Science and Technology Concepts Feasibility Study for Future Lunar & Cislunar Mission Planning: A Comprehensive Evaluation of ISU's Team Project Reports

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Abstract

With the recent focus on returning to the Moon by some of the most relevant actors in the space community, it has become necessary to evaluate the current technological needs to achieve such an ambitious goal. One of the proposed solutions is the Lunar Gateway, which aims at serving as a permanent base to resupply future lunar and cislunar missions, as well as long-distance missions that will potentially reach Mars. This thesis provides a comprehensive analysis of future opportunities for lunar and cislunar missions by revising 143 ISU Team Project Reports (TPRs), from which 9 relevant concepts are selected. A set of recommendations for further research on each of the proposed concepts is outlined, as well as a feasibility assessment to rank their relevance and timeliness for future implementation on the Lunar Gateway and scientific missions to be launched to the surface of the Moon. This study showcases the relevance and potential that research projects performed at the International Space University have in regards to lunar mission planning. .

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List of Acronyms

A

ADR – Active Debris Removal

AMS – Alpha Magnetic Spectrometer

C

CLPS – Commercial Lunar Payload Services

CSP – Concentrated Solar Power

E

ED&L – Entry, Descent and Landing

ER&T – Exploration Research and Technology

EVA – Extravehicular Activities

G

GCD – Game Changing Development program

GCR – Galactic Cosmic Rays

GEO – Geostationary Earth Orbit

GPR – Ground Penetrating Radar

H

HEOMD – Human Exploration and Operations Mission Directorate

I

ISM – In-Space Manufacturing

ISU – International Space University

J

JAXA – Japan Aerospace Exploration Agency

L

LEAG – Lunar Exploration Advisory Group

LER – Lunar Exploration Roadmap

LuGaLiSuS – Luna Gaia Life Support System

N

NASA – National Air and Space Administration

NGSS – Next Generation Space Station

O

OOS – On-Orbit Servicing

ORU – Orbital Replacement Unit

P

P2P-HRI – Peer to Peer Human-Robot Interaction

PV - Photovoltaic

Q

QWIP – Quantum Well Infrared Photodetector

R

RFP – Request For Proposal

RRM3 – Robotic Refueling Mission 3

S

SMD – Science Mission Directorate

SPS – Solar Power Satellite

T

TPR – Team Project Report

I. Introduction

In a recent Request for Proposal (RFP) for Commercial Lunar Payload Services (CLPS) on September 6, 2018, NASA expressed an emphasis on going back to the Moon and expand its partnership opportunities with private and international entities to enable a shorter timeframe to achieve the mission of sending humans back to the Moon (Warner, 2018). At the same time, the recently signed Space Policy Directive 1 by the USA's President, Donald Trump, provides the appropriate conditions to further expand NASA's activities towards space exploration with the clear goal of returning to the Moon and establish the ground basis for future exploration of Mars (Northon, 2018).

One of the proposed solutions is the Lunar Gateway, which aims at serving as a permanent base to resupply future lunar and cislunar missions, as well as long-distance missions that will potentially reach Mars. As discussed by McCurdy (2005) in his analysis on NASA's required transformation to go back to the Moon, the use of an orbiting spacecraft on a lunar orbit will be essential to support the future of space exploration, and it has become a reality as it has been clearly stated on NASA's Exploration Campaign

Figure 1).

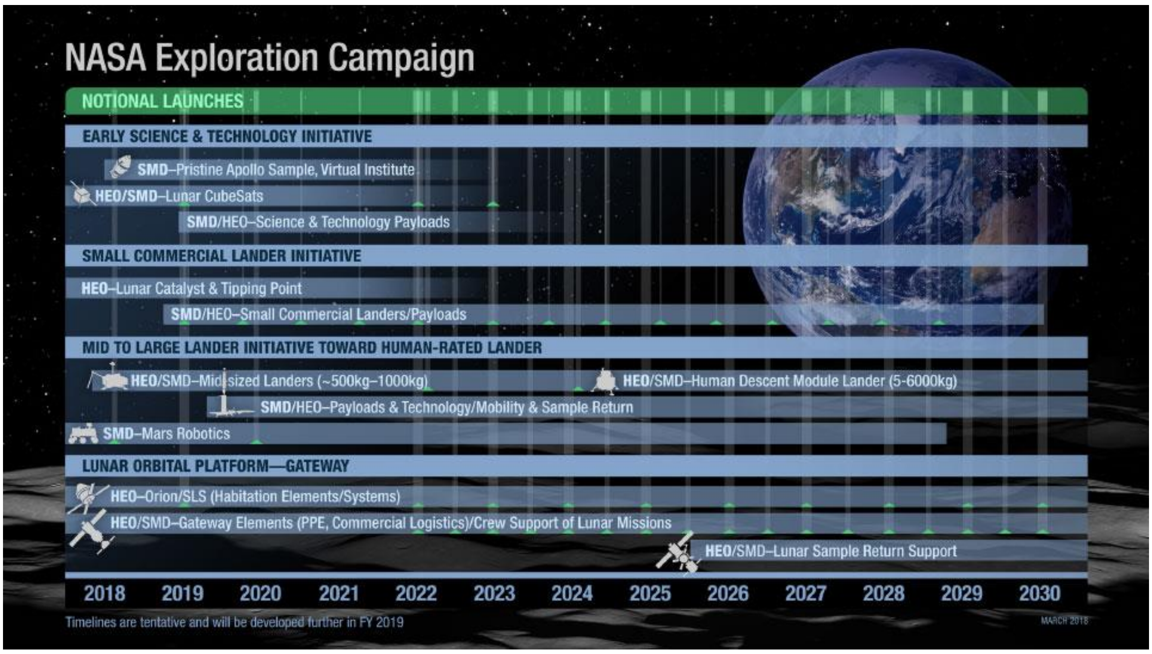


Figure 1 NASA's Exploration Campaign (Dunbar, 2018)

I. Introduction

Similarly to what the International Space Station (ISS) has been offering to date, the Lunar Gateway has been conceived as a permanent spacecraft that would orbit the Moon to offer services to other human and robotic missions, and with the ISS's end of life coming in a near future, it is timely to elaborate on potential areas of focus that could become critical for the Lunar Gateway's operation, as well as unexplored concepts that could enhance or improve the services it aims to provide.

The International Space University (ISU), as part of its academic programs, requires students to work on a Team Project which, at the end of the program, is evaluated through a Final Report and Final Presentation. These projects are focused on solving relevant challenges in the space domain and on proposing innovative concepts for future applications. Based on this, the idea of looking into these projects to find areas of opportunity for NASA was presented by Steve Brody, Vice President of ISU's North American Operations, as a thesis project supported by NASA's Office of the Chief Scientist.

Past ISU Team Project reports may contain ideas that are of current value to NASA's planning for cislunar orbital and/or lunar landing and surface missions. These may have been the prime focus of a past TP or recorded in ancillary material, for example, in TP report annexes. Such concepts or ideas could be scientific or technological, they could also be of value to policy, communications, or commercial considerations. As of January 2019, ISU's on-line catalog contains a total of 141 Team Project Reports, from which the number of reports that might contain valuable ideas regarding missions to land on the Moon or to perform cislunar activities is to be defined through the research activities of this thesis.

I.I Purpose and Scope

As mentioned at the beginning of this chapter, this report aims to identify concepts and ideas for future lunar and cislunar missions that might have been explored in previous Team Project Reports and could be of high value to what is currently a priority of the space exploration's agenda. At the same time, the resulting findings shall be linked to NASA's Lunar Gateway, demonstrating how they could benefit from using it as a platform or how their later development on the lunar surface could be valuable.

To do this, the "*Lunar Gateway's objectives to support scientific discovery and opportunities for a Lunar economy*" (Jackson, 2018) will be used as a base to classify the information. To support a long-term presence of humans on the Moon and other cislunar efforts, four areas of opportunity (Figure 2), as described by NASA too, were identified as primordial for further development of the Lunar Gateway's capabilities (Jackson, 2018):

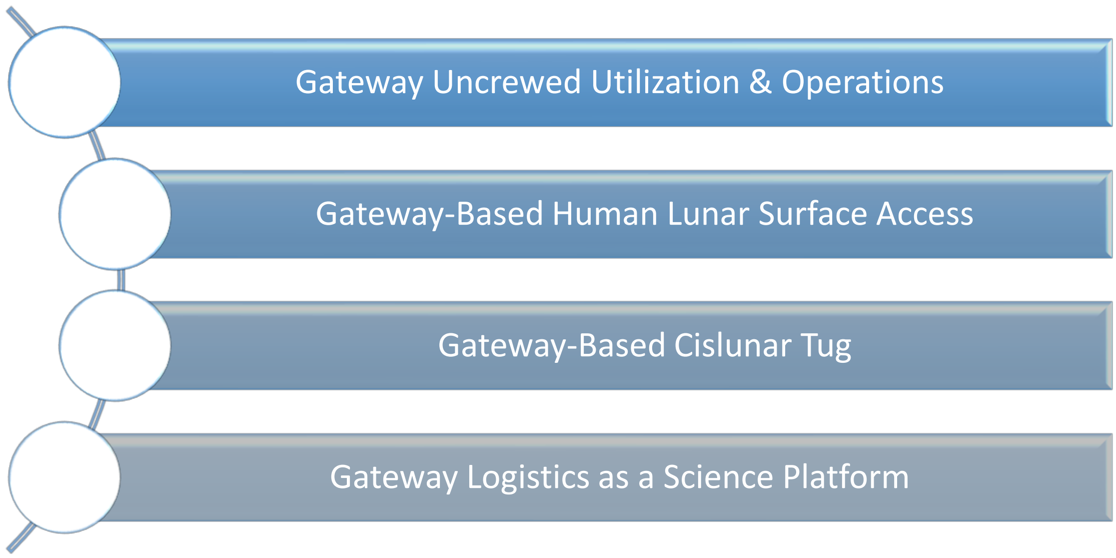


Figure 2 Lunar Gateway's areas of opportunity for further development

These four areas of opportunity were used as main guide when classifying the information found on the TPRs and helped shape the final phase of the thesis where a set of recommendations of potential value to the Lunar Gateway and other future lunar and cislunar missions are outlined.

