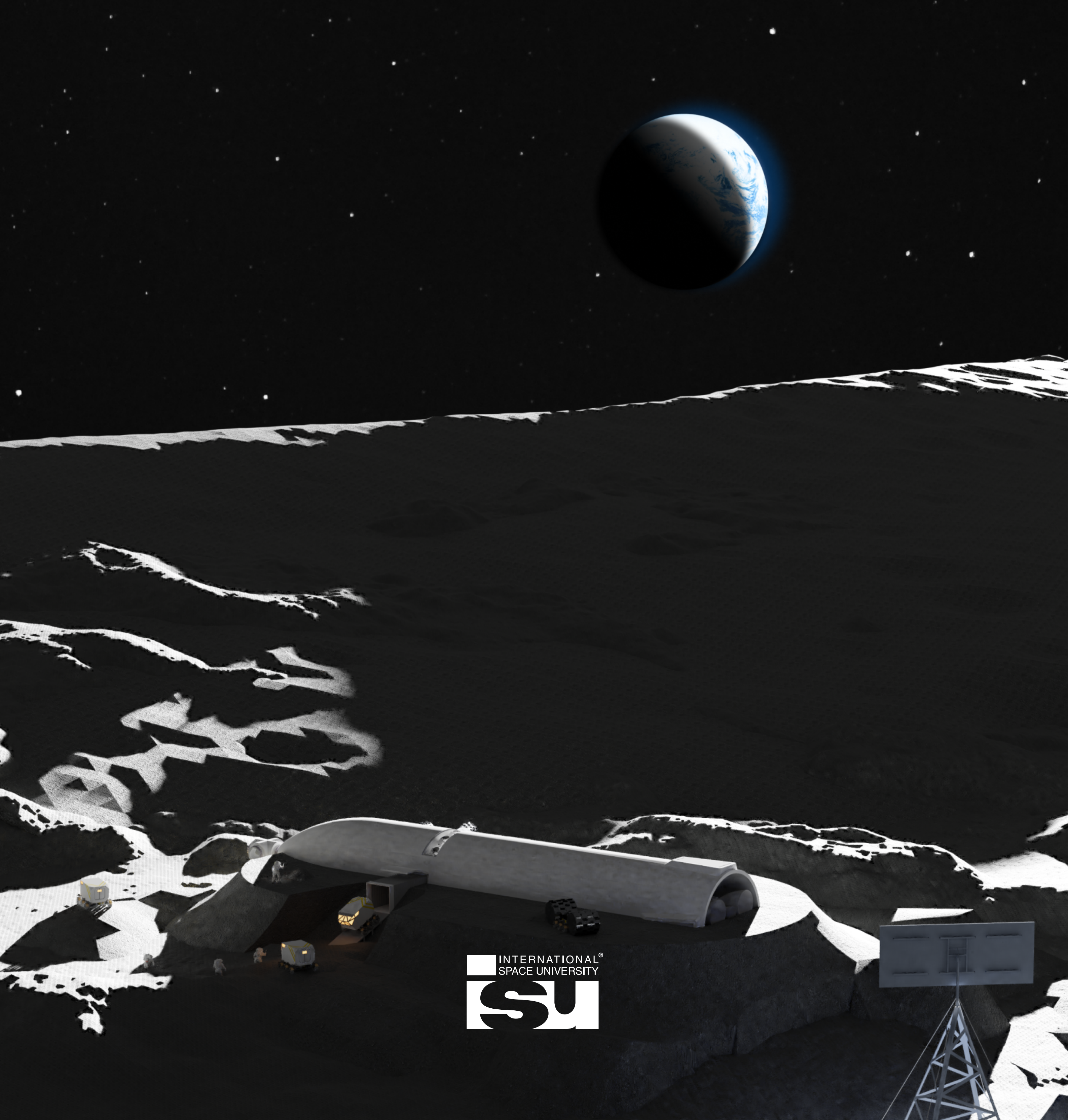
FINAL REPORT
SPACE STUDIES PROGRAM 2021

SOLUTIONS FOR CONSTRUCTION OF A LUNAR BASE



INTERNATIONAL® SPACE UNIVERSITY

isu

In loving memory of Oscar Federico Rosas Castillo – an adventurous, spirited soul who brought us together and made our world a better place. We are better for having known you. May your light shine bright upon us until we see you on theother side of the stars.

Ad Astra

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First we would like to thank the chairs, Rob Postema, Matt Sorgenfrei, and Antonio Gomez, and our teaching associate, Xiaochen Zhang, for their amazing support during this team project. They have been the key factor in supporting this team during the project and therefore to the success of this lunar Team Project.

In addition, we would like to thank the International Space University (ISU) and Space Studies Program (SSP) 2021 staff for making this year's program possible, especially given the circumstances of the Coronavirus disease 2019 (COVID-19).

We would like to thank and acknowledge the presenters who helped guide us on our journey to finding solutions to constructing a lunar base:

Advenit Makaya	Jennifer Edmunson
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Lastly, we acknowledge our sponsor Lockheed Martin Corporation for supporting ISU and this Team Project (TP).

Abstract

Returning to the Moon and establishing a permanent human presence is the next step in human space exploration. This necessitates the development of lunar infrastructure capable of sustaining a permanent human presence. This team presents a supporting framework for rapid, cost-efficient, and supporting construction of a permanent and modular lunar base within the scope of what is technically feasible today in space law paradigms.

The proposed lunar base concept uses the SpaceX Starship Human Landing System as base infrastructure which will be placed horizontally on the lunar surface and transformed into a habitable volume. A crew of modular rovers will aid astronauts by supporting the construction process. Countermeasures are presented to protect the astronauts from the effects of exposure to radiation, lunar dust, extended hypogravity are identified. Psychological and psychosocial factors are included to enhance individual well-being and crew dynamics. Physical and cognitive workloads are defined and evaluated to identify countermeasures, including specific spacesuit parameters.

The construction is to be organized as a multi-national public-private partnership to establish an international authority, a concept that has been successful on Earth but has yet to be applied to space activities on a multi-national level. A public relations and communications strategy built around the value proposition is provided as a way to ensure sustained public, private, and political support for the project. A roadmap is provided, incorporating each part of the construction from human and technical perspectives. Other aspects which are critical to mission success include the cultural significance of the project, legal aspects, developments, budget, financing, and potential future uses. These solutions rely mainly on existing technologies and limited modifications to the lunar lander vehicle, making it a viable solution for the construction of a lunar base in the near future.

Faculty Preface

In recent years, the international space community has been increasingly focused on the Moon as a destination for scientific investigation, human exploration, mining and even space tourism. Space agencies (both national and international) as well as space and non-space industry have developed conceptual plans for establishing robotic and human presence on the Moon in support of these activities. These plans address use cases and requirements for human presence, as well as a multitude of designs for lunar bases. Somewhat underexposed in all these plans are the challenges that the actual construction of a lunar base itself introduces, together with solutions that address and resolve these obstacles.

The challenge initially posed to the "Solutions for Construction of a Lunar Base" team was to start from a specific design for a lunar base, study in detail how to implement it, and then propose a roadmap for the construction of this base. This roadmap was not only meant to include the technical solutions for the construction of the lunar base, but also evaluate this effort from an international, interdisciplinary, and intercultural perspective.

The importance of this topic is highlighted by the fact that this work was sponsored by the Lockheed Martin Corporation and met considerable interest from the guest speakers who provided interesting and challenging presentations to the participants, introducing them to diverse aspects and considerations within the subject of the project.

Within this report, the participants have put forward a very interesting concept and solution for a lunar base. Moreover, they have defined and evaluated a roadmap on how to realize this lunar base, with an interdisciplinary, intercultural and international perspective which are the hallmarks of the International Space University. Following these principles, the participants not only included solutions to the engineering challenges posed by the construction of a lunar base, but also addressed the business and management aspects, including financing for such an ambitious initiative; the issues associated with crew being actively involved in the construction phase; the legal and policy considerations under which a lunar base can be built in the international community; and the ethical and humanity aspects of this construction endeavor on the Moon.

We feel honored to write this preface after working for nine weeks with this very talented and motivated group of participants and having supported them in making themselves into a team and producing this result you are about to read. We appreciate and applaud the immense effort this incredible team of 21 participants from 13 countries have put into creating this result. These participants will be part of a future generation in the space domain, and will hopefully make the most of this experience, building on the life lessons of ISU SSP 2021, and the Team Project "Solutions for Construction of a Lunar Base". Perhaps even more importantly, this cohort of bright space professional will be ready to participate in, and contribute to, future lunar activities in an international setting.

It is our pleasure to offer you this report, anticipating it will represent a valuable addition in the discussion of future lunar habitation and how to establish a lunar base.

We trust you will enjoy reading this report.

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Participant Preface

A tragedy happened during the ISU SSP 2021. Our beloved participant liaison, Oscar Rosas, passed away while attempting to climb Mont Blanc. Oscar was an inspiration to all of us and touched each of us in his own unique way. His strength, both physically and mentally, his kindness, his ambition and his exceptional drive led us to name our lunar base concept in his honor. We are proud to present to you our proposal for Rosas Base.

Our Team Project for construction of the Rosas Base presents a pragmatic approach to returning to the Moon and to achieving a sustainable human presence on its surface. This base will be constructed in a phased and modular program and its main concept is the re-use of the space vehicle itself as a building-block for the construction of the base, thus enabling cost-savings and scalability

In preparation and ideation of this project, we saw a wide array of presentations from experts worldwide. Among them, one of the biggest overarching problems to the construction of a lunar base was sustainability. To solve this, we wanted to leverage the industry's emerging economies of scale to sustainably create a foundational base for science and entrepreneurship while utilizing organization structures from successful major projects on Earth to enable world-wide participation and support. There has been dramatic interest across governments and companies in using the lunar environment for scientific experimentation, medical research, and commercial activities. By lowering the barriers to entry using Rosas Base solutions set and our proposed Public-Private Partnership structure, the Rosas Lunar Authority, these interested players can fund and drive the sustainable construction and operations of a thriving lunar economy.

As Eugene Cernan, the last astronaut of the Apollo Program to step foot on the Moon, climbed the ladder to return to Earth with Apollo 17, he paused and said, "We leave as we came and, God willing, shall return, with peace and hope for all mankind". Rosas Base, the lunar base proposed herein, is the fulfillment of this vision.

Ad Astra, Oscar!

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List of Acronyms

AEB	Brazilian Space Agency 74
ALARA	As Low as Reasonably Achievable 20, 52
ARED	Advanced Resistive Exercise Device 31
ARRA	Rescue Agreement 47, 50
ARS	Acute Radiation Syndrome 29
ASA	Australian Space Agency 74
ASI	Italian Space Agency 74
ATLS	Advanced Trauma Life Support 44
BFO	Blood Forming Organ 29
BWS	Bedford Workload Scale 36
CAPEX	Capital Expenditure 73, 77
CERN	European Center for Nuclear Research 63, 72
CNES	French Centre National d'Etudes Spatiales 74
CNSA	China National Space Administration 74
COO	Chief Operation Officer 63
COSPAR	Committee on Space Research 51
COTS	Commercial Orbital Transportation Service 68
CSA	Canadian Space Agency 53
CSIRO	Australian Commonwealth Scientific and Industrial Research Organisation 74
CT	Computerized Tomography 44
CTO	Chief Technology Officer 62
DLR	German Aerospace Center 74
DNA	Deoxyribonucleic acid 20
E3P	Exploration Envelope Program 74
EBIDTA	Earnings Before Interest Depreciation Tax and Amortization 73, 77
ECG	Electrocardiogram 44
ECLSS	Environmental Control and Life Support System 13, 17–19, 73
EEG	Electroencephalogram 44
EMU	Extravehicular Mobility Unit 38
EPC	Evolved Packet Core 22

ESA	European Space Agency 30, 31, 42, 53, 60, 74
EVA	Extravehicular Activity 17, 30, 38, 43, 45
FAA	Federal Aviation Administration 49
FCC	Federal Communication Commission 49
GCPS	Gravity Compensation and Performance Scale 39
GCR	Galactic Cosmic Rays 20, 21, 29
GISTDA	Geo-Informatics and Space Technology Development Agency 74
HIIT	High-Intensity Interval Training 32
HLS	Human Landing System 1, 7, 8
HR	Human Resources 63
HRP	Human Research Program 30
HUD	Heads-up-display 39
HWG	The Hague International Space Resources Governance Working Group 48, 55
ICRP	International Commission on Radiological Protection 52
IGA	Intergovermental Agreement 53, 54
IISL	International Institute of Space Law 49
IP	Intellectual Property 54
ISA	Israel Space Agency 74
ISECG	International Space Exploration Coordination Group 57, 59–61
ISRO	Indian Space Research Organisation 74
ISRU	In-Situ Resource Utilization 48, 49, 55, 56, 58, 69, 74, 81
ISS	International Space Station 19, 20, 29, 31, 38, 42, 43, 45, 53, 54, 67, 80, 82
ISU	International Space University iv, vi, vii
ITU	International Telecommunication Union 49
IVA	Intra Vehicular Activity 41
JAXA	Japan Aerospace Exploration Agency 53, 74
KARI	Korea Aerospace Research Institute 74
LEAP	Lunar Exploration Accelerator Program 77
LEO	Low Earth Orbit 34, 44, 63, 69, 73, 74
LEVA	Lunar Extra Vehicular Activity 2, 4, 8, 9, 13, 21, 29, 30, 35, 36, 38–41, 60
LH2	Liquid hydrogen 26

LIAB	Liability Convection 47, 50, 53
LLO	Low Lunar Orbit 73
LND	Lander Neutrons and Dosimetry 20
LOX	Liquid oxygen 26
LSA	Luxembourg Space Agency 74
LTE	Long Term Evolution 22
MA	Moon Agreement 47
MBRSC	Mohammed Bin Rashid Space Centre 74
MIS	Minimally Invasive Surgery 45
MLI	Multi-Layer Insulation 16, 20, 21
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator 17
MOROCAS	MOdular RObotic Construction Autonomous System 2–4, 8, 11–13, 15, 17, 21, 25, 35
MoU	Memorandum of Understanding 53, 54
MRI	Magnetic Resonance Imaging 44
NASA	National Aeronautics and Space Administration xii, 21, 28–31, 34, 36, 37, 53, 54, 67, 77
NOSA	Norwegian Space Agency 74
NPS	Nuclear Power Sources 52
NTIA	National Telecommunications and Information Administration 49
O&M	Operations and Maintenance 22
OAE	Otoacoustic Emission 44
OCT	Optical Coherence Tomography 44
OPEX	Operating Expenditure 73, 77, 80
OPS	Operations 63
OSCAR	Observational Surround Crew Assembly Room 13
OST	Outer Space Treaty 47–53, 55, 71
P&L	Profit and Loss 72, 73, 77
PEL	Permissible Exposure Limit 29
pH	potential of hydrogen 26
PMO	Program Management Office 62, 63
POLSA	Polish Space Agency 74
POMS	Profile of Moods State 34

PPP	Public-Private Partnership xii, 59, 60, 62, 66–69, 71–73, 77, 80
PSR	Permanently Shadowed Region 51
R&D	Research and Development 62, 68, 69, 73, 80
REG	Registration Convection 47
RF	Radio frequency 22
RLA	Rosas Lunar Authority 2, 3, 62, 80, 81
RM	Repetition Maximum 31
ROCKY	Resistive Overload Combined with Kinetic Yo-Yo 31
ROI	Return on Investment 59, 66, 69, 73, 77
ROSA	Romanian Space Agency 74
SANS	Spaceflight Associated Neuro-ocular Syndrome 30
SEP	Solar Energetic Particle 20, 21
SPE	Solar Particle Event 29, 30
SS	Starship 3, 4, 11–13, 15, 16, 20, 35, 37, 60, 63
SSAU	State Space Agency of the Ukraine 74
SSO	Swiss Space Office 74
SSP	Space Studies Program iv, vi, vii
TBA	To be announced 74
TLX	Task Load Index xii, 37, 38
TP	Team Project iv
UAE	United Arab Emirates 49
UAE SA	United Arab Emirates Space Agency 74
UKSA	UK Space Agency 74
UN	United Nations 52
UNCOPUOS	United National Committee Peaceful Uses of Outer Space 47, 52
UNSG	United Nations Secretary-General 50, 53
V02	Oxygen Consumption 31
xEMU	Exploration Extravehicular Mobility Units 38

1. Introduction

For millennia, the Moon has made its mark on humanity by inspiring myths, stories, works of art, astronomy, and mathematics while following the human journey from a lunar distance. After our first brief introductions in the 1960s and 1970s, humanity is now ready to take its journey all the way to the Moon itself and permanently make it part of its common future.

In order to make humankind's presence on the Moon permanent, one of the key steps is constructing a lunar base for human habitation. In addition to the fundamental human aspects, this presents a multitude of technical, life-science, cultural, legal, and business challenges and considerations. In this report, the team addresses these aspects and provides potential solutions for an efficient and sustainable construction of a first lunar base.

The goal is to develop a roadmap for the construction of a sustainable, habitable, and permanent lunar base. This will address regulatory and policy frameworks, examine technological and anthropological challenges and empower scientific and commercial lunar activities for the common interest of all humankind.

1.1. Challenges and Considerations

Setting foot on the Moon was not easy, as the Apollo program has shown, and establishing a lunar base comes with even more difficulties. Despite the challenge, this endeavor unites people of different backgrounds and origins but with the same ambition of exploring and transcending humankind's Earth bounds.

Crewed missions come with their own challenges, as humans are the most unpredictable pieces of machinery, making these missions the most difficult to plan. Building a lunar base requires consideration of the environment that the construction crew will live and work in. The Moon environment is hostile to human life and involves a range of risks for consideration, such as radiation, dust, and hypogravity. Additionally, the working environment during construction activities can can lead to medical emergencies. Other challenges pertaining to the construction activities include increased metabolic costs and operating machinery in one sixth of Earth's gravity while wearing a spacesuit.

The legal aspects of constructing a lunar base are crucial. The respect for, and compliance with, international law is critical to "maintain international peace and security and promote international cooperation and understanding" (Art.3 UN General Assembly, 1967).

All of the challenges above are solvable with sufficient time and money, but one of the major concerns over the sustainability of space programs is maintaining interest and funding over long periods while giving a tangible return on investment. Constructing a lunar base will require long-term vision and support to set up and continue running under conventional space financing and political structures, which can change rapidly.

1.2. Solutions

There is a well-established and researched idea of utilizing the large volume and properties of empty fuel tanks to create robust space habitats. This was applied on Skylab, and has been proposed for various rocket stages such as the external tanks on the Space Shuttle. While this is applicable to any sufficiently large rocket body, after surveying the current state-of-the-art launchers and what bodies can be delivered to the lunar surface, the most mature concept was using the SpaceX Starship Human Landing System (HLS) as a structural basis for the lunar settlement, see Figure 1. The reported capabilities, low cost, massive volume, and high mass capacity means that a larger and more capable habitat can be delivered and constructed on the lunar surface, more so than any other concept achievable within the next decade. The concept is to decommission a Starship HLS and transform it into a permanent base while using its entire internal volume, including the fuel tanks, as a habitat.

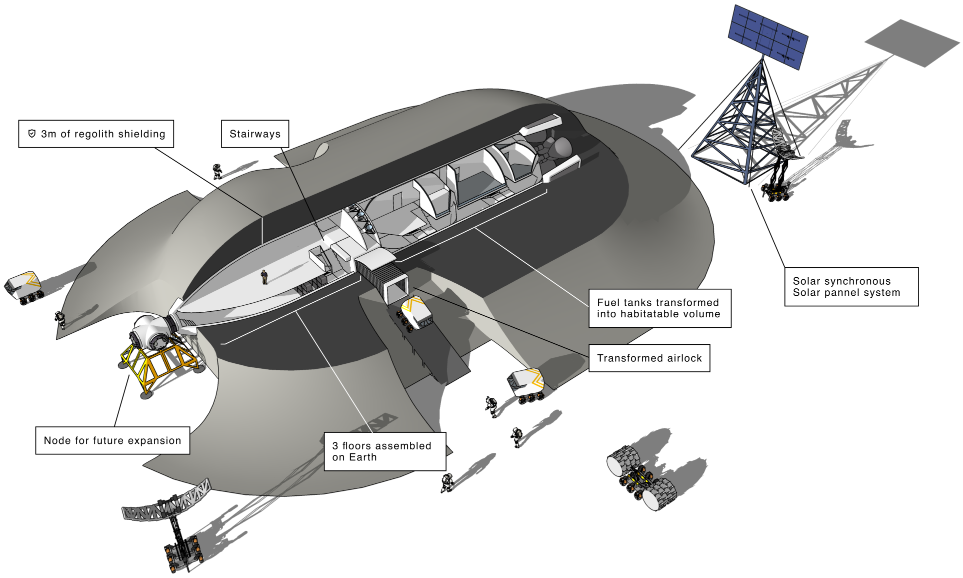

Figure 1: Overview Rosas Base design

The additional volume provided by the conversion of the fuel tanks means there is great potential for renting out this space to other entities to generate revenue and promote sustainability and growth. This plan relies mostly on existing technologies and limited modifications to the vehicle, including using a series of rovers, MOdular RObotic Construction Autonomous System (MOROCAS), for the purpose of setting up equipment to horizontalize the lander on its side. Additionally, they will aid in setting up surface infrastructure and stacking regolith on top of the base for crew protection. This makes the Rosas Base solutions incredibly viable for the construction of a lunar base in the near future.

In addition to the technical concept, the team has proposed a number of solutions to ensure optimal crew performance during the construction operations by mitigating risks such as physiological, psychological, psychosocial well-being, hypogravity, dust exposure, and radiation. These challenges are accounted for in the construction and operations timeline of the base. This includes promoting overall well-being through workload balance and monitoring, optimizing cognitive and physical performance in order to avoid burnout, injures, and illness, and having medical procedures in place in case of emergencies. The adverse effects of hypogravity are being addressed through exercise and coupled with controlled mission lengths. Dust exposure is limited by scheduling and monitoring workload and Lunar Extra Vehicular Activities (LEVAs), in addition to electrostatic removal systems to mitigate dust inhalation. Countermeasures for radiation and micrometeorites include regolith stacking onto the external walls by the MOROCAS, protecting astronauts using radiation shielding technologies within their spacesuits, and allowing for lunar mission duration within acceptable radiation dosages.

Concerning the legal issues, the exploration and use of outer space are not just an affair for certain space-faring states but the province of all humankind, as described by the very first article of the Outer Space Treaty. Therefore, international cooperation in the construction and participation of the lunar base is expected and will be promoted. The participating states will establish a multilateral framework to determine their rights and obligations in relation to the construction. While multilateral frameworks can bridge some of the gaps of international space law, for some issues it is desirable to have agreements and consensus among the international community to avoid potential tensions and conflicts. Examples of these issues include the requirements and procedures to use space resources, specific criteria for the environmental protection of the Moon and other celestial bodies. Special circumstances and unique cases as well as future considerations to this proposed legal framework can be iterated within the Rosas Lunar Authority (RLA) described in further detail below.

All of the challenges above are solvable with sufficient time and money, but one of the major concerns over the sustainability of space programs is maintaining interest and funding over long periods while giving a tangible return on investment. To solve this problem, constructing a lunar base will require long-term vision and support to set up and continue running. This is something conventional space financing and political structures can struggle with as they change rapidly and depend greatly on public interest. When analyzing successful long-term projects, there is a major precedent for successful programs using public private partnerships in the form of an international authority to mitigate public sector risks, efficiently finance projects, and continually operate projects. The RLA is an international authority that is well suited to provide a sound management structure capable of interfacing between international governments and companies while responding to any challenges that arise, like the legal considerations mentioned above. It relies upon public financing from a consortium of potential public contributors in the early stages for research and development as well as initial capital expenditures. Once developed, as the implementation stages begin, the costs shift to the authority, leveraging private financing means and revenue from renting base space and utilities to interested partners to support the base at no further cost to tax payers.

With the established architecture of Rosas Base and mitigated risks governed by the long-term vision of the RLA, the base can be expanded in the future at lower costs, enabling greater potential for participation from partners worldwide. This promotes the potential for the development of a robust lunar economy, closing loops, and further reducing costs while generating more partners, increasing the sustainability and benefits of Rosas Base.

The goal of the Team Project was to develop solutions for the construction of a lunar base for long-term human presence on the Moon within years, instead of decades. The problem was approached from a holistic point of view, by addressing regulatory and policy frameworks, examining technological and anthropological challenges, and empowering scientific and commercial lunar activities for the common interest of all humankind. This report presents the result of this effort - a roadmap for the construction of a sustainable, habitable, and permanent lunar base. An overview of the aspects involved in the construction of this initial lunar base, along with the developed potential solutions is detailed.

1.3. Technical Overview of the Mission

The plan to transform an active vehicle to a large, habitable volume requires a series of technical steps. To assist in this operation, the MOROCAS fleet will be developed and utilized in the transportation sequence

- Starship (SS) Rosas is the first lander to launch and arrive prior to the crewed lander. It is uncrewed and stocked with equipment and supplies to support humans at the base site of the south pole of the Moon. This will later become the permanent base for the incoming crew.

- The crewed SS 501 will follow and land at a safe distance away from SS Rosas.
- The crew will remotely operate the MOROCAS rover fleet from SS 501 for the purpose of deploying power reactors, solar panels, and radiators, as well as drain remaining fuel into their respective tanks.
- The MOROCAS will install a system that will assist crew to horizontalize the SS Rosas on the ground.
- Some crew members will conduct their first LEVA to initiate the horizontal maneuver of the SS Rosas, thus becoming Rosas Base. This is referred to as Groundbreaking Day.
- The crew will install floors, walls, lights, bathrooms, life support systems, ventilation, water tanks, beds, and any other equipment that the habitat requires.
- The volumes will be occupied with their intended equipment, whether this is laboratory equipment, agriculture area, gym, lounge, or infirmary. After completion of the horizontal procedures, the remaining crew members will depart SS 501 and arrive at Rosas Base where they will spend the remainder of the mission.

Rosas Base will be continuously inhabited by crews arriving on visiting landers. Provisions for expansion of the base will also be made so that future modules can be attached to the nose interface of Rosas Base.

The Rosas Base construction roadmap is illustrated in Figure 2.

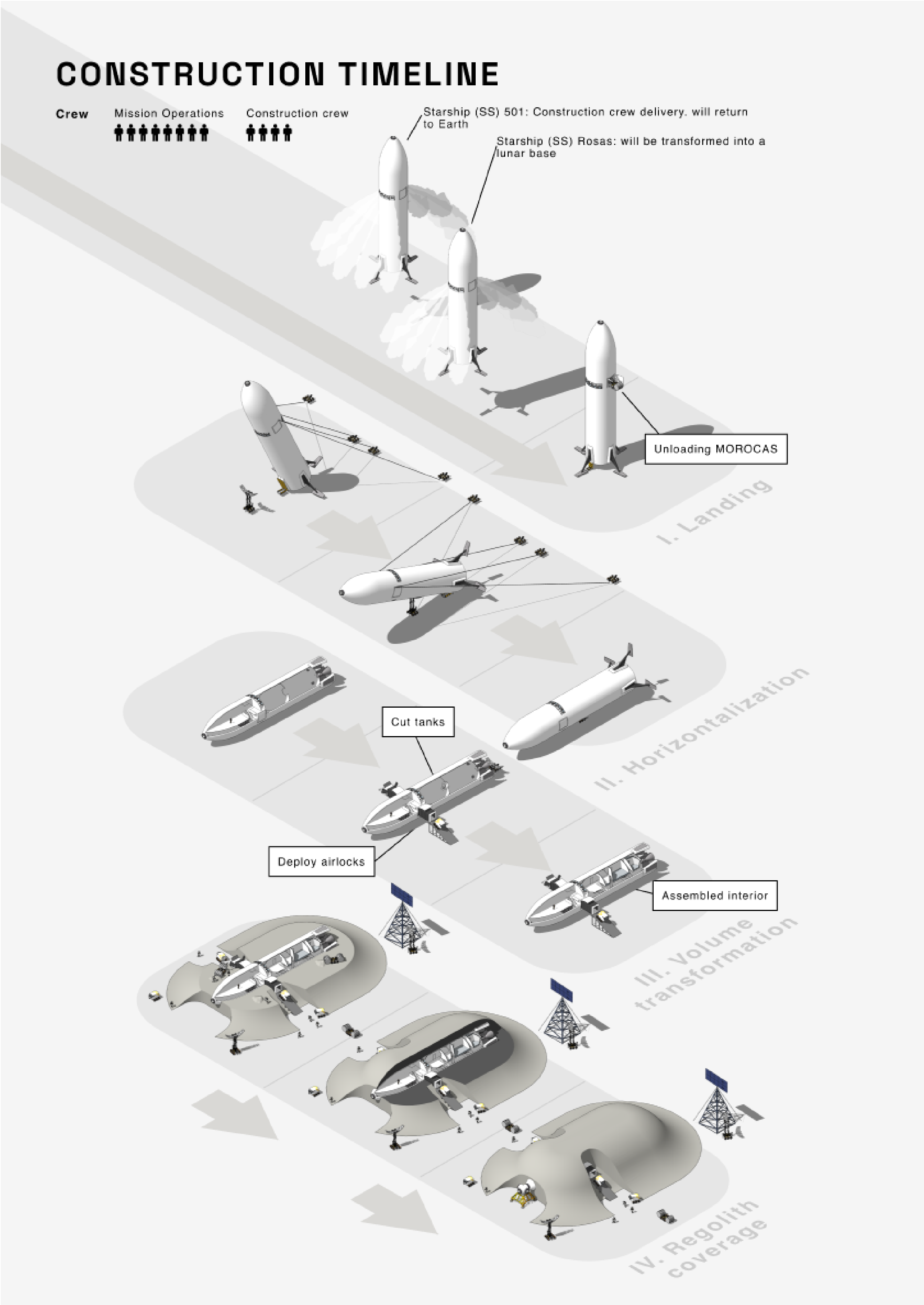

Figure 2: Roadmap for constructing Rosas Base

1.4. Reading Guide

This report is structured as follows. Chapter 2 describes the technical solutions for the construction of the lunar base. Chapter 3 details the considerations for human performance in space and human factors and medical solutions to build a settlement on the Moon. Chapter 4 draws attention to the legal and policy aspects of such an enterprise, and Chapter 5 presents the community engagement and outreach strategy. Chapter 6 describes the organization and timeline from a business and management perspective. Finally, Chapter 7 demonstrates a financial plan for the lunar base.

2. Construction and Subsystem Design

This chapter presents the technical solutions proposed to transform the Starship into a lunar habitat. The chapter is divided into three sections: payload considerations, automated preparation for the horizontalization operations and crewed transformation operations.

2.1. Before Flight

The base concept and its construction are designed to not rely on technologies that are not space proven to make this concept more viable in the near future. This means that the preparations and development of all systems do not require extensive research phases prior to development and implementation. The team also did not base its design on any other missions or spacecraft currently under development other than the SpaceX Starship HLS program. The base assumption in using the Starship is that very limited modifications shall be made to the base structure of the vehicle prior to launch, hence, no re-validation of the vehicle needs to be performed.

