Solutions for Construction of a Lunar Base: A Proposal to Use the SpaceX Starship as a Permanent Habitat

Conference Paper · October 2021

21 authors, including:

Adam F. Abdin
CentraleSupélec
15 PUBLICATIONS **135** CITATIONS
SEE PROFILE

Stefan Amberger
International Space University
1 PUBLICATION **1** CITATION
SEE PROFILE

Emily Apollonio
International Space University
1 PUBLICATION **1** CITATION
SEE PROFILE

Gautier Bardi
isu
1 PUBLICATION **1** CITATION
SEE PROFILE

IAC-21,A3,2B,17,x67165

Solutions for Construction of a Lunar Base:

A Proposal to Use the SpaceX Starship as a Permanent Habitat

Adam Abdin[1,2], Stefan Amberger[1,*], Emily Apollonio[1], Gautier Bardi de Fourtou[1], Karl Bolmgren[1,3], Gianmarco Ciocca[1,4], Monica Ekal[1,5], Alan García[1], Adina Godeanu[1], Damiana Irrera[1,6], Leonard C. L. Lidgard[1], Giorgio Lorini[1], Shay Monat[1,7,*], João Montenegro[1,*], Aiden O'Leary[1,8], Ori Onn[1], Laura Pauzié[1], Charlotte Pouwels[1,9,+], Alexandra Sokolowski[1], Zhuang Tian[1,10] and Alberto Za[1]

[1]*International Space University, Strasbourg, France.*
[2]*Laboratoire Génie Industriel, CentraleSupélec, Université Paris-Saclay, Gif-sur-Yvette, France.*
[3]*Department of Physics, KTH Royal Institute of Technology, Stockholm, Sweden.*
[4]*Centre for Sports Science and University Sports, University of Vienna, Vienna, Austria.*
[5]*Institute for Systems and Robotics, Instituto Superior Técnico, Lisbon, Portugal.*
[6]*Politecnico di Milano, Milan, Italy.*
[7]*School of Mechanical Engineering, Tel-Aviv University, Tel-Aviv, Israel.*
[8]*Orbit Fab, San Francisco, USA.*
[9]*ILEWG EuroMoonMars, The Netherlands.*
[10]*International Institute of Air and Space Law, Leiden University, Leiden, The Netherlands.*

[*]*Speaker*
[+]*Email: charlotte.pouwels@gmail.com*
All authors contributed equally to this work.

Abstract

Returning to the Moon and establishing a permanent human presence is the next step in human space exploration. This necessitates the development of lunar infrastructure up to this task. This contribution presents a framework for rapid, cost-efficient, and supporting construction of a permanent and modular lunar base within the scope of what will be technically and legally feasible today. The proposed concept uses the SpaceX Starship Human Landing System as the foundation for a lunar base. The Starship will be placed horizontally on the lunar surface and transformed into a habitable volume. A workforce of modular rovers will aid astronauts in the construction process, and an array of countermeasures are presented to protect the astronauts from the effects of exposure to radiation, lunar dust, and extended hypogravity. Psychological and psychosocial factors are included to enhance individual well-being and crew dynamics. Physical and cognitive workloads are defined and evaluated to identify effective countermeasures, including specific spacesuit requirements. The proposed construction activities are to be organized as a multi-national public-private partnership to establish an international authority, a concept that has been successful on Earth but has yet to be applied to space activities on a multi-national level. A roadmap incorporating each part of the construction from human and technical perspectives is outlined. Other aspects that are critical to mission success include the cultural significance of the project, legal aspects, budget, financing, and potential future uses of the base. These solutions rely mainly on existing technologies and limited modifications to the lunar lander vehicle, making it a viable solution for the construction of a lunar base in the near future.

Keywords: Lunar base, space exploration, human spaceflight, public-private partnership, space law

1 Introduction

A sustainable and permanent habitat on the Moon has long been discussed since the beginning of the Apollo Missions. To make humankind's presence on the Moon permanent, one of the key steps is constructing a lunar base for human habitation. In addition to the fundamental human aspects, this presents a multitude of technical, life-science, cultural, legal, and business challenges and considerations. This paper proposes a potential solution for an efficient and sustainable construction of a first lunar base.

The idea of utilizing the large volume and properties of empty fuel tanks to create robust space habitats is well-established and researched (see, e.g., [1]). While this is applicable to any large rocket body, in this proposal the SpaceX Starship Human Landing System (HLS) was chosen as the structural basis for a lunar settlement. The additional volume provided by the conversion of the fuel tanks means there is great potential for renting out this space to other entities to generate revenue and promote sustainability and growth. This plan would rely mostly on existing technologies and limited modifications to the vehicle, and a type of rover, MOdular RObotic Construction Autonomous System (MOROCAS), for the purpose of setting up equipment to transition the Starship from its vertical landing position to a horizontal position (horizontalization).

In addition to the technical concept, several solutions are proposed to ensure optimal crew performance during the construction operations by mitigating physiological risks associated with dust, radiation, and hypogravity, as well as psychological and psychosocial well-being. Building a lunar base also requires consideration of the internal environment where the construction crew will work and live. Other challenges to the crew during construction activities include increased metabolic costs and operating machinery in one sixth of Earth's gravity while wearing a spacesuit, as well as the risk of medical emergencies.

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

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

The legal aspects of constructing a lunar base are another crucial element of the proposal. The respect for, and compliance with, international law is critical to "maintain international peace and security and promote international cooperation and understanding" as formulated by Article 3 of the Outer Space Treaty (OST) [2].

These combined challenges are approached from a holistic point of view, by addressing regulatory and policy frameworks, examining technological and anthropological challenges, and by empowering scientific and commercial lunar activities for the common interest of all humankind.