I.II Aims and Objectives

The aim of this thesis is to review all the existent Team Project Reports (TPRs) available at ISU's database that are relevant to future Lunar and Cislunar missions to identify ideas or concepts of value for NASA's lunar/cislunar mission planning, taking into consideration concepts such as robot operation and maintenance, lunar surface exploration, astronaut activities, safety emergencies, in-orbit servicing, amongst others. Complementary to this, this thesis aims at developing a set of recommendations of potential value for NASA's Lunar Gateway and other future lunar/cislunar missions.

To address these aims, the following objectives were established:

O1. To formulate a prioritized list of TPs with technological and non-technological concepts and ideas of potential high value to NASA's and the international community's lunar/cislunar mission planning.

O2. To identify and categorize potential high value technological and non-technological concepts and ideas from these TP reports and assign a level of feasibility to each.

O3. To determine a select number of the most promising concepts and ideas for further research, and formulate an outline, aims, and objectives for a subsequent research phase.

O4. To identify the concepts and ideas, from the final list, that are relevant to the development of the Lunar Gateway.

I.III Report Structure

The first section of this report provides a brief introduction to the motivation behind this thesis, its purpose and scope and the specific objectives that were tried to be accomplished through its development.

The second section describes the methodology that was implemented to achieve the objectives presented in the first section, from selecting and filtering the TPRs, evaluating the relevance of the presented ideas and concepts and finally, the feasibility assessment performed on the most promising ones. A list with 28 preselected reports is presented in this section,. Including a brief description of each of their mission statement and general concept.

The third section provides an overview of the current state of NASA's lunar exploration plans and the rationales behind chosing the Moon and cislunar space as the next destination to establish a permanent human presence and how this will pave the way towards reaching Mars.

The fourth section provides a brief initial analysis of the reports that were selected from the first filter, indicating whether there were or were not ideas or concepts worth taking for a further feasibility evaluation. For those concepts that were identified through the first revision of the TPR, an initial evaluation of the related scientific objectives and justification to using the Lunar Gateway or the lunar surface as platform for further research is provided.

The fifth section presents the feasibility evaluation for each of the selected concepts, a time phased assessment on actions to take and an outline of recommendations for further research.

The sixth section evaluates the performance according to the initial plan for the thesis, providing extra recommendations for future research on this work.

The seventh and final section provides a summary of the recommendations made for future research activities and the final prioritized list of TPRs with potential for further development. A brief subsection on recommendations to ISU for further TPs and areas to focus is also presented at the end of this section.

II. Methodology

This section explains the methodology used for the Team Project Reports' initial selection and concepts' evaluation for the final feasibility and prioritization study.

II.I Team Project Reports' Selection Process

The first phase of this research project was focused on performing an extensive literature review comprising all the lunar-related Team Project Reports from the ISU's database and the current state of NASA's plans to go to the Moon. To achieve this, a filtering strategy had to be applied to the 143 available TPRs in order to perform a more detailed analysis in a later stage. As shown in Figure 3, the first filter consisted on identifying lunar/exploration-related titles to perform a first content evaluation through their Executive Summaries and abstracts. From this step, a total of 28 reports were identified as potential studies of relevant concepts for future lunar and cislunar missions, so, by evaluating each of their mission statements and general concepts, a second filter was applied to help focus the final feasibility evaluation of the concepts.

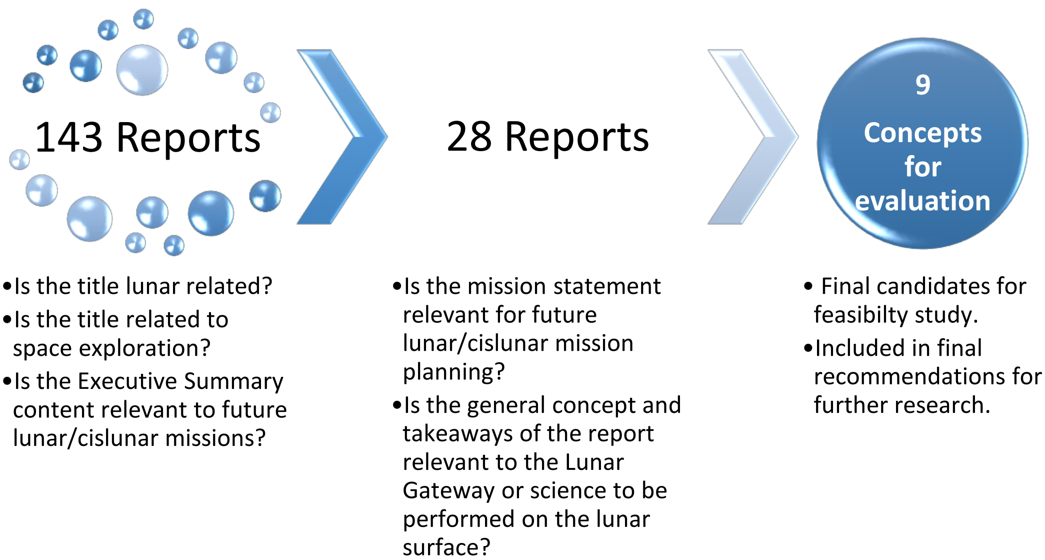


Figure 3 Filtering Process for Concept Identification

A brief description of each of the 28 Team Project Reports' general concept and mission statement are summarized on Table 2, starting with the most recent reports. This phase resulted in a selection of 10 TPRs that were subject to the final feasibility study and on which the final recommendations are built.

As mentioned in the Lunar Exploration Roadmap (LER) developed by the Lunar Exploration Advisory Group (LEAG) (2013), there is still room for development in sustainability matter for future exploration missions of the Moon and Mars; however, given the renewed investment to establish a more permanent human presence in the lunar and cislunar space, it is essential that this topic accelerates its development through close international collaboration between public and private entities. Based on this, a special focus on sustainability was made when evaluating each of the selected concepts.

With this in mind, and keeping the objective of also developing a diverse commercial contribution in the expansion of space exploration, this report builds upon the existing plans of NASA and partners to enable the use of a Lunar Gateway as a precursor step for advanced lunar exploration and scientific activities to be performed on the lunar surface, as well as relevant ideas and concepts that were explored on ISU's TPRs and that could now be better developed thanks to scientific and technology advancements, commercial collaborations and even legal and political reforms.

Goals and objectives for each concept are summarized in their individual section, providing a link to why the Lunar Gateway or the lunar surface are the best platform to implement them. At the same time, based on the Lunar Exploration Roadmap developed by the LEAG, a prioritization has been assigned as to how relevant each concept is to facilitate progress of establishing a permanent human settlement on the Moon. Depending on each concept's link to each of the goals listed on Table 1, a time assessment is provided as to which would be the recommended research actions to be taken in an early, middle and late stage of a future lunar mission.

Table 1 Lunar Exploration Roadmap goals and objectives (Lunar Exploration Advisory Group, 2013)

Goal	Objectives
SCIENTIFIC THEME	
To pursue scientific activities to further understand our place in the universe and to address fundamental questions about its origin	
Goal	**Objectives**
Goal-SCI-A	To understand the formation, evolution and current state of the Moon.
Goal-SCI-B	To use the Moon as an archive storing the Solar System's evolution.
Goal-SCI-C	To use the Moon as a platform for Astrophysical, Heliophysical and Earth observation studies.
Goal-SCI-D	To use the lunar environment as a research tool for its unique characteristics.
FEED FORWARD THEME	
To use the Moon as precursor platform for future missions to Mars and deep space.	
Goal-FF-A	To use the Moon as testbed for technologies that will enable human and robotic exploration of the Solar System.
Goal-FF-B	To use the Moon as testbed for exploration techniques and mission operations, reducing the risks and augmenting productivity of future missions to deep space and Mars.
Goal-FF-C	To prepare for future missions to other celestial bodies.
SUSTAINABILITY THEME	
To enable sustained human presence on the Moon that will enable an eventual permanent settlement.	
Goal-SUST-A	To maximize commercial activity.
Goal-SUST-B	To enable and support collaboration to expand science and exploration.
Goal-SUST-C	To enhance security, peace and safety.

Figure 4 depicts the time phasing frame that was used to assign the timing recommendations for the concept evaluation. Depending on the state of development that was identified for each of the studied concepts, as well as on the concept's relevance to help achieve the previously mentioned objectives, a variance in the time phasing evaluation could be found, but an appropriate justification to such reasoning would be provided within the corresponding section.