2.1.1. Launcher Characteristics and Required Infrastructure

Using the most up to date information about SpaceX's Starship (Figure 3), it is reported that it can carry up to 200 metric tons of mass to the lunar surface inside an 1100 m^3 payload fairing. The assumption of the team is that there is a limitation of 100 tons of useful payload. The Starship uses methane and oxygen stored in two large tanks which are estimated at 600 m^3 and 800 m^3 respectively. These volumes will be transformed into habitable volumes. The bay will need to be modified on Earth prior to the launch with the mounting of rigid supports that will be used as a skeleton for additional interior structures and fittings. This is done to minimize the workload of crew on the Moon. The interior of the Starship will be divided into three equal-height floors connected by stairs.

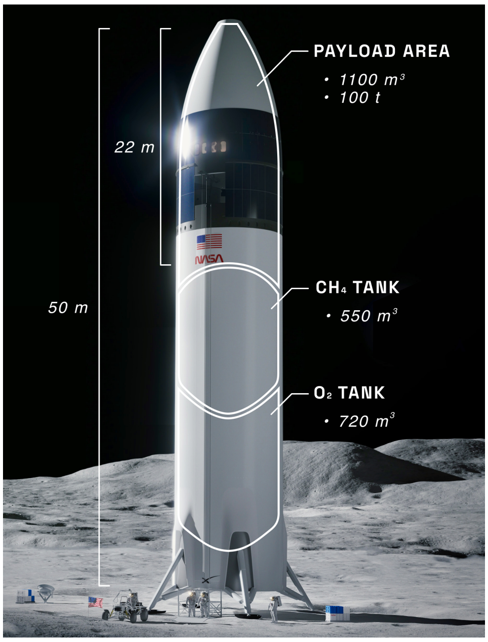

Figure 3: Artist rendering of current design of the Starship HLS concept (Original image credit: Space X) .

The original Space X Starship concept design proposes two airlocks, both provided with cable-suspended elevators used for payload deployment. One of the Starship airlocks will be modified to include a retractable corridor that can be extended up to 5 m away from the main body of the base. This corridor can then be covered by regolith to protect the crew against radiation and micro-meteorites impacts. The second airlock will be re-purposed into an extended observation deck which allows the crew to see their surroundings as well as the Earth.

2.1.2. MOdular RObotic Construction Autonomous System (MOROCAS)

In addition to the transformation of the Starship HLS into a lunar base, it is also necessary to develop a modular, remotely operated, team of robots to perform the majority of the tasks on site and to minimize the number of LEVAs needed. The MOROCAS are a key part of this concept in the construction of the Rosas Base and they are designed in line with the tasks they will need to perform.

The first task that the MOROCAS will perform is the deployment of several systems and tools from the payload area of SS Rosas to the lunar surface. For this purpose, the MOROCAS will be designed to fit inside the airlock and onboard the cable-suspended elevator that will lower it to the ground. The system will be equipped with the necessary tools to perform all the defined tasks such as lifting, grabbing and manipulating objects. All the equipment that will be deployed and set on the lunar surface, such as the solar panels, power reactors and radiators, will be designed to enable easy deployment by the MOROCAS.

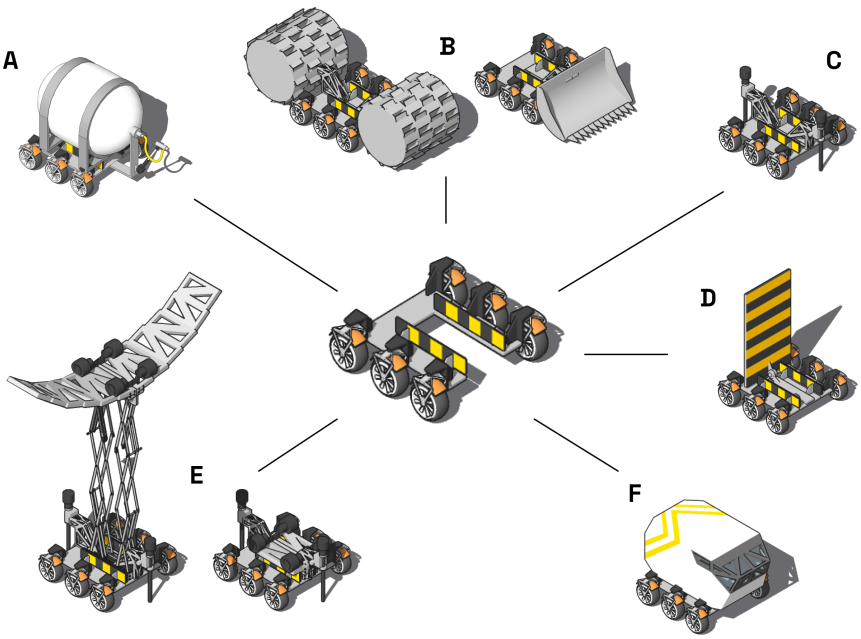

Figure 4: Different modular combinations of MOROCAS

A collection of tools, designed to interface with the MOROCAS, will be developed to perform various tasks (Figure 4), such as:

- **De-tanker and external bladders (A).** The MOROCAS will use the de-tanker to connect to the refuelling ports of the fuel tanks and transfer all the excess oxygen and methane to the external bladders. This contraption will also be used to fill the fuel tanks in the payload volume with air at a later stage. The de-tanker will also drain the water tanks in the payload volume to lighten the load on the vehicle while it is being tipped. This water will be restored in the tanks following the horizontal operations.

- **Regolith moving system (B).** This module will be used to pile regolith into berms as part of the Dep-Ops and to cover the whole station with regolith at the final stage in the construction.
- **Drill and anchors (C).** This module will be used to fix several anchors in the ground as part of Dep-Ops.
- **Hinge (D).** This large contraption is part of the equipment that is used for tipping the Starship and will be deployed during Dep-Ops. This will be connected firmly to the bottom of the SS Rosas and to the anchors installed underneath.
- **Scissor lift (E).** This device will support the body of the Starship from underneath while this is being lowered into its final horizontal configuration.This device will be required to carry a substantial load during the horizontal operations.
- **Crewed rover (F).** This rover will be used by the crew to travel from SS 501 to SS Rosas during the construction activities. The rover will be pressurized and able to act as a temporary habitat for all future LEVAss. It will need to fit as a whole system through the airlock of the base and have an interface with the LEVAs suits in order to make these accessible to the crew while inside the rover.

All activities that the MOROCAS will carry out can be automated. Any activities which are particularly complex or required a high accuracy will be controlled or supervised by the crew arriving onboard SS 501. While activities such as the deployment of the solar panels and the pilling of the regolith can be performed with no human supervision, the installation of the anchors shall be either supervised or controlled remotely by the crew.

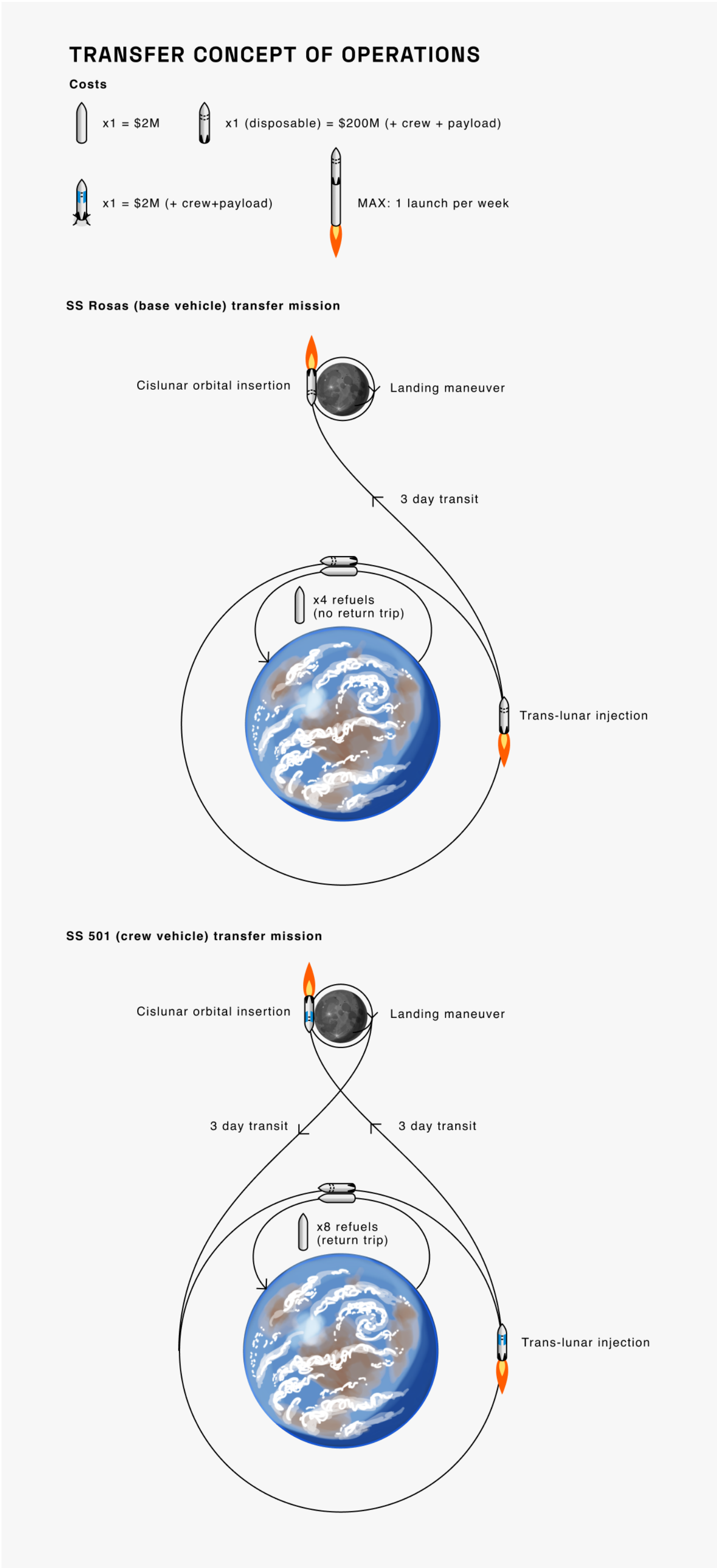

Figure 5: Transfer mission timeline

2.1.3. Landing Site Requirements

Several aspects were considered in the selection of the Rosas landing site. The site shall receive as much light as possible to ensure sufficient energy for the base. It shall also be sufficiently close to the permanently shadowed regions for water extraction. The possibility of maintaining a continuous view of the Earth is also considered highly advantageous for the crew. Lastly, the landing site must provide a flat surface large enough to enable SS Rosas to land safely and remain flat after being positioned horizontally on the ground. The selected landing site which meets all of the requirements above is at the lunar south pole, on the rim of the Shackleton crater at the coordinates 89.78°S, 155.73°W, see Figure 6 (Gawronska, et al., 2020).

Once SS Rosas lands, the surrounding terrain will be prepared using the MOROCAS system: all large rocks will be removed, the terrain will be leveled and two berms will be pilled on either side of the base that will prevent it from moving once it is in its horizontal configuration. The SS Rosas will ideally be landed in such a way so that, when being lowered down, the airlock being transformed into an observation deck will face the Earth.

A second landing site shall be considered for SS 501 arriving after SS Rosas. This site shall have similar characteristics as described above while also being located at a safe distance away from the base: sufficiently close to enable fast transportation of the crew between the two sites but far enough to prevent any damages caused by dust and regolith being thrown away during the landing.

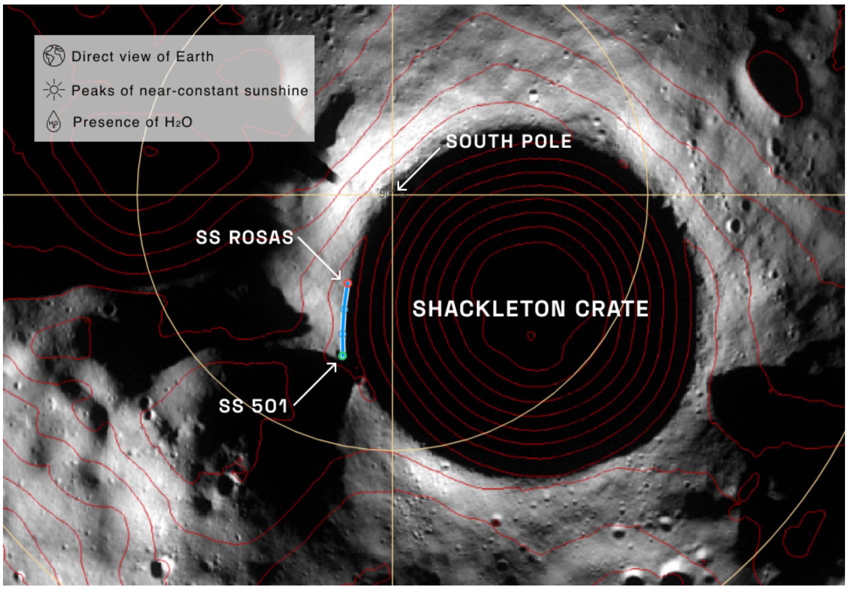

Figure 6: Landing locations of SS Rosas and SS 501 on the peaks of eternal sunshine at the rim of Shackleton crater.

2.2. Remote Operations

The first major task in the transformation of the active Starship platform to a habitat is transferring it from its vertical to a horizontal configuration. Upon landing, SS Rosas will be fully stocked with all the equipment needed for the conversion into the base. An extensive inventory can be found in Appendix A.1. A plan was developed to describe all the steps necessary for this procedure.

2.2.1. Deployment Operations (Dep-Ops)

The MOROCAS will be operated by the crew remotely and will complete a series of tasks to prepare for the horizontalizing procedure. The MOROCAS can travel in and out of the SS Rosas through the airlock while carrying the needed equipment and tools and utilizing it on the surface.

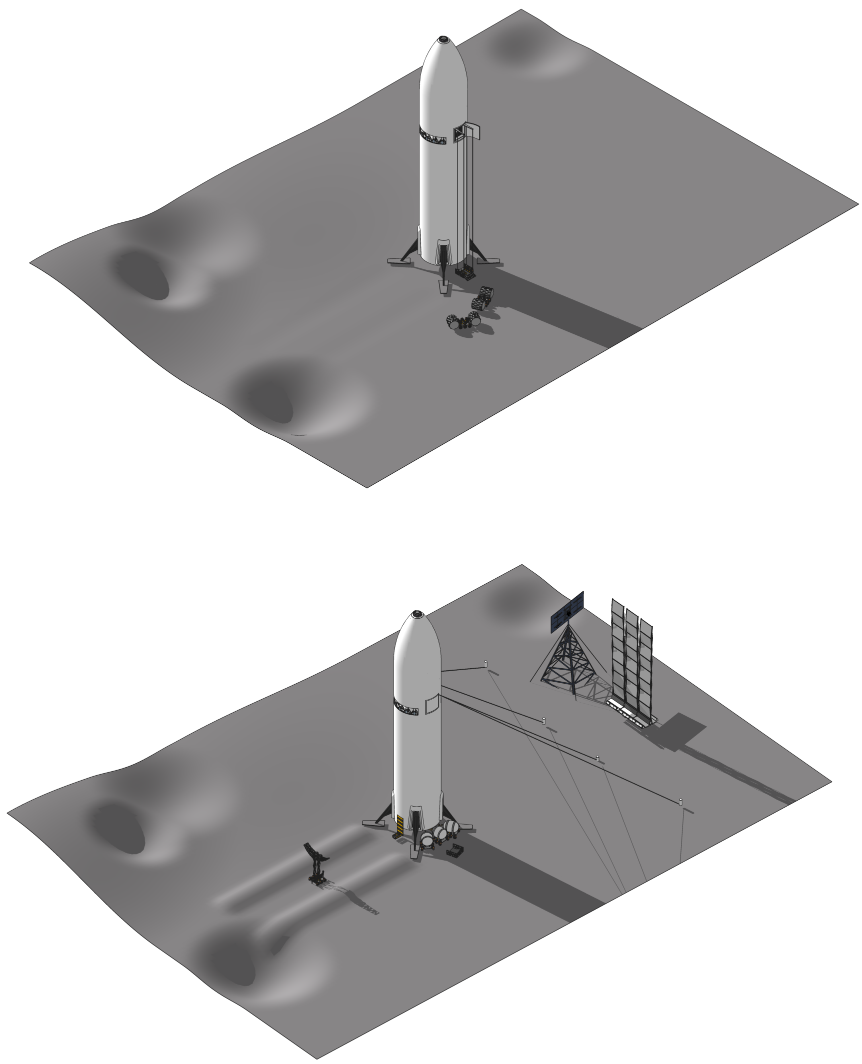

Figure 7: The SS Rosas after landing, at the begining of the Dep-Ops (top) and after the completion of Dep-Ops, ready for horizontalization (bottom).

The following tasks need to be performed by the MOROCAS prior to the reconfiguration of SS Rosas:

- Unload, deploy, connect and activate the solar panels, power reactors, and radiators.
- Partially drain the fuel tanks to an external bladder to reduce the mass during the operation. The amount of fuel remaining in the tanks must be enough to maintain the structural integrity of the whole vehicle. for the same reason, the payload volume was already pressurized with nitrogen, which will be used later to create the desired breathable atmosphere.

- Installation of the hinge mechanism under SS Rosas. This will be connected to the legs and the thrust-puck on one side and to an anchor that will be drilled to the ground on the other side.
- Installation of 4 anchors to which cables will be connected.

Once all the above tasks are completed, the elevators will be disconnected from their cables (each elevator has 2 cables) and each cable will be secured to an anchor. The MOROCAS will then deploy the scissor lift, removed from SS Rosas before the elevator is decommissioned, and position themselves between the two berms, where the Starship would eventually rest. At this point the Dep-Ops are concluded. The crew will then arrive on site to verify that the horizontalizing procedure can begin and monitor the process itself. This stage is referred to as Groundbreaking Day and it is described in the following chapter.

2.2.2. Post-Reconfiguration Activities

After the crew arrives and the vehicle is placed in its horizontal configuration, the last uncrewed activity for the MOROCAS is to autonomously cover the entire vehicle in regolith to enhance the protection from micrometeorites and radiation. The airlocks will be expanded with the pre-installed sleeve-corridor to allow access under the piled regolith. One of the airlock corridors will have an observation deck—Observational Surround Crew Assembly Room (OSCAR)—which allows the crew to see their surroundings as well as the Earth.

2.3. Crewed Operations

The crewed operation phase was designed to have minimum crew time in LEVA suits and minimize the transition between environments with different pressures. Following all the remote-controlled preparations, the crew will land 5 km away from the Rosas Base landing site onboard the SS 501 lander. A list of the crewed activities that follows and the expected duration of each task can be seen in Table 2.

Table 2: A list of the crewed activities and the expected duration of each task

Task	Subtask	Environment	Min. Required Crew	Duration [hrs]	Duration [hmn-hrs]
1. Travel from SS 501 to the Rosas landing site.	1.1 The rovers onboard SS 501 will be depressurized from 0.5 to 0.3 bar.	Two lunar rovers located inside the SS 501 airlocks.	4	2	8
	1.2 The crew will drive to Rosas Base.	Two lunar rovers.	4	0.5	2
2. Supervision of the horizontalizing procedure.	2.1 The crew will verify the tilting mechanism.	Two crew members will be wearing suits and two will be supervising the procedure from their rovers.	4	1	4
	2.2 The crew will supervise the horizontalizing maneuvers.			1	4
	2.3 The crew will verify the successful horizontalizing procedure and will evaluate the payload volume atmosphere.			1.5	6
3. Entry to Rosas Base.	3.1 The two suited astronauts will enter the base directly from their suits and two from the rover. The airlocks of the base will be pressurized from 0.3 to 0.5 bars.	Suits and rover inside Rosas Base airlocks.		2	8
	3.2 Crew will rest and sleep in the airlock of the base.	Payload volume.	4	–	–
4. Conversion of the CH_4 tank.	4.1 The crew will drill a pressurization hole and monitor process		2	3	6
	4.2 The crew will cut the hatch hole in the CH_4 tank.		2	2	4
	4.3 The crew will install the hatch.	CH_4 tank.	4	2	8
	4.4 The crew will install the insulation floors, cables, piping, Environmental Control and Life Support System (ECLSS), etc.		4+		250
5. Conversion of the O_2 tank.	Same procedure as Step 4.	O_2 tank		Same as Step 4.	
6. Configuration of the new internal layout.	6.1 The crew will Install beds, laboratory equipment, furnishing and equipment in the common areas, gym etc.	Rosas Base			N/A

2.3.1. Surface Transportation Infrastructure

The majority of the equipment needed for the construction of the base will be already stored inside the base upon arrival. Hence, the only equipment that the crew will need to bring to the base site their own life support (suits and any additional supplies) and any additional means of transportation such as rovers. The crew will arrive at the base site inside the MOROCAS rovers from their lander in time to supervise the horizontal operations. The crew version of the MOROCAS rovers can be exited through suits that are mounted to the exterior and can be accessed through the suit backpacks. This minimizes the dust exposure of astronauts and keeps the interior of the MOROCAS as clean as possible.

Once the Rosas Base is established, the MOROCAS will compact the lunar regolith and form the first road on the lunar surface. This will significantly reduce the wear on future rovers caused by the cohesive nature of lunar regolith (Gaier, 2007).

2.3.2. Horizontal Configuration of the Lander

The main driver behind the design of the tipping mechanism is the need to minimize the stresses on the body of the vehicle. Any payload that can be outside of the vehicle (such as radiators and solar panels, or equipment that will not be affected by direct exposure to the lunar environment) will be unloaded for this purpose as a safety measure, in order to lower the mass located in the payload area and lower the center of gravity of the whole structure. The inner volume of the tanks and payload area will remain in minimal pressure, only to maintain the structural strength. As the vehicle is lowered it is supported at three points: the hinge at the bottom of the vehicle, the cables halfway up the vehicle and the scissor lift which travels along the vehicle supporting the structure from underneath.

The horizontalizing procedure starts by folding the lander leg that is facing the pre-defined tilting direction. The cables will be slowly deployed by the elevator systems to increase the tilt angle gently. It is assumed that the elevators' winches and their cables can support the load of the vehicle and distribute it along the structure. As the tilting angle increases and the base of the vehicle will tend to slip, the hinge's role is to prevent this from happening while also maintaining the pre-defined alignment of the vehicle.

At a certain tilt angle, the tension on the cables becomes too great (Appendix A.2); This is when the scissor lift contacts the body of the vehicle and transfers the load to the ground. The lift will then start to drive up along the body of the vehicle as it continues to tilt. When the lift reaches the nose of the vehicle, the scissor lift is folded until the body of the vehicle rests on the pre-piled berms. The lift then drives out from underneath the vehicle and can be used again for future modules or other purposes.

2.3.3. Reconfiguration of the Base Interior

Once SS Rosas is reconfigured into Rosas Base, the next task for the crew is to create a single volume with a standard atmosphere (0.5 bar, 25℃, 42% oxygen, 56% nitrogen and 2% carbon dioxide and other trace gasses). Following the horizontal maneuver, the methane shall be fully drained and stored in its respective bladder. The remains in the fuel tank must be vented to ensure the tank is completely empty, to prevent any risk of fire during the interior modifications. The nitrogen in the payload area will be supplemented with the oxygen extracted from the tanks and the oxygen tank will also be supplemented with nitrogen, achieving the desired balance of air and pressure. The methane tank will also be pressurized with air through its refueling port. Once the environment is appropriate for human operation, interior modifications can start.

The pressures between the methane tank, which is empty, and the pressurized compartments, need to be equalized in a safe way, for example by drilling a small hole in the center of the dome of the tank from the payload area. Once the pressures in all compartments reach an equilibrium state, a larger hole will be created into the methane tank followed by the installation of a hatch. The same operation will be applied to the lower oxygen tank from the methane tank, with the additional security of having now the same pressure on both sides (Figure 8). Once completed, the whole interior of the vehicle can be used as a habitable space.

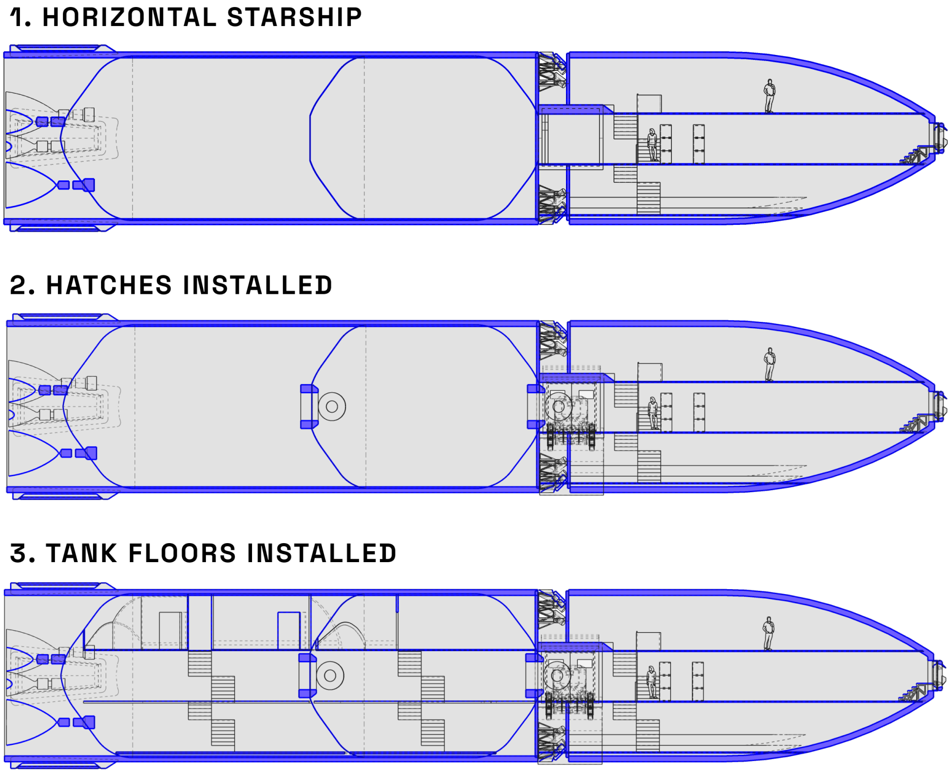

Figure 8: Starship section plane interior.

2.3.4. Installation of Basic Infrastructure

Following the de-tanking procedure and the cleaning of all remaining residue within the tanks, the construction and installation of the base infrastructure will start by covering all the internal walls with insulation material and radiation protection. This insulation will aid in protecting the construction crew until the base confiuration is fully set up and covered by regolith. The crew will install a layer of Multi-Layer Insulation (MLI) (Price and Phillips, 2001), with an additional layer of Polyethylene to protect against radiation (Shavers, et al., 2004).

Following the layering of the insulation, the floors will be installed. The floors come packed in kits stored in the payload bay and will have to go through the different hatches in order to be installed in the fuel tanks. All floors will be suspended on beams and connected to the baffles that are already present inside both tanks. As for the payload bay, the two floors will already be set up on SS Rosas prior to its launch.

Water tanks will be mounted on the upper floor to supplement the radiation protection for the floors below. Tanks of various thickness will cover the entire surface and will be connected to each other.

Cables and pipes will be installed in the base for communication, electricity, ventilation, and water distribution as a last step in the construction of the internal structure of the base.

The final layout of Rosas Base is shown in Figure 9.

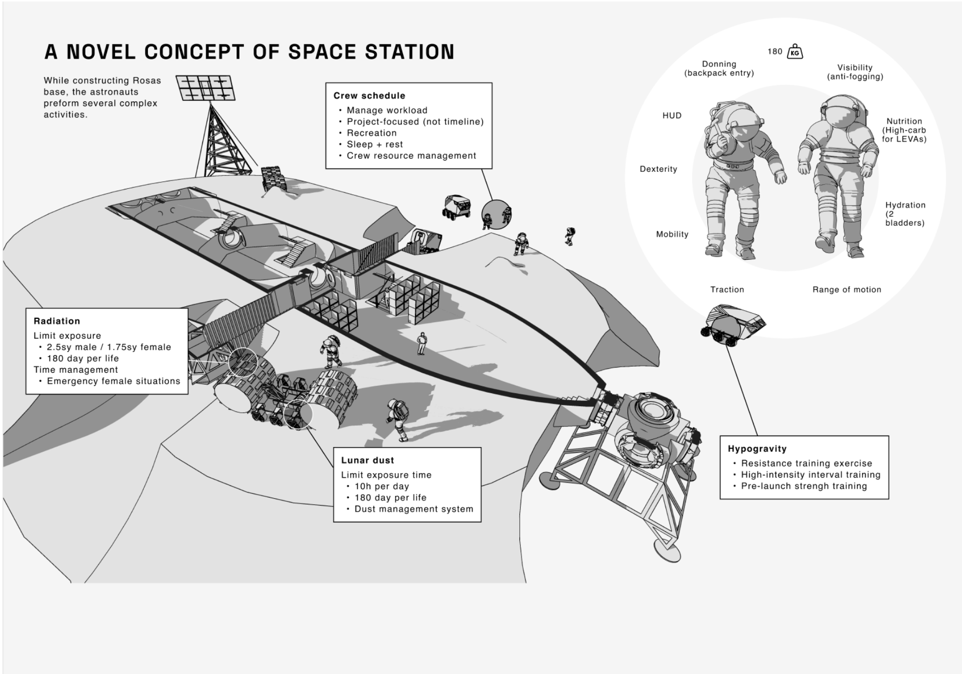

Figure 9: Layout of Rosas Base.

2.4. Rosas Base Subsystems Design

The following chapters describe the considerations and the baseline design concept for all subsystems of Rosas Base, namely power, transportation, environmental control and life support, space environment shielding and communication.

2.4.1. Power

The power required for the construction of the base and for sustaining its habitability consists of different power systems depending on their pre-identified parameters. For the construction, the MOROCAS will have its own Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) power system with a solar panel modification as a backup. Most of the construction equipment will, therefore, depend on the MOROCAS power supply, such as the de-tanker, the scissor lift, the robotic shovels, the drilling machines etc. The power required by the MOROCAS is roughly estimated at 10 kW/day. This value is based on the power to size ratio and required instruments and modular tooling compared to what the Curiosity rover generates (2.5 kW/day) (NASA, 2009).

Once the Rosas Mission crew arrives at the base to assist with the configuration of the first human lunar base, a standalone power system is needed to reduce the risk factor of a power supply. The system used to meet the performance requirements is the power system proposed in Shikar, et al. (2018). This system consists of a combination of energy providers with the focus on nuclear power generation and is capable of providing 18 kW/day for consumption and low maintenance. An illustration of the power system can be seen in Figure 10. It is determined that 12 astronauts use up to 36 kW for ECLSS, communication and Extravehicular Activity (EVA) (Shikar, et al., 2018).