2 The Solution

As seen in the space industry in recent years, re-usability of flight hardware is the key to make space travel more economical. Under this consideration, this paper proposes a radical approach to the term "re-usability" with the concept of converting an entire vehicle, including its fuel tanks, into a lunar base allowing for continuous use of most of the vehicle over years or decades. This paper suggests using the SpaceX Starship HLS as the vehicle to convert into a base for several reasons: it is the vehicle selected to land on the Moon as part of the Artemis mission [3], it has outstanding reported mass-launch capabilities (more than 100 metric tons to the moon), and its large overall internal volume of approximately 2500 m^3 [4]. Converting the fuel tanks of the Starship HLS into habitable volumes will create a permanent base which is about 2.5 times bigger than the habitable volume of the International Space Station (ISS) [5].

2.1 Intended Layout of the Base

The basic layout of the proposed lunar base (Fig. 1) is that of a horizontal Starship HLS placed on the lunar south

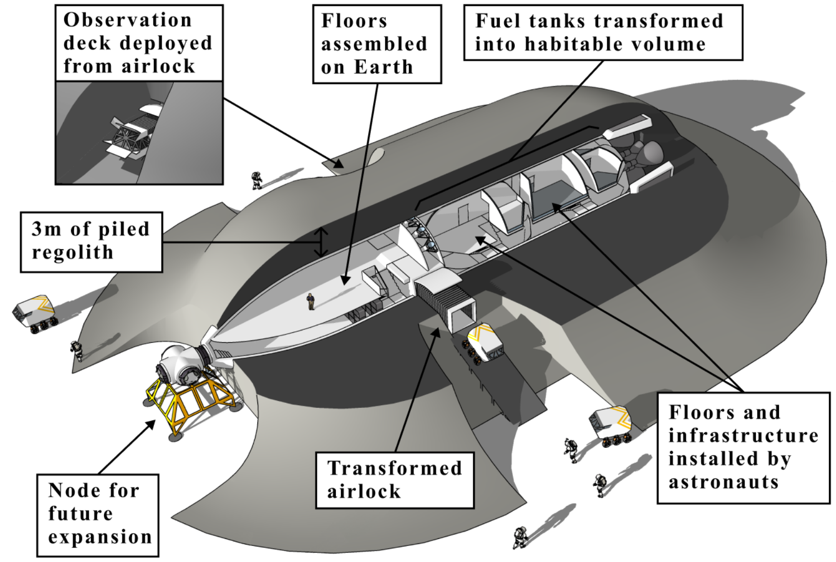

Fig. 1: Conceptual overview of the lunar base showing the Starship lander in its horizontal position and covered with regolith.

pole, on top of the rim of Shackleton crater (see, e.g., [6]). The base will be covered by a 5 m layer of regolith (the material covering most of the lunar surface) to protect the base from radiation and micro-meteorite impacts. Only the airlocks and the nose hatch will be left uncovered from regolith. One of the airlocks will be transformed into an observation deck that will have permanent view of the earth over the lunar horizon. Expansion possibilities will be available through the nose hatch. The interior will have three levels that span the entire length of the vehicle, including the former methane and oxygen tanks (see Fig. 2).

2.2 Basic Assumptions

In order to make this solution for the construction of a lunar base technologically and economically feasible in the near future, minimal modifications should be made to the design of the HLS Starship. Thus, this lunar base concept relies on the structure of the vehicle as given in the latest design published by SpaceX (seen in Fig. 2), which is only capable of landing vertically on the Moon. It is assumed that the structural integrity of the Starship will be granted when transitioned to the horizontal position due to the low gravity, regolith under the vehicle, and the pressure difference between the interior and exterior of the base. The lunar base design does not include making any holes on the outer surface of the vehicle and will utilize only the two available airlocks and the refueling ports.

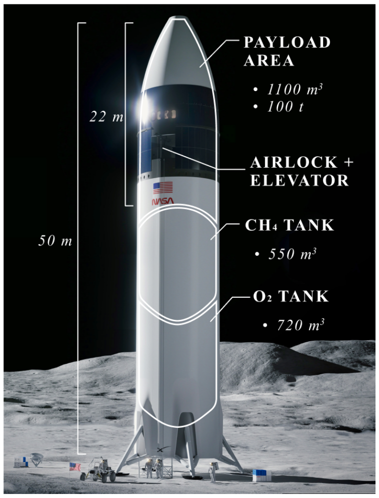

Fig. 2: Artist rendering of current design of the Starship HLS concept (Original image credit: SpaceX) .

3 Mission Concept of Operations

The mission to convert the vehicle into a permanent lunar base is planned to take about two to three months. During this mission, two Starships (one crewed and the other for supplies) will venture to the surface of the Moon. The crew will remotely operate a fleet of robots that will work to transition the vehicle to a horizontal position on the surface. Once the Starship is horizontalized, the astronauts will transform the fuel tanks into habitable volumes and deploy all essential and operational equipment while robots autonomously cover the entire base with regolith.

3.1 Transfer Mission and Landing

The supplies Starship will launch from earth without crew on board and will include all equipment, tools, materials, systems, and provisions that are required to construct and sustain the future base. The crew that will construct the base will launch on a separate vehicle shortly after the launch of the Starship. The two spacecraft will refuel in earth orbit before performing the trans-lunar injection burn. The crewed vehicle will need to sustain the crew during the journey to and from the Moon and in the first few weeks on the surface of the Moon, until the base becomes habitable.

The two vehicles will land on the rim of Shackleton crater at the south pole of the Moon where there is constant sunlight and a permanent view of Earth, as well as the potential for accessible ice, making it an ideal landing site [6]. The two vehicles will land 5 km apart, taking on the assumption that this distance is far enough to mitigate dust and rocks from being ejected during the propulsive landing and damaging the other spacecraft.

3.2 The Modular Robotic Construction Autonomous System Concept

The MOROCAS rover concept is introduced to assist in the construction of the base (see Fig. 3). This fleet of robots will be suitable to carry out all of the extravehicular tasks that can be controlled remotely or autonomously. The MOROCAS should be designed as a flat-bed that can fit inside the airlock of the Starship, carry equipment, manipulate certain tools and navigate on the lunar surface. They will be stored inside the Starship along with the utility equipment that is designed to connect with and operate.

