INTERNATIONAL®
SPACE UNIVERSITY

SPACE MEDICAL CENTER

FINAL REPORT

MARCH 2021

SPACE MEDICAL CENTER

FINAL REPORT

International Space University MSS Program 2021

This MSS 2021 Team Project work was conducted at the ISU Strasbourg Central Campus in Illkirch-Graffenstaden, France.

Cover art and the mission patch were created in Canva. All images were used from the Canva repository. Logos remain the property of the respective organizations used with permission.

Front Cover Art: The project mission patch. The design was based on the services and resources offered by a space medical center. The Rod of Asclepius – a serpent wrapped around a rod – is placed in the center symbolizing the connection to Asclepius, the Greek god of healing and medicine. The wings of a medical caduceus are formed from the wings of a spacecraft to promote the advancement of medical services in space. At the bottom, the Earth serves as a reminder of where the project began. The ISS and the Moon symbolize the proposed locations for a space medical center.

Back Cover Art: The medical caduceus surrounded by a thin border signifying the reaches into space. Sponsor logos are displayed at the bottom of the page alongside a QR which contains a high-resolution video of an orbital space medical center module.

The Executive Summary and the Final Report may be found on the ISU website at http://www.isunet.edu in the “ISU Team Projects/Student Reports” section. Printed copies of the Executive Summary may also be requested, while supplies last, from:

International Space University
Strasbourg Central Campus Parc d’Innovation
Attention: Publications/Library
1 rue Jean-Dominique Cassini 67400 Illkirch-Graffenstaden France
Publications:
Tel +33 (0)3 88 65 54 32
Fax +33 (0)3 88 65 54 47
e-mail: publications@isunet.edu
website: www.isunet.edu

Supporting Organizations or Sponsors

National Aeronautics and Space Administration ***Centre National d'Études Spatiales***

&

We would like to thank our sponsors who contributed their time and expertise in defining key elements of this research. Specific thanks go to Dr. Kris Lehnhardt (NASA) and Dr. Francois Spiero (CNES), for sharing their visions of how an SMC could be created and the role it would assume in the future exploration of space.

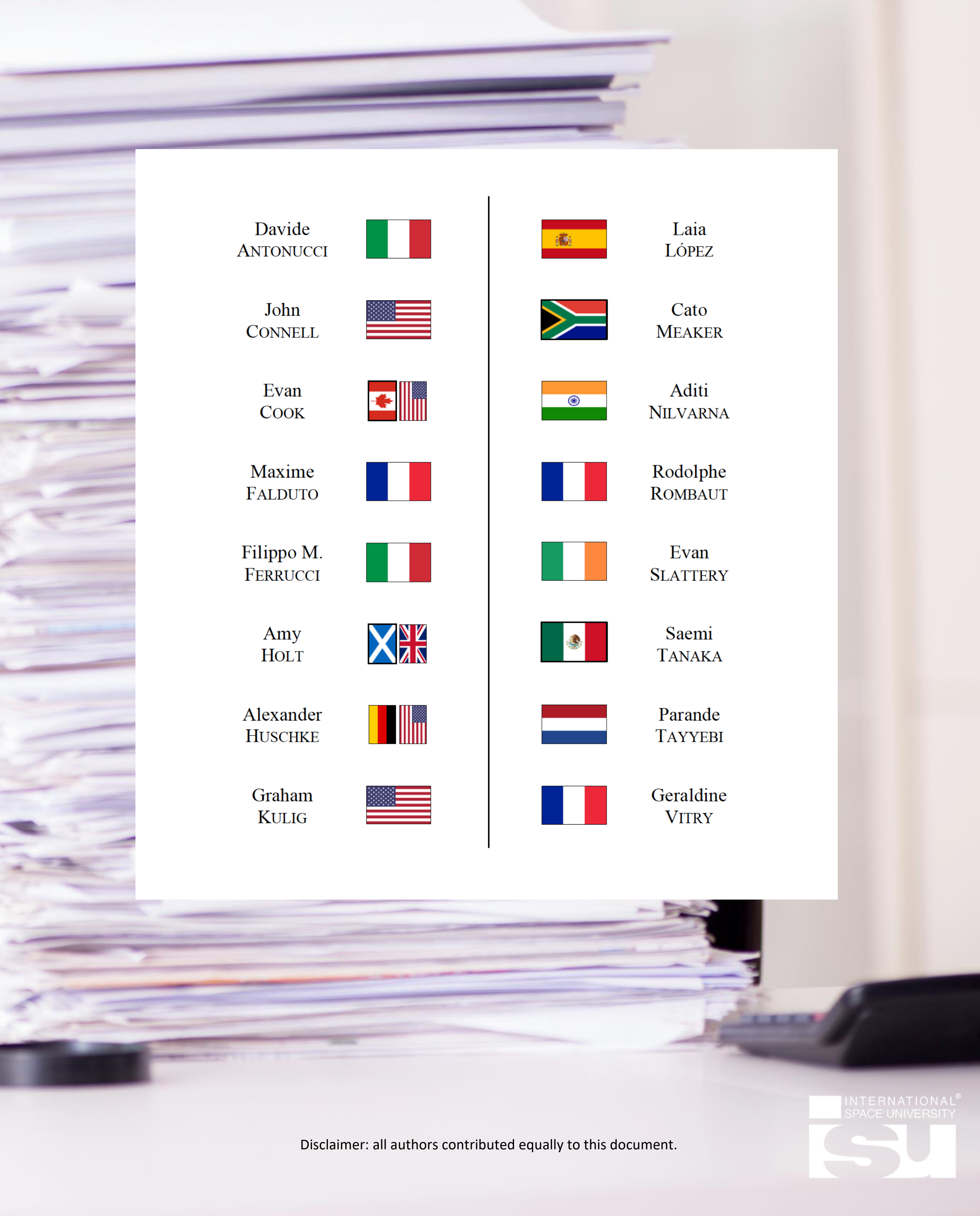
Acknowledgments

We would like to express our gratitude to our advisors Dr. Virginia Wotring and Dr. Taiwo Tejumola for their continued guidance and support. Their broad knowledge and expertise in all space disciplines have been invaluable in the development of this project. We also wish to thank the International Space University faculty for their insight and recommendations during the different stages of the project, and Ms. Stephanie Rocha, Mr. Nicholas Moncussi and Ms. Muriel Riester for their assistance on the project.

Additionally, we would like to thank the external industry experts who have donated their time and knowledge to our research via virtual interviews:

Mr. Amir Blachman,	*Chief Business Officer*	*Axiom Space*
Dr. Ilaria Cinelli,	*President*	*AsHFA*
Dr. Lihi Efremushkin,	*PhD Chemist and Lab Manager*	*Spacepharma*
Mr. Gonçalo Esteves,	*Director and Senior Consultant*	*BPM-D*
Dr. Sara Eyal,	*Associate Professor at the School of Pharmacy*	*Hebrew University*
Dr. Barbara Imhof,	*Co-Founder and Managing Partner*	*LIQUIFER SG.*
Mr. Simon Jenner,	*Human Spaceflight Business Development*	*Axiom Space*
Dr. Smith Johnston,	*Chief Medical Officer*	*Axiom Space*
Dr. Paranjothy Karunaharan,	*Founder and Executive Chairman*	*Aerospacemedic*
Mr. Craig Knott,	*Deputy Chief Medical Officer*	*Axiom Space*
Mr. Christian Maender,	*Director of In-space Research & Manufacturing*	*Axiom Space*
Dr. Emmanuel Urquieta,	*Deputy Chief Scientist*	*TRISH*
Mr. Yossi Yamin,	*Co-Founder & CEO*	*Spacepharma*

List of Authors



Davide Antonucci	🇮🇹	🇪🇸	Laia López
John Connell	🇺🇸	🇿🇦	Cato Meaker
Evan Cook	🇨🇦 🇺🇸	🇮🇳	Aditi Nilvarna
Maxime Falduto	🇫🇷	🇫🇷	Rodolphe Rombaut
Filippo M. Ferrucci	🇮🇹	🇮🇪	Evan Slattery
Amy Holt	🏴󠁧󠁢󠁳󠁣󠁴󠁿 🇬🇧	🇲🇽	Saemi Tanaka
Alexander Huschke	🇩🇪 🇺🇸	🇳🇱	Parande Tayyebi
Graham Kulig	🇺🇸	🇫🇷	Geraldine Vitry

Disclaimer: all authors contributed equally to this document.

Abstract

As mission duration and human presence in space increases, so too will the risk of injury, and likelihood of illness. To ensure long-term settlement of space in-situ medical care will become more essential. This report outlines three different scenarios. Scenario 1 consists of a near-term, space station module and associated configuration to provide optimal medical services to the increasing number of mission crews and space tourists transiting through Low-Earth Orbit in the coming decades. Scenario 2 consists of an idealized modular ground station facility on the lunar surface was developed with the aim of providing sustainable and autonomous medical care for future lunar settlements and human deep space exploration. Scenario 3 consists of a concept for an artificial gravity station that will act as a dedicated space facility in Low-Earth Orbit.

For all three scenarios, medical care, countermeasures, and technologies were analyzed and selected for use in an SMC based upon their capability of providing effective care and preventative measures in confined microgravity or reduced gravity environments. Appropriate present and future medical care for space crews and tourists include primary, acute, critical, pharmaceutical, surgical, and psychological care alongside suitable countermeasures and emergency services.

The scope of this report considers real-life scenarios and current trends in space medical practices. This is in an effort to develop comprehensive in-situ medical care in each proposed environment while complementing current efforts in a synergistic way. The modular approach to constructing a medical center considers scenarios pertaining to the growth of space economies for in-orbit missions, lunar exploration, and space tourism.

Faculty Preface

The 2021-2022 MSS Program brought together graduate students from many countries with training in different disciplines to study space. The class learned together through lectures, workshops, assignments, individual projects and team projects. Although these activities covered a broad range of topics, each emphasized ISU's commitment to intercultural, international, and interdisciplinary education. This year's students also stretched the boundaries of remote learning and electronic teamwork, as we all faced the COVID-19 pandemic: together, but at a distance.

During MSS21, two team projects were completed: Ocean Plastics and the Space Medical Center. This report presents the findings of the Space Medical Center (SMC) team. The report describes the team's analysis of potential designs for medical centers to serve the needs of people in space, whether professional space agency astronauts or those on holiday, and for visits that might last a few days in LEO to those that include building settlements on a planetary surface. Medical needs and capabilities were central, but the team also considered engineering capabilities & requirements, and new funding mechanisms that might allow the SMC to support itself, as well as cultural, ethical, and legal issues associated with an international medical center.

This team included 16 students from 13 countries with diverse experiences and education, working together for a five-month period. The team learned about medical systems used on space missions since the first Mercury flights and discovered a wealth of information on medical instrumentation and equipment. They also examined the historical and predicted needs of medical systems for space missions and worked through potential designs for vehicle areas dedicated to meeting those needs, all while working within the resource limitations of space vehicles and initial planetary shelters. The breadth of their backgrounds, across engineering, life sciences, physics, and business, allowed them to perform an interdisciplinary analysis of needs and capabilities.

The project benefited from consultation with experts in space medicine and new medical technologies, who graciously offered their time and insights. This TP also received generous sponsorships from NASA and CNES, whose representatives told the team about particular agency interests and concerns they wish to solve. NASA's challenge to the students was to design an ISS module that could be a medical center and also be leveraged during down time for other purposes like biomedical research. CNES challenged the students to look further into the future, to a time when space missions would be independent of Earth support and design a medical center with sustainability in mind. Thus, this team of students had the freedom to explore the evolution of space medical centers over time, advancing technology, and changing mission needs.

For much of the team, this project involved learning about medical care for space missions: what might be needed, how it could be delivered, and what preparations should begin soon. Additionally, the whole team learned more about themselves as each completed their individual tasks, with continual communication and review by other team members, moving their whole team closer toward their common goal of a high-quality design, analysis, and final report.

On behalf of the entire ISU faculty and staff, we would like to thank the team members for their dedication and hard work, and we are pleased to share this report with you.

Virginia Wotring, PhD and Taiwo Tejumola, PhD

Author Preface

The concept of a space medical center project was initially proposed by Dr. Ilaria Cinelli, Engineer and President of the Aerospace Human Factors Association, and an ISU alumna. It was born from the need to have a dedicated facility in space to facilitate the protection of the health and well-being of astronauts, space tourists and a potential future workforce alike.

The following report has been created after an extensive literature review and multiple interviews with experts in the field. The information gathered has informed a multitude of decisions made along the way regarding both the structure and function of the medical center. Tradeoffs have been made based upon the center’s location, utility, size, reliability, thermal and power requirements, among others. Each iteration has been reviewed and re-evaluated for its feasibility and usefulness. The final result is ultimately an amalgamation of the medical, legal, political, ethical, scientific, entrepreneurial, and architectural factors that combine to form a complete and functioning medical center.

It is also worth mentioning the environment in which this report was created, as it has been a challenge to accomplish this task in the era of social isolation and confinement. Working out problems on a shared whiteboard or having brainstorming conversations in the same room have been replaced by sharing ideas via online Apps and virtual meetings. The chemistry of physical interaction and looking over one another’s shoulders for ideas and assistance was replaced with the collaboration of chatting via text, through social media and various productivity programs. This project was created using Miro, SketchUp, Slack, Trello, and Zoom, and has been formed through a combination of teamwork over adversity and cooperation over confinement. The structure and content are a tribute to the students, faculty, staff, alumni, and colleagues of the International Space University.

Table of Contents

Abbreviations

ACLS	Advanced Closed Loop System
AI	Artificial Intelligence
ARIS	Active Rack Isolation System
BB	Blood Bank
BEAM	Bigelow Expandable Activity Module
CEVIS	Cycle Ergometer with Vibration Isolation and Stabilization
CHeCS	Crew Health Care System
CMO	Crew Medical Officer
CMRS	Crew Medical Restraint System
COPUOS	Committee on the Peaceful Uses of Outer Space
CSA	Canadian Space Agency
CT	Computed Tomography
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
EVA	Extravehicular Activity
ExMC	Exploration Medical Capability
EXPRESS	Expedite the Processing of Experiments to the Space Station
FAA	The Federal Aviation Administration
FMEA	Failure Mode and Effects Analysis
HRP	Human Research Program
IATCS	Internal Active Thermal Control System
ICH	Intracranial Hemorrhage
IDSS	International Docking System Standard
ISPR	International Standard Payload Rack
ISS	International Space Station
LEO	Low-Earth Orbit
MC	Mission Control
MCC	Mission Control Center
MELiSSA	Micro-Ecological Life Support System Alternative
MIS	Minimally Invasive Surgery
MMPB	Multilateral Medical Policy Board
MRI	Magnetic Resonance Imaging
NASA	National Aeronautics and Space Administration
NDS	NASA Docking System
NIRS	Near Infra-red Spectroscopy
OCT	Optical Coherence Tomography
OST	Outer Space Treaty
PPC	Private Psychological Conference
PPE	Personal Protective Equipment
PNTBT	Partial Nuclear Test Ban Treaty
SANS	Spaceflight-associate Neuro-ocular Syndrome
SMART	Specific, Measurable, Achievable, Realistic, Timely
SMC	Space Medical Center
SMC-LEO	Space Medical Center-Low Earth Orbit
SMC-LUN	Space Medical Center-Lunar surface
SMC-GW	Space Medical Center-Gravity Wheel
TBI	Traumatic Brain Injury
TDRS	Tracking and Data Relay Satellite
TRISH	Translational Research Institute for Space Health
TT&C	Telemetry, Tracking and Command
UHF	Ultra High Frequency
UTI	Urinary Tract Infections
VR	Virtual Reality
WinScat	Windows Spaceflight Cognitive Assessment Tool
WSGT	White Sands Ground Termina

List of Tables

List of Figures

1. Introduction

The near future will likely see humans spending greater lengths of time in deep space as exploration and business opportunities are exploited. Advances in technology will aid in both the transportation and ultimately the settlement of humans in this new environment. However, technology alone cannot, as of yet alter the fact that human beings are inherently vulnerable to many factors within the space environment. They are susceptible to disease and injury, can suffer trauma and develop infections, whilst also being prone to mental health disorders due to isolation and confinement. Therefore, as humanity plans an increasing number of expeditions into space not only in Low-Earth orbit (LEO) but also with the longer-term goal of returning to the lunar surface, access to medical facilities on a regular basis will become critical to mission success.

Prevention and protection for medical conditions are valid countermeasures. However, it is unreasonable to rely on them alone. Humans are complex biological organisms and are prone to unexpected injury or dysfunction. When this occurs, diagnosis and treatment are the mitigating factors. Therefore, the argument can be made for the provision of professional medical services to protect the most important payload of any mission, the human crew. A space medical center (SMC) would be a definitive solution for this problem.

The SMC will serve as a multifunctional unit. It will provide patient medical care including primary, emergency, and critical care. It will also offer dental services, nursing care and mental health care and counselling, along with a comprehensive exercise countermeasures area. The center will be capable of facilitating a variety of commercial research experiments, whilst also providing ongoing staff training all in one space. It should be able to accommodate these diverse functions and convert between them quickly, serving as a comprehensive, multipurpose space-conscious facility.

This comprehensive medical center will act as the central hub for crew protection, serving as a refuge from radiation, hypobaric pressure, and psychological stress. It will function as a doctor's office, emergency room, surgical suite, intensive care unit, recovery ward, and rehabilitation center, all in one. From routine health care and health maintenance, to complicated surgery, this facility will be the clinic and hospital needed to ensure human survival and optimal function in deep space.

Three designs for an SMC are presented in this report, with each pertaining to a different location in space. The first design creates an SMC as an attachment to the International Space Station (ISS) in LEO. This station would be assembled on Earth and transported to the ISS by a heavy launch vehicle. This vision is a more practical, near term solution for LEO to service astronauts and space tourists alike and its design is based on currently available technology. The second design is for creating an SMC on the lunar surface, which would be partially assembled on Earth with final assembly on-site on the lunar surface. This SMC would be larger, enabled by its modular assembly, giving it more workspace and room for medical, research and exercise equipment. This would be a more mid-term solution where more experimental and not-too-distant future technologies could be employed. Finally, the third envisions an SMC in as part of a large, rotating space station in LEO. The assembly would be piecemeal in orbit and it would have a greater capacity for medical and research equipment than the previous iterations. This rotating circular space station would also be capable of generating artificial gravity at one-third of the force on Earth and much more futuristic technologies could be included within its design. Combined, these three scenarios represent the three stages of a potential plan for the evolution of an SMC into an ever larger and more complex and futuristic structure over time.

The core function, however, would remain the same across all SMC designs and the plans described here will provide the full gamut of healthcare, from primary to tertiary care. Capabilities will exist for routine care and health maintenance, along with emergency care, surgical care, and intensive care. The personnel on board will also be trained in a full spectrum of services, that also include Gynecological and dental care. Each single center will encompass all aspects of health and will be capable of changing from one mode of care to another in the same space as the need arises.

To explain the need for a comprehensive medical center in space, the Exploration Medical Capability (ExMC) of the NASA Human Research Program (HRP) has identified one hundred health conditions that are likely to affect crews on deep space missions (Watkins, Barr and Kerstman, 2011). This Space Medicine Exploration Medical Condition List (SMEMCL) provides an evidence-based rationale to prioritize conditions that will be addressed by the medical center. Topping the list are the most likely and most treatable conditions, such as nausea, headaches, back pain, and skin rashes. Other conditions may be less likely but may have more severe consequences, such as appendicitis, cholecystitis, pancreatitis, or an anaphylactic drug reaction. For deep space exploration, these ailments will require mitigation when there is no reasonable expectation of an expedient return to Earth for further care. Therefore, it would be preferable to first learn how to treat these conditions in LEO, which will also provide an ideal location to act as a proving ground for assessing new and upcoming medical capabilities and testing their suitability for future deep space exploration. The SMC-LEO module will act as an ideal testbed for this.

Other services will also add to the complete picture of care. For exercise countermeasures, the SMC-LEO will provide limited exercise equipment since the bulk of such equipment will already be available aboard the ISS. The SMC-LUN on the lunar surface, however, will incorporate comprehensive exercise countermeasures due to a greater availability of space and the added benefit of gravity. Rehabilitation and Nursing care will also be important, and mental health care and counselling will be essential to treat the stress of living and working in the extreme environment of deep space.

All versions of the SMC will also serve as a basic science and clinical research laboratory for the majority of the time when not providing direct patient care. The resources of the medical center will be devoted to biological experiments in microgravity and reduced gravity. Physiological, cellular, and sub-cellular investigations will be conducted, either directly by SMC staff, or with assistance from staff on autonomous, self-contained experiments. In some cases, the same resources dedicated to diagnostic clinical work will serve both clinical and research functions. Clinical diagnoses can also benefit from other high powered research tools, and specialty trained personnel who operate them on board the medical center.

The research conducted on board the SMC will be revenue generating and business partnerships will be formed with private corporations, space agencies, government science agencies, foundations, and universities. These customers will be able to rent research space for their experiments and have SMC personnel perform the research or assist. The commercial research carried out will generate profits to offset the cost of creation and maintenance of the medical center and will be the mainstay of income for the SMC.

Across all disciplines, several aims and objectives have been generated to guide the focus of the SMC. The selected aims listed here in Table 1 were chosen as a sample to demonstrate the goals to be achieved by the design, and the objectives state the methods to achieve them.

Table 1: Aims and Objectives to Determine the Direction and Design of a Space Medical Center

Business	**Aim:**	To develop optimal business opportunities for commercial research
	Objectives:	To identify the appropriate customers for commercial research
		To establish strong business relationships with customers and potential customers
Medical	**Aim:**	To provide excellent healthcare to astronauts and space tourists
	Objectives:	To provide extensive training for medical personnel
		To have the most up to date and reliable imaging methods in space
Research	**Aim:**	To perform ground-breaking research in space
	Objectives:	To provide customers with highly desirable research equipment and resources in space
		To facilitate customers with technical support, scientific consultation, and the hardware facilities and utilities they require
Engineering	**Aim:**	To create a structurally and functionally sound medical center over the long-term that complies with the given project constraints and exceeds its requirements
	Objectives:	To provide radiation shielding that exceeds the protection of the current ISS modules
		To create a multifunctional SMC that converts instantly from research to medical care areas
Legal	**Aim:**	To protect the intellectual property of commercial research partners
	Objective:	To streamline intellectual property and export control regulations documentation
Ethical	**Aim:**	To provide inclusive and culturally appropriate elements and practices at the SMC
	Objective:	To identify direct and indirect implications of bio-ethical considerations involved in the developmental phases of an SMC

To reiterate, the SMC will be a comprehensive medical center with an advanced biomedical research facility along with an exercise and rehabilitation center, all in one. Its function will change on-demand based on need and it will also act as the central hub for crew protection, where it will also be a place of refuge from radiation, hypobaric pressure, and psychological stress. From routine health care, and health maintenance, to complicated surgical procedures, this facility will be the clinic and hospital that human crews will need to guarantee survival and optimal functioning in deep space.

The goal over the next few decades will be to send crewed missions to both the Moon and Mars, therefore it will be essential to prepare for these endeavors. Testing an SMC first in LEO, and then on the lunar surface, could be a crucial first step towards guaranteeing future success on other celestial bodies such as Mars. The designs presented in this report can hopefully function as a test for future plans needed for longer duration missions.

The report below, gives the reader a tour through the considerations required and the designs planned for the three iterations of the SMC. It begins in Chapter 2 with a description of the different scenarios for the site planned for the SMC in LEO, on the lunar surface, and in LEO with a rotating station with artificial gravity. This chapter also identifies the potential customer bases for the commercial ventures of the medical center. Chapter 3 presents the design of the medical center in LEO, with detailed descriptions of its architecture, logistics, and functions. Chapter 4 gives a similar yet abbreviated description of the medical center on the lunar surface, with the advantages stated for the benefits of gravity and additional workspace. Chapter 5 presents design and considerations for a medical center on a rotating station in LEO orbit, creating artificial gravity. Chapter 6 assesses the necessary risks and technological constraints that each iteration of the SMC will encounter. Chapter 7 turns the reader towards the business aspects of these three locations, with further analysis of investments and costs, and finally, Chapter 8 explains the legal and ethical considerations that must be dealt with before embarking on a venture such as this. The policies, treaties, religious and ethical constraints, and requirements to be respected are discussed. The circumferential view given by these multiple approaches will combine to form the holistic model of an SMC given here.

2 Scenario Comparison

Scenario 1

STAGE I

The SMC located in LEO as an attachable module to the ISS.

Scenario 2

STAGE II

The SMC located on the Lunar surface.

Scenario 3

STAGE III

The SMC as a gravity wheel located in LEO.

This report is outlined using a three-step approach, where each step will represent a forward journey that will see humankind expanding beyond LEO and into deep space. For each step, we will propose three configurations for an SMC. These proposed configurations will be the initial attempts of implementing dedicated medical and research facilities in LEO and the Moon and will act as both support and facilitators for human settlement in space.

The SMC can be designed in different ways depending on location, intention, and purpose. The proposed plans for developing SMC iterations are divided into three scenarios or stages. They give a stepwise approach to the possible forms that an SMC could assume over time. In the near-term, an SMC module in LEO, about the size of the Columbus module, that can attach to the ISS. Further into the future, after creation of the Lunar Gateway planned by NASA, ESA, JAXA, and other partners, an SMC could be placed on the lunar surface. Still further into the future, an SMC could be idealized as part of a rotating circular station with artificial gravity, or “gravity wheel”. Each of these iterations have been proposed to adapt to the advancements in spaceflight as humans travel further away from Earth.

2.1 Space Medical Center: Low-Earth Orbit

This first stage of the designs for an SMC will reside in LEO, hereafter referred to as SMC-LEO. Currently, the most likely location for a medical center for both patient care and commercial research is as an attachment to an existing or upcoming space station. The ISS is the most likely host and there are plans for private and public space stations from Axiom Space and the Russian and Chinese governments within the next decade (Axiom Space, 2021; BBC, 2021). With these in mind, the SMC-LEO was designed to be attached to the ISS, but with international docking capability that would mark its compatibility with in-development stations.

LEO is the obvious first step since it is the nearest and most accessible location, and therefore has several benefits. An SMC-LEO is the easiest to reach and resupply. The ISS is already established with an excellent performance record. The crewmembers will be inside the Van Allen radiation belts and will experience less radiation exposure during sojourns. Evacuation, if necessary, can be accomplished within 12 hours. The ISS has a well-functioning ECLSS system, and its large solar arrays provide ample power. For these reasons, the SMC-LEO attachment could benefit from the station’s life support and power systems, while in return offering medical services and payment through funds generated by commercial research and healthcare for space tourism.

For medical operations, the goal is to provide a near-complete spectrum of medical care and an extensive capability for biomedical research. The SMC-LEO will be equipped to be a primary care clinic, emergency room, limited operative suite, intensive care unit, exercise and health maintenance facility, psychological counseling office, and rehabilitation center. It will also host an extensive core laboratory with appropriate technology for a wide variety of in-situ research applications. Additionally, rack space will be made available in the walls and ceiling for customizable and customer-driven research projects.

2.2 Space Medical Center: Lunar Surface

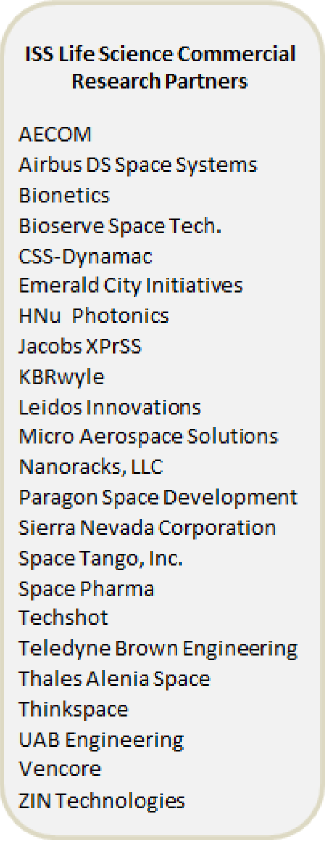
The next step for the SMC concept will be for a medical center on the lunar surface, hereafter referred to as SMC-LUN. This design is in anticipation of the increase in lunar habitation that is expected to occur over the next few decades. After the Lunar Gateway concept has finished construction by the members of NASA’s Artemis program, there will be a need for a medical center on the Moon to service the researchers, construction workers, and possibly miners that will occupy the first lunar habitats. There, they will be isolated from the Earth by a matter of days, without the possibility of a speedy evacuation to Earth in the case of a severe illness or injury.

The SMC-LUN will be larger than the SMC-LEO module. Though it will be costly to deliver building materials to the Moon, gravity will be a benefit throughout construction, and in-situ materials can be used for additional support and for radiation shielding. Therefore, the radiation and micrometeorite shielding can be less than that of LEO, which can save considerable weight and cost. Also, the SMC-LUN could potentially be constructed within a lunar lava tube, which could save considerably on the need for radiation shielding.

The functions for treating patients and performing research offered in an SMC-LEO will be the same in an SMC-LUN, with some modest additions. With the addition of gravity, open surgical procedures can be performed, which could make the difference in saving lives and ensuring individual well-being. Additionally, more space on the Moon can facilitate the use of exercise equipment and a laboratory research space. Also, since an SMC-LUN is planned for approximately 10 to 30 years in the future, the emergence of new technologies for use in both medical care and research could be of great benefit.

2.3 Space Medical Center: Gravity Wheel

The third stage will be for an SMC as part of a rotating "gravity wheel", hereafter referred to as SMC-GW. For this stage, which will occur further in the future than the lunar surface design, the SMC-GW will enjoy both a location in LEO and the benefits of ⅜ g. With this level of gravity, it will be similar to and yet superior to working on the lunar surface. Open surgery will again be possible, and emergent procedures such as cardiopulmonary resuscitation (CPR) will be more practical. Being located in LEO will also be beneficial for simpler and more rapid resupplies for commercial experiments, medical supplies, and pharmaceuticals.



ISS Life Science Commercial Research Partners

AECOM
Airbus DS Space Systems
Bionetics
Bioserve Space Tech.
CSS-Dynamac
Emerald City Initiatives
HNu Photonics
Jacobs XPrSS
KBRwyle
Leidos Innovations
Micro Aerospace Solutions
Nanoracks, LLC
Paragon Space Development
Sierra Nevada Corporation
Space Tango, Inc.
Space Pharma
Techshot
Teledyne Brown Engineering
Thales Alenia Space
Thinkspace
UAB Engineering
Vencore
ZIN Technologies

Figure 1: List of companies and research partners for commercial space life sciences

2.4 Customer Identification

Before delving into the technicalities of the individual SMC iterations, it is important to understand the kind of customers the facility will cater to. In principle, the SMC-LEO could attract some of the same customers as the ISS. The commercial partners that have been performing research with the ISS may wish to expand their in-space research capabilities and welcome additional facilities with a dedicated research staff. NASA is restrained by law from competing with the private sector in LEO, therefore if a U.S. Entity is able to provide resources, such as commercial research capability, NASA would be able to migrate those services to a non-governmental provider (NASA, 2019a). Meanwhile, for clinical activities, the SMC could provide insurance and fee-for-service care to private astronauts while possibly providing medical care to governmental astronauts if certified by the Multilateral Medical Policy Board (MMPB) and Multilateral Space Medicine Board (MSMB) of the ISS (Nicogossian et al., 2016).

2.4.1 Customer Segment: Commercial Research and Space Tourism

Space-based research is a proven asset to develop new technologies and processes that take advantage of the microgravity environment offered by ISS facilities. Democratization of space will give companies more opportunities to perform innovative research in space, thereby generating new commercialization opportunities. Currently, the ISS provides a testbed for new technologies, allowing developers to characterize, optimize, and qualify hardware performance and elaborate on space-qualified equipment which can in turn enable other applications. Of almost 3,000 experiments on the ISS, over one-third of them have been for biology and biotechnology (Witze, 2020). The main research activities carried out in an SMC will be life science research and technology demonstrations. The SMC-LEO could expand opportunities for companies to carry on those kinds of research, creating a profitable niche for itself and serve as a spacious testbed for new technology.

Commercial space tourism, unlike research applications, is still in its infancy. This stage is commonly referred to as a “blue ocean,” meaning a new market with no established competition where entrepreneurs can experiment with novel business models to create value and intercept untapped customer needs. In the next decade, LEO will become an increasingly popular space destination. The ISS, in particular, is attractive as a tourist destination for stays longer than a few days. An SMC-LEO, if strategically integrated in a business model, can represent the enabling element to generate profit (Axiom Space et al., 2018) from both public agency and private astronauts.

While private astronauts could potentially be anyone with the means and availability to travel to space, public agency astronauts are selected by national space agencies. Historically, new candidates have ranged between the ages of 43 and 46, with the average age being 44. However, the average age for astronauts transiting through the ISS is 43 years for females and 46 for males (NASA, 2013; Stierwalt, 2020). Additionally, these individuals are deemed both physically and psychologically healthy following a rigorous selection process with excellent medical care between selection and mission operations.

Meanwhile, space tourists may not have the same fitness levels of public agency counterparts. Space tourism is currently marketed to a small audience consisting of high net-worth individuals. In general, they are older. The average age for this crew is 62 years, with a range from 50 to 70, with a retired NASA astronaut as mission commander. These types of individuals may need more medical care and be in a position to afford high quality care at a premium. Over the next several decades, it is likely that private astronauts will outnumber their institutional counterparts. The average age of early space tourists was 50 years, which could potentially develop into an increasing market.

2.4.2 Future Perspectives for the Lunar Surface

Expansion beyond LEO to the Moon and cis-lunar space will be gradual and driven by practicality. Expansion in these environments will mainly have a scientific focus, with a similar purpose as scientific facilities in Antarctica. Initially, there would likely be few economically profitable activities in an SMC-LUN. But with Artemis program, a return to the lunar surface is expected by the mid 2020's with the end-goal of establishing a permanent settlement: a task that will continue for well over a decade.

Concerning the number of humans working in space, the number is assumed to increase due to lower costs, easier access to space, and a growing infrastructure. It is reasonable to expect the number of people conducting work in cis-lunar space to approach the number of people working in Antarctica, reaching up to a few hundred by the mid to late 21st century. Therefore, the need for an SMC-LUN will continue to expand with the population.

The three iterations of the SMC will be developed to accompany human expansion further into space. Through offering dedicated medical care to private astronauts, public agency astronauts and space tourists, and through providing ample research opportunities in unique locations, the concept of an SMC would help human well-being and scientific advancement flourish in off-Earth environments. Therefore, a dedicated SMC will permit humans to create a sustainable presence in LEO and on the lunar surface.

Therefore, in summary, there will be three versions of a space medical center presented in this report, in LEO, on the lunar surface, and on a gravity wheel in LEO. Each will have core functions which are similar, such as extensive medical care for a multitude of conditions, high-level life sciences research capabilities, and an interactive training center for Earth-to-SMC and SMC-to-Earth education. Yet, each will vary because of the absence or presence of significant gravity and the availability of extended workspace. Each will also share similar opportunities to generate revenue through commercial research and clinical care, yet each will have slightly different customers and different capabilities to offer them. The business model of the SMC, overall, will be discussed further in Chapter 7. Next, the design for the SMC in LEO will be discussed, followed by chapters for the SMC on the lunar surface, and as part of a rotating station in LEO.

3

THE SPACE MEDICAL CENTER IN LOW EARTH ORBIT

Scenario 1

The first scenario is placing an SMC in LEO, the nearest and most accessible location when going into space. The SMC would be an attached module to the ISS, a station capable to support its activities. This section shall propose the five purposes of an SMC-LEO: a health and performance clinic, an emergency center, an exercise and rehabilitation facility, a training center, and a life sciences research facility. Furthermore, it will discuss the design and architecture for Scenario 1.

The first site chosen for an SMC is near to the Earth, in LEO. Just as for the decisions that were made for the location of the ISS during its creation, the SMC in LEO will follow the same path. This area of space is within closest reach for launch with less fuel required than a medium Earth orbit or a geosynchronous orbit. This also simplifies resupply and evacuation in case of an emergency. The radiation levels are also lower here and communication with the ground is nearly seamless. For these reasons, and to test the SMC concept near to Earth, the position in LEO was chosen as a first step. The following chapter now describes all of the aspects to be considered in the SMC design, from medical operations to research processes to engineering plans. Each section will detail the planned activities and capabilities of an SMC. This will be the largest and most detailed description for an SMC site since it explains the core functions that are consistent among all SMC designs, in LEO, on the lunar surface, and in an artificial gravity station.

LEO is a proving ground for exploration of deep space. It is where hypotheses are tested before venturing further from Earth, with firmer conclusions to guide longer explorations. It is also a place to test scientific theories and technologies without pertaining to exploration of the solar system. Many discoveries have been made aboard the ISS for basic science and biomedical research, and many technologies have been advanced in space that have developed beneficial terrestrial spin-offs. For example, the fifth state of matter was achieved on the ISS, and a possible treatment for Duchenne Muscular Dystrophy is in trials-based research with protein crystals on the ISS (Rainey, 2015; JPL, 2020). For this reason, the SMC-LEO will be a center for healthcare and biomedical research, with the majority of operations spent on research. It will function as a commercial laboratory and offer space for specialized and individualized research supported by SMC-LEO staff.

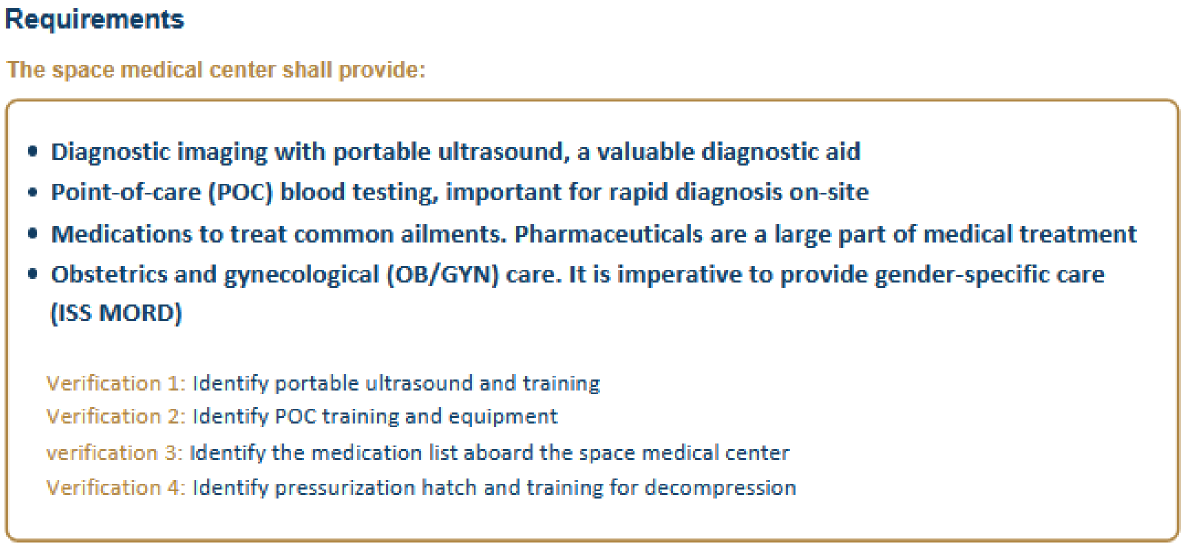
Medical care is also a core operational function of the SMC-LEO. It will serve as a hospital within a space station treating patients with common and minor ailments as well as those with the rarer and more serious conditions. The SMC-LEO will provide routine primary care with basic examinations, testing, and pharmacological treatments, and it will act as a human performance center, emergency room, critical care ward, and psychological counseling center. There will be slight differences in the treatments given in SMC-LEO from the lunar surface and artificial gravity environments, but the basic clinical care and research services in an SMC-LEO will establish the foundation for future in-space medical operations and research opportunities.

The SMC-LEO is required to provide basic care in routine situations and more advanced care for emergent conditions. Basic routine care shall include the use of appropriate pharmaceuticals for common ailments, diagnostic testing, and dental repairs. Emergency and critical care shall include airway management, ventilation, defibrillation, trauma care, and in-depth monitoring (NASA, 2006).

3.1 Low-Earth Orbit Health and Performance Clinic

3.1.1 Primary Care

Primary care is the comprehensive practice of caring for individuals which includes addressing both physical and mental health requirements. Routine care aboard the ISS consists of basic physiological monitoring and treatment for minor ailments with pharmaceutical applications such as analgesics, anxiolytics, or antidepressants (Hodkinson et al., 2017). Simple diagnostic imaging will be performed with a portable ultrasound, which is a useful, versatile, hand-held device capable of imaging many areas of the human body. The primary care requirements for an SMC-LEO are provided in Figure 2.



Requirements

The space medical center shall provide:

- Diagnostic imaging with portable ultrasound, a valuable diagnostic aid
- Point-of-care (POC) blood testing, important for rapid diagnosis on-site
- Medications to treat common ailments. Pharmaceuticals are a large part of medical treatment
- Obstetrics and gynecological (OB/GYN) care. It is imperative to provide gender-specific care (ISS MORD)

Verification 1: Identify portable ultrasound and training
Verification 2: Identify POC training and equipment
verification 3: Identify the medication list aboard the space medical center
Verification 4: Identify pressurization hatch and training for decompression

Figure 2: Primary medical care requirements for a Space Medical Center.

Key parameters for monitoring crew health will include blood pressure to monitor the effects of the microgravity environment and radiation exposure. Blood pressure has traditionally been monitored on the ISS via a leg cuff (Wood et al., 2019), but with the advent of smartwatches and more personalized bio-monitoring devices, it is now possible to obtain an almost nonstop flow of biometric data from astronauts. One such device is Astroskin - a wearable system incorporated into a shirt that is able to monitor not only blood pressure and pulse rate, but oxygen saturation levels and breathing rate - which was developed by Hexoskin and funded by the Canadian Space Agency (CSA) (Canadian Space Agency, 2019). The use of such personalized devices will form an integral part of the ongoing routine care and monitoring in an SMC-LEO. Radiation levels will also be monitored via Crew Passive Dosimeters (CPDs), which space crews will wear throughout a given mission (Schimmerling, 2009).

Eye health will also be monitored closely on missions due to the potential development of Spaceflight-associated Neuro-ocular Syndrome (SANS): a condition causing vision problems characterized by the flattening of the sclera, choroidal and retinal folds, hyperopic refractive error shifts and optic disc edema (Afshinnekoo et al., 2020; Lee et al., 2020). To date it is still unknown as to why SANS occurs (Lee et al., 2020) and there are no countermeasures that currently exist. Therefore, routine eye exams will be carried out regularly on the SMC-LEO using a combination of an ophthalmoscope, Optical Coherence Technology (OCT), and orbital ultrasound. Routine blood work for basic chemistries and hematology, as well as urinalysis, will be performed with point-of-care testing devices, as needed.

Space crews will also be subject to audiological exams both before and after missions. Monitoring hearing once on board the ISS, however, will be more difficult due to the relatively moderate to high levels of ambient noise that are produced by the life support system. However, recent experiments conducted aboard the ISS itself, have exploited otoacoustic emissions (OAEs), which have allowed the monitoring of auditory changes in a quick, non-invasive objective manner (Moleti et al., 2019). Such audiological assessments will be implemented into the medical centers routine as and when they are developed.

Gynecological health in space crews has not been a priority field of research to date, but future missions will see astronauts subjected to increased lengths of time in deep space where routine examinations will most likely need to be implemented. So far, studies on women's health have found that urinary tract infections and urinary retention are common conditions that occur during spaceflight but can be easily treated with oral antibiotics (Drudi and Grenon, 2014). Venous thromboembolism also has a risk of occurring during spaceflight. On Earth the risk is increased for women who also take the combined oral contraceptive pill, but a study on female astronauts found that taking oral contraceptives does not increase this risk in space (Jain et al., 2020). However, further research is still required to fully evaluate the effects of spaceflight on female physiology and gynecological health before longer duration missions can take place. The SMC-LEO will therefore serve as an ideal testbed to implement such research.

3.1.2 Pharmacological Care

Medications will be a mainstay of care aboard the SMC-LEO. For most common ailments and some more serious conditions, pharmaceuticals will serve as a simple treatment option. The NASA Human Research Roadmap of medical conditions in space considers medications to be the primary countermeasure for most conditions, including infections, bone loss, sleep issues, and behavioral issues (Blue, 2019; NASA, 2021a). Similarly, the NASA Exploration Medical Capability (ExMC) has stated that pharmaceuticals are the single most important element of complete medical care, possibly equaling over one-fourth of all medical interventions (Blue, 2019). This means medications could comprise more medical interventions than medical imaging, procedures, and surgical interventions, combined (Antonsen, 2018).

The SMC-LEO will stock the same classes of medications currently available on the ISS. These include antiemetics for nausea, non-steroidal anti-inflammatory drugs (NSAIDs) for minor pain, sedatives for insomnia, oral antibiotics for minor infections, and intravenous antibiotics for more serious infections (Taddeo, Gilmore and Armstrong, 2019). Meanwhile, the shelf-life of a medication could be altered by removing it from the manufacturer's packaging. With humidity, handling, and exposure to oxygen, it is possible that not only the shelf-life could be reduced but the effectiveness of a medication as well (Wotring, 2012). Removing medication from its original packaging, however, is common practice in spaceflight to reduce size and pack efficiently (Wotring, 2011; Blue et al., 2019). In fact, this is considered a knowledge gap in the NASA HRP Roadmap requiring further research in space (NASA, 2021b). There is a NASA Human Health Countermeasures study with planned funding to evaluate the effectiveness of all ISS medications not covered by previous FDA or National Space Biomedical Research Institute after prolonged spaceflight (NASA, 2020a; NASA, 2020b). This is necessary to close this knowledge gap to understand the medical resources available for long duration exploration.

An SMC-LEO pharmacy will include routine medication for pain, allergy, congestion, and sleep disorders. However, emergency, critical, and surgical care also require specific pharmaceutical capabilities while also dealing with long conservation constraints, e.g., anesthetics, vasomodulators, neuromodulators. A better characterization of pharmaceutical formulation and packaging is required to enable efficient and suitable capabilities in space and to enhance molecular stability and shelf-life over high g load and vibration at launch, but also microgravity (Putcha, 2011; Daniels, 2017).

3.1.3 Psychological Care

It is imperative to consider appropriate countermeasures and treatments pertaining to the psychological well-being of space crews and tourists. An individual's psychological health can impact their ability to withstand the rigors of space and adjust to the various factors of isolation, confinement, and stress (NASA, 2011a). It is common for individuals to exhibit psychological symptoms including decreased concentration, decreased motivation, somatic disturbances, and changes in mood or behavior when placed in an isolated, confined, or stressful environment (Clement, 2011). An SMC-LEO will be equipped with the proper tools and treatments to ensure well-being and psychological health.

Many psychological symptoms in space can stem from a range of stressors. External stressors can include microgravity, crew size, equipment malfunctions and the dangerous nature of space (Kanas, 2016). Internal stressors can include isolation from family and friends, interpersonal conflicts, sleep disturbances, and confined conditions (Manzey, Schiewe, and Fassbender, 1995). The longer an individual spends in space, the longer they will be exposed to psychological stressors which can result in the development of more severe symptoms. Most common in-flight symptoms tend to be mild, including depression and anxiety. However, increased duration of in-space travel and the introduction of space tourism could lead to the development of more acute psychological symptoms.

Therefore, an SMC-LEO will need to be able to support psychological conditions, both mild and severe, through a combination of countermeasures and treatments. All countermeasures and treatments, however, will need to operate with the singular aim of providing space crews and tourists with the knowledge and ability to not only stabilize any psychological symptoms, but maintain in-flight performance and minimize risk to crew well-being via in-flight monitoring, in-flight support, and pharmaceutical care (loc. Cit.).

In-flight monitoring can be used to identify potential psychological symptoms or conditions early on. Monitoring cognitive performance, workload, sleep, stress, and behavior can prevent psychological issues from becoming serious threats (Kanas and Manzey, 2008). This can be achieved either remotely from Earth or through on-board monitoring through individual self-monitoring tools. However, remote monitoring can have a potentially negative effect on space crews if it is viewed as a crew control tool rather than a support measure (loc. Cit.). Therefore, an SMC-LEO would be equipped with the necessary equipment for on-board self-monitoring.