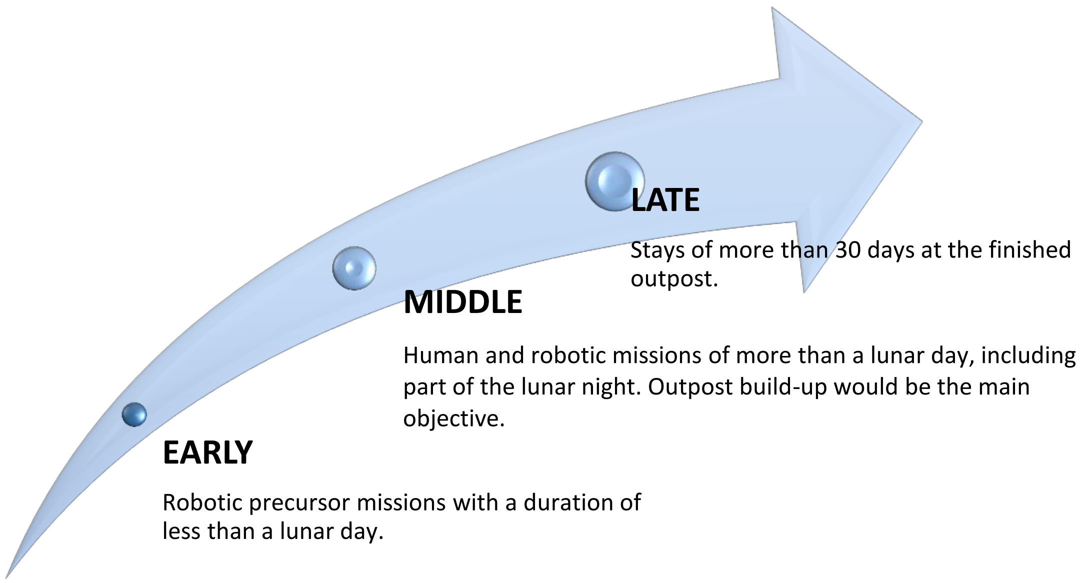


Figure 4 Time phasing for concept evaluation (adapted from (Lunar Exploration Advisory Group, 2013)*)*

Following Objective 1 of this thesis (Aims and Objectives above), to create a prioritized list of the most promising concepts found during this thesis' research, the following criteria were used to assign a level of priority to each concept (Figure 5):

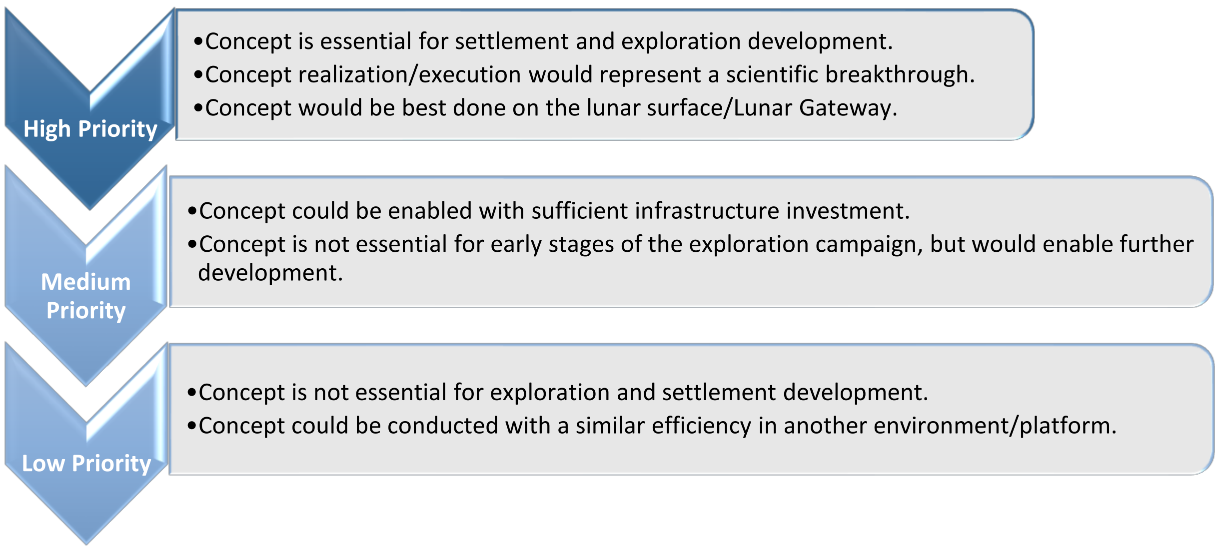


Figure 5 Prioritization criteria for concept evaluation (adapted from (Lunar Exploration Advisory Group, 2013)*)*

Table 2 Description of Relevant Team Project Reports

TITLE	YEAR	GENERAL CONCEPT	MISSION STATEMENT
Sustainable Moon	2019	Development of fifteen lunar sustainability goals and rationales from reviewing existing lunar activities plans, to be integrated to what is currently planned for lunar surface missions.	"To shift the discourse about the Moon towards sustainability by creating a framework that enables people to benchmark lunar activities, ensuring the sustainable use of the Moon and cislunar space" (International Space University, 2019b)
Manufacturing for exploration	2019	Identification of areas of opportunity for in-space manufacturing (ISM) using the ISS as an analogue to a long-duration crewed mission, which is proposed as a case study for ISM and from which a set of recommendations for further development is derived.	"To leverage in-space manufacturing to support a deep space crewed mission" (International Space University, 2019a)
Lunar nights survival	2018	Support up to six astronauts continuously to supply power throughout lunar nights and scale up as power demands increase (up to 10 kW for 10 years). Relevant concepts: • Kilo power fission technology • Photovoltaics, fuel cells and batteries • Automated Rover to lay cable on lunar regolith. • Disaster Recovery Plan (DRP) • International collaborations regulation	"To create a scalable power generation and distribution system for utilization during lunar days and nights to enable a sustained presence on the Moon." (International Space University, 2018)
Starport 1	2016	Concept proposal of a station that contains a section with artificial gravity and another with a microgravity environment, both of which shall be fully functional by 2040. • Relevant concept: Central hub approach – similar to ISS/Gateway	"To conduct a conceptual design for a commercial space station on behalf of Axiom Space, which will allow people to live in an Earth-like environment, while enabling in-orbit manufacturing, scientific research and space tourism." (International Space University, 2016b)
Lunar Hathor: international deep drilling lunar mission study	2016	Study of rationales for deep drilling lunar missions. And assessment of collaboration structures for international space missions.	"To develop a framework for future international space mission collaborations and assess the scientific and technological

			aspects of a deep drilling mission to the Moon." (International Space University, 2016a)
Vision 2040	2015	Identification of driving forces for disruptive changes in five areas of interest for the space sector, as well as challenges to overcome to reach a projected development 25 years in the future.	"To provide strategic roadmaps for ISU by forecasting future scenarios in space exploration and development, identifying signals of disruptive change, underlying driving forces, potential challenges and skills that will be necessary to overcome them."(International Space University, 2015)
AMOOS: Autonomous Mission for On-Orbit Servicing	2014	Revision of Active Debris Removal (ADR) technologies and On-Orbit Servicing (OOS) state of the art, to identify current challenges and outline a set of recommendations for future implementation in satellite servicing. A special focus is given to unmanned space plane and embedded robotics systems.	"To promote a sustainable space environment for future generations conducting a multidisciplinary feasibility analysis of robotics-equipped, autonomous space planes to service satellites and to remove debris from LEO." (International Space University, 2014)
BLISS: beyond LEO into the Solar System. A guide to future space stations	2012	Design of a guidebook for Next Generation Space Stations (NGSS) that identifies primary design drivers in areas such as commercial applications and uses, science, exploration and legal issues. All of these are summarized in a matrix with recommendations for efficient approaches.	"To establish a guide based on design drivers for a next generation space station, built upon diverse partnerships and capabilities, to research and demonstrate key science, technologies and systems necessary to enhance socioeconomic value and expand human exploration beyond LEO"(International Space University, 2012a)
OASIS: operations and service infrastructure for space	2012	Concept proposal of a spaceport network that provides on-orbit refueling and tug services to support space exploration. The main refueling and resupply support focus is located on LEO, having the Moon, Mars and asteroids as the subsequent nodes of the network.	"To develop a progressive network of spaceports using the most cost-effective resources to enable space exploration and commercial activities, and ultimately to extend humanity throughout the Solar System" (International Space University, 2012b)

		Plans for future spaceports and capabilities at that time are assessed to formulate a feasible approach to make the OASIS concept plausible.	
Access Mars: accessing cave capabilities establishing specific solutions	2009	Assessment of usage of martian caves for human habitation as a solution to challenges such as high levels of radiation and harsh climate. Identification of areas for further research to enable cave utilization are listed, while sub-surface operations and thermal control, communications and power systems are investigated to provide a set of recommendations for an architecture for precursor missions.	"To develop a mission architecture for an initial settlement on Mars by assessing the feasibility of cave habitation as an alternative to proposed surface-based solutions" (International Space University, 2009)
Noumenia: building on the Google Lunar X Prize	2008	Identification of the most important stakeholders affected by Google's XPrize through a "stakeholder matrix". Recommendations for such stakeholders are provided as to how to maximize the benefits from Google's XPrize. Relevant concepts: • Environment impact of the Google XPrize, on Earth, the Moon and space. • Technical challenges.	"To develop a set of recommendations that will initiate new involvement in lunar development and maximize stakeholders' benefit from the GLXP, by creating global activity in the competition and beyond" (International Space University, 2008b)
ALERTS Analysis of Lunar Exploratory Robotic Tasks for Safety	2008	Listing of 66 lunar surface tasks to be performed by astronauts. Creation of a "Robotic Solution Decision Tree" that allows the user to easily identify a robotic system that could increase the crew's safety, depending on the type of task to be performed. Proposal to establish an International Space Exploration Safety Board.	"To develop a set of recommendations for crew safety during lunar surface exploration and surface EVA activities, based on a robotics-assisted approach." (International Space University, 2008a)
DOCTOR: developing on-orbit servicing concepts, technology options and roadmap	2007	Gap and feasibility study of on-orbit servicing missions, with a focus on inspection, maneuvering and manipulation activities, as well as their key challenges and opportunities.	"To use an interdisciplinary approach to explore the concept of on-orbit servicing, identify the key existing and future technological, economic and policy drivers, and propose a structured approach to its progressive incorporation into the