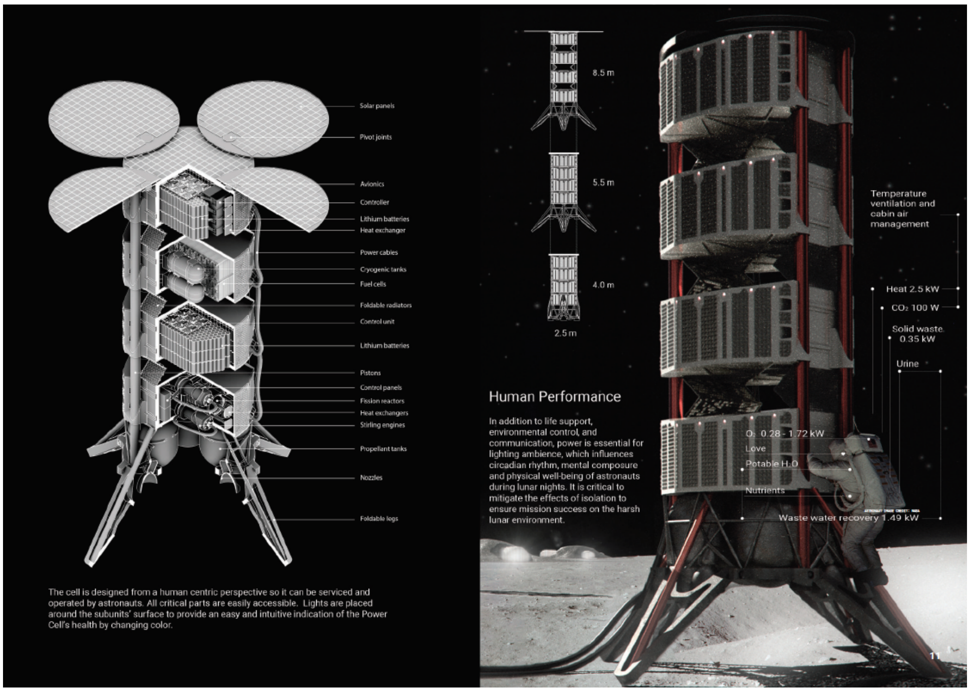

Figure 10: Proposed power system to meet the Rosas Base performance requirements. Reproduced from Shikar, et al. (2018)

As a partial power backup, a solar panel surface field will be placed close to the base. At the South Pole there is an expected solar irradiance of 320 W/m^2 due to the location of 80 ° S to 90 ° S (Kaczmarzyk, Gawronski, and Piatkowski, 2018). The best optimal inclination towards the sun is therefore approximately four degrees. This results in a total required solar field of 75 m^2 and about 20 solar panels to generate 24 kW as a backup.

2.4.2. Transportation

The Rosas Base landing zone will be the arrival and departure port for spacecrafts traveling to and from the base. Proximity to the base is required but the safety distance needs to be maintained. The properties and architecture of the landing zone will impact this location: the more advanced the architecture, with either a sintered, compressed (Gaier, 2007) or otherwise hardened, dust-free ground or dust-guards, the closer it can be to the base. Similarly, the more reliable and tested the landers are, the closer the landing zone can be to the base.

One of the core issues of landing zones, which needs to be addressed, is that landing and take-off abrades surrounding equipment, as the dust and regolith pieces get accelerated by the dust plume, and there is no atmosphere to decelerate the particles (David, 2020).

The Rosas Base inhabitants and robots will construct additional landing zones, either through sintering of the surface, by using the cement-like features of lunar regolith through compression (Gaier, 2007) or by applying various materials to the lunar surface. Such landing zones can be located closer to Rosas Base. Further research on lunar regolith compaction during the construction phase can help in the decision-making process of which technology to use to construct future launch pads.

2.4.3. Environmental Control and Life Support

The Environmental Control and Life Support System (ECLSS) of Rosas Base is assumed to be derived from the ECLSS onboard the International Space Station, hence, the same performance specifications will be assumed. A partially regenerative system is assumed, hence, frequent resupply missions will be required until there is an established and reliable way of producing food and fully recycling water and regenerating oxygen onboard Rosas Base.

Traditionally, the ECLSS is composed of several subsystems which regulate the pressure, temperature, atmosphere composition as well as perform waste management and fire detection and depression. Additionally, facilities such as galleys and lavatories are included. For the purpose of estimating the payload mass and volume required for the launch of SS Rosas, consumables such as food and water are also included in the ECLSS.

To define a baseline for the ECLSS, several assumptions are made about Rosas Base. For the purpose of estimating the mass and volume budget of the ECLSS, a crew of 12, which is double the size of the crew for which the International Space Station (ISS) ECLSS was designed, was assumed. For estimating the minimum quantity of food and water for the crew sustenance, a duration of 100 days was assumed (approximately double the resupply cycle of the ISS).

A mass and volume budget for the ECLSS was computed and an estimated overall system mass of 12,275 kg and a volume of 20.1 m^3 were obtained. A more detailed budget can be found in Appendix A.2.

A layout for the location of the various ECLSS subsystem is shown in Figure 11.

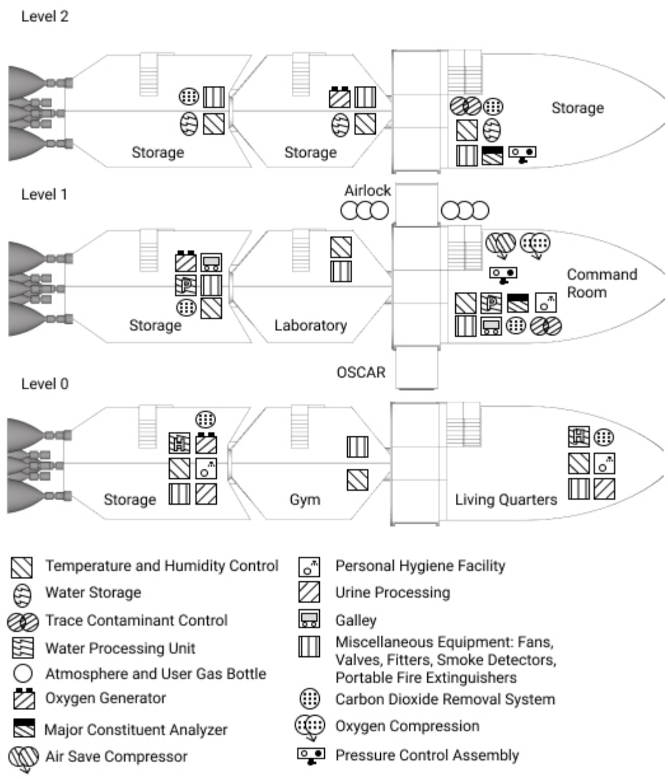

Figure 11: Environmental control and life support system layout.

2.4.4. Space Environment Shielding

The characteristics of the lunar environment pose several challenges to the development of a habitable base. The following sub-chapters will describe the considerations and the proposed solutions to tackle the base thermal control, radiation protection, meteorite shielding, and regolith exposure,

2.4.4.1 Thermal Control

The location of Rosas Base (lunar south pole) is exposed to surface temperatures varying from 50 K to 200 K (NASA's Break the Ice Lunar Challenge, 2021). Rosas Base will eventually be covered by a thick layer of regolith providing a very comprehensive protection. However, before this process is completed, the interior of the base will be thermally insulated using Multi-Layer Insulation MLI.

During the covering process (which is assumed to last for two months) some shallow depressions in the ground will be formed where the regolith is excavated from. These depressions are effectively permanently shadowed areas where radiators can be placed. Similar to the International Space Station, two thermal loops will be used. The first one will be circulating water only inside Rosas Base. Cold water will be used for cooling and the heated water will be reused to heat up other areas of the base. The second thermal loop will be an outer loop that will collect heat from the base and the solar panels and convey it to radiators panels where it will be dissipated into space. Comparing the volume of Rosas Base and the ISS, which is equipped by seven radiators, an estimated number of fourteen radiators will be used to set up the base. Lastly, as this system will remain outside where water would freeze in the pipes, this system will be using ammonia which as a lower freezing point than water.

2.4.4.2 Radiation Protection

The space radiation environment consists of high energetic Galactic Cosmic Rays (GCR) and Solar Energetic Particle (SEP), creating a short- and long-term high radiation risk to the human species for space exploration. As the Moon's surface is consistently bombarded by these GCRs and SEPs, an estimation of the lunar dose rate shall be made around a crater to determine the radiation protection needed for a human lunar settlement.

For this, the dose rate, measured by the lunar Lander Neutrons and Dosimetry (LND) instrument of the Chang'e 4 lander at the Von Kármán crater in the south pole-Aitken Basin is used. This results in a dose rate of 13.2 ± 0.7 µG/h, with about 20% secondary particles from the regolith. The above-mentioned rate has been measured during a solar minimum and therefore mainly consists of GCRs, resulting in an average 2.6 times higher radiation lunar surface dose than inside the ISS (4 µG/h) (Shavers, et al., 2004).

To protect the crew during the construction phase and future permanent settlements, radiation shielding is required. Rosas Base and SS 501 shall be designed according to the international radiation principle: As Low as Reasonably Achievable (ALARA), as low as reasonably achievable, making sure that astronauts sleep, work and live in a safe environment. Reducing the radiation exposure results in less deterministic and stochastic radiation effects, such as cancer and Deoxyribonucleic acid (DNA) mutations.

This can be obtained by using various materials such as: lunar regolith, water, Polyethylene, and/or Aluminum. The lower the weighted average atomic number, the higher the kinetic energy transfer, resulting in a higher radiation protection material. As a solution for Rosas Base, a 3-meter-thick lunar regolith is chosen for the outer covering, as it has been experimentally proven to have an acceptable radiation reduction factor of 0.8% with a soil density of 1.4 $\mathrm{g/cm^3}$ (J. Miller, et al., 2009).

A solar storm shelter will be built around the command center and the airlock in order to protect the sensitive equipment and the crew in case of solar storms. This will consist of an inflatable bladder built on the floor and the walls of the payload bay. In case of emergency, the crew will be instructed to return to the airlock or Level 1 of the payload bay and activate the system which will be draining all the water on the base towards the inflatable walls used for protecting the crew from radiation.

During the base construction and necessary LEVAs the crew will be exposed to a higher radiation level with an estimation of 9.5 mSv. Once the habitat walls will be provided with the 40 cm MLI to protect the habitat and astronauts against GCRs, SEPs and in a later stage the residual secondary particles coming from the regolith, this radiation level exposure will be drastically reduced. In addition, MLI offers temperature insulation properties to prevent temperature fluctuations.

2.4.4.3 Meteorite Shielding

About 33 metric tons of meteoroids cross the Earth's orbit every day but most of them get burnt up on the atmosphere (Dunbar, 2021). Thus, the risk of being hit by a meteorite is not a big concern on Earth's surface. However, as there is no atmosphere on the Moon, every meteorite crossing the Moon orbit will hit its surface. Due to the high speed of these rocks, they could create lots of damage on the surface and are a concern for the lunar base.

According to National Aeronautics and Space Administration (NASA) though there is still a lack of study to estimate lunar impact rate, especially on the Moon's south pole (Dunbar, 2021). More studies will thus be needed to understand the risks of building a lunar base on the Moon surface. In the meantime, to mitigate the consequence of such impacts, the base will be covered by regolith. However, the risk of an astronaut being hit by a micrometeorite of around 1g has been previously studied and is said to be very low (10^{-6}).

2.4.4.4 Regolith Mitigation

Lunar dust regolith is a big hazard for the health of the astronauts and for the health of machinery. The internal parts of the base should be kept as clean as possible from anything entering from the outside, mainly by minimizing going in and out of the base. The airlock will be designed with large brushes that not only sweep away the dust from any entering payload but also electrically discharges the payload to repel small dust particles. Air filters in the airlocks will be replaceable. The LEVA suits will be designed to be entered from their backpacks with a special mechanism, this way the LEVA suit always remains outside the station.

During the construction of the base, the MOROCAS will be entering the payload area to deploy systems outside. The MOROCAS should be designed with smooth surfaces to prevent dust from getting stuck in corners and cracks, making them easier to clean in the entrance to the airlock. The MOROCAS and any other machinery will also be designed with minimum moving parts and using metallic glass bearings.

2.4.5. Communication System

The exploration of the Moon with humans and robots, as well as a permanent settlement, will require significant infrastructure to provide a communication network and positioning, navigation, and timing capabilities.

2.4.5.1 Satellite Communication

The internal communication systems on the Moon considers every activity that is independent of Earth, such as communication surface-to-surface (astronaut-astronaut and astronaut-rover) and signals that are required for the operations of a spacecraft. This includes surface exploration missions far from the base, both with crew and rovers. Communication with a Gateway-like orbiter will also be taken into account.

Some companies have already begun to work towards solutions to this challenge. The most valuable to note is the investigation of an Long Term Evolution (LTE) and 5G lunar network, which is implemented before the arrival of the crew on the lunar surface (Lisi, 2020; Nokia, 2020). Nokia, a cellular company using communication satellites, stated, "This network consists of an LTE base station with integrated Evolved Packet Core (EPC) functionalities, LTE user equipment, Radio frequency (RF) antennas and high-reliability Operations and Maintenance (O&M) control software. This solution has been specifically designed to withstand the harsh conditions of the launch and lunar landing, and promotes operability in the extreme conditions of space." (Nokia, 2020). A requirement is to find the optimal point and the acceptable errors on the surface where the lander is scheduled to arrive, as it is highly dependent on precision of the position.

2.4.5.2 Base Communication

For the communication inside Rosas Base, it is possible to use a mobile device that could be directly linked to the 5G network. Alternatively, radio-signal connections such as Bluetooth, which do not use satellite communications, can be used. The team implemented a solution for the base which considers a fixed communication system for each of the three rooms of the base. In any room will be implemented a basic device composed of a microphone, an amplifier, and a receiver. In case of emergency and human isolation in one room, the astronaut will be able to communicate with the outside environment

2.4.5.3 External Communication Earth to Moon

To have a continuous connection with ground control, it is necessary to develop a communication and navigation system that can transmit the signal from Earth and send it to the Moon and back. Considering that the Moon consistently faces the Earth with the same side, the base located at the south pole will have cycling visibility of Earth. Earth will be visible for approximately 14 days, and during the following 14 days, the Moon will not be visible. This will complete one 28-day-lunar cycle (De Rosa, et al., 2010). From the base, which will be located at the Shackleton Crater, the visibility of Earth improves due to the altitude, making it visible 80% of the year. Under this assumption, the team determined that to have a continuous, direct, and efficient communication with the Earth, a spacecraft constellation will support communication with ground control (Bussey, et al., 2010).

One of the current solutions for consideration is the concept of having small satellites in a halo orbit at the Lagrangian points L1 and L2 (Hamera, et al., 2008), as shown in Figure 12.

This solution suggests achieving constant communication using two spacecrafts in combination at the Earth-to-Moon libration point orbits (Grebow, et al., 2008), with a period of 7.5 days (Hamera, et al., 2008). The spacecraft will consist of three antennas, solar arrays, and the bus. The number of antennas will ensure continuous communication between the two satellites, Earth, and the Moon surface (Hamera, et al., 2008).

To achieve good flexibility, a dual-band approach can be implemented, as shown in Figure 13: Mission data can be transmitted by Ka-band (27 – 40 GHz); tracking, telemetry and command can be transmitted via S–band (2 – 4 GHz) (Hamera, et al., 2008).

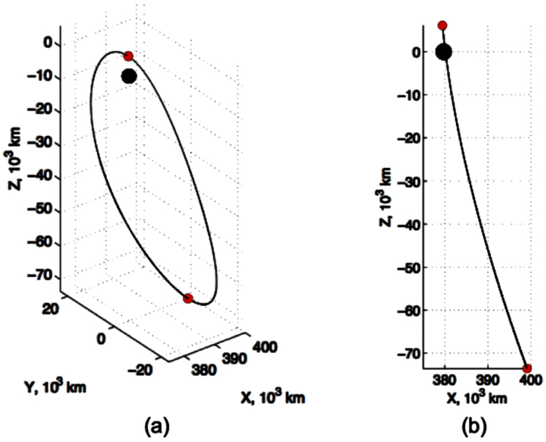

Figure 12: Communication System, Halo Orbit

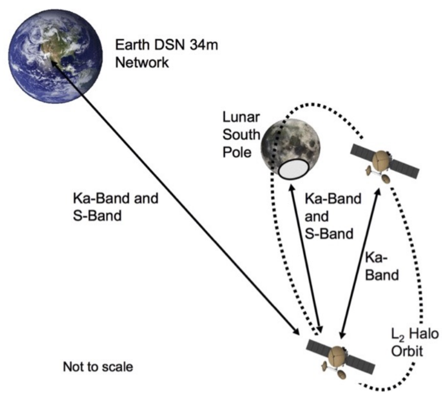

Figure 13: Communication System, Dual-band approach

Table 3 shows the prerequisites needed to build the communication system shown in Figures 12 and 13 (Hamera, et al., 2008).

Table 3: Requirements needed to build the communication system

Spacecraft	
No. of spacecrafts required	2
Orbit	Halo Orbit (period of 7.5 days)
Wet Mass	399.6 kg
Margin link	3 dB
Lunar Relay Element (on the Moon surface)	
Diameter Antenna	25 cm parabolic dish
Power availability	100 W
Earth Ground Station	
System type	Deep Space Network (34 m dish)

However, the requirement to have a good communications link depends on the activities on the Moon. A minimum of 10 Mbps has to be achieved in order to have photo and video exchange between Earth and Moon. This rate can be expanded in the future to to optimize the communication link, as shown in Table 4.

Table 4: Communication requirements for various lunar application Colozza, 2020

Application	Data rate, Mbps	Transmission distance, km
Lunar surface-to-spacecraft relay	1,000	6,500
Lunar surface low-rate communications	10	2,700
Surface-to-lunar science orbiter	100	2,700
Lunar surface human outpost	1,000	2,700

Other constellation solutions have been taken into consideration, such as a three-satellite constellation in a frozen orbit (Hamera, et al., 2008) and a single spacecraft constellation, displacing the vehicle below the trans- or cislunar orbit liberation points (Grebow D., 2010). From this, the first solution shows the most promising results in regards to efficiencies, with the consequence of discarding the other options.

Particularly, the single spacecraft constellation requires the use of more fuel compared to the multibody system and is used for missions that require low altitude. A higher altitude gives a big area coverage, which could be significant for explorations missions far from the base and a future expansion of the settlement (Grebow, et al., 2008).

The main differences concerning the freezing orbit are going to be the low orbit insertion and orbit changing costs, continuous Earth access, a lower number of spacecraft necessary for near global coverage, and higher navigation accuracy, as seen in Table 5 from Hamera, et al. (2008).

Table 5: Differences between halo orbit (L2) and frozen orbit

	L2	Frozen
Insertion cost per satellite	10 m/s	450 m/s
Orbit changing costs $\sim \Delta V$	5 m/s	650 m/s
Earth access (% of orbital period)	100%	95%
Navigation accuracy 3σ	20 m	40 m

Other solutions, which involve stations on the Moon surface, are discarded for multiple reasons, mostly regarding the complexity of building multiple antennas on the surface.

First of all, implementing an antenna network on the lunar surface needs human activity, which implies a lack of connection in the first part of the mission. Having a satellite constellation instead allows having connection ready before the crew lands on the Moon's surface.

Considering avoiding this first problem, other issues should be taken into consideration, such as the hitch of finding a solution for the dust storm, the redundancy that the network must have, and the distance from the base. Distance results in a major concern in case of emergency as well as in the moment the astronauts arrive, since it required to leave the landing site in order to build the station.

Since the final image is going to be particularly elaborate using this type of solution, the team decided to opt for the satellite constellation solution.

2.5. Rosas Base Final Configuration

Figure 14 shows a 3D model of the Rosas Base concept design. The figure displays the exterior structures, such as the modularity node, the airlock and the observation deck, as well as the interior configuration with three rooms, the payload bay and the two re-purposed tanks, divided into three equal floors connected by stairs.

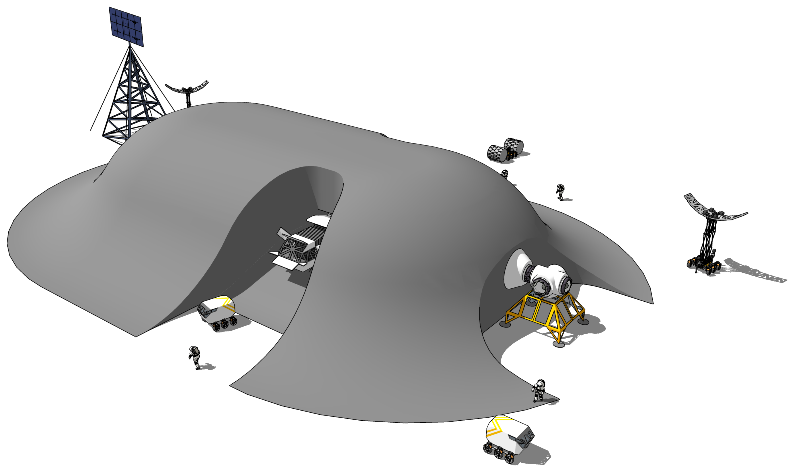

Figure 14: 3D model of Rosas Base

In addition, some more detailed technical drawings can be found in Appendix A.5.

2.6. Future Plans and Expansion

Several considerations for future use and expansion of Rosas Base are addressed by the team and the opportunities are described in the following sub-chapters.

2.6.1. Expanding the Base

It is expected that for the base to be sustainable and cost-effective it will need to be expanded and be able to accommodate additional applications, in accordance to the developed business plan. The base can be expanded by connecting more horizontal Starships from a dedicated node found at the top of the vehicle (seen in Figure 15) or from the airlock corridors. The major challenge here is transporting the additional horizontal Starships to the same site since they cannot land a short distance away from each other. To solve this issue we can use the MOROCAS from the first Starship and the new Starship to distribute the weight of the vehicle as it travels along a "paved" road (created through sintering or compressing the regolith). Assuming there are at least 8 MOROCASs at this stage, each of them will have to carry a weight which is equivalent to 1.5 tons on Earth. This is an achievable load capability for a lunar rover.

Since water has a considerable share of the payload weight in the current plan, using ice from the Shackleton crater instead of importing it from Earth will be a huge saving on launch mass.

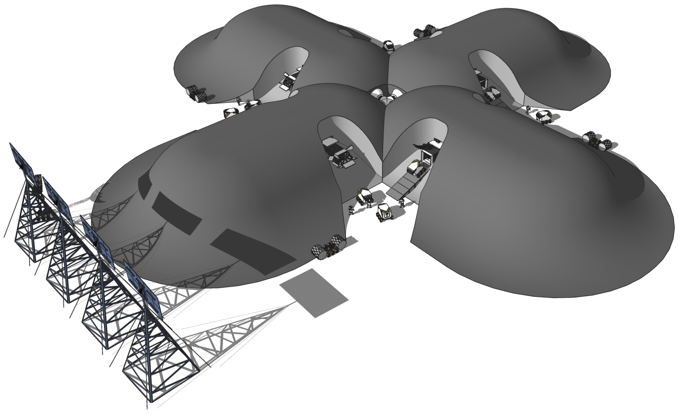

Figure 15: Node dedicated for the expansion of Rosas Base

2.6.1.1 Use of the Base

A proper use of the base has to be taken into considerations, in particular the possible application that could be useful for the development of a self-sustainable base and future concepts.

Since the settlement is going to be built on the south pole, the team considered the use of in-situ the resources, such as the ice-water present in that area (Song, et al., 2021). Particularly, two main concepts are investigated: ice-water as a source for human sustainability and as a source of green propellant production.

One of the main tasks of the water is going to be food production in the upper deck of the base. The crew will have the goal of growing plants in a challenging environment and producing food that can sustain their residence on the Moon. Furthermore, if purified, water can be also drunk by astronauts and used in everyday life.

As well as its use as a source for human sustainability, after the extraction, it is possible to decompose the water through the electrolyte. The oxygen and hydrogen produced can be stored in the liquid phase and used as oxidizer (Liquid oxygen (LOX)) and fuel (Liquid hydrogen (LH2)) for liquid propulsion (Song, et al., 2021).

As shown in recent research, it is also possible to grow plants in the Moon soil. However, challenges are present, due to multiple factors such as a high acidity (low potential of hydrogen (pH)) of the soil (Wamelink, et al., 2014), limitation in the water-holding capacity (Jiang, et al., 2020) and a poor presence of carbon in the soil (Dalton and Roberto, 2008; Jiang, et al., 2020; Wamelink, et al., 2014).

Based on this result, the team will develop at least one room of the base for the study of the regolith and its ability to grow plants. The room needs to have the capacity to allow astronauts to conduct experiments of the lunar soil even with the addition of substances.

One of the main goals that should be achieved is the self-sustainability of the long-term base. To reach this point, the production of food using in-situ resources has to be developed. A relevant candidate for the development of the solution to this problem is the study of aquatic organisms, and the fabrication of recirculating aquaculture systems and integrated multi-trophic aquaculture, which recycles fish waste to convert it into food (Przybyla, 2021).

The team decided to require at least one room of the base for the development of this topic.

2.6.1.2 Future Consideration

Looking at future activities that could be done on the lunar surface, an important role is played by the extraction of the Helium 3, which is available on the Moon soil in high percentage compared to the Earth. This isotope is the main element needed for nuclear fusion and can be a clean source of energy that could be used on the Earth. The use of nuclear energy can give the opportunity to replace the dirty sources of energy used nowadays. Furthermore, the ratio between energy and mass is extremely high, and it can be computed that with less than the equivalent of two Space Shuttle payloads, we could power the United States for one year (Lovegren, 2014).

Another activity that could have a future impact on humanity is the construction of a telescope on the lunar surface. Without any atmosphere, the noise and delay that we usually have on the Earth will be deleted, this will give a better work environment and a different point of view of the universe. In particular, the position of the telescope on the lunar surface is desirable compared to the orbit, since we can build a bigger one and obtain more data from outside.

3. Human Performance Considerations and Solutions

Along with the already mentioned technical and engineering solutions for establishing a lunar base, considerations regarding the presence of humans are essential. Ensuring the physical and mental health of the astronauts represents a critical and primary goal. Since astronauts will also be the core of construction activities and scientific tasks on the lunar surface, their performance should be monitored and optimized. Therefore, solutions for a safe and productive permanence of astronauts on the Moon will be discussed in this chapter, paying specific attention to their physical and psychological well-being, their workload, and the required medical operations.

3.1. Human Factors

Humans are unpredictable, from their physiological needs to their psychological factors. Additionally, the lunar environment presents many challenges that humans would not otherwise experience on Earth. Physiological issues such as lunar dust, radiation, and hypogravity heighten the risks to the crew members. In addition, physical and cognitive workloads will vary in a daily life routine. An assessment of the effects of these workloads is considered with the aim of providing the best possible working environment for our astronauts.

When sending a crew to the Moon for the purpose of building a lunar base, challenges revolving around the human system are anticipated. Therefore, preparation and countermeasures are set in place to keep the Rosas Mission crew healthy while ensuring mission success.

3.1.1. Physiological Issues in Lunar Environments

Creating a first settlement on the Moon has been an aspiration for the humanity since the time of the Apollo era. However, the lunar environment can be very dangerous from a physiological point of view. An assessment of the risks related to dust, radiation and and hypogravity have been made.

3.1.1.1 Dust

Dust on the Moon is one of the biggest constraints when talking about landing and living on the lunar surface (NASA, 2007). Some of the challenges include adhesion of dust to spacesuits, reduced visibility on landing, and inhalation of dust particles. Proper mitigation strategies to manage lunar dust is critical in preserving the health of astronauts. Lunar regolith can range in size, including dust particles smaller than 10 µm, which poses a risk to inhalation, dust adhesion and abrasion, surface electric fields, and dust transport (NASA, 2007).

Optimizing human performance for astronauts depends on a safe and clean environment, free from lunar dust. Airlocks, improved seals, and cleaning procedures will be set in place to ensure a desirable environment. Due to the extremely small size of regolith, the particles can easily reach the lungs, which can cause breathing problems (Lam, et al., 2013). During long duration missions, astronauts could trigger chronic respiratory issues. Experiments have been conducted by NASA for exploration missions, such as removal of particles using electrostatic and dielectrophoretic forces to avoid deposits and accumulations (Calle, et al., 2008).

Solutions

The desire to return to the Moon for longer missions for the purpose of research and exploration did not stop after the Apollo Program (Bilder, 2009; Schmitt, 2006). As previously discussed, the lunar surface materials have an electrical charge due to deposition of cosmic and solar rays, causing toxicity problems to humans. The toxicology studies that have been performed using regolith samples from the Apollo 14 mission, which was collected near the Shackleton Crater, proved that regolith can cause pulmonary infections. Therefore, a dust management system will be designed and implemented on Rosas Base and other habitable bases.

In addition to a dust management system, exposure duration to lunar dust will be managed. Exposure time to lunar dust during the Apollo era was insignificant. For this reason, a study performed at the NASA Johnson Space Center sought to determine an exposure rate to regolith using mice (Lam, et al., 2013). Based on this study, it was learned that astronauts should not exceed LEVA longer than six hours per day and a mission duration of 180 days (0.4 mg/m^3 for 6 months and 0.06 mg/m^3 for a 24-hour period).

3.1.1.2 Radiation

Space radiation is one of the major concerns and risks for the health of astronauts, especially for missions beyond Earth's protective magnetic field and on planetary surfaces without atmosphere. Highly energetic particles in the form of GCRs (from 100MeV/u and up to several Gev/u), Solar Particle Events (SPEs) (typically from 10 MeV to 30 MeV, but can reach several GeV/u), and secondary particles created from their interaction with lunar regolith (backscattered neutrons) are the main radiation sources. Future missions should also be planned considering the space weather and the period of solar maximum. In fact, planning a human long-term space mission during a Sun's maximum period would provide a higher protection from the constant ionizing hazard of GCRs. Recent data from the Chinese robotic lunar lander Chang'E 4 showed that GCR radiation dose equivalent levels on the lunar surface are 2.6 times higher than onboard the ISS (1369 µSv/day vs 523 µSv/day, respectively) (Zhang, et al., 2020). This corresponds to around 500 mSv/year, that is beyond current NASA exposure limit for annual missions on ISS (to make a comparison: annual exposure on Earth is around 2.5 mSv) (Naito, et al., 2020). However, these data have been collected during a solar minimum period, meaning that can be considered as an upper estimation (Zhang, et al., 2020).

Radiation exposures can determine short-term and long-term health issues. Acute Radiation Syndrome (ARS) can arise after an extremely high and sudden exposure to a severe SPE event. This can manifest in the first hours after the event and up to 60 days later because of ionizing radiation, compromising the crew's neurovascular systems, hematopoietic cells, skin, epithelium, intestine, endocrine system, and ability to complete the mission, with mild or moderate symptoms (Hu, Barzilla, and Semones, 2020). Regarding radiation-related acute exposures, the current NASA short-term (30 days) Permissible Exposure Limit (PEL) for acute radiation effects is 250 mGy-Eq to the Blood Forming Organ (BFO) (Hu, Barzilla, and Semones, 2020).