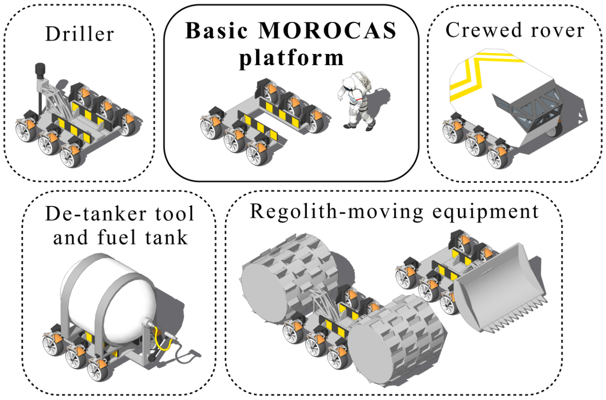

Fig. 3: The MOROCAS and some of its applications and tools installed on it.

Upon arrival on the Moon, the MOROCAS will extract the solar panels, radiators, power reactor, and antennas from the Starship to the surface. The MOROCAS will also drain the excess fuel to inflatable bladders using the de-tanking tool that will connect to the Starship's refueling port. They will then begin preparation of the Starship for its horizontalization by manipulating the tools designed for the different tasks. After the vehicle is transitioned to a horizontal position the MOROCAS will autonomously pile regolith on top of the base with the regolith-moving tools.

3.3 Horizontalization

Once the MOROCAS have deployed the external systems and drained the excess fuels, the load on the vehicle will be reduced significantly as it is being tilted. The pressure inside the vehicle will be high enough to maintain structural integrity but low enough to reduce the vehicle's unnecessary mass. The horizontalization system will have several elements and concepts that are designed to reduce the load on the vehicle at different angles of tilt (Fig. 4). A hinge mechanism will be installed by the MOROCAS to prevent the vehicle from slipping and ensure the vehicle is being tilted in the appropriate direction. The cables of the elevators (seen in Fig. 2) coming down from the airlock will be disconnected from the platform and connected to anchors. These cables will carry most of the load on the vehicle at the earlier stages of the tilting procedure. A scissor lift mechanism will be deployed to transfer some of the loads to the ground on the last phase of the process. The vehicle will settle between two parallel ridges of piled regolith to prevent it from rolling and to support the horizontal structure.

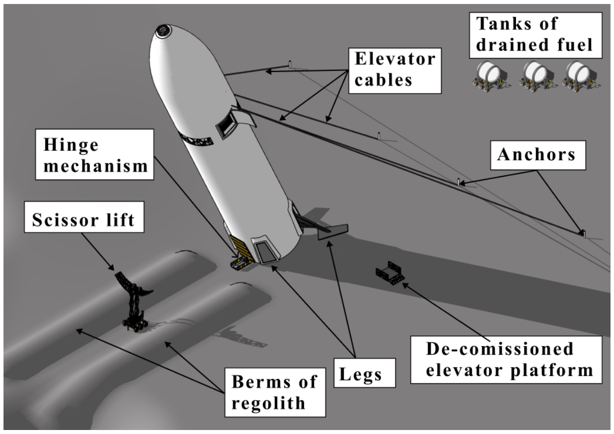

Fig. 4: The horizontalization process and its various components.

3.4 Transformation of Interior Volumes

Once the Starship is horizontal, the remaining fuel will be vented and the tanks will be pressurized with the desired breathable atmosphere. At this point, the crew can enter the base for the first time. Using a specialized cutting tool and safety measures, the crew will cut holes in the domes of the fuel tanks and install hatches in these holes. Over a period of several weeks the crew will unpack from the payload volume and install the equipment and infrastructure in the tanks that will make the Starship habitable and comfortable. This includes thermal and radiation insulation layers, floors, walls, life support systems, electricity infrastructure, ventilation system, communication system, lighting, water, heat removal system, water tanks and pipes, bathrooms, showers, and furniture.

The floors will be fixed to the baffles inside the tanks to create three levels with a floor height of almost 3 m. Considering the circular section of the base, it will have almost 850 m^2 of comfortable floor space. The crew will also deploy the observation deck, visualized in Fig. 1, from the airlock that faces the earth.

4 Life in a Lunar Construction Site

The lunar environment presents many challenges that astronauts would not otherwise experience in weightlessness on the ISS. Physiological concerns on the lunar surface are caused by lunar dust, radiation, and hypogravity. Additionally, physical and cognitive workloads will contribute to fatigue, which is expected to carry a higher level of risk during the early construction phase. An assessment of the effects of these workloads is considered with the aim of providing the best possible working environment for the astronauts. Considerations include improved spacesuit design, crew workload during construction activities, and solutions for dust, radiation, and hypogravity. When sending a crew to the Moon for the purpose of building a lunar base, it is critical that adequate preparation and countermeasures are set in place to keep the crew healthy while ensuring mission success.

4.1 The Lunar Spacesuit

Lunar Extra-Vehicular Activities (LEVAs) impose new requirements for spacesuit design. The primary difference that must be taken into consideration includes walking on a celestial body with gravity different from Earth's [7, 8]. The greatest differentiating factor to spacesuit design when comparing to current spacesuits is mitigating metabolic costs and reducing energy exertion during LEVA.

Considerations for metabolic cost reduction include weight, suit pressure, inertial mass, biomechanics, and stability, with the greatest factor being suit weight. According to an experiment performed by Gernhardt et al. [9], it was found that the optimal suit weight to improve performance by reducing metabolic costs was between 180 kg and 320 kg, with the heavier weight contributing to better performance. Other spacesuit parameters for consideration during LEVA identified by Scheuring et al. [10] include biomedical monitoring and consumables management, such as improved nutrition mechanisms, waste disposal systems, and biomedical sensors, as well as considerations for dexterity, mobility, visibility, range of motion, donning and doffing, traction, and a heads-up-display.