			activities of the space industry.” (International Space University, 2007a)
Full Moon: storage & delivery of oxygen and hydrogen	2007	Evaluation of future challenges for oxygen and hydrogen supply and storage services. The final result is a storage & delivery architecture concept with a “lunar gas station”-like approach.	“To develop a lunar storage and delivery architecture for oxygen and hydrogen, based upon a technical and business analysis to enable exploration of the Moon” (International Space University, 2007b).
Luna Gaia: a closed loop habitat for the Moon	2006	Proposal of a closed-loop habitat system concept for a 12-member human crew on the surface of the Moon, for an 18 to 26 month-long mission. Assessment of systems such as NASA JSC Breadboard, MELiSSA, Bios-1, 2 & 3 and CEBAS.	“To create a responsible framework for the establishment of a long-term lunar settlement, functioning as an efficient self-sustained closed loop system with potential Earth applications.” (International Space University, 2006b)
FERTILE Moon – Feasibility of extraction of resources and toolkit for in-situ lunar exploration	2006	Creation of a cost estimation model tool for ISRU activities, based on a three-layer approach that includes demand, supply and costing. With this Excel/Visual Basic tool, the user should be able to evaluate costs depending on different mission scenarios.	“To develop an evaluation model for economic feasibility of lunar ISRU technologies for hydrogen, oxygen and water production” (International Space University, 2006a).
LunAres: international lunar exploration in preparation for Mars	2004	Analysis of potential science and technology elements that could enable a future mission to Mars and that could be implemented before in a lunar mission as a precursor step to martian implementation. A list of 28 recommendations to implement the suggested exploration program is provided .	“To select, among the identified key concepts, technologies and systems that will enable human Mars exploration, those that can be best tested on the Moon, and suggest a framework for international lunar missions that can be carried out to validate them by 2020, including the enabling policy, legal, societal and economic aspects.” (International Space University, 2004)
METZTLI: an International Space Station approach to lunar exploration	2003	General examination of ways in which the ISS assets and organization can be used to support future exploration activities on the Moon.	“To create an international approach to peaceful lunar development which encourages a permanent lunar presence and furthers space exploration.” (International Space University, 2003)

C.A.S.H. 2021: Commercial Access and Habitation	2001	Creation of a roadmap, from 2001 to 2021, where areas such as tourism, entertainment, space systems servicing and research are studied to identify how their commercialization could develop.	"To document a plan that identifies commercial opportunities for space utilization that will extend human presence in space and that charts the way forward for the next 20 years"(International Space University, 2001)
Autonomous Lunar Transport Vehicle (ALTV): providing a link for scientific research	2000	Autonomous lunar transport vehicle to operate between two bases in 2040. Transport of 550 kg from Shackleton crater to Tsiolkosvsky crater (2123 km). Relevant concepts: • Crew safety • Crew survivability • Vehicle reliability • Vehicle reusability • Legal obligations • Operations cost	"To design a crewed transportation system operating between points on the surface of the Moon to support science missions."(International Space University, 2000a)
Space Tourism: from dream to reality	2000	A summary of the state of the art of space tourism activities and the most important challenges and considerations for it future development, focusing on areas such as pre-orbital space tourism, LEO space tourism (including flights and facilities) and future visions of space tourism.	"To expand opportunities for humans to experience space by proposing a framework for tourism that is enduring, evolutionary and open to all" (International Space University, 2000b)
Open for business: a new approach to commercialization of the ISS	1999	Report divided into two parts, where the first one proposes new solutions to the identified constraints to commercialization of the ISS; the second part proposes two potential commercial applications for the ISS: an International Space Satellite Servicing System and Protein Crystallization.	"To identify the major constraints under which the commercial user of the ISS must operate and to propose solutions for both the partner space agencies and the commercial users themselves, to facilitate the commercialization process" (International Space University, 1999a)
Out of the cradle: an international strategy for human exploration away from Earth	1999	A study of the current state (at that time) of space agencies' plans for future space exploration to set the scenario for a proposed precursor mission. Five different candidate missions are analyzed: • Near-Earth Object (NEO) water extraction • Orbital greenhouse	"To develop an internationally coordinated master plan for human exploration away from Earth and carry out a detailed design study of one exemplary precursor mission" (International Space University, 1999b)

		• Space hotel • Lunar in-situ resource utilization • Lunar rover race Finally, recommendations are provided for further development of a Lunar rover race mission.	
International strategies for the exploration of Mars	1997	A set of strategies comprising policy, technology, international cooperation, resource utilization, societal implications and mission system design considerations for future exploration activities on Mars, having as main objectives: • Planetary science • Search for life • Human presence on Mars Technology development and public support are also included in complementary strategies for future development.	“To create coherent, coordinated strategies and the associated framework for the international robotic and human exploration of Mars” (International Space University, 1997)
Distant Operational Care Center	1996	A modular center for health treatment of astronauts is proposed, with adaptability and expandability as two of the main design drivers. Amongst some of the most relevant concepts explored within this module are: • Dental care and surgical intervention. • Telemedicine with real-time consultation with physicians. • Virtual reality and 3D reconstruction techniques. The final proposed concept is then evaluated in a LEO scenario and a Mars mission scenario.	“To outline the design of a Distant Operational Care Center (DOCC), a modular medical facility to maintain human health and performance in space, that is adaptable to a range of remote human habitats” (International Space University, 1996)
International Lunar Farside Observatory and Science Station (ILFOSS)	1993	State of the art evaluation of scientific research done and to be done on the Moon, to finally list a series of potential science experiments to be performed on the farside of the Moon under the framwork of a future observatory and science station. Recommendations for pigyback payloads are also included.	“To perform an interdisciplinary study of the establishment of an international astronomical observatory and science station on the farside of the Moon” (International Space University, 1993) .
ARTEMIS: a program to map and identify lunar resources	1989	A mission program named “Artemis” is proposed to identify and map lunar resources to prepare for human habitation	“To complete and document a preliminary design of a program focused on identifying

		of the Moon, using a nadir-pointing, three-axis-stabilized spacecraft in a polar orbit above the lunar surface. A not-for-profit organization called "Artemis International Corporation" is proposed as the enabling actor for this mission.	and mapping the lunar resources, with an emphasis on using those resources for human inhabitation of the Moon and other space activities" (International Space University, 1989)
International lunar initiative organization	1988	A detailed multidisciplinary plan to implement a human settelement on the lunar surface, consisting on 14 chapters, each corresponding to a specific discipline, where an assessment of the topics to focus on to ensure a successful development of the settlement is provided, as well as recommendations for further development.	"To draft a multidisciplinary plan for a hypothetical organization to implement a manned lunar base, with a self-sufficient approach, in the year 2030"(International Space University, 1988)

II.II Feasibility Study & Prioritization Process

In order to perform the feasibility study on the selected technology and science concepts, a prioritization matrix (as shown later in Chapter *V. Feasibility Study on Selected Concepts*) was created to assess their potential with an interdisciplinary approach, focusing on four main areas, as depicted on Figure 6.

Figure 6 Focus Areas for Feasibility Analysis

Depending on assigned quantitative values and their weight against specific criteria, a feasibility result of each concept was obtained, as it is shown in detail on the upcoming *Section V. Feasibility Study on Selected* Concepts*,* where a summary of the results obtained from the recommendations and feasibility analysis is provided.

For the Technology Readiness Level (TRL) criteria evaluation, NASA's measurement system was used as the reference frame,which is described on Figure 7.

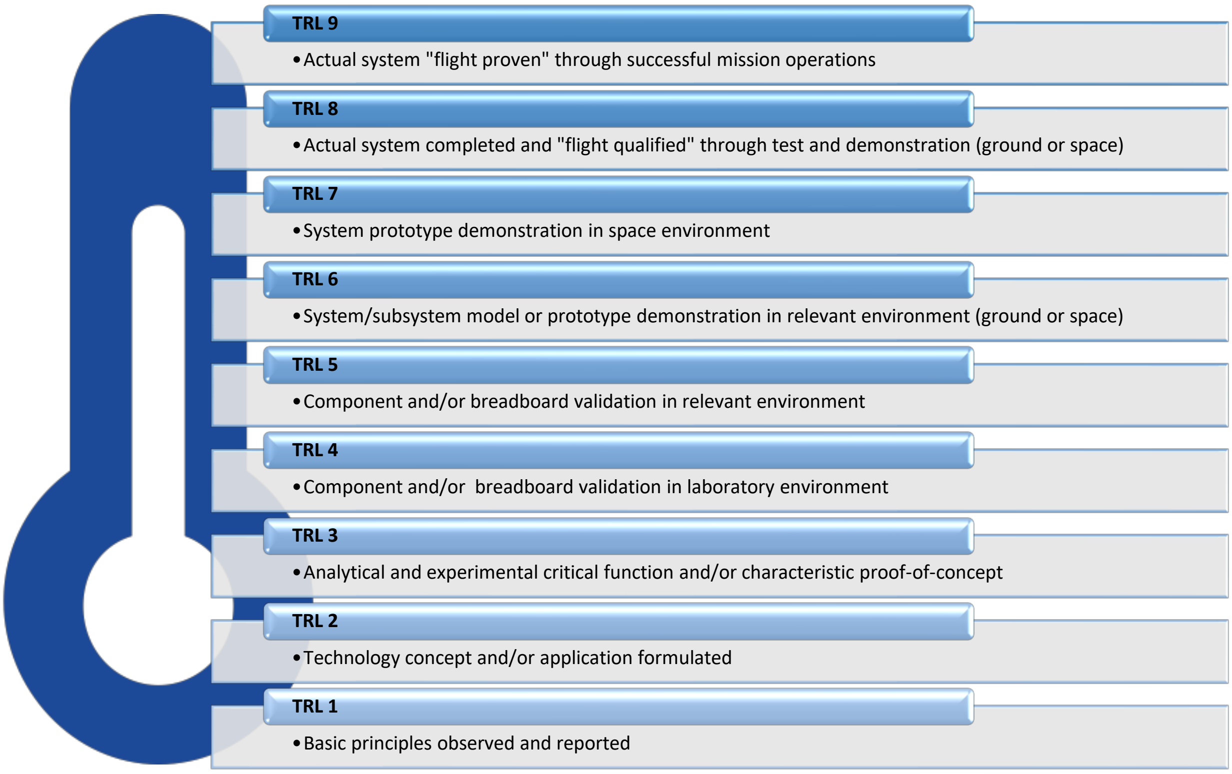


Figure 7 Technology Readiness Level Scale, adapted from (Mai, 2012)

Regarding the Technical criteria for the concepts' evaluation, a weighted measurement is proposed following a set of four parameters to evaluate, as described on Table 3 below. Using a measurement reference score, multiplied by a weighted priority given to each of the parameters, a total score is obtained for the performance criteria of each concept, which is later included in the overall final evaluation for the prioritization of all the evaluated concepts.