The orbital module will be equipped with both the Windows Spaceflight Cognitive Assessment Tool (WinScat) and the MiniCog Rapid Assessment Battery. The WinScat offers five neurophysical tests to assess various cognitive functions including memory, attention, and spatial imagery and to provide the user with an overview of their psychological state. In contrast, the MiniCog Rapid Assessment Battery offers nine tests to assess areas of cognitive function and can be used as an early warning tool to identify decreases in cognitive performance before symptoms arise (Kanas and Manzey, 2008). An SMC-LEO would employ both systems to monitor crew psychological states and to mitigate cognitive decrements. While this technology is already available on board the ISS, relocating it to an SMC-LEO module would allow psychological evaluations to become a part of bi-weekly or monthly physical medical care for a more homogenized understanding of crew well-being.

In-flight support countermeasures are largely used to alleviate psychological symptoms such as depression and anxiety that commonly arise due to monotony, boredom, isolation, and confinement. Common in-flight support countermeasures in LEO include psychological counselling and the use of leisure material (Slack et al., 2016). While these have been effective in mitigating mild psychological symptoms, their effectiveness in mitigating severe symptoms in space have not been tested.

Private psychological conferences (PPCs) are an effective in-flight support countermeasure. PPCs can provide secure professional counselling between individual crew members or tourists in space and psychological support staff on Earth. PPCs can help maintain crew behavioral health and performance through open and honest communication (Kanas and Manzey, 2008) and by providing coping mechanisms for potentially negative psychological symptoms (Slack et al., 2016). It is, therefore, necessary to equip the SMC-LEO with the proper means to provide PPCs.

As medical care in space advances, psychological counselling could be prescribed as part of an in-space treatment regimen. Having PPC technology available in an SMC-LEO could help individuals receive immediate or emergency psychological support. The technology could range from an integrated video communications system within the module racks or could be accessed via designated password-encrypted laptops to ensure privacy and information security. The option of developing a sound-proofed cabin within the orbital module for privacy was also proposed but was ultimately disregarded due to available space. Instead, the orbit module itself would be equipped for private use in-between routine care and research periods to offer scheduled and emergency PPCs.

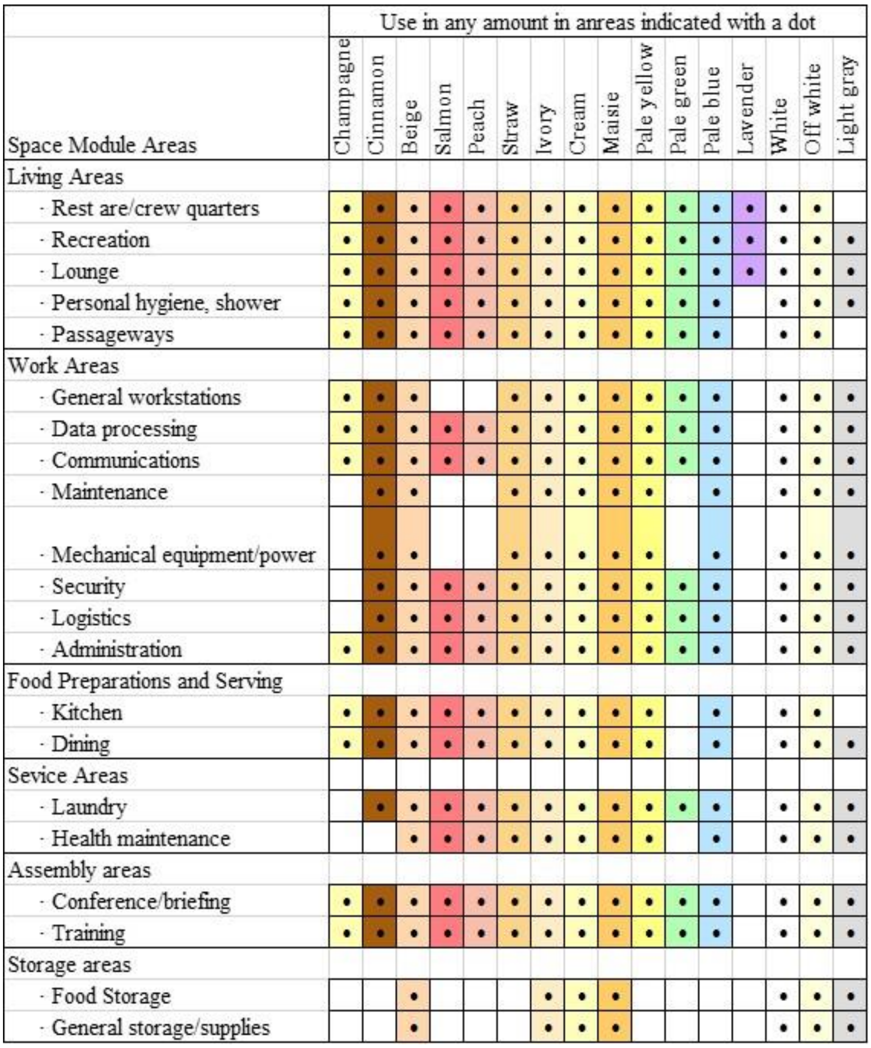
Another necessary support countermeasure is the availability of in-flight leisure material to combat psychological symptoms stemming from boredom or monotony. To date, leisure material in space – including books, music, videos, and recreational software – have been compiled based on the individual crew member interests and either sent ahead or following their arrival in space (Kanas and Manzey, 2008). However, this presupposes that the needs and interests of space crews are stagnant and well-defined. Over time, it is common for individual interests to change. The SMC-LEO module would be designed to provide in-flight leisure material to cover the needs of both space crews and tourists.

Since space is limited within an SMC-LEO, the module will be equipped with several tablet devices, such as Kindles or iPads, and high-capacity, external hard drives which would contain large libraries of available books, videos, music, and photographs. External hard drives are both light-weight and portable. Similarly, tablets are light-weight and multipurpose which makes them ideal for in-flight use. An on-board, digital library would not only provide an effective and countermeasure to psychological symptoms but would provide an immediate response to changing interests thereby mitigating temporary or prolonged psychological conditions stemming from monotony and boredom.

Further, an SMC-LEO will be equipped with appropriate medicines and pharmaceutical treatments for psychological conditions. However, medicines should not be viewed as cures alone. Instead, they should be used as part of a larger treatment program involving either psychological counselling or rehabilitative measures (Mental Health America, 2021).

Some medications have higher demand than others. The average usage for antidepressants and anxiolytics in space is relatively low. In contrast, sleep medication usage is much more pervasive with approximately 78% of surveyed crew members having taken sleep medication during spaceflight (Barger et al., 2014). Since sleep deprivation or interrupted sleep could increase the risk of human error, the amount of available medication aboard the module should reflect the demand. The SMC-LEO will need to provide larger quantities of sleep medication for long-term space crews without sacrificing the available quantities of other medications (i.e., antidepressants, anxiolytics, etc.), which could see a higher demand among short-terms space tourists.

However, psychological medicine use in space is not without risks. To date there has been inadequate tracking of medication uses, prescriptions and side effects in space (Wotring, 2015). While medications have proven to be successful in space, they are not guaranteed to be effective for every individual therefore potentially leaving some psychological conditions untreated. Further study of the efficacy of available medication and a detailed scope of their side effects are essential before committing psychological medications for general use in space crews and tourists.



	Use in any amount in anreas indicated with a dot															
Space Module Areas	Champagne	Cinnamon	Beige	Salmon	Peach	Straw	Ivory	Cream	Maisie	Pale yellow	Pale green	Pale blue	Lavender	White	Off white	Light gray
Living Areas																
· Rest are/crew quarters	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
· Recreation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
· Lounge	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
· Personal hygiene, shower	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Passageways	●	●	●	●	●	●	●	●	●	●	●	●		●	●	
Work Areas																
· General workstations	●	●	●			●	●	●	●	●	●	●		●	●	●
· Data processing	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Communications	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Maintenance		●	●			●	●	●	●	●		●		●	●	●
· Mechanical equipment/power		●	●			●	●	●	●	●		●		●	●	●
· Security		●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Logistics		●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Administration	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
Food Preparations and Serving																
· Kitchen	●	●	●	●	●	●	●	●	●	●		●		●	●	
· Dining	●	●	●	●	●	●	●	●	●	●		●		●	●	●
Sevice Areas																
· Laundry		●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Health maintenance			●	●	●	●	●	●	●	●		●		●	●	●
Assembly areas																
· Conference/briefing	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
· Training	●	●	●	●	●	●	●	●	●	●	●	●		●	●	●
Storage areas																
· Food Storage			●				●	●	●					●	●	●
· General storage/supplies			●				●	●	●					●	●	●

Figure 3: Available colors for spacecraft interiors. Hues with increased brightness and saturation are relegated to sparse use whereas soft colors are used in greater frequency (NASA, 1995).

An adjunct to psychological care is the selection of ambient color in an SMC-LEO. The use of color must be selective to care for a wide range of people while minimizing negative emotional responses. Color can have a profound influence on mood, human behavior, and decision making, and the brightness and saturation of certain colors can lead to visual and psychological overstimulation (Sanad, 2017).

Individuals may attribute different emotional responses to the same color. Certain colors that could benefit medical staff could have negative effects on patients, and contrariwise (National Bureau of Standards, 1978). Muted colors are proven to increase morale, productivity, and concentration in medical staff, thus leading to fewer medical errors, while ‘Earth tones’ are proven to improve patient satisfaction, recovery and reduce stress (Ghamari and Amor, 2016). An SMC-LEO will follow the recommended color selection for ‘health maintenance’ (Figure 3) which includes choices of beige, straw, ivory, pale yellow, pale blue, white and light grey (NASA, 1995). Using these natural and light earth tones, an SMC-LEO will be able to control the psychological impact of color and lower the risk of interior visual oversaturation.

3.1.4 Alternatives to Traditional Medical Imaging

As mentioned in Chapter 3.1.1, a portable ultrasound device will be a mainstay of diagnostic imaging. However, due to mass constraints, it will not be possible to use nitrogen or helium-cooled scanning for medical imaging in space. In their current states, these machines are too large, have excessive power requirements, and require high maintenance. Therefore, alternative methods of medical imaging are sought for near-term and long-term solutions for use in the SMC-LEO.

A reduced-gantry magnetic resonance imaging machine, a smaller version of an MRI without liquid cooling, is currently being tested. The Space MRI Lab at the University of Saskatchewan has been developing smaller MRIs without high power or computing requirements (Figure 4) (Turek, Liszkowski, and Sarty, 2015). A conventional MRI has a gantry with a liquid cooled superconducting electromagnet. The Space MRI is a permanent magnet, or Halbach magnet, that does not require cooling and does not cause the large magnetic field that can be disruptive to nearby electronics. Instead of manipulating the magnetic field gradients, which consumes a great deal of power, the spatial encoding is generated from manipulation of radiofrequency transmissions, requiring little power, and using simpler hardware (Sarty and Obenaus, 2012; Stockmann et al., 2016).

Figure 4: The space MRI can image a wrist or ankle with low power needs and could fit into a mid-locker of an express rack (University of Saskatchewan, 2021).

Additionally, stationary computed tomography (CT) devices for in-space use are under development. A research group at the Massachusetts Institute of Technology and Harvard Medical School has been constructing a CT scanner that is smaller, lighter, less expensive, and has no moving parts, specifically for use in space and other remote environments (Cramer et al., 2018). It can generate 2-D volumetric images and 3-D reconstructions. In its current design, each module weighs one kilogram. The CT scanner could be packaged in small containers and assembled in space and could be stored unassembled when not in use (Cramer et al., 2018). Since there are no moving parts, this could also be combined with a Halbach magnet for a combined CT/MRI in the future.

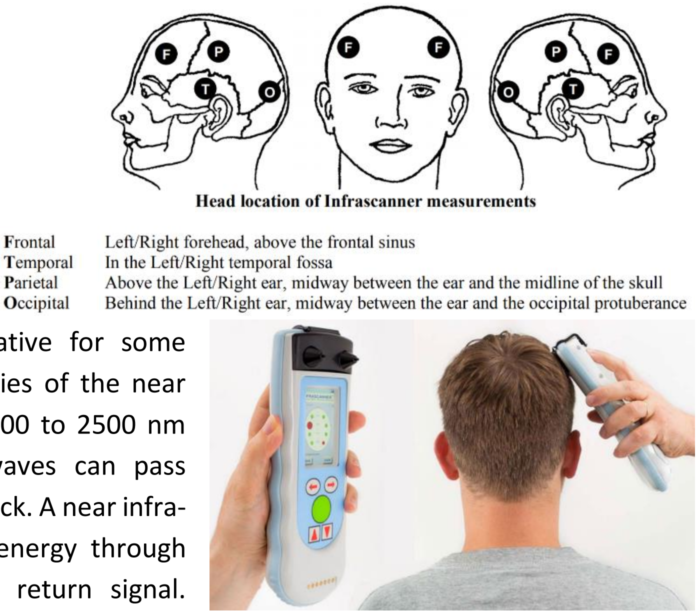


Figure 5: The near-infrared device can detect intracranial hemorrhage by scanning four different locations on each side of the head (InfraScan, 2021).

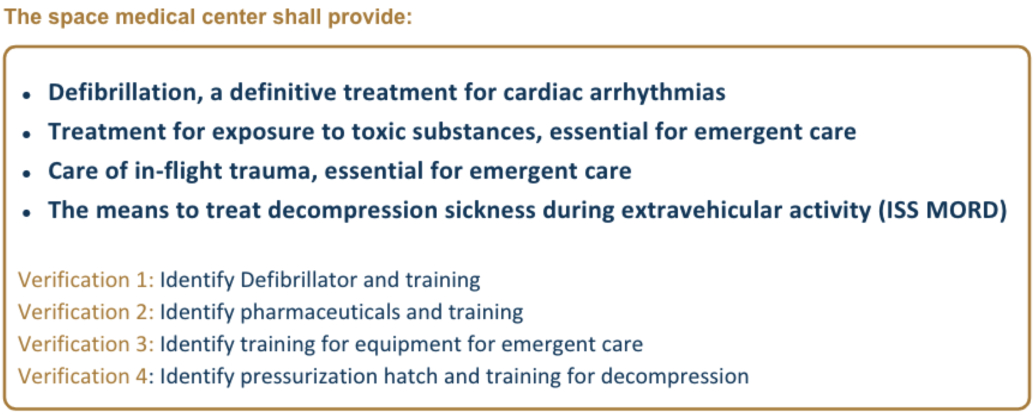
Another alternative, near-infrared spectroscopy (NIRS) handheld devices could be useful aboard the SMC-LEO as an alternative to CT scanning for Traumatic Brain Injury (TBI) with ICH (Figure 5). CT scanning is effective for diagnosing pathology, but it causes harmful ionizing radiation. Meanwhile, infra-red technology may be an alternative for some conditions. NIRS is based on the properties of the near infra-red wavelengths of approximately 700 to 2500 nm (Sakudo, 2016). X-rays and infra-red waves can pass through tissue and can also be reflected back. A near infra-red scanning device can pass infra-red energy through tissue and detect the intensity of the return signal. Different tissues have different absorptions of infra-red wavelengths, and therefore an image can be generated. NIRS is particularly useful for detecting the presence of hemoglobin in tissue. The greater the quantity of hemoglobin, the more absorption of the infra-red waves and less return to the imaging device. This property has been used to create a handheld device that can detect the presence of ICH after TBI. The device has also been used for the evaluation of ICH in pediatric patients due to its lack of ionizing radiation (Bressan et al., 2013).

Further, OCT devices can be used as a suitable alternative. OCT uses low-coherence light of the same wavelength but with different phases to penetrate tissue and then form two-dimensional and three-dimensional images in a way that has been dubbed “optical ultrasound” (Michelessi et al., 2015). Since it gives higher resolution than MRI or ultrasound, there is no need for patient preparation or tissue observation. There is also no ionizing radiation. OCT is useful for ophthalmologic exams (Fioravanti, 2021). It can give detailed images of the retina and show tissue layers in cross-section. In particular, it can show cell organization, integrity of photoreceptors, axonal thickness, and even vascular health (Sherman, 2009; Sherman and Epshtein, 2012; Kashani et al., 2017).

The alternative imaging devices mentioned here would have significant usefulness aboard the SMC-LEO. The smallest, most lightweight is the handheld NIRS device which is already in use by the U.S. military and could be extended to use in space. Meanwhile, the other imaging devices mentioned would be larger and be more difficult to justify transporting to space. The OCT provides useful information, considering the impact of SANS, but it is a large machine. With the stationary CT proposed above, there is also a potential for the creation of a combined space CT/MRI scanner. This would be the most ideal situation.

3.2 Low-Earth Orbit Emergency Medical Treatment Center

On Earth, an Emergency Department is a standard part of any hospital, and a life-saving community service. As of yet, there is no equivalent in space. The purpose of this section is to delineate the medical operations for acute, emergent care aboard the SMC-LEO, including procedures and equipment, based upon the following requirements for acute care in space. The emergency requirements for this type of facility are presented in Figure 6.



The space medical center shall provide:

- **Defibrillation, a definitive treatment for cardiac arrhythmias**
- **Treatment for exposure to toxic substances, essential for emergent care**
- **Care of in-flight trauma, essential for emergent care**
- **The means to treat decompression sickness during extravehicular activity (ISS MORD)**

Verification 1: Identify Defibrillator and training
Verification 2: Identify pharmaceuticals and training
Verification 3: Identify training for equipment for emergent care
Verification 4: Identify pressurization hatch and training for decompression

Figure 6: Emergency requirements for a Low-Earth Orbit Medical Center.

In the event of an emergency, a number of tasks will be undertaken simultaneously. The patient will be transported immediately to the SMC-LEO while the crew assesses the patency of the airway and adequacy of breathing and circulation. An airway can be established at the scene or en-route as needed with orotracheal intubation or cricothyroidotomy. Supplemental oxygen can be supplied, and in-line stabilization of the spine can be maintained.

Once in the SMC-LEO, the patient can be affixed to an examination table and a primary survey of the adequacy of the airway, breathing, circulation, physical stabilization, and exposure can be performed. Cardiopulmonary resuscitation (CPR) can be performed after adequate restraint of the patient and crew. At the same time, vital sign monitoring devices can be attached, and venous catheters can be placed for blood laboratory evaluation and intravenous access for medications and fluids. Electrocardiogram monitor leads can be attached, and cardioversion or defibrillation can be performed as necessary. Hemorrhage, if present, can be controlled and fractures and dislocations can be reduced and stabilized in position. A portable ultrasound can be used to perform a Focused Assessment with Sonography for Trauma (FAST) exam to search for evidence of internal injuries (Savatmongkorngul, Wongwaisayawan, and Kaewlai, 2017).

3.2.1 Patient and Crew Restraint

Both the patient and the crew working on the patient need to be restrained in space. Due to microgravity, a patient needs to be actively fixed in one place to prevent movement during procedures. Therefore, the SMC-LEO will be equipped with a body-length patient restraint and examination table. It will be retractable from one wall of the center and will fix in place so that it rigidly supports the patient while allowing either free access of the crew to work around the patient from all sides or allows one or several members of the crew to fix themselves in position around the table to perform tasks that require force. It will have a head rest, head and torso restraints, and will be based on the Crew Medical Restraint System (CMRS) of the Space Shuttle and ISS (NASA, 2021c). The table surface will also be able to be detached in case the platform is needed to transport a patient to the medical center for mechanical stability.

3.2.2 Critical Care

In the event that there is a major injury or severe illness, a patient may require critical care (Figure 7). This could include endotracheal intubation and ventilation, hemodynamic support with IV fluids and medications, conversion of arrhythmias, control of gastrointestinal hemorrhage, frequent monitoring, possibly invasive monitoring, and possibly placement of invasive drains.

The space medical center shall provide:

- **The means for prolonged oxygenation and ventilation, essential for respiratory failure**
- **Cardiovascular and respiratory monitoring, key to patient's condition and progress (ISS MORD)**

Verification 1: Identify mechanical ventilator and training
Verification 2: Identify cardiac and respiratory monitors

Figure 7: Critical care requirements for a Low-Earth Orbit Medical Center.

For delivery of continuous IV medications, the SMC-LEO will use syringe pumps. These are small, lightweight devices that are simple to use and the medications to be delivered can be drawn from the same syringes used to mix the medications, with little waste. The Becton-Dickson T-34 syringe pump is a good example. It is small, lightweight, and easily fits a 10 ml syringe, which is a common medical supply (Becton-Dickson, 2021).

Monitoring of vital signs such as heart rate, blood pressure, blood oxygen saturation, and electrocardiogram are important during a critical illness. These measurements are required frequently, at every 30 to 60 minutes. Small monitors such as the Philips Intellivue X3 provide this type of capacity in a lightweight and compact design (Philips Healthcare, 2021). Other more invasive monitoring adjuncts could be an arterial or central venous catheter for continuous pressure monitoring and a urinary catheter for determining urine output. Small monitors such as the Intellivue X3 also have a transducer port for continuous pressure monitoring.

3.2.3 Surgical Care

Simple procedures like abscess drainage will be performed with limited equipment and training and without significant contamination of the surrounding cabin environment. Larger procedures, meanwhile, will require additional equipment specialized for microgravity. If an appendectomy or a perforated viscus, such as a perforated gastric ulcer arise, then the procedures to manage them can be performed laparoscopically, with little contamination of the patient or the spacecraft cabin.

Open procedures, meanwhile, will require additional equipment since there is difficulty controlling visualization of the operative field due to the pooling of blood in microgravity and the difficulty controlling contamination of the field due to microparticles suspended when weightless. Restraint of the patient and surgeon are important to perform tasks, and controlling surgical instruments is imperative since they must be accessed easily without losing their position in space. Therefore, special surgical gowns have been created for this purpose, and special enclosure devices have been created to overcome the problems of open surgery in space. These will both be used for open operative procedures. Additionally, robotics can assist in the future with patient and instrument stabilization and with performing some actions during procedures.

The difficulty with open surgery in microgravity, in addition to the need for restraint, is free-floating blood can obscure the operative field, and could contaminate the spacecraft cabin. Contamination is also a problem since unsterile particles and bacteria are suspended in the air in microgravity. Normally, operating rooms on Earth have high air flow, and gravity causes microscopic particles with bacteria to settle to the ground to be collected and disinfected. For these reasons, an enclosure device is needed to maintain the integrity of the operative field. Therefore, open surgery will be planned for the lunar surface, but not in LEO.

3.2.4 Dental Care

Multiple dental conditions are cause for concern in space, therefore the SMC-LEO will need to be equipped to support dental care (Figure 8). Problems can arise slowly as with caries and infections, or suddenly as with trauma and fracture. Dental emergencies include fractures, subluxation (loosening), avulsion, pulpitis (inflammation of the inner pulp of tooth), periodontitis, and abscess. Pain, and dental barotrauma are also possible from rapid change in air pressure, such as in launch and ascent (Calder and Ramsey, 1983). For treatment of these conditions, the SMC-LEO will use many of the same tools and procedures as those aboard the ISS (Hodapp and Jeske, 2019).

The space medical center shall provide:

Adequate dentistry services for minor repairs to prevent significant morbidity (ISS MORD)

Verification: Identify training and equipment for dental care

Figure 8: Dental care requirements for a Low-Earth Orbit Space Medical Center

Telemedicine will also play an important role in dental management. For the SMC-LEO, a dentist at a control center on the ground could assist in real-time. From the control center, a dentist could assist with patient assessment, give vital instructions, and even guide a crewmember through delicate procedures.

3.3 Low-Earth Orbit Exercise and Rehabilitation Facility

3.3.1 Exercise as a Countermeasure to Microgravity

Exercise is an important countermeasure for preventing bone and muscle loss in microgravity. Muscle atrophy leads to the deconditioning of crewmembers with potential negative consequences upon return to gravity. Bone loss also leads to a higher risk of fractures and nephrolithiasis, or kidney stones. Crewmembers will be more at risk if a trauma occurs, and nephrolithiasis is a serious condition. It also causes severe pain and can debilitate a crewmember and have a significant negative impact on a mission. Exercise also relieves stress. With these attributes in mind, the SMC-LEO will provide an area with equipment for simple exercises. Resistance bands are an effective means of providing simulated counterweight. A number of exercises are possible in the space given, and these can be accomplished autonomously. Working with resistance bands could cause minimal torque or vibration to the module in microgravity.

3.3.2 Nursing and Rehabilitative Care

If a crewmember is recovering from a severe illness, or is injured, he or she will need assistance. Recovery, in some cases, is a prolonged process. Therefore, in these situations, not only is medical and pharmacological care important, but nursing care and rehabilitative care as well. Aerospace nurses normally work during prelaunch and post-landing. To date, no nurses have been in space, but there is promise for the future. Either a nurse will need to be present to care for patients, or the nursing role will need to be assumed by crewmembers of the SMC-LEO. Currently, crew members are trained to perform primary nursing duties or to assist the Crew Medical Officer (CMO) (Plush, 2003). The practice is an invaluable component to complete care.

Nursing care is a systemic approach to care, this process functions as a guide to patient-centered care with five main steps. 1) Assessment. This includes critical thinking and data collection. 2) Diagnosis. A nursing diagnosis contains Maslow's Hierarchy of Needs to help prioritize and plan care based on the patient-centered outcome. 3) Planning. This stage creates goals and outcomes based on evidence-based-practice (EBP). Additionally, these goals should follow the SMART analysis. 4) Implementation. This involves the carrying out nursing interventions. 5) Evaluation. This reassesses whether the desired outcome has been reached (Toney-Butler and Thayer, 2020). Nursing care aboard the SMC-LEO for rehabilitation will include but not be limited to vital sign monitoring, wound care, personal hygiene, toileting, medication monitoring and administration, physical rehabilitation, and humane moral support. Whether delivered by trained nurses or educated crew medical personnel, nursing care will be essential to the rehabilitation of ill or injured crew members that require prolonged recovery.

3.4 Low-Earth Orbit Training Center

The SMC-LEO will also have an educational role. In this capacity, there will be continuous on-board training of medical personnel, and the SMC-LEO can be used as a forum for disseminating education to other non-SMC crew and to learning centers on Earth via telecommunications. The primary consideration is continued education of the center's medical personnel. This will include updates, simulations, "just-in-time" training, teleconferences, and telemedicine assistance.

3.4.1 Crew Medical Officer Training

The training for non-physician personnel will be similar to the CMO training for the ISS, but with some enhancements. The ISS CMO is in charge of identifying and treating health problems which could have a high likelihood of occurrence and could be critical to the crew members' health and well-being. The most optimal method to train the CMO to recognize or address health factors is still a work in progress.

According to the *ISS Medical Operations Requirements Document,* there were no gynecological training requirements (NASA, 2005). This showed a gap in training that CMOs needed gynecological routine care as well as common gynecological emergent issues. Assuming there will be women aboard, gynecological care will be a regular element of maintaining astronaut health aboard a SMC.. Psychological care is also an important factor that must be addressed since it can affect the health of crewmembers and have an impact on mission success. Therefore, CMOs aboard the space medical center will be given sufficient training in these important areas.

Non-CMOs such as researchers will also be given medical training. For example, to ensure continuous emergency medical care capability onboard ISS, all non-physician crew members are given training to assist the CMO in a medical emergency. This training enables all crewmembers to manage and assist with standard and emergent medical scenarios (NASA, 2006). The *Flight Crew Medical Training and Certification* for the ISS Program includes *Crew Basic Medical Training*, which covers the following areas: "1) Crew Medical Systems Operations and Maintenance, 2) Environmental Health and Safety Operations and Maintenance, 3) Health Maintenance System Operations and Maintenance, 4) Behavioral Health and Performance training. 5) Securing medical resources prior to the evacuation of a module or vehicle" (loc. Cit.). Therefore, a similar training will be given to the non-CMO crewmembers aboard the SMC-LEO.

3.4.2 Physician Crewmember Requirements

There is no universal agreement on whether a medical doctor would be required on long-duration flights, so the SMC-LEO will ideally be served by a physician crew member. This 'in-flight' physician will be tasked with carrying out a vast array of roles, such as a primary care physician, dentist, psychologist, safety officer, pharmacist, nurse, physical therapist, emergency medical technician, laboratory technician, and medical writer (Soto, 2019). Additionally, physician crewmembers and in-space medical doctors would need to be properly trained in the event of a crew member death. Due to this possibility the SMC-LEO would need to be equipped with areas for body storage, cadaver treatment and body disposal.

To combat any legal ramifications stemming from the death of a crew member on board the SMC-LEO, crewmembers will need to sign an agreement on death risk and conditions. This document would deal with the protocols that would be followed in case they died and would state that the individual is aware and assumes the risk of death in the medical procedures that they will undergo. With the existing parameters on death protocols in space, mechanisms for mourning treatment and technology for body disposals do not currently exist. Several protocols, however, are postulated. From the SMC-LEO, bodies could be sent back to Earth relatively easily. A return evacuation trip could be made, with the body secured within the capsule.

3.4.3 Onboard Medical Training

For physicians and CMOs there will need to be regular updates. Whether the role of a physician or CMO is allocated to a single individual or split amongst several, it will be crucial to maintain regular refresher training on any kind of long-duration mission to keep medical skill sets sharp and avoid skill erosion. Several options exist to implement such 'on-going' training during the mission and could include the utilization of augmented reality or Virtual Reality (VR) approaches, simulation, and online training (Nicogossian et al., 2016; Kuypers, 2013). Telecommunications are essential here. They provide the two-way, interactive communications that are required for didactic skills learning.

With regular updates, the crew members could review the latest information on medical conditions in space with experts on Earth and ask questions to interact in real-time. Crewmembers could also practice procedures, working with experts on the ground and perform exercises with audio and visual guidance. Further, crewmembers could engage in just-in-time learning for medical conditions on board the center and can practice specific procedures just before they are performed live.

Some medical conditions may be outside the scope of either the CMO or the physician. For these, assistance by telemedicine will be indispensable. Physicians on the Earth can walk crewmembers through the steps of diagnosis and treatment, with audio and visual feedback on both sides throughout the way. The physician on the ground can observe symptoms and signs, guide a directed physical exam, assist with extended exams such as using an ultrasound device, help form differential diagnoses, recommend adjunctive tests such as blood lab work, and assign a therapeutic medical or procedural treatment regimen. Telemedicine, in this way, adds virtual expertise to the medical center.

New procedures and techniques can be uploaded to staff on center just as with medical information. The research staff can hear and see the latest developments in their fields and engage with their broader communities. They can also be guided through new laboratory protocols, or even maintenance, calibration, or repair of their intricate research equipment.

Education can also be directed from the SMC-LEO back to the ground. After a relatively short time, the staff of the SMC-LEO will have become adept at performing routine care and research in close conjunction. They will have a moderate quantity of expertise in functioning in this environment and will be able to share their experiences with a broad audience. Everyone from administrators, to medical personnel, to students of all ages could learn from their experiences. Researchers could educate, similarly as they could download their knowledge and experience and pass the wisdom they have gained from working in this unusual and extreme environment back down to Earth.

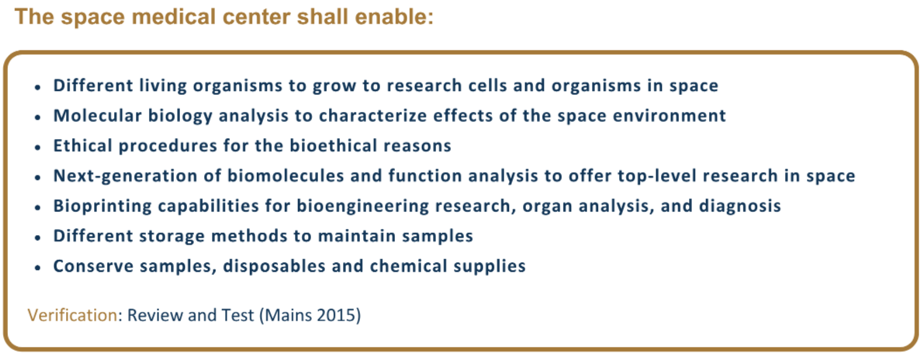
3.5 Low-Earth Orbit Life Sciences Research Facility

Space offers a unique environment to study the effect of ionizing radiation and microgravity on life and physical sciences. Understanding these changes can further expand our knowledge on the biological processes of life leading to innovating technologies, improve health on Earth, and prepare us for exploration missions beyond LEO. The SMC-LEO would serve as a laboratory to study the long-term effects of microgravity and could host visiting researchers, participants for human studies, and test new treatments for terrestrial diseases. When there is no medical emergency, the research laboratory will have an ongoing activity. Therefore, research will be an important aspect of the mission.

This section addresses some of the scientific breakthroughs, medical technologies and treatments in microgravity that could be applicable to the SMC-LEO in the future. The SMC-LEO research program will hold studies in line with the sustainable goals identified by the UN, through 3 research programs: 1) fundamental research, 2) translational, and 3) performance in space research (The United Nations, 2015).

In an SMC-LEO, it will be required to run studies in line with both astronauts and human health issues from molecular to physiological conditions. For this purpose, the SMC-LEO must integrate different capabilities to conform to standard methods and tools in molecular biology while also offering advanced capabilities and cutting-edge technology. This implies four main capabilities either in the orbital module and the lunar surface center: 1) a plant and microorganisms growth facility, 2) a cell culture module, 3) a molecular biology platform, and 4) a bioengineering platform, which will integrate previous space validated technologies (Mains, Reynolds and Baker, 2015).

These capabilities will lessen the number of required manual operations. Cell culture capabilities will enable automated standard laboratory processes such as media feeds, waste removal, sample collection, and protocol additions as well as culture initiation, replenishment, recovery and improved sample collection and storage. In addition, the cell culture capabilities should include automated experiment functions. Figure 9 shows the necessary requirements for the SMC-LEO.



The space medical center shall enable:

- Different living organisms to grow to research cells and organisms in space
- Molecular biology analysis to characterize effects of the space environment
- Ethical procedures for the bioethical reasons
- Next-generation of biomolecules and function analysis to offer top-level research in space
- Bioprinting capabilities for bioengineering research, organ analysis, and diagnosis
- Different storage methods to maintain samples
- Conserve samples, disposables and chemical supplies

Verification: Review and Test (Mains 2015)

Figure 9: Research requirements for a Low-Earth Orbit Medical Center

3.5.1 Fundamental Research, Space for Earth

Fundamental research is an experimental approach to assess the role of a condition in a system, e.g., living systems, and to observe the effects of its removal. Space offers the only opportunity to formally assess the role of the space environment on living systems. Therefore, the following areas of research would be suitable for further study in an SMC-LEO environment.

Figure 10: Microorganisms on an agar plate (NOAA, 2010).

Studies with bacteria onboard the ISS has shown that some bacteria grow faster and become more resistant to drugs due to microgravity. The bacteria flown in space contained more resistance genes and an increased gene transfer capacity. More research is needed to conclude whether these adaptations cause more diseases (Tirumalai et al., 2017; Gilbert et al., 2020; Schiwon et al., 2013). The SMC-LEO will utilize DNA and microbial sequencers to isolate DNA and sequence microbes in real time. Measuring microbial changes in microgravity without sending samples back to Earth is crucial to protect the health of astronauts on long-duration missions. Understanding the unique responses of bacteria to microgravity could lead to the development of new drugs. Furthermore, the SMC-LEO could study high-radiation thriving fungi that convert gamma-radiation into chemical energy with the use of melanin (Shunk et al., 2020). This process, called radiosynthesis, could be used as a protective shield against radiation around the SMC-LEO to protect humans and other life forms living inside.

3.5.2 Translational Research, Space for Humanity

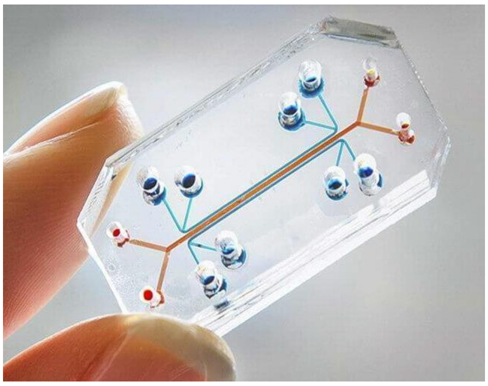


Figure 11: Organs-on-a-chip technology can have far-reaching applications for study of human adaptability to microgravity (Levis, 2016)

The goals of the SMC-LEO translational research program are to run studies supporting the increase of the quality of life in space with the benefit of possible, terrestrial spin-off applications. Organ-on-a-chip (OOCs) (Figure 11) is a small device allowing thousands of living cells to grow in a 3D matrix while providing blood, oxygen, and nutrients to keep the cells alive. This innovative technique provides a way to test the effect of pharmaceuticals without the need for animals. With OOC, scientists are able to measure changes that normally take months or years to happen on Earth. In the future, this medical device could automatically measure cytokine expression and inflammation onboard the SMC-LEO and study the effect of gravity and radiation exposure on human tissue during spaceflight. Thus Lab-On-Chip technology and especially Organ-On-Chip are powerful non-invasive tools for continuous astronaut monitoring and prognosis.

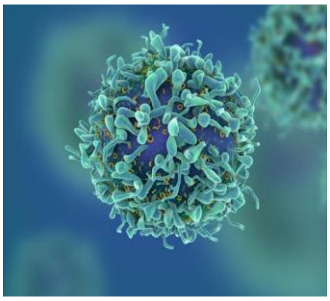


Figure 12: Cancer cell (Sexton, 2019).

Diseases such as Parkinson’s, Alzheimer’s, cancer and heart diseases can be studied aboard the SMC-LEO. 3D tumors form larger structures in microgravity and better resemble the oxygen and nutrient supply of *in vivo* tissues on Earth. Therefore, tissues formed in microgravity are a more reliable model for drug testing. Researchers, universities, institutes, and commercial companies could benefit from testing new cancer treatments and therapeutic products within the SMC-LEO.

Further, stem cell therapies in space will be conducted in an SMC-LEO, for clinical applications on Earth and for future long-term settlements on the Moon (Huang et al., 2020). One of the treatments for age-related health issues is stem cell therapy. With the presence of gravity, stem-cells are difficult to produce. They are grown in a 2D cell culture that’s different from the 3D cell growth within the body. Microgravity enables 3D cell growth and cells have a higher self-renewal ability, a higher survival rate, and are more immunosuppressive than ground controls. Therefore, the environment within the SMC-LEO is ideal to study stem cells in order to improve current stem cell therapies.

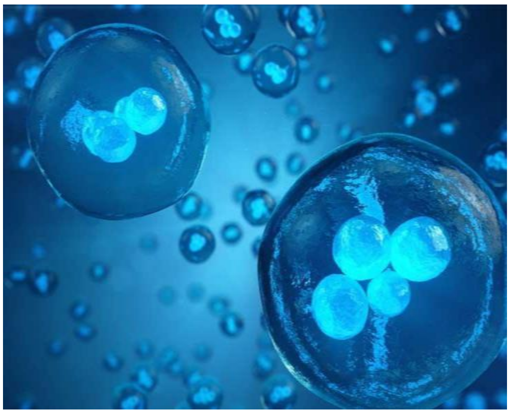


Figure 13: Stem cells (WestGen, 2018).

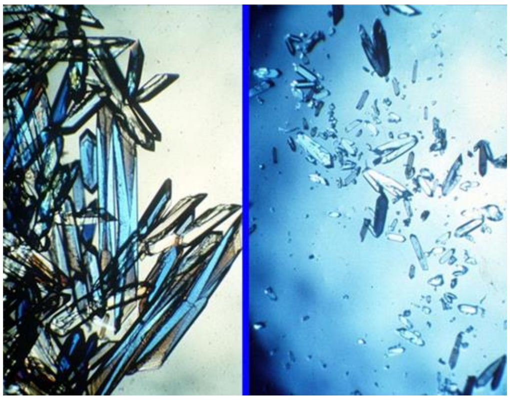


Figure 14: Bovine Insulin crystals grown in space (left) vs. grown on Earth (right) (Tech Briefs, 2021).

Researchers can study the molecular structure of proteins by a process called crystallization. This process has proven to be successful in characterizing potential drug candidates for cancer and metabolic diseases. Under the influence of gravity, some medically important proteins crystallize without a sufficient quality for a detailed structure analysis. In space, crystals grow larger and have a higher order and quality (Figure 14). Therefore, the SMC-LEO will be a valuable platform where future drugs could be developed using protein crystals and could even supply drugs for a space hospital in real-time (McPherson and Delucas, 2015).

Additionally, 3D printing is another tool for on demand biological and medical compound engineering. Already difficult on ground, organ donation in space will not be an option in case of organ failure or fatal injury. Organ 3D bioprinting capabilities will, therefore, account for future deep space mission self-sufficiency and safety. Bioprinted organs could serve as personal external sentinels to assess space effects or drug responsiveness. For research purposes, 3D bioprinting provides ethical alternatives of animal studies and the printing methods are developed for on demand surgical capabilities, either for medical training or intervention, thus supporting optimal logistics for surgery in space (TRISH, Medical Technology Research 2021). Such capabilities will be invaluable for a future SMC-LEO.

3.5.3 Human Performance in Space Research

There is already a considerable amount of available space medicine data. However, there is a considerable lack of cohesive overview access. Overall, the goal of human performance research in the SMC-LEO will be to generate a cohesive and operational database allowing for functional analyses and linkage related to space medicine. This effort will enable personalized healthcare for astronauts and improve countermeasure efficiency. In addition, the human performance in space research program will support studies investigating sustainability and self-sufficiency outer space settlements.

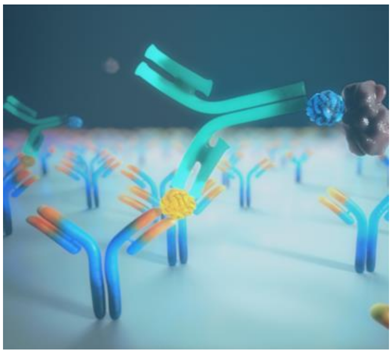


Figure 15: Understanding the physiological responses caused by antigen-antibody interaction, biomarkers could be identified (Quanterix, 2021).

The identification of new biomarkers is a revolutionizing medical strategy and allows for a move towards personalized medicine. However, a specific space biomarker set specific to adaptive and maladaptive physiological mechanisms in space are still lacking. Space biomarkers are essential for astronaut monitoring and for countermeasure effectiveness. From multi-omic and targeted analyses, six biological features of spaceflight have been identified: “oxidative stress, DNA damage, mitochondrial dysregulation, epigenetic changes (including gene regulation), telomere length alterations, and microbiome shifts” (Afshinnekoo, 2020). Further analyses are required to identify specific biomarkers, but research conducted aboard the SMC-LEO will help to support effective astronaut’s healthcare in space.

3.5.4 SpaceMed Database

Classical and high-throughput analyses performed in space generate a large amount of data, though a new space database is needed. While NASA’s GeneLab constitutes the first step in space data acquisition, it focuses primarily on omic data. A new PubMed-like software, specific for all space data, is therefore required. The Translational Research Institute for Space Health (TRISH) has already funded an international Retired Astronauts Medical Data Repository (RADAR) project in this objective (TRISH, 2021). The SpaceMed platform for an SMC-LEO should follow NASA's GeneLab principles as an enlarged space medicine and research platform. Thus, the SpaceMed platform services would conform to standardized methods that integrate Findability, Accessibility, Interoperability and Reusability (FAIR principles, Berrios D.C., 2020). The platform would also be composed of a private data repository web interface, a standardized deposit interface, and a workplace with nonproprietary open and identified data storage, such as the Digital Object Identification (DOI). This SpaceMed software, associated with AI, will ensure private data is not publicly accessible and will provide computer-based assistance for personalized medicine.

These types of research could each be performed in an SMC-LEO in a fully equipped life science laboratory. From fundamental research to the advancement of science, to translational research to solve problems for humans now and in the near future, these examples show that a commercial research facility in an SMC-LEO is a valuable asset. As of 2020, over 30% of the experiments aboard the ISS were for biology and biotechnology (Witze, 2020). That percentage is likely to grow. In the next section, the systems engineering for the SMC design in LEO will be explored in more detail.

3.6 System Design

A thorough design of an SMC-LEO requires an organized, systems engineering approach. In order to arrive at the correct scale, with appropriate external and internal dimension, and for all the dimensions and inclusions in between, there needs to be a thorough analysis of the natural constraints of the project, the requirements of the systems that need to be put in place, and an evaluation of the components that must interact. These are invaluable exercises, rich with detail, documenting the reasons for the tradeoffs weighed and decisions made to create the final product, this final design.

With that in mind, certain natural constraints set the environment in which the design must adapt. For example, LEO can be considered anywhere between 200-2000 km above the Earth's surface and although astronauts experience weightlessness in orbit, gravity is still approximately 80% of that on Earth. Temperature fluctuations can be extremely dependent upon exposure to the Sun and radiation levels are higher than on Earth.

Table 2: Low-Earth Orbit Architecture and Systems Constraints

Constraints	Justification
● The SMC architecture needs to be adapted to the gravitational environment ● Temperatures range between -150° and +100°C ● The radiation impact depends on the destination ● Solar particle events create extreme radiation peaks and space debris limits structural design	● Microgravity in LEO, 1/6 of gravity on the Moon ● Lack of atmosphere (LEO, lunar) and direct impact by the sun ● 2 mSv/year - Earth, 3000 mSv/year - Moon ● Lack of magnetosphere and atmosphere (LEO, lunar)

Constraints given by the space environment, include microgravity, temperatures between -150°C in the shadow and +100°C in the sun, high radiation levels and potential solar particle events as well as the risk of space debris collision. Radiation is a risk that has not been well mediated in space. On the surface of Earth, humans are well protected from solar radiation by the magnetosphere. The radiation exposure astronauts receive in LEO however limits the duration of their missions and thus is a chief concern for human health in space. However, there are currently many avenues being considered for mitigating the effects of harmful radiation. Shielding from this hostile environment is essential and any structure that is designed to function in LEO will need to adhere to specific constraints. Tables 2 and 3 detail the constraints and the requirements, respectively, for the SMC-LEO facility.

Table 3: Environmental Requirements for a Space Medical Center

Requirement	Verification	Justification/Reference
Interior pressure shall be kept at 1atm (1 bar) with a tolerance of +/- 5 %	Barometric test for 12 hours	IECLSSIS Standard; Habitability and survival
Interior temperatures shall be controllable between 17 and 27 °C	Thermal control test for 12 hours	IECLSSIS Standard; Habitability
Special instrumentation, organs and experimental subjects shall be storable between -17 and +8 °C	Freezer test for 12 hours	Enabling advanced experimentation and medical capabilities
CO2 partial pressure shall be kept below 3 mmHg under normal conditions and under 2 mmHg during acute surgical care	Measurement of CO2 levels for 12 hours with crewed test vehicle	IECLSSIS Standard; Habitability and survival; reasonable work environment

*IECLSSIS: International Environment Control and Life Support System Interoperability Standards

3.6.1 Technical Requirements

The SMC-LEO shall be compliant with the Pressurized Payloads Interface Requirements Document (PPIRD) for attachable modules on the ISS (NASA, ESA, and JAXA, 2015). A universal docking system is needed as defined in the International Docking System Standard (IDSS). The interior needs to be modularly extendable by standard payload racks. Sufficient power interfacing must be provided which is regulated in the International Avionics System Interoperability Standards (IASIS) (ISSAP, 2019a). Moreover, thermal control needs to be available according to the International Thermal System Interoperability Standards (ITSIS) (ISSAP, 2019b). Additionally, the structural dimensions of the SMC-LEO are limited by the fairing size of the launching vehicle. Since the SMC-LEO will be attached to a hosting space station, it will need to adapt to certain habitability elements and will require sufficient power sources. The technical requirements the facility should fulfil are represented in Table 4.