4.2 Crew Workload During LEVAs

Mission success of the construction of the lunar base will depend on system designs and development of operation concepts that maximize human performance and efficiency while minimizing health and safety risks for crew members [11]. As such, human factors have been analyzed and evaluated to understand the various types of workload crew members will experience during construction activities. Workload considerations for construction tasks have been categorized using NASA's Task Load Index (TLX) measurements, as shown in Table 1.

Table 1: Predictive workload factors and their description from the NASA [12] TLX.

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

Using the NASA TLX calculator, an analysis of each task was concluded (seen in Table 2). It was found that conversion of the fuel tanks posed the greatest workload, primarily in effort and physical demands. These tasks include operation of heavy machinery, lifting heavy objects, and crew resource management. The construction activity with the lowest amount of workload was entering and exiting the base or spacecraft, where the astronauts move from one environment to another and undergo depressurization.

4.3 Crew Health Risks

The Moon presents unique challenges. Therefore, when sending a crew to the Moon for the purpose of building a lunar base, preparation and countermeasures should be set in place to keep the crew healthy while ensuring mission success. The most important challenges are addressed here and include lunar dust, radiation and hypogravity.

4.3.1 Dust

Lunar regolith varies in size, and at the smallest scale regolith dust particles are small enough for inhalation, posing a risk to the crew [13]. The lunar surface materials also have an electrical charge due to impacts of cosmic and solar rays, causing toxicity problems to humans [14]. Challenges include adhesion of dust to spacesuits, dust tracking into unwanted areas, and inhalation of dust particles, all of which can result in severe health problems to the crew, including chronic respiratory issues. Successful experiments have been conducted by NASA for lunar exploration missions, such as removal of particles using electrostatic and dielectrophoretic forces to avoid deposits and accumulations [15].

Exposure duration of lunar dust occurs primarily during LEVA. A study performed at the NASA Johnson Space Center sought to determine an exposure rate to regolith using mice [14]. The results of this study showed that astronaut LEVAs should not exceed 6 hours, and the total mission duration should not exceed 180 days.

Solutions to the risks of lunar dust include proper dust management systems and monitoring of crew LEVA exposure. A proper dust management system using methods such as electrostatic and dielectrophoretic forces as proposed by Calle et al.[15] should be designed and implemented, as well as airlocks, improved seals, and appropriate cleaning procedures. Carefully planned donning and doffing procedures would also assist in dust management inside the rover and habitat.

4.3.2 Radiation

Space radiation is another major concern during LEVAs, and can have both short-term and long-term effects on crew health. Highly energetic particles in the form of Galactic Cosmic Rays (GCR), Solar Particle Events (SPEs) and secondary particles created from their interaction with lunar regolith are the main radiation sources. Recent data from the Chinese robotic lunar lander Chang'E 4 showed that GCR radiation dose equivalent levels on the lunar surface are 2.6 times higher than onboard the ISS [16]. This corresponds to approximately 500 mSv/year, which is beyond NASA exposure limits for annual missions on the ISS [17].

Acute Radiation Syndrome (ARS) can arise after an extremely high and sudden exposure to a severe SPE, compromising an individual's neurovascular system, hematopoietic cells, skin, epithelium, intestine, endocrine system, and ability to complete the mission with mild or

Table 2: Task Load Index analysis of construction activities using the NASA [12] TLX application

	Mental Demand	**Physical Demand**	**Temporal Demand**	**Performance**	**Effort**	**Frustration**	**Weighted Rating**
Traveling from the crewed spacecraft to the base site	50	35	30	5	35	45	**25.00**
Operation and supervision of horizontalization maneuver	80	45	65	5	50	10	**38.67**
Entering the base	25	40	35	5	10	45	**22.33**
Conversion of Methane tank	65	90	75	5	95	30	**57.67**
Conversion of Oxygen tank	65	90	75	5	95	30	**57.67**

moderate symptoms [18]. Chronic exposure to radiation can cause long-term effects, such as DNA damage.

The currently most feasible mitigation strategy and risk-lowering solution is constant monitoring of the astronauts' radiation exposure and keeping duration of LEVAs as short as possible. Space agencies, such as NASA and ESA have set maximal exposure radiation limits for 1-year missions in Low Earth Orbit (LEO) and for lifetime exposure. These values vary according to age and gender (2.5 Sv and 1.75 Sv for 35 year old males and females respectively) and are meant to maintain a lifetime excess risk of cancer mortality below 3%.

Additionally, emergency plans should be in place in the event of an SPE occurring while astronauts are performing a LEVA. Based on the variable rise times and total duration of SPEs, it is recommended that emergency procedures for taking cover from such an event should not exceed 30 minutes [19]. This time window ensures a low probability of the permissible exposure limit being exceeded [19].

During lunar construction activities, astronauts could be up to 2.5 km away from the lunar station. Using the rover, astronauts would take approximately 10 minutes to return to the base. Pressure differences between the space suit and the lunar base will require depressurization. The critical need for protection from radiation allows for an emergency reduction in pressurization time in the airlock, providing the astronauts opportunity to quickly enter the lunar station and find cover beneath its protective shield. For future exploration missions requiring farther LEVAs, it could be necessary to build bunkers in strategic adjacent areas.

4.3.3 Hypogravity

Prolonged human exposure to hypogravity can result in an altered immune response, sensorimotor and vestibular function, cognitive or behavioral conditions and disorders, reduced bone density, reduced muscle size and function, and impaired cardiovascular function. All of these can affect an astronaut's ability to perform mission tasks. [20] Different regimes and protocols for physical exercise can efficiently mitigate these risks [21, 22, 23].