Regarding the long-term effects, a chronic exposure to radiations can cause DNA damage. If this damage is not repaired correctly, cell death, cellular senescence, and tumorigenesis may occur, along with genome instability and carcinogenesis (Furukawa, et al., 2020). Figure 16 shows the main cancer hallmarks related to space radiation exposure (Patel, et al., 2020). Currently, NASA classifies the long-term risk of radiation carcinogenesis as "medium," meaning that it requires characterization before actually performing such a mission (NASA, 2021).

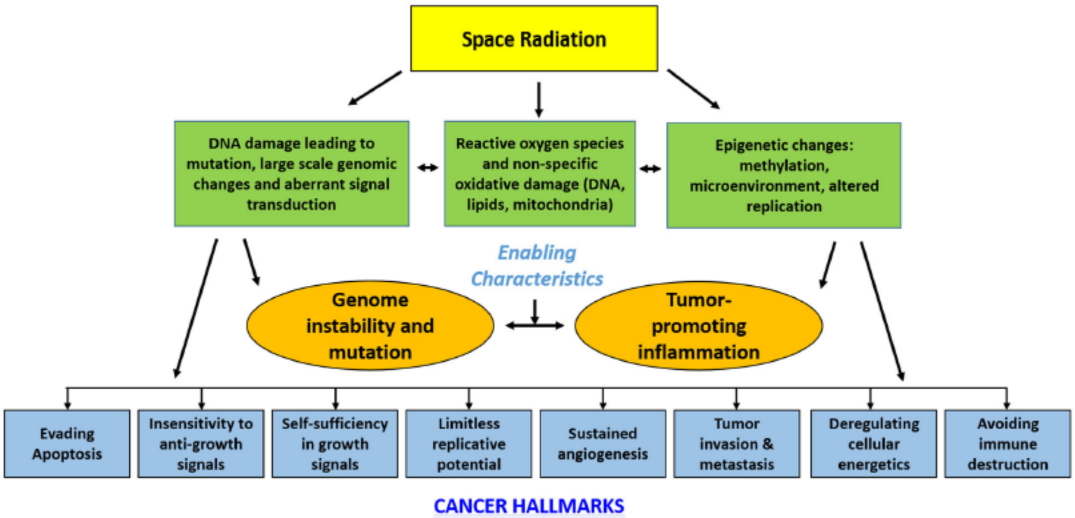

Figure 16: Characteristics of radiation-related long-term damages. Figure reproduced from Patel, et al. (2020).

Solution

Besides the research and development of more effective shielding equipment, the current most important mitigation strategy and risk-lowering solution is the constant monitoring of the radiation exposure of astronauts. Space agencies, such as NASA and European Space Agency (ESA) have set maximal exposure radiation limits for astronauts during a 1-year mission in LEO and for lifetime exposure. These values vary according to variables such as age and gender. For example, current career exposure limits for NASA astronauts are 2.5 Sv for males 35 years old, and 1.75 Sv for same-aged female. These limits are meant maintain a lifetime excess risk of cancer mortality below 3%.

Radiation exposure should be carefully considered especially during the construction activities requiring LEVA. The duration of EVAs should be kept as short as possible.

An emergency plan if an SPE event happens while astronauts are performing a LEVA must be designed. In fact, an SPE event, which is sudden and unpredictable, can deliver an effective dose equivalent of around 2190 mSv/event (Naito, et al., 2020). Currently, the astronauts on ISS are trained to go to the more shielded area of the station (the sleeping area) and to use materials to add shield capability between them and outer space (Hu, Barzilla, and Semones, 2020). Based on the variable rise times and total durations of SPEs, it is recommended that emergency procedures for taking cover from such an event should require 30 minutes at most (Norbury, et al., 2019). This time window should ensure a low probability of the permissible exposure limit being exceeded (Norbury, et al., 2019) .

During lunar construction activities, astronauts could be up to 2.5 km away from the lunar station. Using the rover, astronauts would take about 10 minutes to go back to the station. Then, since the pressure difference between the space suit (0.3 bar) and the lunar base (0.5 bar) is only 0.2 bar, in case of such a sudden and important need it is acceptable to reduce the pressurization time in the airlock up to only a few minutes. This emergency fast pressurization procedure, would provide the astronauts the opportunity to quickly enter the lunar station and find cover beneath its protective shield. For future longer and farther exploration/construction LEVAs, it will be necessary building bunkers in strategic adjacent areas.

3.1.1.3 Hypogravity

Hypogravity is defined as a decreased gravitational field from Earth's. This environment poses considerable physiological challenges to the human body, especially over a long duration mission. This is a primary concern for the future of human space flight because missions to the surface of other planetary bodies will become increasingly longer in duration, lasting for several months and up to years. According to NASA's Human Research Program (HRP) roadmap, these challenges include Spaceflight Associated Neuro-ocular Syndrome (SANS), altered immune response, altered sensorimotor/vestibular function, cognitive or behavioral conditions and disorders, reduced bone density, reduced muscle size and function, and impaired cardiovascular function, all resulting in a risk of compromising health and ability to perform mission tasks (NASA, 2021). Some of these risks have mitigating countermeasures, while others do not yet have approved solutions.

Physical exercise has been proven to be essential and effective for the maintenance of musculoskeletal and cardiovascular functions like strength, power, and endurance during missions of six months onboard the ISS. However, this is still not sufficient to completely counteract the effects of reduced gravity. (Fomina, et al., 2017; Loehr, et al., 2015; Loerch and Reeves, 2015; Petersen, et al., 2016)

Solutions

Devices such as the Advanced Resistive Exercise Device (ARED), the T2 treadmill, and a cycle ergometer will be used as forms of exercise at Rosas Base. Current training schedule on the ISS includes about 1.5 net hours of exercise daily. Crew members will alternate loads between 60 – 85% of Oxygen Consumption (V02) max, and 60 – 85% of the 1 Repetition Maximum (RM) for the resistance (Loehr, et al., 2015; Petersen, et al., 2016). Figure 17 summarizes the current approach of ESA using information from Petersen, et al. (2016). The prevention of work-related injuries and pain due to overuse of muscles, like lower back pain and forearm soreness, will be carefully addressed and prioritized (Scheuring, et al., 2007). Exercise schedules of astronauts on the Moon will be studied and adapted with specific consideration to their exploration and construction activity workload.

	Resistive protocols	Treadmill protocols	Cycler ergometer protocols
Type	Interval (6,8,15 reps, 3–5 sets, daily rotation)	Continuous Interval Slope Individual	Continuous Interval Slope Hill
Load	Variation of load and repetition (6–15 reps, 3–5 sets)	Low/60 %, medium/75 %, high/85 %[a] (alternating daily)	Low/60 %, medium/75 %, high/85 %[a] (alternating daily)
Progression	3–5 %/wk (upper and lower limbs) *Phase 1*: initially [a]lower/50–60 % loads, CM increases load at discretion *Phase 2*: systematic increase based on Phase 1 final load *Phase 3*: maintain high loading or increase (3–5 %)	Between 0 and 5 speed (km/h) or interval duration (min) increase events over mission *Phase 1*: Initially lower loads, CM increases load at discretion *Phase 2*: Individual increase (SLS load [kg], intervals [min]/number, speed [km/h], protocol type based on crew feedback *Phase 3*: continued increase in load (if possible)	Initial workload (W) decrease up to −30 %, increase to 100 % toward end of mission *Phase 1*: Initially lower loads, CM increases load at discretion *Phase 2*: Individual increase of workload (W), intervals (min)/number, protocol "shape" based on crew feedback *Phase 3*: continued increase (if possible)
Duration (average)	60 min	30 min	30 min

CM crewmember; *CMS* countermeasures; *IRED* interim resistive exercise device (LDM 1 + 2); *ARED* advanced resistive exercise device (LDM 3–8); *TVIS* treadmill with vibration isolation and stabilisation system (LDM 1–3); *T2* 2nd generation treadmill (LDM 3–8); *CEVIS* cycle ergometer with vibration isolation and stabilisation system (LDM 1–8); *VELO* Russian cycle ergometer; *SLS* subject loading system

[a] Intensity/ % relative to individual's maximal capacity

Figure 17: ESA's exercise protocol description taken from Petersen, et al. (2016)

The novel aspect of the cycle ergometer is allowing astronauts to cycle with arms and legs at the same time with a time-efficiency aim (Hill, et al., 2019; Nagle, Richie, and Giese, 1984). This is important because the lunar crew is required to perform construction and exploration activities that rely on upper body functionality, for example carrying loads or efforts with a high power demand(English, et al., 2019). The T2 treadmill will be important to maintain leg power and coordination. The Resistive Overload Combined with Kinetic Yo-Yo (ROCKY) rowing machine will also be installed (NASA, 2016; Petersen, et al., 2016). According to NASA, this device is designed for aerobic activity and for strength training, with loads of up to 180 kg for the purpose of performing exercises such as squats, deadlifts, and heel raises, as well as upper body exercises like bicep curls and upright rows. This will provide astronauts the right preparation for their construction activities, preventing working inability and injuries.

Recent research and findings have also shown that High-Intensity Interval Training (HIIT) can be beneficial to the cardiovascular health, as well as to neuromuscular functionality and power, more so than the canonic low intensity cardio training, suggesting that it should be prioritized (English, et al., 2019; Hurst, et al., 2019; T. W. Jones, Petersen, and Howatson, 2019; Steele, et al., 2019). In addition to the higher effectiveness, HIIT also minimizes the time needed for training, better fitting the busy schedule of astronauts.

Along with the exercise and construction activities, regular and periodic physiological tests will be carried out to collect data to monitor and protect the health of astronauts and plan future mission lengths. Collecting information on unknown physiological responses is vital to establishing an optimally safe duration of human presence on a lunar base.

The Moon's hypogravity environment also offers new opportunities. Astronauts will have the ability to stand in the base, which allows for high intensity movements like jumps, plyometric exercises, and resistance strength exercises. These movements will be performed in a dedicated fitness area with all exercise equipment in one location. Plyometric exercises are a useful tool to stimulate bone strength, neuromuscular function, and cardiovascular activity. They have been shown to counteract hypogravity-related decrements with a positive relationship to hopping height (Weber, et al., 2019).

Besides the physiological benefits, it should be considered that a fun, variable, engaging, and entertaining physical activity will improve several psychological and psychosocial aspects (Lakicevic, et al., 2020; McKay and Standage, 2017). Athletic activities on Earth are designed to entertain and engage participants, therefore, the same principle will be adopted for extraterrestrial environments. Coincidentally, new communication technologies and advancements in sport video games mimic specific sport tasks, and are known as exergames. Physically active video games have been proven to improve some cognitive and physiological functions (Park, et al., 2020; Stanmore, et al., 2017; Yu, et al., 2020). Within the designated area for fitness (see Figure 18), these social sporting activities will be implemented after final configuration of Rosas Base.

Some examples of exergames and their respective required action is provided in Table 6. Lunar base astronauts will play and perform these activities with other colleagues in the base, or in communication with family or friends on Earth. These activities will be performed on a weekly basis and incorporated into the scheduled training program. Additionally, astronauts can use this as part of their time for leisure and relaxation.

Table 6: Exergames examples and related physical stimulus

Exergame	**Required physical performance**
Bowling	Squats and lunges
Basketball free throws	Jumping
Archery	Arm strength
Dancing	Dynamic coordination, cardiovascular

These solutions based on exercise and limited exposure to hypogravity are designed to preserve the health of astronauts, and maintain the required level of cardiovascular and neuromusculoskeletal performance to complete their scheduled exploration and construction activities, thus lowering the risk of illness and task-related injuries, and maintaining psychological well-being.

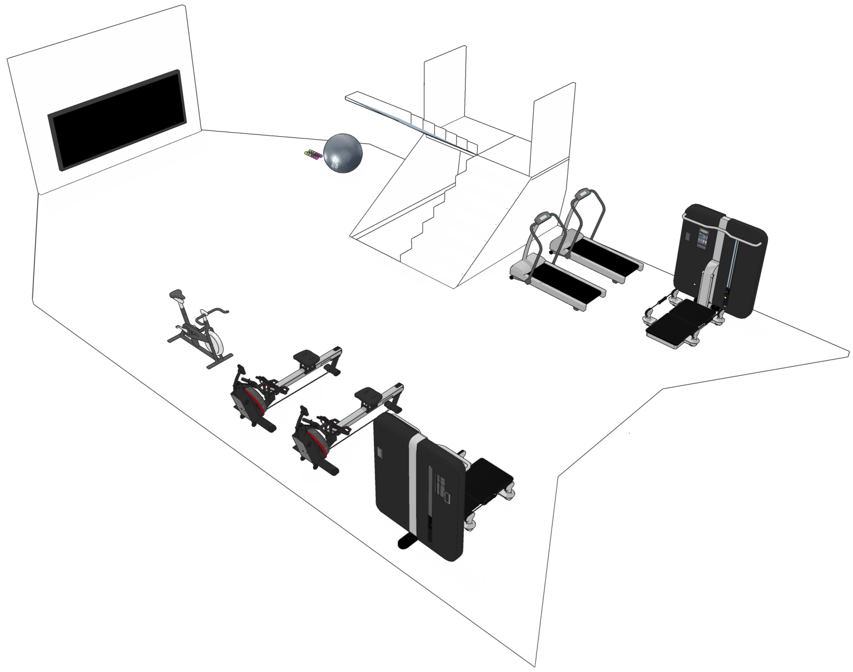

Figure 18: Layout design of the exercise area, consisting of 2 ARED, 2 treadmills (T2), 2 ROCKY, 1 cyclo ergometer, and the area for exergames and group sessions.

3.1.2. Psychological Health and Psychosocial Dynamics in lunar environments

Maintaining optimal psychological status and psychosocial well-being during Rosas Mission is imperative for the health and safety of the astronauts and for the positive outcome of the mission. Psychological well-being refers to an individual's mental, emotional, and behavioral state, while psychosocial dynamics refer to the crew dynamics among the group. Factors affecting humans in isolated, confined, and extreme environments include physical conditions, habitability and life support, crew characteristics, and mission attributes, examples of these factors and the relationship among them can be seen in Figure 19.

Unsurprisingly, individual psychological issues have been demonstrated to have the potential to impact psychosocial relationships and social dynamics (Oluwafemi, et al., 2021; Tafforin, et al., 2015). For example, in the "Mars-500" analog mission, higher anxiety was positively correlated with negative interpersonal interactions (Tafforin, et al., 2015). Individual emotions influence the morale of other members and thus, the group atmosphere. In a hostile and isolated environment, each is professionally dependent on the others. (Wagstaff and Weston, 2014). This implies that the group agreement must be good in order for the work to be done properly.

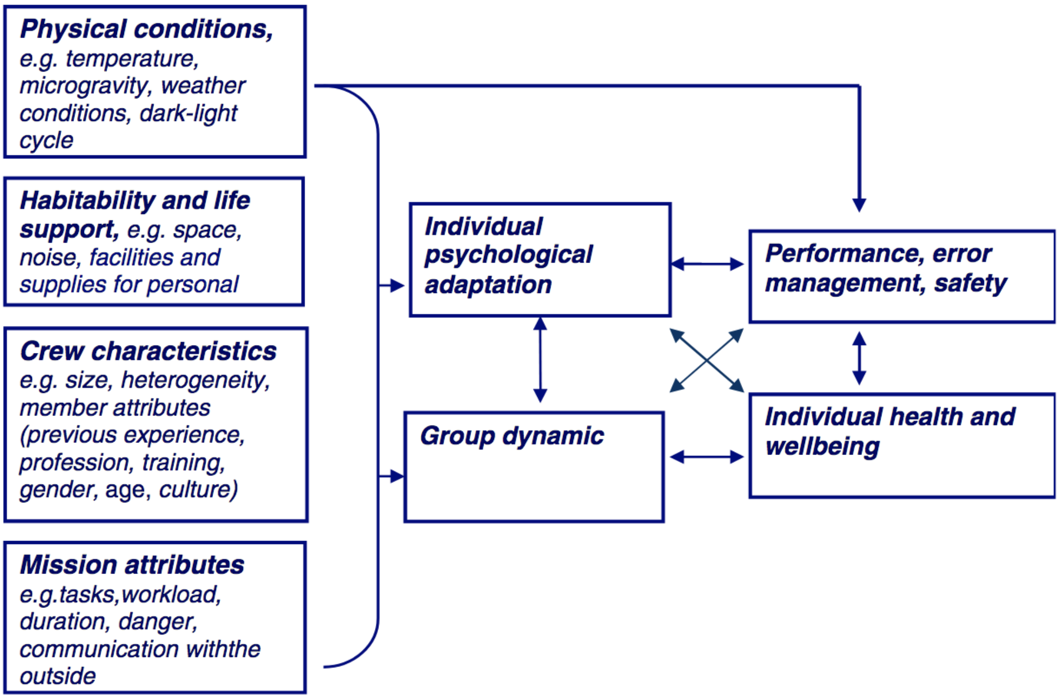

Figure 19: Factors affecting human adaptation in isolated and confined extreme environments. Reproduced from (Sandal, Leon, and Palinkas, 2006).

There are many psychological and psychosocial challenges facing astronauts during a mission, including isolation, confinement, environmental stressors, monotony, lack of privacy, multicultural differences among crew members, insufficient or excessive workloads, nutrition, fatigue, homesickness, and great distance from Earth and family (Kanas, et al., 2009; Marazziti, et al., 2021; Oluwafemi, et al., 2021). While isolation has been experienced and described during past missions on Low Earth Orbit (LEO), the lunar environment poses new difficulties that need to be fully addressed and mitigated, like the greater distance from Earth.

Each of these factors, individually or in combination can lead to an augmented risk of individual (including behavioral conditions and psychiatric disorders) and team behavioral health decrements, like inadequate cooperation, coordination, communication, tension, loosening of the team cohesion, subgrouping, scapegoating and psychosocial adaptation, compromising the safety and the performance of the mission (Marazziti, et al., 2021; NASA, 2021). Currently, NASA classifies these risks as “medium,” stating that they require mitigation solutions and can be accepted only with monitoring (NASA, 2021).

The 520-day long Mars analog mission showed a high inter-individual likelihood to experience psychological issues (Basner, et al., 2014). For instance, crew members with higher Profile of Moods State (POMS) short form disturbances were more likely to report depression symptoms, and crew members with higher stress and physical exhaustion profiles accounted for the majority (85%) of perceived conflicts with mission control. At the same time, two crew members reported no behavioral or psychological disturbances at all, but that doesn’t provide absolute certainty of perceived difficulties.

Research has also shown that space environmental condition (low gravity and radiation) can affect cognitive functions of the astronauts, like spatial memory, psychomotor abilities, and complex learning, which are important cognitive functions for space operation (Kanas, et al., 2009; Oluwafemi, et al., 2021).

Solutions

For the homesickness and isolation challenges worsened by a greater distance from Earth, adjustable schedules and private communications with family will be helpful (Oluwafemi, et al., 2021). The same authors also proposed that the access to entertaining moments and surprises may be helpful to manage possible stress, monotony, and work-related issues. As discussed in the previous section, the implementation of an area where astronauts can exercise and practice more various and entertaining activities together and even in connection with their families on Earth, directly supports these psychological and psychosocial needs (Lakicevic, et al., 2020; McKay and Standage, 2017).

For the group atmosphere, the goal is to provide the crew with adequate preparation before going to the lunar surface on dealing with their own emotions, promoting positive adapting solutions (putting into perspective, positive refocusing and reappraisal) instead of maladaptive ones (expressive suppression, catastrophizing, rumination) (Wagstaff and Weston, 2014). Accordingly, crew members should train together (even in survival and extreme conditions) and with the ground control team during the pre-launch period, to improve cohesion and communication skills (Kanas, et al., 2009). Indeed, the choice of the crew is crucial due to distinct personality traits that need to be accounted for, making living together challenging in the long term (Paul, et al., 2010).

The creation of a varied interior design replicating Earth's huge variety of different stimuli has been suggested to be useful for the promotion of positive moods (Botella, et al., 2016; Oluwafemi, et al., 2021). For example, pictures, screens, and virtual-reality technologies can be used to display relaxing or joyful images and sounds of Earth's nature, like forests, deserts, oceans, and cities (Botella, et al., 2016). Also, the management of lights for circadian rhythms, and noise for stress should be carefully addressed (Marazziti, et al., 2021; Oluwafemi, et al., 2021).

It has been proposed that astronauts should also have time to run a personal scientific experiment or project, a "pet-project," with the aim of boosting personal purposefulness (Oluwafemi, et al., 2021).

3.2. Crew Activities

Mission success of the construction of the lunar base will depend on system designs and development of operations concepts that maximize human performance and efficiency while minimizing health and safety risks for crewmembers (NASA, 2019). As such, human factors of construction activities have been analyzed and evaluated to help the crew manage workload, create schedules, and assess risks to ensure optimal mental and physical performance. This section seeks to determine necessary human factors and workload considerations for construction tasks.

The Apollo Recommendation Summary report (Scheuring, et al., 2007) identified that human factors and crew scheduling were two major areas necessitating further consideration. Mitigation strategies to be implemented during the construction to the lunar base will be built around a mission focused approach rather than a timeline to reduce temporal demand. Adequate time for activities will be built within the framework of the schedule, including contingency time for construction activities.

Upon arrival to the lunar surface, the crew will wait 48 hours before performing mission tasks. The wait period allows for acclimation to the lunar surface environment and time for the astronauts to get proper rest after their transit from Earth. The first two weeks will be reserved for remote handling of the MOROCASs to prepare the ground for horizontal configuration of the SS Rosas. This will involve human-machine interaction, where the risks are quite low. As such, it will be two weeks before any LEVAs are conducted. However, this does pose a risk to cognitive performance, as it is recommended that all critical tasks be complete within the first week of arrival to avoid the operation of complex tasks under cognitive and physical degradations (NASA, 2019). Nonetheless, an additional week will not inhibit the crew from performing at an optimal level for the horizontal configuring of the base.

3.2.1. Crew Schedule and Workload

Construction activities will require the astronauts to perform tasks in a new environment while wearing a 180 kgf spacesuit. This brings new risks and new human factors that normal construction activities on Earth would not otherwise present. Therefore, physical and cognitive workload challenges and solutions are provided. These workloads are considered when human performance is critical to a mission objective. Complex LEVA activities, such as the ones being proposed, will increase the workload and stress levels of the astronauts (Rai, Kaur, and Foing, 2012). It is important to understand these limitations and how they are measured to identify and implement countermeasures.

NASA utilizes two different tools to estimate, measure, and evaluate workload. The Bedford Workload Scale (BWS) is used to measure crew workload after tasks are complete, an example of a BWS can be seen in Figure 20. It is determined that nominal task workload on the BWS to be a 3 or less, while off-nominal tasks should be a BWS of 6 or less (NASA, 2019). Anything between 6-10 should be avoided.

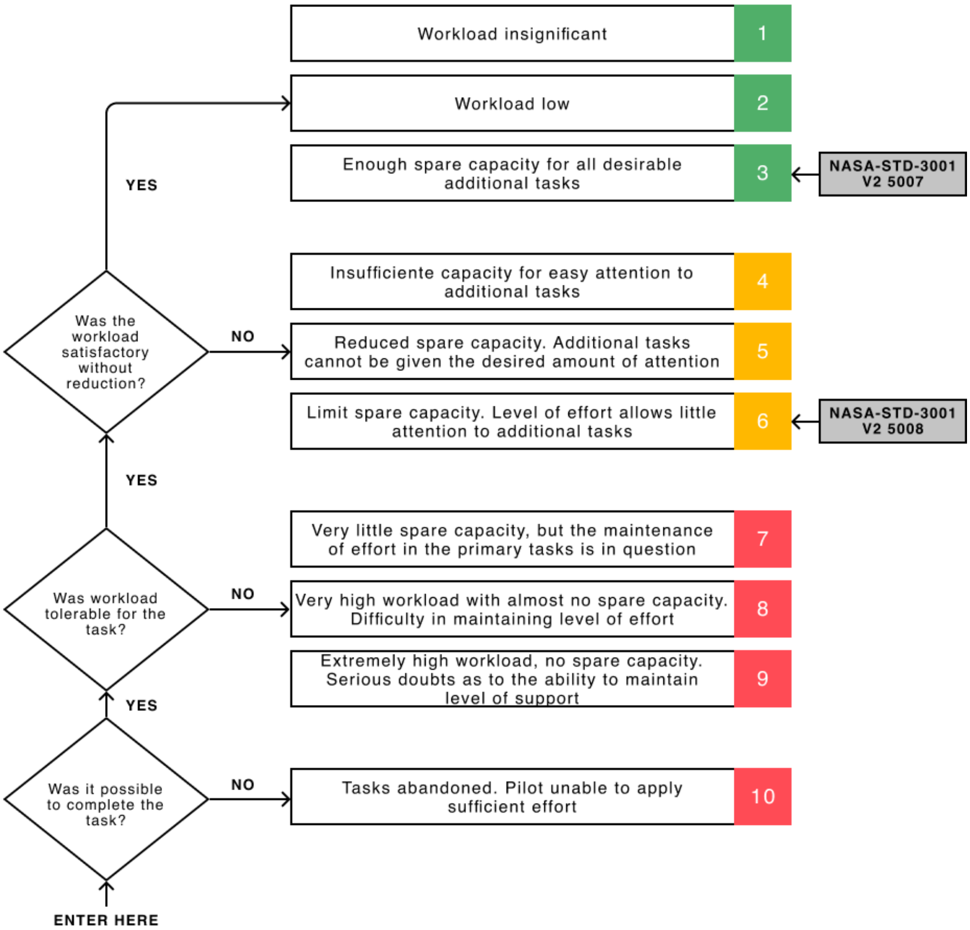

Figure 20: The Bedford Workload Scale from (Roscoe, 1984) as cited by NASA's NASA Human Performance Research group (2020).

Another measurement tool used by NASA is the Task Load Index (TLX), which is a subjective workload assessment tool (NASA Human Performance Research group, 2020). The purpose of this tool is to estimate and measure overall workload based on mental demand, physical demand, temporal demand, performance, effort, and frustration (see Table 7 for descriptions). This tool is a reactive measurement to understand workload that has been complete. Therefore, an estimation of workload factors has been made to produce the anticipated workload for each construction activity.

Using the NASA TLX calculator, an analysis of each task was concluded (seen in Table 8). It was found that conversion of the CH_4 and O_2 tanks posed the greatest workload, primarily in effort and physical demands. These tasks include operation of heavy machinery, lifting heavy objects, and crew resource management. The construction activity with the lowest amount of workload was embarkation of Rosas Base, where the astronauts move from one environment to another and undergo depressurization.

Table 7: Predictive workload factors and their description from the NASA NASA Human Performance Research group (2020) TLX

Workload Factors	Description
Mental Demand	Thinking, deciding, calculating, remembering, looking, searching
Physical Demand	Pushing, pulling, turning, controlling, activating
Temporal Demand	Time critical, leisurely/frantic
Performance	Performance success and satisfaction
Effort	Physical and mental effort to accomplish level of performance
Frustration	Insecure, discouraged, irritated, stressed, annoyed

Table 8: Task Load Index analysis of construction activities using the NASA NASA Human Performance Research group (2020) TLX application

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	Weighted Rating
Traveling from SS 501 to SS Rosas landing site	50	35	30	5	35	45	**25.00**
Operation and Supervision of Horizontal Maneuver	80	45	65	5	50	10	**38.67**
Rosas Base Embarkation	25	40	35	5	10	45	**22.33**
Conversion CH_4 Tank	65	90	75	5	95	30	**57.67**
Conversion of O_2 Tank	65	90	75	5	95	30	**57.67**

3.2.2. Physical Workload

The TLX identifies physical workload as a major factor during some of the construction activities. Other contributing factors to physical workload on the lunar surface includes gravity and spacesuit factors such as suit weight, suit pressure, and suit mobility (Belobrajdic, Melone, and Diaz-artiles, 2021). While some mitigating factors include the use of exercise as previously mentioned, other contributing factors to improving physical performance are improved spacesuit parameters during LEVAs.

3.2.2.1 Spacesuit Parameters as a Solution for Physical Workload

After understanding the scope of human factors within construction activities, spacesuit design must be considered. Spacesuit design directly affects crew performance during configuration of the horizontal base and other lunar activities. Current Extravehicular Mobility Units (EMUs) used for space walks outside the ISS for EVAs were designed 45 years ago without consideration for exploration of other celestial bodies (NASA Office of Inspector General, 2021). As such, Exploration Extravehicular Mobility Unitss (xEMUs) are necessary to support human movement during complex tasks at higher levels of gravity and extreme temperature swings (Belobrajdic, Melone, and Diaz-artiles, 2021; NASA Office of Inspector General, 2021).

As identified by Belobrajdic, Melone, and Diaz-artiles (2021), attention in spacesuit design should include prevention of buildup of carbon dioxide in the bloodstream (hypercapnia); thermal regulation and humidity control; nutrition, hydration, and waste management; health and fitness requirements; decompression sickness; radiation shielding; dust mitigation strategies; and health monitoring and injury prevention. Furthermore, concept of operations, including astronaut fatigue, psychological well-being, and operational challenges will drive the decision process of spacesuit design factors for the lunar base crew.

The greatest differentiating factor to spacesuit design when comparing to current spacesuits is mitigating metabolic costs and reducing energy exertion during LEVAs. When operational concepts require astronauts to walk longer distances, the effects of suit weight will increase. Astronauts constructing Rosas Base will be expected to walk up to 5 km, with an additional 5 km for off-nominal tasks and emergencies. Gernhardt, et al. (2009) states that weight of the suit will become an inhibiting factor after 10 km of walking. As such, the weight of the suit will be critical in reducing metabolic costs. According to an experiment performed by Gernhardt, et al. (2009) the effects of suit weight on metabolic rate and the subjective Gravity Compensation and Performance Scale (GCPS), it was found that the heavier suit weight was associated with better performance, up to 320 kg. Therefore, based on the construction activities on the lunar surface, the appropriate suit weight for LEVAs should range between 180 and 320 kg with the optimal weight being 320 kg.

Additional factors to consider for metabolic costs that are not as critical but worth noting include suit pressure, inertial mass, biomechanics, and stability. Biomedical monitoring and consumables management, such as improved nutrition mechanisms and waste disposals, inclusion of two drinking bladders (one for water and one for a non-caffeinated, high-energy drink), improved waste management system, and improved biomedical sensors will be included. Other spacesuit parameters identified by Scheuring, et al. (2007) include functionality and human factors, as shown in Table 9.

