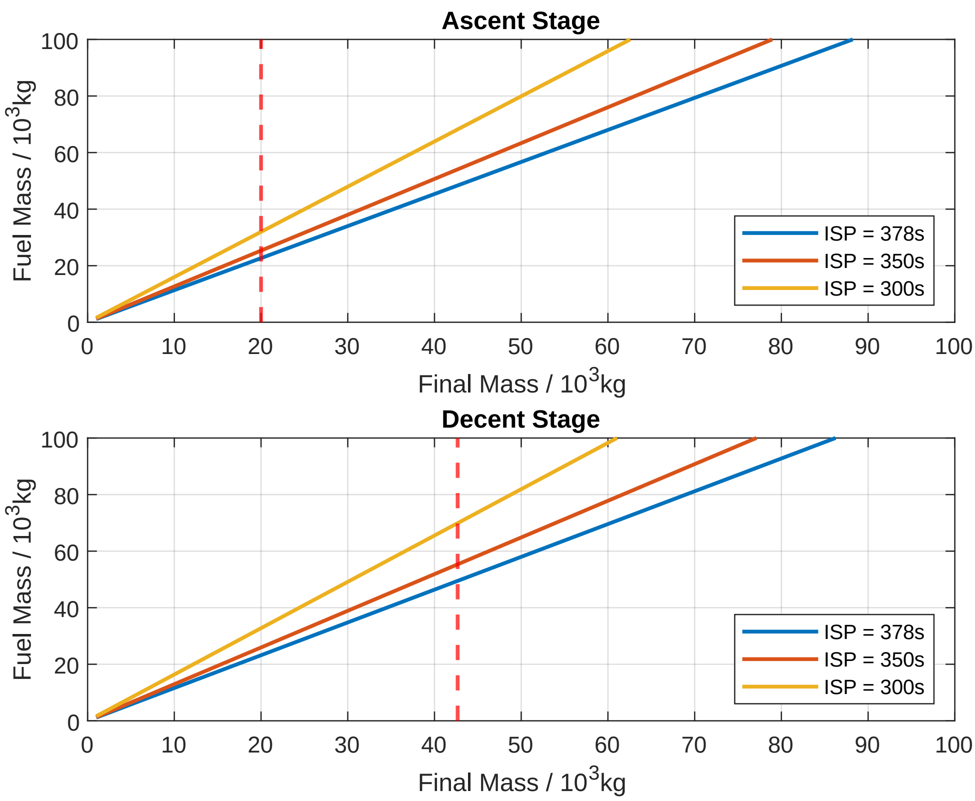


Fig. 5–10: Final mass towards propulsion masses for a two staged HLS. Indicating the ascent stage on the top and the descent stage below. Three different ISP's are displayed and a vertical dashed line indicates a idealized configuration for a 20 t spacecraft.

5.4 Mission Mode Analysis

This section investigates the four different concepts that were presented and their properties. The concepts, also referred to as modes, differentiate mainly in their duration, when looking at a single crewed mission and ECLSS. The variation of the ECLSS mainly results in a change of the payload capacity, whereas the duration influences all aspects of the concept from the logistic flights required to the MCC tasks. In order to get a time frame, where all concepts are comparable to each other, a period of a year was selected. During a year the continuous mode will perform two crewed missions, while the campaign mode is designed to launch one crew per year. The concepts were designed in such a way that allows repetition of the same scheduled on a yearly basis, making a one-year period the optimal observation time frame suitable for analysis.

5.4.1 Working Hours

The hours available to the crew is a substantial parameter in spaceflight, as the crew members can not work 24 hours seven days a week, especially during long missions. The time that is available to do work is therefore analyzed for the four different concepts. The working time available is split into operational work, which is necessary to conduct the mission, and routine work, which can include science experiments or other tasks non-mission essential. All four scenarios use a similar amount of crew time for ECLSS maintenance since it is difficult to quantify this characteristic specifically for newer systems. This maintenance work is part of the operational hours.

Table 5–2 gives the sum of all hours available to the crew throughout a year, on the basis of a single crew member. It includes the times arising from a single mission, written in parenthesis for the continuous mode, and thus this hour can be interpreted as the hours per person. The times presented are the operational hours required to conduct the mission and the routine hours available. During these hours scientific experiments and work can be conducted. For the campaign mode, no differentiation between the regenerative and the non-regenerative mode is conducted as the total amount of hours are identical. The major tasks arising are in both cases the same and the working hours therefore equal. The EVA hours available are given in an extra column but are also included in the routine hours, as the time available for an EVA might not necessar-

Tab. 5–2: Working hours per year and crew member for the different mission modes, giving the hours for a single mission in brackets

Mode	Operational [h]	Routine [h]	Possible EVA's [h]
Non- and Regenerative campaign mode	270	245	56
Regenerative continuous mode	824 (412)	2010 (1005)	294 (147)
Non-Regenerative continuous mode	906 (453)	1904 (952)	266 (133)

ily be used. This column highlights the possible available hours. Hours resulting from the Lunar excursion are also included in these numbers. Detailed tables about the hours available per week for each mission concept can be found in the Supplementary Tables section in the Appendix A.

The graphical distribution of the working hours available is given in Figure 5–11 displaying the operational and routine hours for the two continuous modes and for the campaign mode. The regenerative continuous mode provides the most crew time for routine work not related to the operation of the mission. The total count of 2834 working hours results from the fact that two crews are overlapping each other for a duration of 12 weeks and hence creates this high amount of hours within the duration of a year. The numbers are calculated per crew member for both missions combined, thus the total available hours need to be multiplied by four. The non-regenerative continuous mode shows less available routine hours but has approximately the same total time available. This slight difference results from the ECLSS additional supply flights. They consume crew time for unloading and loading of the cargo spacecraft and these weeks have a different working scheduled for two weeks. Further, both continuous modes include several hours of monitoring and Lunar support work. These might not be required shifting hours from operational to routine work. Also the schedule for the campaign mode sees less margin for errors and buffer, than the continuous concepts.

In addition to the hours available onboard Gateway and during the transfer from Earth are the hours resulting from the Lunar excursion. They are also given in Figure 5–11. A single Lunar excursion with a duration of 28 days requires a total of 63 operational hours and can provide about 123 working hours, where a total of 42 hours could be EVAs. The numbers hold true for a single crew member. For the continuous modes the hours double as two Lunar executions are conducted throughout the period of a year.