The astronaut construction crew should therefore engage in different forms of exercise including resistance strength training, aerobic, and high-intensity interval training. Two modified versions of the Advanced Resistive Exercise Device (ARED), which include two treadmills, two rowing machines, and one cyclo ergometer, could be used for for this purpose. This equipment enables aerobic training, resistance strength training, and high intensity interval training benefiting cardiovascular and neuromuscular functionality [24]. The base should also include space for plyometric exercises to stimulate bone strength, neuromuscular function, and cardiovascular activity [25]. Astronauts should also have the opportunity to train together to promote teamwork, sport, and psychological and social benefits.

5 A Progressive Lunar Economy

It is important to identify the proper financial framework that is most suitable to foster the lunar base construction process. In this paper, it is argued that Public-Private Partnerships (PPPs) are the most suitable financial structure for enabling economically viable lunar base construction and operation activities. This section will justify this choice by comparing the PPP framework to the traditional funding approach for high-risk space-related projects. While the benefits of considering a PPP approach are provided, they are not without drawbacks. This section further identifies and discusses the challenges for constructing the base under a PPP framework.

5.1 Private Public Partnership

PPPs are an arrangement within which the private sector assumes more responsibility for the finance, management, and ownership of the public project than in traditional funding approaches. In traditional approaches, the public sector assumes the full responsibility and finance of the project. In contrast, PPPs transfer a significant amount of the project risks and costs to the private partners. The main premise for the effectiveness of this arrangement is that private partners manage those risks efficiently, typically better than the public actor, as they are motivated to increase the profits for their activities by reducing any operational, business, and organizational inefficiencies. One of the key points of a successful PPP relationship is the ability of the public entities to attract private capital by giving political support, legal assurances, and government funding with the aim of decreasing the technological and capital risks so that private companies can benefit from an acceptable Return on Investment (ROI).

5.1.1 Market breakdown and legal considerations

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

Early market products from lunar activities will likely be comprised of experimental data and samples. A possible pathway to create a market for these products is to target the scientific community. It is important that the public actor fosters such a market for science data via suitable grant schemes [26]. Another pathway is the establishment of milestone payments to companies in the early development phases, whereas, when the company achieves its milestone, they would receive the agreed payment. Other possibilities to creates commercial acquisition opportunities for private actors include:

- Transportation services to orbit;
- Spacecraft services in cislunar space;
- Propellant markets in LEO and in lunar orbit;
- Cislunar commercial communications networks;
- Surface elements (i.e. rovers, habitats, equipment, In-Situ Resource Utilization (ISRU)).

A trade-off analysis is performed with the objective of identifying how the PPP model can be adapted to the development project of the base. The outcome of the analysis is the division in activities that are best publicly funded and those that are best privately funded.

The macro-areas in which the lunar base development is divided can be summarized in: Research and Development (R&D), production, integration, validation, transportation, surface construction, Moon operation (including surface operations, in-orbit operations), and maintenance and re-supply. The trade-off drivers that are taken into consideration for the analysis are:

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

For each of these drivers, a value is assigned based on the guidelines in Table 3, from which it is possible to assess how those drivers correlate to the private funding decisions:

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

Table 3: Values assignments of drivers

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

represents a high possibility to attract private partners.

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

The outcome of the trade-off analysis, shown in Table 4, is that the first stages of the development of the base would be more adequately financed by public funding, while the later stages would be more attractive to private funding since the relationship between the probability of making profit and the risks is advantageous.

5.2 *Economic Assessment for Constructing The Lunar Base*

Using the PPP framework described above with mixed public-private funding at various steps, the program budgeting includes a breakdown of unit costs that would translate into Profit and Loss Report, Cash Flow Statement, and Balance Sheet. For the Program budgeting, Profit and Loss (P&L) scheme was used with bottom-up cost analysis. In cases where the team had access to a subject matter expert or was able to find a relevant resource in literature or publications, this has been used. The budget is therefore by no means complete and requires more solid research and validation with relevant space agencies and private companies. However, the budget can be used as an indicative overview. It should be noted that, for clarity and brevity, in this section we only discuss the outcome of the financial analysis and we do not present the detailed financial breakdown. This could be made available upon request.

The economic analysis conducted showed that the overall projected program cost is around \$4b of which \$3b will be publicly funded spread over three years and \$1b representing the private enterprise investment which will kick-in during the third year. The P&L analysis shows that with projected revenues of \$500m, \$800m and \$1.5m in years three, four, and five respectively, the Moon development project could reach a positive Earnings Before Interest Depreciation Tax and Amortization (EBIDTA). This is, further, illustrated in Fig. (5). Accordingly, ROI for the private investor is forecasted after the seventh year (three to four years after the private investment is made). It is likely that the Moon base will offer opportunities for significant commercial activities and profits for private enterprise. These may include entertainment (television broadcasting etc.), tourism, and pharmaceutical research. Therefore, a targeted business development effort should be planned and executed to approach relevant private partners and construct the PPP scheme with them.

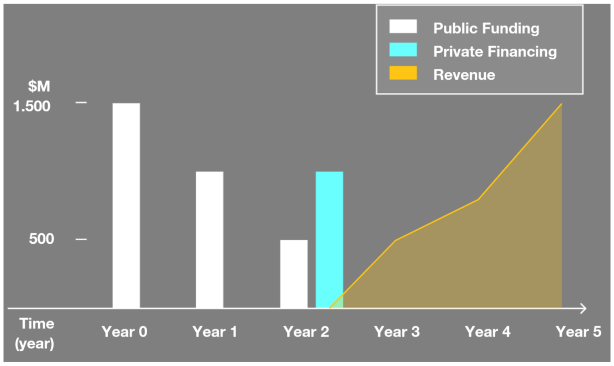

Fig. 5: Overview of the financial timeline for constructing the proposed lunar base showing proportion of needed public funding; proportion of expected private funding and expected revenue each year.