Table 9: Spacesuit parameters for optimized human performance on the lunar surface

Dexterity	Gloves to include power assist to reduce wear and tear and injuries to hand during repetitive tasks.
Mobility	Increased mobility to the overall spacesuit by reducing pressurization to improve hip and knee flexion.
Visibility	Anti-fogging technologies will be installed in the helmet to avoid fogging during heavy exertion.
Range of Motion	A neck ring is added to improve range of motion and peripheral visibility
Donning/Doffing	Backpack entry/exit with self-closing capabilities
Traction	Traction selection for lunar boot functioning. Specific traction factors are selected using the HUD based on geological conditions and activity.
Hydration	Two drinking bladders (one for water, another for caffeine-free high-energy drink)
Nutrition	Inclusion of a high-carb protein supplement to be consumed through a straw during LEVAs
Heads-up-display (HUD)	HUD to display biomedical data on demand.
Mass	Weight of suit is 180 kgf to optimize metabolic costs

3.2.3. Cognitive Workload

Cognitive capabilities are considered among individuals and within a team. These capabilities include attention, memory, decision making, problem solving, logical reasoning, and spatial cognition (NASA Human Performance Research group, 2020). Cognitive workload is defined by the NASA Human Performance Research group (2020) as the amount of mental exertion placed on a human during system interactions. Risks to cognitive workload and performance include microgravity, radiation, stress, low attentional arousal, and excessive task demands. Mental overload occurs when the demands of the task are so great that they are beyond the attentional capacity of the operator Figure 21. As such, an appropriate balance of workload should be distributed to engage crewmembers in the task while allowing spare mental capacity to handle circumstantial issues.

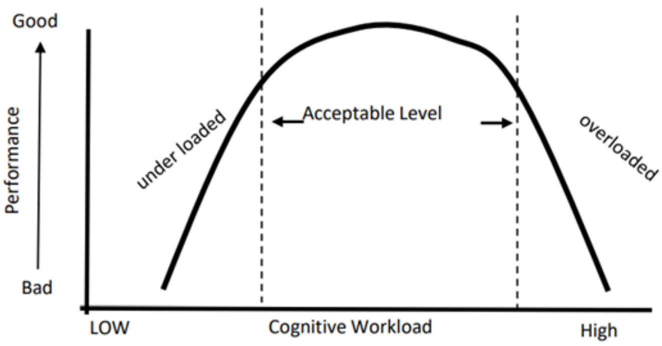

Figure 21: Cognitive workload and its effect on human performance taken from NASA Office of the Chief Health and Medical Officer (NASA Human Performance Research group, 2020)

Research has shown that the space environment, including low gravity and radiation, can affect cognitive functions of the astronauts, such as spatial memory, psychomotor abilities, and complex learning, which are important cognitive functions for space operation (Oluwafemi, et al., 2021) (Kanas, et al., 2009). Additionally, cognitive workload is threatened during some of the most safety-critical tasks, when crews are multi-tasking, processing numerous inputs, and making decisions concerning multiple problems. Astronauts during previous lunar missions performed simple tasks, yet those astronauts performing LEVAs still reported serious mental fatigue (Scheuring, et al., 2007). As such, two solutions are proposed to mitigate cognitive workload: adequate sharing of tasks among crew members, and highly functional human-system interfaces to support crew tasks (NASA, 2019).

3.2.4. Crew Scheduling as Solutions for Cognitive Workload

Managing crew workload is an integral factor to minimizing risks and optimizing individual and group performance. This can be done with the application of crew scheduling to ensure mission-focused success. According to (Scheuring, et al., 2007), a common theme among Apollo astronauts was an "overwhelmingly packed schedule" and should therefore incorporate countermeasures for mental fatigue, allowing adequate time for activities. As such, the LEVA will be conducted by the crew on a rotational basis. Each crew member will perform no more than two consecutive LEVAs followed by at least one day reserved for Intra Vehicular Activities (IVAs), as recommended by Scheuring, et al. (2007). IVAs will vary and include crew support, maintenance, and lunar base chores. Each crew member will have one day per seven days reserved for rest and leisure activities.

The crew schedule will incorporate generic activities, exercise, construction activities, public affairs office events, unexpected maintenance, human factors analysis, system activities, and crew conferences, which can be seen in Table 10. A sample crew schedule has been generated for Groundbreaking Day to provide visualization of expected duty time, see Appendix A.4. Factors considered when developing the crew schedule were time to complete the tasks; consequence and time to recover from errors; the nature, type (e.g., independent versus team tasks) and environmental conditions of the tasks, and state of the human and the team (NASA Human Performance Research group, 2020). This allowed for appropriate crew quantity selection to support the tasks and labor hours required.

Throughout the duration of Rosas Mission, crew members will be given simultaneous sleep periods of eight hours that will be protected in the daily schedule. While some crew members may have trouble sleeping, it is important to optimize sleep productivity to ensure proper rest and increase human performance for future tasks. As such, the use of sleeping medication will be encouraged and provided to improve sleep quality when necessary. Additional solutions to ensuring quality sleep are obtained by each crew member, and exercise will be a beneficial component to the schedule, as it can be used as a form of rest and relaxation for some individuals (Scheuring, et al., 2007).

Table 10: Human factors considerations to reduce insufficient and excessive cognitive workload on the lunar surface as summarized from NASA (2019)

Recreation	Scheduled recreational activities throughout the course of the mission
Rest	Mental and physical rest promoted through rest and leisure time and is incorporated regularly in the schedule to allow for adequate rest between LEVAs.
Sleep	Adequate sleeping quarters are designed to reduce outside noise and allow for privacy
Stress	Adequate time for all activities in the schedule is given
Crew resource management	Authority structure is defined

3.2.5. Workplace Culture

The lunar base construction process is an international and intercultural effort. Team interactions are heavily dependent on culture, and play a significant role in the performance and psychological health of the crew. A review on cultural factors at the ISS (Boyd, 2005) concluded that cultural differences between Russian cosmonauts and American astronauts could have negative impacts on the mental health of a space station crew. This could be because of increased effort required to build and maintain relationships, increased misunderstandings, or cultural isolation. It is expected that these factors will increase on the lunar surface, being that it enhances isolation properties. This will be addressed by promoting the emergence of a unified team culture, which would help bridge intercultural differences.

Values are acts or virtues that allow us to interact or coexist with other individuals, which govern the behavior of individuals and their aspirations. Astronauts have common values and experiences as they go through the same selection process and are part of the community of space travelers. Astronauts are motivated, adaptable, and can function effectively with others in a group. ESA astronaut Thomas Pesquet stated in a 2016 interview with Le Figaro, “Space agencies do not need superheros, warriors, or big egos, but rather people who know how to work as a team, be patient, get along with others, and communicate. You have to be able to know when to lead and when to follow.” leadership when you have to, but you also have to follow when you have to follow” (Tristan Vey, 2016).

In the same way that a ribbon is cut, or the first ground is broken during ceremonies related to construction on Earth, a construction project on the Moon also needs its own rituals and symbols to create not only a crew but a team. For example, badges are used as space mission insignia and have long been part of the culture surrounding space exploration. These badges are worn by crew members participating in a given mission. As such, the SS 501 crew will design their own mission patch to foster team spirit.

Spiritual or religious practices can be an important ritual for crew members. An illustrative example can be found in airports, where there are prayer spaces dedicated to several religions. This space is also a place of meditation and ideal to combined spirituality and tranquility. Space and time for such rituals on the moon will be created to help the crew deal with their emotions, stay connected with Earth, and optimize crew dynamics.

Art is another cultural factor that can make the lunar workplace more suitable for humans. In fact, the Moon itself has inspired a multitude of artistic impressions, including that of astronauts (e.g. Bean, 2021). Rather than the art on Earth being influenced by the Moon, The Moon

Gallery (Sitnikova, Glukhova, and Foing, 2020) is an example on Earthly art being placed on the moon. Involving artists in, e.g., the interior design of the base could improve the habitability of the base while at the same time generating more attention to the construction project. With the construction of Rosas Base, the lives and deeds of its crews will help define the future of space art and lunar culture.

3.3. Medicine and Risk Management

The overall health of the astronauts, especially in emergency situations, is a fundamental component of the mission's success. It is essential to predict possible medical emergencies and develop systems that can successfully address these critical issues. Activity on the Moon brings new challenges, as the only basis available is related to the Apollo missions of the last century, which consisted of no more than three days. Normal activities of the astronauts on the ISS are in microgravity and result in a schedule devoted primarily to maintenance and scientific research, with only rare events requiring an EVA. In the case of the construction of a lunar base, the activities will have additional physical challenges and will require movement of heavy loads. This identifies a set of circumstances in which the risk of incurring accidental injuries increase, leading to a greater importance of accident prevention access to appropriate emergency equipment. Additionally, astronauts will be fully briefed on loss-of-life procedures in the event of a fatal injury of a crew member on the lunar surface.

3.3.1. Potential Emergency Pathologies on the Lunar Surface

Astronauts during the construction activities will need to complete different tasks in a high-risk environment. Overall risks that could jeopardize the crew during the horizontal maneuvers will include structural damage to the vehicle during the horizontalizing process, excessive amounts of methane left over in the tanks, and pressure equilibrium is not as desired. Due to these risks, the crew will feel a heightened sense of temporal demand. Some tasks during the horizontalizing process will be more critical than others and pose more risks. Specifically, the conversion of CH_4 and O_2 tank will require a high level of physical demand and focus. Drilling the pressurization hole will require the operation of heavy machinery. Installing the hatch will be labor-intensive and place a lot of physical demand on the crew due to loads of different weights. This increases the risk of encountering accidents that can develop trauma of different calibre. Thus, incapacitation is a concern and could compromise the mission. This increases the risk of encountering accidents that can develop trauma of different calibre that is of highest concern due to its incapacitating and mission-compromising potential.

Common causes of trauma on Earth include airway obstruction, hemopneumothorax (accumulation of air and blood between the lungs and pleura), bone fractures, head injuries, and bleeding. Relevant to exploration of the Moon and lunar construction activities is the potential for crush-type and penetrating injuries, both of which may compromise protective-suit integrity. This could cause catastrophic decompression into the space vacuum. Moreover in hypogravity, the bodily fluid shifts increase the intracranial pressure. Consequently, the severity of traumatic or spontaneous intracranial hemorrhage may be increased.

As for medical emergencies not related to trauma, we can identify several pathologies that if not treated lead quickly to the exitus of the patient. Among the most likely on the Moon are appendicitis, cholecystitis and the formation of kidney stones or biliary stones. These potentially life-threatening conditions highlight the need for on-board diagnostic and treatment solutions. Diagnose systems are set in place to identify less severe conditions that mimic symptoms of other serious pathologies. For instance, one Cosmonaut in 1982 reported symptoms of appendicitis and was evacuated, while after his return on Earth he was diagnosed with prostatitis (Campbell, et al., 2004).

3.3.2. Diagnosis in Emergency Conditions

When there is a medical emergency, it is important to have real-time access to the patient's physiological data and the capability to do imaging analysis targeted to the problem. The physiological data of astronauts (e.g. heart rate, blood pressure, and temperature) can be obtained continuously with wearable devices, that can also be used to check their health status during normal activities. Biological biomarkers can be obtained by analyzing samples of blood, urine, or saliva, directly with compact chip-based diagnostics devices, like the ones developed by miDiagnostics®. For imaging, multiple devices are needed to cover diagnostic needs in the different possible emergency conditions, both for traumas and non-traumatic injuries.

Ultrasound and X-ray imaging are essential systems that provide fast imaging useful for traumatic injuries. Small and portable ultrasound devices have been developed, they are easy to use and provide accurate information of the cardiovascular system and the soft tissues. A device for X-ray images would be useful not only for detecting bone and joint damage or dental problems, as well as damage to other organs, for example, lung issues caused by regolith. For head injuries a new portable device has been developed that uses near-infrared waves to detect intracranial hemorrhage by scanning different locations of the head (InfraScan®).

More accurate imaging, like Magnetic Resonance Imaging (MRI) and Computerized Tomography (CT) scans, is useful to diagnose non-traumatic injuries to evaluate the need for surgical intervention. On Earth, these devices need a complex system, which are usually big and heavy, and they may need a strong magnetic field that may be dangerous in an enclosed environment. New systems are being developed that despite being smaller, guarantee good resolution images. In addition to this, it may be useful to perform an Electroencephalogram (EEG) to detect potential brain damage, which requires light electrodes that can also be used in other systems to perform Electrocardiogram (ECG) and vestibular analysis (e.g., vestibular evoked myogenic potential). Other diagnosis systems are required to provide periodic controls, such as Optical Coherence Tomography (OCT) devices for Otoacoustic Emission (OAE) Machines for hearing.

3.3.3. Emergency Treatments

The work necessary for the construction of the lunar base involves intense manual physical activity, with transport of heavy material in a hypogravity environment, instead of the microgravity environment found in LEO. For this reason, it is necessary to improve the emergency medical kit and identify which devices are needed on the spacesuit, inside the base and in the medical room, to perform the correct Advanced Trauma Life Support (ATLS) procedures.

During working activities in a non-pressurized environment, the greatest risk relates to the possible perforation of the spacesuit, as might happen during drilling activities. In this case it is necessary to intervene within a few seconds, as it takes only 10-15 seconds of depressurization to lose consciousness or otherwise cause serious and irreversible damage. In this case, the astronauts must have at hand easily accessible and quickly usable instruments. Essential is the presence of adhesive tape able to adhere despite the presence of any regolith on the surface, but effective only for small perforations.

For larger lacerations, for example to the limbs, it would be useful to develop a system consisting of a soft extensible tube with a closing system similar to a tourniquet, in which you can insert the limb where there is loss of pressure to block the depressurization, to safely reach the lunar base. These devices should be folded into a small container that fits on the spacesuit and can be quickly accessed within a few seconds with a controlled ejection system.

In the event of trauma during an EVA, it is essential to have a telescopic stretcher or splints in the rover, so that the astronaut can be safely transported in a protected environment. It is also important to have oxygen tanks, to ensure a usable reserve even if an astronaut has a shortage after stabilizing a hole in the spacesuit.

A medical room will be set up to ensure that a patient can be treated properly. This room will be equipped with all the furniture needed to give medical assistance, including one light hospital bed, transfusion device, airway support, a complete set of medications and bandages, and more. To perform imaging the various diagnostic systems described above are present. Additionally, to ensure the operability during unforeseen circumstances, such as electric shortages, the systems are backed up by an independent battery. Moreover, surgical equipment is needed to perform important emergency surgeries. Lastly, there will be a dedicated communication system for medical emergencies.

3.3.4. Emergency Surgery

Any surgical emergencies during a lunar mission can seriously compromise the outcome of a mission, and could result in requiring an emergency return trip to Earth. In that case, the patient needs to stay in stabilized conditions for at least three days during transit and has to endure strong gravitational forces upon re-entry to the Earth. Therefore, further treatments for more severe conditions such as multi-trauma, kidney stones, appendicitis, and cholecystitis would need to be provided at a designated medical center on the lunar surface.

Performance of surgical procedures during spaceflight was demonstrated to be feasible using an animal model. Anesthesia, complex dissections, hemostasis, wound closure, restraint of surgical instruments, and wound healing were all successfully performed without difficulty (Campbell, et al., 2004). In the case of a surgical emergency on the Moon, we must aim to perform maneuvers that allow a quick recovery of physical conditions to reduce the risk of compromising the outcome of the mission. For this reason it is preferable to use non-invasive techniques. A 3D printer in the lunar base that allows printing both surgical instruments and personalized casts will be provided. This guarantees both a tailor-made construction of the necessary medical equipment and a significant savings in terms of the volume occupied in the base.

For closed head injuries with intracranial hemorrhages, blunt or penetrating trauma, gastrointestinal hemorrhages, kidney stones, cholecystitis, or appendicitis a surgical system as the Da Vinci Xi from Intuitive®can be used. This system allows performing Minimally Invasive Surgery (MIS) across a wide spectrum of surgical procedures and consists of a surgeon's console and a patient-side cart with four interactive robotic arms controlled from the console, where the surgeon can operate and see the surgery area in real-time. This console allows other physicians from Earth to give advice and provide operational direction. Currently, it is not possible to conduct operations from Earth due to the long communication delay of up to three seconds due to the lack of tactile feedback. For cardiovascular problems, such as blood clots, it is necessary to have an endovascular surgical system that allows the placement of stents and guarantee minimally invasive procedures.

The high risks associated with building a lunar base combined with the difficulties of reaching Earth in an emergency, increases the importance of having efficient medical and surgical capabilities. Therefore, crew well-being is reliant upon the capabilities of treating health issues on the Moon that would otherwise necessitate a return to Earth, resulting in abortion of the mission. For this reason, it is necessary for a radical change in the design of mission roles. Currently on board the ISS, the Crew Medical Officer is not required to be a physician and is typically a specialist in a non-medical discipline with 60 hours of medical training (Kirkpatrick et. al., 2009). However, this mission with the purpose of constructing a lunar base, will require two surgeons to have completed a long formation course prior to launch to learn how to treat the different medical emergencies that might occur. Additionally, advanced emergency medicine courses will be mandatory for all other crew members.

4. Legal and Policy Aspects

For the construction of Rosas Base some legal and policy aspects have to be addressed. Three key legal issues deserve particular attention: (i) How to construct a lunar base in accordance with international space law; (ii) How to develop a multilateral framework to promote and govern international cooperation in this process; (iii) How international law should be further developed to better accommodate the needs of lunar base construction activities.

4.1. Compliance with International Space Law

Human activities in outer space are not operated in a legal vacuum but regulated by international space law. At the core of this legal framework are the five space treaties adopted under the auspices of the United National Committee Peaceful Uses of Outer Space (UNCOPUOS). These include the Outer Space Treaty (OST), the Rescue Agreement (ARRA), the Liability Convection (LIAB), the Registration Convection (REG), and the Moon Agreement (MA). These treaties provide "an embryonic yet almost all-encompassing legal regime for space activities" (Von der Dunk, 2018). The OST provides the fundamental principles for the exploration and use of outer space and would therefore be the focus of the following discussion.

The MA specifically regulates human activities on the Moon and other celestial bodies within the solar system. It provides that "the Moon and its natural resources are the common heritage of humankind," and therefore an international regime should be established "to govern the exploitation of the natural resources of the Moon, as such exploitation is about to become feasible" (cf. Article 11 UN General Assembly, 1979).

The practical effect of the MA is rather limited as it has only attracted 18 ratifications and 4 signatures as of January 2021 (UNOOSA, 2021b). None of the major space-faring nations: China, Russia, or the United States have ratified the MA. In particular, the effectiveness of the MA has been denied by a U.S. Executive Order, which states that: "the United States is not a party to the Moon Agreement. Furthermore, the United States does not consider the MA to be an effective or necessary instrument to guide nation-states, regarding the promotion of commercial participation in the long-term exploration, scientific discovery, and use of the Moon [...]" (U.S. Executive Order 13914, 2020). Meanwhile, the MA is still binding to its state parties, which include some countries active in the space field such as Austria and the Netherlands.

4.1.1. Freedom to Use and Explore Outer Space

Article I of the UN General Assembly (1967), provides that "outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States." The term "exploration" means "to find out whether any use is possible" and the term "use" can be read in a broad and general manner to include "exploitation of outer space and of celestial bodies" for both economic and non-economic ends (Hobe, 2009). It can be argued that the construction of Rosas Base and the use of space resources constitute an exercise of such freedoms. However, the rights granted are subject to certain limitations.

One inherent limitation within Article I is that the exploration and use of outer space "shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind." While this provision is "not clearly defined and can be subject to varying interpretations," it expresses a general idea that "the use of space should somehow benefit mankind" (Masson-Zwaan, 2017). The construction of the lunar base certainly has the potential to benefit all humankind in many aspects. This process can enrich our scientific knowledge of the universe, and serve as a stepping stone for deep space crewed missions towards Mars and beyond. In addition, the exploration and exploitation of resources may help solve different problems on Earth, such as energy deficiency, agricultural challenged areas and medical research.

The freedom of exploration and use should also be read against Article II of the OST, which lays down the principle that outer space, including the Moon and other celestial bodies, is not subject to national appropriation by any means. In conjunction with Article I of the OST, this principle "has generally been perceived to establish outer space as a 'global common', an area not subject to any individual state's legal authority and jurisdiction yet free for all states to access," provided remain compliant with international law (Von der Dunk, 2018).

The Rosas Base construction activities do not contravene with Article II of the OST. This is ensured by the fact that no claims of sovereignty or proprietary rights will be made over any land on the Moon or lunar resources in place. As will be discussed in sections 4.1.1.1 and 4.1.1.2, the construction process will only use the land commensurate to the mission requirements and utilize extracted resources.

4.1.1.1 Land Use and Safety Zone

Article I (2) of the OST provides that "there shall be free access to all areas of celestial bodies." A literal interpretation of this provision appears to outlaw the construction of the lunar base since this would somehow restrict the free access of other states to the Moon. However, the contextual reading of the OST tells a different story. Article XII of the OST stipulates that all stations on the Moon shall be open to representatives of other states on a basis of reciprocity. It implies that the construction of a lunar base is legitimate, otherwise this obligation would lose its pre-requisite (Salmeri, 2020). In addition, Article VIII addresses the ownership of "objects landed or constructed on a celestial body," which affirms the right to build infrastructures on the Moon. Moreover, Article IV(2) of the OST prescribes that the Moon and other celestial bodies shall be used exclusively for peaceful purposes and prohibits the establishment of military lunar bases. Therefore, Rosas Base should only be used for peaceful purposes such as scientific research.

A potentially more controversial issue is the establishment of safety zones in the vicinity of the lunar base. The Artemis Accord describes "safety zone" as an "area wherein [...] notification and coordination will be implemented to avoid harmful interference." It also sets out several principles for the safety zone which include the criteria for determining its size and scope and the notification requirements (cf. Section 11(7) Artemis Accords, 2020). The Building Blocks for the Development of an International Framework on Space Resource Activities adopted by The Hague International Space Resources Governance Working Group (HWG) also indicates that the establishment of a safety zone around an area identified for space resource activity is "necessary to assure safety and to avoid any harmful interference with" such activity. It also suggests that a state may restrict access to a certain area for a limited period of time, provided that timely public notification and justification are given (The Hague WG, 2019).

For the Rosas Base construction project, the intention is to declare a safety zone to demarcate the areas where construction and related activities are taking place for the purpose of minimizing potentially harmful interference. Access of other states to these areas will not be hindered, but prior consultation and coordination are needed to ensure the safety of our activities as well as those of the potential visitors.

4.1.1.2 In-Situ Resource Utilization

In-Situ Resource Utilization (ISRU) is understood as a practice to “generate product with local materials,” including to “use the Moon’s resources to produce water, fuel, and other supplies as well as [. . .] to excavate and construct structures on the Moon” (NASA ISRU, 2020). In the absence of any definitive and generally acknowledged regime at the international level, the the U.S. Commercial Space Launch Competitiveness Act, which recognizes the property rights of U.S. citizens over any space resource obtained was passed in 2005 (NASA ISRU, 2020).

The International Institute of Space Law (IISL) issued a position paper in 2015 which states that “there is no international agreement, whether the rights to take and consume non-renewable natural resources, including minerals and water on celestial bodies.” It further states that “in view of the absence of a clear prohibition of taking of resources in the Outer Space Treaty one can conclude that the use of space resources is permitted,” and accordingly “the new United States Act is a possible interpretation of the Outer Space Treaty” (IISL, 2015).

The U.S. approach has been followed by Luxembourg, the United Arab Emirates (UAE) and recently Japan, who have also adopted national laws that allow operators under their jurisdiction to carry out space mining activities in a manner consistent with international law. As a justification, Luxembourg made an analogy to fishing on the high seas: “Space resources are appropriable, in the same way as fish and shellfish are, but celestial bodies and asteroids are not, just like the high sea is not” (Government of Luxembourg, 2016). Following this line of reasoning, while outer space itself cannot be appropriated, individual states would be entitled to license space mining companies to “go fishing” in outer space (Von der Dunk, 2018).

Accordingly, it should be noted that in order to ensure the legal certainty of the ISRU activities related to the construction of Rosas Base, (e.g., use of local regolith and water) they should be conducted within the jurisdiction of, and be licensed by, those states that explicitly recognize the rights of ISRU.

4.1.2. State Responsibility

Article VI of the OST provides that states shall bear international responsibility for national activities in outer space, whether such activities are carried out by governmental or non-governmental entities, and for ensuring that such activities are carried out in conformity with international law. This means that international law is relevant and needs to be complied with, whether Rosas Base construction is conducted by private entities, public authorities, or as a public-private partnership.

According to Article VI of the OST, the activities of non-governmental entities in outer space, including the Moon, shall require authorization and continuing supervision by the appropriate state. This constitutes the legal basis for states to enact national space legislation to authorize and continually supervise private space activities. International obligations imposed on states are generally transposed to private entities through national law, in particular the licensing process. Therefore, it is important for the private operators involved in Rosas Base construction to be licensed by the appropriate state. For instance, in the U.S. the Federal Aviation Administration (FAA) oversees, licenses, and regulates commercial launch and reentry activities within the U.S. jurisdiction (FAA, 2021). The FAA exercises this responsibility consistent with public health and safety, safety of property, as well as the national security and foreign policy interests of the U.S. (FAA, 2021). Meanwhile, the Federal Communication Commission (FCC) administers non-Federal use including commercial use, and therefore private space entities approach the FCC for radio spectrum allocation (FCC, 2021).

At the international level, FCC, in collaboration with the National Telecommunications and Information Administration (NTIA), register U.S. satellite networks with the International Telecommunication Union (ITU) (NTIA, 2021). The ITU coordinates among the administrators of different states to ensure harmonious spectrum use (NTIA, 2021).

4.1.3. International Liability

For the construction of Rosas Base, modules and other space objects would need to be launched from the Earth and landed on the Moon. Damage can be caused to other states during the transportation in cislunar space, the lunar landing phase, and the operation on the lunar surface. Therefore, it is important for the operators to be acquainted with the potential risks for legal liability.

Article VII of the OST, together with the elaboration by the LIAB, establish the liability regime for space activities. According to this regime, the launching state is liable for damage caused by its space objects. Damage means personal injury including loss of life and impairment of health as well as damage to property (cf. Article I(a) UN General Assembly, 1972).

The term “launching state” refers to a state which launches or procures the launching of a space object and a state from whose territory or facility a space object is launched. This broad definition means that there could be several launching states against which the victim can claim compensation for the damage incurred. These states are jointly and severally liable for the damage caused, and they may conclude agreements regarding the apportioning among themselves of the compensation to be paid. Notwithstanding such agreement, a state sustaining damage has the right to seek the entire compensation from any or all of the launching states (cf. Article I(c) and Article V UN General Assembly, 1972).

A launching state shall be absolutely liable for damage caused by its space object on the surface of the Earth or to aircraft in flight. Regarding damage caused in outer space, a launching state shall be liable only if the damage is due to its fault or the fault of the persons for whom it is responsible. While compensation obligation is imposed upon states under the LIAB, states could seek recourse from private operators through the enactment of national legislation by prescribing insurance requirements and indemnification procedures (UN General Assembly, 2013).

To minimize the risks of potential liability, it is critical for the operations in outer space, including on the Moon, to be compliant with international law. It is recommended to carry out consultation and coordination before and during the process of constructing Rosas Base. It is also be recommended for operators to take out insurance, especially for third party liability.

4.1.4. Protection of Astronauts

Article V of the OST qualifies the legal status of astronauts as “envoys of mankind.” While this concept is not further defined in international space law, it entails a humanitarian element in terms of the effective protection of people involved in the exploration of outer space on behalf of all humankind (Dunk and Goh, 2009).

Article V further provides three specific obligations on the protection of astronauts. First, states shall render all possible assistance to astronauts “in the event of accident, distress, or emergency landing” on their territory or on the high seas. Second, astronauts of different states shall mutually render all possible assistance. Third, states shall immediately inform other states and the United Nations Secretary-General (UNSG) of any phenomena they discover in space which could constitute a danger to the life or health of astronauts. More specific provisions regarding the protection and rescue of astronauts are prescribed in the ARRA.

As the planned Rosas Base will be constructed ultimately for human habitation, the safety and health of astronauts therein are of paramount concern. Since more than one lunar base can be expected to be built, all possible assistance will be rendered for astronauts in other lunar bases. This includes the prompt provision of information regarding any threatening phenomena. In addition, the base will also call on other states to fulfill the same obligations in good faith to ensure the well-being of all envoys of humankind.

4.1.5. Due Regard, Environmental Protection, and Consultation

Article IX of the OST imposes three essential limitations on the freedoms in outer space, namely that in the course of space activities states shall: (i) be guided by the principle of co-operation and mutual assistance and pay due regard to the corresponding interests of others; (ii) avoid harmful contamination of outer space and adverse changes in Earth's environment resulting from the introduction of extraterrestrial matter, and to adopt appropriate measures to this end if necessary; and (iii) undertake appropriate international consultations in the case of anticipated potentially harmful interference.

All these requirements point to the direction that space operators should respect the rights and interests of others in the exploration and use of outer space. For instance, appropriate international consultation should be undertaken in case of possible overlap of safety zones or conflict involving the freedom of access to celestial bodies (The Hague WG, 2019).

Regarding the protection of both terrestrial and space environment, the Committee on Space Research (COSPAR) Panel on Planetary Protection maintains and promulgates Planetary Protection Policy as an internationally agreed-upon standard to guide compliance with Article IX of the OST (Fisk, 2017). This policy establishes five categories of requirements for planetary protection according to a combination of target body and mission type (cf. COSPAR PPP, 2021). Missions to the Moon were originally assigned to Category I where "no planetary protection requirements are imposed." Following the discoveries indicating ice deposits in the Permanently Shadowed Regions (PSRs), in 2008 COSPAR has re-categorized the Moon to Category II which is for bodies where "there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried out by a spacecraft could compromise future investigations" (COSPAR PR, 2021).

In 2021 COSPAR has updated its Planetary Protection Policy for missions to the Moon. These missions would remain under Category II, while two sub-categories have been added for lunar surface missions. In particular, sub-category IIb concerns all Moon surface missions whose nominal mission profile accesses PSRs and the lunar poles, in particular latitudes south of 79°S and north of 86°N (COSPAR PR, 2021), which covers the location where the Rosas Base construction is intended to be carried out.

All missions falling under sub-category IIb shall provide planetary protection documentation and an organic inventory. The documentation includes a short planetary protection plan, brief Pre- and Post-launch analyses, and a Post-encounter and End-of-Mission Report (cf. COSPAR PPP, 2021)). The inventory is a list of materials on the spacecraft, and under sub-category IIb the required inventory "includes organic products that may be released into the lunar environment by the propulsion system as well as life support systems, if present; and organic materials carried by the spacecraft that are present in a total mass greater than 1 kg" (COSPAR PR, 2021).

4.1.6. Nuclear Power Sources

Due to their compactness, high power output and other attributes, nuclear power sources are particularly suited to space missions which require more power than can be generated by solar panels or by other means, especially interplanetary missions such as crewed missions to the Moon (UNOOSA, 2021a).