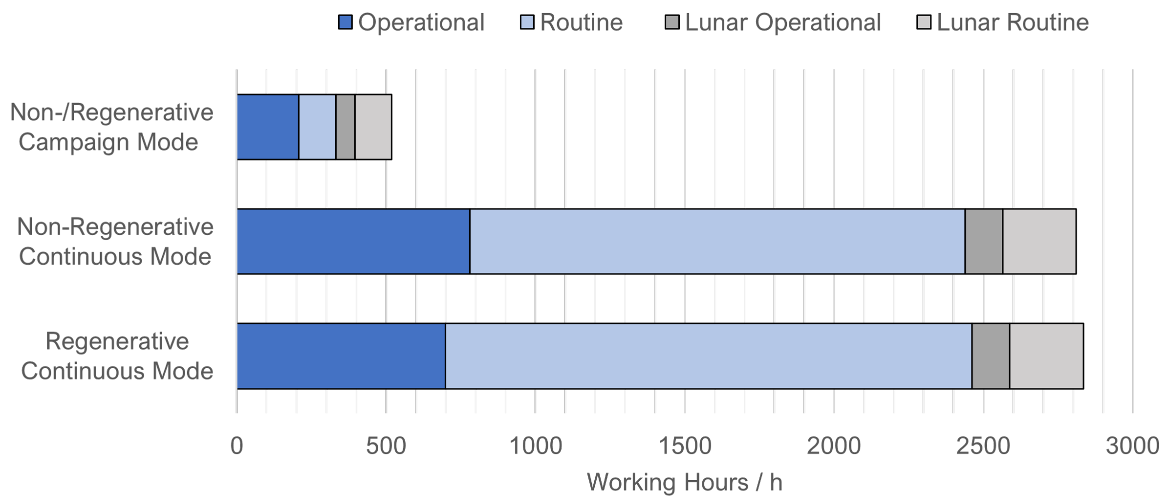


Fig. 5–11: Working hours for the different modes throughout a year conducted by a single crew member, divided in operational hours, routine hours and hours available during the Lunar excursion

5.4.2 Spaceflights

As spaceflights are a vital element to enable a mission to the Moon their intervals and payload masses are evaluated. The focus lies on the deep space elements, that perform the flight after the TLI burn to the Moon. The launch vehicles themselves are not evaluated in detail in the course of this thesis.
Besides the key values of the spacecrafts, the redundancy of different vehicles themselves plays a vital role. This can cause the payload to decrease in some cases, but the reliability of the supply chain is increased drastically and thus considered more important. In case a vehicle is unable to launch or grounded, the other system can be used instead. This was considered in all concepts and an alternation of the DSL vehicle type was conducted where feasible. From the evaluation in subsection 5.1.1 the optimal supply sequence for a year was found. For the regenerative continuous mode it is one Dragon XL and one Cygnus, as for the non-regenerative mode where two vehicles of each type are used. For the regenerative and non-regenerative campaign mode a single flight is sufficient. Thus making a redundancy no option. An overview to these numbers can be found in Table 5–3 in the DSL column.

The Orion is so far the only deep space crew vehicle and thus no alternation is planned, but if a further crew vehicle becomes available the crewed flights might be conducted through multiple vehicle types as well. The number of flights to and from the Gateway for the Orion are also listed in Table 5–3 in dependency of the different modes.

The masses given in the columns on the right of Table 5–3 indicate the required ECLSS supply masses for the Gateway station alone and a combination of the Gateway and the HLS supply together. The cargo mass provided in the final column on the right describes the payload masses available throughout the year. This mass is not required for the life support supply and thus can be used for additional equipment, fuel and EVA payloads. Orions internal payload capacities are neglected for this calculation. They can be used for emergency supplies and to return cargo back to Earth.

Tab. 5–3: Number of spaceflights and masses per year

Mode	Total	Orion	DSL	Gateway ECLSS Mass [kg]	HLS ECLSS Mass [kg]	Cargo Mass [kg]
Regenerative continuous mode	4	2	2	4771	1521	1708
Non-Regenerative continuous mode	6	2	4	10647	1521	3832
Regenerative campaign mode	2	1	1	511	761	3729
Non-Regenerative campaign mode	2	1	1	1140	761	3099

The cargo mass of the Orion will be in the area of the low hundred kilograms. A visual representation of these masses split into the supply flights required is given in Figure 5–12 the masses all add up to the values given in Table 5–3.

Figure 5–12 shows how the payloads are distributed on the planned flights. Black horizontal lines separate each spacecraft and it can be identified that some are able to transport 5000 kg at once and some only 3000 kg, as it was assumed for the Dragon XL and Cygnus EX respectively. The required supply masses for the ECLSS onboard the Gateway are colored in orange and for the HLS in gray. These supplies include consumer goods like food, but also maintenance equipment needed for the operation of the ECLSS. The free available cargo mass is shown in green. Further, it can be seen that for the continuous modes the absence of a supply flight will lead to a shortage in the ECLSS onboard the Gateway. A single flight can not transport the entire mass required at once, thus the crew depends on the arrival of these supplies.

Due to the severe impact of a launch delay or failure, it is recommended to conduct an additional payload flight to the station before the beginning of the permanently crewed routine sequence. Through this, a supply flight brings the required goods not for the weeks to follow but for the weeks after the arrival of the next DSL. This creates a buffer for a complete loss of a DSL. Otherwise, the absence of a launch supplying the crew will lead to the abortion of the mission. The supply interval for the regenerative continuous mode is six months and three months in the non-regenerative case. For the campaign mode buffer is not required as the DSL, providing all necessary supplies, already launched prior to the crew.

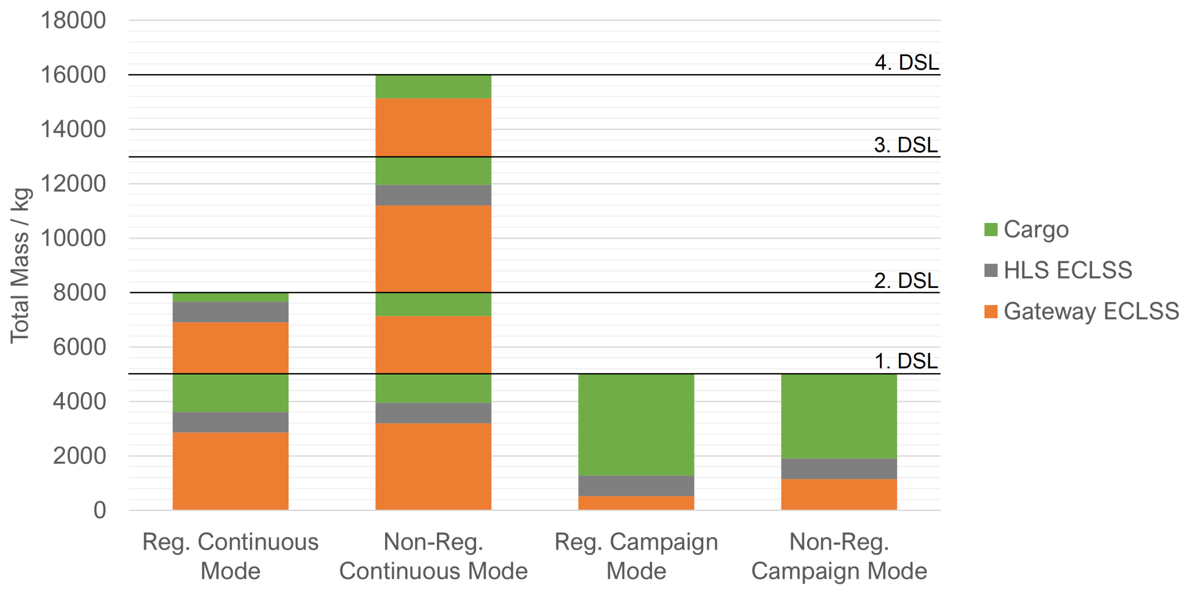


Fig. 5–12: Total logistic supply mass throughout a year for the four different mission modes, resulting from each DSL spaceflight. Split in the Gateways and HLS ECLSS supply mass and the available cargo mass. Black horizontal lines highlight the payload maximums per spacecraft.