Table 4: Matching between mission phase and funding type

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

5.2.1 Long term sensitivity analysis

It should be noted that the estimated costs for construction of the proposed lunar base are highly uncertain as little information exists on the costs of performing the described technical tasks even in the near future. However, this section is an attempt at providing a general sensitivity analysis on these estimates and in discussing the validity of the proposed economic analysis.

The ISS provides a valuable insight into what governments have been willing to pay to fund science operations. The United States accounts for roughly 76.6% of the research activity on the station, and spends approximately $3-4b per year on the operational expenditures of the ISS [27], which has a total pressurized volume of 916 m^3 [5]. Using this share of research activity as a baseline to generate a conservative estimate of the budget allocation per volume, we get a utilization of approximately 700 m^3 and use the lower bound Operating Expenditure (OPEX) cost of $3b per year. That means that the United States, as an indicative baseline, could be willing to pay $4.28m per m^3 per year.

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

5.2.2 Alternative sources of funding

Another attractive possibility for funding within PPPs are project bonds. These bonds allow for debt-based financing of projects, and can offer low interest rates and larger funding capacity when compared to other funding sources. Given the short construction time of the proposed base and its extensions and the ability to rent out space and utilities on board each new Starship base, there is a great case for rapid return on investment which may make project bonds an attractive option for expansion and other potential space construction projects. Additionally, this has a great benefit for sustainability, opening the opportunity for individuals to participate directly in lunar activities, and be directly involved, potentially increasing support for future governmental and business ventures on the Moon. This is recommended as a future investigation and extension of the present proposal.

6 Legal considerations

International space law governs human activities in outer space, and it is crucial to ensure that the planned construction activities abide by these laws. This legal framework is built abiding by the treaties adopted under the auspices of the United National Committee Peaceful Uses of Outer Space (UNCOPUOS), of which the OST[2] provides the fundamental principles for the exploration and use of outer space.

6.1 Freedom to use and explore outer space

Article I of the OST, provides that "outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States." It can be argued that the construction of the base and the use of space resources constitute an exercise of such freedoms. However, the rights granted are subject to certain limitations. One limitation within Article I is that the exploration and use of outer space "shall be carried out for the benefit and in the interests of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind." While this provision is "not clearly defined and can be subject to varying interpretations," it expresses the idea that "the use of space should somehow benefit mankind" [28], which the establishment of a permanent lunar habitat certainly has the potential to do.

Article II of the OST lays down the principle that outer space, including the Moon and other celestial bodies, is not subject to national appropriation by any means. The base construction activities do not contravene Article II of the OST, as no claims of sovereignty or proprietary rights will be made.

6.2 Land use and safety zone

Article I (2) of the OST provides that "there shall be free access to all areas of celestial bodies", which appears to outlaw permanent constructions on the Moon as this would restrict the free access to an area. However, Article XII of the OST stipulates that all stations on the Moon shall be open to representatives of other states on a basis of reciprocity. This implies that the construction of a lunar base is legitimate, otherwise this obligation would lose its pre-requisite [29].

Another potential issue is the declaration of safety zones around the construction area. The Artemis Accord describes "safety zone" as an "area wherein [...] notification and coordination will be implemented to avoid harmful interference." It also sets out principles for safety zones [cf. Section 11(7) 30]. *The Building Blocks for the Development of an International Framework on Space Resource Activities* adopted by The Hague International Space Resources Governance Working Group (HWG) also indicates that the establishment of a safety zone is "necessary to assure safety and to avoid any harmful interference with" space resource activities [31]. This means that it is feasible to declare a safety zone around the lunar base for the purpose of minimizing potentially harmful interference.

6.3 In-situ resource utilization

Though there is no definitive and internationally accepted ISRU regime, the U.S. Commercial Space Launch Competitiveness Act recognizes the property rights of U.S. citizens over any space resource [32]. This approach has been followed by Luxembourg, the United Arab Emirates and Japan. In order to ensure the legal certainty of the ISRU activities related to the construction of the base, like the use of lunar regolith and water, these activities will be conducted within the jurisdiction of, and be licensed by, those states that recognize the rights of ISRU.

6.4 Environmental protection

Article IX of the OST imposes that space activities avoid harmful contamination of outer space and adverse changes in Earth's environment resulting from the introduction of extraterrestrial matter, and to adopt appropriate measures to this end if necessary.

Regarding the protection of both terrestrial and space environment, the Committee on Space Research (COSPAR) Panel on Planetary Protection maintains the Planetary Protection Policy as astandard to guide compliance with Article IX of the OST [33].

The proposed construction mission falls under subcategory IIb of the Planetary Protection Policy. This category concerns all Moon surface missions whose mission profile accesses permanently shadowed regions and the lunar poles. As a result, a planetary protection documentation and an organic inventory will be required of the mission.

6.5 Multilateral Cooperation Framework

The OST preamble states that broad international cooperation in space "will contribute to the development of mutual understanding and to the strengthening of friendly relations among States and people."

A prominent example of international cooperation in the space domain is the ISS. The ISS Intergovermental Agreement (IGA) "established the overall cooperative framework for the design, development, operation and utilization of the ISS and addressed several legal topics." Its successful implementation for more than two decades "set a great precedent for future large international space collaborations, such as lunar and planetary exploration missions" [34]. Therefore, the multilateral cooperation framework for this mission will be modeled after the ISS IGA.

7 Conclusion

Conventional space projects have become a huge cost to tax payers and can change with the politics of each election cycle. This makes them difficult to maintain, and even harder to see the tangible benefits. Constructing a permanent lunar base has many potential positive impacts for life on Earth, in-orbit infrastructure, and deep space ambitions. To capitalize on these points in a rapid, cost efficient, and sustainable way, the solutions outlined in this proposal make a strong case that this vision is achievable within this decade.