In 1992 the United Nations (UN) General Assembly adopted the Nuclear Power Sources (NPS) Principles as a set of guidelines to ensure the safe use with NPS in outer space (UNOOSA, 2021a). The NPS principles are "devoted to the generation of electric power on board space objects for nonpropulsive purposes" (cf. *Principles Relevant to the Use of Nuclear Power Sources In Outer Space* 1992), which therefore applies to our case.

The fundamental requirement is that "the use of nuclear power sources in outer space shall be restricted to those space missions which cannot be operated by non-nuclear energy sources in a reasonable way." To this end, the NPS has set forth general goals and criteria for the avoidance of radiation exposure and radioactive contamination of outer space. Moreover, prior to the launch of space objects of NPS onboard, a thorough and comprehensive safety assessment shall be conducted, covering "all relevant phases of the mission" and "all systems involved." The results of such safety assessments shall be made publicly available and shall be informed to the UN Secretary General prior to each launch. As regards nuclear reactors, they may be operated on interplanetary missions, but shall not be made critical before they have reached their interplanetary trajectory (cf. Principle 3&4 of *Principles Relevant to the Use of Nuclear Power Sources In Outer Space* (1992)).

In addition, in 2009 UNCOPUOS adopted the Safety Framework for Nuclear Power Source Applications in Outer Space. The Safety Framework recognizes that space NPS are the only viable energy option to power some space missions according to current knowledge and capabilities. It also states that "safety should always be an inherent part of the design and application of space NPS" to avoid the potential hazards that could be caused by the presence of radioactive and nuclear materials in space NPS (cf. Safety Framework Preface). However, the focus of the Safety Framework is "the protection of people and the environment in Earth's biosphere from potential hazards associated with" space NPS applications. The protection of humans in space, as well as the protection of environments of other celestial bodies are beyond the scope of the Safety Framework (cf. Safety Framework Scope). As the energy generator for Rosas Base is located on the Moon, its radiation risks to the people and the environment on Earth are low. Therefore, the Safety Framework is not of direct relevance to Rosas Mission.

Finally, to ensure radiation safety, the International Commission on Radiological Protection (ICRP) sets forth the ALARA principle, which stands for keeping radiation exposure "as low as reasonably achievable." This principle consists of three basic protective measures: time, distance, and shielding. Each of them concerns a certain aspect regarding the exposure of individuals to radioactive source (CDC, 2015). The ALARA principle is relevant to Rosas Mission and will be implemented throughout the mission including during construction and operation phases.

4.2. Multilateral Cooperation Framework

The promotion of international cooperation is in the spirit of international space law. The OST preamble states that broad international cooperation in the exploration and use of outer space for peaceful purposes "will contribute to the development of mutual understanding and to the strengthening of friendly relations among States and people." This concept has been reiterated and reinforced throughout the UN space treaties.

A prominent example of international cooperation in the space domain is the ISS. The ISS legal framework is built on three levels of international cooperation agreements: on the top level is the ISS Intergovermental Agreement (IGA) signed in 1998 by the fifteen governments involved; the middle level is the Memoranda of Understanding (MoUs) between NASA and each co-operating Space Agency including ESA, Canadian Space Agency (CSA), Roscosmos and Japan Aerospace Exploration Agency (JAXA); and at the lowest level are various bilateral implementing arrangements between the space agencies (ESA IGA, 1998).

The IGA "established the overall cooperative framework for the design, development, operation and utilization of the ISS and addressed several legal topics." Its successful implementation for more than two decades "set a great precedent for future large international space collaborations, such as lunar and planetary exploration missions" (NASA IGA, 2018). Therefore, it can be expected that the IGA would be and should be modeled after for future international cooperation in space endeavors, including the construction of Rosas Base.

4.2.1. State of Registry

Article VIII of the OST provides that a state "on whose registry an object launched into outer space is carried shall retain jurisdiction and control over such object, and over any personnel thereof." This means that the state of registry is entitled to exercise sovereignty, including the application of its laws, over its registered space objects and personnel thereof (Schmidt-Tedd and Mick, 2009).

The obligation and requirements for registration are provided in the REG. More specifically, the launching state shall register the space object in its national registry. When there are two or more launching States, they shall jointly determine which one of them shall register the space object. The State of registry shall also furnish to the UNSG the required information concerning its registered object, which shall be recorded in a Register maintained by the UNSG.

According to Article 5 of the IGA, each partner shall register as space objects the flight elements it provides in accordance with the REG, and "shall retain jurisdiction and control over the elements it registers [...] and over personnel in or on the Space Station who are its nationals." Each partner shall also own the elements they respectively provide (cf. Article 6(1) IGA). In this sense, "the ISS is more a combination of nationally owned space elements than an 'international' space station per se" (ESA Patent, 2021).

This approach will be followed for the construction of Rosas Base, that each partner state shall register the elements and modules it provides. Accordingly, each partner state shall exercise authority and control over its registered object and its nationals. The rationale is to ensure the exercise of international responsibility for national activities in outer space by the appropriate state, as outer space, including the Moon, is not subject to national appropriation and does not fall under any national sovereignty.

4.2.2. Cross-Waiver of Liability

Other than in the circumstances provided in Article 16 of the IGA the fundamental liability rules set forth in the LIAB apply to ISS activities for any damage caused by the Partner States. It further provides that if a claim arises from the LIAB, the partners "shall consult promptly on any potential liability, on any apportionment of such liability, and on the defense of such claim". (cf. Article 17 IGA).

Under the assumption that risks are inherent in the participation in ISS related activities, and in the interest of encouraging such participation, Article 16 of the IGA establishes a cross-waiver of liability between the partners and their related entities for damages arising from activities relating to the building and use of the ISS (St.Arnaud, et al., 2013). More specifically, the IGA prohibits any partner or its related entities from claiming against another partner or its related entities for damage arising from ISS activities.

There are some exceptions to this cross-waiver of liability. It is not applicable to a claim between a partner and its own related entities. Neither does it apply to damage caused by willful misconduct, claims made by a person for bodily injury or death, and intellectual property claims (cf. Article 16(3)(d) IGA).

It can be expected that the construction of Rosas Base would confront many technical challenges and complexities, and risks of damage are inherent in the process. To ensure and promote the long-term cooperation of the parties involved, it is argued that the legal arrangements for international cooperation should be modeled following this cross-waiver of liability approach.

4.2.3. Intellectual Property Rights

According to the 1996 Space Benefits Declaration, "contractual terms in [...] cooperative ventures should be fair and reasonable and they should be in full compliance with the legitimate rights and interests of the parties concerned as, for example, with intellectual property rights." Therefore, Intellectual Property (IP) rights arrangements should be included in cooperation agreements to protect the legitimate rights and interests of the parties involved.

The IGA provides an example of how IP issues are to be dealt with in the course of international cooperation in outer space. The main objective is to avoid the infringement of IP rights owned by another partner or its related entities(ESA IGA, 1998). These issues can be divided into two categories, namely the use of patented technologies and goods made on Earth or onboard the ISS, as well as the protection of knowledge and creation derived from activities and experiments carried out in the ISS.

As regards the former category, the ISS partners "have the obligation to mark their technical data or goods with a notice that indicates any specific conditions regarding how those data or goods may be used" by others (ESA IGA, 1998). Regarding the latter category, Article 21(2) of the IGA provides that, in relation to IP law, "an activity occurring in or on a Space Station flight element shall be deemed to have occurred only in the territory of the Partner State of that element's registry." For instance, U.S. IP law will be applicable to an invention realized in a U.S.-registered ISS element "as the invention is deemed to have occurred on US territory" (ESA Patent, 2021).

A similar arrangement can be adopted for IP-related issues during the construction of Rosas Base, such as the testing of new materials and constructing technologies on the Moon. However, what is different from the ISS is that scientific experiments may be conducted completely outside any elements provided, namely on the lunar surface. Partner states should enter into prior consultation and agreement on the attribution of IP rights. One potential solution would be to agree that a state shall extend its national law to IPs deriving from activities carried out by its registered objects or its nationals outside any constructed architectures on the Moon.

4.3. Pathway Forward

As part of the Artemis program, NASA aims to develop Artemis Base Camp at the South Pole of the Moon as its first sustainable foothold on the lunar frontier (NASA Plan, 2020). Meanwhile, China and Russia have signed a MoU regarding the construction of the International Lunar Research Station (CNSA, 2021) and has recently unveiled a roadmap for its construction (A. Jones, 2021). Perhaps more lunar settlement plans are underway with the growing interests in lunar resources and cislunar space (Goswami, 2020).

The construction of several lunar bases by different (groups of) states is not a problem, all these efforts should be encouraged as they embody efforts in the exploration and use of outer space without discrimination of any kind. However, the lunar bases constructed at the same time may lead to divergent norms and legal arrangements which may not accommodate one another and could cause tensions and conflicts. Therefore, the interest in constructing a lunar base should encourage states to come to agreement on the governance of activities on the Moon. It is acknowledged that states, especially many space-faring nations, are reluctant to conclude new treaties on space activities, a realistic approach is to establish some internationally agreed upon guidelines and codes of conduct in this regard. These non-binding instruments should include the following elements:

1. Requirements and procedures on the use of land, including the establishment of safety zones in outer space.
2. Regulations on the ISRU. International Agreements at the global level on the legality and procedures of ISRU are desired, and in this regard the Building Blocks issued by HWG may serve as a starting point for international dialogue and discussion. Moreover, different norms may be established for different categories of lunar resources according to their characteristics, scarcity, and difficulty of exploitation.
3. Clarification on the legal status of private space participants. More specifically, whether they should be classified as "envoys of mankind" under the OST and enjoy the same rights of protection as professionally trained astronauts, or whether specific rules should be established for these private participants.
4. Standards on lunar environment protection, including guidelines on the operations of sintering of lunar regolith as well as the avoidance and mitigation of lunar dust and debris.
5. Guidelines on the use of nuclear power sources on the Moon, in particular to protect astronauts and the lunar environment from the potential radiation risks thereof.

5. Community Engagement and Outreach

Constructing a lunar base requires long term vision and support. The goal is to build a sustainable lunar base and avoid the pitfalls for lack of funding. A value proposition will be discussed including sociocultural benefits, scientific advancement, and technology transfer. Finally, one major consideration is the implementation of the engagement and outreach strategy.

5.1. Historical Considerations

Scientific discovery, financial benefits, and national security concerns are often invoked as drivers for space exploration. The main drivers pushing humans to space, as argued by Griffin (2007) in his speech during the Quasar Award Dinner in 2007, are fundamental human characteristics that have been with our species since the dawn of humanity. Things like curiosity, challenge, and inspiration drive not only humans as a collective, but also the individuals choosing to work within space exploration. In his book *The Overview Effect* Frank White wrote “The human space program has existed in the collective unconscious of Humanity since the dawn of awareness” (White, 1987).

The human urge to explore is evident when looking at the history of human migration. From the first humans leaving the African continent to the first ocean exploration and modern space exploration, the rationales remain remarkably similar. The main rationales for one of the early organized exploration initiatives were curiosity, financial returns, control and presence, prestige, and opening up a way for future activities (Sandrone and Wagner, 2009). The same rationales are applied to space exploration. Up until now, however, this kind of exploration has been more about curiosity than any cost-effective business.

The benefits of space exploration are in the sciences and things that this exploration teaches us about humankind, the universe, and our Earth. Space exploration is contributing to the United Nation’s 17 sustainable goals by promoting education, doing ecological research, or studying human health.

Potential lunar construction planners face many of the same challenges as did early Antarctic explorers: remoteness, isolation, and extreme conditions. Some approaches taken by expeditions between the years 1899-1917 included overwintering in frozen-in ships, pre-fabricated wooden huts, and emergency huts of local rock and ice (Lewander, 2002; Pearson, 1992). These techniques can be viewed as analogs of techniques to use on the Moon (lander habitat, prefabricated habitat, and ISRU).

While a lunar base may be built for many distinct reasons, once a permanent human presence on the Moon is established, the buildings themselves become monuments. This could be a monument to the creativity and curiosity of humankind, that drove us to settle our only satellite, and fully inhabit our planet Earth.

> “We like to do what I’ll call monument building. We want to leave something behind for the next generation, or the generations after that, to show them that we were here, to show them what we did with our time here. This is the impulse behind cathedrals and pyramids and many, many other things.” (Griffin, 2007).

The lunar base will rise from the lunar soil as the world has seen rise the Great Wall of China, the Pyramids in Egypt, the Colosseum, or the Taj Mahal. The majority of those who participated in the construction of such monuments never saw them finished. The lunar base will be the construction that encourages the world to dream, and stands for much more than the activities it is designed to contain and support. The work of designers and builders will therefore not be neglected, and communication and recording of the construction process will increase the viability of the base from a general opinion point of view.

5.2. Value Proposition

The core message of the value to be communicated to stakeholders is the value proposition. Our value proposition includes the sociocultural, scientific, and technological benefits that the project will generate.

5.2.1. Sociocultural Benefits

"That's one small step for a man, one giant leap for mankind." More than 50 years later, these words are still resonating in the collective mind. At that time, nobody could have anticipated the cultural impact of Apollo missions. The first landing on the moon gave a new vision of the Earth and its place in the universe. For the astronauts, seeing the Earth so fragile in this vastness of space made them realize how vulnerable this planet is. This was dubbed the Overview effect by (White, 1987).

> "I realized up there that our planet is not infinite. It is fragile. That may not be obvious to a lot of folks, and it is tough that people are fighting each other here on Earth instead of trying to get together and live on this planet. We look pretty vulnerable in the darkness of space." — Alan Shepard (Getlin, 1994)

The role of astronauts is crucial, not only for their testimonies but also as symbols. The Apollo 11 astronauts were considered heroes all over the world. They brought back from space the message to the public that this world is too small to fight over and that the beauty and diversity of our Earth must be preserved. Walking on another celestial body brought inspiration back to Earth. After astronauts had inspired people, the years that followed saw an increase in people seeking personal development and, maximizing their potential, because anything was possible (Chaikin, 2007). Those astronauts have inspired the young. The children who have seen them set foot on the Moon have grown and the 1990s has seen the development of many scientists, and engineers, as well as talented directors and writers inspired by space travel (Chaikin, 2007).

Against a backdrop of segregation, the American space conquest has been perceived as the highlight of racial inequalities (Chaikin, 2007). Cultural diversity is essential, especially when trying to build a new society on another celestial body.

After Apollo 11, people lost interest in the Apollo mission. One of the main problems was the technical understanding of this landing and the rationales of this. The problem of understanding also led to the hoax theory that men never went there. To get people to believe in Rosas Base, we must make them understand it clearly.

Through the rise of social media nowdays, information can spread faster than ever. Unfortunately, lies and falsehoods tend to spread faster than the truth (Vosoughi, Roy, and Aral, 2018), creating a challenge for nations and government bodies to get support from decision makers, politicians and the public. Public outreach activity shapes the culture on Earth and acceptance of lunar exploration across the global population. While there is no doubt that the Apollo era had an influence on our culture, it was difficult to measure it at the time. Today, with modern digital communication campaigns, Key Performance Indicator tracking, and social media engagement measurement, there is an improved understanding of what works.

The International Space Exploration Coordination Group (ISECG) is a forum consisting of 14 space agencies and is addressing the challenges of communicating with the public. In an ISECG study from 2019, the agencies prepared a collaboration for “Broad public engagement in future lunar exploration”. Some of the recent success factors for outreach include collaboration with mission partners, nationality of astronauts determines media interest, bandwidth is a limiting factor, and non-astronaut activities require a more creative approach.

One of the points that requires being addressed on a global level is the finding on the nationality of astronauts and the resulting outreach success. It seems logical, but also worrying at the same time, because it means that our Earth’s culture and support for lunar activities might not develop equally across the globe or at the same speed. While the national stakeholders, regardless of public or private investors, will be exposed to national outreach activities to communicate milestones, successes, or foster education, there is a risk that countries without a strong national space program will not benefit from cultural influences and trends resulting from lunar exploration.

5.3. Scientific Advancements

The lunar base will be an arena of scientific development in the long term. One of the major changes from Earth to the Moon is gravity. Hypogravity on the Moon will allow the observation of the formation of proteins, while the shaping of proteins is different than in Earth’s gravity. Experiments will be carried out on astronauts and their health will be monitored to know the effect of the lunar environment on them. Medical observations and experiments can also be conducted in the base, providing useful results for the benefit of all humankind.

Building the base in the south pole of the Moon allows the extraction and use of water. The intuitive use of water is its direct consumption, so we must confirm the water is safe for astronauts. This water can also be used for agriculture: growing plants in an environment as hostile as the Moon would be a major scientific advance. Aquaculture is another possibility. To have fresh fish for astronauts on the Moon would be something unprecedented. Water can also be split to create oxygen which is a precious resource and multifunctional; it can also be transformed into propellant for launchers. These applications suggest that the lunar base will allow major scientific advances.

All such new findings will require a broad engagement with the scientific community, the education sector, and the public, be that to connect the scientific community to potential research opportunities on the Moon or to communicate scientific results on Earth. Recent successful science outreach activities ranged from dedicated education programs, interactive learning methods, partnering with scientific non-profit organizations up to use of new technology such as Virtual Reality (ISECG, 2019).

5.4. Technology Transfer

Regarding technological and economic benefits, this mission offers promising prospects. Technologies developed during construction of the lunar base will potentially lead to spin-offs benefiting life on Earth, akin to freeze-dried food, cooling suits and dialysis machines which resulted from the Apollo missions (NASA Spinoff, 2009). A multitude of technological advances can be expected over the course of construction of a sustainable lunar outpost, including advances in protection against radiation and dust-pollution, and innovative and efficient power supply solutions using nuclear, solar or hybrid approaches.

As demonstrated with reusable landers, a focus on reuse and sustainability will drive down costs. Finally, the task of constructing the base itself will be a major economic endeavor with incentives for many private companies to enter the space economy and boost the pace of technological development for space missions. An example of this is the NASA Tipping Point solicitations, wherein contracts have been awarded for the development and demonstration of smart propulsion systems, robotics for lunar surface operations, communications, and cost-effective and sustainable power solutions, among others (NASA, 2020). Rosas Base will be built in collaboration with private entities, in return for space on the habitat, which could be utilized for setting up lunar hotels, Earth observation decks, lunar workspaces, or laboratories for 3D printing and ISRU.

Space Agencies today are active in promoting technology transfer. NASA, for example, is offering licensing of existing technologies - NASA Technology Transfer Program - via a dedicated patent catalog. The organization regularly offers webinars and workshops to engage with non-traditional audiences to raise interest in these technologies. Similarly, the European Space Agency EVA has created a dedicated Technology Transfer Program (ESA - Technology Transfer, 2021), including a set of Business Incubation Centers to foster interest, inspiration, and implementation. Recent examples range from using space-based data for new applications, and connectivity solutions to subsystems for satellites. It will be crucial to maintain the communication and outreach activities regarding future developments and opportunities. These could include start-ups using the new technologies, Return on Investment (ROI), and opportunities to become involved as an entrepreneur.

Similarly, since the approach is a Public-Private Partnership (PPP), also private entities involved in the construction of the lunar base will be expected to justify their investments on a regular basis – be that towards their employees, private investors or financing institutes. Typically, commercial organizations provide quarterly reviews that are targeted at financial stakeholders. However, in the case of the construction of a lunar base as a highly visible public and global endeavor, those organizations are expected to become more visible to the public and might have to adapt their engagement and communications strategy towards broader audiences. This in return gives more commercial entities an incentive to consider entering the lunar market and become inspired to create new business models using Rosas Base, or expand beyond. For a continuous lunar economy to work, measurement of Return on investment and relevant key performance indicators, as well as their communication will become the baseline for strategic marketing of Rosas Base and its future economy.

5.5. Implementation

Although the ISECG (2019) study provided several recommendations for engagement with a broad audience, this section will focus only on implementation of such recommendations during the construction phase.

From neurosciences and marketing studies, it is known that emotional or cognitive retention and engagement are significantly better when accompanied with visual content (Manic, 2015). Video content is known to perform better than imagery alone (Al-Seghayer, 2001). It is also known that content delivered in-person by humans is perceived as more trustworthy and has higher emotional retention value than content delivered in other formats not involving a speaker (Darius, Gundabattini, and Solomon, 2021). Finally, the results from ISECG are supported by studies in learning and development, demonstrating that experiences and participation lead to higher retention rates and trust (Hammers Specht, 1985).

The recommendations from ISECG (2019), applied to the construction of the lunar base is broken down into the following requirements for engineering and mission architecture:

- Rosas Base will be equipped with high-resolution cameras for the a third-person perspective
- The development of bandwidth capacity for sending high-resolution imagery or support live-streams during the construction phase will maintain the support of involved stakeholders and the public
- The communications infrastructure will enable near-real-time communication, interaction and participation
- Media on Earth will play a key role in using imagery, video, audio and Virtual Reality experiences to connect audiences with activities on the Moon

When it comes to content, all ISECG involved agencies agree, that a strong commonality and integrated communications will be key. This might pose a challenge within a PPP architecture, due to the involvement of several parties. Therefore, it will be necessary to entrust a single entity in the form of a dedicated internationally active marketing agency with the overall branding, messaging and communication strategy. Especially during the first phase of the mission, namely the construction, this brand and key messaging will be built up, and the network with involved partners will be created.

Of course, key milestones will be communicated and will affect the need for imagery, video content, astronaut involvement, or live streams and engagement. A first set of such milestones has been identified. These include a press release at a major space conference to announce the PPP agreement, launch of the SS Rosas, launch of the SS 501, landing of SS Rosas, landing of SS 501, first LEVA in over 50 years, horizontalizing operations, first entry into Rosas Base, and inauguration of Rosas Base.

ISECG (2019) recommends focusing more on cultural aspects rather than only scientific and engineering aspects. This might drive further engagement with the audience. There are some ideas to start implementing these during the construction phase. Construction of Rosas Base will require a mindset shift in society to accept that humankind is becoming a multiplanetary species. Such debates will be fostered in social media, television, news articles, and educational programs. The construction phase could also inspire arts and music. Just as the Greek composer Vangelis was inspired by the ESA Rosetta mission to create an entire album (ESA Blogs and Emily, 2016), similar engagement with the artistic community should to be promoted, if not even incentivized.

Channels for participation will also reach into the gaming industry, by providing actual imagery and footage to create immersive realistic experiences and stories. For example, using the popular Kerbal Space Program to build the lunar base virtually at the same time as the actual construction is ongoing, could engage and educate the audience about realistic challenges and solutions. Traditional board games similar to Settlers of Catan, or building Rosas Base in Lego, including regular releases of extension sets, are an alternative analog possibility to foster partnerships with popular culture during the early stages of the lunar base.

Commercially involved parties will be encouraged to consider non-traditional channels and formats to create more entrepreneurship and business models for the lunar economy. Rather than presenting quarterly figures in a traditional manner, the leaders of these organizations have the potential to rise to celebrity status and deliver their messages and progress their visions in inspiring keynote addresses. Generally, partnering with non-typical space actors through sponsorships, or through winning them as investors, gives visibility and rise to business opportunities, just as recently shown by Porsche SE investing into rocket technology at Isar Aerospace (Porsche SE, 2021). Such partnerships will require a strong partner management and public affairs approach to win over more organizations of this type.

Finally, ISECG pointed out the use of social media, in particular the increased use of influencers (ISECG, 2019). Although there are already several influencers dedicating their content to space, non-space influencers could be incentivized during the construction phase to further promote lunar activities. These could range from exclusive visits to lunar analogs of Rosas Base up to (simulated) photo opportunities.

6. Organization and Timeline

This section will discuss the organization structure derived from the Public-Private Partnership scheme to create an international authority, called RLA. This authority will coordinate with governments and businesses worldwide to provide the legal frameworks, research, development, testing, launch, construction, operations, outreach, and future planning that govern Rosas Base. Together these elements are organized into a cohesive vision and timeline by RLA for sustainable lunar development.

6.1. Organization Structure

The organizational structure refers to how the various tasks of the construction project are divided and how units coordinate in the organization. It helps define job specialization and division into departments. Construction of Rosas Base is an extremely complex project which requires coordination between many contractors and teams over a long duration of time.

We define the organizational scheme assuming a PPP financial framework. We opt for creating a Program Management Office (PMO) which overseas, advises and contracts the different entities needed to complete the construction. The main roles of the Rosas Base PMO are to define the subsystem specifications, manage the specification requirements, contract the enterprises needed to perform the construction tasks, supervise, and oversee the construction, and operate the lunar base. To fill these roles, several departments and personnel within them need to be specified, with a defined organizational hierarchy, as shown in Figure 22.

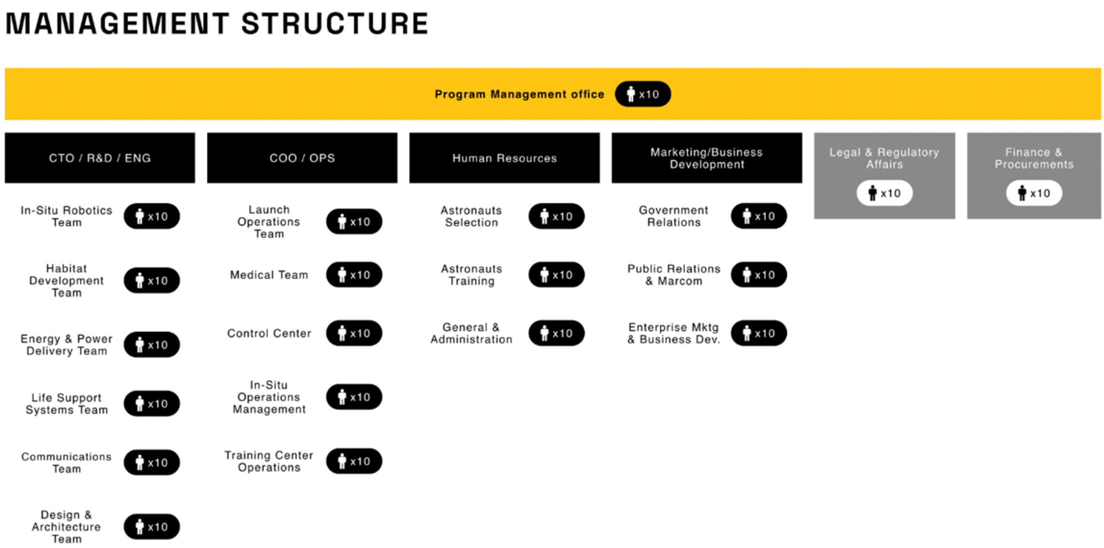

Figure 22: Management structure for the office responsible of the construction of Rosas Base

The PMO is the top management office and is composed of deputies, assistants, and representatives from the public authority who will perform audits and ensure that the public actor is represented. The PMO may be considered as the headquarters of the construction program with the role of managing all strategic decisions.

The next management level represents the different departments that will oversee specific functions and activities. Particularly, six departments are needed to manage the range of functions needed for the construction program. These departments include:

- The research and development Research and Development (R&D) and engineering office, headed by the Chief Technology Officer (CTO).
- The Operations (OPS) office, headed by the Chief Operation Officer (COO).
- The Human Resources (HR) department.
- The marketing and business development office.
- The legal and regulatory affairs office.
- The finance and procurement office.

Each of these offices is further divided into several specialized teams responsible for specific activities and functions. The breakdown of the teams as well as the number of individuals estimated to be required per team is shown in Figure 22. These teams cover all the critical functions necessary to ensure the proper management of the Rosas Base construction program.

It is, also, important to discuss the form of governance that the PMO will follow. We identify two alternatives for the governance of the PMO each with a different set of strengths and drawbacks:

- The first possibility is to establish the PMO as a part of the independent lunar base authority created to manage and operate Rosas Base. This independent authority (discussed in Section 7.1) would help bring together several international stakeholders representing government agencies and government offices as well as representatives of partner private actors. As previously discussed, the establishment of this independent authority can follow the model of creation of European Center for Nuclear Research (CERN), which was created by an international treaty and has proven to be sustainable. The drawback of this option is that it could be difficult to reach widespread international agreements on the participating agencies, nation states and actors, and to define and establish an international treaty which has a sufficient consensus between all participating members. This poses a problem for the subsequent creation of the PMO which will need to oversee the construction process.
- The second alternative is to fully delegate the program management to a private corporation that follows the legal and governance framework of the country in which it resides. This would significantly reduce the legal and governance considerations needed to establish the PMO, but it would risk not sufficiently representing the interest of the other international stakeholders throughout the construction project.

It should be noted that, in either case, the public actor oversees the performance of the PMO through internal representatives with the role of auditing the program development and ensuring that the public actors' considerations are considered.

As is evident by the two proposed alternatives, careful deliberation should be given to the form of governance that the program management organization would follow. This would require a detailed assessment of the strengths of each model and a discussion among the project stakeholders to reach a consensus on the most important political and legal objectives of this organization.

6.2. Major Program Milestones and Timeline

The program is envisioned in four phases: pre-launch, launch and transfer to the Lunar surface, construction, and expansion, as shown in the timeline in Figure 23. The pre-launch phase covers the planning and contracting of operations along with research, development, testing, and qualification of payload. As a part of the ground activities, the interiors of SS Rosas will be refurbished to suit the horizontal configuration following a similar development, testing, and qualification cycle. It will, then, be assembled with the payload, and sent to SpaceX for launch. The launch phase will consist of the Starship fuel depot entering LEO, while multiple tanker versions of the Starship refuel it over a span of a few weeks (4 tankers for SS Rosas and 8 tankers for the crewed versions), as illustrated in Figure 5. Once refueled, the lander containing either cargo or crew docks to the fuel depot and makes its way to the lunar surface. The construction phase commences once SS Rosas and SS 501 land on the Moon. By the end of this phase, Rosas Base will be minimally viable - equipped with the minimum power, communications and life-support systems required to sustain the crew. Expansion operations of the base include improvements to the interior design, connection of multiple Starship-like modules together for a larger, habitable area, as well as steps towards economic growth, business development and sustainability of the lunar habitat.