Table 3 Performance parameters for concept weighted evaluation

Criteria	Parameter	Top Performance	Measurement Reference	Weight
Technical	Operational Efficiency	Concept operates with a low power consumption	Specific power (W)	4
	Autonomy	Concept is fully automated, does not require crew intervention to operate	• Concept requires human intervention (1 pt) • Concept can be teleoperated (2 pt) • Concept is fully automated (3 pt)	3
	Safety	Concept's operation does not represent a hazard to crew or other infrastructure element	• Does it require human operation? o Yes (1 pt) o No (2 pt) • Is it made of radioactive elements? o Yes (1 pt) o No (2 pt)	2
	Adaptability	Concept can be used for other different purposes	Concept has been linked to other applications: • Yes (2 pt) • No (1 pt)	1

To weigh the relevance of each of the proposed criteria for the prioritization process, a criterion one-on-one weighing excersise was performed as shown in Table 4. Comparing the importance of each criterion on each row over those on each column, an overal weight grade was obtained, following this rules:

- If the criterion on the row is more important than the one on the column, then the one on the row is awared two (2) points, while the column criterion obtains cero (0) points.
- When criteria are not comparable, or depend on each other, both obtain one (1) point.

Table 4 One-on-one criteria weighing

Criteria	Technical	Economic	Scheduling	Policy/ Legal	Weight
Technical (Performance, Safety)	1	2	0	2	5
Economic (Cost)	0	1	0	2	3
Scheduling (TRL)	2	2	1	2	7
Policy/Legal	0	0	0	1	1

Justification:

The objective of this thesis is to determine which concepts show more potential for a future implementation on lunar and cislunar missions, and from this, to outline recommendations for further research; based on this premise, the criteria that will allow a concept to become feasible within the established timeline for lunar exploration were awarded a higher priority when performing the comparison exercise. For example:

- While allowing a sustainable human presence on the Moon is one of the main goals for future missions, it is more important, time-wise, to ensure proper performance of the concept first.
- Despite the existence of some international treaties that could question the implementation of a certain concept, having mature concepts or operating technologies is more relevant for their feasibility.
- Technology readiness level of the concept is more important than the proposed performance, therefore, “Scheduling”. criterion is given a higher rank over “Technical”.
- “Scheduling”. criterion is given a higher rank over “Economic” based on the assumption that a significant investment has already been made to reach the concept’s TRL.
- “Scheduling”. criterion is given a higher rank over “Operational” since the second criterion depends on the first one.
- “Policy/Legal” criterion is given the lowest ranking in this evaluation based on the lack of development in this area and

A similar reasoning was adopted by the National Research Council of the National Academies (2007) on its analysis of the scientific rationales for exploring the Moon, setting as the highest priority the scientific merit of the concept, followed by realism of achieving its goal and finally the TRL required by the concept to carry out its intended activity, within an defined timeframe.

Finally, to weigh the remaining criteria: Economic and Policy/Law, a simple Yes/No question evaluation is proposed to award a grade, as explained on Table 5.

Table 5 Weigh evaluation for Economic, Sustainability and Policy/Law criteria

Criteria	Parameter	Top Performance	Measurement Reference
Economic	Impact on budget	Concept can be developed or/operates without a overpassing an established budget	$22.6 billion USD for NASA’s FY 2020 (NASA, 2019)
Policy/Law	Violation of: • Outer Space Treaty • Moon Treaty • Liability Convention • Rescue Convention	Concept does not violate any international Treaty in outer space or on Earth	• Does the concept have a questionable operation according to any international Treaty? ○ Yes (1 pt) ○ No (2 pt)

III. Why Should We Go Back to The Moon?

It is interesting to witness the renewed international interest to go back to the Moon, specially being so close to celebrating the 50th anniversary of the Apollo 11 mission landing on the lunar surface, only that this time, there are more than two main actors involved. The Chandrayaan-2, Chang'e-4 and Beresheet missions are some examples of the dynamic panorama of this new space dynamism, and the already mentioned plans of NASA, ESA and Roscosmos of engaging in more ambitious missions show that there is a special reason driving this dynamism (McKie, 2019); what is motivating all these players to bet on a future on the Moon? This section provides a brief overview of the main reasons that justify the current development of science and technology that will allow humankind's return to the Moon.

III.I In-Situ Resource Utilization

One of the biggest constraints in mission design is mass, not only because of its impact on the amount of energy required to move a spacecraft or the amount of resources that can be carried on board for mission support, but also because it limits the amount of scientific instruments that can travel with it, increasing the breach between the limited scientific research that has been done to date and what could be achieved (Sanders, 2010). A potential solution for this problematic is In-Situ Resource Utilization (ISRU), a concept based on the use of resources available locally, which, in this case, comes mainly from lunar regolith. Through ISRU, mission costs can be reduced and better prospects for permanent settlements on the lunar surface can be secured (as depicted in Figure 8), but obeying the current trend in commercial activities in space, such as space mining, the drivers behind the support of ISRU activities keep increasing.

Figure 8 Main areas of impact of ISRU activities for lunar missions

Water can be obtained from lunar regolith, which is a vital resource for future explorers; linking this to the first area of impact listed on Figure 8, in-situ production of mission consumables provides key capabilities to sustain life, produce and store power, and refueling spacecraft (Sanders, 2010). These activities represent big business opportunities for private entities that are leaning toward mining and refueling technology development, which has worked as catalyst to open collaborations between them and space agencies, as it can be observed through the recently released CLPS project, where at least four of the twelve chosen payloads to be supplied through a commercial partnership, has the objective of studying lunar regolith for future ISRU activities (Northon, 2019).

Adding to the potential in mission consumables support, ISRU development can also help decrease mission risks linked to long-duration exposure to the space environment, such as radiation damage on the crew and the mission infrastructure, while at the same time, it can facilitate emergency response to system failure where support from Earth-based resources would not be feasible. Despite the potential benefits from ISRU activities, the reality is that none of the proposed concepts has ever been tested on-site, under the real conditions they would be meant to operate.

Developing ISRU technologies will help prepare future crewed missions to the Moon and the establishment of a permanent settlement on its surface. Reduction of costs and risks for future lunar and cislunar missions will constitute precursor activities for taking humans to Mars and to enable commercialization of space.

III.II Lunar Gateway Science Opportunities

Despite the progress that science has experienced thanks to the use of the International Space Station as a platform for research and experimentation, it is certain that there are still limitations to the testing environment that a Low Earth Orbit (LEO) offers. Human exploration of deep space will involve exposure to more hazardous conditions, such as cosmic radiation and very limited supplies for life and mission support. To better understand how the lack of protection of the Earth's magnetosphere, for example, could affect living organisms, it is necessary to establish a research platform beyond LEO (Quincy et al., 2018), this is why a platform orbiting the Moon offers a great opportunity to investigate the biggest technological and scientific challenges for deep space exploration.

A key factor weighing in the scientific research capabilities of the Lunar Gateway is the periodicity in which crewed activities are planning to be performed on board of it. As described by Quincy et al. (2018), a crew of four astronauts would arrive to the Gateway, once a year for a 30-day mission in which maintenance and research activities would have to be performed. From a biological point of view, two approaches can be adopted for experimentation: the first one, to understand the interaction between human habitats and microorganisms, and the second one, to understand the interaction between microorganisms and hardware directly exposed to the space environment. From this, two areas will need to be addressed for advanced technology development: autonomy of the on-board systems and stability of the operational conditions.

Apart from gaining a better understanding of how deep space could affect living organisms, it is possible that the Lunar Gateway could assist in the research of our planetary history. It is believed that lunar regolith stores key information that could help the scientific community in their quest to understand the origin of life, as it has undisturbed material dating from the creation of our Solar System.(NASA, 2018) As mentioned before, through ISRU and other drilling activities, the study of lunar regolith could bring a deeper understanding and broader knowledge of our Solar System.

Besides the relevance for life sciences that research made on the Lunar Gateway represents, there is also a vast list of technology areas where this platform could help develop a more advanced infrastructure, as listed by Fong (2018), Figure 9 briefly describes these areas of opportunity.