5.4.3 Levels of Activity

To quantify the level of workload applying to the MCC, an algorithm was developed to visualize the different major events appearing throughout the mission. This resulted in the creation of a diagram displaying the different levels of activities over time, as shown in Figure 5–13. The resolution thereby goes down to a week and thus more and less intense weeks are identified. Each level refers to a major task or operational situation arising for the MCC. When multiple of these events take place simultaneously they add to each other and increase the level of activity. The major events are in accordance with the Sequence of Events presented in the previous chapter. Explicit information can be found in the MCC row of the Sequence of Events, as shown in Figure 4–18 for the regenerative continuous mode, Figure 4–19 for the non-regenerative continuous mode and Figure 4–5 for the campaign mode.

The base level of activity, level 0, is assigned to the automated operation of the Gateway as this is the quietest operational condition. Every other event receives the absolute value of one and thus if multiple events are happening simultaneously the total level of activity is increased. The contributing activities that were identified are described in the following.

- **Crewed operations:** refer to the presence of a crew. Indicated in the Sequences of Events with the shortcut 1G or 2G to highlight the existence of one or two crews with four astronauts each. The capital letter indicates the location, G referring to the Gateway and M to the Moon. As every crew increases the level by the value of one, two crews result in the activity level of two. During this time MCC needs to supervise and support two crews and missions and thus a higher workload is the consequence.
- **Lunar operations:** describe the excursion to the surface of the Moon. As the excursion down to the surface of the Moon is connected to a high amount of intensive tasks, an additional level is added during this period. The events included in this level of activity are the undocking, flight phases, and landing of the crewed HLS. And further, the high amount of EVA's on the surface. These tasks increasing the stress on the crew and the ground control team. In the Sequence of Event diagrams, these operations are labeled with 1M, where the number indicates the number of crews on the surface, in this case, one.
- **Transfer and docking:** refers to the launch, spaceflight between Earth and Moon and the rendezvous and docking with the Gateway station, for both crewed and uncrewed vehicles.
- **Undocking and transfer:** describes the undocking, spaceflight back to Earth and landing in the case of a crewed vehicle. For the DSL it stands for the undocking and disposal maneuver.
- **Startup:** referring to the startup and activation of the Gateway from the automated mode to a crewed mode.

- **Automated:** as mentioned before the automated or standby operations are referred to as level 0 and thus only occur in the campaign mode during the time no mission is taking place. But during this time the Gateway still requires ground control from a MCC, even though the workload might be reduced, it is not zero.

In Figure 5–13 the different levels of activity for the different mission modes are given. The timescale indicates the weeks throughout the period of a year. The numbering of the weeks given on the x-axis refers to the numbering used for the continuous mode, as shown in Figure 4–18. Therefore the number starts with week 21. The Lunar excursions are shaded in gray and during these periods an increase in the activity level can be identified. The labels 'Orion Launch' refer to the weeks where the launch, transfer and arrival of the Orion spacecrafts takes place. 'Orion Return' marks the week of the spacecrafts return to Earth. An increase in the activity level can be seen in these weeks and also in the DSL transfer weeks. These weeks are marked with a dart in accordance to the color used for the scenario.

The operational events for the campaign modes are identical for the regenerative and non-regenerative case. They only differ in their DSL cargo payload and thus the orange line indicates both mission modes. The time frame for the campaign mode was selected so that the Lunar excursion is happening simultaneously with the continuous mode. This enables a representative comparison and means week 1 from the Sequence of Events, as shown in Figure 4–5, starts in week 43 in the level of activity diagram Figure 5–13. Before this week the orange shaded area marks the Gateways transition from the automated to the crewed mode. During this startup period a higher workload for the ground control team will arise. Afterwards, in week 44 the DSL reaches the Gateway before the crew indicated with an orange dart in Figure 5–13.

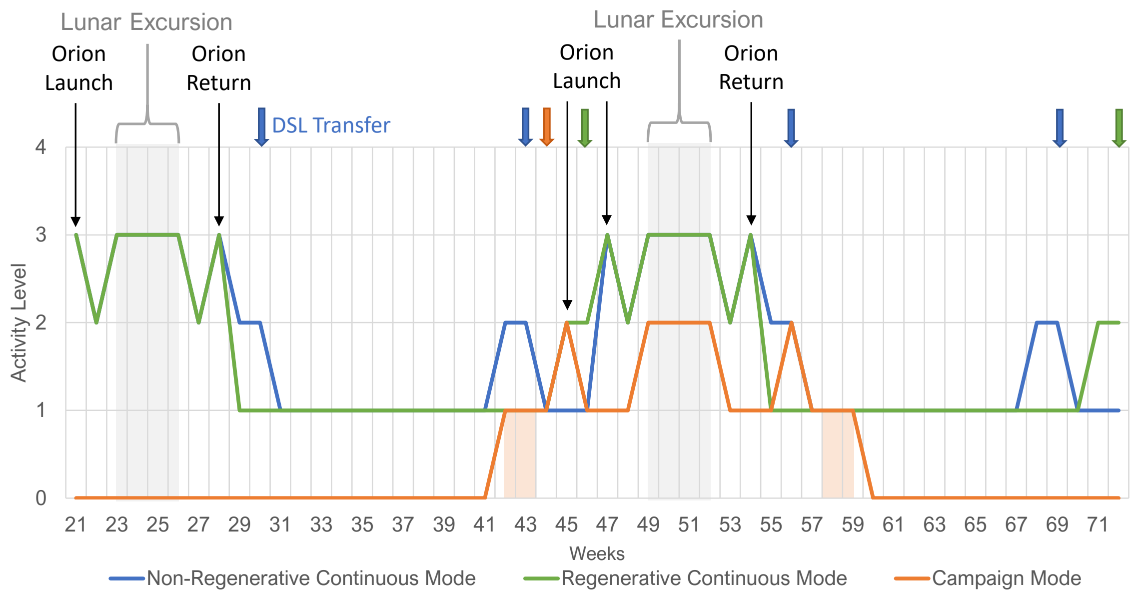


Fig. 5–13: Activity Levels for all mission modes throughout a 52 week period

The green line gives the regenerative continuous mode starting with the flight of the second crew towards the Gateway in week 21. This adds to a total activity level of three, as two crews are present plus the launch, transfer and docking of the Orion spacecraft is taking place. This is identical for the non-regenerative case displayed with the blue curve that is covered by the green curve. In week 22 the level drops to two, as now only two crews are on the Gateway. As the Lunar excursion takes place, the activity raises back to level three until week 27, when the Lunar excursion has ended and both crews are onboard Gateway again. Thereafter the level peaks again for week 28 as one crewed Orion returns to Earth. Now two crews are present and one spaceflight is taking place. After week 28 the continuous modes start to differentiate as the resupply logistic intervals are different. For the non-regenerative case a peak can be identified in week 42 and 43 resulting from the DSL being undocked and disposed, followed by the launch, transfer and docking of the next vehicle in the following week. For the regenerative case this takes place just before the arrival of the next crew in week 45 and 46. The continuous modes start to repeat themselves with the start of week 47, marking half a year. Now the next crewed mission launches to Cis-Lunar space.