The major challenges from a technological, human health, legal, and financial perspective each have scalable answers that exist within the scope of knowledge, technology, frameworks, and funding that exist today. The core novel engineering approach in this mission of turning fuel tanks and stages into bases is not a new one. It is well supported by examples such as Skylab and proposals like converting the external Space Shuttle tanks to orbital bases. Using the immense volume and capacity of Starship-like vehicles allows for the support equipment and infrastructure to be sent, operated, and adapted with just a few lunar landings for low and sustainable costs. This equipment does not require technological breakthroughs, creating efficient development and design phases.

In the transportation phase, the ability to send a large amount of support equipment allows for solutions to human spaceflight challenges such as radiation, micrometeorites, and dust mitigation such as stacking regolith and electrostatic removal, respectively. The huge internal volume addresses the physiological and psychological needs of astronauts. Even with large crews, there is plenty of space and utilities to support additional activities from other parties that can provide revenue generation for a sustainable and expandable base. These activities in both the public and private sectors are well supported and within the spirit of the legal framework provided by the five international treaties on space, preventing appropriation while promoting freedom of exploration, free use of outer space, assistance to astronauts, due regard, and international partnership and cooperation. All of this respects IP concerns using valuable international public-private frameworks such as those implemented on the ISS.

In further support, utilizing a PPP in the form of an international authority provides a high degree of credibility and sustainability, allowing it to accomplish more and reach more partners with less resources than either a public or private entity. The base is constructed using public funding for the development and initial capital expenditures over a three-year period. This is followed by private operations of the base for the purpose of sustainability, bringing in governmental and private partners to generate revenue that can fund expansion, using established infrastructure for a lower overall cost. This international authority provides a long-term vision that will grow with lunar activities and respond effectively to any challenges that arise. The interdisciplinary solution for construction of a lunar base provides a new approach to accessibility and permanent, scalable presence on the lunar surface that can be sustainably supported. The lessons learned and promoted in the base model, if implemented, will promote international science, cislunar economic development, and future exploration that will become an important steppingstone to the stars.

Acknowledgements

This work was performed as part of the participation at the International Space University's Space Studies Program of 2021 as a team project resulting in a final report, *Solutions for Construction of a Lunar Base*. We would like to thank Lockheed Martin for sponsoring this project. We would also like to thank our project chairs, Rob Postema, Matt Sorgenfrei, and Antonio Gomez, and our teaching associate, Xiaochen Zhang, for their constant support which led to the success of this team project.

J. Montenegro and A. García illustrated the graphics. J. Montenegro and S. Monat first conceived the idea of a Starship lunar base. All authors contributed equally to the conception of the proposed lunar base and its solutions.

A. Abdin, S. Amberger, E. Apollonio, K. Bolmgren, G. Ciocca, M. Ekal, S. Monat and C. Pouwels contributed to the writing of the manuscript.

Acronyms

ARED	Advanced Resistive Exercise Device
ARS	Acute Radiation Syndrome
COSPAR	Committee on Space Research
EBIDTA	Earnings Before Interest Depreciation Tax and Amortization
GCR	Galactic Cosmic Rays
HLS	Human Landing System
HWG	The Hague International Space Resources Governance Working Group
IGA	Intergovermental Agreement
ISRU	In-Situ Resource Utilization
ISS	International Space Station
LEO	Low Earth Orbit
LEVA	Lunar Extra-Vehicular Activity
MOROCAS	MOdular RObotic Construction Autonomous System
OPEX	Operating Expenditure
OST	Outer Space Treaty
P&L	Profit and Loss
PPP	Public-Private Partnership
R&D	Research and Development
ROI	Return on Investment
SPE	Solar Particle Event
TLX	Task Load Index
UNCOPUOS	United National Committee Peaceful Uses of Outer Space

References

[1] Samuel I. Wald, Christopher K. Cummins, and Jeffrey Manber. Outpost: A wet-lab habitation platform for leo and beyond. *2018 AIAA SPACE and Astronautics Forum and Exposition*, 2018.

[2] UN General Assembly. Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, 1967.

[3] NASA. Source Selection Statement, Appendix H: Human Landing System, Option A Next Space Technologies for Exploration Partnerships-2, 4 2021.

[4] SpaceX. Straship User Guide, 3 2020.

[5] NASA.gov. International Space Station Facts and Figures, 5 2021.

[6] A. J. Gawronska, N. Barrett, S. J. Boazman, C. M. Gilmour, S. H. Halim, Harish, K. McCanaan, A. V. Satyakumar, J. Shah, H. M. Meyer, and D. A. Kring. Geologic context and potential EVA targets at the lunar south pole. *Advances in Space Research*, 66(6):1247–1264, 9 2020.

[7] Blaze Belobrajdic, Kate Melone, and Ana Diaz-artiles. Planetary extravehicular activity (EVA) risk mitigation strategies for long-duration space missions. *NPJ Microgravity*, 2021.

[8] NASA Office of Inspector General. NASA'S DEVELOPMENT OF NEXT-GENERATION SPACESUITS. Technical report, 8 2021.

[9] Michael L Gernhardt, Jeffrey A Jones, Richard A Scheuring, Andrew F Abercromby, Jennifer A Tuxhorn, and Jason R Norcross. Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems. In *Human Health and Performance Risks of Space Exploration Missions*, chapter 14, pages 333–358. 2009.

[10] Richard A. Scheuring, Jeffrey A. Jones, Joseph D. Novak, James D. Polk, David B. Gillis, Josef Schmid, James M. Duncan, and Jeffrey R. Davis. The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations. *Acta Astronautica*, 63(7-10):980–987, 2007.

[11] NASA. NASA-STD-3001, Volume 2: Human Factors, Habitability, and Environmental Health. *NASA Technical Standards*, 2, 2019.

[12] NASA Human Performance Research group. NASA Task Load Index, 2020.

[13] NASA. Lunar Regolith Management. In *Technology Exchange Conference*, Galveston, TX, 2007.