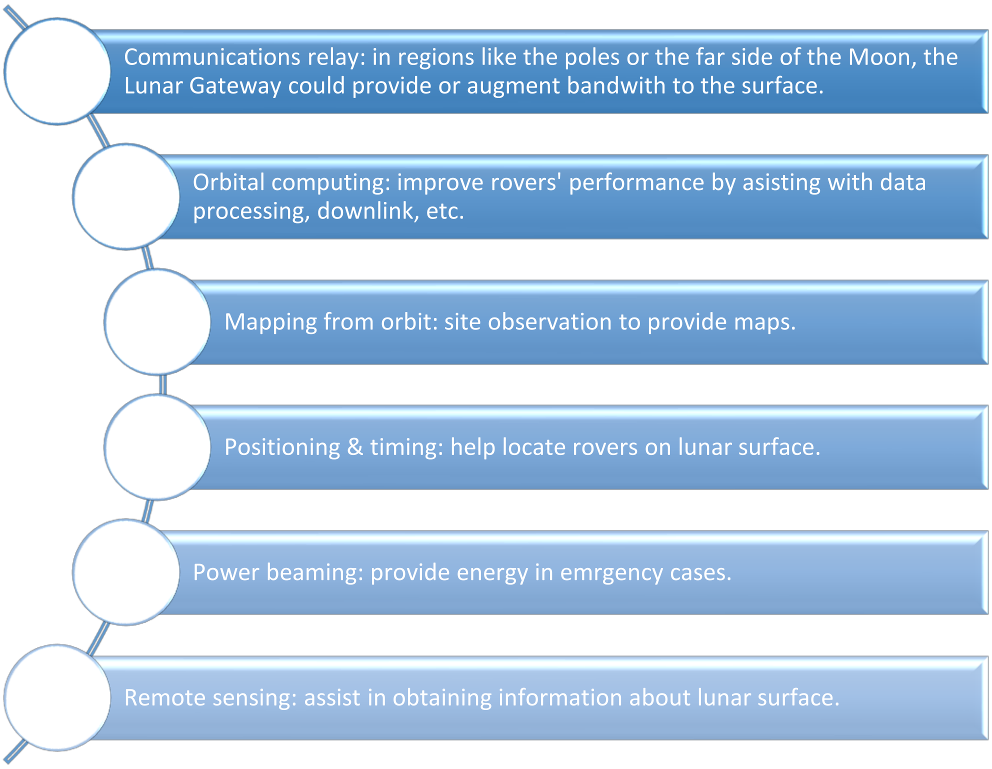


Figure 9 Lunar Gateway's areas of impact for technology development (adapted from (Fong, 2018)*)*

III.III Let's Go to Mars

The dream of going beyond the Moon and explore Mars, specifically, has been one of the main drivers behind scientific and technology developments that are pushing the boundaries in space. Despite the success that robotic missions have had reaching the red planet and setting the foundations for future human exploration, there is still a big breach in our capabilities to perform research that will allow humans to migrate to Mars. Our capabilities to perform scientific experiments and to support life in LEO have already been tested and proven through the ISS' missions, but the level required to allow deep space exploration has not been reached yet. The most logical next step is to upgrade our current technology test it in an environment closer to Mars.

NASA's Lunar Exploration Campaign (Figure 10) shows this reasoning, making it clear that, in order for humans to reach Mars, it is necessary to translate our current development into the lunar hostile environment. On another note, it is no longer an all-government exclusive endeavor what will provide the right conditions for a successful completion of this mission, public private partnerships (PPPs) have become a key element sustaining the rapidly evolving field of space exploration. Be it by sending lunar landers, rovers and commercial crews, it is necessary to adopt an approach centered on using locally available resources, detaching from our current dependence on Earth-based ones.

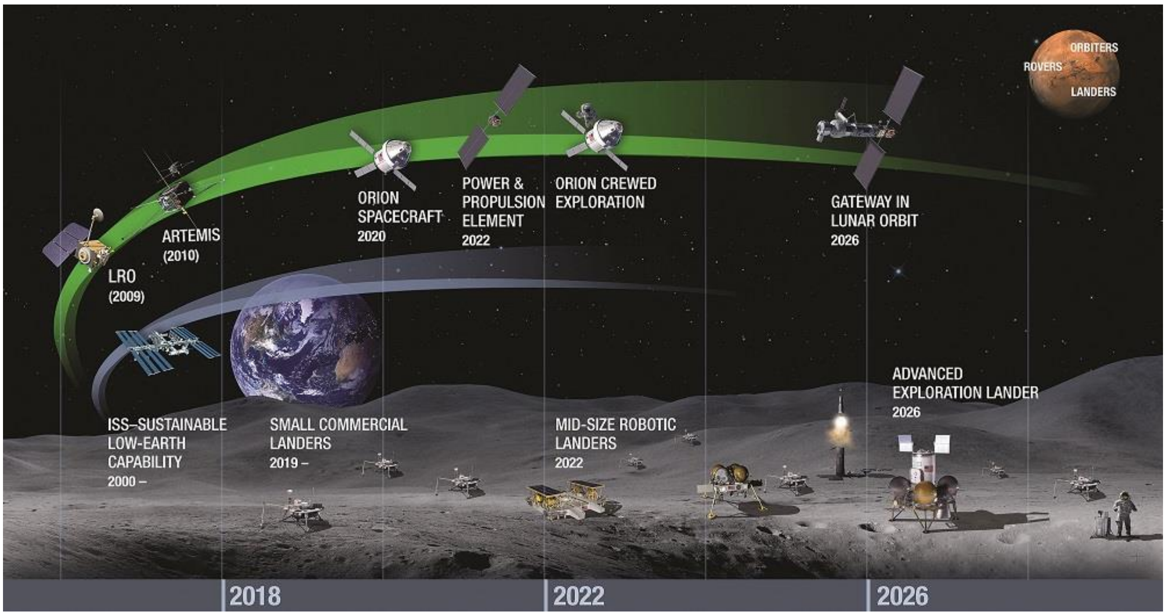


Figure 10 NASA's Lunar Exploration Campaign

The Lunar Gateway has been conceived as a strategic step to help transition from the platform the ISS has been offering since late 2000, integrating the international and public private partnerships approach with the clear objective to serve as a facilitator for longer-duration missions. With the joint efforts of NASA, ESA, Roscosmos, JAXA and CSA –to date-, the Lunar Gateway will not only serve as support base for lunar surface activities and other cislunar-located spacecraft, but it will also support other deep space missions and monitor the effects of deep space on crews (NASA, 2018).

Sending humans to the Moon to establish a permanent presence on its surface and on cislunar space will develop the required conditions to send humans to Mars and advance in the development of future deep space missions.

IV. Relevant Team Project Reports Analysis

After having filtered the 143 TPRs into a shorter list of 26 reports, a guide to proceed with the selection and clasification of information had to be set. For this, NASA's Exploration, Research and Technology (ER&T) analysis on promising technologies to advance future lunar and martian mission development was used as a reference to evaluate the concepts that the author found as relevant for this thesis. Table 6 lists the main critical technologies identified by the ER&T program for current and future development, based on current capabilities and considerations for planned missions and commercial partnerships strategies, such as the CLPS program.

Table 6 Exploration Capability Required Evolution (adapted from (NASA, 2018)*)*

	Demand Areas/Mission	Cislunar Short Stay	Cislunar Shakedown	Lunar surface
Working in space and on the Moon	ISRU	Exploratory ISRU technologies	Exploratory ISRU technologies	ISRU propellant production + other consumables
	Surface Power			Kilopower-rated technologies
	Habitation & Mobility	Initial short duration	Deep space transport habitat	Surface habitat
	Human/Robotic & Autonomous Ops	Crew-operated	Earth-monitored robotics	Human/Robotic exploration activities
	Exploration EVA	Systems for limited duration activities	Systems for limited duration activities	Systems for surface activities
Staying Healthy	Crew Health	Short-duration systems	Long-duration systems	Long-duration systems
	Environmental Control & Life Support	Short-duration systems	Long-duration systems	Long-duration systems
	Radiation Safety	Forecasting technologies	Forecasting and shielding technologies	Forecasting and shielding technologies
Transportation	Ascent from Lunar Surface			Lunar Ascent technologies
	Refueling/Resupply Capabilities	Refueling technologies	Resupply technologies	Refueling technologies
	ED&L			Autonomous/Precision landing
	In-Space Power & Propulsion	Medium power systems	High power systems	
	Commercial Cargo and Crew	Opportunity for development	Opportunity for development	Opportunity for development
	Communication & Transportation	RF & Optical technologies	Optical technologies	Optical technologies

These areas of opportunity provide a general overview of the current capabilities for lunar exploration and help set a starting point when identifying concepts with potential value for further research and development in ISU's TPRs. In this section a brief summary of each of the 28 TPRs is provided and an initial evaluation of concepts that match the goals and objectives previously described in Table 1 is presented. This section constitutes the second stage of the reports' filtering process, from which a reduced list of concepts for a detailed feasibility evaluation will be obtained.

The following evaluation was performed in the same order as listed in Table 2 *Description of Relevant Team Project Reports*. Wherever an idea or concept was identified to meet the matching requirements that were mentioned before, a table with an initial relevance evaluation is provided at the end of the corresponding subsection.

IV.I Lunar Nights Survival

Providing power in space is a hard mission, doing it in the lunar environment, however, is known to present significant challenges due to the limited availability of resources and the harsh conditions of lunar nights, for example. To establish a permanent presence on the lunar surface, this issue needs to be addressed; based on the current objectives of spacefaring stakeholders, it seems timely to evaluate the possibility of developing the technology that will tackle this challenge. Lunar Nights Survival TPR presents the "Power Cell" concept, a multi-source power solution for generation and distribution throughout lunar nights for a six-person crew and with the capability to scale up depending on future lunar settlement demands.

This challenge can be classified within an area of opportunity mentioned in Table 6 above; under the LER Objective-SUST-B and Objective-FF-B, to enable a collaborative expansion of science and exploration on the surface of the Moon, it will be necessary to procure a power generation system that, besides coping with the harsh conditions of lunar nights, it can also follow renewability and ISRU as drivers for technology design, following a distributed transmission infrastructure approach. Nuclear Stirling engines and photovoltaic technologies are the main components of the "Power Cell", which is based on a subunit integration format for continuous operation, allowing the concept to be scalable and adaptable to the outpost demand and the extreme environment, such as very low temperatures or the lack of sunlight for an extended period. Figure 11 shows an overview of "The Power Cell" integration of sources and its supply to the main loads in the outpost, such as rover charging, ISRU and scientific-related activities.