5.4.4 Application to MCCs

In general, the continuous mode adds to a higher activity level, due to the presence of at least one crew throughout the entire year and two crews during the Lunar excursion and Gateway overlaps. For the campaign mode it has to be considered that even during the periods where activity level 0 is indicated, operational tasks for stationkeeping during the automated mode occur.

The campaign mode shows the lowest levels of activity as a single crew is present and the major events were distributed so they do not occur simultaneously. The DSL therefore arrives before the crewed mission launches and undocks after the crew has returned to Earth. Therefore a maximum of activity level two is never surpassed.
For the continuous mode the maximal level, level three, is reached during the time when two crews are present, either on their transfer or on the surface of the Moon. During weeks when both crews are onboard Gateway a drop from the activity level three to two can be identified.

As multiple different agencies and commercial contributors are present in this scenarios. The distribution of the tasks to the different MCCs can be conducted on the basis of various approaches. For the transfer of the vehicles the companies or agencies that developed and tested it is most likely going to take the lead in mission control. This is due to the high degree of automation that is required and thus the ground control team needs to be very familiar with the system. When considering the Gateways onboard operations, multiple possibilities arise as the modules are manufactured by different agencies and sub-components are often provided by another agency. Therefore a distribution of the arising tasks and abilities might be reasonable and a joint operational concept like on the ISS today seems favorable. This becomes increasingly appealing when crews traveling to Cis-Lunar space consist of international members.

5.4.4.1 Options for Mission Control Tasks Distributions

Options for the distribution of the mission control tasks, that arise for these future missions depending on the concepts presented are mentioned in this subsection. As the communication link from Earth to the Gateway and Orion as well as the surface of the Moon will be possible for both NASA and ESA the two deep space networks can act as a backup system for each other. Through this the location of the MCC on Earth is irrelevant. This enables different scenarios for the responsible MCC.

- Module-based:
  Every participating agency or company provides the mission control and support for its own module. It also refers to vehicles and ground stations. This option is to some degree comparable to today's ISS operation. It enables the use of multiple MCCs around the globe and each member participating in the spaceflight scenario. Already existing communication channel can be utilized and competences from agency's sides are already present.
- Location-based:
  In this scenario a single MCC would be responsible for the crew and vehicle depending on its location. A single MCC can take over the entire ground control of the Gateway station in NRHO. Other participating agencies could then take care of other vehicles during the transfer or when they are on the surface of the Moon. This concept would allow a clear distribution of the competences, but would require a technology and information exchange about vehicle hardware. As this might not be supported when commercial companies are providing this vehicles a joint mission control would be required or the integration of vehicle specialists into the ground control teams.
- Mission-based:
  The MCCs from the participating agencies each support a crewed mission. This would require all MCCs to acquire all competences and would result in high workload phases and low workload phases. The exchange of critical information's might become difficult, but the option exists.

For the different mission scenarios presented different MCC task distribution options are more or less appealing. The module-based concept is appealing for the continuous mode as this makes a wide distribution of the increased tasks and workloads possible. Also the location-based concept would be beneficial for the continuous mode, as the intense tasks would be distributed throughout the different MCCs. The mission based concept might be most appealing for the campaign mode as workloads remain comparably low. To conclusively identify the options an in depth investigation is necessary but surpasses the scope of this thesis.

5.5 Summary of Mission Analysis

The purpose of this section is to create a representation of the strengths and weaknesses of the four operational modes towards each other. As the previous sections described the specific properties of the presented scenarios the focus now lies on the correlations and contrasts between them. Thus numbers for the parameters gathered, like the payload masses or working hours, need to be brought to a coherent scale to make them comparable. The values based on a single mission as well as a yearly basis are presented. As the continuous mode was designed to support a permanently crewed station the annual investigation is crucial. The logistics and resupply flights are designed to work most efficiently on an annual scale, including two missions. Presenting only the numbers for a single mission would therefore distort the results.

The method to harmonize the different scales was selected carefully in order not to distort the results through the process of normalization. To generate a wider picture three different normalization options where evaluated. First the distribution of values from 1 to 10 for the minimal to the maximal value was calculated. This method showed its frauds in obtaining the correct proportions and had difficulties with small numbers. The second option considered, was the normalization of the values towards the highest arising number of each category, via vector normalization. This option showed good proportional results, but due to the nature of vector normalization large values arising in one mode showed larger values, than the appearance of two high values in different modes. This again creates a distortion of the greater picture. The method chosen was to normalize the values towards the highest arising value of each category. This allows to keep the proportions and high values in multiple modes are displayed as such. Further this method allows a full comparison of the different criteria, where each criteria is assigned the identical weight.

5.5.1 Criteria

The different criteria selected represent major influencing parameters that were found to quantify the concepts in the best way. The properties do not inherent duplicative characteristics to allow an overall comparison. Therefore the five criteria listed below are selected.

- **Routine working hours:** The routine working hours describe the available working hours. They can be used for scientific experiments and other tasks. The routine working hours stand in contrast to the operational hours.
- **Lunar EVA hours:** The Lunar EVA hours describe the absolute hours that are spend on an EVA on the surface of the Moon. They are the vital part of the total hours spent on the Moon and are identical for each Lunar excursion.
- **Gateway ECLSS resupply mass**: Describing the mass sole required to supply the ECLSS of the space station. Without this mass the mission is not possible. It excludes the mass required to support the HLS.

- **Cargo mass available:** Considers the available additional cargo payload mass. To calculate this, the Gateways ECLSS mass as well as the HLS ECLSS mass is subtracted from the DSL vehicles payload capacity.
- **Number of spaceflights:** Describes the total number of spaceflight required, including the crewed Orion flights and the uncrewed logistic flights.

These criteria all show different units and scales that are normalized towards the highest arising value of each criteria. This allows to present them in a single diagram. The diagram creates comparison of the different modes by their criteria, where the proportions are kept in a dimensionless manner.

5.5.2 Mission Perspective

The criteria and their corresponding values for the four different mission modes are given in Table 5–4. The numbers are for a single crewed mission. The non dimensional value between zero and one is provided in parenthesis. It is calculated with respect to the highest number arising for each criteria and displayed in Figure 5–14. Therefore the highest values always corresponds to the value 1.00. Notice that the highest value might not correspond to the best value. This is the case for the required ECLSS masses, and the required flights, where a lower number can pose an advantage over a higher number.

The hours given for the routine working hours and the Lunar EVA hours are for a single crew member only, as they are identical for all four crew members. The total working hours available can be calculated by multiplying the numbers by four for all modes alike. The regenerative continuous mode shows the highest number of routine working hours. The value is by a factor four higher than for the campaign mode.