[14] Chiu Wing Lam, Robert R. Scully, Ye Zhang, Roger A. Renne, Robert L. Hunter, Richard A. McCluskey, Bean T. Chen, Vincent Castranova, Kevin E. Driscoll, Donald E. Gardner, Roger O. McClellan, Bonnie L. Cooper, David S. McKay, Linda Marshall, and John T. James. Toxicity of lunar dust assessed in inhalation-exposed rats. *Inhalation Toxicology*, 25(12):661–678, 2013.

[15] C I Calle, J L Mcfall, C R Buhler, S J Snyder, E E Arens, A Chen, M L Ritz, J S Clements, C R Fortier, and S Trigwell. Dust Particle Removal by Electrostatic and Dielectrophoretic Forces with Applications to NASA Exploration Missions. Technical report, 2008.

[16] Shenyi Zhang, Robert F. Wimmer-Schweingruber, Jia Yu, Chi Wang, Qiang Fu, Yongliao Zou, Yueqiang Sun, Chunqin Wang, Donghui Hou, Stephan I. Böttcher, Sönke Burmeister, Lars Seimetz, Björn Schuster, Violetta Knierim, Guohong Shen, Bin Yuan, Henning Lohf, Jingnan Guo, Zigong Xu, Johan L. Freiherr von Forstner, Shrinivasrao R. Kulkarni, Haitao Xu, Changbin Xue, Jun Li, Zhe Zhang, He Zhang, Thomas Berger, Daniel

Matthiä, Christine E. Hellweg, Xufeng Hou, Jinbin Cao, Zhen Chang, Binquan Zhang, Yuesong Chen, Hao Geng, and Zida Quan. First measurements of the radiation dose on the lunar surface. *Science Advances*, 6(39), 9 2020.

[17] Masayuki Naito, Nobuyuki Hasebe, Mana Shikishima, Yoshiharu Amano, Junichi Haruyama, Jose A Matias-Lopes, Kyeong Ja Kim, and Satoshi Kodaira. Radiation dose and its protection in the Moon from galactic cosmic rays and solar energetic particles: at the lunar surface and in a lava tube. *Journal of Radiological Protection*, 40(4), 12 2020.

[18] S. Hu, J.E. Barzilla, and E. Semones. Acute radiation risk assessment and mitigation strategies in near future exploration spaceflights. *Life Sciences in Space Research*, 24, 2 2020.

[19] John W. Norbury, Tony C. Slaba, Sukesh Aghara, Francis F. Badavi, Steve R. Blattnig, Martha S. Clowdsley, Lawrence H. Heilbronn, Kerry Lee, Khin M. Maung, Christopher J. Mertens, Jack Miller, Ryan B. Norman, Chris A. Sandridge, Robert Singleterry, Nikolai Sobolevsky, Jan L. Spangler, Lawrence W. Townsend, Charles M. Werneth, Kathryn Whitman, John W. Wilson, Sharon Xiaojing Xu, and Cary Zeitlin. Advances in space radiation physics and transport at NASA. *Life Sciences in Space Research*, 22, 8 2019.

[20] NASA. NASA Human Research Roadmap, 2021.

[21] Linda H. Loerch and Jacqueline M. Reeves. Exercise countermeasures on ISS: Summary and future directions. *Aerospace Medicine and Human Performance*, 86:A92–A94, 12 2015.

[22] James A. Loehr, Mark E. Guilliams, Nora Petersen, Natalie Hirsch, Shino Kawashima, Hiroshi Ohshima, and Jacqueline M. Reeves. Physical training for long-duration spaceflight. *Aerospace Medicine and Human Performance*, 86:A14–A23, 12 2015.

[23] Nora Petersen, Patrick Jaekel, Andre Rosenberger, Tobias Weber, Jonathan Scott, Filippo Castrucci, Gunda Lambrecht, Lori Ploutz-Snyder, Volker Damann, Inessa Kozlovskaya, and Joachim Mester. Exercise in space: The European Space Agency approach to in-flight exercise countermeasures for long-duration missions on ISS. *Extreme Physiology and Medicine*, 5(1), 8 2016.

[24] Christopher Hurst, Jonathan P. R. Scott, Kathryn L. Weston, and Matthew Weston. High-Intensity Interval Training: A Potential Exercise Countermeasure During Human Spaceflight. *Frontiers in Physiology*, 10, 5 2019.

[25] Tobias Weber, David A. Green, Julia Attias, Wolfram Sies, Alexandre Frechette, Bjoern Braunstein, and Jörn Rittweger. Hopping in hypogravity- rationale for a plyometric exercise countermeasure in planetary exploration missions. *PLOS ONE*, 14(2), 2 2019.

[26] Eligar Sadeh, David Livingston, Thomas Matula, and Haym Benaroya. Public-private models for lunar development and commerce. *Space Policy*, 21(4):267–275, 11 2005.

[27] NASA Office of Inspector General. NASA'S Management and Utilization of the International Space Station. Technical report, NASA Office of Inspector General Office of Audits, 7 2018.

[28] Tanja Masson-Zwaan. Legal Aspects of Space Debris. In Christophe Bonnal and Darren S. McKnight, editors, *IAA Situational Report on Space Debris - 2016*, chapter 11. International Academy of Astronautics, 2017.

[29] Antonino Salmeri. Developing and Managing Moon and Mars Settlements in Accordance with International Space Law. *Proceedings of the 71st International Astronautical Congress.*, 2020.

[30] Artemis Accords. Principles for a Safe, Peaceful, and Prosperous Future, 2020.

[31] The Hague WG. Building Blocks for the Development of an International Framework on Space Resource Activities. 2019.

[32] NASA ISRU. Overview: In-Situ Resource Utilization, 4 2020.

[33] Lennard A. Fisk. Planetary Protection: The COSPAR Perspective. Irvine CA, 6 2017.

[34] NASA IGA. 20 Years Ago: Station Partners Sign Intergovernmental Agreement (IGA), 1 2018.