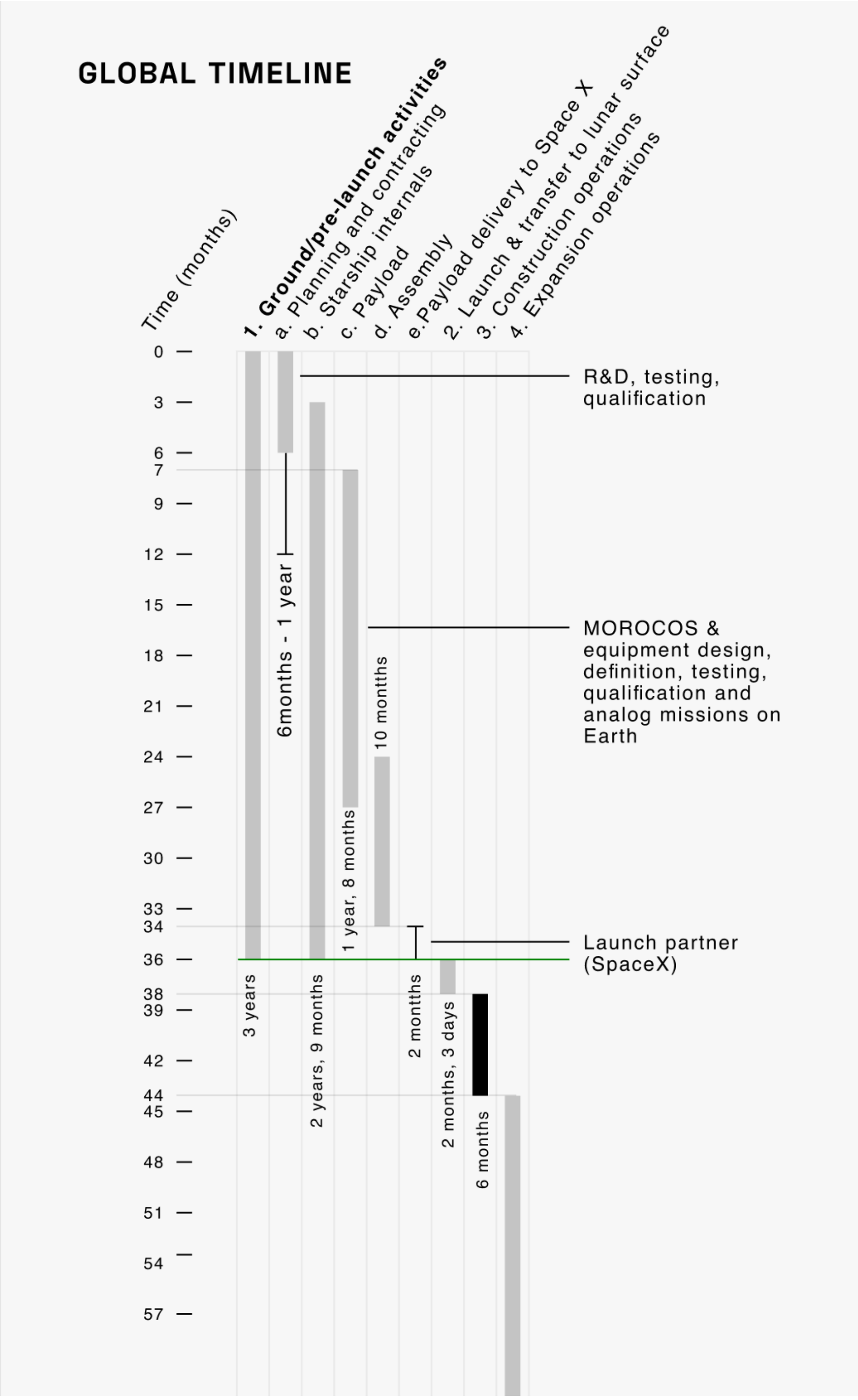

Figure 23: Business global timeline.

7. Financial Plan

Building on the recommendations and needs of previous sections, this chapter focuses on mechanisms of PPPs, program budget and financing, as well as a long-term sensitivity analysis discussing alternative sources of Funding. Within the mechanisms of PPPs, the trades with traditional funding sources, use in space projects, framework for the Rosas Base, and potential challenges in the implementation of this model are explored. Within the program budget and financing, the breakdown of potential sources of funding and financial profit and loss tables are displayed to show the feasibility of this proposal under current funding schemes. This is followed by the section on long-term sensitivity analysis and alternative sources of funding, which explores the feasibility of expanding the base utilizing this established infrastructure and PPP model. Together these provide a valuable study into the economic potential and sustainability of this construction approach.

7.1. Mechanisms of Public-Private Partnership

It is of critical importance to identify the proper financial framework that is most suitable to foster the lunar base construction process. In this report, it is argued that PPPs are the most suitable financial vehicle structure for enabling economically viable lunar base construction and operation activities. This section will justify this choice, first by comparing the PPP framework to the traditional funding approach for high-risk space-related projects and then by providing a set of examples for a successful implementation of PPP in these projects. The benefits of considering a PPP approach are provided, however, since PPPs are not without drawbacks, this section further identifies and discusses the challenges for constructing Rosas Base under a PPP framework. Furthermore, an assessment is provided for the funding breakdown between the public and private actors that aims to minimize the business risk and maximize the potential for a successful and timely completion of the project. Finally, conclusions and further recommendations are discussed.

7.1.1. Public-Private Partnerships versus Traditional Funding Approaches

PPPs are an arrangement within which the private sector assumes more responsibility for the finance, management, and ownership of the public project than in the traditional funding approaches. In traditional approaches, the public sector assumes the full responsibility and finance of the project. In contrast, PPPs transfer a significant amount of the project risks and costs to the private partners. The main premise for the effectiveness of this arrangement is that private partners manage those risks efficiently, typically better than the public actor, as they are motivated and incentivized to increase the profits for their activities by reducing any operational, business, and organizational inefficiencies. One of the key points of a successful PPP relationship is the ability of the public entities to attract private capital by giving political support, legal assurances, and government funding with the aim of decreasing the technological and capital risks so that private companies could benefit from an acceptable ROI. This is driven by the fact that a prosperous PPP can only exist when there is a favorable benefit-to-cost ratio for private entities, which implies that ROI is greater than risk. The relationship between ROI and risk level and, particularly, the region of confidence at which investments are most likely to occur can be visualized in Figure 24.

PPPs of this nature characterize how space commerce has evolved in other areas, such as satellite communication and navigation, commercial launch vehicles and remote sensing. This is also likely a successful formula for lunar development. This comes with several challenges,

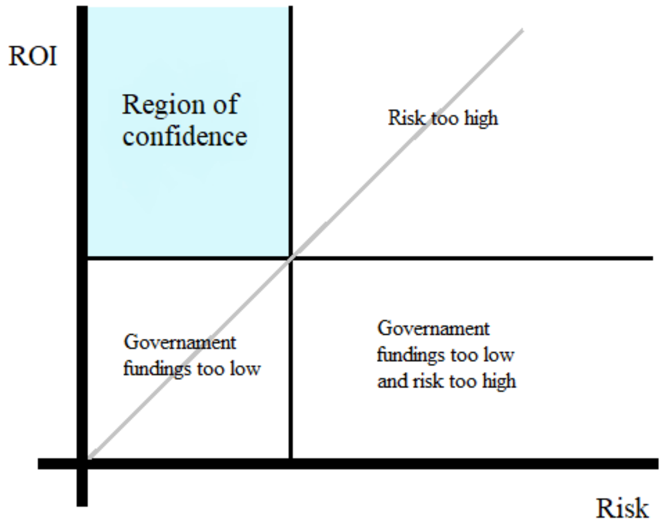

Figure 24: Relationship between return of investment and risk. Adapted from Hashimoto (2009).

however. Constructing Rosas Base is a high-risk project which includes a range of activities with inherent technical, organizational, and financial challenges. Traditional government funding approaches, while still needed, may not be able to efficiently ensure the oversight of the full project. Commercial companies exist today that are capable of providing support for some of these activities and who can capitalize on related future commercial opportunities.

7.1.2. Public-Private Partnerships in Space Projects – an Overview

In recent years, the application of PPP approaches in space-related projects has seen a significant increase relying on a variety of contractual arrangements and division of tasks between the public and the private actors. One of the most known examples is the NASA transition from a government-owned and operated cargo delivery system to the ISS to a privately-owned and operated cargo delivery system with multiple competitors (C. Miller, et al., 2015). In this case, the PPP was established combining both development and operation, and the primary market for the private actor was the government or the public actor itself. We denote this form of PPP as PPP of Type-1. PPPs in space projects could be mainly divided in 4 categories, as can be seen in Table 11 (Hashimoto, 2009).

Table 11: Main categories of public-private partnerships in space projects

	Government Customer Market	**Commercial Customer Market**
PPPs in construction and operation	Type 1	Type 2
PPPs in operation	Type 3	Type 4

Note that in the categorization presented in Table 11, construction refers to design and building activities and operations refers to operating and maintenance activities. Most space projects under PPPs fall within one of the categories presented in Table 11. Notable examples of successful space projects organized under a PPP structure and their nature are illustrated in Table 12 (Hashimoto, 2009).

Table 12: Examples of successful (PPP) space projects and their categorization

PPP category	Space Project	Nature of project	Country or Region	PPP structure	Main sources of funding
Type 1	Commercial Orbital Transportation Service (COTS)	Space transportation	US	Public: NASA Private: SpaceX and Orbital Sciences	Public: $800m Private: Not available
Type 2	Galileo	Navigation	Europe	Public: European Union (EU) Private: 8-members	Public: 100% development cost + 1/3 deployment cost. Private: 2/3 deployment cost and full operating cost
Type 3	Space Shuttle	Space Transportation	US	Public: NASA Private: United Space Alliance	Public: 100% development. Private: 100% launch cost
Type 4	Ariane 5	Space transportation	Europe	24-shareholder joint venture	Public: 100% development. Private: 100% launch cost

Of particular interest to the Rosas Base construction project is the case of COTS, that falls within the Type-1 PPP-category. This partnership between NASA and commercial actors resulted in a successful development of two launch vehicles: SpaceX's Falcon 9 and Orbital's Antares. Indeed, NASA estimated that it would have costed the agency $3.9b to develop these systems using traditional contracting methods, whereas the reported SpaceX cost was around $443m. This represents an 89% reduction in costs compared to the estimated traditional approach (C. Miller, et al., 2015). Other examples include the Atlas V and Delta IV launchers that were developed by Lockheed Martin Corporation and Boeing, respectively, within a similar approach driven by large private investments, and a comparatively smaller government funding.

The brief overview conducted clearly identifies that a successful commercialization of a space project relies on the role of the public actor to not only contract for the R&D and use of new technologies but to, also, facilitate the transfer of these technologies to the private sector and promote the development of markets that could sustain the new areas of space commercialization. To this end, in the next section, we discuss the benefits and challenges that are identified for establishing a successful PPP to finance the Rosas Base construction project.

7.1.3. Constructing Rosas Base Under a Public-Private Partnership Framework

In this section the PPP is analyzed in the context of the development of Rosas Base. Two key questions arise: *Which form should this PPP take and what are the plausible scenarios for its successful implementation?* Moreover, what challenges and business risks would such a project face and what could be a solution to mitigate these risks?

7.1.3.1 Market Breakdown and Legal Considerations

A critical issue to address for the successful establishment of a PPP is to identify the potential markets that can exist from lunar construction activities and lunar missions.

Early market products from lunar activities will likely be comprised of experimental data and samples. A possible pathway to create a market for these products is to target the scientific community. It is important that the public actor fosters such a market for science data via suitable grant schemes (Sadeh, et al., 2005): Another possibility is to establish a milestone payment to companies in the early development phases, whereas, when the company achieves its milestone, they would receive the agreed payment. Other possibilities to creates commercial acquisition opportunities for private actors include:

- Transportation services to orbit
- Spacecraft services in cislunar space
- Propellant markets in LEO and in Lunar orbit
- Cislunar commercial communications networks
- Surface elements: rovers, habitats, equipment, ISRU, among others.

A trade-off analysis is, therefore, presented with the aim to identify how the PPP model can be adapted to the Rosas Base development project.

The mission phases and the trade-off drivers are presented and consequently how these two elements are correlated to each other is discussed. The outcome of the trade-off will be the division in activities that are publicly funded and those that are privately funded.

The macro-areas in which the Rosas Base development is divided can be summarized in: R&D, production, integration, validation, transportation, surface construction, Moon operation (including surface operations, in-orbit operations) and maintenance/re-supply.

The trade-off drivers that are taken into consideration for the analysis are:

- Revenue: the ability to have a good ROI from financing and investing in constructing Rosas Base.
- Capital risk: the possibility that the entity would lose money from an investment in capital.
- Technology readiness level: a measure for the maturity of the technology used in the project.
- Schedule efficiency: the ability to accomplish the planned sub-activities within the established time interval and with no added expenses.

For each of these drivers, a value is assigned based on the guidelines in the following Table 13.

Table 13: Values assignments of drivers

Value	Revenue	Capital risk	Tech readiness level	Schedule efficiency
0	Very poor revenues possibilities	Very high potential loss	High number of competitors with an established market	High risks of planning delay
1	Poor revenue possibilities	High potential loss	Few competitors and product ready	Medium risk of planning delay
2	Good revenues possibilities	Low potential loss	Few competitors and product not ready	Low risk of planning delay
3	Excellent revenues possibilities	Negligible potential loss	No competitors	No risks of delay

From Table 13 it is possible to assess how those drivers correlate to the private funding decisions:

- Revenues: high score means that it is easier to find a private partner, on the contrary low revenues do not appeal private partners.
- Capital risk: high score discourages private partners getting involved in the activities.
- Tech readiness level: high value means having competitors that already fulfill the user needs, high value is not good for involving private partners.
- Schedule efficiency: high value means that the planned operations have a high potential for being completed on time with no added expenses. This represents a high possibility to attract private partners.

Overall, public funding will be used for activities that achieve a low score in the sum of the trade-off values and private funding will be used for activities that achieve a high total score. It is assumed that the threshold between one funding source and the other will be at a total score of 6 (the median score).

Table 14: Matching between mission phase and funding type

Phase	Revenue	Capital risk	Tech readiness level	Schedule efficiency	Total score	Funding
R&D	0	0	3	0	3	PUBLIC
Production	0	1	0	1	2	PUBLIC
Integration	0	2	0	1	3	PUBLIC
Validation	0	3	0	2	5	PUBLIC
Surface construction	0	2	2	0	4	PUBLIC
Surface Operations	3	2	2	2	9	PRIVATE
In-orbit Operations	2	2	3	3	10	PRIVATE
Maintenance / Re-supply	3	2	2	3	10	PRIVATE
Transportation	2	3	1	3	9	PRIVATE

The outcome of the trade-off analysis, shown in Table 14, is that the first stages of the development of Rosas Base would be more adequately financed by public funding, on the other hand the later stages would be more attractive to private funding since the relationship between the probability of making profit and the risks is advantageous.

Another important consideration relates to how to foster a commercial market for lunar development activities within the existing legal framework. While this is primarily a legal discussion, it is important to briefly provide an overview of the plausible pathways and to select which is best suited to the nature of the lunar construction project. There are several approaches that the public actor can pursue in relation to PPPs and lunar development. These can be summarized as follows (Sadeh, et al., 2005):

1. Market-based: both access to and use of lunar resources are treated as private goods.
2. Free access and free use (as codified by the current OST regime), which represents a benefit-sharing approach to space development.
3. Free access but restricted use through divisibility of lunar resources. Like the governance of geostationary orbital slot designations and electromagnetic spectrum allocations for the telecommunications sector.
4. Free use but restricted access. Like the approach that has been applied to government-sponsored remote sensing activities

The first two approaches may not be the most suitable to foster a successful private sector participation in the lunar base construction project: the first approach goes against the current OST regime of non-appropriation and might require significant legal and governmental changes before it is implemented. The second approach does not provide sufficient incentive for private actors to participate in the development of outer space, since they cannot maintain any intellectual property rights. The third option would only allow a market to develop for activities that would not require property rights, such as scientific activities and tourism. This could represent a plausible scenario during the first phase of the construction process as it maintains the current OST regime. However, it is not sufficient to sustain commercial activities for the long term. The fourth approach is an extension that allows free use of resources for exploration and science activities directed at public welfare with an accompanying regime of restricted access via property rights for commercial activities. This latter scheme seems to be the most suited approach moving forward towards fostering PPP for the construction of the lunar base.

7.1.4. Challenges to Consider for a Successful Implementation of a Public-Private Partnership for the Rosas Base Construction Project

The challenges of the Rosas Base construction project are the result of the extraordinary complexity and uniqueness of the mission. This leads to technical risks and possible cost escalation. The public partner may face challenges defining laws and policies that suit the project, which also are accepted by the entire space community. The most important challenges for the successful implementation of a PPP for constructing a lunar base can be summarized as follows:

1. Uncertainty in the long-term commitment of the public actor.
2. High degrees of technical and development risks.
3. Significant capital requirements.
4. Long and uncertain project development periods.
5. Lack of clear and transparent resource utilization and property rights.

One possibility to address the business risk is for the public actor to provide low interest loans for the private firms to proceed with the construction activities and purchase commercial services at specified prices once the infrastructure is operational. Another possibility is the creation of an independent authority that owns and manages the infrastructure while contracting private firms to accomplish the work. This would allow the proper management of business risk at the initial phase of the project where no commercial activities are established yet. Authorities typically blend the power of government with the economic efficiency of private actors. A successful implementation of this model is CERN, which is an international authority created by international treaty and proved to be a successful entity in managing a complex and largely non profitable project. The aim for such an authority for the lunar development project is to transition from the "non-profit" model to a profitable "usage fee" model that allows it to fund itself. As mentioned before, this requires the development of suitable commercial markets from the lunar construction activities.

7.2. Program Budget and Financing

Using the PPP framework described above with mixed public-private funding at various steps, the program budgeting includes a breakdown of unit costs that propagate into Profit and Loss Report, Cash Flow Statement, and Balance Sheet. The program financing section includes a breakdown of agencies looking to pursue lunar activities within the foreseeable future and the funding they have allocated. These agencies could also serve as the early-adopter customers of the Rosas Base, generating revenue and facilitating coverage of maintenance costs as well as return on investment. The volume of agencies and funding could promote future expansion of the base as a focal point in the development of sustainable lunar economies.

7.2.1. Program Budget

For the Program budgeting, Profit and Loss (P&L) scheme was used with bottom-up cost analysis. In cases where the team had access to a subject matter expert or was able to find a relevant resource in literature or publications, this has been used. The budget is therefore by no means complete and requires more solid research and validation with relevant space agencies and private companies. However, the budget can be used as a good indicative overview.

In order to compile an overview of Capital Expenditure (CAPEX) and Operating Expenditure (OPEX), the team worked through a set of work packages to which recurring and non-recurring cost were associated. These include: all transportation cost of crew and payloads from Earth via LEO, Low Lunar Orbit (LLO), landing, and return to Earth; maintenance; mission control; astronaut training including analogs; administration and management; and design, development, manufacturing, assembly, integration and test of: subsystems, rovers, tooling and machinery, construction materials, IT-systems, software, power, and ECLSS.

Note that because the commercial activity of the PPP private enterprise partner is not yet identified, no direct cost is provided, and only CAPEX and OPEX are considered in the proposed P&L. A projection of revenues is considered in years four and five in order to forecast the point of positive Earnings Before Interest Depreciation Tax and Amortization (EBIDTA) and ROI.

7.2.2. Program Financing

The financial analysis performed includes a five-year financing plan, considering that the first five years are dedicated to R&D, construction, and setup. After this setup phase, the analysis shows that Rosas Base is expected to enter a more stable recurring cost structure with projected revenues and could potentially reach ROI for the private enterprise within less than ten years from the program kick-off.

The first three years are planned to be financed by public funding (namely Space Agencies). This is coherent with most PPP schemes where the setup cost is taken by Governments. During the following Years 3-5, a private enterprise partner will step-in with an initial investment and will take over the recurring operational costs.

As a reference, the following public budgets have already been allocated to lunar exploration and settlement programs, as summarized in Table 15:

Table 15: Public funding sources

Agency	Lunar budget	Starting	Ending	Allocated	For	Source
Brazilian Space Agency (AEB)	unclear	2021		yes	Artemis contribution with lunar robotics	Brazil Government Website (2020)
Australian Space Agency (ASA) / Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO)	$150m, out of which approx 0.75 have already been allocated to two companies	2019	2023	yes	IoT/Comms, but rest is open	Australian Government - Department of Industry and Website (2021) and Satnews (2021)
Italian Space Agency (ASI)	No dedicated lunar budget			yes	Lunar Comms, included in ESA budget (Moonlight Initiative), Interest in Robotic exploration and Instruments, ISRU, cislunar constributions - all ESA funded	Agenzia Spaziale Italiana (2020)
French Centre National d'Etudes Spatiales (CNES)	Approx $850m (€719m) in 2021 total, unclear lunar share			yes	Lunar robotics payloads and surface instrument	CNES (2020) and France Science (2021)
China National Space Administration (CNSA)	unclear			yes	Lunar Research Station	A. Jones (2021)
German Aerospace Center (DLR)	Approx $335m (€285m) in 2019 for national program overall	2019	To be announced (TBA)	TBA	Possibly robotics, extraterrestrial science and human spaceflight	German Aerospace Center (2019)
ESA	Yes, spread across various domains	2020	2024	yes	Lunar Nav&Comm solution, Gateway contribution	ESA (2021)
Geo-Informatics and Space Technology Development Agency (GISTDA) Thailand	unclear	2020	~2027	yes	Lunar orbiting satellite	OpenGov Asia (2020)
Indian Space Research Organisation (ISRO)	$80m (600 crore)	2021	TBA	yes	Chandrayan-3, ISRO budget increasing; interest in Human Spaceflight	ISRO (2020)

Table 15: (continued)

Agency	**Lunar budget**	**Starting**	**Ending**	**Allocated**	**For**	**Source**
Israel Space Agency (ISA) + SpaceIL	$75m	2021		yes	BERESHIT2 Lunar Lander	
JAXA	Approx $92m (¥100b)	2021	2021	yes	Artemis, Gateway, Lander, South Pole exploration	Si-soo (2021)
Korea Aerospace Research Institute (KARI)	Approx $442m (₩521b)	2019	~2029	yes	Orbiter and landing module, science payload, and deep space communication	Korea Aerospace Research Institute (KARI) (2021)
Luxembourg Space Agency (LSA)	$116m Luxemburg Fund	2014	TBA	yes	Moon Mining, landers, rovers	Foust (2018) and Government of Luxembourg (2016)
Norwegian Space Agency (NOSA)	unclear	2020	2024	yes	Comms/Ground Segment within ESA budget	Ellingsen (2020)
Polish Space Agency (POLSA)	unclear			yes	Lunar robotics and rovers - contributions to Artemis and ESA	Polish Space Agency (2021)
Romanian Space Agency (ROSA)	unclear, probably no lunar budget	2014	2020	no	Only outreach agreement with moonvillage association	Romanian Space Agency (2014)
Roscosmos	unclear	2025	2037	yes	Lunar Orbiting Station and base with China	A. Jones (2021)
State Space Agency of the Ukraine (SSAU)	Unclear, but in the roadmap	2018	2032	yes	Domestic spacecraft for exploration, scientific equipment, space tugs for LEO to Lunar transportation	State Space Agency of Ukraine (2012)
Swiss Space Office (SSO)	unclear, not a space agency as such			yes	Exploration Envelope Program (E3P), Gateway, life sciences	The commission for Space research (CSR) and Swiss National Academy of Sciences (SCNAT) (2019)
United Arab Emirates Space Agency (UAE SA) and Mohammed Bin Rashid Space Centre (MBRSC)	unclear			yes	Lunar rover independent of Artemis (MBRSC)	Gibney (2020)

Table 15: (continued)

Agency	**Lunar budget**	**Starting**	**Ending**	**Allocated**	**For**	**Source**
UK Space Agency (UKSA)	\$2.75m (£2m)	2020	~2024	yes	Communication and navigation services	UK Space - The Space Trade Association (2021)

The NASA budget is unmistakably the largest known budget allocated for lunar exploration and settlements. Although figures for the Chinese-Russian International Lunar Research Station could not be found, they can be assumed to be also be large budgets. Considering that Rosas Base is based on a United States designed infrastructure, the SpaceX Starship, it is unlikely that any Russian or Chinese budgets would contribute to its establishment.

However, the known national budgets for lunar exploration and settlement total up to $2b, without taking the United States into this calculation. Although most of these budgets are already allocated, this table indicates which nations have a strategic interest in financing a lunar endeavor, both now as well as beyond the budget rounds as displayed above. It can be therefore assumed that parts of these future budgets could be allocated to the Rosas Base program. In addition, it is worth noting that the total available budget could be much higher, since some nations have lunar Programs in their strategic roadmap, without communicating the budget allocated to them.

Regarding the technology focus, many of the aforementioned lunar programs are contributing to the Artemis Program. In more detail, most of these technologies focus on the Gateway, communication, navigation, robotic exploration, human exploration and a substantial number of scientific payloads. What is missing, or at least is not explicitly put forward, are technologies, tools, materials, and machinery to construct a lunar base. These are gaps that need to be addressed when allocating new, or re-allocating existing budgets.

Looking at this table mid-term, it is worth noting that there are few nations that have still unallocated budgets. Worth mentioning are the Canadian Lunar Exploration Accelerator Program (LEAP) program as well as the Luxemburg Fund. To have certain technologies developed sooner than later, these budgets are deemed to be most interesting, as they can be made available earlier than the above-mentioned several-year budgets.

For Rosas Base, it would be necessary to market the base to secure the near-term and long-term available funds accordingly. Timely action and communications as well as a strong Public Relations strategy would be needed to raise interest among relevant stake holders.

It is believed that crowdfunding would also be an interesting route for the initial build-up stage as these activities appeal to a wider audience. These activities would require a dedicated Marketing Plan, identifying addressable markets and strategies which are not scoped in this report.

The overall projected program cost is $4b of which $3b will be public funded spread over three years and $1b will be the private enterprise investment which will kick-in during the third year. The P&L analysis shows that with projected revenues of $500m, $800m and $1.5m in years three, four, and five respectively, the Moon enterprise could reach a positive EBIDTA. Accordingly, ROI for the private enterprise is forecasted after the seventh year (three to four years after the private investment is made). It is likely that the Moon base offers opportunities for significant commercial activities and profits for private enterprise. These may include: entertainment (television broadcasting etc.), tourism, and pharmaceutical research. Therefore, a targeted business development effort will be planned and executed to approach relevant enterprise partners and construct the PPP scheme with them.

For the purposes of financials, we baseline a 5 year depreciation evenly split at 20% yearly, as shown in Tables 16-18 (see Appendix A.6 for a detailed breakdown of the calculations).

Table 16: Profit and loss report in millions

	YEAR0	YEAR1	YEAR2	YEAR3	YEAR4	YEAR5
Revenue	$-	$-	$-	$500	$800	$1,500
Direct cost						
Gross margin	$-	$-	$-	$500	$800	$1,500
OPEX	$(39)	$(75)	$(355)	$(602)	$(602)	$(602)
EBITDA	$(39)	$(75)	$(355)	$(102)	$198	$898
Amortization / Depreciation		$(191)	$(301)	$(617)	$(617)	$(427)
EBIT	$(39)	$(266)	$(656)	$(719)	$(420)	$471
Interest	$-	$-	$-	$-	$-	$-
EBT	$(39)	$(266)	$(656)	$(719)	$(420)	$471
Taxes	$-	$-	$-	$-	$-	$-
Net Profit	$(39)	$(266)	$(656)	$(719)	$(420)	$471
Cumulative profit/loss	$(39)	$(306)	$(962)	$(1,681)	$(2,100)	$(1,630)

Table 17: Cash flow in millions

	YEAR0	YEAR1	YEAR2	YEAR3	YEAR4	YEAR5
Cash in	**$1,500**	**$1,000**	**$1,500**	**$500**	**$800**	**$1,500**
Revenue	$-	$-	$-	$500	$800	$1,500
Equity	$1,500	$1,000	$1,500	$-	$-	$-
Public Funding	$1,500	$1,000	$500	$-	$-	$-
Private Financing	$-	$-	$1,000	$-	$-	$-
Debt	$-	$-	$-	$-	$-	$-
Cash out	**$(993)**	**$(627)**	**$(1,934)**	**$(605)**	**$(605)**	**$(605)**
Direct cost	$-	$-	$-	$-	$-	$-
CAPEX	$(954)	$(552)	$(1,579)	$(3)	$(3)	$(3)
OPEX	$(39)	$(75)	$(355)	$(602)	$(602)	$(602)
Repayment	$-	$-	$-	$-	$-	$-
Interest	$-	$-	$-	$-	$-	$-
Tax	$-	$-	$-	$-	$-	$-
Treasury position	**$507**	**$880**	**$446**	**$341**	**$535**	**$1,430**

Table 18: Balance sheet in millions

	YEAR0	YEAR1	YEAR2	YEAR3	YEAR4	YEAR5
Assets	**$1,461**	**$2,194**	**$3,038**	**$2,319**	**$1,900**	**$2,370**
Fixed assets	$954	$1,315	$2,592	$1,979	$1,364	$940
Cash in the bank	$507	$880	$446	$341	$535	$1,430
Liability	**$1,461**	**$2,194**	**$3,038**	**$2,319**	**$1,900**	**$2,370**
Equity financing	$1,500	$2,500	$4,000	$4,000	$4,000	$4,000
Retained profit	$(39)	$(306)	$(962)	$(1,681)	$(2,100)	$(1,630)
Liabilities	$-	$-	$-	$-	$-	$-

7.3. Long Term Sensitivity Analysis and Alternative Sources of Funding

Using this initial base, within the PPP framework, there will be the RLA coordinating with paying parties that rent out base space and utilities to an authority autonomously funding the base operations of the base and any new capital expenditures. One of the very promising potential benefits of this base is scalability. After the R&D and capital expenditure of the first base was funded by the public sector, this framework provides infrastructure that can lower the costs for each successive conversion of a Starship, enabling greater return on investment and sustainability. The exact points at which it is attractive to add on additional bases is driven by the revenue of the first base, the market potential, and the mechanisms of the funding source. It should be noted that before propagating too far into the future, further study is required to validate these estimated costs, but this section exists to give a low-fidelity estimate of what is achievable.

The ISS provides a valuable insight into what governments have been willing to pay to fund science operations. The United States accounts for roughly 76.6% of the research activity on the station, and spends approximately $3-4b per year on the operational expenditures of the ISS (NASA Office of Inspector General, 2018), which has a total pressurized volume of 916 m^3 (NASA.gov, 2021). Using this share of research activity as a baseline to generate a conservative estimate of the budget allocation per volume, we get a utilization of approximately 700 m^3 and use the lower bound OPEX cost of $3b per year. That means that the United States as a baseline is willing to pay $4.28m per m^3 per year.

This conservative ISS data point when applied to Rosas Base provides a valuable input as to what an order of magnitude revenue from public sector partners, interested in lunar activities, could be. Of course, this is not a perfect metric as microgravity volume usage is different than hypogravity volume usage, but the larger form factor of the volume on Rosas Base could provide benefits to make up this difference, and is well suited for this low-fidelity analysis. Based on the technical specifications discussed above, if two-thirds of the usable volume of the converted fuel tanks were allocated for the RLA to rent out, that would total up to greater than 1,000 m^3. If the ISS cost metric were used as a price metric for the 1,000 m^3 allocated for rental, that would mean $4.28b per year in revenue. This is more than enough to cover the operational expenditures of operating the single Rosas Base, estimated at roughly $600m per year, for which the minimum volumetric price would be $0.6m per m^3 per year to purely maintain the base. Bounding the price and expected revenue between these two numbers could ensure greater participation of governments and private entities, while generating funds for future projects and expansion.