Tab. 5–4: Overview table on parameters for a single mission, giving the proportion with respect to the highest value per criteria in parenthesis

Criteria	Regenerative Continuous Mode	Non-Regenerative Continuous Mode	Regenerative Campaign Mode	Non-Regenerative Campaign Mode
Routine working hours	1005 h (1.00)	952 h (0.95)	245 h (0.24)	245 h (0.24)
Lunar EVA hours	42 h (1.00)	42 h (1.00)	42 h (1.00)	42 h (1.00)
Gateway ECLSS resupply mass	2386 kg (0.45)	5324 kg (1.00)	511 kg (0.10)	1140 kg (0.21)
Cargo mass available	1853 kg (0.50)	1915 kg (0.51)	3729 kg (1.00)	3099 kg (0.83)
Number of spaceflights	2 (0.67)	3 (1.00)	2 (0.67)	2 (0.67)

This corresponds to the fact that a single mission in the continuous mode is of six months duration compared to only six weeks for the campaign mode. When considering a single mission, the Lunar EVA hours are identical for all modes, as they where designed to be equal for every mission independent of the duration or used ECLSS. As no surprise the non-regenerative continuous mode requires by far the highest amount of ECLSS supplies.
Further for a single mission only the non-regenerative continuous mode requires multiple DSL flights and therefore shows a total of three spaceflights. The other modes only require a single DSL flight plus the Orion, resulting in a total of two flights. Noticeable is that even though the non-regenerative continuous mode has an additional DSL flight, the available cargo mass is considerably lower compared to the campaign modes. The campaign modes show a large cargo payload capability when considering that the Dragon XL is used with a total capacity of 5000 kg.

Figure 5–14 shows the normalized values for the five criteria. The non-regenerative continuous mode shows the highest value for the required number of flights and the Gateway ECLSS supply mass. For these two categories a lower value is favorable and thus especially when considering the ECLSS mass the campaign mode shows its advantage towards the continuous mode. For the number of spaceflights required the regenerative continuous mode is possible with a total of two flights. Thus the campaign mode is of no direct advantage in this point.

Regarding the single mission perspective, the campaign mode shows its strength for both ECLSSs in the available cargo mass and low resupply mass. They enable the same amount of lunar EVA hours as the continuous modes, but lack behind in the available routine working time. Further, they show no real advantage in the number of required spaceflights except in comparison to the non-regenerative continuous mode.

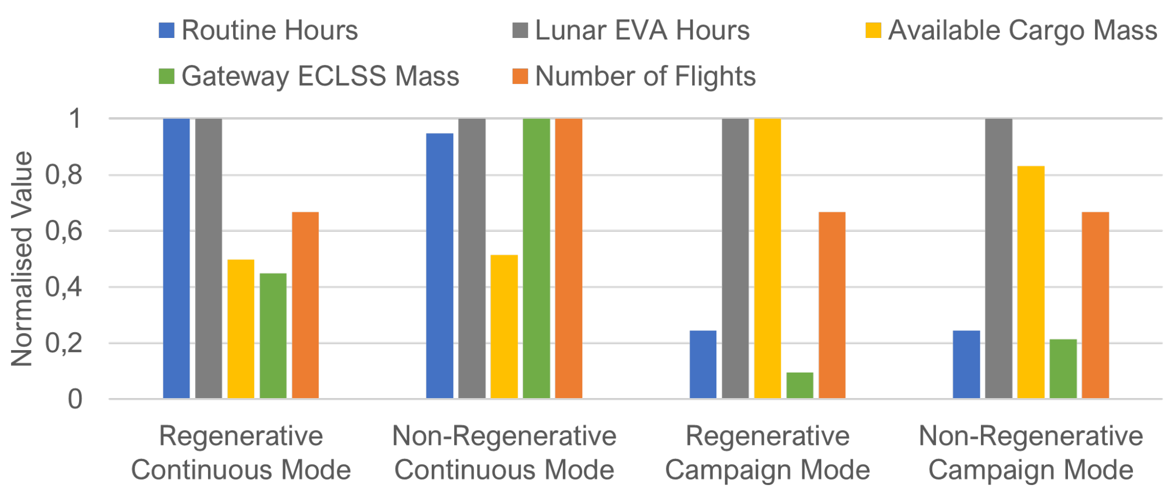


Fig. 5–14: Proportion values towards the highest occurring value of the different criteria for a single mission. The criteria are displayed for each mission mode respectively.

5.5.3 Annual Perspective

The annual consideration compares the four modes based on a one year duration. As the continuous modes are designed to conduct two missions a year to enable a permanently crewed Gateway station. For the campaign mode a single mission is expected to take place per year. The values for an annual operation are given in Table 5–5, with the normalized value in parenthesis. The normalization is again conducted with respect to the highest value arising for each criteria specifically throughout the four different modes. The normalized values are displayed in Figure 5–15.

The locations of the maximal values do not change between the mission and annual consideration in a substantial manner. Besides the available cargo mass and the Lunar EVA hours. Most values are doubled for the continuous mode as now two missions are conducted.

When considering the available routine working hours, the regenerative continuous mode provides the highest amount of almost a factor ten higher than for the campaign modes. The non-regenerative continuous modes do not lack far behind the regenerative case. This is due to the two weeks where the DSL is docking and undocking to the station. The weeks require a higher amount of operational hours, thus reducing routine hours.

On an annual basis the continuous mode enables the double amount of EVA hours on the surface of the Moon, as they conduct a total of two Lunar excursions. This stands in contrast to the campaign mode where only a single excursion takes place. As the routine hours for the campaign modes are comparably low to the continuous modes. This allows less time for experiments or remote operations on the surface of the Moon. The campaign mode designed in this concept also neglects the possibility for a support of the Lunar ground crew from the Gateway. This is because only one

Tab. 5–5: Overview table on parameters for a year, giving the proportion with respect to the highest value per criteria in parenthesis

Criteria	Regenerative Continuous Mode	Non-Regenerative Continuous Mode	Regenerative Campaign Mode	Non-Regenerative Campaign Mode
Routine working hours	2010 h (1.00)	1904 h (0.95)	245 h (0.12)	245 h (0.12)
Lunar EVA hours	84 h (1.00)	84 h (1.00)	42 h (0.50)	42 h (0.50)
Gateway ECLSS resupply mass	4771 kg (0.45)	10647 kg (1.00)	511 kg (0.05)	1140 kg (0.11)
Cargo mass available	1708 kg (0.45)	3832 kg (1.00)	3729 kg (0.97)	3099 kg (0.81)
Number of spaceflights	4 (0.67)	6 (1.00)	2 (0.33)	2 (0.33)

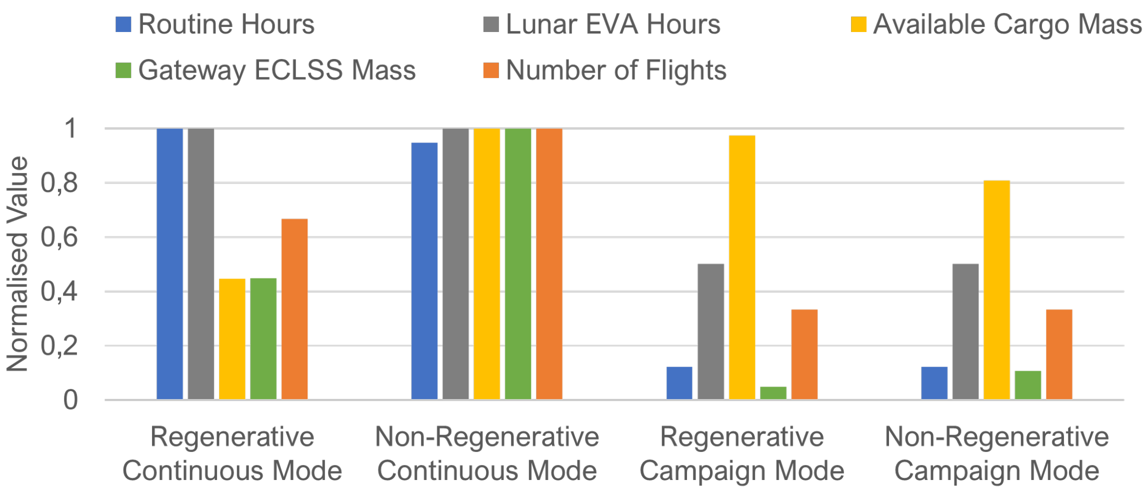


Fig. 5–15: Proportional values towards the highest occurring value of the different criteria for a duration of a year. The criteria are displayed for each mission mode respectively.