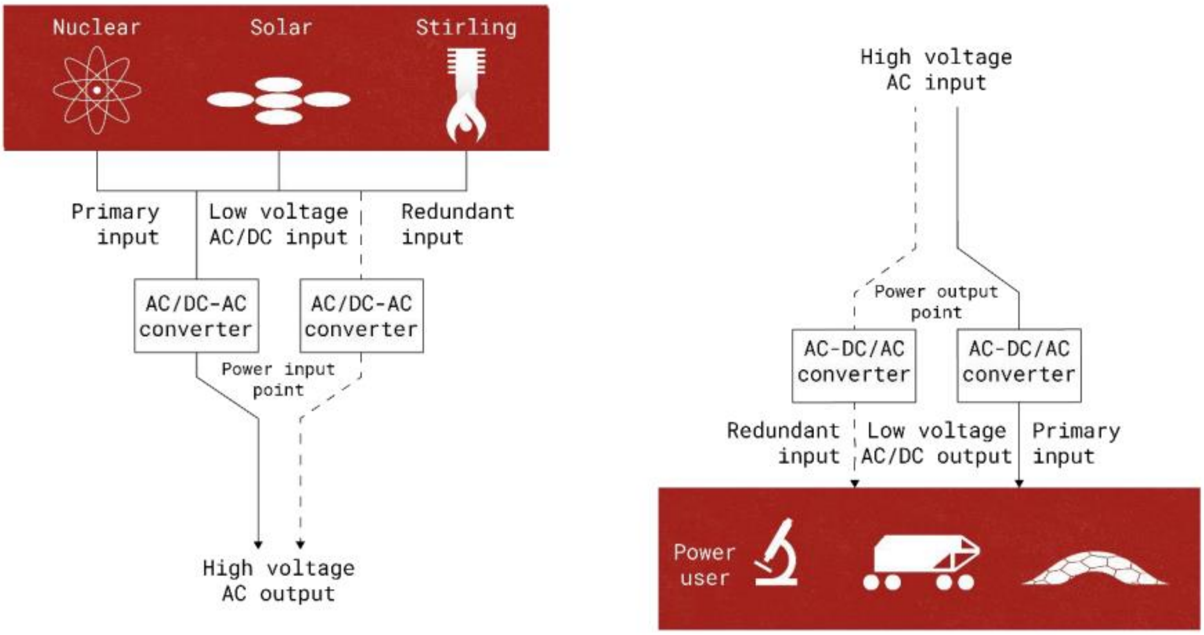


Figure 11 Lunar Night Survival Grid arrangement, from power generation to loads (International Space University, 2018).

Through the literature review performed for this thesis, no specific example that integrates these technologies for a distributed power generation system was found, which indicates that there is room for further development in this matter. Nevertheless, the individual technologies that "The Power Cell" proposes to integrate have, to some extent, been studied for their future application in lunar outposts.

In the case of the nuclear Stirling engine, a similar concept has already been evaluated by NASA and has recently completed a successful experimental phase in March 2018 (Anderson and Wittry, 2017); the *Kilopower*, a project investigated by the Game Changing Development (GCD) program, represents the non-dependent to sunlight source for power generation. At the same time, nuclear energy provides a more reliable option for power generation due to the amount of research that has already been done on it and the actual technology readiness level of its components.

Concentrated Solar Power (CSP) is another concept that was briefly explored in the Lunar Night Survival TPR and that could be of relevance for future lunar missions as well. Although this technology has not been tested as a space system yet, industrial applications have demonstrated it could be used as an efficient power source for ground operations. As stated by Smitherman, (2013) CSP systems offer a better approach to photovoltaic (PV) conversions, which is a constant issue among light-dependent power systems, being more efficient during night operations due to its use of reflectors and heat engines to produce power.

Despite this technology being rated with a TRL of 9, there is still the lack of flight heritage as a major issue to allow an actual transfer into space applications; therefore, it is essential to start considering running tests of this technology in a lunar-like environment or to include its validation as part of the scientific research that will be done in the coming lunar exploration activities.

Further research on CSP technologies will also allow to have a better understanding of the costs involved in operating this type of systems. So far, only rough order-of-magnitude figures are available as to how costly it would be to implement this in space, but, taking into consideration land-area requirements, PV arrays, ground segment infrastructure and space operations, a CSP system is considered to be more cost-effective than, for example, Solar Power Satellites (SPS) (Smitherman, 2013).

Similarly, another technology concept that was briefly evaluated in this TPR is Solar Power Satellite (SPS), which, opposite to CSP technologies, has been studied in more depth as to how to develop it in space. Literature suggests that the main challenge with this concept lies on the PV converter efficiency of its space segment. Although the latest improvements in solar cell efficiency are close from reaching a 50%, its real impact on the end-to-end efficiency is not significant enough to increase the feasibility of this concept for its future implementation on lunar missions, the main obstacle being the area of the required collector (approximately 3 km^2 for a 50% efficiency, with a reduction to 1.65 km^2 if a 90% efficiency is ever reached) (Smitherman, 2013). Nevertheless, following the same objective, these two concepts can be classified within the identified need to provide power on the lunar surface in a range larger than the kilowatt rate. Therefore, further research and considerations need to be outlined in the upcoming lunar exploration plans.

Based on this preliminary analysis of why it would be relevant to perform further research on the proposed concept of "The Power Cell" and some of the briefly mentioned support technologies, such as the CSP and SPS, a focused evaluation is summarized on Table 7.

Table 7 "The Power Cell" system evaluation for implementation on the lunar surface

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To implement a power supply system that can cope with the lunar environmental conditions throughout a lunar night, providing energy to a 6-person mission. A distributed, scalable and adaptable to demand format is to be implemented.	**Science Objectives:** • To demonstrate integration of PV and nuclear power system technologies as a viable energy source for Lunar surface power consumption and robotics operation. • This system will combine nuclear Stirling, PV and wireless transmission technologies as energy sources, while fuel cells, batteries and flywheels will be used as storage devices.
Why is the Lunar Gateway and/or the lunar surface the optimal environment for this instrument/research?	• Power supply is one of the main constraints for planetary surface activities and operations; before going to Mars, it is necessary to test and develop a robust and sound power sypply system on the Moon. • Environmental conditions on the lunar surface will help prepare technology for the hazardous conditions in Mars. Extreme temperatures, long exposure to radiation and variation in power demand will challenge technology development and help prepare for what will be encountered on the martian surface. • The Lunar Gateway may be an option to study future capabilities to beam power from PV technology to the lunar surface. Its adaptability to operate from different orbits and the fact that it will have crew support for certain periods could help kickstart operations of an orbital solar power system.

A more detailed evaluation of this concept, its feasibility and recommendations for further research will be outlined on the following section.

IV.II Starport 1

This report works as a guide for a future design of an ISS-like spacecraft, called "Starport 1". Based on a pre-established set of requirements defined by Axiom Space, research on different subsystems configuration, building, integration, operation, maintenance and end-of-life management within the spacecraft is provided, to finally propose a roadmap for the concept's future implementation.

The reason why this report was initially considered within the candidates for potential valuable concepts or ideas for future lunar and cislunar missions was because, as the Lunar Gateway will be replacing the current operations that are based on the ISS, some design considerations for the Starport 1 concept could be adapted to the Lunar Gateway to expand its capabilities to perform scientific experiments and to test new technologies, especially since those considerations were originally defined for testing on LEO, meaning that better results for future deep space missions could be obtained from cislunar space.

After reviewing each of this TPR's section however, it was concluded that rather than having a new or innovative concept as a proposal, the report constitutes a technology review with a heavy focus on the commercial opportunities that could be exploited from in-space manufacturing activities performed in LEO. Apart from these commercial opportunities, two other concepts could be worth analyzing with more detail through future lunar missions: Radiation protection and an air revitalization system.

For the radiation protection, the Starport 1 TPR identified the materials and configuration shown in Figure 12 as good candidates to provide the appropriate level of radiation shielding at a LEO location.

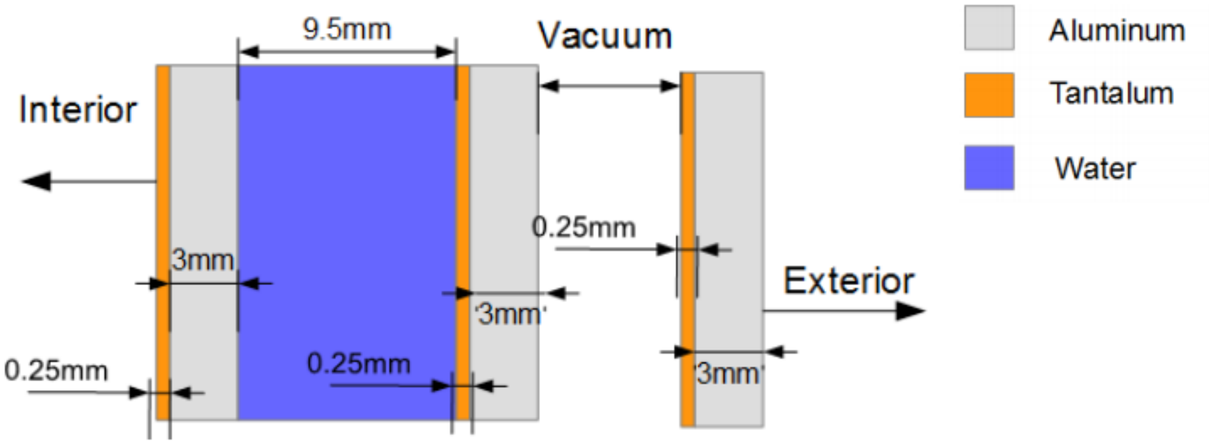


Figure 12 Cross-section view of the proposed radiation shielding (International Space University, 2016b)

In addition to these, Kevlar was also considered as a debris-shielding material for a layer between the outer and central layers, making this a more robust option for either cislunar or lunar surface applications. Based on this, it could be suggested that further studies on this concept be performed in a space environment as part of the coming lunar missions. Although some of the focus in this matter is currently being given to ISRU to offer radiation shielding solutions, a good approach to integrate these materials could be through a radiation measurement platform like the Matroshka AstroRad Radiation Experiment (MARE), which is planned to fly on board Artemis 1, previously known as Orion Exploration Mission-1 (EM1) (Gaza et al., 2018). The MARE concept, however, is focused on monitoring the effects of radiation on biological tissue and not on other materials of high relevance to hardware operations.