For construction of additional bases, there are a number of components that have been designed to be reusable for construction purposes, and with the research and development costs already expended on the first base, the costs of building additional bases will be lower, especially if lunar activities and materials processing can help close loops and generate needed materials on the Moon in the future. Purely examining the cost reduction from savings due to reusability and a lack of research and development needs, constructing a second lunar base would come to a value of around $1.6b (see A.6). This is well within the potential profit of a year or a few years of operation, depending on the number and scale of customers, which based on the funding of public agencies for lunar activities, and interest of private entities, we expect many.

If profit is insufficient, one of the attractive ideas with historical precedence for funding within PPPs are project bonds. These bonds which allow for debt-based financing of projects, can offer low interest rates and larger funding capacity when compared to other funding sources. Given the short construction time of future base construction and the ability to rent out space and utilities on board each new Starship base, there is a great rapid return on investment case which may make project bonds attractive options for expansion and other potential space construction projects. Additionally, this has a great benefit for sustainability, opening the opportunity for individuals being able to participate directly in lunar activities, and have skin in the game, potentially increasing support for future governmental and business ventures on the Moon if successful.

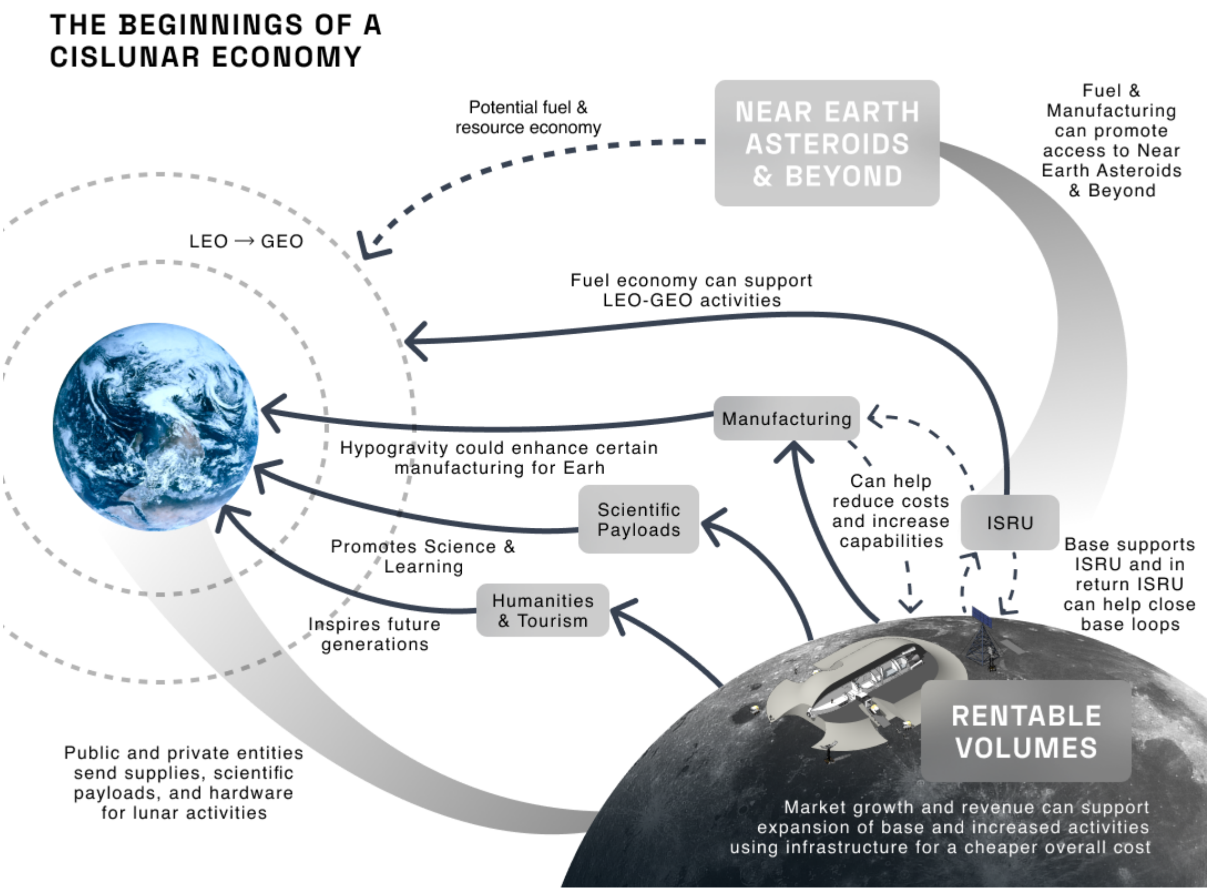

Figure 25: The emerging Cislunar economy

Because of the lower construction costs and scalability of the operational expenditures, the price of renting space and utilities on Rosas Base could be reduced by the RLA to encourage more players to join in and generate a larger overall revenue. This increase in the number of players will positively contribute to the lunar environment and economic development. Together a consortium of partners, potentially driven by the RLA, could develop the lunar region to increase capabilities and reduce costs further by developing ISRU and manufacturing to close loops, generate fuels, and produce tools. In conclusion, using the RLA framework to leverage the economies of scale of Rosas Base can increase the efficiency and sustainability of the construction of lunar bases in the future. A schematic illustrating this can be seen in Figure 25.

8. Conclusion and Recommendations

Creating a permanent lunar base has been the aspiration of institutions worldwide since before the Moon landing over 50 years ago. One of the dramatic gaps seen historically in this idea, and space programs in general, has been sustainability. Conventional pace projects have come at huge cost to tax payers and can change with the politics of each election cycle. This makes them extremely hard to maintain, and even harder to see the tangible benefits of. Despite these challenges, historically, the benefits have been huge in their positive contributions to life on Earth through direct inspiration, science, technology, and more indirect contributions such as education and spinoffs. Keeping this historical context in mind, by constructing a permanent lunar base there are many potential positive impacts for life on Earth, in-orbit infrastructure, and deep space ambitions.

To capitalize on these points in a rapid, cost efficient, and sustainable way, the solutions outlined in this report make a strong case that this vision is achievable within this decade. The major challenges from a technological, human health, legal, and financial perspective all have scalable answers that exist within the scope of knowledge, technology, frameworks, and funding that exist today.

It has been the opinion of many industry experts over the years that there are no business cases to be made on the Moon, meaning that lunar activities are inherently unsustainable. This argument begins to crumble as permanent infrastructure is developed to support these activities. The barriers to entry arise because of the large economies of scale required to achieve this infrastructure development in a way that has return on investment. With the recent emergence of reusable high mass, high volume launch and on-orbit capabilities, we suddenly find that these economies of scale are achievable and attractive.

The core novel engineering approach in this mission of turning fuel tanks and stages into bases is not a new one. It is well-supported by examples such as Skylab and proposals like converting the external Space Shuttle tanks to orbital bases. Using the immense volume and capacity of Starship-like vehicles allows for all the support equipment and infrastructure to be sent, operated, and adapted with just a few lunar landings, all at a low and sustainable cost. None of this equipment requires technological breakthroughs, meaning the development and design phases can be short.

In the transportation phase, the ability to send so much support equipment allows for solutions to human spaceflight problems such as radiation, micrometeorites, and dust mitigation such as stacking regolith and electrostatic removal, respectively. The huge internal volume also suits the needs of astronauts physically and psychologically incredibly well. Even with large crews, there is plenty of space and utilities to support additional activities from other parties that can provide revenue generation for a sustainable and expandable base.

These activities in both the public and private sectors are well supported and within the spirit of the legal framework provided by the five international treaties on space, preventing appropriation while promoting freedom of exploration, free use of outer space, assistance to astronauts, due regard, and international partnership and cooperation. This is all while respecting IP concerns using valuable international public-private frameworks such as those implemented on the ISS.

In further support of this, utilizing a Public-Private Partnership in the form on an international authority provides a high degree of credibility and sustainability, allowing it to accomplish more and reach more partners with less resources than a public or private entity could alone. Using public funding for the development and initial capital expenditures over a three-year period to construct Rosas Base, followed by private operation of the base to support it for years to come, bringing in eager governmental and private partners to generate revenue from use of the space and utilities that can fund eventual expansion of the base, using the established infrastructure for a lower overall cost. This international authority provides a strong long-term vision that will grow with lunar activities and respond effectively to any challenges that arise. This end-to-end interdisciplinary solution for construction of a lunar base provides never before seen accessibility and permanent, scalable presence on the lunar surface that can be supported sustainably and responsibly for years to come. The lessons learned and promoted here in the Rosas Base model, if implemented, will promote international science, cislunar economic development, and future exploration that will become an important stepping stone to the stars.

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A. Appendices

A.1. Equipment Transported by Starship Rosas

	Item	Quantity	total packed volume [m^3]	total mass [kg]	Requirements
MOROCAS equipment	MOROCAS	4	9.4	1200	Modular Robotic Construction Autonomous System.
	Detanker	1	6.3	100	Transfers methane, oxygen, nitrogen and water to the external fuel tanks.
	Shovel	4	2	400	To pile regolith
	External fuel tank	4	1	1000	An inflatable bladder to Store the fuels and gasses.
	Anchor	5	1.4	500	Used to secure the four cables and hinge to the ground.
	Hinge	1	15.6	1000	A very rigid structure that connects the bottom of the starship to the ground.
	Drilling bit	1	0.1	100	Used to dig the hole for the anchor.
	Scissor lift	1	6	250	Carries the load of the starship as it is being tilted.
Externally deployed equipment	Solar panels	20	2.3	30	
	Solar panel mounts	20	2.2	20	To set the solar panel vertically.
	Radiators	28	62.5	14000	
	Methalox powered generator	1	0.3	50	Uses excess fuel for high-power requirements.
	Power reactor	2	43.8	10000	The reactor from SSP18 TP "Survival of the lunar night".
	Antennas	2	0.5	100	For external communications
Airlock equipment	Elevator	2		200	
	Airlock	2	54	2000	
	Elevator winch	4		800	Lowers the elevator to the ground and also used in the horizontalizing process.
	Airlock corridor	2		200	An expendable system that extends from the entrance of the airlock.
	Windowed room	1	15.6	2000	A viewing port with windows that will connect to the airlock corridor.
Equipment for the conversion of tanks to habitat	Nitrogen	1		794	Stored in the volume of the payload bay
	Hatch cutting system	1	0.3	100	Used to cut holes in the common domes of the tanks
	Hatch	2	3.8	600	Installed in the cut hole in the domes
	Insulation	1	60.5	1452	Will line the walls of the tanks for thermal and radiation protection.
	Floor supports and boards	1	37.5	5250	Floors for the tanks volumes.

A.2. Tension of the cables during horizontalization

Simplifying the forces acting upon the vehicle as it is being tilted, we can derive the following free-body diagram (Figure 26):

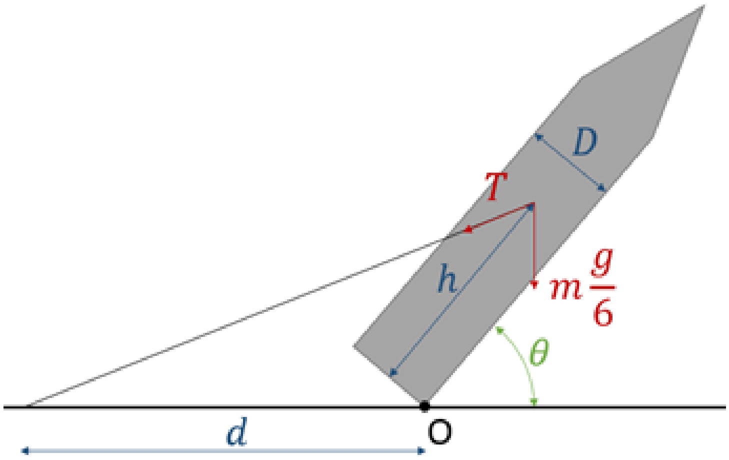


Figure 26: A free body diagram of the vehicle as it is being tilted.

Where D is the diameter of the vehicle (9 m), T is the tension on the cables, m is the mass of the vehicle, h is the height of the elevator (to which the cables are connected), θ is the tilt angle, O is the rotation hinge, d is the distance from to hinge to the anchors. The underlying assumption here is that the center of gravity is exactly at the location of the elevator. This remains to be verified but with the given data and assumptions it is not far from that point. Thus, for simplification this assumption was made. Using these assumptions, we can derive the equilibrium equation of moment around the hinge:

$$-m\frac{g}{6}\left(h\cos\theta - \frac{D}{2}\sin\theta\right) + c\cdot T\sin\delta = 0 \tag{1}$$

where,

$$c = \sqrt{h^2 + \left(\frac{D}{2}\right)^2}, \tag{2}$$

$$\delta = \gamma - \arctan\frac{c\sin\gamma}{d + c\cos\gamma}, \tag{3}$$

$$\gamma = \theta + \arctan\frac{D}{2h}. \tag{4}$$

The estimated mass of the vehicle during the horizontalizing procedure was found to be about 72 tons (as can be seen in the inventory list in Table A.1). The distance d was defined arbitrarily to be equal to h. With these a function $T(\theta)$ can be derived and sketched:

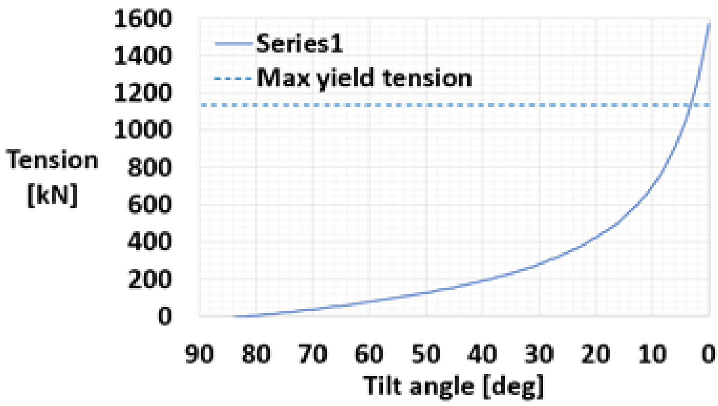


Figure 27: The tension of on the cables as a function of the angle of the vehicle. Max yield tension refers to the yield strength of Aramid cables with diameter of 1 cm.

As can be seen from 27, at lower angles the tension on the cables becomes greater than the maximum yield strength of one of the strongest cables available (Aramid cable). For this reason, the scissor lift mechanism is necessary. It will take the load of the vehicle from the cables at lower angles. The load on the scissor lift increases as the angles increase, and the lift moves along the body of the vehicle.

A.3. Environmental Control and Life Support budget

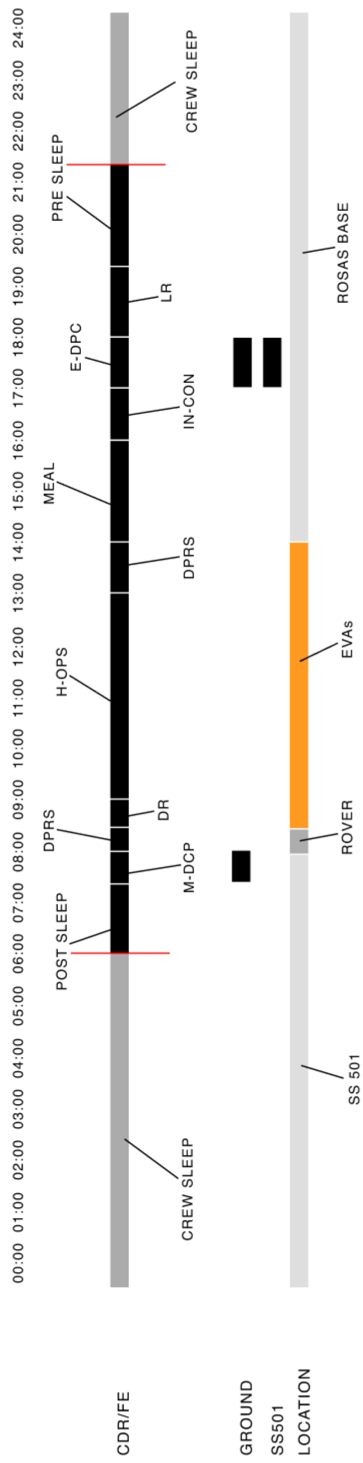
ECLSS Subsystem	Mass (kg)/Unit	Volume (m3)/Unit	No. of Units	Total Mass (kg)	Total Volume (m3)
Temperature and Humidty Control System	150	0.2	9	1350	1.8
Oxygen Generation System	680	0.7	4	2720	2.8
Waste Management (Water Processing + Urine Processing)	1385	0.7	2	2770	1.4
Fire Detection and Suppression	35	0.1	9	315	0.9
Carbon Dioxide Removal System	390	0.6	6	2340	3.6
Trace Contaminant Control System	240	0.2	1	240	0.2
Personal Hygiene Facility	455	2.3	3	1365	6.9
Galley	150	0.8	2	300	1.6
Misc	100	0.1	9	900	0.9
Total	N/A	N/A	N/A	12300	20.1
Expendables					
Water (Consumption Only)				4236	
Food				744	
Clothes (one unit assumed to be kg clothes/p/day)	0.6		N/A	720	

A.4. Rosas Base Crew Schedule

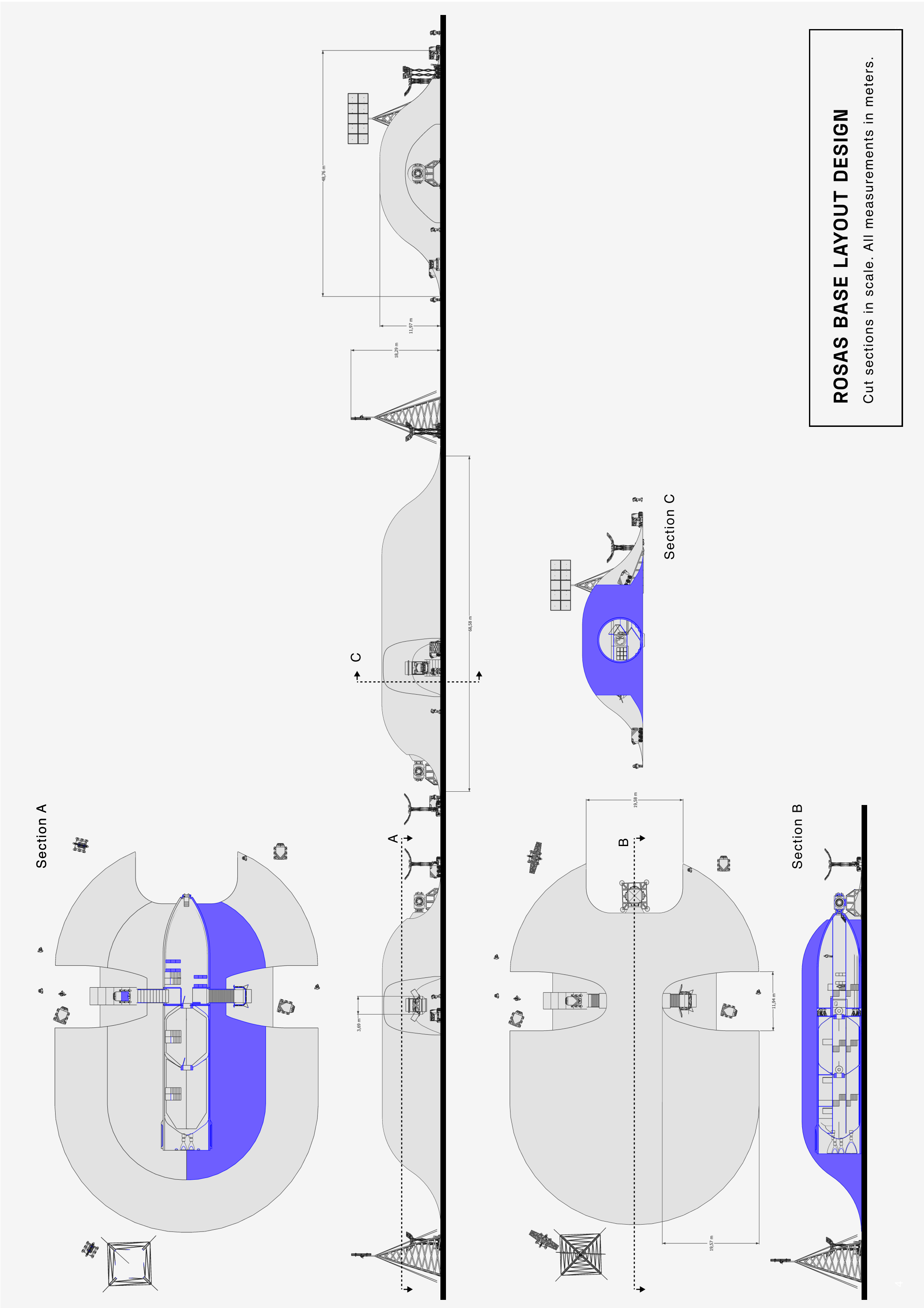
SAMPLE CREW SCHEDULE

Milestone	Groundbreaking Day
Number of Crew	4
LEVA Time	08:00 - 14:00
LEVA Hours	6 hours
Crew Wake Time	06:00 - 21:30
Crew Wake Hours	15.5 hours

DPRS	Depressurization
IN-CON	Internal systems check for constraints
DR	Drive
H-OPS	Horizontalization Operations
LR (Includes decompression time)	Leisure and relaxation
M-DPC/E-DPC	Morning/Evening Daily Planning Conference



A.5. Technical Drawings



A.6. Financial tables

Payload Costs Breakdown and Maintenance

Vertical (Landing Configuration)	R&D (Non-Recurrent Engineering) Cost ($)	Unit Cost (Production) ($)	# of Units (for single Base)	Reusable for additional Construction Missions? (Y/N)	Component Lifetime (year)	Unit Maintenance+ Resupply/ Lifetime (% of Unit Cost)	Unit Maintenance Cost ($M/year/Unit)	Total Maintenance Cost ($M/year)	Total Unit Costs per Base ($M)	Total Cost Future Base ($M)	Total Cost (Single Base) ($M)
Rosas Variant Starship	100.00	0.00	1.00	N	20.00	10.00	0.00	0.00	0.00	0.00	100.00
Morocos	405.75	135.25	4.00	Y	10.00	150.00	20.29	81.15	541.00	0.00	946.75
Detanker	5.00	10.00	1.00	Y	10.00	150.00	1.50	1.50	10.00	0.00	15.00
Scissor lift	0.50	2.00	1.00	Y	10.00	150.00	0.30	0.30	2.00	0.00	2.50
Robot shovels	0.10	1.00	4.00	Y	10.00	150.00	0.15	0.60	4.00	0.00	4.10
Hinge	0.20	1.00	1.00	Y	10.00	150.00	0.15	0.15	1.00	0.00	1.20
Anchors	0.50	0.20	5.00	Y	10.00	150.00	0.03	0.15	1.00	0.00	1.50
Drillling bit		0.20	1.00	Y	10.00	150.00	0.03	0.03	0.20	0.00	0.20
Solar panels	0.00	20.00	16.00	N	10.00	120.00	2.40	38.40	320.00	320.00	320.00
Radiators	0.00	0.10	28.00	N	10.00	120.00	0.01	0.34	2.80	2.80	2.80
Methalox power generator	0.00	0.25	1.00	Y	20.00	120.00	0.02	0.02	0.25	0.00	0.25
Power reactor	0.00	10.00	2.00	N	20.00	20.00	0.10	0.20	20.00	20.00	20.00
External communication antenna	4.00	1.00	2.00	Y	20.00	120.00	0.06	0.12	2.00	0.00	6.00
Horizontal (post-tipping)											
Nitrogen	0.00	1.50	1.00	N	1.00	100.00	1.50	1.50	1.50	1.50	1.50
Water	0.00	0.28	1.00	N	1.00	100.00	0.28	0.28	0.28	0.28	0.28
Hatch cutting system	5.00	10.00	1.00	Y	10.00	100.00	1.00	1.00	10.00	0.00	15.00
Hatches	0.20	1.00	1.00	N	20.00	100.00	0.05	0.05	1.00	1.00	1.20
Insulation	0.00	73.00	1.00	N	20.00	50.00	1.83	1.83	73.00	73.00	73.00
Floor support and boards	0.00	0.20	1.00	N	20.00	10.00	0.00	0.00	0.20	0.20	0.20
Walls	0.00	0.10	1.00	N	20.00	10.00	0.00	0.00	0.10	0.10	0.10
Water tanks	1.00	0.25	20.00	N	5.00	100.00	0.05	1.00	5.00	5.00	6.00
Agriculture equipment	0.00	20.00	1.00	N	5.00	100.00	4.00	4.00	20.00	20.00	20.00
Power lines	0.00	0.50	1.00	N	20.00	10.00	0.00	0.00	0.50	0.50	0.50
Internal communication system	0.00	1.00	1.00	N	10.00	120.00	0.12	0.12	1.00	1.00	1.00
ECLSS	114.33	85.75	4.00	N	5.00	25.00	4.29	17.15	343.00	343.00	457.33
Entrance corridor	0.50	0.10	1.00	N	20.00	10.00	0.00	0.00	0.10	0.10	0.60
Oscar	10.00	30.00	1.00	N	10.00	50.00	1.50	1.50	30.00	30.00	40.00
Dedicated equipment											
Beds	0.00	0.01	16.00	N	20.00	100.00	0.00	0.01	0.16	0.16	0.16
excercise equipment	40.00	80.00	1.00	N	20.00	25.00	1.00	1.00	80.00	80.00	120.00
infirmary and surgery equipment	0.00	0.10	1.00	N	2.00	100.00	0.05	0.05	0.10	0.10	0.10
washing machine	0.50	0.25	1.00	N	20.00	100.00	0.01	0.01	0.25	0.25	0.75
										0.00	
Airlock equipment										0.00	
elevator	0.50	0.50	2.00	N	5.00	100.00	0.10	0.20	1.00	1.00	1.50
elevator winch	0.03	0.10	4.00	N	5.00	100.00	0.02	0.08	0.40	0.40	0.43
airlock equipment	0.00	0.10	2.00	N	20.00	100.00	0.01	0.01	0.20	0.20	0.20

	R&D (Non-Recurrent Engineering) Cost ($)	Total Maintenance Cost ($M/year)	Total Unit Costs per Base ($M)	Total Cost Future Base ($M)	Total Cost (Single Base) ($M)
Totals ($M)	688	153	1,472	901	2,160

Financials - Detailed Yearly Capex-Opex Cost Breakdown

Description	Qty	Cost MUSD	Total	CAPEX/OPEX	Y0	Y1	Y2	Y3	Y4	Y5
No of Lander Missions					0.0	0.0	2.0	4.0	4.0	4.0
Space Transport										
Starship Habitat - Procurement	1	400	**400**	**C**	100.0	200.0	100.0	0.0	0.0	0.0
Starship Habitat - Launch	1	10	**10**	**O**	1.0	0.0	9.0	0.0	0.0	0.0
Starship Tanker - Launch for Habitat Refueling	4	10	**40**	**O**	4.0	0.0	36.0	0.0	0.0	0.0
Starship Tanker - Launch & Lander Refueling	8	10	**80**	**O**	0.0	0.0	160.0	320.0	320.0	320.0
Starship Lander- Launch	1	10	**10**	**O**	0.0	0.0	20.0	40.0	40.0	40.0
Moon Settlement										
Payload R&D	1	688	**688**	**C**	344.1	344.1	0.0	0.0	0.0	0.0
Payload MAIT	1	1472	**1472**	**C**	0.0	0.0	1472.0	0.0	0.0	0.0
Payload Maintenance	1	153	**153**	**O**	0.0	0.0	0.0	152.7	152.7	152.7
Supplies per Moon Inhabitant / yr	7	0.5	**3.5**	**O**	0.0	0.0	3.5	7.5	7.5	7.5
Space Suit MAIT	1	50	**50**	**O**	12.5	25.0	12.5	0.0	0.0	0.0
Space Suits	20	5	**100**	**C**	0.0	0.0	1.0	1.0	1.0	1.0
HQ										
Salaries	155	0.15	**23.25**	**O**	8.1	15.1	23.3	4.5	4.5	4.5
Office OPEX (rent, utilities)	1	0.25	**0.25**	**O**	0.1	0.3	0.3	0.3	0.3	0.3
General Costs										
Insurance	1	20	**20**	**O**	0.0	0.0	20.0	20.0	20.0	20.0
Frequency License	1	5	**5**	**O**	0.0	0.0	5.0	5.0	5.0	5.0
Control Center										
Salaries	100	0.08	**8**	**O**	2.8	5.2	8.0	2.4	2.4	2.4
Office OPEX (rent, utilities)	1	0.25	**0.25**	**O**	0.1	0.3	0.3	0.3	0.3	0.3
Equipment	1	5	**5**	**C**	1.5	2.0	1.5	0.1	0.1	0.1
IT and Software	1	2	**2**	**C**	0.6	0.8	0.6	0.1	0.1	0.1
Communications Earth-Moon (subcontract)	1	35	**35**	**O**	0.0	7.0	35.0	35.0	35.0	35.0
Moon Office										
Salaries (of Moon Builders)	30	0.15	**4.5**	**O**	2.3	4.5	4.5	4.5	4.5	4.5
IT and Software	1	5	**5**	**C**	1.5	2.0	1.5	0.5	0.5	0.5
Training Center										
Salaries (of training staff and subcontractors)	150	0.08	**12**	**O**	6.0	12.0	12.0	4.0	4.0	4.0
Office OPEX (rent, utilities)	1	5	**5**	**O**	2.5	5.0	5.0	5.0	5.0	5.0
Equipment	1	5	**5**	**C**	1.5	2.0	1.5	1.0	1.0	1.0
IT and Software	1	2	**2**	**C**	0.6	0.8	0.6	0.5	0.5	0.5
Analog Habitat	1	4	**4**	**C**	4.0	0.0	0.0	0.0	0.0	0.0
Analog Starship & Cowtipper	1	400	**400**	**C**	400.0	0.0	0.0	0.0	0.0	0.0
Analog Payloads & Systems	1	100	**100**	**C**	100.0	0.0	0.0	0.0	0.0	0.0
Analog Facility maintenance /yr	1	1	**1**	**O**	0.0	1.0	1.0	1.0	1.0	1.0

CAPEX/OPEX	Sum of Y0	Sum of Y1	Sum of Y2	Sum of Y3	Sum of Y4	Sum of Y5	Totals ($M)
C	954	552	1,579	3	3	3	3,094
O	39	75	355	602	602	602	2,276
Grand Total	**993**	**627**	**1,934**	**605**	**605**	**605**	**5,370**

HOW DO YOU HAVE A PARTY IN SPACE?
YOU PLAN-ET

....

WHY DID THE RESTAURANT ON THE MOON FAIL?
IT HAD NO ATMOSPHERE

....

A PHOTON WALKS THROUGH AIRPORT SECURITY. THE SECURITY GUY ASKS HIM IF HE DOESN'T HAVE ANY LUGGAGE, SO HE RESPONDS:
"OH NO, I'M TRAVELING LIGHT"

Jokes as told by Oscar Federico Castillo Rosas


SOLUTIONS FOR CONSTRUCTION OF A LUNAR BASE
ROSAS MISSION
SPONSORED BY
LOCKHEED MARTIN