crew is present. The continuous mode enables this support, where the crew onboard the Gateway can operate robotic vehicles or support the EVA's in real time, as the signal delay between the surface and the NRHO is close to negligible.
The non-regenerative continuous mode reaches the highest values in almost all criteria. This does not come as a surprise as the concept also includes the highest amount of mass to be transferred. Thus resulting in more flights and the positive effect of having more cargo mass available. The higher amount of total flights brings the advantage of creating a vehicle redundancy. This redundancy can also be achieved for the regenerative continuous case, but the redundancy leads to a decrease in the available cargo mass for this mode. This can also be identified when comparing the value of a single mission towards the annual operations. The available cargo payload for the regenerative continuous mode is lower in the annual operations, because when using two different vehicle types, the larger one will have to carry some of the supplies for the second mission. Assuming that the smaller vehicle is used for the second mission. This results from the ECLSS masses for the Gateway and the Lunar excursion that surpasses 3000 kg together. As this corresponds to the mass the Cygnus EX was assumed to carry and the mass for the regenerative continuous mode is 3147 kg. Thus the first flight needs to be conducted by the Dragon XL or the second flight needs to be advanced by a view weeks to prevent a supply shortage.

On an annual basis the continuous mode reaches the higher score in all criteria. This comes as no big surprise as two missions are conducted. Regarding the available cargo payloads, the campaign modes are still able to compete. Concerning the Gateways ECLSS mass and the number of flights, where lower values are more favorable, here the campaign mode shows substantial advantages.

5.5.4 General Comparison

As the five criteria are all considered equally important an overall comparison is possible. For this, the normalized values for each mode are summed up. Values, where the highest values are not corresponding to the best, are simply subtracted from one creating the inverse, which is then added to the others. The so created sums are normalized with respect to each other creating a logical representation in where the best mode scores the value 1.00 compared to the others. This computation is conducted for the mission and annual inspection. It allows identifying the most favorable mode under the selected unweighted criteria. Important to notice is, that the mission perspective cannot be compared to the annual perspective directly as the criteria are not normalized towards the identical maximal values. Figure 5–16 shows the total normalized values for the four concepts modes on the mission and the annual level.

Figure 5–16 shows that for a single mission the regenerative campaign mode scores the highest value resulting in the 1.00 when normalized. The regenerative continuous mode follows close behind. Interestingly it even scores better than the non-regenerative campaign mode. This results from the high routine hours and same numbers of spaceflights allowing the continuous mode to reach this value. The non-regenerative continuous mode shows the lowest value in the mission based comparison with a value of 0.707, relatively far behind the other scenarios.
On the annual level the regenerative continuous mode represents the most favorable option. This does not come as a surprise as the routine working hours are the highest, together with two Lunar excursions allowing the highest EVA hours.

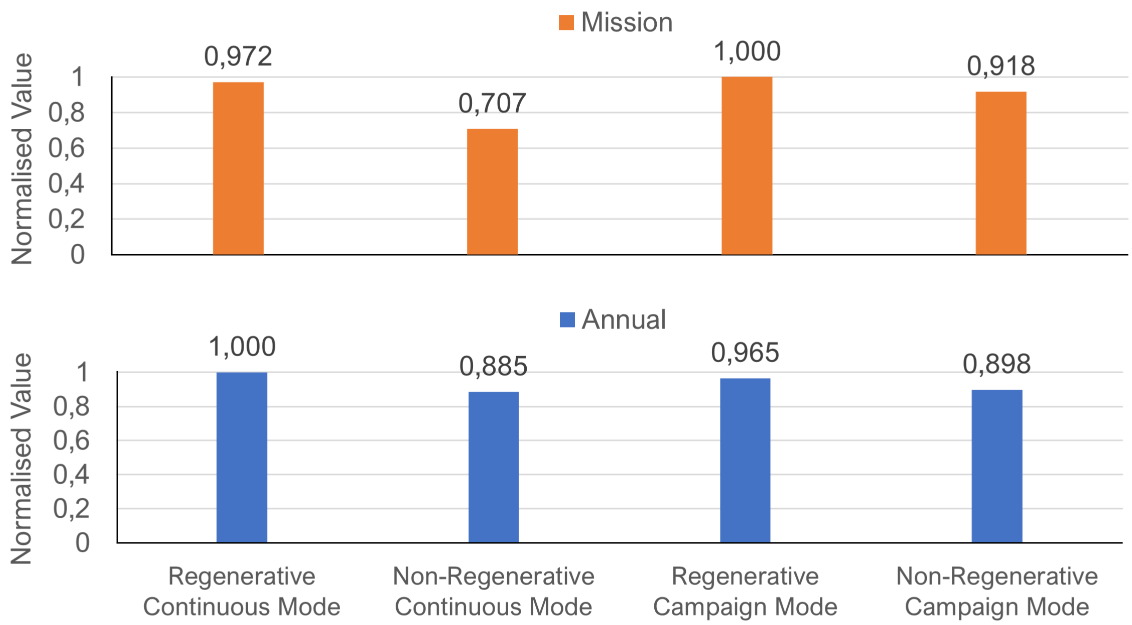


Fig. 5–16: Sum of normalized values for all four concepts on mission (orange) and annual (blue) basis. Allowing to identify the most favorable concepts under the selected criteria with the use of equal weights.

Other values for the regenerative continuous mode are in the intermediate range but non of them are the lowest. The regenerative campaign mode scores high as well, even without reaching the top score in any of the criteria. The non-regenerative continuous mode now shows a better value than on the single mission level but still represents the least favorable option.

Further, it can be identified that the regenerative options are generally more favorable over the non-regenerative. This evaluation has to be handles with care. The main influencing factor from the ECLSS on the mission scenarios is through the resupply mass. The required maintenance masses for the ECLSS were included through the Gateways ECLSS mass. Thus this criteria holds general information about the ECLSS properties. However, deceasing launch costs can make the impact through high resupply masses less important, as mentioned by Jones (2018). The reduced complexity and higher reliability could promote the use of a non-regenerative mission scenario.