Table 4: Technical Requirements for a Space Medical Center

Requirement	Verification	Justification/Reference
Outer structure of the orbital version shall be compliant with the standards of attachable modules on the ISS	Review	Pressurized Payloads Interface Requirements Document (PPIRD) Adaptation of SMC, as part of a larger structure
Components shall be organized in modularly extendable units	Review	International Standard Payload Racks (ISPR), Modularity, extendibility
Access to power supply of at least 15 kW	Review, Interface Inspection and Test	Power supply of all units International Avionics System Interoperability Standards (IASIS)
Access to backup batteries in case of power blackout	Review, Inspection and Test	Power operability is critical for the sustainability
Autonomous communication system connected to the hosting habitation able to communicate to ground directly or via relay satellite	Inspection, Review	International Communication System Interoperability Standards (ICSIS); Independence of communication
Module shall be attachable to the International Space Station (ISS)	Inspection, Review, Docking Test	International docking system standard (IDSS), integration flexibility
Must be attachable to another habitat structure	Inspection, Review, Docking Test	Docking mechanism dependent on future habitation
The SMC shall provide standard interfacing capabilities to the ECLSS of the hosting habitation.	Inspection, Review, ECLSS Test	International Environmental Control and Life Support System Interoperability Standards
The SMC shall provide have access to the active and passive thermal control systems of the hosting habitation	Inspection, Review, thermal stress test	International Thermal System Interoperability Standards (ITSIS)

3.6.2 High-Level Architecture

The SMC-LEO will be attachable to the ISS and therefore shall abide by the following criteria. As it will be attachable to agency and later on to private space stations, various possible architectures were considered including attachable modules, nodes with extra docking ports, and inflatable modules. The main functional constraints are presented in Table 5.

Table 5: Functional Constraints for High-Level Architecture

Constraints	Justification
● The structural dimensions of a SMC module are limited by the fairing size of launching opportunities ● Oxygen, temperature, and pressurization depend on hosting habitation as well as available power	● The heaviest launch vehicles fairing available are Falcon Heavy, Atlas V, and soon New Glenn, SLC, and Starship ● The SMC infrastructure has to adapt to habitability characteristics and needs sufficient power sources

3.6.2.1 Module Selection

The SMC-LEO may create a novel outer shell of a space station, but it will be influenced by dimensions that have already been well established on ISS missions. It is necessary to choose a module dimension in order to design the SMC-LEO configuration. The selection will be based on the cross-section between system requirements and emergency center layouts as well as what is possible to deploy today. Below (Table 6) is a list of the notable ISS modules which were considered in the design selection of the SMC-LEO.

Table 6: ISS Module Properties (DLR, 2020).

Module	Purpose	Dimension (m) (length x diameter)	Mass (kg)
Zarya	Storage	12.60 x 4.10	19,323
Zvedza	Service	13.10 x 4.15	19,050
Destiny	Laboratory	8.53 x 4.27	14,515
Harmony	Utility hub	6.10 x 4.20	13,608
Tranquility	ECLSS, WC, Exercise	6.71 x 4.48	15,000
Columbus	Laboratory	6.9 x 4.5	12,775
Kibo	Laboratory	11.20 x 4.40	15,900

The Zarya module is one of the oldest modules of the ISS. Originally used for power, it is now mainly used for storage. It is large in length, but its dimensions and thin diameter are not desirable for the spacious and symmetrical layout necessary for a medical center. Harmony and Tranquility both have desirable length and diameter, but they act as connecting modules with the different segments of the ISS. Due to this, they each have six berthing locations which limit the space that can be used for storage. The Zvedza service module had one of the longest ISS modules with a thin diameter. Its main purpose is to provide life support to the ISS inhabitants including oxygen generation and water recovery systems. Although it provides copious length for SMC-LEO implementation, this size is unnecessarily large and may not be feasible due to the cost of launching such a cumbersome module.

The Destiny module has many appealing characteristics such as its role as a research facility and its wide diameter coupled with its generous length. This module therefore will be considered for the SMC-LEO design and configuration. The Columbus module, which is managed by ESA and acts as a laboratory module, is of desirable length and diameter. Its configuration would allow for an SMC-LEO to be easily replicable inside of a Columbus-type shell. Kibo is a large laboratory module but may not be feasible considering the larger mass and the limited availability of launch vehicle fairing sizes for this length. Alternatively, due to the rise of commercial space station manufacturers like Axiom Space, an SMC-LEO could outsource the module development to one of these players. Further study is required to establish the feasibility of such a route.

However, after reviewing the various dimensions and system requirements, the Columbus module and the Destiny module were selected as a starting base for the dimensions for the SMC-LEO (Figure 16). The dimensional constraints were detailed as 4.5 meters in diameter, between 6.7 and 8.5 meters in length, and between 12,775 kg and 14,515 kg in mass.

Figure 16: Columbus Module (left) and Destiny Module (right) together serve as the basis for the design of an attachable SMC module to an orbital space station (Mansfield, 2021; Free3D, 2021).

A design option for the inflatable modules such as the concept proposed by Bigelow Aerospace. The Bigelow Expandable Activity Module (BEAM) is one example that has already been demonstrated successfully on the ISS. The BEAM is deployed in a compressed configuration for launch and docking and is later inflated to its full size (Seedhouse, 2015). Figure 17 shows two possible configurations for the SMC-LEO including inflatable modules attached to the main module. Moreover, external pressurized oxygen tanks are included in the concept on the right side as well as additional docking ports similar to the Harmony node.

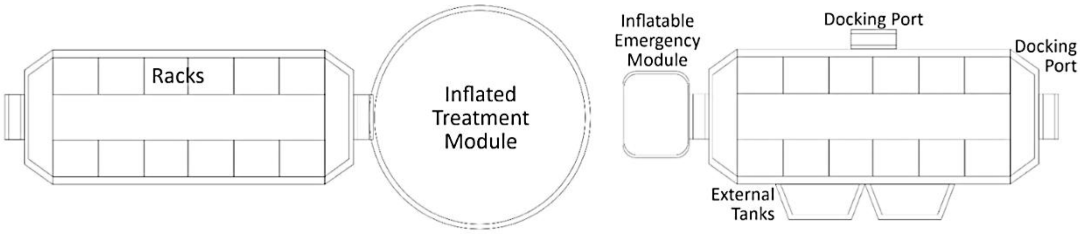


Figure 17: Possible configurations for an SMC-LEO. Left: an attached, inflatable, cylindrical. Right: an inflatable module with two docking ports and two or more external oxygen tanks.

The option of a node with several docking ports was initially considered to enable modular extension of the SMC-LEO and the possible attachment of an inflatable emergency unit. Given the high safety and shielding requirements for the SMC-LEO, inflatables as a main treatment area are not a feasible option. However, the idea of Inflatables as an emergency unit would still be an option. For that matter, a docking port would need to be integrated. But at this point the SMC-LEO is designed without further extensions.

Likewise, the external oxygen tanks will not be included in the basic configuration as an airlock will not be required and safety requirements will be fulfilled without additional life support. The Environmental Control and Life Support System (ECLSS) provides sufficient oxygen for life support aboard the ISS. However, a medical oxygen tank will still be required for emergency purposes. For safety reasons it would be reasonable to store pressurized tanks on the module exterior to minimize risks stemming from pressure releases or tank bursts.

3.6.2.2 Safety Requirements

For safety reasons the SMC-LEO structure shall minimize radiation exposure by approximately 80 percent (with upcoming radiation shielding technologies) against Solar Particle Events (SPEs) and Galactic Cosmic Rays (GCRs). The SMC-LEO will also have the ability to monitor and predict radiation conditions for crew safety and is verified by testing radiation sensors according to Nasa Std.3001 Vol 1 (NASA, 2007). Moreover, the SMC-LEO shall be protected against man-made objects (<0.02 m in size) and natural debris (micrometeoroid velocities <18 km/s) in space as defined in NASA STD 8719 (NASA, 2011). It is verified by high-impact test on structural models and in this way structural punctures will be avoided. Table 7 details the facility safety requirements.

Table 7: Safety Requirements for a Low-Earth Orbit Medical Center

Requirement	Verification	Justification/Reference
Minimize radiation exposure by approx. 80 percent against SPE and GCRs for system and crew protection.	Simulation and test in a high radiation environment.	Radiation protection according to Nasa Std.3001 Vol 1 (NASA, 2007).
Protect against man-made objects (<0.02 m in size) and natural debris *velocities <18 km/s).	High-impact test on structural models.	NASA STD 8719 (NASA, 2011b).
Protect against toxic spills and pressurized vessel punctures.	High-pressure test on safety valves, inspection of potential toxic spills.	Control of toxic spills and safety of pressurized vessels will be determined (NASA, 2016a).
Ensure an independent emergency oxygen supply with approx. 12L/min at 120 psi.	Review of oxygen capacities, testing of valves and tanks.	Backup for emergency (NASA, 2021d).
The SMC must provide chemical storage, separation, and isolation of Acid, bases, and inflammable chemicals. The SMC must provide wearable chemical protections.	Leak test to storage areas for chemicals, Inspection of protective gear.	Chemical safety procedures to minimize toxic release risk (NASA, 2016a). Protection gear for chemical handling and in case of toxic release (Loc. Cit.).

3.6.2.3 Integrated Shielding Approach for Low-Earth Orbit

An SMC should consider both a medical center in Earth orbit and another that considers the need for a medical center that can travel with humans past earth orbit to lunar destinations. Both short and long-term considerations for these endeavors are discussed in this section in reference to the space radiation environment.

A recurring theme for the future of human spaceflight is ISRU. Biotechnologies and their associated byproducts will be important to consider using to lower the need for resupply missions. Melanin has a special property that allows it to absorb radiation that would otherwise damage cells (Wolbarsht et al., 1981). Radiosynthetic Fungi are capable of producing melanin in abundance. A 1.7 mm thick lawn of *Cladosporium sphaerospermum* on the ISS has been shown to reduce radiation exposure by at least 1.82%, with an upper limit at 5.04% as compared to a control (Shunk et al., 2020). This implies that radiosynthetic fungi can be used as a biotechnology in space, and also as a bio-factory to produce melanin pigments to later form a radiation shield.

For an SMC-LEO, there are a number of advantages and methods of implementing this biotechnology. For one, ISRU cuts down on the mass and thus cost required for most radiation shielding technologies and is a form of biotechnology that can be reproduced many times independently of resupply missions. This form of biotechnology as compared to better shielding materials such as lead, or other heavy metals is also lightweight, self-replicating, and self-regenerating. Related, this type of fungus has been observed to be growing on the exterior of the ISS (Onofri et al., 2007). Having an active culture of any microorganism can be detrimental to humans' health, but because of its nature, *C. sphaerospermum* can exist as paneling on the exterior of the SMC-LEO, so long as it is not exposed to the vacuum of space directly. It may be most efficient to have this type of shielding only in certain areas of SMC-LEO, such as on the exterior of sleeping quarters. Further research on maintaining a large culture in varying layers with scaffolding for the fungus will be important.

Though using organisms to produce usable chemicals is both renewable and promising, biotechnologies are expensive, and produce limited quantities of desired products. Further, biotechnologies such as these require maintenance and thus resource use. Resources are in short supply in space, and on other planetary bodies, so any supplies that go towards fungi and not humans can be problematic.

To mitigate potentially deadly radiation, an integrated radiation shielding approach is proposed for the SMC-LEO. Radiation is dominated by Galactic Cosmic Rays (GCR), Solar Particle Events (SPEs), and the secondary radiation ejecta that is being created by interference of primary radiation with the shell of space habitat/module and the interior surroundings such as the racks, spacesuit, etc. Therefore, understanding the radiation shielding characteristics of materials is an important step towards an integrated radiation countermeasure approach in space, where passive shielding can play a significant role. The SMC-LEO will obey the approach of ALARA- As Low As Reasonably Achievable. Most of the radiation flux inside the ISS changes as a result of solar cycle impacts on GCR intensity regulation, modulation of GCR with respect to ISS's position in the magnetosphere region, and uncontrolled events like SPEs (Narici et al., 2017).

An SMC-LEO will likely mitigate radiation in a similar way that the ISS currently does, with the following suggested improvements. The proposed solution for additional shielding of the module will be divided into exterior, and interior shielding.

1. Exterior Shielding:

   The structure of the SMC-LEO will act as a radiation barrier. The shell of the SMC-LEO module can be protected by an extra layer of bioshield. The bioshield can be composed of fungus compost that will act as a natural shield. The fungus C. *sphaerospermum,* or the melanin it produces, could be used in conjunction with protective material like Kevlar. This fungus can also be sandwiched between the closed-cell composite metal foam panels. These panels can be mounted on the exterior wall of the SMC-LEO module. More research must be done with radiosynthetic fungi to determine the life of the panels, as the culture must be actively maintained in order to ensure a high radiosynthetic absorption is occurring as it continues to grow. The panel replacement via EVAs and the operating life of the panel used highly depend on the fungus growth rate factor in its active state. The placement of the panels will also depend on the operability inside the SMC-LEO module. This will reduce the effort that might be required for fungus application in its active state. Currently, liquid water is used on the ISS in the event of an increased radiation event. However, it was not chosen for use as a shielding material in this section because liquid water is a valuable resource better used for human consumption. It is also not the lightest form of shielding currently available.

2. Interior Shielding:

   The interior shielding will be provided by racks that will be manufactured from polyethylene or Kevlar or an integrated layer of these two materials together. Kevlar exhibits performance characteristics as strong as those of Polyethylene. For shielding material that is 100 kg/m2, the dose rate and dose equivalent rate were observed with a reduction factor greater than 30 percent and 50 percent respectively, as studied by Narici et al. (2017). It has additional characteristics like impact resistance and flexibility which makes it a good candidate material for the integrated radiation shielding approach.

   Another approach that would support the goal of integrated radiation shielding would be the use of Microencapsulated phase change materials (MEPCMs). The phase change materials (PCM) is a concept that exploits the principle of latent heat and works on the basis of providing heating/cooling effect by releasing/absorbing the energy. The PCM microcapsules can be used in the spacesuits of the SMC-LEO crew along with exterior and interior shielding approaches. This countermeasure will not only provide shielding from primary/secondary radiation ejecta but also provide protection from the radiation emitted by the medical equipment. The MEPCMs are packed with the paraffin core and lead tungstate ($PbWO_4$) shell that gives it the properties of thermal energy storage and a good radiation shielding function against gamma radiation (Lou et al., 2019). Further in-depth studies are required to determine the efficiency of these microcapsules by considering the space radiation quantification because as of now the MEPCMs study is only limited to terrestrial uses.

3.6.2.4 Module Specification

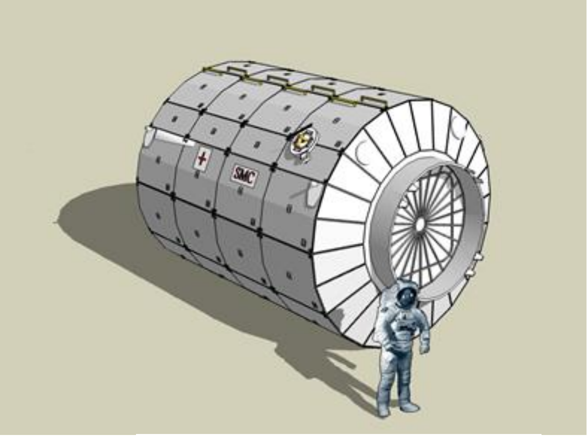


Figure 18: Outer configuration is inspired by the Columbus module.

Based on the assessment of module options, a preliminary design choice has been made for the SMC-LEO. The SMC-LEO module (Figure 18) is inspired from the Columbus module and has a NASA docking system (NDS) standard docking port to the ISS or other stations.

Stemming from the dimensions in Table 8, the module can be launched with most of the heavy launchers that are currently in the market as Ariane 5, Falcon 9, and Atlas V. The wall thickness needs to be sufficiently significant for mitigating risks related to radiation for the crew, as well as providing sufficient structural strength to endure the different launch phases of the module. The value of wall thickness selected is 6 mm. The Columbus module has 4 mm in total. The extra 2 mm are selected due to higher shielding requirements. The material retained for the SMC-LEO module is stainless steel. As a total in-orbit mass 13 metric tons are estimated.

Table 8: Specification of a Low-Earth Orbit Medical Center Module

Parameter	Specification	Remarks
Diameter	4.5m	Standard diameter for ISS modules
Length	6.7m	Sufficient space for all required elements including free rack lockers for experiments from private customers. Compatibility with standard size launchers
Total on-orbit mass	13,000 kg	Estimated based on the Columbus module
Wall thickness	6mm	4mm standard wall thickness plus 2mm for extra shielding requirements
Material	Stainless steel	Corrosion resistant
Shielding	1.7 mm thick coating of sphaerospermum	.09m thick layer required for sufficient shielding
Electrical Power	13.5 kW 120 V (DC)	120VDC Standard interface to ISS, max 6kW for an active rack, while in total not exceeding 13.5 kW

3.6.3 Interfaces

3.6.3.1 Standard Docking Interface

For compatibility reasons an SMC-LEO will be attachable to multiple potential hosting space stations, with a near-term target being the ISS. This requires standardized docking capabilities. The NDS has become the standard for the American implementation of the IDSS (ISSAP, 2016). For the Russian segment, the APAS-95 docking system is used. In order to bridge these two systems, an International Docking Adapter (IDA) may be used if the SMC-LEO is attached to an APAS-95 port.

3.6.3.2 Thermal, ECLSS & CHeCS Interfaces

The Internal Active Thermal Control System (IATCS) provides heat collection, transportation, and rejection. The heat collection system is composed of cold plates, heat exchangers, rack flow control assemblies and manual flow control valves. The thermal control subsystems in each rack are connected to the IATCS which transfers heat from each rack and module to dedicated thermal radiators on the truss structure of the ISS. The detailed design would follow thermal control standards such as the SSP 57000 Pressurized Payloads Interface Requirements Document (NASA, ESA and JAXA, 2015). This thermal control system would be implemented for a similar orbital medical center.

The SMC-LEO will be attachable to the ISS ECLSS system and provide temperature control between 17 and 27 degrees, pressure control around one bar, and CO2 filtering to levels below 3mmHg and 2mmHg during acute care. Life support systems, such as carbon dioxide removal and oxygen generation, are only placed in central ISS nodes and modules whereas temperature and humidity control can be found in almost every part of the ISS. Miscellaneous equipment such as fans, valves, filters, smoke detectors and portable fire extinguishers are included in every module and node.

As the ECLSS is the main system for environmental control and life support, an SMC-LEO will be equipped with appropriate interfacing to the main system. Additionally, the SMC-LEO could have its own Advanced Closed Loop System (ACLS) for redundancy purposes giving it a higher degree of independence and safety. In the case that ACLS is unavailable, the SMC-LEO could be equipped with a zeolite unit for filtering CO2 instead.

The Crew Health Care System (CHeCS) on the ISS is composed of the Health Maintenance System for medical care, the Environmental Health System (EHS) for monitoring internal environment, and the Countermeasures System including hardware and procedures for exercise (Clement, 2013). The SMC-LEO will primarily cover the first aspect of health maintenance, but to a higher degree both physical and mental health. Regarding exercise, the orbital medical center will not provide advanced equipment as these are already available on the ISS and can be used in a shared manner.

3.6.4 Interior Design Configurations

The interior of the SMC-LEO module consists of twelve ISPR standard racks (Figure 19), four on the left side, four on the right, and four on the ceiling. The floor contains four lockers with additional storage space for water tanks, medical oxygen tanks and wastage. There are two main areas: the medical and research area. Five ISPR racks are allocated each to medical and research purposes including active racks for operation and passive racks for storage (Table 9). Active ISPRs have more capabilities and allocated power than the passive ISPRs. The Medical Care and Research area has a total volume of 12.8m^3 individually, each payload rack has a storage capacity of 1.6m^3.

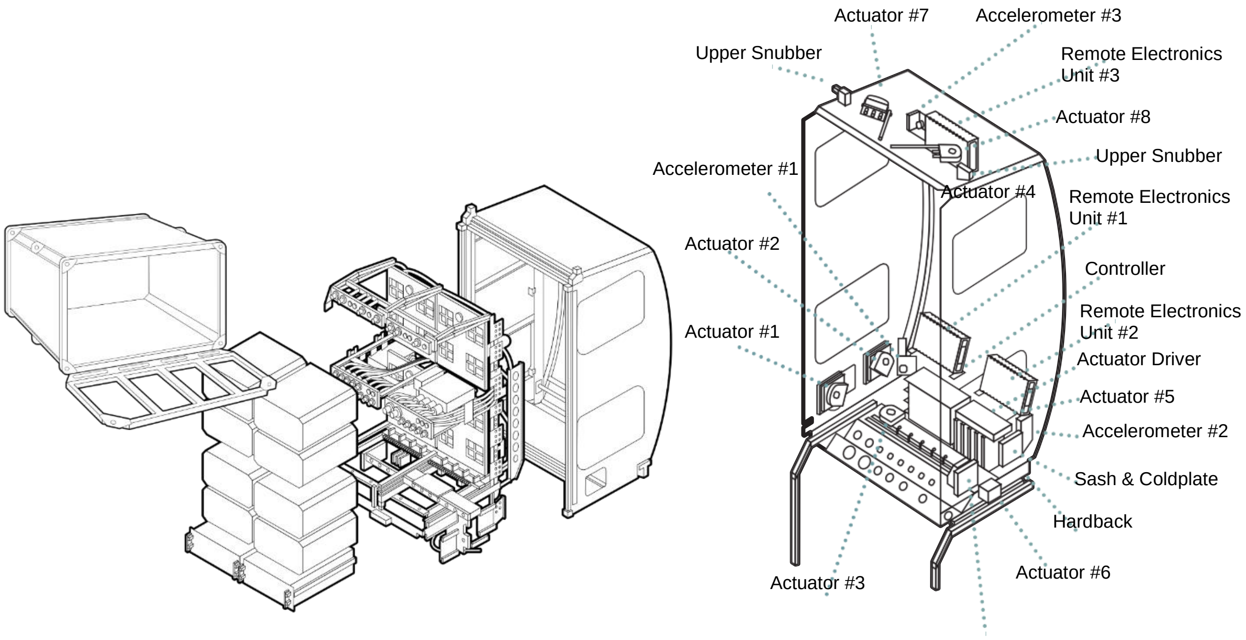


Figure 19: Sketch of an ISPR with interfacing gear for power harness, cooling loops, and data interface with the Integrated Vibration Damping System (ARIS). The ARIS system (right) is equipped with several actuators for electromechanical damping. Additional standard storage boxes are attached to the ISPR (NASA, 2015a).

Table 9: Orbital Module Rack Allocation

Parameter	Rack allocation	Remarks
Number of racks (ISPR)	12	On the left side, right side, and ceiling
Storage lockers on the floor	4	For auxiliary tanks
Medical racks (ISPR)	5	Passive storage ISPR and active ISPR
Research racks (ISPR)	5	Passive storage ISPR and active ISPR
ECLSS/ ACLS rack (ISPR)	1	1 rack in case of the European ACLS
Additional rack (ISPR)	1	Modularly extendable for future purpose
Water tanks	2	In the floor
Medical oxygen tanks	2	In the floor
Fire extinguisher	1	In the area of the hatch
Smoke detectors	2	In the area of the hatch and the window
Active radiation detector	1	In the ceiling

3.6.4.1 Spatial Allocation and Rack Layout

The entrance of the SMC-LEO module will give access to a decompression chamber. On the opposite side of the module, a window will be built into the wall and will permit the crew to have a recreational area when no medical or research operation is running. The medical area of the orbital module is located near the entrance of the module, to provide ease of access in an emergency, and the research area in the other section of the module near the window. Table 10 details the human performance requirements associated with spatial allocation.

Table 10: Human Performance Requirements for a Low-Earth Orbit Medical Center

Requirement	Verification	Justification/Reference
Fully in line with safety regulations module shall be operated by trained astronauts under the lead of the Crew Medical Officer	Astronaut Training and Tests, Review of Protocols and Standards	NASA Space Flight Human System Standard, NASA-STD-3001 Volume 1: Crew Health; NASA-STD-3000 Crew Safety
Provide ergonomic workspace for parallel activities of research and medical operations	Simulation, Inspection of work radius and accessibility	Ergonomic workspace; crew safety; multifunctionality hosting several persons
Provide accessible movement to minimized bottlenecks	Simulation, Review, Inspection of accessibility	Smooth operability, safety, ergonomic workspace
The intensive care unit shall be accessible and ready for operation immediately at all times	Simulation, Review, Inspection of accessibility	Vital for medical care, especially for emergencies
Provide opportunities for stabilizing the workspace and the astronauts operating in it for all respective units	Test of stabilization gear, inspection	Restraints in microgravity to stabilize astronauts during all activities
Be maintainable by astronauts without disassembly of parts	Inspection and Operational test	Maintenance

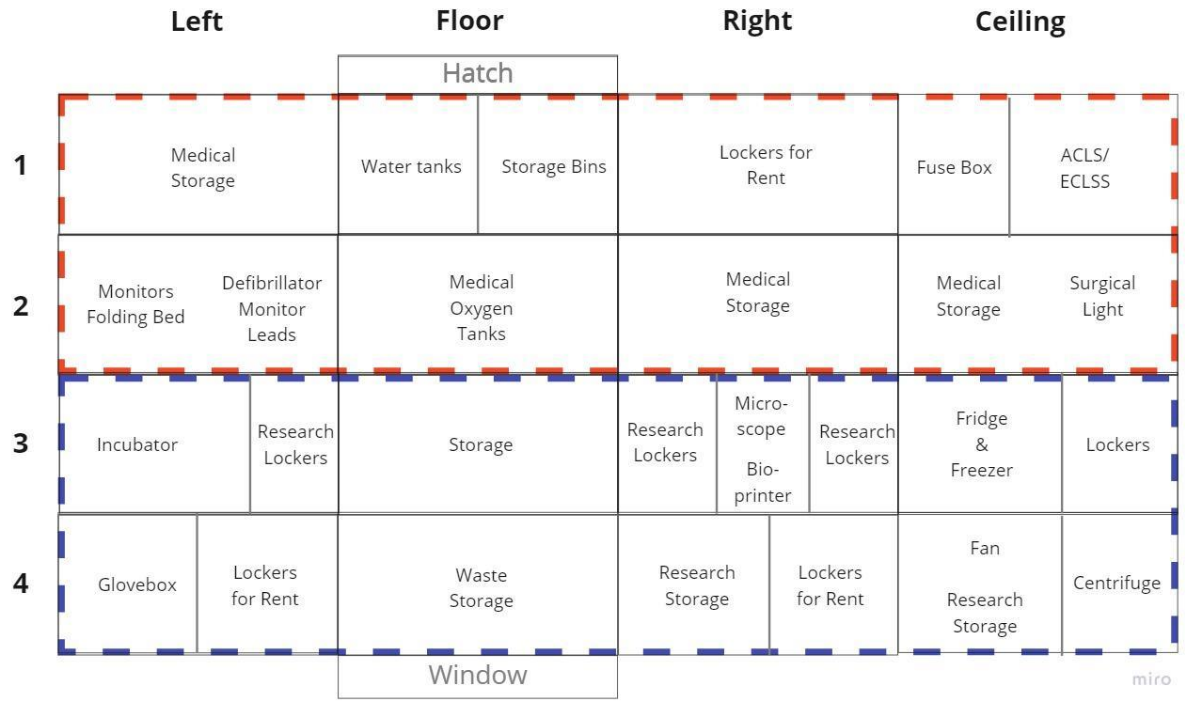


Figure 20: Technical drawing of the unfolded module including all four sides: left wall, floor, right wall, and ceiling and showing the rack allocation, their components, equipment, and storage.

All medical and research equipment and instruments have been allocated to different racks according to their size, functionality, operational relevance, and ergonomic aspects. The Medical care area, (Figure 20; red) consists of payload racks L1, L2, R1, R2, C1, C2, F1 and F2. The Research Area, (Figure 20; blue) consists of payload racks L3, L4, R3, R4, C3, C4, F3 and F4. The payload racks have customizable configurations with different sized lockers within each payload, each labelled A to Z.

3.6.4.2 Medical Rack Layout

The orbital module is optimized towards the medical treatment area with a collapsible patient table at its center. The medical area is designed to be close to the hatch and the research part close to the window to guarantee access at all times. The medical area will be composed of a table of operations disposing of three hinges, that can fold as a table, as a bed, and as a chair. The equipment of the medical area includes a portable ultrasound machine, a defibrillator, monitor leads, medical supplies, fuse box, two central-mounted examination lights, as well as a fire extinguisher located near the entrance. Two monitors and a laptop are fixed on each wall on retractable arms that can swivel to face other directions. A laparoscopic tower is also included in the medical area. This tower is equipped with a monitor, light source, insufflator, camera control unit, suction-irrigation system, diathermy controller, and a video recorder. Open surgery will not be included in the orbital version due to microgravity constraints. Blood cannot be contained properly unless there is a mechanism to suck blood from an open wound and transfuse it back into the patient’s body. Table 11 and 12 provide an overview of the rack and equipment constraints and spatial allocation of the medical racks, respectively.

Table 11: Medical Constraints for Rack and Equipment Allocation

Constraints	Justification
● No equipment can be stored or deployed over the face of the medical care racks ● Telemedicine capabilities will be limited to the communications capacity and availability of the SMC system hardware ● Medical equipment and medications need to be stored at temperatures between 15 and 30°C	● There can be no obstruction to the medical care racks in case of emergency ● The bandwidth and available signal for real-time communication will depend on the SMC equipment ● Medical equipment and pharmaceutical effectiveness can be affected by temperature

Table 12: Spatial Allocation of Medical Racks

ID	Medical Rack	Content
L1	Medical Care Rack	Personal protection, blood draw, diagnostic instruments, diagnostic equipment and monitors, routine medications, dental care, airway and oxygenation, emergency/CPR medication kits, wound care
L2	Medical Care Rack	Folding patient table, monitors, surgical equipment, defibrillator, leads, IV pumps, tubing, and invasive lines
R1	Medical Care Rack	Lockers for rent, medical storage space, fuse box
R2	Medical Care Rack	Patient hygiene, suction and cleaning supplies, ultrasound, anesthesia, electrocardiograph
C1	ECLSS	Fuse box, ACLS/ECLSS
C2	Medical Storage	Extra storage, surgical lights
F1	Storage	Water tanks, storage bins
F2	Storage	Medical oxygen tanks

3.6.4.4 Research Rack Layout

The SMC-LEO shall provide ergonomic workspace and needs to be accessible at all times, thus avoiding bottlenecks, especially during medical emergencies or maintenance operations. Restraints are needed throughout to guarantee stability during operations. The SMC-LEO shall at all times be led by a Crew Medical Officer (CMO) according to NASA Space Flight Human System Standards, NASA-STD-3001 Volume 1 on Crew Health and NASA-STD-3000 on Crew Safety (NASA, 2007).

The research area located near the window is composed of a glovebox and an incubator located on two racks near to each other. On the other side or the research area, one rack is composed of a microscope, bioprinter, and a flow cytometer. On the ceiling of the research area, three freezers and one fridge are included to conserve the research supplies and natural and bioprinted organs. Additionally, a centrifuge, a low noise ventilation fan, and a radiation detector are included. Table 13 provides an overview of the spatial allocation of the research racks.

Table 13: Spatial Allocation of Research Racks

ID	Research Rack	Content
L3	Incubator	Incubator for cell culture, storage lockers for research equipment
L4	Glovebox	Glovebox for cell culture, storage lockers for research equipment
R3	Research Rack	3D bioprinter, microscope, research lockers, storage space
R4	Research Rack	Molecular biology, lockers for rent
C3	Refrigeration	Three freezers, one refrigerator, locker for research
C4	Centrifuge and Storage	Centrifuge, storage space, fan/air ventilation
F1	Storage	Extra storage
F2	Storage	Waste storage

3.6.4.5 Operational Requirements

For operational continuity and cleanliness reasons, waste storage capacities will be required for up to six months in case a resupply mission and waste disposal pickup gets cancelled. Parts that can be cleaned and recycled shall be recycled. For the same reason medical supplies shall be kept available for at least six months. Table 14 details the main operational requirements.

Table 14: Operational Requirements for a Low-Earth Orbit Medical Center

Requirement	Verification	Justification/Reference
Provide medical supplies for continuous service for minimum 6 months without resupply	Calculation, review	Self-sustainability
Provide recycling capabilities for transforming waste into a source of supplies for the mission and using nutrients of organic material	Inspection and Test of recycling capabilities	Self-sustainability
Non-recyclable waste products shall be storable in a dedicated area for at least 6 months	Storage review and inspection	Avoid spatial bottleneck in case cargo delivery, waste disposal delayed
Emergency sequences shall be implemented in the control system as a Fail-Safe mechanism	Test of emergency situations	Safety
Follow the standards for fault tolerances and redundancy of the hosting habitation	Calculation, high-load tests	Fault traceability to avoid single or multi events failures

The different configurations and operating modes of SMC-LEO are depicted in Figure 21 and 22. The table of operations is retractable into one of the medical racks in order to offer different spatial configurations: a medical treatment mode with a non-retracted patient-table, a research mode with the patient table being collapsed into the wall, and a rehab and exercise mode.

In addition to the research and medical racks, the SMC-LEO will be equipped with fire and smoke detectors, radiation detectors, and a waste storage section. On Earth the buoyancy effect due to gravity leads hot gases to rise as the density of the medium decreases. Thus, smoke detectors are typically placed on the ceiling of a room. In space there is microgravity and hence no buoyancy which makes smoke more difficult to control. Smoke detectors, therefore, will be integrated on all sides. A separate storage section in the floor is for waste disposal. This space is not fully occupied and can be complemented by a recycling station in the future. The SMC-LEO will also be equipped with a fuse box where the circuits for all the racks are controllable.

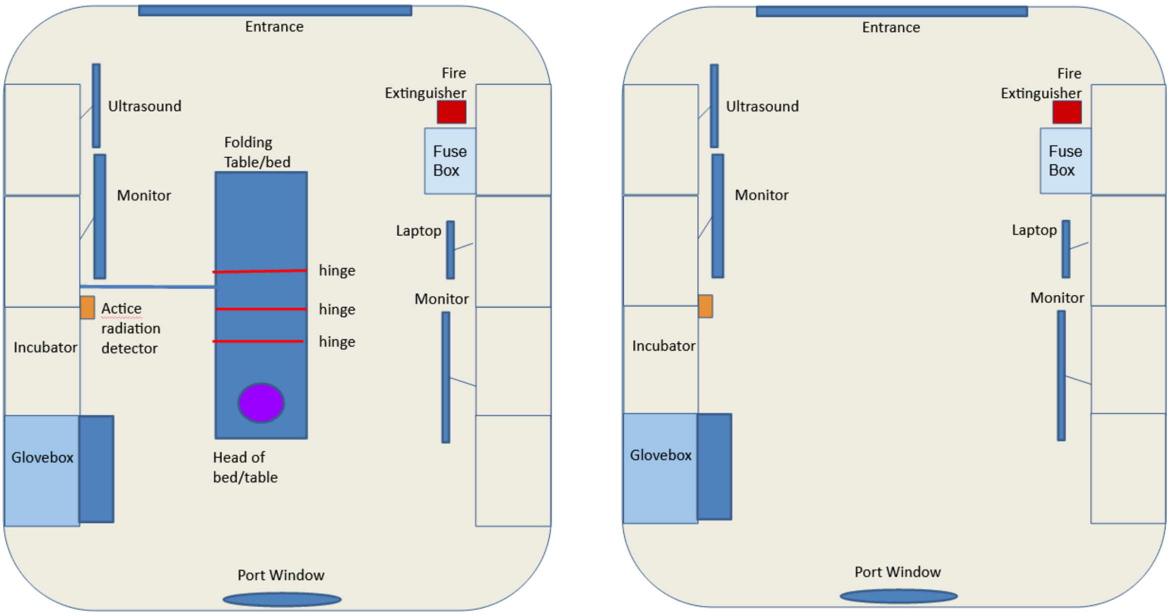


Figure 21: Top view of the module in different operating modes. Left: configuration in medical treatment mode with a collapsible patient table. Right: configuration in research mode with the patient table stowed into the wall.

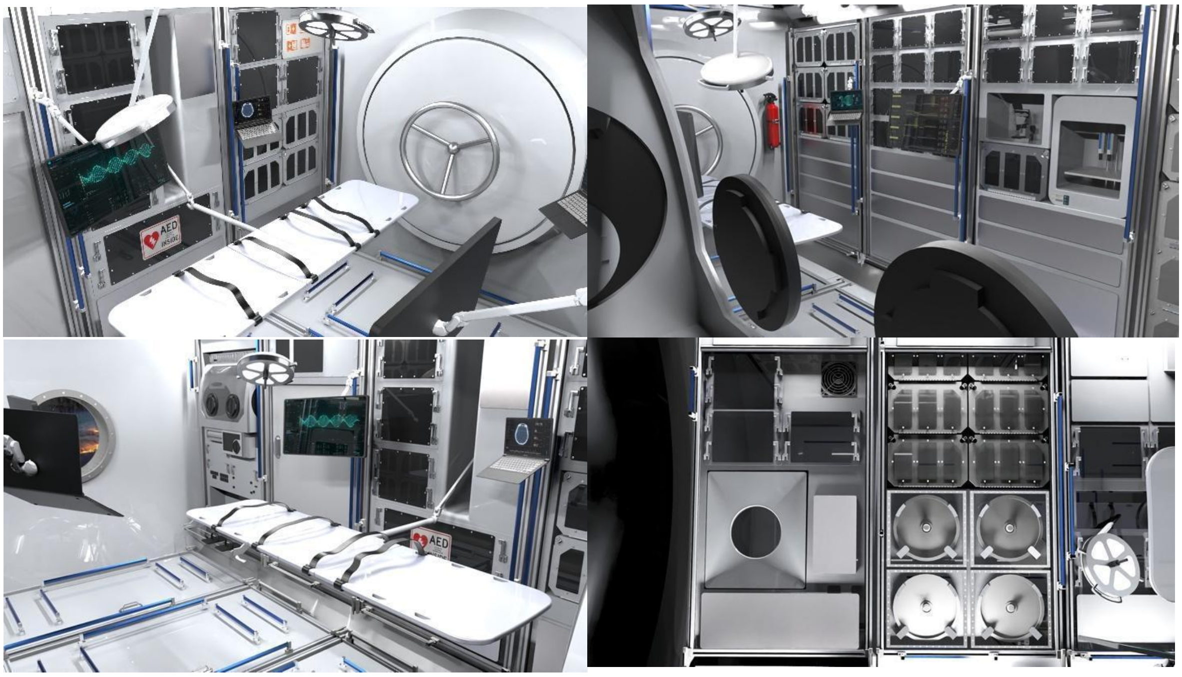


Figure 22: 3D illustrations of the SMC-LEO. Upper left: view from the window with the entrance in the back. Upper right: view of the research area from the glovebox displaying the microscope and bioprinter. Lower left: view of the medical area with the collapsible table. Lower right: view of the ceiling centrifuge, ventilation fan, radiation detector, freezers, and refrigerators. Image Credit: Jeremy Battermann.

Architectural considerations for subconscious psychological well-being are integral to the design of an SMC-LEO. Design elements known as 'Healing architecture' uses concepts including natural light, spatial orientation, and visuals to provide continuous psychological crew support. The aim of these elements is to ensure a given healthcare space does not look or feel like a "facility" but instead an inviting space that is conducive to patient well-being and recovery (The Korte Company, 2020). The use of artificial depictions of nature (i.e., photographs, paintings, videos) and the addition of a port window would be considerable additions in offering psychological comfort for in-SMC-LEO space crews and tourists. While these elements are not included in the preliminary stage design as depicted in Figure 23, they will be necessary considerations before a final manufactured design is developed.

A port window would theoretically allow for the addition of natural light to alleviate crew exposure to continuous artificial light. The ever-changing view from a window can provide positive "salutogenic" experiences from seeing the Earth (NASA, 2011a) and can reduce sensory monotony, isolation, and confinement (Kanas and Manzey, 2008). Positive experiences can increase cognitive function and can decrease potential in-flight psychological symptoms.

Figure 23: Representation of the simulated window in the SMC-LEO Module. Image Credit: Jeremy Battermann.

However, the addition of a window could lessen the structural integrity of the SMC-LEO module. Despite the benefits of including a window, the window will be replaced with an artificial viewport to maintain the stability of the module structure. A high-resolution LED-screen, structured to look like a normal window on the module wall (Figure 23), would be programmable to different visuals from space to Earth environments depending on the needs of a given individual. Though this would not permit natural light into the SMC-LEO module, it would still provide SMC-LEO patients with a restful and stress-reducing experience and a unique programmable vantage point for in-module exercises. Since stress is compounded in space, the benefit of a port window – even a virtual one – to see beyond the scope of the facility is essential.

3.7 Mission Elements

The following sections deliver the phases of the mission from launch to operations. After selection of the proper vehicle for delivery into LEO, where the tradeoffs for each option are mentioned, the telemetry and tracking as well as communications structures are described. Then, once these are established, the separate elements of the operations phase are delineated.

3.7.1 Launch Vehicle Selection to LEO

In order to construct a space medical center, launch vehicle selection must be considered. Since the retirement of the Space Shuttle in 2011, a SpaceX Falcon 9 has deployed the BEAM. Apart from the Russian Proton and Soyuz no other vehicle has delivered modules to the ISS. Soyuz is a tried and tested rocket for delivering astronauts to the ISS but the modules it has delivered have been relatively small (Krebs, 2019). Therefore, the Soyuz is excluded from this trade-off.

The three main parameters that will determine vehicle suitability are the payload fairing, the payload mass, and the cost. The payload fairing must be able to fit the module in a cylindrical dimension. The launch vehicle, depending on its boosters, should have a max payload to LEO of at least 14,515 kg (maximum mass, defined in module selection). The cost will define the selection after the other criteria have been met, with the cheapest option ideally being the most feasible. From these criteria, three potential launch vehicles have been selected for their mission suitability:

- Ariane 5 at ~$100M
- ULA Atlas V (531) at ~$73M
- SpaceX Falcon 9 at ~$62M

Figure 24: Suitable Launch Vehicles (The Verge, 2017).

The Ariane 5 is the flagship launch vehicle of Europe and is the global benchmark for launches to Geostationary Transfer Orbit (GTO) (Arianespace, 2021). With the imminent release of the Ariane 6, the cost of Ariane 5 launches has been reduced by 40% (from approximately US$175m to US$100-105m) to compete with SpaceX in the Asian market. At this new price point, the Upper Berth of the launcher – reserved for the larger payload – may be priced in the US$60-70m region, with the Lower Berth costing around US$40-45m (Serdata, 2019), placing it much closer in price to its main competitor SpaceX. However, it is difficult to know if the SMC-LEO will share a launch with another spacecraft. If the SMC-LEO was to launch with another spacecraft Ariane 5 could prove to be the cheapest option. But, if the SMC-LEO was to solely launch atop of an Ariane 5 it would prove to be far more expensive than the other options. The ULA Atlas V also has a strong success rate. Using ULA's launch vehicle quotation system (United Launch Alliance, 2021), the exact model the SMC-LEO needs to complete the mission is the Atlas 531. The launch would cost $73M, proving its suitability. However, this price would still be too high, considering the competition.

The best launch vehicle available is the SpaceX Falcon 9 (Figure 24). This vehicle is the most popular launch vehicle on the market and has been used to bring astronauts to the ISS as well as the BEAM module, which it delivered to the ISS in 2016. Furthermore, due to its reusable elements, the launch price is $62M and it is readily available on the commercial market. Therefore, considering the market trends and the current availability of launch vehicles this would be the best selection for any near-term plans to launch the SMC-LEO. If the module length needed to be increased, this eliminates the possibility of using any of the SpaceX launch vehicles due to the limited payload fairing dimensions - leaving the United Launch Alliance and Arianespace launch vehicles as the best selection.

3.7.2 LEO Command, Control and Communications Architecture for TTC

There are different communications architecture, frequencies, and links that an SMC-LEO could use in an orbital module. The available systems have been developed to a conceptual level, having International Telecommunication Union (ITU) restrictions, allocations, and regulations into consideration (Shin, 2014). Ideally, the module will use the following three types of communications:

- Ground link. This link will enable Mission Control (MC) to receive and send TTC and will serve as the link for any audio or video communication, including possible telemedicine.
- Ship to ship: This link will provide continuous TTC for the ISS and the transient links with other ships while docking.
- Internal: This link will provide a baseband for crew communication across different modules.

The parameters for the necessary communications systems for an SMC-LEO are laid out in Table 15 including the frequency bands, architecture, and ground and space receiving systems.

Table 15: Comparison of ISS Communications Systems for a Space Medical Center
*Data from the ISS extracted from (Dempsey, 2017; NASA, 2016b; NASA, 2017a).

Parameter	ISS*	Space medical center LEO
Frequency bands	S-band Ku-band UHF	S-band Ku-band Ka-band
Communications architecture	The ISS communications system is complex and has changed over the years. The normal flow of communications architecture is that data travels from the ISS using different frequencies to Mission Control through ground stations and vice versa	See Figure 25
Ground receiving system	GRGT and WSGT	GRGT and WSGT
Space receiving system	Constellation of TDRSs	Constellation of TDRSs

The uplink and downlink communication between the SMC-LEO and the ground segment is fairly straightforward. The signal travels through the Tracking and Data Relay Satellites (TDSR) to the ground stations, either White Sands (WSGT) or Guam (GRGT). These stations send the signal to Mission Control. Mission Control (Figure 25) is simplified as one element but could represent any Mission Control center around the globe, depending on the operation. For uplink communication, the process is repeated but in the opposite direction.

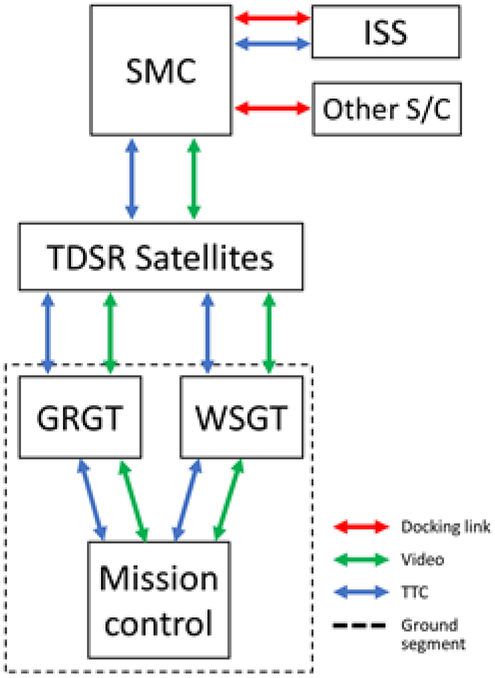


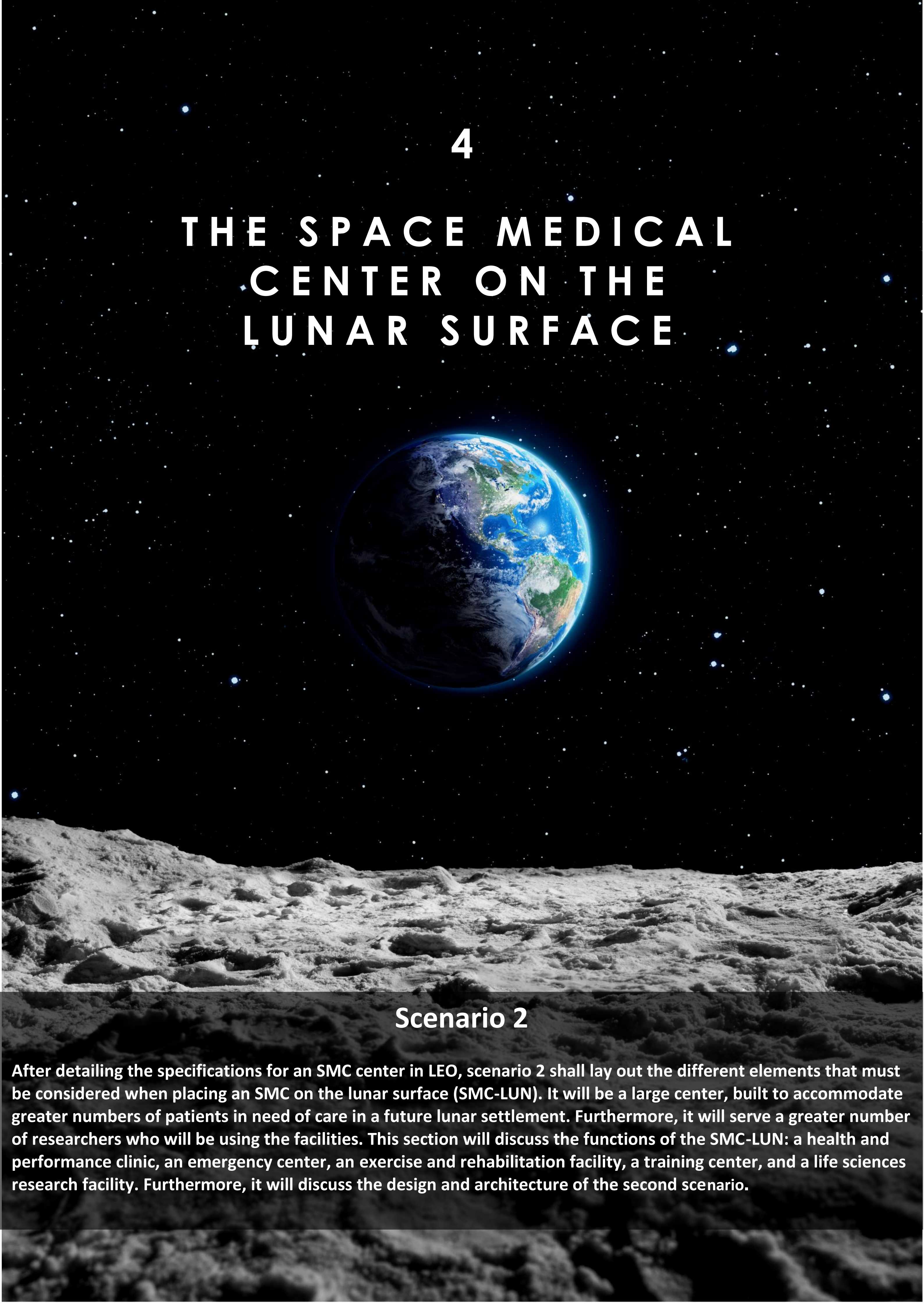
Figure 25: Communications architecture for an orbital module. Different colors for video, TTC, and docking link are presented in different bands.