5.5.4.1 Stability of the general comparison

The stability of the presented mission and annual comparisons results is very low. As the values are so close together, the change of a single value of a criteria can alter the entire comparison. Also due to five criteria being used in the computation, changes are more severe. This holds especially true for the number of spaceflights. Due to the low numbers, a change by only a single value can change the entire outcome of the comparison. For instance a change of the required numbers of flights for the regenerative continuous mode from four to five would result in a shift of the best score from this mode to the regenerative campaign mode. A change in the working hour or masses is not as dramatic, depending on the size of the fluctuation.

On the other side, a change in the required spaceflights would subsequently also change the entire concept. From this, the presented analysis pictures a realistic image of the four modes in their direct comparison. It also shows that without weighing the criteria it is difficult to identify the best option as the strengths are distributed so equally between the four modes.

5.5.4.2 Final Statement

Altogether the different concepts inherent different strengths and weaknesses. It will be dependent on the objective of the mission if a higher amount of working hours or a sole excursion to the surface of the Moon with a descent amount of payload is favored. Besides different weights of the listed criteria, additional criteria can be relevant. The ECLSS selection impacts the logistics and supply masses, especially for the continuous mode. For the campaign mode, this effect is comparably small even though the resupply mass in the non-regenerative campaign mode is about twice as high as for the regenerative case. The absolute values still lie way below the DSL's limit, with approximate 1000 kg to spare.

5.6 Final Discussion

This section will discuss conclusively major aspects and risks that were discovered during the development of the four different scenarios and their analysis. Some of these can impact the operations to the extent that the entire mission will have to be aborted. Their properties are discussed in the following and thereafter a look at the integration of automation is taken.

5.6.1 Risks and Constrains

The presented concepts are designed to enable a mission to the Gateway and the Moon. When certain parameters are altered it could potentially risk the entire mission and lead to an abortion. These critical parameters are discussed in the following.

One of the most crucial conditions in order to accomplish the conduction of the continuous modes missions is the successful and on time arrival of the DSL spaceflights and the crewed Orion spacecrafts. This is more critical for the DSL than the Orion, as the Orion launch delay would most likely lead to an interruption of the continuous crewed station. But does not pose any risks to the survival of the crew. Minor launch delays of up to two days were considered in the development of the timelines and do not pose a major risk. Buffer days that are used as routine days are therefore placed after or close to the arrival of a spacecraft. As a total loss of a vehicle would lead to a longer delay of the arrival of logistics, it is mandatory for the continuous mode to have a long-time supply onboard. This non-regenerative supply should be present on the Gateway also to compensate for possible ECLSS failures. As the Gateway together with the Orion and the HLS has various of ECLSSs available, sufficient redundancy is given. To ensure the presence of this buffer it is necessary for the continuous mode to launch an additional DSL before the start of the described concept sequence. Alternatively, it has to be made sure that the extra supplies required were delivered to the Gateway on previous missions. The variation of the DSL vehicle types as described, further increases the supply security in case a vehicle is grounded. It also opens the market for more commercial providers or agencies.
The campaign mode is less vulnerable towards a flight delay or failure. The DSL launches prior to the crewed Orion and carries all the supplies required to the Gateway. The DSL even has enough free payload available to carry a sufficient amount of extra supplies. The payload available is more then double the amount for the required ECLSS mass, for both the regenerative and the non-regenerative case and both spacecrafts, the Dragon XL and the Cygnus EX. A delay of this spaceflight would therefore lead to a delay of the entire mission. For the regenerative case, it needs to be evaluated if additional non-regenerative goods should be brought to compensate for potential ECLSS failures. For the non-regenerative campaign mode this question does not arise as the entire mission is already non-regenerative. The advantage of using multiple different types and thus manufacturers of the DSL spacecrafts is not as important to the survival of the crew for campaign mode as there is no time frame in which the Gateway needs to be resupplied.

Buffers for any operational tasks were implemented in the developed concepts. A extension of a task or delay poses no immediate threat the operations. The buffer is created either through additional routine days that can be used for operational tasks if required. And the fact that the working days were designed on a seven hour basis. Allowing the crew to work longer shifts without stressing exhaustion and overwork if necessary. This is in general more applicable to the continuous mode, as the schedule sees more room for buffers than the campaign mode. The campaign mode shows less flexibility towards delays as many operational tasks occur. Especially week 11 before leaving the Gateway and returning to Earth sees no additional buffer day. If required, the stay onboard Gateway could be extended. The ECLSS supply for this period could be brought as a buffer or taken from the Orion. The human rated spacecraft is planned to be used for a total of ten days, but enables the supply of the crew for 21 days. The Orion's ECLSS supply capability is considered as an emergency reserve as the Orion also acts as a emergency vessel for all concepts.

5.6.2 Automation

The application of automation in present spaceflight is already very advanced, enabling rockets to launch and re-land automatically as well as to perform autonomous docking and undocking maneuver. This trend is going to continue and is of vital importance for deep space missions as ground control can not interact with the vehicle in real time anymore. This problem is not as sever for Cis-Lunar space as signal delays are still low allowing slow moving vehicles to be remote controlled. Acting as a testing ground, automated processes can be verified and observed, to gather the know how for missions to Mars. Another crucial aspect is that through automation the workload on the crew can be reduced and thus less operational time is required for maintenance and more time for routine work is made available.

When considering the four presented scenarios, automation already is considered to take place comparable to advanced ISS systems and supply vehicles. This implies that DSL and human spacecrafts like the Orion and the HLS are operating autonomously and do not need the crew to actively control the vehicle. It is likely that for early missions and as long as the experience gathered with the use of the vehicles is still low, the crew will take over a monitoring task, able to intervene if necessary. For crewed docking and undocking maneuver the crew will follow and monitor the maneuver as the events are of such a significance that it seems unlikely for the crew to conduct routine science experiments during this time. Required operational times are going to be reduced and not the entire crew needed for the docking maneuver. When applying this to the timelines the operations hours could be reduced for these maneuver, as the typical rendezvous was considered to take six hours and an additional two hours of leak check until the hatch is opened. Including prior orbit insertion maneuver and preparations, the operational hours are likely to be reduced, but as the nature of these maneuver is connected to acceleration and changes in motion it might be problematic to conduct routine work.

Automation will also find increasing application in the monitoring and control of ECLSS systems and processes. Future systems are expected to require less interaction and through that the crew has more time available. This impacts the timelines but changes are not too sever as these routine maintenance tasks are performed during the weekly four hours of house keeping. Increased automation might give the astronauts a less busy housekeeping session, but in this early state no drastic change in the operational timeline is expected.

In conclusion, operational hours are not expected to be reduced drastically through an increase in automation. In the development of the concepts a high level of automation was already considered and performing routine task during automated maneuvers can present certain challenges. Automation will play a more significant role in the uncrewed operations for logistics and assembly. Hereby the ground control teams will need to monitor and command these operations.

6 Conclusion and Outlook

6.1 Conclusion

The presented concepts demonstrate in a systematic way how to conduct a mission to the Gateway and the surface of the Moon in the post assembly phase. The selected operational modes highlight the differences between a permanently crewed and a campaign-style mission operation. Further, they indicate vital and important aspects and limitations to be considered in future Cis-Lunar operations.

Through the investigation of proposed deep space exploration plans, an insight is gathered and possible solutions to unsolved or undecided issues are developed. For the DSL size and capabilities two vehicles with a payload of 3000 kg and 5000 kg are selected. The HLS ECLSS resupply mass is calculated for the use of a CAMRAS system to be 761 kg for four crew members and a four week period.
In four different scenarios, a permanently crewed deep space station is compared to a short-term operation, while considering a regenerative and an non-regenerative Gateway ECLSS. All of these scenarios include the identical Lunar excursion to ensure their comparability.
The four scenarios have different strengths and weaknesses. For the campaign scenario, the stay on Gateway is three weeks before and after the Lunar excursion to enable the activation of the Gateway from its standby configuration. The alternation of the ECLSS does not impact the operations besides changing the required resupply masses. However, these masses are comparably low to the DSL's capacities, thus a single logistic flight is sufficient. An alternation of the used DSL type reduces the margin for free available cargo. The scenario utilizing a regenerative ECLSS on a continuously crewed Gateway provides the highest amount of available crew time and requires one resupply flight every six months. For the non-regenerative continuous concept the crew time is still high, but the required resupply masses are increased, leading to a doubling of the mandatory resupply flights requiring four DSL spaceflight within a year. The multiple logistic flights provide the advantage of redundancy, through the use of various types of spacecrafts. As in the continuous concepts a crew is present throughout the entire year, including 12 weeks where two crews are present, the workload for MCC is higher than for the campaign mode.
Limitations of the ECLSS are identified during the crew overlaps on the Gateway. The carbon-dioxide levels approach critical values when the regenerative CDRA is used. Additional investigations about the HLS's fuel requirement highlighted the problem of using a large SSTO making refueling via the Gateways DSL flights difficult.

In total, deep space missions pose multiple challenges but also a wide range of opportunities. A wise selection of the operational scenario can help to achieve a successful mission and the presented concept provides an insight into the possible scenarios.

6.2 Outlook

As the thesis has covered a wide range of topics, future work can be derived in various directions. Influencing factors to the created concepts can be subjected to further in-depth investigations.

An influence on the concepts results from the HLS or the DSL spacecrafts. Their development is not too advanced, but they show a great impact on the scenarios. As the HLS vehicle and landing architecture as well as the used ECLSS is not selected, the development and evaluation of the most reasonable option is of interest for the future. The question of the re-usability of the landing module in combination with the Gateway showed certain limitations that need to be met and should be considered for future work. Investigations also arise for the DSL vehicles, that were assumed to have certain payload masses. As their development proceeds, their impact on the scenarios needs to be evaluated.

When considering the Lunar excursion, an in-depth concept for the surface stay requires further investigation. A variation of the crew size or the duration of the excursion could notably impact the overall concept. Other factors like the HLS payload capacity or certain mission objectives can also be considered in a more detailed Lunar timeline. This thesis only covers the case where the HLS acts as a habitat during the Lunar excursion. As a Lunar base is expected to be developed a supply and operational scheme for this base in combination with the Gateway is of interest for future research. Especially, once more concrete information becomes available.

Further, the established concepts can be elaborated in-depth once more information regarding the planned mission goal and objective are available. The developed timelines still include a reasonable buffer as working days are designed to not surpass seven hours. A variety of tasks will not require one hour, so the creation of a more detailed timeline will be possible in the future. If certain mission objectives are known, it also allows conducting a specific evaluation of the presented concepts. Through this, the advantages or disadvantages of one concept over the other can be identified explicitly, enabling a weighted analysis.

An investigation into the exact functionality of the automated Gateway and the transition to the non-automated mode is of interest for future work, as the campaign mode depends on this functionality. The impact on the presented operational procedures will also be a matter of this investigation.

As developments and plans for future Cis-Lunar missions proceed, information and changes will arise. Looking to the future, a fascinating area of deep space exploration lies ahead.

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A Supplementary Tables

The tables presented here provide a more detailed insight on the working hours required for operational tasks and routine work for each mission mode. In the first column the weeks are labeled with their description, followed by the location of the primary crew of interests and the hours spent during a single mission. Table A1 displays the Regenerative Continuous Mode, Table A2 the Non-Regenerative Continuous Mode and Table A3 the Campaign Mode, regenerative and non-regenerative alike.

Tab. A1: Available working hours for the regenerative continuous mode per crew member during a single mission (33 weeks)

Week	Location	Operational [h]	Routine [h]	EVA /EVA prep. [h]
21, Orion Launch	Orion	28	21	-
22, Transition	Gateway	35	6	-
23, Lunar Arrival	Moon	22	21	7/6
24/25, Lunar Excursion	Moon	5	40	14/12
26, Lunar Ascent	Moon	31	22	7/6
27, Gateway Arrival	Gateway	25	14	-
28, Orion Return	Gateway	22	20	-
29-44, Routine	Gateway	5	40	7/6
45, DSL Disposal	Gateway	26	13	-
46, DSL Docking	Gateway	25	14	-
47, Orion Launch	Gateway	20	22	-
48, Transition	Gateway	12	28	-
49, Lunar Arrival	Gateway	13	26	-
50/51, Lunar Execution	Gateway	5	31	-
52, Lunar Ascent	Gateway	14	29	-
53, Gateway Arrival	Gateway	19	20	-
54, Orion Return	Orion	25	7	-
Total:		412	1005	147/126

Tab. A2: Available working hours for the non-regenerative continuous mode per crew member during a single mission (33 weeks)

Week	Location	Operational [h]	Routine [h]	EVA /EVA prep. [h]
21, Orion Launch	Orion	28	21	-
22, Transition	Gateway	35	6	-
23, Lunar Arrival	Moon	22	21	7/6
24/25, Lunar Excursion	Moon	5	40	14/12
26, Lunar Ascent	Moon	31	22	7/6
27, Gateway Arrival	Gateway	25	14	-
28, Orion Return	Gateway	22	20	-
29, DSL Disposal	Gateway	26	13	-
30, DSL Docking	Gateway	25	14	-
31-41, Routine	Gateway	5	40	7/6
42, DSL Disposal	Gateway	26	13	-
43, DSL Docking	Gateway	25	14	-
44-46, Routine	Gateway	5	40	7/6
47, Orion Launch	Gateway	20	22	-
48, Transition	Gateway	12	28	-
49, Lunar Arrival	Gateway	13	26	-
50/51, Lunar Execution	Gateway	5	31	-
52, Lunar Ascent	Gateway	14	29	-
53, Gateway Arrival	Gateway	19	20	-
54, Orion Return	Orion	25	7	-
Total:		453	952	133/114

Tab. A3: Available working hours for the campaign mode per week and crew member

Week	Location	Operational [h]	Routine [h]	EVA /EVA prep. [h]
1, Orion Launch	Orion	34	12	-
2, Gateway Arrival	Gateway	32	7	-
3, Gateway Operations	Gateway	12	33	7/6
4, Lunar Preparation	Gateway	32	7	-
5, Lunar Arrival	Moon	22	21	7/6
6/7, Lunar Execution	Moon	5	40	14/12
8, Lunar Ascent	Moon	31	22	7/6
9, Return to Gateway	Gateway	32	7	-
10, Routine	Gateway	5	40	7/6
11, Gateway Shutdown	Gateway	41	0	-
12, Orion Return	Orion	19	16	-
Total:		270	245	56/48