Each frequency will have a specific use and need aboard an SMC-LEO. Ka-band will be used for ship-to-ship communications with the ISS and other spacecraft. This band will also be used for communications with astronauts in the case of EVA. Ku-band will be used to transmit any video to and from the SMC-LEO. This will be especially helpful for telemedicine purposes. S-band will be used for all ground communication and TTC. This includes the audio from telemedicine, personal crew calls, and medical data transfer.

Placing an SMC in LEO is the most realistic and important first step. Therefore, this large chapter shed light on the multiple components of the core designs for the SMC-LEO designs. Reviewed here were the medical operations for every level of health care from routine, primary care to emergency care and intensive care. Mental health services, exercise, and rehabilitation were also discussed, with equipment and personnel for each. The extensive research capabilities that will be possible on the SMC-LEO were explored. A researcher in a commercial partnership with the SMC will have confidence that his or her project will be managed professionally and with many of the same resources as on Earth. As mentioned, there will be fundamental research on the most elemental forms of how our biological systems function, which will be important for the greater scientific and academic community. There will be translational research, examining the forms of research that are directly applicable to humans on earth, working with drug protein crystals, stem cells, organs-on-chips, and others. Additionally, there will be research on human performance in space, with work on biomarkers, studying genomics and other insights to crew health and protection. For engineering principles, the technical and safety requirements dictated the overall size and structure of the SMC physical plant as well as the shielding and pressurization solutions. The construction of the standard medical and research equipment racks and view their contents and location were identified, with each important component having a specified position in the layout, based on function and proximity to like components. Lastly, a proper short-list of launch vehicles was selected, and the communications structure to manage telemetry, tracking, and voice and data relays was diagrammed in the plan.

4

THE SPACE MEDICAL CENTER ON THE LUNAR SURFACE



Scenario 2

After detailing the specifications for an SMC center in LEO, scenario 2 shall lay out the different elements that must be considered when placing an SMC on the lunar surface (SMC-LUN). It will be a large center, built to accommodate greater numbers of patients in need of care in a future lunar settlement. Furthermore, it will serve a greater number of researchers who will be using the facilities. This section will discuss the functions of the SMC-LUN: a health and performance clinic, an emergency center, an exercise and rehabilitation facility, a training center, and a life sciences research facility. Furthermore, it will discuss the design and architecture of the second scenario.

The next stage of the SMC will take place on the lunar surface. It will be a much larger center, built to accommodate the larger numbers of patients to be cared for at a future lunar community, and to serve the greater number of researchers who will be using the facilities. The functions of this SMC-LUN will be the same as for the SMC-LEO. This center will act as a primary care health and performance clinic, a psychological care office, an emergency treatment center, an exercise and rehabilitation center, and a life sciences research laboratory.

The lunar environment presents many challenges (Table 16) from partial gravity to a thin atmosphere and extreme temperature gradients. For this reason, the study of the lunar environment and its adaptability for human habitation is essential. This chapter aims to study the potential locations, architectures, design, and configuration of a medical center on the lunar surface. In addition, the research practices, medical operations, and sustainability actions have been addressed in order to provide a wide framework of the lunar medical center operation.

Table 16: Key Parameters in Lunar Environments (Mankins and Mankins, 2020).

Key parameter	Description
Partial gravity	⅙ Earth's gravity, changes the applications for a space medical center
Vacuum	Lack of atmosphere results in exposure to vacuum
Temperature gradient	Gradient between -150°C and +100°C between night and day; -250°C in permanently shaded areas
Day and night cycle	14 days daylight, 14 days night; the cycle poses a challenge to power generation, thermal control, and psychological well-being
Lunar dust	Granular sharply edged regolith is a potential hazard, but also a very useful resource for habitation shielding

One of the major challenges on the Moon is partial gravity, equivalent to about ⅙ the gravity of Earth. This implies that structures only have to carry one sixth of loads for the same mass as on Earth. This also has implications for the SMC-LUN itself, such as on treatment or exercise. Open surgery is theoretically plausible since it is unlikely that blood will float and obstruct visualization of the surgical field like it would in microgravity. However, the fluid mechanics are significantly different with only a fraction of Earth's gravity. Likewise, exercising on treadmills or with weightlifting racks is not feasible without adjustments to the lunar environment. Due to the lack of atmosphere the habitat on the Moon will require internal air pressurization. This means that all interfaces between humans and the hostile lunar environment need pressurization and each habitation module needs an airlock.

Lunar dust poses another challenge to sustainable operations on the Moon. The dust is composed of extremely small and granular regolith with most particles measuring just under a millimeter. Regolith is extremely sharp-edged as erosion due to weather, water, climatic and tidal events do not occur on the Moon apart from solar radiation, solar particle events and galactic cosmic rays. Thus, regolith is a potentially dangerous hazard (Slyuta, 2014). Conversely, regolith can also be used as a construction material once in-situ resource utilization (ISRU) becomes feasible. Loose regolith can be compacted or sintered to additively manufactured habitat structures (Kalapodis, Kampas, and Ktenidou, 2020).

Scenario 2 assumes that humans will have begun to settle on the lunar surface by 2040. This primary settlement will be small in size and consist of approximately 40 individuals. The success of maintaining such a settlement will depend upon its capability to be self-sustaining and largely independent from Earth with regards to resupply requirements. Therefore, local production of energy, building materials, food, oxygen, and water will be essential if the settlement is to be truly self-sufficient.

4.1 Lunar Health and Performance Clinic

Medical care on the lunar surface will be similar in many ways to the care given in LEO, but with some notable exceptions. The addition of gravity provides certain benefits, such as stability when working with patients, ease of mixing drugs and drawing up medications, and the ability to perform procedures without the difficulty of microgravity. It will also restore certain problems, such as falls and crush injuries. The following sections detail the differences in care that are specific to the lunar surface.

With the addition of partial gravity, falls will be possible, and traumas will be more common. Objects that were in microgravity can now fall and cause injuries. The incidence of major illnesses such as appendicitis will be similar, but their treatment can differ. If an astronaut or spaceflight participant suffers from a perforated abdominal viscus or appendicitis, laparoscopic or even open surgery would be more feasible on the lunar surface than in LEO. Blood would not pool as it would in microgravity or contaminate a cabin environment. Surgical instruments would also be more stable with gravity and the surgeon and crew would not require special restraints in order to apply force to the patient. Evacuation from the lunar surface will also be more difficult. A return trip to Earth will take approximately five days. There will be strong gravitational forces upon re-entry to the Earth, so a patient would need to be stable enough for a multi-day journey and significant physical forces. Therefore, more treatments for more severe conditions such as multi-trauma, sepsis, pancreatitis, and cholecystitis would need to be provided at a medical center on the lunar surface.

4.1.1 Primary and Pharmacological Care

Routine care on the lunar surface and in the gravity wheel medical centers will consist of the same standardized elements as it does on the ISS module from Scenario 1, and on Earth. Primary care encompasses disease prevention advice, strategies, diagnosis, and treatment, and is a broad ranging field of health. It is likely that the technology used in the diagnosis and treatment of patients may advance and change in the future, but the fundamental aspects of the care are predicted to stay the same. Longer duration space missions will inevitably lead to new challenges and requirements for primary care countermeasures.

Since the options for resupply will be more limited on the lunar surface, the medications of the SMC may encounter issues with shorter life-span or decreased effectiveness. Repackaging to conserve space and weight, combined with exposure to light, heat, humidity, radiation, and oxygen, could cause premature degradation, as mentioned previously. Therefore, the SMC on the lunar surface will provide temperature-controlled storage containers with additional shielding to protect this precious cargo.

4.1.2 Psychological Care

Knowledge about psychological well-being in a lunar environment is largely unknown. To date, no human-crewed mission has remained on the lunar surface for an extended duration and no human has remained in a spaceflight environment for longer than fourteen consecutive months (Kanas, 2015). Therefore, the efficacy of some support measures cannot be relied upon in an SMC-LUN. While some countermeasures are capable of being used both in LEO and on the Moon, it will be essential for an SMC-LUN to provide autonomous care for countermeasures and treatments to suit the lunar environment.

PPCs could be negatively impacted on a lunar surface environment. Depending on the location of a medical center on the lunar surface, PPCs could be used to some regular effect. If a medical center were located on the near side of the Moon with direct line-of-sight to the Earth, then PPCs could remain an effective countermeasure accounting for a few-second delay in communication. However, if a medical center were located on the far side of the Moon with no direct line-of-sight to the Earth, then the delays in communication would render PPCs less effective (Slack et al., 2016).

A potential substitute for PPCs in this instance would be the addition of a human psychiatrist or psychologist to the lunar settlement crew. Such a person could serve as an on-board consultant to conduct in-person conferences similar to a PPC. Unlike a PPC, however, a designated psychologist would remain a part of the crew and would therefore be unable to remain completely objective as they would be exposed to the same psychological stressors, issues, and influences as the rest of the crew (Kanas and Manzey, 2008). Further study on the efficacy of psychological counselling would be necessary before developing a space medical center on the lunar surface.

Additionally, the loss of visual connection to the Earth can result in a psychological loss of connection to both home and safety and could cause specific psychological symptoms in deep space crews including homesickness, depression, and other unpredictable conditions (Clément, 2011). To counteract these symptoms, the SMC-LUN could be equipped with VR equipment to provide individually tailored and interactive Earth environments for eliciting positive psychological responses. This can be either through individual VR headsets or, as lunar settlements grow in the future, large-scale VR chambers. Current LED and VR technology could easily be integrated into an SMC-LUN to virtually interact with Earth environments thereby mitigating potentially negative reactions stemming from increased isolation or confinement in a lunar surface environment.

In terms of psychological pharmaceutical care, there is very little information on the use and efficacy of medicine in prolonged deep space environments, and the studies undertaken on medicine in Earth orbit have been minimal. While there are no figures to back up the use of medications in deep space, the same medications approved for use in LEO (Chapter 3.1.3) could be used in a lunar medical center, provided they are able to care for psychological symptoms that may become more potent with greater distances and durations from Earth.

4.2 Lunar Emergency Medical Treatment Center

4.2.1 Emergency and Critical Care

With the advantage of gravity, emergent care will be simpler and more effective in many ways. Restraining patients and staff to work on an injured patient will not be as critical, since the patient will not move when minor force is applied. This will make airway management more effective, with the ability to better control the patient and manipulate the head and body with the additional force of gravity acting as a counterforce. Cardiopulmonary resuscitation, in particular, will also be more practical. More force can be applied, more easily, and crewmembers can change roles performing compressions more quickly. There will also likely be more space to work in the SMC-LUN. Meanwhile, transporting a patient may be more difficult, due to gravity, and lunar dust causing contamination of clean or sterile fields could also be a problem, even indoors, on the Moon in an emergency.

Intensive care on the lunar surface will have some advantages with gravity and some disadvantages. Preparing and delivering intravenous medications will be simpler. It is difficult to separate liquid medication from air when drawn in a syringe or delivered into intravenous tubing. Gravity also assists with drainage from invasive tubes and drains. Meanwhile, patients would have more pressure ulcers on the lunar surface than in microgravity due to more forceful contact on the skin at pressure points in a medical bed. Also, blood pressure will also vary depending on position in lunar gravity, whether laying or standing, and respiratory mechanics will be less favorable in gravity where the weight of the chest wall will impede mechanical ventilation.

4.2.2 Blood Transfusion

The SMC-LUN will have a refrigeration unit with a dedicated section for storage of blood products. The purpose will be to maintain a supply for research and medical purposes. Along with equipment for separation of blood components and the ability to test blood, this capability will be known as the Blood Bank. It will consist of a refrigeration unit at 4°C, a freezer at -25°C, and a blood warmer. Furthermore, it will take advantage of the SMC-LUN centrifuge and microscope.

Hematological research can be performed aboard the SMC-LUN to study the effects of lunar gravity and radiation on the blood. Therefore, the blood bank will serve as the center for transfusion medicine. There is no medication at this time that can replace blood product transfusion for certain. The gold standard for treatment is replacement of blood products to control bleeding and restore oxygen carrying capacity. If a need arises, a transfusion will be performed aboard the SMC-LUN.

The blood bank would serve the same purpose on the lunar surface but would benefit from having gravity and more working space. With gravity, frozen plasma could be rewarmed in hot water baths, which warms more evenly and prevents the formation of cryoprecipitate. Gravity would also facilitate working with centrifuges, making blood component separation easier. Having extra space, the size of the refrigerator and freezer units could be expanded. This would allow the retention of all units of donated plasma which could further the hematological research capability and would extend the size of the pooled collections of plasma available to each crewmember in case of emergency. Finally, with additional space and equipment on the lunar surface, cross-matching for non-autologous transfusion. Finally, having additional space could mean having additional equipment such as microscopes available for blood processing and even crossmatching if a crewmember happens to be a universal donor. The other functions of the BB would remain similar to the SMC-LEO.

4.2.3 Surgical Care

Closed head injuries with intracranial hemorrhage, blunt or penetrating trauma, gastrointestinal hemorrhage, cholecystitis, or appendicitis could arise at any time during a mission. A patient in SMC-LEO could be stabilized and evacuated to Earth in the event of gross injury or urgent surgical disease. If a patient in SMC-LUN however, it will be important to have the ability to perform surgery when medical management alone would not be sufficient.

In an SMC-LUN, there could also be the possibility for robotic telesurgery, since the technology in this field may have advanced considerably by the time a lunar station is created. Laparoscopy as a closed surgery technique follows the principle of Minimally Invasive Surgery (MIS), with minimal opening of the skin and working within the body using cameras for visualization. The field of MIS, especially laparoscopy, has seen major advancements in recent years including the integration of cutting-edge technologies, such as 3D visualization and AR assistance for surgeons. One such system is the "telerobotic surgical system with integrated robot-assisted laparoscopic ultrasound capability" proposed by Leven et al. in 2005 from Johns Hopkins University, called the DaVinci Canvas. It consists of a stereo endoscope for 3D visualization within the closed surgical domain and a robotically assisted intraoperative ultrasound probe that can be directly placed on the surface of tissues such as the liver and has the capability of autonomously conducting repetitive movements. This may be useful for surgery in the future for the SMC-LUN.

The space medical center shall provide:

A suitable operative table with patient and surgeon restraints need for fixation in low gravity (ISS MORD)

Verification: Identify key table and crew member restraints

Figure 26: Surgical care requirements for an SMC-LUN.

4.2.4 Remote Surgery – Telesurgery

Remote surgery, also known as telesurgery, may be possible in some forms of assistance in an SMC-LEO. However, it may also be possible in extended forms for an SMC-LUN. The technology is still at an early stage, but it has promise for significant advancement in the future. Telesurgery is the performance of surgery on a patient that is not physically in the same location through "telepresence" (Haidegger, Sándor and Benyó, 2011). With this surgery over a distance, it can connect any two points that are in communication, such as the Earth and the Moon.

Telesurgery can take three forms, depending on the strength of the communications connection between the surgeon and the operative site. The type of telesurgery depends on the strength of the communication link. To elaborate, telemedicine and telesurgery can occur in real-time or offline, and it can be divided into these categories (Rosser, Young and Klonsky, 2007):

- *Store-and-forward teleassistance:* occurs when two-way communication is limited to only one-way transmission at a time. Information is received, then evaluated offline, and feedback is then sent to the original location afterward.
- *Remote monitoring:* occurs in real-time with one-way transmission that enables medical officials to collect data about patients from a distance, with different sensors in real-time.
- *Interactive telepresence:* occurs when real-time, two-way communication provides instant-to-instant interactions. This communication link then supports several forms of interactions.

The current technology for fully remote telesurgery with the sole surgeon at a distant site, is too large with too much mass to be practical in space. The most effective surgical system to date is Intuitive's Da Vinci Surgical System which allows surgeons to perform minimally-invasive surgery with precision and accuracy. The Da Vinci robotic arm can perform a wide range of different medical operations, including cardiac, gynecology, and general surgical (Carfagno, 2019). However, there would need to be a considerable reduction in size of the Patient Cart robotic assembly to be practical on the Moon.

On the lunar surface there will be several advantages due to the presence of gravity. First, there will be less need for restraints for the patient and the medical crew. The patient will be more fixed to the examination or operating table and the staff will not need the same attachment to the table or the floor in order to apply force to the patient. Second, open surgery will be possible on the lunar surface because there will be less contamination of the operative field and cabin environment by blood since there will be gravity to cause the blood to run toward the Moon. There will not be the need for containment devices to protect the patient and to maintain a clear surgical view. The cabin environment will also not be contaminated by blood which is a biohazard that is difficult to disinfect, and which could interfere with electrical equipment in microgravity. Third, surgical instruments would not need a special management device to prevent loss or contamination of instruments. The instruments could be placed on sterile operative trays near the operative field just as on Earth. Through each of these advantages, medical care on the lunar surface could be remotely reinforced especially during initial lunar operations when other infrastructure could be lacking.

4.3 Lunar Exercise and Rehabilitation Facility

4.3.1 Exercise

The 17% Earth gravity on the Moon will be insufficient to maintain adequate bone density and to prevent muscle atrophy. In a NASA review of the potential effects of lunar gravity on bone demineralization, there is expected to be a 21% bone loss per year without effective countermeasures (Keller and Strauss, 1993). Therefore, an exercise regimen needs to be implemented on the lunar surface that addresses this issue. Since any exercise weights delivered to the Moon would have ⅙ the weight on the Moon, the cost would be prohibitive to send free weights to the Moon for use with exercise. Therefore, one solution could be to exercise without free weights. The crew members at a lunar outpost could rely on exercise machines based on resistance, instead of gravity. This will require the same type of resistive exercise equipment currently used on the ISS.

The Advanced Resistive Exercise Device (ARED) is a multipurpose exercise device. It uses vacuum chambers for constant resistance and flywheels for variable resistance (NASA, 2021e). It was created with an action and feel that mimics the forces experienced when lifting weights on Earth. It is also compatible to facilitate transfer to space and it has space heritage, with routine use on the ISS for 13 years. Another solution could use in-situ resources, such as lunar regolith for exercise weights. For free weights, pulverized regolith could be added to specialized containers for exercise. This would be similar to special container bags that hold beach sand for use as weights (Myerson, 2020).

An exercise machine that uses in-situ resources could also be considered for use on in an SMC-LUN, although this machine would be take up a considerable amount of room. Using local resources, containers of pulverized regolith could be attached to a machine that moves weights by lever and pulley mechanisms, similar to exercise machines on Earth that move weight plates by cable systems.

Cardiovascular training will also be important. This type of conditioning is an essential part of a health maintenance regimen. Bicycle ergometers are one solution that are small, lightweight, simple to use and maintain, and can give feedback on performance. The settings and output can be tracked, and a person's performance can be evaluated over time. Currently on the ISS, there are two exercise bicycles, the Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) in the U.S. segment and the Veloergometer in the Russian segment (Norcross et al., 2007). These types of ergometers, equipped with seats and body harnesses, could be used on the lunar surface with similar effectiveness. The vibration isolation and stabilization systems for these ergometers, however, would not be as necessary in an SMC-LUN, unless there was a need to protect sensitive equipment or experiments from excessive vibration.

Some athletes prefer a treadmill, however. This type of device may also promote greater bone density, with greater axial forces applied to the long bones of the legs during exercise due to the upright position. There are also two treadmills aboard the ISS which could be useful on the lunar surface, the Russian treadmill, and the Combined Operational Load-Bearing External Resistance Treadmill (COLBERT) (NASA, 2021f). Since there is insufficient gravity on the Moon to use a normal treadmill without harnesses effectively, a treadmill on the lunar surface will require body harnesses with resistance bands, akin to treadmills on the ISS. This additional force will allow effective use of the treadmill and will better simulate the force of gravity on Earth.

4.3.2 Nursing and Rehabilitative Care

Nursing care will likely play a larger role on the lunar surface than in LEO due to fact the medical center will be serving a small to mid-sized settlement, similar to an Antarctic station or larger. For this reason, there will likely be a greater need for thorough, well-rounded, holistic care. For rehabilitation, this kind of care is not replaceable by medication or procedures. It is essential to proper recovery and will be provided to suit the needs of this SMC location.

4.4 Lunar Training Center

Crew training in the SMC-LUN, similar in preparation of medical and non-medical staff as the SMC-LEO, will be essential for exploration of the lunar surface. There will still need to be extensive training in routine and emergency medical care, and these procedures will need to be practiced in simulation before embarking on the missions. Gynecological and psychological care will also need to be reinforced since these have been traditionally under-represented areas of training for medical personnel, historically, as mentioned previously. For training by telecommunications, the response times may be slightly delayed. Therefore, telesurgery could encounter difficulties, but two-way telemedicine is possible and will likely be a staple of the medical toolkit. Teleconferencing from the Moon would also be an engaging avenue for education on Earth. Classrooms and conferences would be enthusiastic about the opportunity to converse with crewmembers on the Moon.

4.5 Lunar Life Sciences Research Facility

The SMC-LUN is designed to function autonomously including both the life support system and medical capabilities. It is expected that current technologies, and research and development will reach their top readiness level for space use in the next 5-10 years. As such, current emerging technologies are already envisioned for the final delivered SMC-LEO estimated around 2025, and for SMC-LUN in the near future. The SMC-LUN will implement all these emerging technologies as a testbed for technology capabilities in partial gravity for future deep space missions. These technologies are developed to support self-sufficiency and sustainability of the whole mission. Thus, envisioned technologies are those relevant either for life support systems or medical/research development. Medical and research technologies can be classified in 4 categories: individual empowerment, artificial intelligence (AI) assistance, personalized medicine, and on-demand care. These categories and the associated technologies under development are presented below.

4.5.1 Individual Empowerment

Increasing the patient empowerment and compliance is now recognized as an essential determinant of healthcare quality and prognostic. Digital health, VR, video games, and wearable mood editors are technologies identified to support astronaut's empowerment in their healthcare. Digital health places the patient as an active aspect of their own healthcare. Technologies that give a quick and interactive access to their health status will be implemented in the SMC-LUN system. In particular, the SMC-LUN will implement the Emerald sensor that will provide essential information about astronaut sleep, vitals, and behavior by wirelessly analyzing radio signals specific to movement, breathing, sleep, and other behavior (TRISH innovation 2021). Tattoo-like wearable sensors, and biofuel biosensors will be an essential part of this digital health plan and will be implemented in the required Personal Protective Equipment (PPE) kit of each astronaut. Recorded information will be directly accessible on personal mobile devices while emergency vital signs will be an open access to a common point of care analysis device.

VR devices and video games simulation will play a key role in astronaut and inflight training. A "*Mixed Reality (MR) Care-Delivery Guidance System to Support Medical Event Management on Long Duration Exploration Missions*" is in development for a 2-year study. The Mixed Reality (MR) Care-Delivery Guidance System is a software that will provide medical training scenarios for probable medical events in deep space and long duration missions, with SMART checklist guidelines. Other virtual programs and video games are currently being developed by the Level Ex company to specifically train to practice surgeries and medical procedures in space (TRISH, 2021).

TRISH is currently funding the development of a *"*device that utilizes ultrasound techniques to alter the excitability of specific brain tissue*"* to improve mood (TRISH, A Wearable to Focus the Astronaut Mind). This technology already exists with well-established efficiency on the ground but is not suitable for space. The mind editor designed for space will be wearable and will also include a computer-based algorithm providing prognostics and estimation of the astronaut mood and even functional recovery after a stroke. The wearable mood editor will then support astronaut's mental well-being and healthcare performance. This wearable mood editor could be required as a mandatory PPE.

4.5.2 Artificial Intelligence Assistance

Artificial Intelligence (AI) is achieving diagnosis performance in various medical fields, e.g., radiology, histopathology, cardiology, dermatology, gastroenterology, and ophthalmology (Topol 2019). The ideal SMC-LUN must implement and rely heavily on AI assistance for diagnosis and decision-making. Ideally the medical center will contain an interface integrating personalized health history, physical examination, laboratory assessment information and on-board available treatments to output the best treatment recommendations. AI must be trained to integrate information and discriminate from adaptive mechanisms specific to space and those that are maladaptive. With these remaining challenges, fully capable AI assistance technologies will likely be available in 5-10 years and are thus included in the SMC-LUN technologies capabilities.

4.5.3 Personalized Medicine

Molecular biology has now reached the advent of the so-called era of “omics” and full high-throughput molecular analysis. Precision medicine technologies, allowing molecular level diagnosis, and personalized medicine technologies, allowing molecular phenotype characterization and healthcare adaptation, are improving the medical success rate. A similar strategy should be applied to astronauts to ensure the efficiency of countermeasures in space. Different technologies shall be implemented in the SMC-LUN to enable biomarker detection and analysis in support of astronaut’s precision and personalized medicine.

4.5.4 On Demand Care - Bioengineered Pharmaceuticals

One major issue for long duration and deep space missions is the storage and conservation of pharmaceuticals. Over time the degradation of reactants and enzymatic reactions occur, which impairs the stability and efficiency of pharmaceutics. An ideal strategy would be to produce needed pharmaceutical on site when they are needed. Bacteria can be modified to produce proteins, modulate the immune system, and remove toxins (TRISH, 2021). Bacteria can reproduce quickly and easily, forming millions of settlements. Most importantly, bacteria can be easily stored for a long period. A lot of studies are funded by TRISH to develop methods based on microbial pharmaceutics production in space. These studies are investigating the development of a personalized prebiotic therapy system derived from astronauts’ gastrointestinal resident microbiota, a long-term in situ delivery of therapeutic microbes by gastrointestinal devices, and a probiotic method to combat mental health risk in space (TRISH, Medical Technology Research 2021). Similarly, in-situ medication plant-based production methods are also under development while dry cell-free systems are also investigated for biomolecules storages (TRISH, Medical Technology Research 2021). The advent of bioengineered pharmaceuticals will mark a turning point for deep space and long duration missions.

4.6 Design Process

Similar to Chapter 3 on the design for an SMC-LEO, the operations for medical care and commercial research for an SMC-LUN have been discussed including the nature of the tasks to be performed and any differences that will be expected in partial gravity on the Moon. Next, the plans for the structural design will be addressed offering possible sites for location and avenues for shielding to match. A discussion of the layout of an SMC-LUN and its possible interior design, based on medical and research activities and equipment needs will follow. Since the Moon is an isolated community, the basic biological requirements of a small habitation are strict, and the ideas presented on methods of improving ecological sustainability within the habitat will be addressed including the designs for a larger, multi-unit SMC.

4.6.1 Potential Architectures

In recent years, several studies on lunar architectures have been conducted. These include inflatable surface architectures and lunar lava tube habitats, both of which could be feasible solutions for an SMC-LUN. Inflatables have several advantages, the most obvious being the efficient packing and thus resource-saving transportation. Further, they are very light-weight and durable. Deployment and assembly are relatively easy, and redeployment to a different place is also possible. Overall, the development and manufacturing are more cost effective. However, inflatables also come along with a number of problems. One is the limited habitability due to the shape of the final inflated configuration and empty spaces that cannot be used. Even more concerning is its limited stability as there are fewer supporting structures for higher stiffness. Another problem arises when reentering the lunar habitat after an EVA. The inflatable has limited capabilities to reliably prevent lunar dust from getting from the airlock into the habitability zone.

Another potential architecture is the cave structure found in lunar lava tubes. These are large pits in the lunar surface that were formed naturally by basaltic lava eruptions. In some cases, these lava tubes extend into subsurface tunnel systems providing an interesting location option for a lunar habitat. The main advantage of a habitat within a lunar lava tube is its natural protection against potentially frequent meteorite impact. The diameter of such lava tubes can vary strongly. Potential candidates that have been identified range from 10 meters and 150 meters in diameter (Haruyama et al., 2013).

One site with potential candidates for a hosting lava tube is the Philolaus crater near the lunar North pole on the Earth-facing side of the Moon. The temperatures during a lunar day in this region can rise up to 100°C whereas during the lunar night temperatures drop to -150°C or lower (Spudis, 2018). Over 200 pits can be found in this area, which are permanently blocked from sunlight. (Lee and McDonald, 2018). Figure 27 depicts a conglomerate of three lava tubes ranging from 8 to 13 meters in diameter.

The criteria for selection of a potential site for the SMC-LUN includes protection against radiation and meteorites, SMC accessibility, construction complexity, and modular extendibility. In terms of protection against radiation and meteorite impact, the lunar lava tube is the better option, as it offers a natural subsurface shelter to any structure in it. Whereas the meteorite impact in lava tubes can be reduced much better than in a surface habitat, protection against radiation on the surface can also be achieved to nearly the same extent as in the lava tubes by advanced shielding technology.

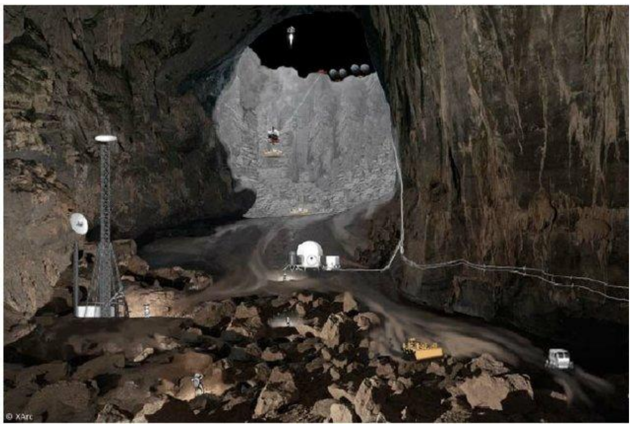


Figure 27: Impression of a simple lunar lava tube architecture (Ximenes, Elliott, and Bannova, 2012)

The downside of lava tubes is its limited accessibility and increased construction complexity compared to on-surface solutions as it requires advanced logistical infrastructure to transport and build structures in such an environment. Modular extension of structures in the lava tubes will be more or less feasible depending on the local geological topography. In any case it will be easier to extend an on-surface habitat than a sub-surface configuration. Given the immense complexity of developing a lava tube architecture, the on-surface habitat is considered the more realistic option for the foreseeable future. In the long-term, a lunar lava tube could also become feasible (Ximenes, Elliott and Bannova, 2012).

4.6.2 Lunar Medical Center Design

The first design is located in the near 2040. In this time frame, one major module is considered the most feasible solution on the assumption that 20 to 30 specially trained astronauts will live and work on the lunar surface. These astronauts can be either institutional or private with a focus on scientists, medical specialists, engineers, maintenance, and construction workers, and potentially a select few wealthy tourists. This assumption is estimated according to current plans by NASA and ESA to send astronauts to the Moon again in the mid-2020s.

4.6.2.1 Integrated Shielding Considerations for the Lunar Surface

A possible scenario is to construct the SMC-LUN by 2040-2060. For radiation protection, the lunar regolith and water-based radiation shielding approaches are highly suitable. Lunar regolith itself has some radiation shielding properties but it can be combined with radiosynthetic fungi, or melanin for an integrated radiation shielding approach. By 2060, possible active shielding approaches could be used as well.

Passive shielding against GCR is still limited by mass, regardless of how powerful a radiation attenuator can be. Reducing the estimated dose equivalent of the amount of Lunar radiation energy to the average Earth dose (230 mSv/a to 6.2 mSv/a) a 0.21m thick layer of *C. sphaerospermum* would be needed. Therefore, the material should be dense enough to have a higher linear attenuation coefficient. Lunar regolith combined with fungi or melanin would require approx. 0.09m thick layer of the mixture as mentioned earlier (Shunk et al., 2020).

The SMC-LUN habitat can also use water effectively within the next 20 years. The outer dome-shaped structure of the SMC-LUN can be utilized for water shielding. One-sixth gravity will be challenging for using water as a radiation shield. Nevertheless, it is also possible to use water in capsulated form as a phase change material. It will save the resources and time for making the water circulate. Encapsulated water is easy to change and discard. A note to mention here, wastewater can be used for encapsulation and used around the SMC-LUN for shielding. In order to effectively shield gamma rays and keeping in mind the mass attenuation coefficient, the water layer in circulation or encapsulated form needs to be calculated according to the half value shielding principle.

Performing EVAs exposes astronauts to 2.6 times more radiation than the astronauts experience on the ISS (Zhang et al., 2020). This poses a threat to crew health in an SMC-LUN, especially if the mission on the Moon is for a longer duration of time. The integrated approach of shielding for the crew may require dietary countermeasures such as using plum, blueberry, or strawberry powder and spacesuits with thick layers of effective shielding materials (Shukitt-Hale et al., 2007).

In sum, the future implementation of radiation shielding must look at an integrated approach and take into consideration the engineering and medical countermeasures. It is inadvisable to only look at some specific materials or elements that provide radiation shielding. The SMC-LUN shall consider all of the above-mentioned solutions for its real-time application in the future.

4.6.2.2 Design Configurations and Systems Design

Various design configurations have been compared and evaluated based on their utility and compliance with the functionality of an SMC-LUN. The criteria for the tradeoff were immediate access to the emergency area, sterility within the medical and research area, connectivity, and easy access to all parts of medical and research facilities. Moreover, it was required to have advanced imaging diagnostic capabilities, a distinct exercise area, dental care, routine care, emergency care and a rehabilitation zone including recreation.

The first two configurations (Figure 28) have only one floor for both medical and research areas. These differ by the placement of its emergency unit. In the first configuration, the emergency unit is in a corner near the docking hatch and in the center, there is a central pillar with storing capacity. A central pillar has the advantage of giving additional stability to the dome structure. In the second, the emergency unit is placed in the center of the dome for better accessibility.

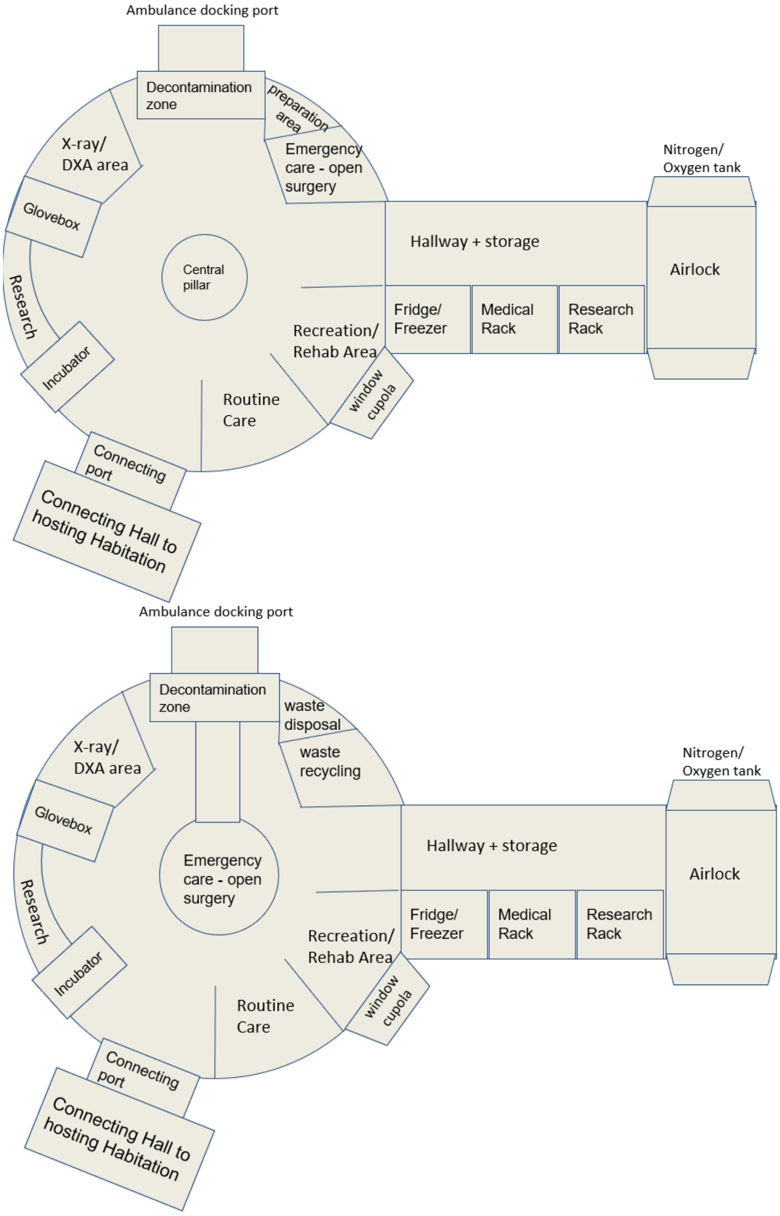


Figure 28: Two initial designs with similar configurations with both medical and research on one floor. Configuration1 (left): the center is occupied by a central pillar. Configuration 2 (right): the emergency unit is placed in the center.

Ultimately it was decided to have two floors, the first one for medical and the second for research. The final configuration is depicted in Figure 29 with floor breakdowns in Figures 30 and 31 for the medical and research areas respectively. The research area was considered to have a hallway on the second floor, but due to increased complexity of the connecting hallway and airlock this idea was abandoned.

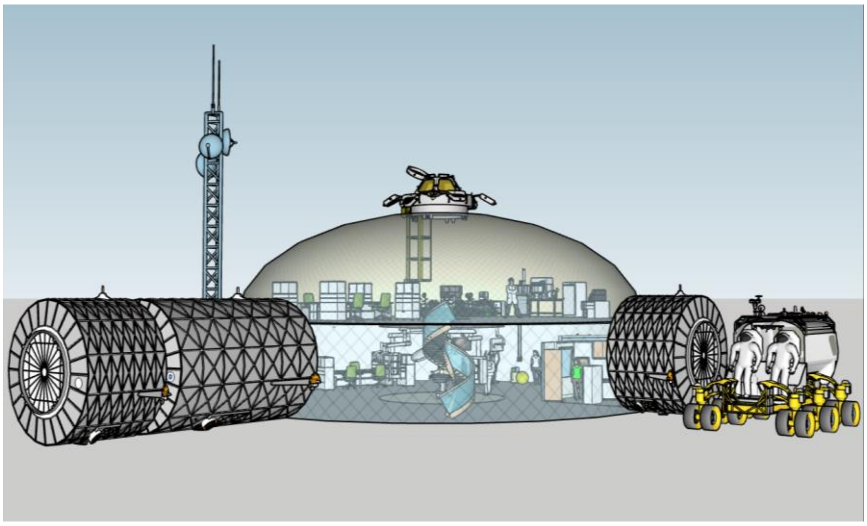


Figure 29: The lunar module is divided into two floors. The airlock module is followed by a hallway connecting to the main dome. The first floor is dedicated to medical purposes; the second floor to research. The architecture includes a docking port to a space ambulance.

The hallway and the airlock are based on the American Destiny module with a diameter of 4.5 meters and a length of 8.5 meters. For the SMC-LUN this length could be shorter as the hallway is mainly used for storage. The airlock in Figure 30 consists of an additional decontamination zone to ensure that no lunar dust is carried into the SMC-LUN. The standard configuration for this consists of externally attached EVA suits that can be accessed from the inside. However, it also has the capability of opening the airlock hatch for entering with the entire suit.

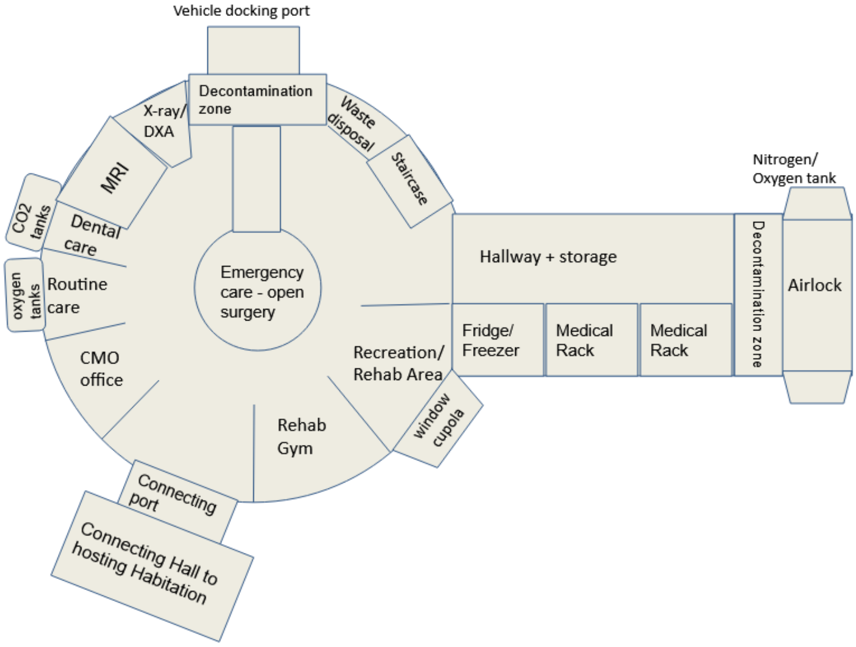


Figure 30: Configuration 3 (ground floor) depicting the medical area and the entrance modules composed of an airlock, decontamination zone, and hallway with storage capacity.

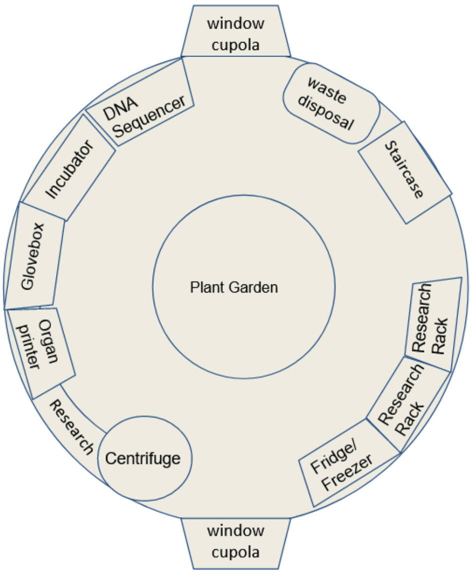


Figure 31: Configuration 3 (second floor) depicting the research area for protein crystallization and stem cell research among others under partial gravity conditions. In the center, a plant garden is included for research on self-sustaining agriculture with local resources.

4.6.2.3 Diagnostics and Imaging

Specific MRI and X-ray chambers are added to the ground floor design. MRI provides a variety of applications for diagnostic imaging. However, the considerable size and mass of the instruments make their application in space limited. Additionally, the massive magnetic field poses the risk of electromagnetic interference with the electronic equipment. Thus, MRIs need to be confined in separate rooms without metal components in it to prevent undesired interferences.

A functioning MRI system adapted to the constraints of space has not been designed yet. However, design proposals for crucial parts, such as the low-cost homogeneous portable permanent magnets are currently in development (Chapter 3.1.4) (Hugon et al., 2010). These magnets, which are relatively lightweight, can propose a system for a small MRI with a weight of about one tenth of the weight of terrestrial MRIs (Hills, Wright and Gillies, 2005; Doğan et al., 2009; Sarty et al., 2012). Such a concept is considered feasible and applicable for an SMC-LUN.

4.6.2.4 Emergency Unit

The emergency care section (Figure 32) has been placed in the center of the SMC-LUN on the ground floor. The main reason for this is access from all sides at all times which will accelerate operations and facilitate the job of the surgeon. There were two considerations: locating the emergency section next to the ambulance docking port or in the center of the room. Ultimately, the emergency section was placed in the center of the facility for functionality and ease of access, despite the benefits a central pillar would offer for stability.

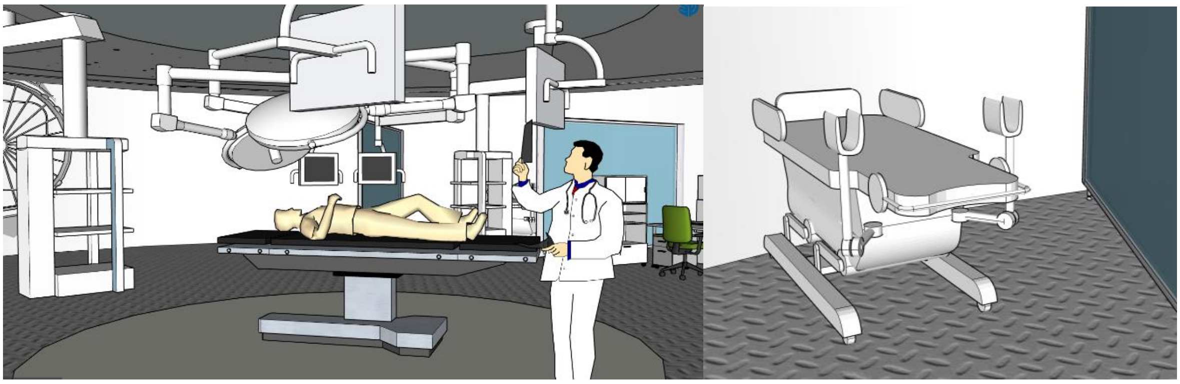


Figure 32: Left: emergency area with instruments and a laparoscopic tower Right: a patient recovery bed.

4.6.2.5 Rehabilitation Operations

The main challenge of exercising on the surface of the Moon is the partial gravity. This leads to a very different style of movement, akin to hopping than walking. For a treadmill, (Figure 33) this means there would have to be additional restraints and extra resistance load. Heavy weightlifting is unfeasible. For more information on exercise materials in an SMC-LUN, see Chapter 4.3.

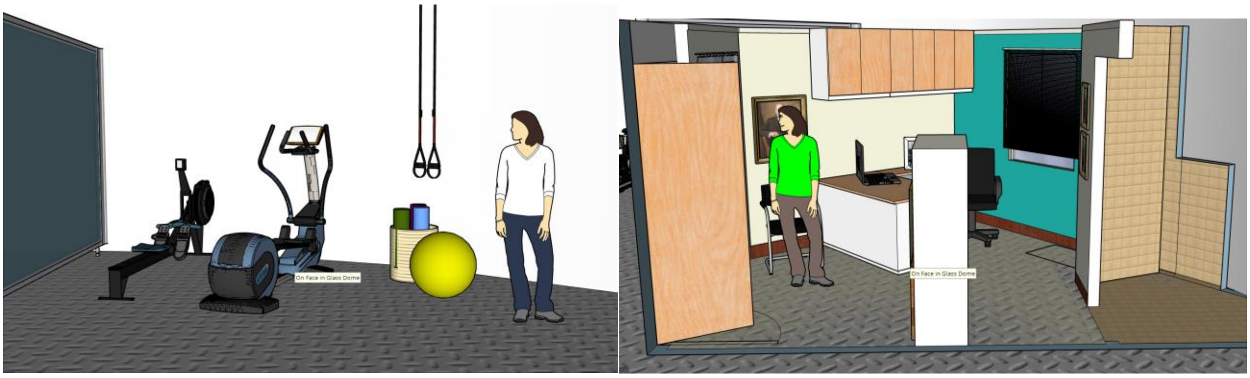


Figure 33: Left: lunar exercise equipment including a specially adapted cardio treadmill. Right: CMO office.

4.6.2.6 Research Area

The research area consists of a fridge, freezer, centrifuge, computer desk, 3D organ printer, glovebox, incubator, DNA sequencer, and has space for future additions. Figure 34 shows the research area and its components. The dimensions are not correct in relation to the space within the dome. For information on what research activities will be carried out in an SMC-LUN, see Chapter 4.5.

Figure 34: Left: the research area and components. Right: a plant area for research and recreational purposes.

4.6.2.7 Healing Architecture

An SMC-LUN would be able to incorporate more ‘healing architecture’ elements due to the increased space. Plants and living vegetation will be implemented to reinforce psychological well-being by way of a living vegetation pond on the second floor. Adding living vegetation not only allows for humans to maintain a connection with nature, but plants are a constantly changing, interactive material which can help to combat the otherwise rigid structure of a medical center.

However, the SMC-LUN will be unable to implement windows. While two cupola windows are slated into the top floor design to permit some natural light, windows in patient care areas are not included. Without windows, patients and medical staff could develop depression, homesickness, or other unpleasant psychological symptoms stemming from increased isolation and confinement (Kanas, 2015). To combat these symptoms, it will be necessary to simulate the effects of windows in patient care and recovery areas, similar to the SMC-LEO window application (Chapter 3.6.4.4). This can be achieved through the application of high-resolution LED screens mounted onto the walls of the medical center that are framed to look like normal windows. With this technology, individuals can change the ‘view’ from the window from a database of high-quality images of different landscapes and locations depending on their given preference.

4.6.3 Biological Sustainability

Some basic requirements for a biologically sustainable human population have been calculated in Table 17 (Mankins and Mankins, 2020). To achieve a self-sustaining status, the settlement will need to implement the use of an artificial closed loop ecosystem. Mimicking what naturally occurs in Earth's biosphere, it is possible to create a contained system through utilizing processes such as the nitrogen, oxygen, and water cycles. This can be done alongside the use of various microorganisms, humans, and higher plants for a biologically sustainable human population on a lunar settlement.

Table 17: Basic Requirements for Biologically Sustainable Lunar Population (Mankins and Mankins, 2020)

Requirement	Quantity
Number of settlers	40
Crop Land Area (@1,500 m²/person)	60,000 m²
Food Eaten Per Day	70 kg /day
Water Required for Farming (30-day Recycling)	3,410 MT
Water for Personal Use (30-day Recycling)	131 MT
Required Mass of Air (5 m ceiling)	~750 MT
Soil (Shallow, Moist)	~50,000 MT
Living 'Mass' (Human/Other)	2,400 kg /120,000 kg
Light Required/Waste Heat	~64 MW
Farming Thermal Mgt. Power (if Active Required)	~100 MW electric
Average Power for 'Personal Use'	~1 MW
Total Bio-Driven Mass Required	~5,000 MT

MW = Megawatts, MT = Megaton

The ISS currently uses a closed-loop system in ECLSS, whereby clean air and water are produced onboard, thus minimizing the need for frequent resupply missions. There are also several closed loop biological systems in development, including NASA's Advanced Life Support System Test Bed (ALSSTB), and the Micro-Ecological Life Support System Alternative (MELiSSA) (Ciurans et al., 2021) (Figure 35). Scenario 2 assumes such a closed loop system has been developed and functions efficiently with either zero or minimum waste or loss. The success of the settlement with regards to its self-sufficiency and independence from Earth will be largely dependent upon the effective functioning of such a system.

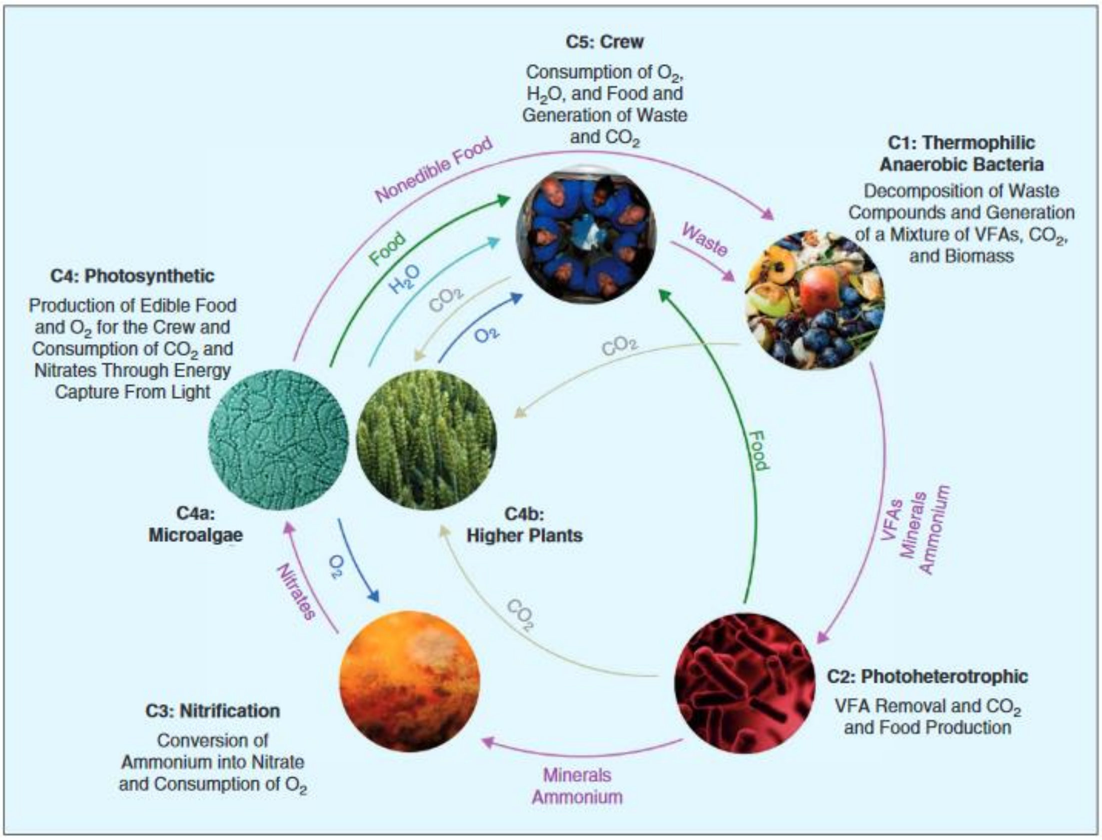


Figure 35: The MELiSSA ecological system interacts with different ecological compartments to produce food, oxygen, and water while recycling waste, non-edible foods, and nitrates (Ciurans et al., 2021).

Further, the cost of delivery for expendable items will be at a premium. Therefore, it will be imperative to reuse, recycle, or repurpose items of importance. Sustainable energy from natural sources and ISRU will also be essential to maintaining a sustained human presence on the Moon. Among the actions that can be taken, the SMC will harness solar power, repurpose solid organic waste from food and excrement, and obtain water in-situ from water ice in lunar craters.

Solar power will be an important part of the electrical supply to the space medical center on the Moon. Solar arrays will be attached to the overall station and contribute substantially to the medical center's energy needs. With natural sources of energy, the SMC will have greater sustainability in the long term. Solar energy will have gaps in production and will rely on battery storage for periods without sunlight. However, it will be a reliable and sustainable energy source over the long-term.

Solid organic waste will also be repurposed to achieve better sustainability. Solid biological waste from inedible food, waste food, and excrement can be collected for use in multiple ways. The organic matter can be used to promote the growth of biomass which could be used as a fuel alternative, and for the direct thermal energy that a contained biomass provides. Second, this organic material could be combined with pulverized regolith to create a fertile soil for growing food crops, plants for pharmaceuticals, or other useful plants. Fruits and vegetables could be grown in this neo-soil. Several types of fungi could be produced for food, structural purposes, insulation, or medications, and hemp and other fibrous plants could be grown for their structural properties and usefulness.

Water is an essential aspect of life. The cost of transporting water can be prohibitive to a lunar settlement, however. Therefore, environmental control systems will recycle as much water as possible, and other local sources will need to be incorporated into the long-term plan. These in-situ resources will be deposits of water-ice on the lunar surface, often located in craters. The distance from the medical center to the water source will depend on the mining and transportation systems available at the lunar settlement.

Plants will serve a variety of functions in the SMC-LUN. They will form part of the vital ecosystem described above as part of the life support system itself through the production of oxygen and the removal of carbon dioxide. They are also a key element in the food chain and will provide a source of nutrition and vitamins. They can also be utilized in the processing of biological waste. Therefore, ‘space greenhouses’ will be incorporated into the settlement design to ensure agricultural systems can be employed on a large enough scale to produce an adequate supply of fresh food and oxygen for the settlement. Plants could also be genetically engineered to become resistant to radiation exposure, along with being utilized in the sustainable production of pharmaceutical drugs. This will be extremely useful in the SMC-LUN where medical supplies will be both limited and in demand and will further contribute to the lunar settlements capacity for self-sustainability and reduce resupply mass and missions required from Earth. Invertebrate life forms will also be introduced in the form of insects, which will not only assist in the pollination of the crops but can themselves also be farmed as a source of protein.

Increased sustainability of the SMC-LUN is not only about cycling all available nutrients as part of essential fuel of the artificial ecosystem. Of importance is the ‘10% rule’ which posits that about 10% of energy is passed from one trophic level to the next. One strategy on the lunar settlement would be to find a way to increase this ratio of 10% or alternatively increase the energy extracted from this 10% contained in biomolecules. Managing energy flow through the ecosystem will require a more complete understanding of the thermodynamic law in living systems. Further, this ecosystem must be considered as a strictly closed one, so losing human biomass after dying would imbalance the ecosystem and impair sustainability. Solar illumination has been shown to correlate with biomass productivity (Raven, 2011b). Solar illumination can provide the primary energy input of the system. Thus, a sustainable artificial ecosystem would be one that reproduces and follows biological thermodynamics flow.

4.6.4 Advanced Modular Lunar Medical Center

An advanced SMC-LUN should be able to service upwards of 500 permanent settlers on the Moon by 2060. The basic configuration is modularly extended and integrated into a larger structure with a central node connecting all SMC modules and a morgue. Table 18 and Figure 36 present the key requirements and concept of an advanced modular SMC-LUN.

Table 18: Key Requirements for 500+ Lunar Population (Mankins and Mankins, 2020).

Requirement	Quantity
Number of settlers	500
Crop Land Area (@1,500 m²/person)	750,000 m2
Food Eaten Per Day	875 kg /day
Water Required for Farming (30-day Recycling)	42625 MT
Water for Personal Use (30-day Recycling)	1310 MT
Required Mass of Air (5 m ceiling)	~9375 MT
Soil (Shallow, Moist)	~625000 MT
Living 'Mass' (Human/Other)	30000 kg / 1500000 kg
Light Required/Waste Heat	~800 KW
Farming Thermal Mgt. Power (if Active Required)	~1250 MW electric
Average Power for "Personal Use"	~12.5 MW
Total Bio-Driven Mass Required	~62500 MT

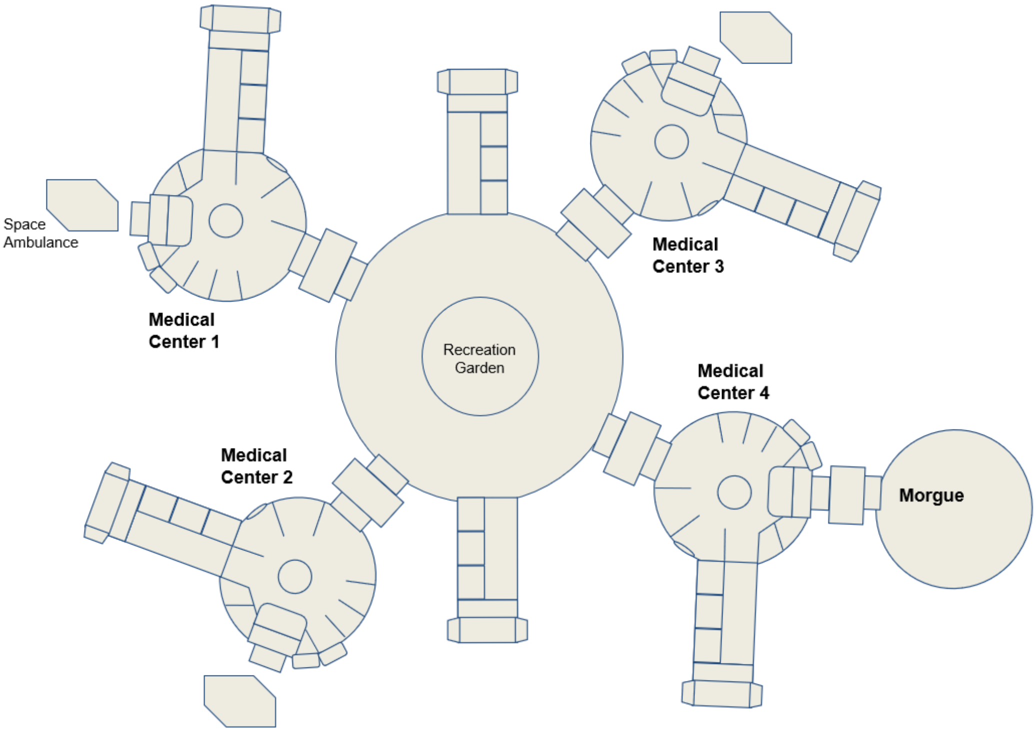


Figure 36: The advanced concept in 2060 is the modular extension based on the near-term basic configuration. Several smaller SMC modules are attached together to form a larger structure with a central station.

In the future where a settlement on the Moon could exist, an SMC-LUN would require a morgue that can store the corpses of dead people until autopsies or sustainable body disposal that has been mentioned in Chapter 8.3 can be performed. The morgue would be attached to the SMC-LUN as one of its facilities and therefore, it would be under the same oxygen levels and conditions. Bodies would be stored using refrigerators to decrease decomposition. However, the temperature on the Moon changes drastically depending on its exposure to sunlight and due to its thin atmosphere. These natural low temperatures could also be used to refrigerate the bodies and decrease decomposition. If the SMC-LUN is located in an area with low temperatures, such as inside a crater where sunlight does not reach, the morgue could take advantage of these temperatures and would not require a refrigerator for the conservation of the body.

The ecologic method that recycles corpses into useful soil can be seen as a new beginning. It would help human society to cope with death and strengthen the human relationship with nature inhabiting inside the modules. However, the moral implications of having a morgue should also be considered. Only the authorized personnel of the SMC-LUN could access the bodies in the morgue, and they would only be visible to other habitants when SMC-LUN personnel consider they are ready for its ecologic disposal treatment.

4.6.4 Lunar Emergency Rescue Vehicle

When a medical emergency occurs on Earth, an ambulance transports the patient to a nearby hospital. Though no major emergency has yet occurred in space, the increasing number of people living on the lunar surface in the future increases the probability of potentially severe emergencies. Some of the many medical emergencies that could be fatal if not treated quickly include dust inhalation, radiation sickness, heat/cold exposure, cardiac arrest, and head injuries. Many accidents could happen away from an SMC-LUN, for example, a dangerous fall while on an EVA or a reduction in temperature in a spacesuit due to a malfunctioning temperature regulator. If a fatal medical emergency happens far from an SMC-LUN, an emergency space vehicle is required to address emergencies. Therefore, a space ambulance will be required as part of an SMC-LUN. The space ambulance (Figure 37) would be able to dock directly with a lunar habitat to transport patients from a pressurized cabin to a pressurized habitat, without the need for a protective extravehicular outer suit. This would require a runway attached to the airlock.

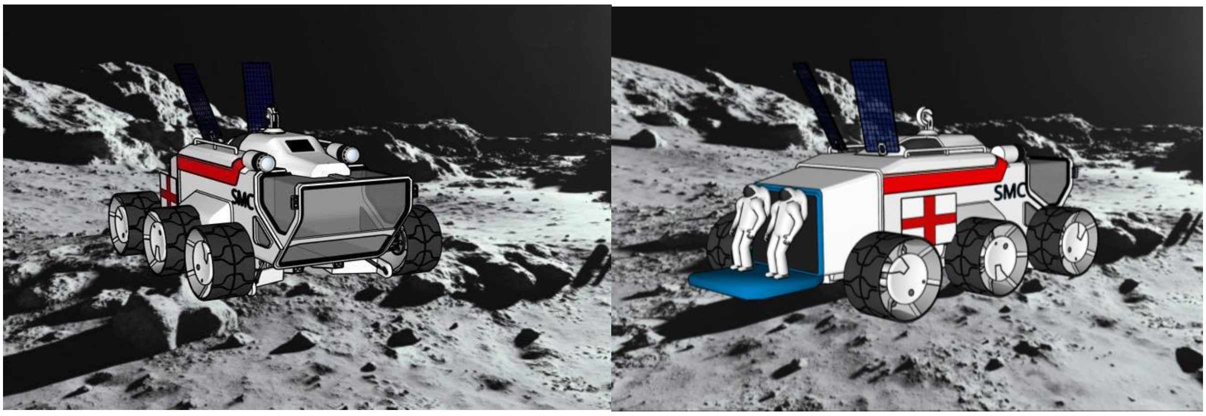


Figure 37: A ground-based space ambulance for lunar emergencies.

The space ambulance would need to accommodate one driver, a CMO, and a patient. As seen in the Figure 38, the driver and the CMO are able to exit the vehicle through a suit port attached to the outside of the spacecraft. To exit the space ambulance, an astronaut enters the suit from inside the vehicle to separate the suit from the ambulance. Additionally, the space ambulance would be equipped with a stretcher, emergency airway equipment, an oxygen tank, basic and advanced life support medications, cardiac monitors, a defibrillator, and other emergency supplies.

It is important to note is that any vibrations during transportation of a patient on the lunar surface will likely be detrimental to patient health. Therefore, a requirement of a space ambulance will be soft transportation of the vehicle. A partial solution could be the adjustment of the patient table on a gimbal with strong hydraulic damping capabilities. Another solution is to have a space ambulance with high precision control and shock absorbers. Private citizens that may be less trained than traditional astronauts will likely inhabit this lunar habitat. Injuries are more likely to happen, and thus it is worthy to consider the vehicles that will potentially save lives on the Moon by transporting them to the SMC-LUN.

4.7 Mission Architecture

4.7.1 Lunar Launch Alternatives, Logistics and Technology Selection

For the lunar based missions, a different class of launch vehicles must be considered – the super heavy-lift launch vehicle. A super heavy-lift launch vehicle is a launch vehicle capable of lifting more than 50 tons of payload to LEO. It is difficult to figure out how exactly an SMC-LUN will be launched to the Moon in the next 20-40 years. Figure 38 shows the vehicles that have been used for lunar missions in the past, the current fleet, and the future vehicles that might be used.

The Falcon Heavy as well as the ULA Heavy mentioned previously are some of the current launch vehicles capable of bringing a reasonably sized payload to the Moon currently. The SLS launch vehicle is the next launch vehicle that will bring humans to the Moon by 2024, the first mission since the last Apollo missions aboard the Saturn V. China’s Long March 9 will be capable of bringing massive payloads to lunar orbit and beyond, and should be available by the 2030’s. In this period the Russian space program plans to have its Yenisei vehicle available for lunar missions. The most promising vehicle of the pictured launchers is the upcoming SpaceX Starship (formerly BFR), planning to visit the Moon as early as 2023.

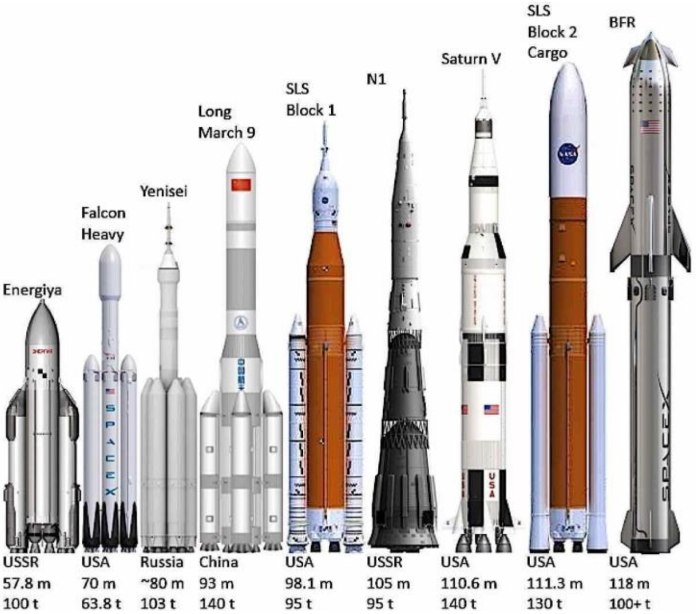


Figure 38: Super-Heavy Launch Vehicles (EDI, 2017).

4.7.2 Lunar Command, Control and Communications Architecture for TTC

It is difficult to design a lunar communication system in detail since current technologies are continuing to evolve. However, the installation of an SMC-LUN is conditional on the previous existence of a habitation on the Moon. Therefore, one thing is certain: communication between the Moon and Earth will need a reliable infrastructure. Assuming that the current infrastructure between Earth and orbit will still be operational, a communications architecture for the SMC-LUN (Figure 39) was conceptually designed for the lunar surface.

The communication between the SMC-LUN and mission control on Earth could rely on the Deep Space Network infrastructure. The downlink communication would be sent from the lunar surface to Earth and be received by one of the Deep Space Communication Complex (in position when the signal gets to Earth). This could be either the Canberra station (CDSCC), Goldstone (GDSCC), or Madrid (MDSCC). The signal then would be transmitted to mission control. For the uplink communication, the same process would be repeated in the opposite direction.

For this stage to work according to the diagram and ITU regulations, the TTC link would best work in X-band. This frequency has been selected to provide ground coherent three-way. The uplink frequency has to be between 7190 to 7235 GHz and the downlink frequency between 8450 and 8500 GHz, since it would be located under 2M km from Earth (Shin, 2014).

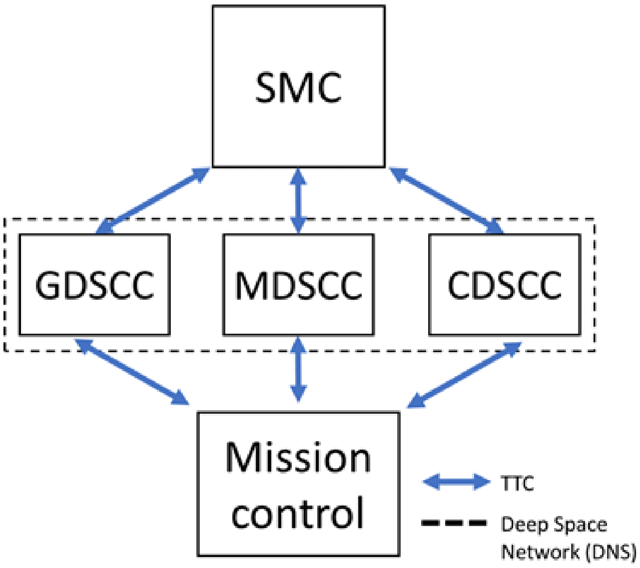


Figure 39: Communications interface. Only TTC was considered considering the distance between the Moon and the Earth.

In contrast to the SMC in LEO, this SMC will be larger and with less shielding. It will still need to withstand pressurization but can be covered in regolith or positioned in a lava tube for added shielding. It will be constructed on the lunar surface from modular parts delivered there since the ability to rely on in-situ materials such as sintered regolith is still untested technology, and it is questionable if that construction can withstand internal pressure loading and remain air-tight. The daily functions of this SMC will remain largely the same as the SMC in LEO, but with a larger facility and with the addition of gravity, there will be some changes. Simple procedures that require force to maintain the patient in position without moving away from a caregiver will be easier, including emergency procedures such as cardiopulmonary resuscitation, and having greater space will allow more room for exercise equipment and psychological counseling offices. More research equipment and personnel can be housed in this larger SMC, and the type of research there will likely be more advanced. The methods that were described here represent techniques that could be possible in the not-too-distant future, and other futuristic methods may also be included in that category for use in this center a few decades from now. The launch providers chosen, and communications system described were based on current technology, but though the technology may change, the principles that guided these decisions for the systems chosen will likely remain the same or similar.

5

THE SPACE MEDICAL CENTER WITH ARTIFICIAL GRAVITY

Scenario 3

After detailing the specifications for an SMC center in LEO attached to the ISS and an SMC on the lunar surface, Scenario 3 shall lay out the different elements that must be considered when having an SMC in a gravity wheel in LEO. Medical procedures within the SMC-GW that are not possible in microgravity will become a reality. This section will discuss the functions of an SMC-GW: a health and performance clinic, an emergency center, an exercise and rehabilitation facility, a training center, and a life sciences research facility. Furthermore, it will discuss the design and costs of the third scenario.

Prolonged exposure to the microgravity environment results in a variety of physiological changes in and on the human body. This includes muscle atrophy, bone loss and cardiovascular deconditioning. It is important to note that these changes are adaptations to microgravity, and thus are not inherently negative. However, the longer a body spends in microgravity, the greater the discomfort, and the rehabilitation period upon return to Earth. The ability to simulate gravity on board a space station provides a number of benefits for a wide range of individuals.

The proposed gravity wheel will exist in LEO. A diverse modular approach will allow for different types of operations to be conducted. Medical procedures within the SMC-GW that are not possible in microgravity will become a reality, such as surgery, intubation, and CPR. The SMC-GW will also provide an interesting median data point for research purposes that can exist between the previous research done in microgravity and 1g. Further, the projected gravity on the SMC-GW is ⅜g to simulate the gravitation on Mars, further attracting researchers and providing a place for astronauts to train. However, the exact gravity conditions at which human performance is maximized is not known, so further research within this station will seek to answer that question.

Existing in LEO also allows for accessibility to commercial companies to buy modules as a tourist resort. Although space tourism is not yet possible, it is a burgeoning industry in which the SMC-GW may be able to play a key role in supporting and benefitting from. For context, the SMC-GW is subject to the same conditions as the SMC-LEO, and will utilize the same technologies for construction, radiation shielding, and interior design. The estimated timeframe for completing the SMC-GW varies, but can be estimated for completion between 2027-2050. Scenario 3 investigates the aforementioned variables in greater detail to provide a step forward in expanding humanity’s presence in space.

5.1 Gravity Wheels: Concepts Over Time

The concept of a rotating wheel for the purpose of creating artificial gravity was first proposed by Konstantin Tsiolkovsky in 1883 and was later taken up by Wernher von Braun in the 1950’s (Clément, Bukley and Paloski, 2007). Von Braun dismissed any detrimental consequences of existing in microgravity, initially asserting “there are some medical men who are concerned at the prospect of permanent weightlessness—not because of any known danger, but because of the unknown possibilities. Most experts discount these nameless fears” (Braun, 1952). He could also clearly see the benefits that could be afforded by producing an artificial gravity environment in space, as he then went on to propose what became known as the ‘von Braun wheel’.

The idea has since been explored by various individuals and groups and variations on the original design have emerged. These include the O’Neill Cylinder and the Stanford Torus (O’Neill, 1974; NASA, 1977). More recently, NASA has revisited the idea of employing a rotating wheel structure in the form of a multi-purpose mission space exploration vehicle (MMSEV) entitled the Nautilus-X (Henderson and Holderman, 2011) (Figure 40). This proposal was ultimately abandoned due to problems arising from stability, and overall stress on the structure, and cost.

Figure 40: NASA’s Nautilus-X is a multi-purpose platform that can accommodate a wide variety of missions. It integrates various propulsion platforms and life support systems along with guidance, navigation, and control systems (Henderson and Holderman, 2011).

The necessity for this kind of research is high, as the adjustment to earth gravity from space produces short term pain, swelling, and unknown long-term effects. The following are excerpts from the American astronaut Scott Kelly in his book “Endurance: My Year in Space, a Lifetime of Discovery” after he spent 360 consecutive days in space:

“Every part of my body hurts. All my joints and all of my muscles are protesting the crushing pressure of gravity...They [his legs] are swollen and alien stumps, not legs at all...Normally if I woke up feeling like this, I would go to the emergency room. But no one at the hospital will have seen symptoms of having been in space for a year….Our space agencies won't be able to push out farther into space, to a destination like Mars, until we can learn more about how to strengthen the weakest links in the chain that make space flight possible: the human body and mind” (Kelly, 2017).

The average Mars mission will take at least two years, if not more. Yet it is apparent that half of that time was more than enough to significantly change Scott Kelly’s body in LEO. To qualify this point, Kelly has recovered from many of these short-term symptoms but experiencing them nonetheless is a barrier for those willing to venture into space. Understanding how to mitigate and ultimately negate the effects of microgravity is not only an important consideration for human exploration of space, but also seemingly necessary. Regardless of the challenges still to be addressed, the conceptual idea of creating an artificial gravity environment on board a space station remains a possibility within the next 20-40 years and can further be justified by the high cost of maintaining microgravity structures such as the ISS.

5.2 Cost Justification

Though the ISS is an incredible achievement, it is also one of humankind's most expensive. The ISS completed construction in 1998, making 2021 the 23rd year it has been functioning. This equates to ~8395 days that it has been in service. Assuming that the maximum crew (6) has always been inside the ISS since its inception, this results in 50,370 person-hours of human time spent in the ISS, or 1,208,880 hours. 1/12 of each day in the ISS for each person is spent exercising, or two hours per day. Multiplying the total person hours by the amount of time spent exercising each day by each astronaut results in 100,739.95 total hours that have been dedicated to exercise in the ISS since 1998. It can be estimated that each hour one astronaut spends on the ISS is equal to $10,000, so $20,000 per day is spent on exercise time. Over 23 years, this amounts to approximately $1 billion, or a yearly rate of $43.8 million. Assumptions were made on a constant 6-person crew at the ISS, and the rough estimate for the hourly rate of astronaut time.

This $1 billion figure relative to the estimated total cost of the ISS ($150 billion) is small. However, based on its dimensions, the gravity wheel will be able to host up to 400 people. Applying the calculations above to 400 people changes the figure dramatically, and a benefit of a gravity producing station can be seen. If 400 people had to spend 2 hours a day exercising, this equates to $2.9 billion a year, roughly the cost of the yearly maintenance of the ISS itself. Besides being a logistical problem of organizing a space large enough with sufficient equipment to allow 400 people to use machines daily, $2.9 billion is about ⅛ th of NASA's annual budget in 2021. This money can be reallocated, and although the price of maintaining an astronaut will likely decrease in the future, building more structures akin to the ISS that must function in microgravity would not follow the vein of increasing sustainability. With a rough cost justification, a design can be implemented.

5.3 Gravity Wheel Health and Performance Clinic

The medical risks on a station with artificial partial gravity are similar to those on the lunar surface. With gravity, there are risks of falls and crush injuries that are not seen in the microgravity of LEO. Therefore, though bones will be stronger, there will be more fractures due to trauma. There will also be more traumatic brain injuries and intracranial bleeding such as subdural and epidural hemorrhages. Meanwhile, headaches and nausea may be less common than in microgravity, due to a better vestibular adjustment to partial gravity. Renal stones would also be less common in partial gravity due to better bone health with greater musculoskeletal integrity. Less fluid shifting in partial gravity may also lead to less vision problems from SANS.

Largely, to treat most of the medical conditions aboard the gravity wheel, the SMC-GW will follow the same medical operations as for LEO and the Lunar surface. There will be many similarities for medical procedures for simple ailments and emergency care. Tylenol/Paracetamol will still likely be an effective remedy in the future as a painkiller and epinephrine will still likely be a drug of choice in an emergency with hemodynamic instability. The procedures themselves, such as choosing a simple oral medication or topical cream for minor ailments, or choosing intravenous medications for serious conditions, will also likely remain constant. There is also not likely to be a great difference in the principles of some procedures such as orotracheal intubation or tube thoracostomy. The equipment may differ, but the practice will likely be similar and follow the same order of application.

5.3.1 Primary Care

With the benefit of ⅓g, the procedures that were difficult in microgravity become simpler. For example, separating air from fluid in medication bottles, syringes, and IV tubing will be simpler. In microgravity, a fluid surrounds an air bubble and the liquid coats the surface of the syringe, leaving the air trapped in the center. An abdominal exam is easier to perform and more meaningful when a physician or crew medical officer can place pressure more easily and with greater force in a gravity environment, also. Heart sounds and heart murmurs can also sound different based on position when in gravity. Neurological exams can have the added benefit of testing walking and gait, as well as balance. Simple procedures such as blood drawing are also easier with gravity since objects can be left on trays or on the patient table and they will remain in place without the need for additional restraint.

5.3.2 Pharmacological Care

Similar to the SMC-LEO, the SMC-GW will stock the same cadre of medications as the SMC-LEO. In deeper space, it will also suffer from greater radiation than LEO and this may possibly have a negative effect on some medications over the long term (Blue et al., 2019). Otherwise, the pharmacological care will be the same as for the SMC-LEO.

5.3.3 Psychological Care

Depending on the location of the gravity wheel in LEO, MEO, or cis-lunar orbit, there will be slightly different levels of isolation due to differences in the ability to return to Earth in the event of an emergency. Differences in location can have profound effects on a crew member's mental health. These varied needs would be accounted for by additional counseling services, as necessary. Otherwise, the psychological care would be delivered according to the same plan as for the SMC-LEO.

5.4 Gravity Wheel Emergency Medical Treatment Center

5.4.1 Emergency Care

The presence of gravity is both harmful and helpful in space. It is harmful because falls and accidents will be more common in a station with gravity. Meanwhile, the assistance of gravity will be more of an advantage when performing cardiopulmonary resuscitation (CPR) will be simpler and more effective, as the patient will not need the same restraint to a treatment table or backboard and the caregivers will not need to be restrained to the same degree as in microgravity. The force of CPR could also be greater and therefore, perfusion could be improved.

5.4.2 Critical Care

Intensive care will also be facilitated by gravity. For intubated patients on mechanical ventilation, pulmonary aspiration would be less likely if gastric contents are not free-floating. Invasive drains used for clinical monitoring such as urinary catheters will be more effective and will give a reliable output to follow. Sacral decubitus ulcers, or bed sores, will be more common in gravity, however, even if just in reduced gravity.

5.4.3 Surgical Care

Surgery will be greatly assisted by the presence of gravity, for example during laparoscopic surgery, the abdominal contents will follow gravity and will not obscure the visual field. In microgravity, abdominal contents are free to move about the abdomen and can obscure the visual field. Open surgical technique will have even greater benefits with gravity. In microgravity, venous blood pools at the site of exit and can obscure the vision of the target of the procedure. With gravity, the blood will run off the patient, toward the table. Surgical instruments will also remain in place without special restraint equipment. Often, there are many instruments in a surgical pack, and being able to locate and retrieve the correct instrument at the correct time is important.

5.4.4 Dental Care

Dental instruments will also be able to be placed on trays without the need for additional restraints or aids to maintain their position, as would be needed in microgravity. Tooth fragments or filling fragments made from drilling or sculpting will also be easier to collect since they will fall to the dependent areas and remain in place. The patient will also be more stable in the examination chair and the medical crewmember will not require the same restraints in order to put force on the patient.

5.5 Gravity Wheel Exercise and Rehabilitation Facility

5.5.1 Exercise

The exercise regimens for the crewmembers would be the same as those used at the SMC-LEO, but there would not be use of in-situ lunar resources such as regolith-filled weights. The SMC-GW would use resistance devices similar to the ARED device on the ISS. The cardiovascular devices would also be the same as the SMC-LEO and on the lunar surface, with restraint harnesses for additional loading, since partial gravity would not be sufficient to prevent all bone loss.

5.5.2 Nursing and Rehabilitative Care

The nursing care on the SMC-GW would be similar to that given on the lunar surface. There would be a greater need for nursing services due to an expected, larger population. With gravity, falls and crush injuries are again possible, and many of these may need prolonged rehabilitation services.

5.6 Gravity Wheel Training Center

The training center here would have the same function as in LEO or on the lunar surface. It will provide a means of updating the medical crew on important topics and techniques. It will give instructions “just-in-time” to crewmembers before more complex procedures, and it will provide an avenue to discuss medical issues with colleagues on Earth.

5.7 Gravity Wheel Life Sciences Research Facility

The SMC-GW will integrate a similar research program as the orbital and the lunar surface SMC modules. However, the SMC-GW will provide new research capabilities due to the presence of ⅜g. While the comparative analyses of 1g and microgravity is well documented, very little data is reported on intermediary values. Moreover, available data comes from parabolic flights, drop towers, or random positioning machines, and are thus limited by tile exposure and environment bias. Phylogenetic and systematic observations suggest a scale effect of the gravitational influence on organisms (Gilles 2005). However, there is no evidence that the model is linear for all gravitational values. The SMC-GW research program will enable gaps to be filled on the understanding of gravitational biology and more interestingly, the ⅜ g, which is also the gravitational force on Mars. Therefore, the SMC-GW could then constitute a testbed for the Mars mission gravity environment, exploring countermeasures, technologies, and ergonomic adaptations. This module will be able to function as the absolute countermeasure of potential physiological change and recovery, upon gravity reentry after one-year of microgravity acclimation on the way to Mars.

A modular construction on this station will allow for more diversification of research as compared to the SMC-LEO and SMC-LUN. Up to twenty modules in two hemispheres allows for entire modules to be dedicated to research specific fields. The current approach of sending science experiments to the ISS requires extreme miniaturization of the scientific payload to be operated by a trained individual. With more room and a greater diversity of researchers on the SMC-GW, larger and more complex science can be conducted. This will result in better high-throughput data, allowing for research to progress faster. Worthy of consideration are the topics discussed in sections, with a particular focus on growing organoids as human analogs in space. Human performance in space will likely take center stage in these research endeavors, as both short- and long-term changes in human physiology can be measured by the presence of biomarkers such as sclerostin, osteocalcin, bone-alkaline phosphatase, and tartrate resistant phosphatase, which are all useful for determining how muscle and bones change in response to mechanical loading and unloading. This relates to the broad goal of increasing the understanding how the human body reacts on a molecular level to a partial gravity environment, which is imperative for future missions to the Moon and Mars.

5.8 Design Process

5.8.1 Dimensions

Structurally speaking, the ability to build an SMC-GW will likely be one of the greatest architectural challenges ever undertaken. There are a number of engineering obstacles that arise from such a structure and need to be addressed if the gravity wheel is to be a feasible project. The original design that von Braun imagined was successful only in concept; physically speaking, it was unrealistic. One of the most important challenges will be the balance between how much gravity can be generated, and how this critical value affects other values such as angular velocity, and radius. Some of the early designs sought to generate 1g on the station, which, according to the equation for centripetal acceleration, $a = -\omega^2 r$, would require a station that is 35 km in radius. This keeps the angular velocity low at 1 RPM but is wildly out of the size limit for a structure in space. Keeping the gravity value at 1g but lowering the radius is a delicate balance, however. According to the research shown in Figure 41, the higher the RPM, more training days are required to acclimate the human body, and the chances of 100% of the population reaching a higher RPM threshold is smaller. This would create a barrier for commercial customers. Only a small amount of research has been done on how much rotation, and thus angular velocity, the human body can take before loss of consciousness. The heart of this question directly relates to the Coriolis Cross coupled illusion, which essentially is how much tumbling and rotation the human vestibular system can take before disorientation, dizziness, and loss of consciousness.

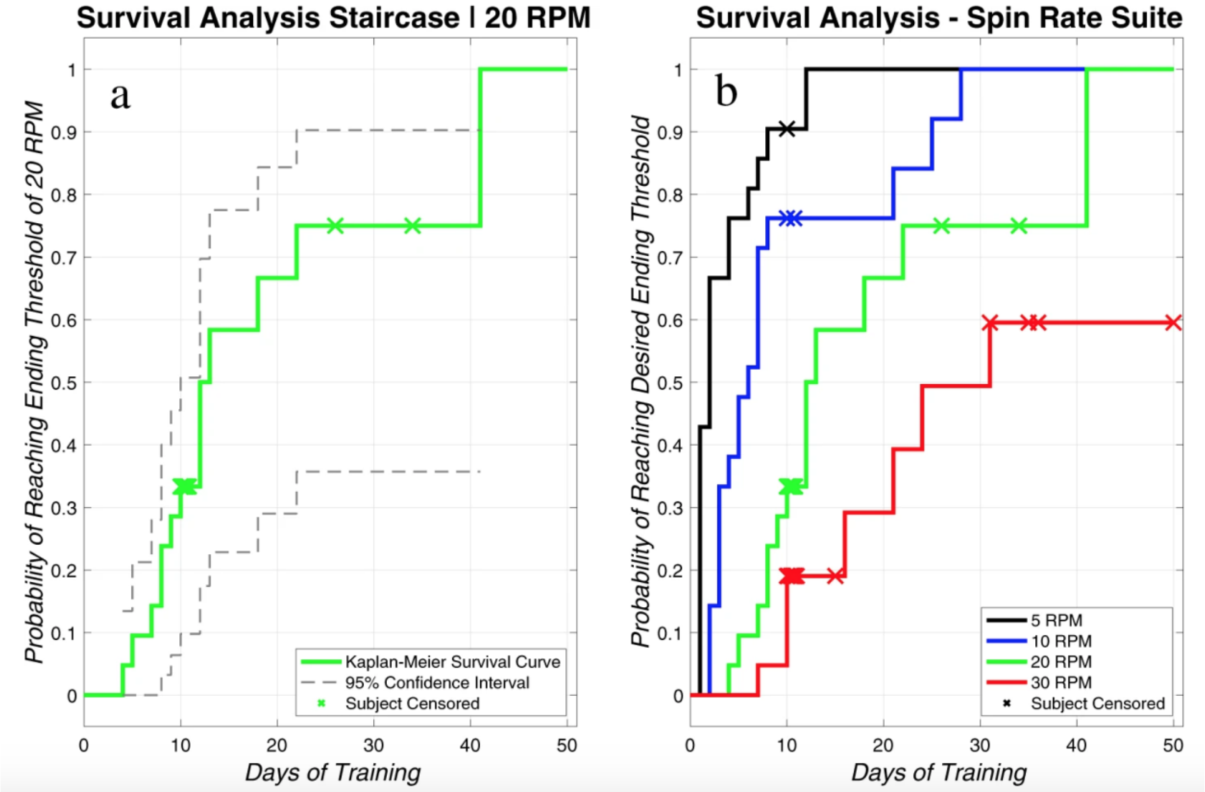


Figure 41: Left: Probability of the study's participants' bodies acclimating to 20 PRM. Right: A gradient of varying RPM data. Each line shows a different spin rate, and each plateau signals the final point at which the study participant's bodies are expected to stop acclimating to the indicated RPM (Bretl and Clark, 2020).

Figure 41 (Bretl et al., 2020) shows that incremental training can force the body to adapt to much higher spin rates than normal. This study was limited by the number of participants, and the fact that it was only carried out on Earth where conditions are at 1g. Further, this experiment was conducted by using the Human Eccentric Rotator Device (HERD), in which participants were positioned upright in a chair. They were spun about a vertical axis at varying speeds in the dark, with white noise to eliminate auditory cues from the HERD in an attempt to best replicate the lack of vestibular stimuli in space. Though a rotating wheel in space will have a longer spin-axis, the physiological changes experienced while adjusting to increased centrifugal force remains similar between this experiment and a gravity wheel. While these conditions are conducive to what simulated rotation may feel like on a SMC-GW, this study may be best addressed by performing a similar experiment in microgravity.

It is critical to note that this structure will likely not exist within the next 20 years. As this is speculative research, 30 RPM has been deemed unnecessary, and would likely put a large amount of stress on the structure and the passengers. Considering the aforementioned variables, this is why the proposed radius of the SMC-GW is 58.86m, which allows for ⅜g, spinning at 15 RPM.

5.8.2 Docking Accessibility

One major technical challenge will be docking space vehicles with this rotating structure. The docking vehicle needs to be able to precisely adapt to the rotation of the station at a given port. These ports could be placed at the center rather than at the outer ring of the rotating structure. In this way, the docking vehicle can rotate around its own axis. Guidance and control algorithms are currently being adapted for use in space for docking with a rotating structure (Wilde et al., 2016).

Another possible configuration would be the addition of a non-rotating part which could function as a zero-G zone in the rotating space station. This would make docking for resupply missions considerably easier, while also enhancing the capabilities of an SMC-GW by having a zero-G zone and a partial gravity zone. In this case, a sophisticated interface will be required that is able to connect between the rotating and non-rotating part of the space structure. This could be achieved in two different ways: the addition of an intermediate section that can be coupled and decoupled between the non-rotating part and the rotating part, or the addition of a large clutch between the rotating and non-rotating part.

For the first option, an intermediate segment can be equipped with an engine or thrusters similar to the rotating part to enable synchronization between the parts. Both sections would be on a joint shaft connected with bearings to enable a decoupled configuration from the rotating shaft. Once the intermediate segment undocks from the non-rotating segment, the engines will accelerate the intermediate segment to the same rotational speed as the rotating segment permitting the system to move horizontally towards the rotational segment for docking. In the reverse case, the intermediate segment needs to undock from the rotational segment, slow down to zero angular speed, and dock with the non-rotating station.

In the second option a large clutch as part of a transformation gear can be used and would consist of a friction disc and a pressure disc between the rotating and non-rotating side. To connect, the discs would need to be pressed together as a standard configuration. In this way, both parts are held together by friction and thus rotate together. In order to decouple both parts, a large diaphragm spring needs to be added. If an external force presses on it, the inner part of the spring will be pressed inside whereas the outer ring of the spring will be inverted. With the inverted outer ring of the diaphragm spring, an external force to press the two discs together will be lacking, thus decoupling the entire system. However, the non-rotating part needs to have the capability to reduce or increase its rotational speed due to the inertia of movement.

5.8.3 Propulsion Systems and Energy Production

For stability and orbital maintenance, the SMC-GW will need a constant rotational speed to simulate gravitation. In order to generate the required thrust, the station needs a propulsion system to enable it to spin at a constant rotational speed. This constant propulsion can be achieved by thrusters which are essentially small fuel-based rocket engines and would consume enormous amounts of energy for initial rotation. Once rotating however, only slight adjustments to maintain rotation, and orbit will be required. Another way to accomplish this would be large electromotors that provide constant rotation. These would require large amounts of electricity that would need to be provided by an external power source.

In order to provide continuous energy supply for the station and its engines providing constant rotational speed, the rotating station requires a power source. Depending on the size of the station, there are several options. For a system that is rather small, large solar arrays could be feasibly assembled as an evenly distributed circular extension around the entire outer habitation ring extending the overall radius of the structure. Another potential system for a rather large structure would be nuclear fusion, assuming this will become feasible several decades from now. The heat generated by the fusion reactor would be transferred to large vapor turbo generators to produce electricity. A third option for very large structures could be large solar mirrors, able to focus light onto an interface that can transfer the resulting heat to turbo generators for producing electricity (Wade, 2019).

5.8.4 Stabilization

The SMC-GW needs to have an equal distribution of mass around its outer circumference. Otherwise, the net surplus of mass on one side would lead to an uneven angular momentum during rotation, which in turn would disturb the required continuous rotation and lead to an uncontrollable wobbling effect. Each added mass will require a countermass on the opposite side of the outer ring. Ideally, the entire outer ring will have a perfectly evenly distributed mass around its circumference.

A rotating station with evenly distributed mass already has a high degree of stability. For an SMC-GW around Earth or other celestial bodies, the rotating habitat could additionally be equipped with a stabilization tether. In principle, the tether will stabilize the gravitational gradient between the large structure and the tether pointed towards the celestial body. The larger the tether, the higher the gravitational gradient and the more stabilizing its effect (Huang et al., 2018).

5.9 Construction and Material Delivery

In-space manufacturing is the future of the space industry. In order to construct the SMC-GW, a robust launching and material supply strategy would be required to assemble the wheel’s structure. It can either be constructed on planetary surfaces and assembled in-orbit, or it can be entirely manufactured in orbit with the help of Lunar Gateway and ISS robotic arms. Countries like the U.S.A, China, India, Russia, Japan are prioritizing ISRU in order to create a sustainable presence in space and on the Moon. In the next 30 years, the development of machinery to be launched and used on the Moon would also enable the construction of the SMC-GW.

NASA’s advanced manufacturing technology division is investigating the development of fabrication labs (FabLabs). This kind of lab would be established in one of the Lagrange points known as lunar-Lagrange FabLabs between 2020-2025 (Clinton, R.G., 2014). It would also enable the use of ISRU and build of items from different types of materials – metals, composites, plastics etc. required for the gravity wheel construction. NASA is also looking at the Commercial Infrastructure for Robotic Assembly and Servicing (CIRAS), which is focusing on robotic manipulators and space-based assembly (Bradley Stoor, by J. and Col Peter Garretson Maxwell., 2018). In conclusion, the gravity wheel construction capabilities will be catered to by the changing space technologies and governmental/commercial space activities.

5.10 Commercial Use

The Orbital Assembly Corporation, a space construction and manufacturing company founded by the Gateway Foundation, announced date-specific details about its Voyager Station, the first commercial space station operating with artificial gravity (Spry, 2021). The Station will accommodate up to 400 guests and consist of two hemispheres with twelve modules each. Besides having the necessary modules for the station's operation, each hemisphere will have modules allocated for recreational purposes such as restaurants, bars, a gymnasium, and an auditorium. The station is expected to provide the modules with artificial gravity near Mars' level (~40% of Earth's) and also possess a built-in ECLSS. There will be modules for paying customers, as well as laboratories for national space agencies and hotel chains with rooms for tourists and villas for the extremely wealthy, corporations or individuals. These modules will be completely configurable according to the customer's needs. Space agencies will be able to buy and configure modules as they choose and then later sell these positions to cover their expenditure. It is predicted that the reselling of space property will completely change the dynamic of space expenses (The Gateway Foundation, 2019). The proposed SMC-GW, whether integrated into the Orbital Assembly Corporation’s concept or standing alone, will benefit from this commercial model as a way to attract willing customers and generate revenue.

As part of the internal infrastructure, it is important to note that part of the population aboard the gravity wheel will be employees. This poses a unique challenge, as maintaining a consistent crew for internal maintenance will require specific considerations. One facet of the astronaut selection process that NASA considers is selecting middle-aged to older astronauts over younger astronauts due to the ethical constraints of elevated radiation exposure in space. Further, these individuals will need to be trained to work in this specific environment as it pertains to the spin rate, ⅜g, and emergency protocols. This will likely require the owner of the gravity wheel to formulate a new and specific set of requirements for its employees. This population will likely be composed of unselected space agency astronaut volunteers and will be used on a rotating basis. This can be further complicated by the number of privately rented modules, which may have to assign their own employees, such as lab techs, nurses, and doctors depending on the function of each module.

To qualify the aforementioned points, the Orbital Assembly Corporation and Gateway are still a long way from producing a viable product. The Orbital Assembly corporation expects construction to be completed by 2027, but this is considered liberal by some estimates. However, the pursuit of the concept, and formation of two distinct companies with support from SpaceX is a testament to the drive to increase long duration missions in space.

5.11 Future Considerations

There are a plethora of factors that limit long duration, and sustainable human missions to space. Each generation of humans is limited by the technological capabilities of the time period they are born into. This is why the primary contents of this report concerns itself with producing a Columbus-like module add-on to the ISS for medical and research operations in space. However, this report would be incomplete, and remiss if it were not to consider combating microgravity directly. Not doing so means adjusting every minute aspect of life in space to living in an environment that humans are not adapted to for the long term. There are many challenges associated with constructing a massive structure such as cost, launch capability, commercial partnerships, shielding, and general public interest. These account for many of the barriers that have plagued the construction of a gravity wheel since it was first realistically proposed by von Braun over 60 years ago. At some point however, dealing with life in microgravity and the myriad complications it produces reaches a cost convergence point with combating the problem of microgravity directly. For this and other reasons, it is imperative that the future of both medical and research operations in space seriously consider producing artificial gravity. To continue to explore space without such a concept is akin to working with both hands tied behind one’s back, and a needless risk for the astronauts that dedicate their lives to exploring the cosmos.

This chapter has given the design strategy for a self-contained SMC in a rotating space station in LEO. The artificial gravity will positively benefit the crew in numerous ways. Next, the following chapter will discuss the risks involved for an SMC and the technologies chosen to reduce or mitigate these risks to best serve the needs and constraints of the SMC.

6 Risk & Emerging Technology Identification

Whether human illness or equipment failure, or another cause, there is no system with zero risk. Therefore, the course taken here was to make an adequate assessment of risks, evaluate their consequences, make tradeoffs to avoid risks, and plan mitigations as needed and as possible. Risk assessment and risk management are processes that are best implemented repeatedly from the conceptual design phase until the end of the mission operations. The following sections give detail on the medical and engineering risks anticipated for the SMC and the choices of equipment based on these assessments. Not all technologies are equal, considering the difficult environment of space and the forces required to get there. Well-informed decisions were made for the technologies included in this design and the evidence for this will be presented here.

6.1 Risk Assessment

In order to properly address the feasibility of the proposed SMC configurations, it is necessary to conduct a thorough analysis of the risks affecting each environment and stage. Possible medical, structural, and operational failures were considered early on to justify the three designs. The medical risks to humans in space dictate the types of care required, whilst the specific risks to the SMC structure and equipment directly influence what needs to be included or reinforced to maintain a proper SMC function. In previous chapters, the medical and engineering tradeoffs were given to round out the design strategies and give a clearer picture of the framework and capabilities of the SMC in each location, for each scenario or stage. Now the risks previously identified will be expanded upon.

6.1.1 Medical Risks

To identify the structure, equipment, and training needed for a space medical center, it is imperative to assess the risks to patients, commercial partners, crewmembers, and the station itself. Risks can come in many forms and all risk cannot be eliminated. Many, however, can be avoided or mitigated, given adequate preparation and carefully planned systems operations.

Considerable thought has been given to the possible medical risks of long-duration spaceflight. The NASA Human Research Program (HRP) ExMC has determined a list of 100 conditions most likely to require prevention or mitigation. The Space Medicine Exploration Medical Condition List (SMEMCL) contains conditions that range from a high likelihood of occurrence and low consequence to health to conditions that have a low likelihood of occurrence and a high consequence to health (Watkins, Barr and Kerstman, 2011). The likelihood and consequence tables for risks based on distance from Earth and mission duration according to the NASA Human System Risk Board are shown in Table 19.

Table 19: Health Risks to Crew and Mission Success (NASA, 2021b)

DRM Categories	Mission Duration	Operations		Long-Term Health	
		LxC	Risk Disposition *	LxC	Risk Disposition *
Low Earth Orbit	6 months	3x2	Accepted	3x2	Accepted
	1 year	3x3	Accepted	3x2	Accepted
Deep Space Sortie	1 month	3x2	Accepted	3x1	Accepted
Lunar Visit/ Habitation	1 year	3x3	Requires Mitigation	3x2	Requires Mitigation
Deep Space Journey/Habitation	1 year	3x4	Requires Mitigation	3x4	Requires Mitigation
Planetary	3 years	3x4	Requires Mitigation	3x4	Requires Mitigation

Note: LxC is the likelihood and consequence rating. The information above was last approved by the Human System Risk Board in 4/2019.

Among these are conditions that occur frequently that are simple to treat, such as headaches and nausea, along with conditions that are rare but difficult to treat, such as appendicitis and sepsis (Figure 42). The most common ailments seem to have the least impact on mission completion and can include skin rashes, along with respiratory and digestive irritation. However, some illnesses with low probability could cause significant negative effects to a mission, including the death of a crew member. Robertson et al. (2020) with 28 subject matter experts in surgery, medicine, mission operations, human factors, and psychology identified medical events with low survivability. They also identified conditions with greater impact to mission completion.

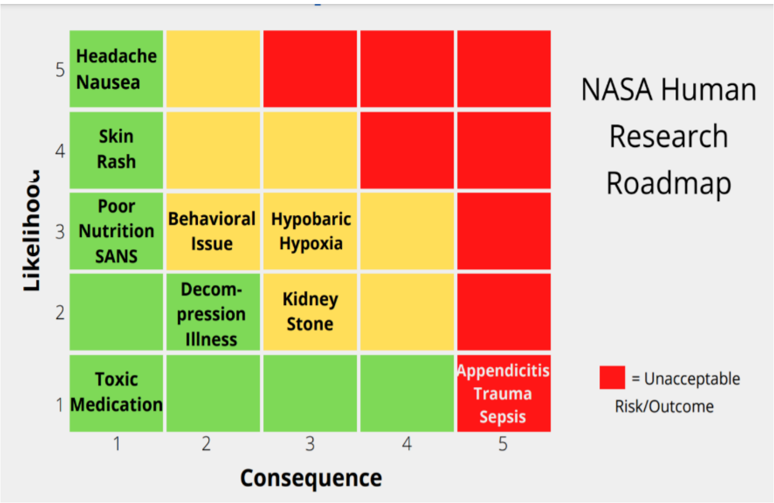


Figure 42: The NASA HRP assesses medical conditions that could threaten exploration missions based on their likelihood of occurrence and probability of consequence. (NASA, 2021b).

The most common medical risks during long-duration spaceflight missions are radiation, loss of bone density, and behavioral health disturbances (IOM, 2001). These cannot be prevented and require mitigation in-flight. Radiation and loss of bone density are not likely to have immediate impacts on crew function or the completion of a mission but can have longer-term effects lasting post-flight.

Priorities identified previously included the need for trauma/acute medical care, whilst NASA-derived priorities included the need for autonomous medical care, the need for protection from radiation, the need to maintain performance and behavioral health, preventing bone-related disease, and providing advanced technology for human support. Astronauts and space tourists have certain risks of medical conditions that cannot always be predicted. Certain conditions, some mild and some life-threatening, can still be present in otherwise healthy crew. Examples can include trauma, appendicitis, pancreatitis, gallstones, kidney stones, and dental conditions (Ball et al., 2012). Most of the conditions that will arise during long-duration space flights will be common disorders that can be prevented or mitigated with minor interventions. Pharmaceuticals and minor repairs will be the mainstay of treatment for simple ailments. Rarer conditions such as appendicitis will need planned mitigations such as intensive or surgical in-flight intervention to prevent loss of life or damage to a mission or program.

6.1.2 Structural and Operational Risks

Aa series of potential risks are common with each scenario. The following is a description of the risk assessment for this type of clinical and research facility, discussing risks such as chemical toxicity and equipment failure. The SMC will have a variety of chemicals on board that could cause hazards, such as toxic contaminants, fire hazards, secondary radiation, etc. With the assumption that every machine fails at some point and that space is a hostile environment, medical equipment could perform differently from its original rated efficiency if an error occurs. A single-point system failure or a cascading effect of a multiple-point system failure has the potential to interrupt a specific capability or abort a mission. Any failure in part of a medical system has an impact on medical care and could lead to severe illness, injury, or loss of life. In this report, the risk assessment process is kept simple and easy to understand. By considering the mission requirements, the following risk assessment is identified as a preliminary one-step process for individual and component risk identification.

To assess potential failures and risks that could occur during the development and operation of the SMC, a Failure Mode and Effects Analysis (FMEA) has been performed to determine which potential mitigation strategies could be implemented as countermeasures. The failure modes are the different scenarios for which the operability of the SMC could lose capability and possibly no longer function. The effects of these failures represent the potential consequences for which these scenarios can lead to defects, harmful outcomes, death, or waste. The goal of the FMEA analysis is to also build a functional redundancy within the system to achieve high reliability during the conceptual phase itself. The approach followed during the application of this methodology to the SMC was to first assess and break down the different subsystems of the center and to categorize them by function. The different categories are routine care, emergency care, surgical care, medical equipment, auxiliary medical equipment, electronics, and medical supplementary. The next step was to assess the potential failure modes associated with each of these subsystems. Once the potential failures were assessed, the possible causes of these failures were identified as well as the potential effects of these failures. Table 20 below, categorized by different routine cares, represents critical risks based on the FMEA analysis:

Table 20: FMEA Analysis of Space Medical Center Risks.

ID No.	Subsystem/ Component name	Potential failure modes	Potential causes of failure	Potential effects of failure	Recommended emergency actions	S	O	S * O	M S	M O	MO * MS
Routine Care											
1	Ultrasound	Device Operation Failure	Battery failure/voltage leak, Software failure	Failure to diagnose	Possible examination through stethoscope	4	3	12	3	2	6
Emergency Care											
2	Oxygen delivery system	Partial oxygen supply, leaks, absolute device failure	Valves/couplings failure, oxygen delivery hose damage	Morbidity/ death	Back up oxygen tank	5	2	10	2	2	4
3	Oximeter	Display errors, Device operational failure	Sensor failure, moisture	Misdiagnosis	Use istat	4	3	12	3	2	6
4	Defibrillator	Display errors, Device operational failure, Delivery of wrong level of shocks	Failure of electrodes, Failure of hardware/software, Failure of switch buttons responsible for shock delivery	Death	Pre-cordial thump	5	4	20	5	3	15
5	Medical suction	Failed to provide suction, Absolute device failure	Pump failure, low efficiency/quality	Death, infection	Build extremely high reliability equipment & provide backup system	5	3	15	4	2	8
Surgical Care											
6	Laparoscopic instruments	Failure to image, Device Malfunction, Absolute device failure	Insulation Failure, Failure of fluids and light transmission, surgical instruments failure, faulty connection of cables, human errors/human decisions, video circuit failure	Death	Possible open surgery	5	4	20	5	3	15
7	Ventilator	Device Operation Failure	Alarm failure, defective cooling system, battery failure, Power supply fluctuation	Death	Bag Valve Mask-disposable	5	4	20	4	2	8
Medical treatments/equipment											
8	Telemedicine setup	Loss of consultation	Loss of connection, delayed response	Death/morbidity	Routine comms	5	4	20	4	4	16
9	Bone densitometer DXA	Imaging error, Absolute device failure	Moisture, environmental temperature, power surges/outages, software failure/errors, tissue typing errors/image error	Failure to diagnose	Ultrasound bones	4	3	12	3	1	3
10	Electrocardiograph	Loss of ECG signal/waveforms, Device failure, Error in Imaging	Contamination of ECG cables, uncontrolled instrument environment	Failure to diagnose	Physical examination/ultrasound	4	4	16	3	2	6
11	Dental instruments	Device Operation Failure	Mechanical failure-Failure of devices like saliva ejector, air water syringe, ultrasonic scaler	Morbidity	Pain medicine/evacuation/antibiotics	5	3	15	5	2	10

S: Severity score 1-5
O: Occurrence score 1-4
S*O: Overall score
MS: After mitigation actions severity score 1-5
MO: After mitigation actions occurrence score 1-4
MS*MO: After mitigations actions overall score

Table 20 Continued

ID No.	**Subsystem/ Component name**	**Potential failure modes**	**Potential causes of failure**	Potential effects of failure	Recommended emergency actions	S	O	S*O	AS	AO	AS*AO
Auxiliary medical equipment											
12	Preservation device - refrigerator - freezer	Partial operation or Absolute Operational failure	Refrigerant leak, Compressor failure, thermostat failure, condenser failure	Death of frozen cells, Chemical reagents (enzymes) functional failure, Failure of experiments, Failure to blood transfusion, Death of the patient	Medical blood transfusion through available crew on-board (look for Universal Donor with blood type "O"), Research- Move the bio-items to another preservation device, if it possess contamination risk to the module- discard it safely.	4	3	12	3	2	6
13	Biohazardous waste disposal/Waste collection system	Integrated system failure	Pump failure, suction failure, electrical failure, hose failure	Contamination of environment, Potential health hazard, Congestion/clogging of hazardous material in the ducts	Manually collect the waste, venting out hazardous gas with the help of fans, isolating the module in case of toxic exposure	4	3	12	4	2	8
Emergency Tanks											
14	Oxygen tanks	Oxygen leak, explosive decompression	Pressure valve failure, puncture	No backup, death, potential damage to systems	Possible Electrolysis of oxygen	5	2	10	4	2	8
Medical Supplementary/essential accessories											
15	Medical personal protection equipment, gloves, masks Harnesses for patient and crew Air filters Fuse box Measurement devices Processing equipment for clean water and used water Carbon dioxide cannister Chest tube	Hardware/software failure, device/measurement equipment failure.	Leak, Electronics failure, electrical failure, mechanical failure, material failure	Morbidity/Unconsciousness/Death	Emergency backup. Always order some extra supplies via cargo delivery if any potential failure is detected and if any essential supply is near to its consumption. Logistics assessment is recommended to keep the medical inventory up to date.	5	2	10	4	2	8

Once the risk scenarios, potential causes and effects of failures were identified, the score assessment for each risk was performed. Risks were characterized by their severity which also corresponds to the degree of impact of the consequences. Risks were also characterized by their occurrence or likelihood and given the severity and occurrence scores. An overall score was calculated by multiplying them and then the next step was to address recommended actions to mitigate these risks. Finally, each of the risks was defined by two overall scores, before mitigation, and after mitigation.

The matrices give four categories of risk prioritization: low, medium, high, and extreme. Based on our results, before mitigation, there are 15 risks that are classified as extreme priority risks. Then, after mitigation, there are four risks that are classified as extreme priority risks, then five high risks, five medium risks, and one low risk. Given our results, our mitigation strategies would enable the reduction of extreme risks, severities, and occurrences. Table 21 and 22 below categorized by different routine care risks represent the critical risks based on the FMEA analysis.

Table 21: Before Mitigation Severity-Occurrence Matrix

Before Mitigation					
Severity	5	🟨	🟥 2,15,14	🟥 5,11	🟥 4,6,7,8
	4	🟨	🟧	🟥 3,12,1,9,13	🟥 10
	3	🟩	🟨	🟧	🟥
	2	🟩	🟨	🟨	🟧
	1	🟩	🟩	🟩	🟨
		1	2	3	4
		Occurrence			

Table 22: After Mitigation Severity Occurrence Matrix

After Mitigation					
Severity	5	🟨	🟥 11	🟥 4,6	🟥
	4	🟨	🟧 5,7,13,14,15	🟥	🟥 8
	3	🟩 9	🟧 10,1,12,3	🟧	🟥
	2	🟩	🟨 2	🟨	🟧
	1	🟩	🟩	🟩	🟨
		1	2	3	4
		Occurrence			

6.2 Criteria Review of Pertinent Technology

The SMC is planned to be a top-level medical and research integrated platform. The equipment for it has been selected to perform medical analysis, monitoring, treatment, and research studies in space. The hallmarks of the technologies utilized onboard the SMC will be miniaturization, user-friendliness, real-time responsiveness, and precision analysis.

6.2.1 Criteria

Potential technologies were assessed based on their multi-functionality, risk relevance, and technology readiness level. For multi-functionality criteria, we evaluated different purposes such as research (R), bio-molecular research (B), diagnostic (D), medical (M), and treatment (T). The Risk Relevance criteria concept is based on the popular Risk-Index Scheme, with risk versus necessity to the SMC. This scheme assessed each technology according to the risks it can treat or diagnose. Consequently, a technology's importance to the SMC was defined as low, medium, or high. The Technology Readiness Level (TRL) was assessed according to the defined scale (Figure 43). For scenario 1, a technology was selected with a TRL of 6 and above. Also, other factors, such as volume, dimensions, cost, maintenance, reusability, life expectancy and time performance were also considered but were not regarded as important as the main three factors.

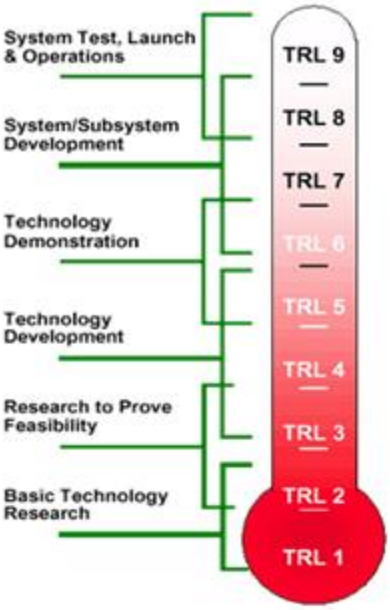


Figure 43: NASA Technology Readiness Level Scale with descriptions (ESA, 2008).

6.2.2 Potential Technologies for an SMC

The potential technology Tables 23, 24, 25 and 26 show an overview of the technologies considered for the SMC. They are categorized according to monitoring, diagnosis, treatment, research, and exercise.

Table 23: Monitoring Technologies for a Space Medical Center

Application		Technology	Multi-Functionality	Risk Relevance	TRL
Scenario I	Scenario II	Electrocardiogram (ECG)	R, M, D	High	9
Scenario I	Scenario II	Oximeter	R, M, D	High	9
Scenario I	Scenario II	Wearable sweat sensor	R, M, D	High	6
Scenario I	Scenario II	Biofuel-powered e-skin sensing platforms	R, M, D	High	6
Scenario I	Scenario II	Chemiluminescence based biosensor	R, M, D	High	9
Scenario I	Scenario II	Stretchable wireless optoelectronic system	R, M, D	Medium	6
Scenario I	Scenario II	Bio-Monitor/Astroskin	R, M, D	Low	8-9

Table 24: Diagnostic Technologies for a Space Medical Center

Application		Technology	Multi-Functionality	Risk Relevance	TRL
Scenario I	Scenario II	Ultrasound	R, M, D, T	High	9
-	Scenario II	X-ray	R, M, D, T	Low	6
-	Scenario II	CT scan	R, M, D	Low	4
-	Scenario II	MRI	R, M, D	Low	4
Scenario I	Scenario II	Flow Cytometry/ Miniaturized flow cytometer	R, B, M, D	Medium	9
-	Scenario II	DXA	R, M, D	High	8
Scenario I	Scenario II	Imec "miDiagnostics" disposable blood testing	R, M, D	High	7
Scenario I	Scenario II	ASTRO3DO	R, M, D	Medium	6
Scenario I	Scenario II	"the NASA analyzer"	R, M, D	High	9
Scenario I	Scenario II	Bio-Analyzer	R, M, D	High	9
Scenario I	Scenario II	i-Stat	R, M, D	High	9
Scenario I	Scenario II	POBA,	R, M, D	Medium	9
-	Scenario II	Microfluidic based genotyping	R, B, M, D	Medium	4
Scenario I	Scenario II	Portable 1Drop Diagnostics	R, B, M, D	High	9

Table 25: Treatment Technology for a Space Medical Center

Application		Technology	Multi-Functionality	Risk Relevance	TRL
Scenario I	Scenario II	Laparoscopy (closed surgery)	T	Med	9
-	Scenario II	Robotic Surgery (Da Vinci)	T	High	5

Table 26: Research Technology for a Space Medical Center

Application		Technology	Multi-Functionality	Risk Relevance	TRL
Scenario I	Scenario II	PCR machine	R, B, M, D	High	9
Scenario I	Scenario II	Biological hood/ Glovebox	R, B	High	9
Scenario I	Scenario II	Centrifuge	R, B, M, D	High	9
Scenario I	Scenario II	Incubator	R, B, M, D	High	9
Scenario I	Scenario II	Digital PCR	R, B, M, D	High	6
Scenario I	Scenario II	Miniature Mass Spectrometer	R, B, M, D	High	6
Scenario I	Scenario II	Organ-on-chip		High	6
-	Scenario II	In-Space Manufacturing module (3D printer FFF)	M, T		6

In conclusion, now the risks have been determined for the SMC. The medical risks of disease and human “failure” are juxtaposed with the engineering risks of equipment failure. The decision analysis for choosing equipment for the SMC has also been made. Only those technologies with a Technology Readiness Level of 6 or above were selected, and the devices with more multi-functionality were more desirable. Next, the entrepreneurial factors of running an SMC will be reviewed, identifying customers, and developing revenue streams.

7 Business Considerations

An SMC requires funding, like any other program. Its operation needs to be self-sufficient, and self-sustaining, and where possible, generate a profit. The following chapter delves into the costs associated with this type of venture and gives the plans to recuperate these costs and to make the SMC financially stable. It will cover the medical and research suppliers to be negotiated with to have affordable equipment. It also discusses the customers than can generate revenue streams to drive the profitability of the SMC. Finally, it gives the position of the SMC in relation to its customers, partners, resources, and costs.

The market for the space medical center will be based on its research and clinical activities. With commercial entities entering the space arena, the space sector is projected to be worth a trillion dollars in 2040, according to several major world banks (Table 27).

Table 27: Projections of the Space Economy Size by 2040
(Berrisford, 2018; Goldman Sachs, 2017; Morgan Stanley, 2017; Bank of America Merril Lynch, 2017)

Projections of the Size of the Space Economy by the 2040s	
UBS	$926 billion
Goldman Sachs	$1 trillion
US Chamber of Commerce	$1.5 trillion
Morgan Stanley	$600 billion – $1.75 trillion
Bank of America (Merrill Lynch)	$2.7 trillion

With accurate identification of the market and a strategic business plan, an SMC can capitalize on this growth. It could be the largest private biomedical research center in LEO and on the Moon. Further, it could represent the first private clinical service of its kind, able to service public agency and private astronauts. From an economic standpoint, it is important to differentiate the revenue streams so if one operation loses significance, the others can partially offset the loss.

7.1 Economic Constraints

Table 28: Economic Constraints

Constraints	Justification
- Constrained by customer expectations and profile - Budget constraints from institutional customers - Potential acquisitions of space-applicable equipment from suppliers are limited by its current TRL	- Operational and medical needs between professional astronauts and private space tourists are different - Budgets of space agencies as potential customers are limited - Make or buy decisions depend on the suppliers' ability to certify their equipment for the space environment and guarantee to deliver on time

7.2 Space Tourism: Costs

Space tourism is still a limited phenomenon, and as such, very few financial figures are available. Meanwhile, according to founder and CEO of Social Capital Hedosophia Chamath Palihapitiya, space tourism will make revenues in excess of $600 million by 2023, with nearly 50% of profit margins (Fernholtz, 2019). Also, between 2001 and 2009, Space Adventures Inc. provided spaceflight services to seven space tourists to the ISS using spare seats onboard Russian Soyuz capsules. The overall cost for the week spent on board was approximately $20M (Sheetz, 2020). Recently, Axiom Space announced the first crew of private astronauts that will pay approximately $55 million each to spend 8 days at the ISS (Axiom Space, 2021).

Suborbital flights are expected to dominate the market, with 82% of revenues generated (Figure 44). This will occur due to lower ticket prices, higher demand, and more competition. Additionally, suborbital launch windows are more frequent than those for orbital: over 3,000 flights could be undertaken by 2028 (Northern Sky Research, 2020).

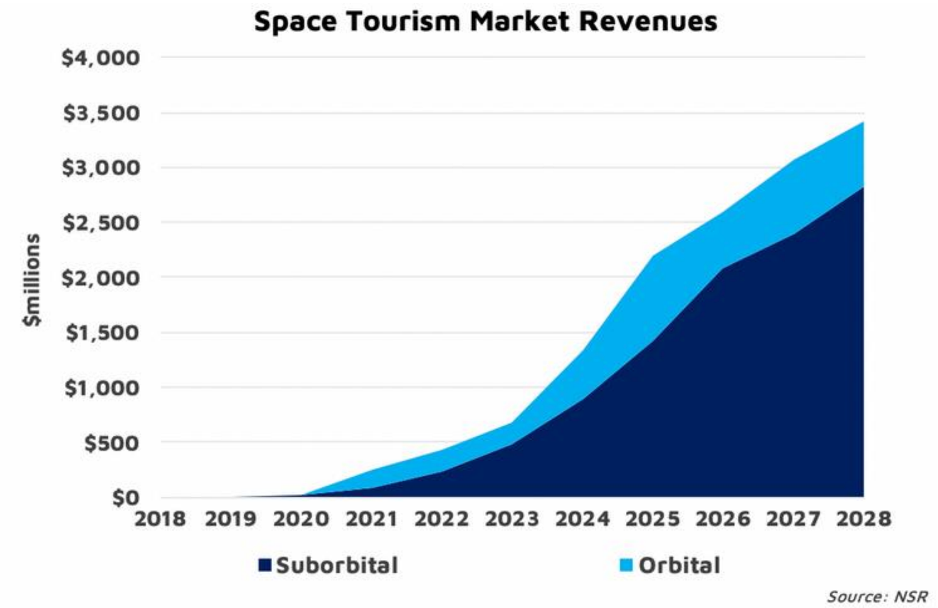


Figure 44: Space tourism market forecasted revenues and from 2018 to 2028 (Northern Sky Research, 2020).

7.3 Suppliers

The health and medical sectors offer a wide range of potential equipment suppliers (Table 29). However, given the requirements and constraints of an SMC and the space environment, only a portion of these medical suppliers offer products for applicable in-space use. From the range of potential medical suppliers, twelve were identified as considerable options for supplying medical technologies for an SMC. While it is difficult to say which companies would supply an SMC, these companies are the candidates for providing applicable and reliable technological systems.

Table 29: List of Potential Medical Suppliers

Medical supplier	Country	Supplied Technology
Imec	Belgium	Digital and nanotechnologies, MiDiagnostics device
Abbott Laboratories	United States	Healthcare devices, blood analyzer i-stat1
Carré Technologies	Canada	Cardiac monitoring equipment, Bio-monitor device
Philips	Netherlands	Philips/ATL model HDI 5000, ultrasound system ActiWatch Spectrum, activity monitor device
General Electric Healthcare (GE)	United States	Vivid E95 cardiac ultrasound device
Techshot	United States	Dual-energy X-ray absorptiometry (DXA) imaging device
Siemens Healthineers	Germany	Magnetom, resonance imaging system
Intuitive	United States	Da Vinci surgical system; Ion endoluminal system
Stryker	United States	Mako Smart robotics, 3D images of the bone structure
Smith & Nephew	United Kingdom	Navio surgical system, 3D model of the bone structure
Stony	Japan	E-mail ventilator, inhalation anesthesia system
Thermo Fisher scientific	United States	Pathological anatomy systems, microbiological analysis, diagnostic tests

7.3.1 Research Equipment Suppliers

To enable research capabilities in Scenario 1; the SMC would need to work closely with current ISS research equipment suppliers. Current ISS suppliers were compiled to provide an overview of the potential for research studies (NASA, 2021g). Each piece of equipment was compiled along with its supplier for a total of 163 pieces of research equipment across all the domains. With this data a graph was created (Figure 45) below.

From the graph it can be deduced that over 60% of the research equipment is supplied by the top 7 organizations listed (NASA, JAXA, Techshot Incorporated, the University of Alabama in Tuscaloosa, BioServe, Astrium Gmbh and ESA). Of this 60%, approximately 45% were from space agencies. It will be important to liaise with the agencies, allowing them to easily access the SMC for new research methods which will drive innovation and establish the center as a vessel for scientific innovation.

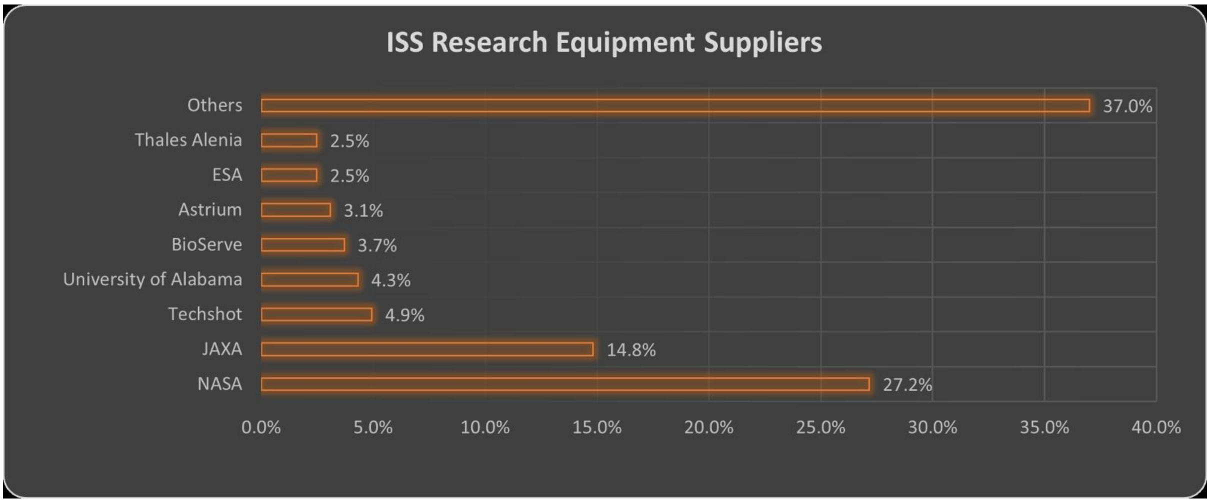


Figure 45: Percentage of research equipment on NASA's Space Station Research Explorer (NASA, 2021g)

Techshot incorporated is the largest supplier from the commercial marketplace. They supply approximately 4.9% of research equipment, which includes the Avian Development Facility (ADF), Advanced Space Experiment Processor (ADSEP), Biofabrication Facility (BFF), Cellcult, Fluid Processing Cassette (FPC), as well as the Multi-use Variable-g Platform (MVP).

Also, the University of Alabama in Tuscaloosa supplies custom items to the ISS. They have supplied 4.3% of the research equipment on the database, placing it as the largest academic institution supplier. This equipment includes the commercial refrigerator/incubator module, cryo chiller, general laboratory active cryogenic ISS experiment refrigerator, glovebox, freezer, as well as the microgravity experiment research locker incubator. The SMC will need these solutions not only for research equipment, but also for the storage of important medical samples and pharmaceuticals in both Scenarios 1 & 2.

BioServe Space Technologies supplies approximately 3.7% of research equipment in the biology and biotechnology domains. This is closely followed by Astrium Gmbh who works with ESA in supplying 3.1% of the current ISS research equipment catalog studied. Thales Alenia Space should also be considered a regular supplier of external facilities that enable research to be carried out outside the ISS as well as inside. Lowell, Sierra Nevada Corp., Danish Aerospace Centre, KBR Labs, and Airbus all have a stable presence with 1.9% of research facilities supplied each in this assessment.

There are many suppliers to the ISS currently and a large proportion of the research equipment is NASA, as the SMC is developed it is essential to have NASA involved in the supply chain. It is difficult to know what the supplier proportion may look like in 20 to 30 years, but an increase in the commercial sector supply to the space sector is likely to increase. Scenario 2 will focus more on these commercial suppliers as a means to effectively creating an operational supply chain for bases on other celestial bodies.

7.4 Costs Associated with a Space Medical Center

As a medical facility, the end-goal of the module is to provide a service to astronauts. For this reason, the best way to approach the project is to outsource the project, assembly, and as much of the operations as possible to a third party. This approach is necessary in order to cut the costs of R&D of a pressurized human-rated space module. This would require high development costs and long development times, creating a company structure much larger and resource intensive than one that just needs to operate a facility. This way costs are contained, and operations are significantly streamlined. The SMC is unlikely to see or have to address serious traumas. For this reason, it is important for module architecture to be multifunctional, so that some research operations can be performed on a regular basis in between any medical treatment. Therefore, a large portion of the module will be devoted to scientific research, allowing private entities to develop, and run their own experiments. The Columbus Module was used as a blueprint for the initial development of the project.

Table 30: Approximate cost allocation for the Columbus module. Data gathered internally.

Phase	Extended definition	Cost in $ (Millions)
Phase A	Feasibility Studies	30
Phase B	Preliminary Definition	119
Phase C/D	Detailed Definition, Qualification and Production	1075
Phase E	Utilization (initial)	44

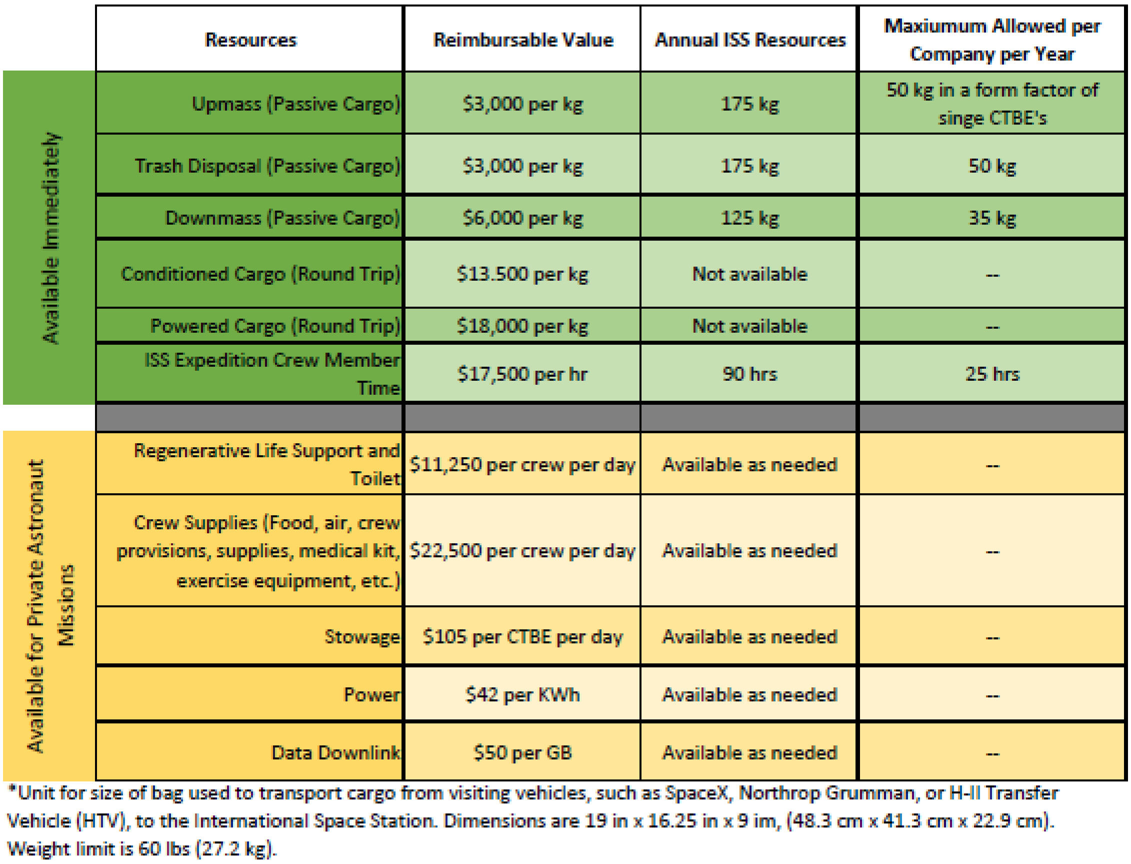
Additional costs regarding the adaptation of the interior as a laboratory amount to $152 million. Total cost was estimated at $1.42 billion, rising to $1.55 billion when considering launch costs, delays, and other factors that influenced the mission timeline plan. Starting from those data and taking into account that the manufacturer of the module will take advantage of economies of scale and technologies superior to the ones available for the construction of the Columbus, it can be estimated that the total cost of the module to be close to $1 billion not including launch costs, that will vary depending on the launcher selected. Meanwhile operating the facility-including resupply, telecommunication equipment, ground control, repairs and so on- will have a yearly cost estimated at $250 million. Over its lifetime the cost of the SMC will be in the range of $4.75 billion.

Regarding the planetary configuration, it is estimated that the basic version would cost almost twice the amount of the orbital one, under current economic considerations and at parity of weight and volume, while the advanced version is x2.5. This estimation has been made considering the greater complexity of the mission caused by several factors. Compared to the LEO version, the longer distance to reach the Moon implies rising transport costs. Moreover, given that no launch vehicle currently available is equipped with wide enough fairings to contain the whole structure yet, multiple launches will be needed. Assembly costs on the Moon will also be greater due to the difficulties in the lunar environment.

7.5 Costs Associated with a Low-Earth Orbit Medical Center

For cost reasons, the construction of the SMC-LEO would be outsourced. To create a company to manage its construction would be expensive and redundant. For this reason, the best method to approach the project is to outsource the assembly, and much of the operations, to a third party. This approach is necessary to decrease the costs of research and development of a pressurized, human-rated space module. This would require high development costs and long development times, creating a company structure much larger and more resource intensive. This way costs are contained, and operations are significantly streamlined. For construction, it is important for module architecture to be multifunctional, so that some research operations can be performed on a regular basis in between any medical treatment. Therefore, a large portion of the module will be devoted to scientific research, allowing private entities to develop, and run their own experiments. The Columbus Module was used as a blueprint for the initial development of the project.

For reference, the cost of Skylab from 1966 to 1974 was approximately $10.4 billion (2010 dollars) (Newkirk and Ertel, 1977). Meanwhile, the cost of the larger ISS from 1985 to 2015 was approximately $150 billion (2010 dollars), including $54 billion for 36 space shuttle flights at $1.4 billon, each (Lafleur, 2010; NASA, 2021h). The Columbus module of the ISS was constructed in Europe by EADS-Astrium (now the Airbus Group) as the main contractor, and assembled in Bremen, Germany (ESA, 2021) The initial contract was for €658 millon (1996 Euros) (ESA, 1999). This became approximately $2 billion in 2008 when it was connected to the ISS (CBS News, 2008). Figure 46 below details the current costs associated with the use of the ISS depending on crew constitution and duration.



	Resources	Reimbursable Value	Annual ISS Resources	Maxiumum Allowed per Company per Year
Available Immediately	Upmass (Passive Cargo)	$3,000 per kg	175 kg	50 kg in a form factor of singe CTBE's
	Trash Disposal (Passive Cargo)	$3,000 per kg	175 kg	50 kg
	Downmass (Passive Cargo)	$6,000 per kg	125 kg	35 kg
	Conditioned Cargo (Round Trip)	$13.500 per kg	Not available	--
	Powered Cargo (Round Trip)	$18,000 per kg	Not available	--
	ISS Expedition Crew Member Time	$17,500 per hr	90 hrs	25 hrs
Available for Private Astronaut Missions	Regenerative Life Support and Toilet	$11,250 per crew per day	Available as needed	--
	Crew Supplies (Food, air, crew provisions, supplies, medical kit, exercise equipment, etc.)	$22,500 per crew per day	Available as needed	--
	Stowage	$105 per CTBE per day	Available as needed	--
	Power	$42 per KWh	Available as needed	--
	Data Downlink	$50 per GB	Available as needed	--

*Unit for size of bag used to transport cargo from visiting vehicles, such as SpaceX, Northrop Grumman, or H-II Transfer Vehicle (HTV), to the International Space Station. Dimensions are 19 in x 16.25 in x 9 im, (48.3 cm x 41.3 cm x 22.9 cm). Weight limit is 60 lbs (27.2 kg).

Figure 46: The price of using resources and astronaut time on the ISS (NASA, 2019b).

7.6 Revenue Streams

7.6.1 Astronauts

The primary to monetize a medical center in LEO is through an insurance policy. Such a system, while valid, may not be enough to gather the interest of investors. In fact, it’s too susceptible to fluctuations in the number of private initiatives and is limited by the maximum number of astronauts allowed on a station. It is therefore necessary to look at novel ways in which such a module could fit in and synergize with existing space endeavors.

Space tourism companies will almost certainly send trained personnel along with their customers, capable of handling unexpected situations and maintaining the station and transport vehicle in good condition. Those subjects are expected to be retired government astronauts. This makes them ideal candidates for conducting the experiments which astronauts on the ISS refuse to partake. The resulting data can be exchanged with other entities for money (private companies) or benefits from government space agencies or other space companies. Private customers could also voluntarily apply themselves for taking part in such experiments, in exchange for a price reduction or public acknowledgment. While this approach would not net the company a financial benefit, it could broaden the pool of people capable of affording such an experience.

Being able to engage in space tourism in the near future will primarily be dependent upon personal wealth. On average the people in possession of such wealth are 55+ years old and predictably not as fit as a professional astronaut. This means that it could be possible to gather data that government agencies would not otherwise be able to collect from these individuals and exchange it for liquidity or services. Finally, NASA could book a station for a certain period in order to conduct focused medical training on the station, either in block (whole structure/launch capsule filled with professional astronauts) or as part of a regular tourist mission. This last option could also be of marketing interest for the company.

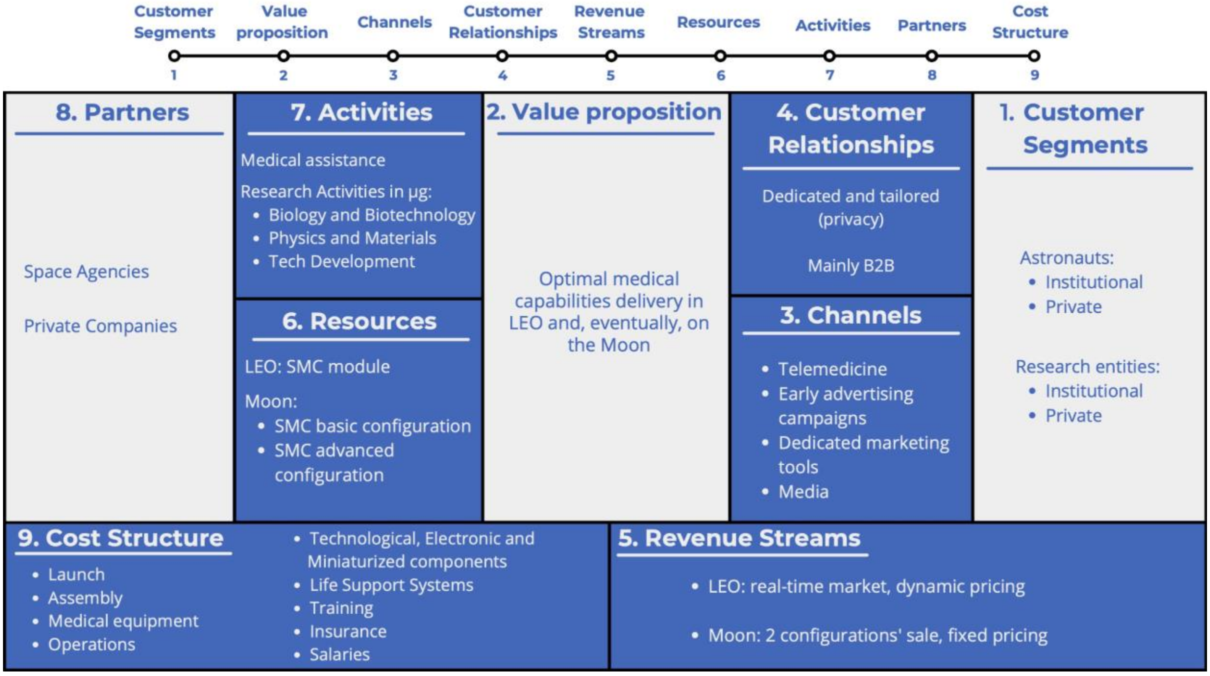
7.6.2 Research Revenues

As private facilities in LEO grow in number, so will competition. The best strategy in this regard would be to specialize in HPS and life science research in order to maximize the value of equipment developed for medical care, paying attention to tools with applications in both areas. Ultimately the pooling of resources in a single module should be enough to incentivize companies to prefer the SMC over another service provider. The price will take into consideration both the space occupied inside the module’s racks and the required hours necessary to operate it.

7.6.3 Lunar Revenues

It is hard to predict what will happen in the next 40+ years. While some aspects are given, such as the decrease in prices, it's difficult to quantify the entirety of the decrease over this period. Additionally, in transporting infrastructure onto another planetary body, other complications must be considered such as landing or constructing equipment. The estimated cost of a planetary module would be almost double an orbital module under current economic considerations. Business operations will likely be circumscribed to produce settling equipment for government agencies. The presence of business opportunities has yet to be ascertained, but a major opportunity would consequently create a cascade effect that would rapidly see a rise in infrastructure and the number of humans in space.

7.7 Non-linear Business Model Canvas Proposal



8. Partners

Space Agencies

Private Companies

7. Activities

Medical assistance

Research Activities in µg:
- Biology and Biotechnology
- Physics and Materials
- Tech Development

6. Resources

LEO: SMC module

Moon:
- SMC basic configuration
- SMC advanced configuration

2. Value proposition

Optimal medical capabilities delivery in LEO and, eventually, on the Moon

4. Customer Relationships

Dedicated and tailored (privacy)

Mainly B2B

3. Channels

- Telemedicine
- Early advertising campaigns
- Dedicated marketing tools
- Media

1. Customer Segments

Astronauts:
- Institutional
- Private

Research entities:
- Institutional
- Private

9. Cost Structure

- Launch
- Assembly
- Medical equipment
- Operations
- Technological, Electronic and Miniaturized components
- Life Support Systems
- Training
- Insurance
- Salaries

5. Revenue Streams

- LEO: real-time market, dynamic pricing
- Moon: 2 configurations' sale, fixed pricing

Figure 47: The Business Model Canvas elaboration followed the “Business Model Generation” sequence, proposed by Osterwalder and Pigneur in 2010.

1. Early customers will be limited to agency astronauts and space tourists. In the future, as space activities grow and new uses for space environments are discovered, space tourism will serve as the queue-opener to encourage businesses to set up their activities in LEO and beyond, leading to the creation of new jobs for highly trained workers.
2. Value proposition is to provide medical capabilities in LEO and beyond while operating a structure capable of carrying out research in a way that benefits space agencies and privates.
3. Customers can discover the SMC through targeted advertising and social media.
4. Relationships with the customers will be direct, dedicated, and personal to ensure optimal customer service and to ensure absolute privacy. Medical personnel will be trained to perform all relevant activities in space.
5. The SMC will offer several services in orbit, ranging from research to healthcare. Pricing strategies will follow a dynamic approach on a case-to-case basis. On the Moon, two configurations would be available according to the size of the settlement with fixed pricing.
6. The SMC will have three configurations: an attachable module for LEO, a settlement configuration for a planetary surface, or a section as an orbital gravity wheel. Each includes specialized medical equipment for space-related needs.
7. Proposed activities include medical assistance in space or on the Moon and multiple testbeds for different research activities in miniaturized laboratory environments.
8. Partners can be either private companies or space agencies and will facilitate the implementation of the mission.
9. Costs of the SMC-LEO will be similar to the ones associated with building and operating an ISS module. The costs of the Columbus module were analyzed since its size is comparable to the SMC-LEO. The planetary version is estimated to cost double that of the module version under the current economic values. However, technological developments may bring costs down.

7.8 Business Recommendations

Due to the international nature of space and existing regulations it’s unfeasible to run the facility at profit. The Outer Space Treaty (OST) requires the provision of assistance to astronauts in need and providing this care to later bill the astronaut or the agency, due to different medical practices in different countries, making a profit out of it could create attrition. It becomes more plausible if the assistance is provided at cost, as in the minimum amount of money necessary to keep the station running, as there is little to no reason why someone should be contrary to that. Additionally, putting too much stress on health risks - in order to justify a high cost of the service to make a profit- could actually impair the ability of space tourism companies to find customers, ultimately harming the whole space tourism sector.

As seen in the Investment section, investors in both the space and medical fields expect high returns in a relatively short time, so private funding is not a useful option from the point of view of the SMC. The best route to develop the center is to treat it as a PPP, with government agencies providing the initial funding to a 3rd party non-for-profit organization that will handle the maintenance of the SMC. Over its lifetime the center will be able to generate enough revenues to repay the investment and stay operational. Operating the SMC at cost is also very beneficial for Space Agencies, as private entities would be greatly incentivized to experiment with microgravity while at the same time maintaining an operative medical facility in orbit.

In conclusion, the reader is now acquainted with the business opportunities available through the SMC. The customers and suppliers to the SMC have been identified and the avenues for revenue through commercial research and space tourism have been explained. Also, a non-linear business model canvas was proposed, giving a well-rounded picture of the SMC business environment. Next, the policy, legal, and ethical considerations for the SMC shall be detailed.

8 Legal & Ethical Considerations

In this chapter, an analysis of the applicability of the main legal tools on the SMC is carried out. Ethical and religious considerations are also discussed, as well as health regulations for space tourism. As a second part, subchapters 8.4 and 8.5 present a proposal for a Memorandum of Understanding (MoU) as well as a code of conduct. These legal deliverables considering all the legal, ethical, business, and religious considerations discussed in the first part of the chapter.

8.1 Applicability of Treaties, Principles & Guidelines

The following legal analysis considers the various international space treaties, principle, and guidelines and their relevance to an SMC. After the applicability is discussed, key terms were identified. These key terms are later mentioned in the legal deliverables proposed at the end of this chapter. The applicability of these documents will depend on whether or not they have been ratified by the launching State. This analysis assumes all legal documentation has been appropriately ratified.

8.1.1 Treaties

1. The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (1967)

Also called the OST, it represents the legal basis of international space activities. This treaty applies to the SMC because it contains important principles such as:

- The use of outer space for peaceful purposes (Art. I)
- The freedom of scientific investigation (Art. I)
- The non-appropriation principle (Art. II)
- Non-weaponization principle (Art. IV)
- The international responsibility and liability for national activities in outer space of the Member States (Art. VI and VII)

- The jurisdiction of objects launched into outer space (Art. VIII)
- The commitment to conduct space activities avoiding harmful contamination of space, celestial bodies, and the Earth’s atmosphere (Art. IX)

2. Agreement on the Rescue of Astronauts, the Return of Astronauts, and the Return of Objects Launched into Outer Space (1968)

The Rescue Agreement was made to assist astronauts in case of accident, distress, or emergency, recognizing all astronauts as mankind's envoys in outer space. Since the mission and vision of the SMC go along the same core values, the Rescue Agreement represents the source of law to ensure human safety in space.

3. Convention on International Liability for Damage Caused by Space Objects (1972)

The Liability Convention (LIAB) serves as the legal basis to hold the States accountable for their operations in outer space and the consequences these might bring. It states the reasons to claim payment of compensation for damages and the procedures for the settlement of claims. It applies to the SMC, most likely to the first scenario. That an SMC located on the lunar surface could cause damage on the surface of the Earth or to aircraft in flight is much less likely. However, considering the launch as part of the mission of an SMC, then the damages become more probable.

4. Convention on Registration of Objects Launched into Outer Space (1975)

The Registration Convention ensures the identification of objects launched into space. It was intended as a legal tool that would assist affected States to be able to file a claim for compensation for damages. Within this legal framework, the SMC falls under consideration of the Registration Convention.

5. Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (1979)

The Moon Agreement is the most recent space treaty of the UN. This treaty deepens what is already established in the OST. It was made to safeguard the Moon and its use for peaceful goods, not militarization. It also gives the Moon and all its resources the status of common heritage of humankind. The establishment of an SMC on the lunar surface would be under the consideration of the Moon Agreement if the founding nations have signed and ratified the treaty.

6. Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space, and Underwater (1973)

The Partial Nuclear Test Ban Treaty (PNTBT) was signed under the political climate of the cold war. It was intended to prohibit any nuclear testing or explosion. In only five articles, it was established that the Nations that ratified this treaty should not undertake any nuclear testing or explosion in the atmosphere, in outer space, or underwater, including territorial waters or high seas. This treaty does not apply to the SMC because no nuclear source of weapon or energy is planned to be used in the project.

7. Convention Relating to the Distribution of Program-carrying Signals Transmitted by Satellite (1974)

The Brussels Convention or the Satellites Convention establishes the obligation of States to prevent unauthorized distribution of program-carrying signals transmitted by satellite in their territory or from it. This treaty does not apply to the SMC since no type of public transmission to or from it is planned. Outside of crew telemetry and communication with the SMC.

8.1.2 Principles

This section briefly introduces the international principles related to the operations of the SMC and discusses whether or not these principles apply. Principles do not create legal obligations and cannot be ratified. However, they often refer to or derive from international law.

1. Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space (1962)

The Outer Space Declaration is an agreement on how the exploration of outer space should be carried out. A common definition of the principles that should be followed when carrying out space activities. This Declaration settled the baselines for the future five treaties to come in the International space law. Given that these five treaties apply to the SMC, this declaration is also applicable to the project.

2. Principles Governing the Use by States of Artificial Earth Satellites for International Direct Television Broadcasting (1982)

The Direct Broadcasting Satellite Principles are several common principles on which the States have agreed on conducting the television broadcasting activities. These do not apply to the SMC given that it is not intended to broadcast television signals from it.

3. Principles Relating to Remote Sensing of the Earth from Outer Space (1986)

The Remote Sensing Principles built from Art. I of the OST. These fifteen principles explain how remote sensing activities shall be carried out through peaceful purposes. Specifically made for platforms carrying sensors to capture images from the Earth, they do not apply to the SMC.

4. Principles Relevant to the Use of Nuclear Power Sources In Outer Space (1992)

The Nuclear Power Sources Principles are eleven principles that comprise the PNTBT. They establish safe conduct of use for space objects that contain nuclear power sources. These do not apply to the SMC because it is not planned to use any kinds of nuclear power.

5. Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries (1996)

The Space Cooperation Declaration also referred to as the Space Benefits Declaration presents eight principles that have the intention of favor and encourage cooperation between nations in space activities. It was made to benefit all countries regarding their economic development. It deepens in the cooperation principles stated in the OST. These principles apply to the SMC since it is intended to be an international cooperation development.

8.1.3 Guidelines

This section presents the guidelines that relate to the SMC project. Likewise, it is briefly discussed whether or not said guidelines could be applicable for the project. UN Guidelines are not a legally binding document. However, it is stated that all member States and international organizations should take measures based on them on a voluntary basis.

1. Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space (2007)

Observing the growing and impending problem of space debris, the Committee on the Peaceful Uses of Outer Space (COPUOS) wrote these guidelines. They present near-term mitigation proposals, based on avoiding the production of debris by mission operations. Long-term mitigation guidelines are also presented based on advice on satellite de-orbiting (based on the size of the space objects to be deorbited). This document could apply to a project like the SMC. The proposed guidelines would have to be considered from the initial phases of the project, going through design, manufacturing, launch, operation, and of course disposal.

2. Safety Framework for Nuclear Power Source Applications in Outer Space (2009)

These guidelines are the result of a joint effort between the COPUOS and the International Atomic Energy Agency (IAEA). They integrate safety standards for the use of nuclear applications in outer space. It is not a legally binding document, but it is intended to provide voluntary guidance. This document does not apply to the SMC because it is not intended to use any kind of nuclear application.

3. Guidelines for the Long-term Sustainability of Outer Space Activities (2018)

The long-term sustainability guidelines were created to align space activities with the UN Sustainable Development Goals (SDGs). These voluntary guidelines define how to carry out space activities so that humanity can continue to carry them out for an indefinite period. They are a direct answer to the growing demand and development of space technologies.

Considering that the SMC is a project with different phases and bearing in mind that these phases will be carried out in the medium-term future, it is useful to follow these guidelines. With a sustainable development of space activities, it will be more likely that a project like the SMC can be carried out.

8.1.4 Key Term Identification

After reviewing the aforementioned principles, treaties and guidelines, several key terms are identified based on their relevance to the project and its scope. These key terms were the base of the legal deliverables presented at the end of this chapter, the MoU proposal and the Physician-patient Code of Conduct.

Key terms:
Utilization, registration, ownership, responsibility, collaboration, liability, funding, communications, data and good sharing, evolution, transportation, crew, intellectual property, health data protection, criminal law, withdrawal.

8.2 Space Tourism Health Regulations

Historically, only a small number of people have been to space. This is starting to shift to include more of the general population. Space tourism, however, is currently only targeting a small audience primarily consisting of wealthy people. New actors in space tourism are creating a new approach for holidays according to revenues linked to tourism. The new market has huge potential and is split in two different services: sub-orbital flights and orbital flights. These two markets are in two different development advancements. Regarding an SMC which will be into orbit or based in a settlement on a celestial body, the focus is on orbital flights in the space tourism market (King, 2020).

One of the main challenges regarding this sector is the development of safety and health standards and medical procedures for commercial passengers. No standard has been established yet for space tourists, unlike the crew and pilots of spacecraft vehicles who are selected based on rigorous medical standards. Despite these medical standards for the crew members, many health space-related problems still occur, and medical risks associated with untrained participants are still yet unknown due to the lack of investigation from a tourism perspective.

Being able to treat medical problems for space tourists in an off-Earth facility like an SMC could enhance not only the research and understanding of medical risks but the analysis of medical consequences and risk countermeasures in a space environment. Most of the knowledge we currently have involving medical health issues in space has been provided by astronauts who have attended specific training prior to their spaceflight and who know how to handle in-space medical situations. However, there has not been much research conducted on untrained participants since the medical impacts and health risks for these participants vary depending on orbital or sub-orbital flight. A majority of sub-orbital space flights have been performed by untrained participants, so some knowledge regarding untrained participants has been recorded (King, 2020). Sub-orbital flights and orbital flights present many different risks to humans from elements such as high speed, radiation, microgravity, and flight duration to name a few. The medical conditions required to participate in sub-orbital flights are less constraining than orbital flights, though further rules and guidelines, specifically medical regulations for orbital flight tourism and the establishment of an SMC, would need to be developed for in-orbit missions or settlements on celestial bodies.

Figure 48: Crew Dragon capsule. The first all exclusively private astronaut flight organized by Axiom Space will use the Crew Dragon capsule, owned by SpaceX (Parsons, 2019).

The Center of Excellence for Commercial Space Transportation produced standards and guidelines for sub-orbital flights as well as for orbital flights, but there is still uncertainty regarding the establishment of medical guidelines for the commercial space flight industry (Jennings et al., 2012). The Federal Aviation Administration (FAA) requires second class medical tests whereas some aerospace physicians consider these second-class medical tests unsuitable. Some interest groups have produced some medical guidelines for commercial spaceflight but there are currently no FAA documents available to the public which summarize these guidelines and standards. However, the standards and guidelines produced by the Center of Excellence for Commercial Space Transportation provide some insight. Commercial space companies will be able to use these guidelines through risk profiles and safety standards. Currently, participants taking part in commercial spaceflight are informed preflight about the risks and dangers that can accompany space travel. However, the information provided about risks and specific medical conditions is rather generic (Jennings et al., 2012). These guidelines were made into two sections, sub-orbital, and orbital spaceflight.

Figure 49: Example of sub-orbital flight vehicle: Virgin Galactic's SpaceShipTwo (Malik, 2016)

For the sub-orbital missions (Figure 49), it is assumed that accelerations will not exceed a certain amount of Gs. If the flight participant endures more Gs, they will have to pass certain medical tests required for orbital flights. Commercial spaceflight participants will also participate in only one flight per day. A questionnaire will need to be filled out by the participant and a physical examination will need to be carried by a physician (Jennings et al., 2012).

For the orbital missions, as with the sub-orbital flights, the guidelines from the Center of Excellence for Commercial Space Transportation state that the participant should not endure a maximum amount of G's in different flight phases such as acceleration, nominal re-entry, and ballistic re-entry. These guidelines assume that the spacecraft used would not dock with the ISS, and that no physician and minimal medical diagnosis would be available. The spacecraft would include only a minimal medical kit. The establishment of an SMC would provide the necessary medical assistance that is currently lacking for commercial participants. The time of spaceflight will also be limited depending on the medical condition of the participant. Regarding the radiation aspect, the guidelines assume that the radiation dosage experienced by the space tourist would not exceed the dosage an airline passenger would experience in one year. Therefore, an SMC, in LEO or on the Moon, would need to be equipped with radiation protection and medication to treat radiation to provide suitable countermeasures and mitigate radiation effects.

However, a mental health evaluation is also carried out to detect or prevent any psychological stressors that could lead to a risk of injury or death. Underlying behavioral problems is a critical issue which could lead to the endangerment of the participant if they don't have the ability to perform critical functions such as communications with other crew members and emergency procedures. The mental health evaluation should focus on psychiatric problems such as personality and anxiety disorders, depression, claustrophobia, and also on addictions and disorders in sleep and circadian rhythms.

8.3 Ethical and Religious Considerations and Protocols

As long duration space flights and exploration are a near-term objective for the space industry, it is essential to have an autonomous SMC in order to be able to treat the astronauts. In such a facility it will be important to study the role that ethics and religion play as part of human interactions. The importance of these disciplines imposes some constraints in the design and development of the SMC activities that have been identified. This chapter addresses the ethical and religious considerations of the SMC. In the case of an SMC on other celestial bodies such as the Moon, other types of mechanisms can also be performed such as the burial of the bodies underground or, cremation. However, these last two methodologies potentially implemented on the Moon would not be sustainable.

Human bodies contain different elements such as water and nitrogen. For this reason, the corpses could potentially be used to become soil to grow plants. This process has already been presented by the company *Recompose*. The company proposes to place the corpse in a vessel covered with wood chips (Figure 50), where thermophilic bacteria convert the remains into usable soil. This way, waste is minimized and CO_2 emissions that cremation would cause are prevented (Recompose, 2020). By using this methodology death could be seen as a new beginning. Additionally, the fact that plants and food could potentially grow from this soil would help human society to cope with death. A process like this on the lunar surface would contribute to the sustainability of the closed loop life support system and would also increase the relationship of humans with nature.

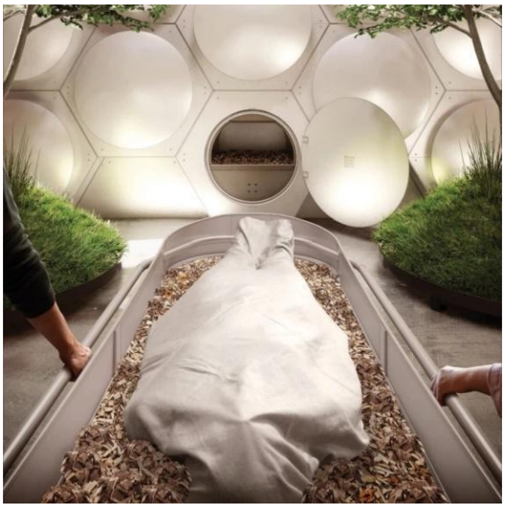


Figure 50: Ecologic method proposed by the company *Recompose* to turn a corpse into useful soil (Recompose, 2020).

Another issue to consider in the SMC is that treatments should respect the religious habits of others as much as possible, in the form of a mutual agreement. However, the agreement should also impose priorities and restrictions of the performance of religious habits and other medical tasks. In addition, religion might also influence the individuals' opinion on blood transfusion, withholding or withdrawing of life-sustaining therapy, analgesics and the use of medications that are produced using animals, gelatin, or alcohol (Al Husseini, 2011). Astronauts should be aware of the treatments and medicines they are using and should compromise to follow the physician's instructions regarding astronaut health.

Another factor that would be influenced by ethics on the SMC is resource limitation. Medical supplies are limited due to volume and launch restrictions. If resupply is not possible, the ethical point of view would be a constraint in the output of decisions, rules, and hierarchies of the rationalization of supplies (Pass, 2009). To mitigate a potentially negative outcome in the future of resource limitation, the crew members of the SMC shall follow a protocol that will address the possibility of resource limitation. A clear definition on the procedure for rationing of resources in case of resource limitation and unavailability of supplies would be required.

The ethical view on birth control should also be considered in the operations of the SMC. Pregnancy can be considered as a health risk factor in space. A suggested solution would be for crew members to willingly give up their fertility temporarily in order to decrease mission risk. However, in many cultures the right to reproduction is considered a fundamental freedom, which would cause an ethical constraint to the implementation of birth controls. For this reason, it is necessary for the crew members of the SMC to follow a birth control policy that treats and analyses the dangers and risks of pregnancy, giving birth, and treatments of newborn babies.

Finally, in an SMC, astronauts' data would be collected and analyzed in order to ensure their health, well-being, and safety. This would suppose a loss of confidentiality and brings the ethical concern towards the right to privacy and the disclosure and use of clinical data. As it has been mentioned in section 8.2.10, a policy should be implemented in order to consider and treat the extent at which astronauts allow themselves to be monitored and share their data and medical results publicly.

8.4 Space Medical Center Agreement Proposal (Memorandum of Understanding)

The following is the first of the two legal deliverables proposed in this chapter. It takes into consideration the key terms listed in Chapter 8.1, as well as the ethical and religious considerations earlier made. It applies them to the development and operation of an SMC. Pulling inspiration from the ISS Intergovernmental Agreement (IGA) (1998), the MoU is suited to the specific needs of the SMC.

8.4.1 Utilization

The utilization of the SMC must respect space international law, including the OST, the Moon Agreement, the Rescue Agreement, the LIAB & the Registration Convention, and must not in any way contravene in the aforementioned treaties. This Agreement does not modify duties and commitments of the Partners established in the aforementioned Treaties, rather it provides a complementary description of how exactly these principles apply to the SMC.

8.4.2 Registration

The SMC will have to have its components registered in the country in which the company building the components is based. If parts are built by several companies or in collaboration with space agencies ‘Partners’, each company or agencies is responsible for registering the components they supply (article II of Registration Convention). Some Partners in the center may regroup under one single Entity for the purpose of registering their components should they wish so (for example, Europeans may regroup under ESA just like they do for the ISS, other grouping may be envisaged). The country/countries, in which the company building the SMC is/are incorporated shall retain ‘jurisdiction & control’ over their components. These countries shall also retain ‘jurisdiction & control’ over their own nationals (article VIII of OST & article II of Registration Convention).

8.4.3 Ownership

Partners of the SMC will maintain ownership rights on components they provide and must communicate ownership claims to other partners (registration). Partners may register elements under one single organization (e.g. Europeans under ESA, several companies under one consortium). However, private entities are allowed to claim ownership title of elements of the center in their own name. The transfer of ownership of these elements is also permitted (whether to a public or private entity) but transfer of ownership must be communicated to Partners. Ownership or registration of components does under no circumstances give claim to ownership or registration of materials, goods or data emanating from activities undertaken on board the SMC (see Intellectual Property).

8.4.4 Responsibility

Partners share management responsibility for the SMC and their decision-making processes must include all Partners and aim to achieve decision making by consensus, unless specified otherwise by MOU defining specific delegation of responsibility between Partners. In the event the center is docked to another station (such as the ISS), management responsibility shall be extended to Partners of the docked station and each Partner oversees technical and design aspects of the components they supply. The Partners are deemed individually responsible for technical and design aspects of the components they supply and must cooperate with other Partners to ensure the overall design is coherent and harmonious.

8.4.5 Collaboration

Partners shall convene every year to assess and foster collaboration. Given some elements of the SMC may evolve over time, Partners are also bound to collaborate with each other, and are encouraged to make proposals, so long as they are congruous with the general project.

8.4.6 Liability and Liability Cross-Waiver

Unless specified differently, Partners are bound by the Liability Convention (LIAB). Should a dispute arise, Partners shall convene swiftly and assess possible occurrence, apportionment, and defense against such liability. They can negotiate accords relating to the apportionment of liability in the event of joint of multiple liability claims.

For the Liability Cross-Waiver, Partners shall agree to waive all claims against each other in the event damage occurs during Protected SMC Operations. This waiver applies to Protected SMC Operations and covers States, Private entities, and personnel, and requires that Partners waive all claims against entities or personnel in the event of damage (injury, death, damage, loss of revenue, other damages) occurring during Protected Operations.

Protected SMC Operations are defined as, but not limited to: Ground activities (testing, training, integration), launch activities

- Medical Center activities (medical, research, experimental, operations, maintenance)
- Transit activities (SMC displacement)
- In-space assembly
- In-space disassembly
- Decommissioning activities

This cross-waiver of liability is not applicable to intellectual property disputes, damage deemed to be an intentional wrongdoing, damage relating to a Partner and one of its related entities (e.g., suppliers), damage resulting in the deterioration of health or death of a natural person (this is covered by the Physician-Patient Code of Conduct).

8.4.7 Funding

Partners share the costs related to building and operating the SMC and also decide on the budget allocated to the center every seven years for a period of seven years. Additional funds may be voted every year to accommodate unforeseen necessary activities and the overall burden must be borne by all Partners in a fair fashion, but the Partners are free to organize themselves and decide how exactly they cover the costs of the SMC. The Partners shall contain costs of the center in order to respect the budget allocated and must also collect and supply funds for the SMC. Should a Partner face funding issues, it must promptly inform the other Partners, who may convene in order to assess the situation and decide on how to proceed in order to resolve the issue.

8.4.8 Communications

Two Partners/Entities shall be designated by vote to supply two main communications systems for the SMC, but supplementary communications systems are allowed, so long as they do not hinder the two main communications systems. The center shall maintain these two main communications systems at all time, even if/when it is docked to another station. The two Partners/Entities designated to supply the two main communications systems shall facilitate sharing of information to the other Partners/Entities and shall under no circumstances use their capacity as main communications suppliers to hinder communications of other Partners/Entities. Communications shall respect the principles laid out in the 'Sharing of Data & Goods' article.

8.4.9 Data and Goods Sharing

A Partner must transfer data & goods deemed to be requisite for the achievement of a Partner's responsibilities. Partners must process requests for data and goods presented by another Partner relating to SMC activities in a prompt and diligent manner. However, Partners are not required to process requests of data & goods in breach of its national legislation. The transfer of data and goods relating to SMC activities by one Partner to another is bound by the following restrictions:

- The providing Partner of data or goods must communicate which data or goods are subject to export control regulations and provide guidelines regarding how those data or goods may be utilized by the receiving Partner.
- Data or goods subject to export control regulations shall not be used by an entity or person other than the receiving Partner, prime contractors, and subcontractors.
- Data or goods subject to export control regulations shall not be used for any other purpose than that of conducting SMC activities.
- Data or goods subject to export control regulations shall not be used without previous authorization from the providing Partner

The providing Partner must indicate data or goods that are subject to proprietary rights and supply the receiving Partner and its contractors (prime and subcontractors) guidelines detailing how such data or goods can be used, manipulated, reproduced, divulged, and communicated. Should data or goods transferred be subject to some form of protection or secrecy, the providing Partner shall indicate such data or good and supply the receiving Partner and its contractors (prime and subcontractors) guidelines as to how such data or goods can be used, manipulated, reproduced, divulged and communicated. This transfer may involve a security of information agreement defining specific elements relating to the transfer, use, manipulation, reproduction, divulgation, and communication of such protected or sensitive information data or goods. Should the receiving Partner not be in a position to offer satisfactory conditions to the providing Partner for the transfer of data or goods subject to some form of protection or secrecy, then the transfer does not need to be enacted. Data or goods transferred subject to some form of protection or secrecy can only be transferred should both the providing and receiving Partner agree to it. The withdrawal of one Partner from this Agreement shall not impact aforementioned duties & commitments relating to transfers that have taken place before the withdrawal of the Partner.

8.4.10 Evolution

Partners & Entities recognize the evolutionary nature of the SMC and any evolution must respect the overall coherence/harmony of the project i.e., must be for medical purposes. One Partner/Entity shall be nominated by vote every seven years to oversee that any evolution respects the overall coherence/harmony of the SMC. Evolution must be subject to proposals (see ‘Collaboration’ article) and discussed between Partners as the Agreement does not impact rights, duties and commitments of Partners relating to future substantial evolutions.

8.4.11 Transportation and Crew

Partners & Entities are allowed to access the SMC by public or private transportation capabilities. Partners are also encouraged to share their transportation capabilities with each other (for material & personnel). Partners shall supply transportation capability for a return trip to another Partner if this Partner is in no position to secure transportation capabilities by itself. Transportation shall not impact in any way Intellectual Property or the Handling of Data & Goods. For the Crew, Partners & Entities are allowed to send their certified personnel to the SMC and the selection of certified personnel will be established in a separate agreement amongst Partners & Entities. Responsibility & ethical issues relating to medical aspects shall be addressed in a separate document.

8.4.12 Intellectual Property

The term 'intellectual property' is defined by Article 2 of the Convention Establishing the World Intellectual Property Organization (Stockholm, 14 July 1967) as an activity that is considered to have taken place in the territory of the Partner's State of the SMC s registry. Should there be several Partners registering the SMC under a single Entity, an activity is considered to have taken place in the overall territory of the Entity (e.g., Europe for ESA like in ISS, another geographic zone for an international private consortium). The two above paragraphs establish the location of the invention or discovery, which is a separate matter than intellectual property rights attached to such invention/discovery that could occur while undertaking activities onboard the SMC, these are covered in the following paragraphs. In the event a person's activities onboard the center results in an invention or discovery, the deemed location of the invention or discovery (determined by the previous paragraphs) shall not impact the intellectual property rights acquired by that person when filling for a patent application, which is a separate matter. In the event a person's activities onboard the SMC results in an invention or discovery, the person may fill patent applications in the countries or geographic zones of their choice (e.g., national patent offices, the International Patent Office). In the event a person's activities onboard the SMC results in an invention or discovery, and if the person is not a national from the country or geographic area (set of countries) in which the centers module is registered, the country of set of countries (represented under a single umbrella organization) shall not implement any measure (such as secrecy laws and restraining orders) aiming to prevent the person from filing patent application in the countries or geographic zones of the person's choice (e.g. national patent offices, the International Patent Office).

The above paragraph shall not impact the right of States in which a patent is filed to apply its laws and measures (such as secrecy laws and restraining orders) to the patent once it is filled on Earth. If and when Partners have regrouped under one single Entity, and own intellectual property rights in more than one national jurisdiction (because the Entity encompasses different national jurisdictions, e.g., different European countries under ESA or private companies under an international consortium); the Partners shall not attempt legal action against intellectual property rights violation in more than one such jurisdiction. Example: If ESA is an Entity composed of European Partners of the SMC, intellectual property rights protected by a European jurisdiction may not be retrieved in more than one European jurisdiction; similarly, if an American Canadian consortium is an Entity of the SMC, intellectual property rights protected by the American and/or Canadian jurisdiction may not be retrieved in more than one of these jurisdictions i.e. USA or Canada. If and when Partners have regrouped under one single Entity which is covered by several national jurisdictions (e.g., different European countries under ESA or private companies under an international consortium); no national jurisdiction included in this single Entity may refuse to grant intellectual property rights if those rights are granted in another national jurisdiction covering the same single Entity.

8.4.13 Health Data Protection

A specific Health Data Protection MoU will have to be agreed on by Partners of the SMC. As the US HIPAA (Health Insurance Portability and Accountability Act of 1996) is regarded as being too protective (Armstrong et al., 2005), the SMC could get inspiration from the EU GDPR (General Data Protection Regulation (2016)) and find the right balance between patient data protection and the right to big data sets for astronaut health.

8.4.14 Criminal Law

Partners can make use of criminal jurisdiction over their own nationals and in the event of wrongdoing resulting in harm, injury or death of a national of another Partner/Entity, or resulting in damage or destruction of components of another Partner/Entity, the jurisdiction of the victim Partner/Entity may consult with the jurisdiction of the purported offender and request to exercise its own jurisdiction on the purported offender, and:

- Upon acceptance by the jurisdiction of the purported offender, the jurisdiction of the victim may proceed with prosecution of the wrongdoer
- Upon rejection by the jurisdiction of the purported offender, the jurisdiction of the victim may not proceed with prosecution of the wrongdoer, unless the jurisdiction of the purported offender cannot guarantee the jurisdiction of the victim that it will assess the matter in the aim of prosecuting the purported offender.

8.4.15 Withdrawal

Withdrawal from this Agreement is possible, and the notice period is set to one year. Withdrawal of one Partner or Entity does not impact the duties and commitments of the remaining Partners and Entities and withdrawal of one Partner of a particular Entity (composed of several Partners) is carried out individually and does not trigger withdrawal of the other Partners of the Entity. In the event a Partner or Entity withdraws from the Agreement, the remaining Partners and Entities shall convene in order to secure the preservation of the SMC mission.

8.4.16 Lunar Medical Center Agreement Proposal (MOU)

In the event that the SMC is placed on the lunar surface (Scenario II), the SMC Agreement Proposal would take into account all the aforementioned elements and would also probably include extra articles specifically pertaining to extra care in respecting the Moon Agreement & the OST. For example, extra care would be needed to make sure the installation of a lunar base would not be seen as appropriation of the Moon’s territory. Also, there might be dispute between signatories of the Artemis Accord and the non-signatories, so an MoU should accommodate signatories and non-signatories. Vigilance would also need to be taken in ensuring no contamination of the Moon surface occurs. Shipment and use of material and medication could be a source of potential contamination of the lunar surface. Transport & waste disposal procedures will have to be undertaken in such a way that no contamination of the Moon’s surface occurs.

8.5 Physician-patient Code of Conduct

Here is presented the second of the two legal deliverables that are proposed for the SMC. In case of dealing with an SMC attached to the ISS, a Code of Conduct will need to agree with the ISS Medical Operations Requirements Document (MORD). In addition, it shall be exclusive to the medical operations on the SMC, and coordinated and approved by the Medical surgeons, Mission Operations, and the MMPB (NASA, 2003). Medical intervention aims to establish rules and behavioral conduct and is required. This code of conduct shall serve as a baseline to regulate the procedures and agreements in the medical operations.

The code of conduct implemented on the SMC shall establish a behavioral protocol and response to in-flight medical events. This document shall be revised by the Multilateral Medical Operations Panel (MMOP) and MMPB for potential modifications and updates. The main areas that the SMC code of conduct shall deal with are the following:

1. Physician-patient communication: The patient shall communicate all necessary information regarding their mental and physical health to the physician on board the SMC.

2. Physician objectivity: The physician in charge of the medical operations shall remain impartial towards their patients. They shall perform medical procedures and treatments based on their medical knowledge.

3. Medical risks: The physician shall be aware of all the medical challenges and risks that the tasks of each crewmember may induce.

4. Biomedical monitoring: Patients shall agree and commit to the monitoring of body parameters such as temperature, radiation exposure and heart rate. In addition, the patients shall agree that certain medical evaluations will be performed in order to adjust their medication and physical training.

5. Patient compromise: If a crew member wants to use the SMC medical facilities, they shall compromise to follow the SMC operations protocol and the orders and rules of the physicians responsible for the facility.

6. Rehabilitation: If a crew member requires rehabilitation treatments, the patient shall be eager to be under daily health status reports in order to assess the improvement of their condition. In addition, the patient shall be participative and communicative with the physicians.

7. Emergency treatment of a patient that has not agreed to have our services: The rescue agreement, which elaborates on article 5 and 8 of the OST states that “States shall take all possible steps to rescue and assist astronauts in distress and promptly return them to the launching State” (United Nations Office for Outer Space Affairs, 1968). According to this agreement, the SMC physician is obliged to provide its services to astronauts in an emergency situation even in the cases of astronauts that have not paid to be able to use the SMC services.

8.5.1 Physician Liability

In an SMC, the physician shall be responsible for the in-flight medical operations and crew members' health. The individual that follows this role shall have the responsibility to intervene in any scenario where the health of a crew member is at risk. All patients that want to have the SMC service shall fill a form agreeing and recognizing the dangers and risks that undertaking medical operations suppose. In case of a medical malpractice from the SMC physicians employed, an investigation shall be performed. This investigation would have the same steps and phases as an investigation on Earth and would require the confirmation of the professional relation physician-patient, proof of malpractice and testimonies.

8.5.2 Patient Obligations

Another factor that should be considered is whether or not it should be compulsory in an SMC for patients to obey the physician's orders. The role of the physicians on board of an SMC is to ensure that the crew health is not at risk. For this reason, it is clear that any essential medical procedure performed in order to avoid the endangerment of the crew health should be undertaken in a compulsory manner. However, other situations where the physician recommends a patient to follow a procedure that is not essential and does not suppose the endangerment of the crew health should be considered.

In this last case, the treatment or the performance of the procedure does not directly influence the crew risk. Therefore, in such scenarios, the individual rights and will of the patient shall be respected. The patient shall be able to decide whether or not wants to undergo the medical procedure, based on its needs. However, if the outcome of the medical procedure or treatment affects the mission objective or endangers the crew, the patient shall be obliged to follow the instructions of the physician. In order to ensure that patients follow the orders of the physicians, an agreement shall be signed by the patients in which they compromise to follow the physician's order in case of health risk or endangerment of the mission.

In conclusion, there are a multitude of legal and ethical factors to have been considered for the creation and operation of an SMC. This kind of entity does not yet have a legal precedent in space and therefore, though some factors of prior space treaties and agreements pertain to this situation, there are some that still need to be written. For example, the Memorandum of Understanding between patients and physicians at the SMC will be needed to breach the gap in policy and protection for both parties. Also, for the SMC, privacy of health information and protection of intellectual property are paramount. Patients must have protection for their personal safety and wellbeing and researchers need to have protection of their intellectual discoveries and creations. The SMC will need to safeguard both. The SMC also must meet the cultural and ethical needs of its patients, and staff. Several ethical considerations require adherence, such as the physician-patient relationship guidelines, and there are religious concerns, especially regarding death of a space traveler, that need to be respected. Now that the discussion of legal and ethical considerations has concluded, the discussion and recommendations from the entire document can be presented in the next section.

9. Discussion & Conclusion

The creation and maintenance of a medical center in space, whether in Earth orbit or beyond, carries with it an astounding amount of complexity. Relying on previous missions and established frameworks for medical care in space is helpful but fails to address all of the anticipated obstacles an SMC may face. For this reason, this report was broken down into three coherent sections in order to examine a sustainable human presence in LEO, on the lunar surface, and within a gravity producing environment.

An SMC-LEO has the benefit of being attached to ISS but is completely novel in its existence as its own dedicated module. For this reason, it is important for the design of the SMC to be based on known risks, but the creation of a novel interior to serve medical and research purposes must also be considered. Keeping in mind launch and mass constraints, a reasonable size was chosen to host emerging and tested medical equipment that can also support research in space. The efficient operation of an SMC hinges upon the utilization of sustainable and high throughput technologies, as well as simulating an Earth-like medical center to the greatest capacity. The impact of the research and constraints in this report is of the utmost importance for human survival in space. There are a number of recommendations in order for the SMC-LEO to function at the highest capacity.

1. **Establish a universally agreed upon legal framework.** Mission duration for astronauts continues to increase, as well as the number of private astronauts. Establishing a universally agreed upon legal framework, as well as a business model that includes healthcare, insurance, and the outsourcing of construction will result in an SMC that is effective, useful, and expandable into the future.

2. **Space agencies outsource research projects to private companies.** Because medical emergencies in the history of human spaceflight have been relatively rare, the vast majority of the time spent in the SMC-LEO will be dedicated to research activities. Space agencies' budgets can be limited by having to factor in everything from launch costs to astronaut salaries, which impedes the speed and funding of research endeavors. For this reason, it is recommended that space agencies outsource research projects to private companies. Both parties benefit, as the private entity can propose and develop an experiment to be done on the SMC-LEO, while the agency takes care of the transportation, and execution of the experiment. Both parties will benefit from sharing the data, as well as a reduction in cost.

3. **Construction and infrastructure be outsourced to private companies for the lunar surface.** As a foundation for medical care is built in LEO, it becomes increasingly important to examine the next step: habitation on the lunar surface. Whilst many aspects may remain the same, the environment is fundamentally different. Current medical data is based off of life in 1g or microgravity, but the novelty of ⅙g on the Moon changes how research and medical care is done. Further, the ability for resupply and evacuation to Earth is less of an option on the lunar surface, which greatly increases the impact of the aforementioned sustainability principles. Sustainability on the lunar surface will likely conflict with the harsh aspects of survival in a vacuum that can be both frigid, and scorching depending on the lunar cycle. This brings into question how the human psyche will deal with isolation, nutrient recycling, and death. Regardless, it is posited above that the ability to do specific activities such as surgery, and bioengineering will be aided by the gravity in the lunar environment. Specific challenges such as lunar dust, transportation to and from the lunar

settlement, and radiation shielding will need to be met with simple, yet futuristic technologies. Ultimately, a limitation of this aspect of the plan is the unknown reaction of human health to a partial gravity environment in the long term. Future research will seek to mitigate the musculoskeletal effects of partial gravity, detrimental effects of long-term isolation, and the structural challenges of living in a vacuum with enormous temperature gradients. Further, it is important to note that although space agencies are paving the way for lunar habitation as represented by the Artemis mission, it is recommended that construction and infrastructure be outsourced to private companies for the lunar surface. This can take the form of using a SpaceX Starship to transport raw buildings materials to the surface, or by supporting private robotic companies to search for water ice deposits for example. Partnerships like this lower costs, increase participation in space, and promote a sustainable human presence in space on a shorter timeline.

4. **Generate gravity in Earth orbit to allow for more medical procedures, cost reduction, promoting expansion, and reduce muscle/bone degeneration.** It is imperative to note that of the limiting factors of long duration missions in space, microgravity poses one of the largest threats. The future of a sustainable human presence in space should seek to not only adapt to microgravity, but to overcome it. The idea of producing gravity in space is not new and has been proposed before. The concept has largely been limited by the technology of the time, and a willingness to pursue the idea. With the advent of the Artemis program and the ultimate goal of creating a human settlement on Mars, producing gravity will be critical to human health, and thus medical operations in space. A gravity wheel that spins will be attractive on a commercial, research, and medical level, especially as designs can be tweaked to mimic the gravity of Mars, for example. This wheel will provide a training ground, as well as an important middle point for the research that has been done in space thus far. It is unknown at which level of gravity that human performance in space can be maximized, or at least result in the least number of alterations to the human body. Creating a middle point between microgravity and 1g is an important step forward to being able to answer that question more fully. Though futuristic, the effects of long-term missions in microgravity are too serious to ignore, and thus the future of deep space crewed missions will hinge upon the creation of partial gravity. As a headline, a spinning gravity wheel in space is flashy, but it is recommended to both private entities constructing it, and agencies participating in the gravity wheel that human safety is the paramount concern. This relies heavily on in-orbit robotic assembly to reduce human risk, as well as rigorous testing of the materials on earth. Although the initial duration of paying customers on the gravity wheel will likely be kept to a minimum due to cost, they should be subject to space agency-like training to ensure emergency protocols can be navigated, and the risk to human life is limited. Lastly, the gravity wheel may be an enormous expense, but there is a potential to limit expenditures by taking a real estate approach to the modules. Contracts for buying one, or many modules should have reciprocity in which modules can then be sold or leased after a set amount of time. This will help to attract commercial businesses, as well as generate capital for the gravity wheel. However, because human safety is paramount it is recommended the SMC on the gravity wheel have a dedicated number of modules equipped with the latest medical and research technology to keep humans safe aboard the vessel.

Following these proposed recommendations will result in a space medical center in three different environments that is uniquely adapted to operate at the highest efficiency. Human health in space is still the priority, and this set of recommendations will aid in maximizing human well-being.

Conclusion:

In sum, the SMC is proposed to be a swiss army knife for medical and research operations in space. Though medical data in space exists due to the ISS, a dedicated medical center designed specifically for supporting the future of both private and public astronauts, as well as research endeavors is yet to be developed. Due to the OST, nations and parties in space have an obligation to assist astronauts in space. With the number of citizens in space projected to increase due to the burgeoning space tourism industry, the necessity for an SMC to operate efficiently is paramount. There are a number of names in which the current era of spaceflight can be called. However, the common thread that weaves through each is that this era will be defined not by single nations or agencies with political agendas, but by cooperation and partnerships. This evolution is unfolding through the more transparent interaction of agencies, private industry, and society. No matter the name assigned to this era, human safety will always be paramount in space, which underscores how imperative the existence of a space medical center is. This being a novel proposal, this report is limited by a myriad of requirements, yet bolstered by decades of research in space. By approaching this report with three scenarios, the present, near future, and far future of humans’ presence in space has been detailed. The future of human spaceflight is continually evolving, but will rely on sustainable, and innovative practices in order to establish a permanent presence in LEO, the lunar surface, and beyond.

References

Afshinnekoo, E., Scott, R.T., MacKay, M.J., Pariset, E., Cekanaviciute, E., Barker, R., Gilroy, S., Hassane, D., Smith, S.M., Zwart, S.R., Nelman-Gonzalez, M., Crucian, B.E., Ponomarev, S.A., Orlov, O.I., Shiba, D., Muratani, M., Yamamoto, M., Richards, S.E., Vaishampayan, P.A., Meydan, C., Foox, J., Myrrhe, J., Istasse, E., Singh, N., Venkateswaran, K., Keune, J.A., Ray, H.E., Basner, M., Miller, J., Vitaterna, M.H., Taylor, D.M., Wallace, D., Rubins, K., Bailey, S.M., Grabham, P., Costes, S. V, Mason, C.E. and Beheshti, A., 2020. Fundamental Biological Features of Spaceflight: Advancing the Field to Enable Deep-Space Exploration. *Cell*, [online] 183(5), pp.1162–1184. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/33242416> [Accessed 6 Dec. 2020].
Al Husseini, D.I., 2011. The Implications of Religious Beliefs on Medical and Patient Care. *Master of Science in Organizational Dynamics Theses*, [online] 46, p.41. Available at: <http://repository.upenn.edu/od_theses_msod%0Ahttp://repository.upenn.edu/od_theses_msod/46>.

Antonsen, E.L., Mulcahy, R.A., Rubin, D., Blue, R.S., Canga, M.A. and Shah, R., 2018. Prototype development of a tradespace analysis tool for spaceflight medical resources. *Aerospace Medicine and Human Performance*, [online] 89(2), pp.108–114. Available at: <https://pubmed.ncbi.nlm.nih.gov/29463355/> [Accessed 12 Mar. 2021].

Arianespace, 2021. *Company profile - Arianespace*. [online] Available at: <https://www.arianespace.com/company-profile/> [Accessed 18 Feb. 2021].

Armstrong D, *et al.*, (2005) Potential impact of the HIPAA privacy rule on data collection in a registry of patients with acute coronary syndrome. *Arch Intern Med*. 165 (10): 1125–9.

Axiom Space, 2018. LEO Commercialization Concept. [online] Available at: <https://www.nasa.gov/sites/default/files/atoms/files/leo_commercialization_study_results.pdf> [Accessed 6 Mar. 2021].

Axiom Space, 2021. Meet Ax-1, The Beginning of a New Era. [online] Available at: <https://www.axiomspace.com/ax1> [Accessed 3 Mar. 2021].

Axiom Space, 2021. World's First Commercial Space Station. [online] Available at: <https://www.axiomspace.com/> [Accessed 10 Mar. 2021].

Ball, C.G., Kirkpatrick, A.W., Williams, D.R., Jones, J.A., Polk, J.D., Vanderploeg, J.M., Talamini, M.A., Campbell, M.R. and Broderick, T.J., 2012. Prophylactic surgery prior to extended-duration space flight: Is the benefit worth the risk? *Canadian Journal of Surgery*, 55(2), pp.125–131.

Bank of America Merril Lynch, 2017. *To Infinity and beyond - Global Space Primer*. [online] Available at: <https://scholar.google.com/scholar?q=To Infinity and beyond Global Space Primer> [Accessed 12 Mar. 2021].

Barger L., Flynn-Evans E., Kubey A., Walsh L., Ronda J., Wang W., Wright K. and Czeisler C., 2014. *Prevalence of Sleep Deficiency and Hypnotic Use Among Astronauts Before, During and After Spaceflight: An Observational Study*. [online] Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4188436/> [Accessed: 4 Feb. 2021].

Baylor College of Medicine, 2021. *Translational Research Institute*. [online] Available at: <https://www.bcm.edu/academic-centers/space-medicine/translational-research-institute> [Accessed 7 Feb. 2021].

BBC, 2021. China and Russia to build a lunar space station. [online] BBC News. Available at: <https://www.bbc.com/news/world-asia-china-56342311> [Accessed 10 Mar. 2021].

Becton-Dickson, 2021. *T34 Ambulatory Syringe Pump 3rd edition - BD*. [online] Available at: <https://www.bd.com/en-uk/products/infusion/infusion-devices/cme-ambulatory-infusion-systems/t-series-syringe-pumps/t34-ambulatory-syringe-pump-3rd-edition> [Accessed 6 Feb. 2021].

Berrios, D.C., Galazka, J., Grigorev, K., Gebre, S. and Costes, S. V., 2021. NASA GeneLab: Interfaces for the exploration of space omics data. *Nucleic Acids Research*, [online] 49(D1), pp.D1515–D1522. Available at: <https://pubmed.ncbi.nlm.nih.gov/33080015/> [Accessed 12 Mar. 2021].

Berrisford, C., 2018. *Longer Term Investments*. [online] Available at: <https://www.ubs.com/content/dam/WealthManagementAmericas/documents/space-p.pdf> [Accessed 12 Mar. 2021].

Blue, R.S., Bayuse, T.M., Daniels, V.R., Wotring, V.E., Suresh, R., Mulcahy, R.A. and Antonsen, E.L., 2019a. Supplying a pharmacy for NASA exploration spaceflight: challenges and current understanding. *npj Microgravity*, [online] 5(1). Available at: <http://dx.doi.org/10.1038/s41526-019-0075-2>.

Boeing and Bachman, 2020. *NASA Faults Boeing for 'Critical Software Defects' in Starliner - Bloomberg*. [online] Bloomberg. Available at: <https://www.bloomberg.com/news/articles/2020-02-07/nasa-lashes-boeing-for-starliner-software-flaws-in-test-flight> [Accessed 7 Dec. 2020].

Bradley Stoor, by J. and Col Peter Garretson Maxwell Air Force Base, L.A., 2018. *In-Space Manufacturing: A Roadmap to the Future.*

Braun, W. von, 1952. Man Will Conquer Space Soon: Crossing the Last Frontier. *Collier's Magazine*, [online] pp.24–29. Available at: <https://www.unz.com/print/Colliers-1952mar22-00024/>.

Bressan, S., Daverio, M., Martinolli, F., Dona', D., Mario, F., Steiner, I.P. and Da Dalt, L., 2013. The use of handheld near-infrared device (Infrascanner) for detecting intracranial haemorrhages in children with minor head injury. *Child's nervous system : ChNS : official journal of the International Society for Pediatric Neurosurgery*, [online] 30(3), pp.477–484. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/24232074> [Accessed 27 Feb. 2021].

Bretl, K.N. and Clark, T.K., 2020. Improved feasibility of astronaut short-radius artificial gravity through a 50-day incremental, personalized, vestibular acclimation protocol. *npj Microgravity*, [online] 6(1). Available at: </pmc/articles/PMC7450067/> [Accessed 26 Feb. 2021].

Calder, I. and Ramsey, J., 1983. Odontocrexis- the effects of rapid decompression on restored teeth. J Dent, 11(84), pp.318–23.

Canadian Space Agency, 2019. *Bio-Analyzer: Near-real-time biomedical results from space to Earth - Canada.ca*. [online] Health Science. Available at: <https://www.asc-csa.gc.ca/eng/iss/bio-analyzer.asp> [Accessed 25 Nov. 2020].

Carfagno, J., 2019. Robotic Surgery Systems. *DocWireNews*. [online] 15 May. Available at: <https://www.docwirenews.com/future-of-medicine/top-5-robotic-surgery-systems/>.

CBS News, 2008. *STS-122/ISS 1E Mission Archive*. [online] CBS News: Kennedy Space Center. Available at: <https://www.cbsnews.com/network/news/space/122/STS-122_Archive.html> [Accessed 12 Mar. 2021].
Ciurans, C., Bazmohammadi, N., Vasquez, J.C., Dussap, G., Guerrero, J.M. and Godia, F., 2021. Doğan, N., Topkaya, R., Subaşi, H., Yerli, Y. and Rameev, B., 2009. Development of Halbach magnet for portable NMR device. *Journal of Physics: Conference Series*, [online] 153(1), p.012047. Available at: <https://iopscience.iop.org/article/10.1088/1742-6596/153/1/012047> [Accessed 11 Dec. 2020].

Clément G., 2011. *Fundamentals of Space Medicine*. [e-book] El Segundo: Springer. Available through: ISU Library website <https://ebookcentral.proquest.com/lib/isulibrary-ebooks/reader.action?docID=770092&ppg=5> [Accessed: 5 Feb. 2021].

Clement, B.M., 2013. Crew Health Care System (CHeCS) Design Research, Documentations, and Evaluations. [online] Available at: <https://ntrs.nasa.gov/citations/20110011351> [Accessed 27 Feb. 2021].

Clément, G., Bukley, A. and Paloski, W., 2007. History of Artificial Gravity. In: *Artificial Gravity*. [online] New York: Springer New York.pp.59–93. Available at: <https://link.springer.com/chapter/10.1007/0-387-70714-X_3> [Accessed 25 Feb. 2021].

Clinton, R.G., 2014. The Road to Realizing In-space Manufacturing (Powerpoint slides). Available at: <file:///C:/Users/Amy/Downloads/20140008760.pdf > [Accessed 01 Feb. 2021].

COPUOS and IAEA, 2009. *Safety Framework for Nuclear Power Source Applications in Outer Space*. Vienna.

Cramer, A., Hecla, J., Wu, D., Lai, X., Boers, T., Yang, K., Moulton, T., Kenyon, S., Arzoumanian, Z., Krull, W., Gendreau, K. and Gupta, R., 2018. Stationary Computed Tomography for Space and other Resource-constrained Environments. *Scientific Reports*, [online] 8(1), pp.1–10. Available at: <www.nature.com/scientificreports> [Accessed 26 Feb. 2021].

Daniels, V., Bayuse, T., Mulcahy, R., McGuire, K. & Antonsen, E., 2017. The pathway to a safe and effective medication formulary for exploration spaceflight. Tech. Rep. 13658, Proceedings of the NASA Human Research Program Investigator Workshop (2017).

DLR, 2018. Data and modules - DLR Portal. [online] Available at: <https://www.dlr.de/content/en/articles/missions-projects/iss/iss-data-modules.html> [Accessed 3 Mar. 2021].

Drudi, L. and Grenon, S.M., 2014. *Women's health in spaceflight*. *Aviation Space and Environmental Medicine*, Available at: <https://www.researchgate.net/publication/262582064_Women's_Health_in_Spaceflight> [Accessed 6 Feb. 2021].

EDI, 2017. Once more to the moon — NASA may use a commercial rocket to speed up the EM-1 moon mission planned for June 2020 - *EDI Weekly: Engineered Design Insider*. [online] Available at: <https://www.ediweekly.com/once-more-to-the-moon-nasa-may-use-a-commercial-rocket-to-speed-up-the-em-1-moon-mission-planned-for-june-2020/> [Accessed 18 Feb. 2021].

ESA, 1999. Columbus: Europe's Laboratory on the International Space Station - BR144. [online] European Space Agency, Directorate of Manned Spaceflight and Microgravity. Available at: <http://www.estec.esa.nl/spaceflight/> [Accessed 12 Mar. 2021].

ESA, 2008. *Technology Readiness Levels Handbook for Space Apllications*. [online] Available at: <https://artes.esa.int/sites/default/files/TRL_Handbook.pdf> [Accessed 10 May 2021].

ESA, 2021. *ISS: Columbus Module*. [online] EO Portal Directory. Available at: <https://earth.esa.int/web/eoportal/satellite-missions/i/iss-columbus> [Accessed 12 Mar. 2021].

European Union (2016) *The General Data Protection Regulation* 2016/679 (GDPR)
Fernholtz, T., 2019. Virgin Galactic goes public with Social Capital Hedosophia. [online] Quartz. Available at: <https://qz.com/1662061/richard-bransons-virgin-galactic-goes-public-with-social-capital-hedosophia/> [Accessed 3 Mar. 2021].

Fioravanti, 2021. *Optical coherence tomography - OCT*. [online] Ophthalmology Surgery Center Fioravanti. Available at: <https://www.fioravantioculista.it/en/portfolio-articoli/optical-coherence-tomography/> [Accessed 27 Feb. 2021].

Free3D, 2021. ISS Module - Destiny 3D Model. [online] Available at: <https://free3d.com/3d-model/iss-module-destiny-677.html> [Accessed 18 Feb. 2021].

Ghamari, H. and Amor, C., 2016. *The Role of Color in Healthcare Environments*, Emergent Bodies of Evidence-based Design Approach. Sociology and Anthropology, [online] 4(11), pp.1020–1029. Available at: <http://www.hrpub.org>. [Accessed 30 Nov. 2020].

Gilbert, R., Torres, M., Clemens, R., Hateley, S., Hosamani, R., Wade, W. and Bhattacharya, S., 2020. Spaceflight and simulated microgravity conditions increase virulence of Serratia marcescens in the Drosophila melanogaster infection model. *npj Microgravity*, [online] 6(1), pp.1–9. Available at: <https://doi.org/10.1038/s41526-019-0091-2> [Accessed 11 Mar. 2021].

Gilles C., Klaus S., 2005. Fundamentals of Space Biology. *Research on Cells, Animals, and Plants in Space*. P13-26

Goldman Sachs, 2017. *Profiles in Innovation: The next investment frontier*. [online] Equity Research. Available at: <https://www.coursehero.com/file/36950158/Goldman-Sachs-Spacepdf/> [Accessed 12 Mar. 2021].

Haidegger, T., Sándor, J. and Benyó, Z., 2011. Surgery in space: The future of robotic telesurgery. *Surgical Endoscopy*, 25(3), pp.681–690.

Haruyama, J., Morota, T., Kobayashi, S., Sawai, S., Lucey, P.G., Shirao, M. and Nishino, M.N., 2013. lunar holes and lava tubes as resources for lunar science and exploration. In: *Moon: Prospective Energy and Material Resources*. [online] Springer-Verlag Berlin Heidelberg.pp.139–163. Available at: <https://link.springer.com/chapter/10.1007/978-3-642-27969-0_6> [Accessed 20 Feb. 2021].

Henderson, E.M. and Holderman, M.L., 2011. Technology applications that support space exploration. In: *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit 2011*. [online] pp.1–21. Available at: <https://www.researchgate.net/publication/266163759_Technology_Applications_that_Support_Space_Exploration> [Accessed 26 Feb. 2021].

Hills, B.P., Wright, K.M. and Gillies, D.G., 2005. A low-field, low-cost Halbach magnet array for open-access NMR. *Journal of Magnetic Resonance*, [online] 175(2), pp.336–339. Available at: <https://pubmed.ncbi.nlm.nih.gov/15935715/> [Accessed 11 Dec. 2020].

Hodapp, M. and Jeske, A., 2019. Chap. 29 - Dental Considerations. In: M.R. Barratt, E. Baker and S. Pool, eds. *Principles of Clinical Medicine for Space Flight*, 2nd ed. pp.861–884.

Hodkinson, P.D., Anderton, R.A., Posselt, B.N. and Fong, K.J., 2017. *An overview of space medicine*. [online] *British Journal of Anaesthesia*, The Author(s). Available at: <http://dx.doi.org/10.1093/bja/aex336>.

Huang, P., Russell, A.L., Lefavor, R., Durand, N.C., James, E., Harvey, L., Zhang, C., Countryman, S., Stodieck, L. and Zubair, A.C., 2020. Feasibility, potency, and safety of growing human mesenchymal stem cells in space for clinical application. *npj Microgravity*, [online] 6(1), pp.1–12. Available at: <https://doi.org/10.1038/s41526-020-0106-z> [Accessed 26 Feb. 2021].

Huang, P., Zhang, F., Chen, L., Meng, Z., Zhang, Y., Liu, Z. and Hu, Y., 2018. A review of space tether in new applications. *Nonlinear Dynamics*, 94(1), pp.1–19.

Hugon, C., Aguiar, P.M., Aubert, G. and Sakellariou, D., 2010. Design, fabrication and evaluation of a low-cost homogeneous portable permanent magnet for NMR and MRI. *Comptes Rendus Chimie*, 13(4), pp.388–393.

InfraScan, I., 2021. Infrascanner-White Paper A Handheld Brain Hematoma Detector Executive Summary. [online] Available at: <https://infrascanner.com/wp-content/uploads/2020/05/Infrascanner-white-paper-03.2020.pdf> [Accessed 27 Feb. 2021].

Institute of Medicine (IOM), 2001. *Safe Passage: Astronaut Care for Exploration Missions.* [online] Washington, DC: The National Academies Press. Available at: <https://doi.org/10.17226/10218.>.

ISSAP, 2019a. *International Avionics System Interoperability Standards (IASIS)*.

ISSAP, 2019b. *International Thermal System Interoperability Standards (ITSIS)*.

Jain, V., Ploutz-Snyder, R., Young, M., Charvat, J.M. and Wotring, V.E., 2020. Potential venous thromboembolism risk in female astronauts. *Aerospace Medicine and Human Performance*, 91(5), pp.432–439.

Jennings, R., Vanderploeg, J., Antunano, M. and Davis, J., 2012. *Flight Crew Medical Standards and Spaceflight Participant Medical Acceptance Guidelines for Commercial Space Flight*. [online] Available at: <https://spacemedicineassociation.org/download/commercial_space_flight_medical_care_documents/COE-Commercial-Space-Flight-2012.pdf> [Accessed 12 Nov. 2020].

JPL, 2020. NASA's Cold Atom Lab Takes One Giant Leap for Quantum Science. [online] Jet Propulsion Laboratory. Available at: <https://www.jpl.nasa.gov/news/nasas-cold-atom-lab-takes-one-giant-leap-for-quantum-science> [Accessed 10 Mar. 2021].

Kalapodis, N., Kampas, G. and Ktenidou, O.J., 2020. *A review towards the design of extraterrestrial structures: From regolith to human outposts*. *Acta Astronautica*, .

Kanas N. and Manzey D., 2008. *Space Psychology & Psychiatry*. [e-book] El Segundo: Springer. Available through: ISU Library website <https://isulibrary.isunet.edu/index.php?lvl=notice_display&id=10274> [Accessed: 5 Feb. 2021].

Kanas N., 2015. *Psychology in Deep Space*. [online] Available at: <https://thepsychologist.bps.org.uk/volume-28/october-2015/psychology-deep-space> [Accessed: 2 Feb. 2021].

Kashani, A.H., Chen, C.L., Gahm, J.K., Zheng, F., Richter, G.M., Rosenfeld, P.J., Shi, Y. and Wang, R.K., 2017. *Optical coherence tomography angiography: A comprehensive review of current methods and clinical applications*. *Progress in Retinal and Eye Research*, Available at: <https://pubmed.ncbi.nlm.nih.gov/28760677/> [Accessed 27 Feb. 2021].

Keller, T.S. and Strauss, A.M., 1993. *Bone loss and human adaptation to lunar gravity*. Report N93-I4002. In: NASA2nd Conference on Lunar Bases and Space Activities. NASA, Houston, TX.

Kelly, S. and Cryan, S.P., 2016. *International Docking Standard (IDSS) Interface Definition Document (IDD) . Revision E*. [online] Available at: <https://www.internationaldockingstandard.com/download/IDSS_IDD_Revision_E_TAGGED.pdf>.

Kelly, S., 2017. Astronaut Scott Kelly on the devastating effects of a year in space. [online] The Sydney Morning Herald. Available at: <https://www.smh.com.au/lifestyle/astronaut-scott-kelly-on-the-devastating-effects-of-a-year-in-space-20170922-gyn9iw.html> [Accessed 28 Feb. 2021].

King, A.K., 2020. *The Future of Space Tourism*. [online] Available at: <https://crsreports.congress.gov> [Accessed 11 Nov. 2020].

Krebs, G., 2019. DC 1 (SO 1, Pirs, Progress-M-SO 1) / MRM 2 (Poisk, Progress-M-MIM). [online] Gunter's Space Page. Available at: <https://space.skyrocket.de/doc_sdat/dc-1.htm> [Accessed 3 Mar. 2021].

Kuypers, M.I., 2013. Emergency and wilderness medicine training for physician astronauts on exploration class missions. *Wilderness and Environmental Medicine*, 24(4), pp.445–449.

Lee, A.G., Mader, T.H., Gibson, C.R., Tarver, W., Rabiei, P., Riascos, R.F., Galdamez, L.A. and Brunstetter, T., 2020. *Spaceflight associated neuro-ocular syndrome (SANS) and the neuro-ophthalmologic effects of microgravity: a review and an update*. *npj Microgravity*, Available at: <https://pubmed.ncbi.nlm.nih.gov/32047839/> [Accessed 6 Dec. 2020].

Lee, P. and McDonald, R., 2018. *Possible Lava Tube Skylights Discovered Near the North Pole of the Moon*. [online] SETI Institute. Available at: <https://www.seti.org/press-release/possible-lava-tube-skylights-discovered-near-north-pole-moon> [Accessed 20 Feb. 2021].

Leven, J., Burschka, D., Kumar, R., Zhang, G., Blumenkranz, S., Dai, X., Awad, M., Hager, G.D., Marohn, M., Choti, M., Hasser, C. and Taylor, R.H., 2005. DaVinci Canvas: A telerobotic surgical system with integrated, robot-assisted, laparoscopic ultrasound capability. In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. [online] Med Image Comput Comput Assist Interv.pp.811–818. Available at: <https://pubmed.ncbi.nlm.nih.gov/16685921/> [Accessed 14 Dec. 2020].

Levis, L., 2016. *Harvard's Wyss Institute has developed organs-on-chips to transform drug testing*. [online] Harvard Magazine. Available at: <https://harvardmagazine.com/2015/12/mimicking-organs> [Accessed 11 Mar. 2021].

Lou, L., Jiang, Z., Zhang, Q., Liu, D., Zhou, Y., Zhang, K., He, R., Fan, J., Yan, H. and Yang, W., 2019. Phase change microcapsules with lead tungstate shell for gamma radiation shielding and thermal energy storage. *International Journal of Energy Research*, [online] 43(14), pp.8398–8409. Available at: <https://onlinelibrary.wiley.com/doi/abs/10.1002/er.4838> [Accessed 23 Feb. 2021].

Mains, R., Reynolds, S. and Baker, T., 2015. *A Researcher's Guide to: Cellular Biology*. [online] Available at: <https://www.nasa.gov/sites/default/files/atoms/files/np-2015-03-018-jsc_cellular_biology-iss-mini-book-508.pdf>.

Malik, T., 2016. Virgin Galactic's SpaceShipTwo Unity Takes 1st Flight with Mothership. [online] Space. Available at: <https://www.space.com/34025-virgin-galactic-spaceshiptwo-unity-first-mothership-flight.html> [Accessed 7 Mar. 2021].

Mankins, J.C. and Mankins, W.M., 2020. Biological Requirements for a Sustainable Settlement on Earth's Moon. In: *Proceedings of the International Astronautical Congress, IAC*. [online] pp.1–8. Available at: <https://iafastro.directory/iac/paper/id/59630/summary/>.

Mansfield, C.L.M., 2021. *NASA - Columbus Leaves Europe, Heads for America*. [online] Available at: <https://www.nasa.gov/mission_pages/station/structure/Columbus_module.html> [Accessed 18 Feb. 2021].

Manzey D., Schiewe A. and Fassbender C., 1995. *Psychological Countermeasures for Extended Manned Spaceflight*. [pdf] Available at: <https://www.sciencedirect.com/science/article/abs/pii/009457659598736S> [Accessed 2 Feb. 2021].

Mason, C. E,. 2021. The Impact of Spaceflight on the Human Body and Preparing for Mars (PowerPoint slides).

McPherson, A. and Delucas, L.J., 2015. Microgravity protein crystallization. *npj Microgravity*, [online] 1(1), pp.1–20. Available at: <www.nature.com/npjmgrav> [Accessed 12 Mar. 2021].

Mental Health America, 2021. *Medication*. [online] Available at: <https://www.mhanational.org/medication> [Accessed: 4 Feb. 2021].

Michelessi, M., Lucenteforte, E., Oddone, F., Brazzelli, M., Parravano, M., Franchi, S., Ng, S.M. and Virgili, G., 2015. *Optic nerve head and fibre layer imaging for diagnosing glaucoma*. *Cochrane Database of Systematic Reviews*, Available at: <https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD008803.pub2/full> [Accessed 27 Feb. 2021].

Moleti, A., Zompanti, A., Sanjust, F., D'Amico, A., Pennazza, G., Trichilo, M., Orlando, M.P., Cerini, L., Deffacis, M., Santonico, M., Sisto, R. and Crisafi, A., 2019. Is there a risk for the astronauts' hearing in a microgravity environment? the Acoustic Diagnostics experiment on board the ISS. In: *Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019*. Genova, Italy: Institute of Electrical and Electronics Engineers Inc.

Morgan Stanley, 2017. *A New Space Economy on the Edge of Liftoff*. [online] Available at: <https://www.morganstanley.com/Themes/global-space-economy> [Accessed 12 Mar. 2021].

Morgan Stanley, 2020. Space: Investing in the final frontier. [online] Available at: <https://www.morganstanley.com/ideas/investing-in-space>.

Narici, L., Casolino, M., Di Fino, L., Larosa, M., Picozza, P., Rizzo, A. and Zaconte, V., 2017. Performances of Kevlar and Polyethylene as radiation shielding on-board the International Space Station in high latitude radiation environment /639/166/984 /639/766/25 /128 article. Scientific Reports, [online] 7(1), pp.1–11. Available at: <www.nature.com/scientificreports/> [Accessed 22 Feb. 2021].

NASA, 2019a. NASA Interim Directive (NID): Use of international Space Station (ISS) for Commercial and Marketing Activities. [online] Human Exploration and Operations Mission Directorate. Available at: <https://nodis3.gsfc.nasa.gov/OPD/OPD> [Accessed 3 Mar. 2021].

NASA, 2019b. Commercial and Marketing Pricing Policy. [online] Available at: <http://www.nasa.gov/leo-economy/commercial-use/pricing-policy> [Accessed 11 May 2021].

NASA, 2013. Information Summaries Astronaut Fact Book. [online] Available at: <www.nasa.gov/centers/johnson/about/resources/jscfacts/index.html>.

NASA, 2006. Medical Operations Requirements Document (ISS MORD) International Space Station Program. National Aeronautics and Space Administration, Johnson Space Center, Houston, TX.

NASA, 2021a. Human Research Roadmap - Risks. [online] Available at: <https://humanresearchroadmap.nasa.gov/Risks/> [Accessed 29 Jan. 2021].

NASA, 2021b. Risk of Adverse Health Outcomes & Decrements in Performance due to inflight Medical Conditions. [online] HRR - Risk. Available at: <https://humanresearchroadmap.nasa.gov/risks/risk.aspx?i=95> [Accessed 14 Dec. 2020].

NASA, 2021c. Shuttle-Mir History/Science/Life Support Risk Mitigation/Crew Medical Restraint System (CMRS). [online] Available at: <https://spaceflight.nasa.gov/history/shuttle-mir/science/lsrm/sc-lsrm-cmrs.htm> [Accessed 6 Feb. 2021].

NASA, 2021d. Oxygen Delivery System. [online] Available at: <https://lsda.jsc.nasa.gov/Experiment/exper/13605> [Accessed 23 Feb. 2021].

NASA, 2021e. The International Space Station Advanced Resistive Exercise Device. [online] Available at: <https://technology.nasa.gov/patent/MSC-TOPS-59> [Accessed 24 Feb. 2021].

NASA, 2021f. NASA - COLBERT Ready for Serious Exercise. [online] Space Station. Available at: <https://www.nasa.gov/mission_pages/station/behindscenes/colberttreadmill.html> [Accessed 26 Feb. 2021].

NASA, 2021g. Space Station Research Explorer on NASA.gov. [online] Available at: <https://www.nasa.gov/mission_pages/station/research/experiments/explorer/> [Accessed 18 Feb. 2021].

NASA, 2021h. Budget Documents, Strategic Plans and Performance Reports. [online] Available at: <https://www.nasa.gov/news/budget/index.html> [Accessed 12 Mar. 2021].

NASA, 2020a. Development of Predictive Degradation Models and Determination of Bioequivalence of Pharmaceutical Preparations Contained in the Medical Kits on Board the International Space Station. [online] Available at: <https://humanresearchroadmap.nasa.gov/Tasks/task.aspx?i=2131> [Accessed 11 May 2021].

NASA, 2020b. FDA Comprehensive Stability Evaluation of Three Medications. [online] Available at: <https://humanresearchroadmap.nasa.gov/Tasks/task.aspx?i=1352> [Accessed 11 May 2021].

NASA, 2011a. Psychology of Space Exploration. [pdf] Available at: <https://www.nasa.gov/pdf/607107main_PsychologySpaceExploration-ebook.pdf> [Accessed: 4 Feb. 2021].

NASA Office of Safety and Mission Assurance, 2011b. NASA Technical Standard: Process for Limiting Orbital Debris. [online] pp.53–54. Available at: <https://standards.nasa.gov/sites/default/files/standards/NASA/PUBLISHED/A/nasa-std-8719.14.pdf>.

NASA, 1995. Man-Systems Integration Standards (MSIS) Volume I: Architecture. [online] Available at: <https://msis.jsc.nasa.gov/Volume1.htm> [Accessed 12 Mar. 2021].

NASA, 2005. SSP 50260 (Revision C Draft 6.1 August 2005) International Space Station Medical Operations Requirements Document (ISS MORD) International Space Station Program. Johnson Space Center, Houston, TX.

NASA, ESA and JAXA, 2015. Pressurized Payloads Interface Requirements Document International Space Station Program SSP 57000. [online] Available at: <https://ntrs.nasa.gov/search.jsp?R=20190001390> [Accessed 24 Feb. 2021].

NASA, 2015a. External Payloads Proposer's Guide to the International Space Station. [online] Available at: <http://espd.gsfc.nasa.gov/isseppg/> [Accessed 10 May 2021].

NASA, 2007. NASA Space Flight Human System Standard Volume 1. [online] Available at: <https://standards.nasa.gov/sites/default/files/nasa-std-3001_vol1.pdf> [Accessed 22 Feb. 2021].

NASA, 2016a. International Space Station Independent Safety Task force. 4(1), pp.64–75.

NASA, 2016b. Space Network (SN). [online]. Available at: <http://www.nasa.gov/directorates/heo/scan/services/networks/sn> [Accessed 8 Feb. 2021].

NASA, 2017a. Tracking and Data Relay Satellite (TDRS). [online]. Available at: <http://www.nasa.gov/directorates/heo/scan/services/networks/tdrs_main> [Accessed 8 Feb. 2021].

NASA, 1977. Space Settlements: A Design Study. [online] Available at: <http://large.stanford.edu/courses/2016/ph240/martelaro2/docs/nasa-sp-413.pdf>.

NASA, 2003. International Space Station Medical Operations Requirements Documents (ISS MORD) SSP 50260. Houston, TX.

National Bureau of Standards, 1978. *Color in the Health Care Environment*. Washington, D.C.

Newkirk, R.W. and Ertel, I.D., 1977. *NASA SP-4011 SKYLAB : A Chronology*. National Aeronautics and Space Administration, Washington, DC.

Nicogossian, A.E., Williams, R.S., Huntoon, C.L., Doarn, C.R., Polk, J.D. and Schneider, V.S., 2016. *Space physiology and medicine: From evidence to practice, fourth edition*. *Space Physiology and Medicine: From Evidence to Practice, Fourth Edition*.

NOAA, 2010. *NOAA Ocean Explorer: Deep Sea Medicines*. [online] Available at: <https://oceanexplorer.noaa.gov/explorations/03bio/background/microbiology/media/figure_03.html> [Accessed 11 Mar. 2021].

Northern Sky Research, 2020. *Supply, not the Sky, is the Limit for Space Tourism*. [online] Available at: <https://www.nsr.com/supply-not-the-sky-is-the-limit-for-space-tourism/> [Accessed 10 Mar. 2021].

Northon, K., 2019. NASA Opens International Space Station to New Commercial Opportunities. NASA. [online] Available at: <http://www.nasa.gov/press-release/nasa-opens-international-space-station-to-new-commercial-opportunities-private> [Accessed 8 Dec. 2020].

O'Neill, G.K., 1974. The colonization of space. *Physics Today*, [online] 27(9), pp.32–40. Available at: <http://physicstoday.scitation.org/doi/10.1063/1.3128863> [Accessed 26 Feb. 2021].

Onofri, S., Selbmann, L., de Hoog, G.S., Grube, M., Barreca, D., Ruisi, S. and Zucconi, L., 2007. Evolution and adaptation of fungi at boundaries of life. Advances in Space Research, 40(11), pp.1657–1664.

Osterwalder, A. and Pigneur, Y., 2010. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*.

Pass, J., 2009. Medical Astrosociology: Ethical Dilemmas in Space Environments. *AIAA Space 2009 Conference and Exposition*.

Pease, R., 2003. *Medical Dictionary*. USA: Merriam-Webster.

Philips Healthcare, 2021. *IntelliVue X3 Patient monitor*. [online] Available at: <https://www.usa.philips.com/healthcare/product/HC867030/intellivue-x3-patient-monitor> [Accessed 6 Feb. 2021].

Plush, L.M., 2003. Origins, founding, and activities of the Space Nursing Society. Journal of Pharmacy Practice, . Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners. *Office*, [online] (December), p.323. Available at: <http://www.hq.nasa.gov/office/codeq/doctree/praguide.pdf>.

Putcha, L., Taylor, P.W. and Boyd, J.L., 2011. *Biopharmaceutical challenges of therapeutics in space: Formulation and packaging considerations*. *Therapeutic Delivery*.

Quanterix, 2021. *The Top 5 Reasons We Love Biomarkers*. [online] Available at: <https://www.quanterix.com/the-top-5-reasons-we-love-biomarkers/> [Accessed 12 Mar. 2021].

Rainey, K., 2015. ISS Benefits For Humanity: Hope Crystallizes. [online] Available at: <http://www.nasa.gov/mission_pages/station/research/news/crystals> [Accessed 10 Mar. 2021].

Recompose, 2020. *Ecological Death Care*. [online] Available at: <https://recompose.life/> [Accessed 21 Feb. 2021].

Reichter, M., 2001. The Future of Human Spaceflight. *Acta Astronautica*, Vol. 49, pp.495–522.

Robertson, J.M., Dias, R.D., Gupta, A., Marshburn, T., Lipsitz, S.R., Pozner, C.N., Doyle, T.E., Smink, D.S., Musson, D.M. and Yule, S., 2020. Medical Event Management for Future Deep Space Exploration Missions to Mars. *Journal of Surgical Research*, [online] 246, pp.305–314. Available at: <https://doi.org/10.1016/j.jss.2019.09.065> [Accessed 14 Feb. 2021].

Rosser, J.C., Young, S.M. and Klonsky, J., 2007. Telementoring: An application whose time has come. *Surgical Endoscopy and Other Interventional Techniques*, 21(8), pp.1458–1463.

Sakudo, A., 2016. Near-infrared spectroscopy for medical applications: Current status and future perspectives. Clinica Chimica Acta, [online] 455, pp.181–188. Available at: <https://pubmed.ncbi.nlm.nih.gov/26877058/>.

Sanad, R., 2017. *A Study of the Factors Affecting Colour Meaning and Emotional Response*. [online] New Trends and Issues Proceedings on Humanities and Social Sciences, Available at: <www.prosoc.eu>. [Accessed 30 Nov. 2020].

Sarty, G., Sharp, J., Tomanek, B., Turek, K., Obenaus, A., Scott, A., Piche, L., Kontulainen, S., Chilibeck, P., Farthing, J., Baxter-Jones, A. and Pierson, R., 2012. *A magnetic resonance imager for the international space station*. *Proceedings of the International Astronautical Congress, IAC*, .

Sarty, G.E. and Obenaus, A., 2012. Magnetic resonance imaging of astronauts on the International Space Station and into the solar system. *Canadian Aeronautics and Space Journal*, 58(1), pp.60–68.

Savatmongkorngul, S., Wongwaisayawan, S. and Kaewlai, R., 2017. *Focused assessment with sonography for trauma: Current perspectives*. *Open Access Emergency Medicine*, Available at: </pmc/articles/PMC5536884/?report=abstract> [Accessed 7 Feb. 2021].

Schimmerling, W., 2009. *Space Radiation Dosimetry*. [online] Available at: <https://three.jsc.nasa.gov/articles/dosimetryposted3.pdf>.

Schiwon, K., Arends, K., Rogowski, K.M., Fürch, S., Prescha, K., Sakinc, T., Van Houdt, R., Werner, G. and Grohmann, E., 2013. Comparison of Antibiotic Resistance, Biofilm Formation and Conjugative Transfer of Staphylococcus and Enterococcus Isolates from International Space Station and Antarctic Research Station Concordia. *Microbial Ecology*, [online] 65(3), pp.638–651. Available at: <https://link.springer.com/article/10.1007/s00248-013-0193-4> [Accessed 11 Mar. 2021].

Seedhouse, E., 2015. *Bigelow Aerospace*. *Bigelow Aerospace*. Springer International Publishing.

Serdata, 2019. *Arianespace lowers Ariane 5 launch price to combat SpaceX in Asia-Pacific contest - Seradata*. [online] Available at: <https://www.seradata.com/arianespace-lowers-ariane-5-launch-price-to-combat-spacex-in-asia-pacific-contest/> [Accessed 18 Feb. 2021].

Sexton, C., 2019. *Cancer cells have a transformative impact on neighboring cells*. [online] Earth News. Available at: <https://www.earth.com/news/cancer-cells-neighboring/> [Accessed 12 Mar. 2021].

Sheetz, M., 2020. *How SpaceX, Virgin Galactic, Blue Origin and others compete in the growing space tourism market*. [online] Available at: <https://www.cnbc.com/2020/09/26/space-tourism-how-spacex-virgin-galactic-blue-origin-axiom-compete.html> [Accessed 7 Dec. 2020].

Sherman, J. and Epshtein, D., 2012. *The ABCs of OCT*. [online] Review of Optometry. Available at: <https://www.reviewofoptometry.com/article/the-abcs-of-oct> [Accessed 27 Feb. 2021].

Sherman, J., 2009. *Photoreceptor integrity line joins the nerve fiber layer as key to clinical diagnosis*. *Optometry*, Available at: <https://pubmed.ncbi.nlm.nih.gov/19465337/> [Accessed 27 Feb. 2021].

Shin, D.K., 2014. *201 Frequency and Channel Assignments*. [online] Available at: <http://deepspace.jpl.nasa.gov/dsndocs/810-005/> [Accessed 9 Feb. 2021].

Shukitt-Hale, B., Carey, A.N., Jenkins, D., Rabin, B.M. and Joseph, J.A., 2007. Beneficial effects of fruit extracts on neuronal function and behavior in a rodent model of accelerated aging. *Neurobiology of Aging*, [online] 28(8), pp.1187–1194. Available at: <https://pubmed.ncbi.nlm.nih.gov/16837106/> [Accessed 24 Feb. 2021].

Shunk, G.K., Gomez, X.R. and Averesch, N.J.H., 2020. A Self-Replicating Radiation-Shield for Human Deep-Space Exploration: Radiotrophic Fungi can Attenuate Ionizing Radiation aboard the International Space Station. [online] Available at: <https://doi.org/10.1101/2020.07.16.205534> [Accessed 23 Feb. 2021]

Silvia Tower et al., 2016. *Microgravity Yoga*. [online] NASA Space Apps challenge. Available at: <https://2016.spaceappschallenge.org/challenges/space-station/astrocize/projects/micro-gravity-yoga> [Accessed 24 Feb. 2021].

Slack K., Williams T., Schneiderman J., Whitmire A., and Picano J., 2016. *Evidence Report: Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders*. [pdf] NASA. Available at: <https://humanresearchroadmap.nasa.gov/evidence/reports/BMed.pdf> [Accessed 2 Feb. 2021].

Slyuta, E.N., 2014. Physical and mechanical properties of the lunar soil (a review). *Solar System Research*, [online] 48(5), pp.330–353. Available at: <https://link.springer.com/article/10.1134/S0038094614050050>.

Soto, J.A., 2019. The Mars Doctor: Medical Affairs Reaching Deep Space. In: *Proceedings of Mars Society International Convention*. [online] Los Angeles. Available at:

<https://www.researchgate.net/publication/336672248_THE_MARS_DOCTOR_MEDICAL_AFFAIRS_REACHING_DEEP_SPACE>.

SpaceX, 2020. *Falcon Users Guide*. [online] Available at: <https://www.spacex.com/media/falcon_users_guide_042020.pdf> [Accessed 12 Mar. 2021].

Spry, J., 2021. Company plans to start building private Voyager space station with artificial gravity in 2025. [online] Space.com, Available at: <https://www.space.com/orbital-assembly-voyager-space-station-artificial-gravity-2025> [Accessed 28 February 2021].

Spudis, P.D., 2018. *About Those "Polar Lava Tubes"*. [online] Air & Space Magazine. Available at: <https://www.airspacemag.com/daily-planet/about-those-polar-lava-tubes-180967854/> [Accessed 20 Feb. 2021].

Stierwalt, S., 2020. Do You Have What It Takes to Be an Astronaut? - Scientific American. [online] Scientific American. Available at: <https://www.scientificamerican.com/article/do-you-have-what-it-takes-to-be-an-astronaut/> [Accessed 3 Mar. 2021].

Stockmann, J.P., Cooley, C.Z., Guerin, B., Rosen, M.S. and Wald, L.L., 2016. Transmit Array Spatial Encoding (TRASE) using broadband WURST pulses for RF spatial encoding in inhomogeneous B0 fields. *Journal of Magnetic Resonance*, [online] 268, pp.36–48. Available at: </pmc/articles/PMC4909507/> [Accessed 26 Feb. 2021].

Taddeo, T., Gilmore, S. and Armstrong, C., 2019. Chap 6. Spaceflight Medical Systems. In: M.R. Barratt, E.S. Baker and S.L. Pool, eds. *Principles of Clinical Medicine for Space Flight*, 2nd ed. pp.201–232.

Tech Briefs, 2020. Variable Gravity Device Enables Medical, Pharmaceutical Research. [online] Available at: <https://www.techbriefs.com/component/content/article/tb/spinoff/health-and-medicine/36541?m=692> [Accessed 10 May 2021].

The Gateway Foundation, 2019. SpaceX Starship and The Voyager Rotating Space Station. [video] Available at: <https://www.youtube.com/watch?v=vTNP01Sg-Ss&t=1192s> [Accessed 28 February 2020].

The Korte Company, 2020. *Building smarter healthcare through better interior design*. [online] Available at: <https://www.korteco.com/construction-industry-articles/building-smarter-healthcare-through-better-healthcare-interior-design/> [Accessed 30 Nov. 2020].

The Verge, 2017. *NASA is losing the race to build a better rocket - The Verge*. [online] Available at: <https://www.theverge.com/2017/5/10/14886570/nasa-space-launch-system-rocket-ula-blue-origin-spacex> [Accessed 18 Feb. 2021].

Tirumalai, M.R., Karouia, F., Tran, Q., Stepanov, V.G., Bruce, R.J., Ott, C.M., Pierson, D.L. and Fox, G.E., 2017. The adaptation of Escherichia coli cells grown in simulated microgravity for an extended period is both phenotypic and genomic. *npj Microgravity*, [online] 3(1), p.15. Available at: <www.nature.com/npjmgrav> [Accessed 11 Mar. 2021].

Toney-Butler, T.J. and Thayer, J.M., 2020. Nursing Process. StatPearls Publishing. [online] Available at: <https://www.ncbi.nlm.nih.gov/books/NBK499937>.

Topol, E.J., 2019. High-performance medicine: the convergence of human and artificial intelligence. *Nature Medicine*, [online] 25(1), pp.44–56. Available at: <https://pubmed.ncbi.nlm.nih.gov/30617339/> [Accessed 12 Mar. 2021].

TRISH | Baylor College of Medicine, 2020. *There's an App for That – Leveraging Machine Learning to Improve Health Care Decisions*. [online] Available at: <https://www.bcm.edu/academic-centers/space-medicine/translational-research-institute/research/trish-innovations> [Accessed 12 Oct. 2020].

TRISH | Baylor College of Medicine, 2020a. *Microbe Therapy for Deep Space*. [online] Available at: <https://www.bcm.edu/academic-centers/space-medicine/translational-research-institute/research/trish-innovations/microbe-therapy-for-deep-space> [Accessed 10 Dec. 2020].

TRISH | Baylor College of Medicine, 2021. *Medical Technology Research*. [online] Available at: <https://www.bcm.edu/academic-centers/space-medicine/translational-research-institute/research/research-portfolio/medical-technology-research> [Accessed 12 Mar. 2021].

TRISH | Baylor College of Medicine, 2021b. *Non-Contact Sleep, Vitals and Behavior Sensing to Predict and Protect Astronaut Health*. [online] Available at: <https://www.bcm.edu/academic-centers/space-medicine/translational-research-institute/research/trish-innovations/non-contact-sleep-vitals-and-behavior-sensing-to-predict-and-protect-astronaut-health> [Accessed 12 Mar. 2021].

TRISH | Baylor College of Medicine, 2021c. *Video Games to Advance Virtual Simulation in Space Medicine*. [online] Available at: <https://www.bcm.edu/academic-centers/space-medicine/translational-research-institute/research/trish-innovations/video-games-to-advance-virtual-simulation-in-space-medicine> [Accessed 12 Mar. 2021].

Turek, K., Liszkowski, P. and Sarty, G., 2015. A Permanent Halbach Magnet for Wrist MRI at the International Space Station. In: *66th International Astronautical Congress, October 12 - October 16.* Jerusalem, Israel: International Astronautical Federation.

UNGA, 1962. *Declaration of Legal Principles Governing the Activities of States in the Exploration and Use of Outer Space*. [online] Available at: <https://www.unoosa.org/pdf/gares/ARES_18_1962E.pdf> [Accessed 29 Jan. 2021].

UNGA, 1982. *DBS Principles*. [online] Available at: <http://www.unoosa.org/oosa/SpaceLaw/nps.html> [Accessed 29 Jan. 2021].

United Launch Alliance, 2021. *RocketBuilder*. [online] Available at: <https://www.rocketbuilder.com/start/configure> [Accessed 18 Feb. 2021].alth America

United Nations, 1963. *Treaty banning nuclear weapon tests in the atmosphere, in outer space and under water*. Moscow.

United Nations, 1974. *Convention on the Registration of Objects Launched into Outer Space*.

United Nations, 2015. *The 17 Goals*. [online] Available at: <https://sdgs.un.org/fr/goals> [Accessed: 18 February 2021].

United Nations Office for Outer Space Affairs, 1968. *Rescue Agreement*. [online] Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Objects Launched into Outer Space. Available at: <https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introrescueagreement.html> [Accessed 18 Feb. 2021].

United Nations Office of Legal Affairs, 1974. *Convention relating to the distribution of programme-carrying signals transmitted by satellite*. Brussels.

United Nations, 2021. *The 17 Goals: Sustainable Development*. [online] Available at: <https://sdgs.un.org/fr/goals> [Accessed 12 Mar. 2021].

United Nations. 1967. *Treaty on principles governing the activities of states in the exploration and use of outer space, including the Moon and other celestial bodies* (Issue January).

United Nations. 1969. *Agreement on the Rescue of Astronauts, The Return of Astronauts and the Return of Objects Launched into Outer Space* (Vol. 63, Issue 2).

United Nations. 1972. *Multilateral Convention on the international liability for damage caused by space objects* (Vol. 961, Issue 13810).

United States (1996) *The Health Insurance Portability and Accountability Act of 1996* (HIPAA or the Kennedy–Kassebaum Act)

University of Saskatchewan, 2021. *Space MRI Lab - Gordon Sarty Research Group*. [online] Available at: <https://research-groups.usask.ca/gordon-sarty/> [Accessed 26 Feb. 2021].

UNOOSA, 1986. *Principles Relating to Remote Sensing of the Earth from Outer Space*. [online] Available at: <https://www.unoosa.org/pdf/gares/ARES_41_65E.pdf> [Accessed 29 Jan. 2021].

UNOOSA, 1992. *Principles Relevant to the Use of Nuclear Power Sources In Outer Space*. [online] Available at: <http://www.unoosa.org/oosa/SpaceLaw/nps.html> [Accessed 29 Jan. 2021].

UNOOSA, 1996. *Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries*. [online] Available at: <https://www.unoosa.org/oosa/en/ourwork/spacelaw/principles/space-benefits-declaration.html> [Accessed 29 Jan. 2021].

UNOOSA, 2010. *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*. Vienna.

UNOOSA, 2013. *United Nations Treaties and Principles on Space Law*. [online] *United Nations Website*, Available at: <http://www.oosa.unvienna.org/oosa/SpaceLaw/treaties.html>.

UNOOSA, 2018. *Guidelines for the Long-term Sustainability of Outer Space Activities*. Vienna.

Wade 2019. *Von Braun Station*. [online] Available at: <http://www.astronautix.com/v/vonbraunstation.html> [Accessed 1 Mar. 2021].

Watkins, S., Barr, Y. and Kerstman, E., 2011. The space medicine exploration medical condition list. Houston, TX

WestGen, 2018. Genomically Tested embryos provide extreme genetic value! [online] Available at: <https://westgen.com/boost-your-investment-with-genomically-tested-embryos/human-or-animal-cells-on-blue-background-concept-early-stage-embryo-medicine-scientific-concept-stem-cell-research-and-treatment-3d-illustration/> [Accessed 12 Mar. 2021].

Wilde, M., Ciarcià, M., Grompone, A. and Romano, M., 2016. Experimental Characterization of Inverse Dynamics Guidance in Docking with a Rotating Target. *Journal of Guidance, Control, and Dynamics*, 39(6), pp.1173–1187.

Witze, A., 2020. Astronauts have conducted nearly 3,000 science experiments aboard the ISS. Nature.

Wolbarsht, M.L., Walsh, A.W. and George, G., 1981. Melanin, a unique biological absorber. Applied Optics, 20(13), p.2184.

Wood, K.N., Murray, K.R., Greaves, D.K. and Hughson, R.L., 2019. Inflight leg cuff test does not identify the risk for orthostatic hypotension after long-duration spaceflight. *npj Microgravity*, [online] 5(1). Available at: </pmc/articles/PMC6789148/?report=abstract> [Accessed 6 Dec. 2020].

Wotring V., 2015. *Evidence Report: Risk of Therapeutic Failure Due to Ineffectiveness of Medication*. [pdf] NASA. Available at: <https://humanresearchroadmap.nasa.gov/evidence/reports/pharm.pdf> [Accessed: 5 Feb. 2021].

Wotring, V.E., 2011. Evidence Report : Risk of Therapeutic Failure Due to Ineffectiveness of Medication. In: *Human Research Program, Human Health Countermeasures Element*. [online] Johnson Space Center, Houston, TX.: National Aeronautics and Space Administration.p.82. Available at: <http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110015816.pdf>.

Wotring, V.E., 2012. Chapter 10: Conclusions: Special Challenges of Long Duration Exploration: Packaging and Shelf Life. In: *Space Pharmacology*. New York, NY: Springer.p.84.

Wotring, V.E., 2015. Medication use by U.S. Crewmembers on the International space station. *FASEB Journal*, 29(11), pp.4417–4423

Ximenes, S.W., Elliott, J.O. and Bannova, O., 2012. Defining a mission architecture and technologies for lunar lava tube reconnaissance. In: *Earth and Space 2012 - Proceedings of the 13th ASCE Aerospace Division Conference and the 5th NASA/ASCE Workshop on Granular Materials in Space Exploration*. American Society of Civil Engineers (ASCE).pp.344–354.

Zhang, S., Wimmer-Schweingruber, R.F., Yu, J., Wang, C., Fu, Q., Zou, Y., Sun, Y., Wang, C., Hou, D., Böttcher, S.I., Burmeister, S., Seimetz, L., Schuster, B., Knierim, V., Shen, G., Yuan, B., Lohf, H., Guo, J., Xu, Z., Von Forstner, J.L.F., Kulkarni, S.R., Xu, H., Xue, C., Li, J., Zhang, Z., Zhang, H., Berger, T., Matthiä, D., Hellweg, C.E., Hou, X., Cao, J., Chang, Z., Zhang, B., Chen, Y., Geng, H. and Quan, Z., 2020. First measurements of the radiation dose on the lunar surface. *Science Advances*, [online] 6(39), p.eaaz1334. Available at: <http://advances.sciencemag.org/> [Accessed 24 Feb. 2021].

INTERNATIONAL®
SPACE UNIVERSITY

SPONSORS:

NASA

cnes