This concept relates to Goal-SCI-D, which focuses on using the lunar environment as a research tool for its unique characteristics and can also be transferred, on the same grounds, to the Lunar Gateway, since its location on a lunar orbit would provide valuable information on an early stage of the lunar exploration roadmap. Table 8 below summarizes a first rationale on why this concept might be relevant to take for further research and development in future lunar missions.

Table 8 Radiation shielding concept evaluation for testing on the Lunar Gateway and/or on the lunar surface

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To provide the required level of radiation shielding, to internal structures and crew members in a beyond-LEO environment and offer measurements on material degradation as a result of long-term exposure to radiation beyond LEO .	**Science Objectives:** • To assess long-term radiation exposure damage using layered radiation sheilding, on both, biological and non-biological samples. • To evaluate the potential of Kevlar as radiation and debris impact shield, in a cislunar environment. • To evaluate use of radiation sensors.
Why is the Lunar Gateway and/or the lunar surface the optimal environment for this instrument/research?	The Lunar Gateway is exposed to high radiation levels being in cislunar space and can provide data from long-term exposure scenarios. This information can set the baseline for future radiation shielding for Mars exploration missions. If testing was to take place on the lunar surface, early studies on protection against micrometeoroids could also be performed.

When evaluating the materials that will be carried within the initial payload of the Artemis-1 Mission, an environment compatibility study needs to be made on the proposed candidates, as suggested by Oeftering et al.(2011), since chemical bond breaks and polymers degradation pose significant crew hazards; further research in this matter needs to be addressed, especially considering that lunar bases will need suitable radiation shielding that can endure long term exposure to alien environment conditions.

This investigation is of high priority based on NASA's Human Research Program, though the implementation of developments on this matter would be allocated to a later phase within the lunar exploration program.

Another interesting concept proposed on this TPR is an air revitalization system based on swing adsorption. This type of system has different variations on the principle it follows; from thermal cycling and vacuum separation, to electric adsorption, being this last one the one that Starport 1 concept focuses on, proposing the use of an activated carbon monolith block to which an electric current is applied, triggering air regeneration.

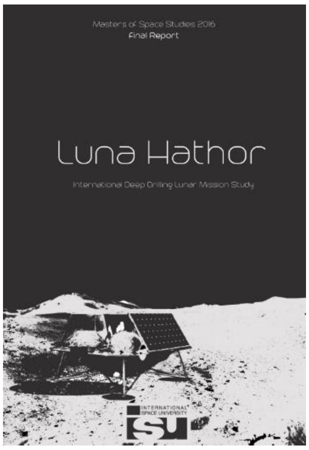
Although no detailed evaluation on this concept for space applications was performed on the report, there is a potential value for future lunar settlements and the development of Life Support Systems (LSS) since it is low in energy consumption and does not require ancillary pressurized systems to operate, reducing the complexity for future implementations in space. However, more research on the size and material composition needs to be made for space applications. Table 9 provides an initial analysis on the potential for further research and development of the proposed air revitalization concept using the lunar surface as a test bed.

Table 9 Air revitalization concept evaluation for testing on the lunar surface

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To efficiently remove CO_2 accumulation from the air in a future lunar settlement, procuring a low consumption of energy for an easier integration to other LSSs.	**Science Objectives:** • To characterize porousn and conductive materials that can be used in a swing adsorption system for CO_2 removal. • To develop reliable subsystems for life support with a low payload cost for the early stages of the settlement development.
Why is the Lunar Gateway and/or the lunar surface the optimal environment for this instrument/research?	A Lunar settlement development will be constrained by the payload than can be delivered by the first rocket launches of the Artemis program and by the development of ISRU technologies, making it essential to have a closed system sheltering life. Keeping in mind that the ultimate goal so far is to send humans to Mars, it becomes essential to develop and test life support subsystems that can withstand extreme environmental conditions and that can be as independent as possible from Earth. These conditions will be available on the lunar surface.

Finally, a brief description of potential commercial opportunities for in-space manufacturing on board the Starport 1 is provided, mentioning the potential of pharmaceuticals, optic fiber, radiation shielding, protein crystals and bio-printing as an extra service that could be provided; however, there is no concrete proposal on a novel approach for the manufacturing process or a new scientific objective that could be addressed through these activities.

IV.III Lunar Hathor: international deep drilling lunar mission study



The Lunar Hathor proposed mission has a particular approach to the main driver behind it, putting science as an added value instead as the primary goal. Its aim is to assess the feasibility and motivation for a lunar deep drilling mission, comprising four general sets of rationales with specific interests each: Policy & Security, Economy, Science & Technology, and Public Participation & Outreach. For the purpose and scope of this thesis more attention was dedicated to the Science & Technology rationales. The science objectives for this TPR are linked to engineering considerations as follows:

1. *"To achieve a soft landing on the surface of the Moon.*
2. *To drill and extract samples from at least 20 m below the lunar surface.*
3. *To deliver sample analysis information by sample-return or in-situ activities (International Space University, 2016a)"*

An interesting concept, though not applied to the final configuration of the proposed mission, is Plasma drilling, developed by Zaptec Inc. and Shackleton Energy Company. Using high-energy density plasma, this type of drill breaks and pulverizes the surface regolith, retrieving the pulverized samples with compressed CO_2. This novel concept, however, has not been tested in field and limits integration of other instruments due to its large size and mass (approximately 250 kg of gear) (Johansen et al., 2014). As for the energy required to power this instrument, a peak power of 1 kW is required to drill in the range of 50m-100m of depth (Zaptec As., 2018), which would also require further research to increase its efficiency..

At the time when this concept was evaluated for the Lunar Hathor proposal, the instrument's TRL and research on the potential of ISRU lacked the momentum that current lunar exploration objectives bring to the space sector; because of this, Table 10 below provides an introductory first analysis on this concept's relevance for future lunar missions and the advantages of pursuing further research on it.

Table 10 Plasma drill concept evaluation for testing on the lunar surface

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To enable deep subsurface drilling and sampling for ISRU on the Moon	**Science Objectives:** • To study repository of volatile chemical compounds, their composition and distribution. • To assess the risks and hazards that volatile chemical compounds reservoirs can pose to crewed and robotic activities. • To understand the effects of space weather on regolith and how it affects its evolution. • To enhance study techniques of other planetary surfaces for future exploration activities.
Why is the Lunar Gateway and/or the lunar surface the optimal environment for this instrument/research?	This concept would leverage from the unique conditions on the lunar surface because they simply cannot be found elsewhere. In order to allow future exploration of other airless bodies, it is necessary to test the required technology on-site. There is a need to provide and secure a local source of consumables on the surface of the Moon

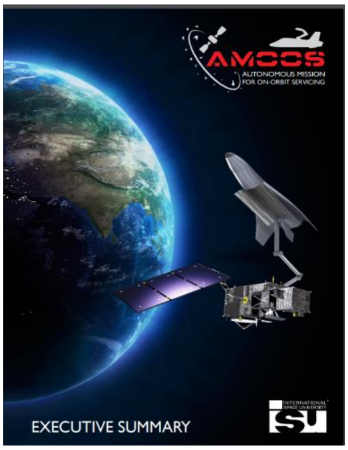
Gaining more knowledge about the precise location of volatile chemical compounds and their composition will not only benefit the scientific community, but it will also establish a base for business plan development in the commercial sector.

IV.IV Vision 2040

This report considers five main areas of opportunity to forecast the next 25 years in the future of the space sector. These areas include: real-time Earth applications, orbital stations, lunar bases, lunar and asteroid mining, and human presence on Mars. Potential challenges and signs of disruptive change are identified for each of these areas to then formulate a set of recommendations for ISU to adapt its educational and outreach programs to maintain a leading position in the space sector.

Although the recommendations regarding the educational approach for ISU were not relevant for this thesis' scope, the author decided to consider the future challenges and signs of disruptive change sections of the *Vision 2040* report for her research, especially the ones related to lunar missions and precursor steps for Mars human exploration. Nevertheless, after close examination of the real content of these sections, no special concepts or relevant ideas were identified for further evaluation.

IV. V AMOOS: Autonomous Mission for On-Orbit Servicing



The concepts analyzed in this TPR come relevant to the current planning of the Lunar Gateway's capability to provide on-orbit services to near-by spacecraft and, to a certain point, to execute self-servicing tasks as well.

Despite the fact that the debris situation on the Moon environment is not as alarming as the current one on Earth, it comes timely to start identifying the future actions that will need to be followed to avoid reaching the same point of debris accumulation around our planet. This is why, besides considering the on-orbit servicing concepts as relevant for this thesis analysis, it was also decided to evaluate the proposed debris removal approach of the AMOOS TPR.

One of the most ambitious goals for the future of humanity on the Moon is to establish a permanent settlement on the lunar surface, it is quintessential then to start considering security measures against objects that will be orbiting the Moon. In 2017, after having lost contact with Indian spacecraft Chandrayaan-1 in 2009, NASA found the missing spacecraft orbiting the Moon using radar technology from the Lunar Reconnaissance Orbiter (LRO) (MacDonald, 2017); this means that even before starting populating lunar orbits with spacecraft that were intentionally put there, just as it is done through Space Situational Awareness (SSA) activities that monitor objects orbiting Earth, it will be primordial to keep track of spacecraft orbiting the Moon, especially considering that the lunar environment conditions greatly differ from those in Earth. The lack of an atmosphere that can provide a natural shield against objects coming towards the surface of the Moon makes it essential to consider ADR activities as a priority for the Lunar Gateway.

For on-orbit servicing purposes, an interesting concept integrating robotic vision systems and robotic control systems is proposed, opening the discussion about the processing power required to operate a system like this and the need for an accurate state observer to be developed.

Another interesting proposal is a set of recommendations to develop industry standards. Although this is not a science or technology concept, it does correspond to one fo the goals described in Table 1; Goal-FF-B, "*To use the Moon as testbed for exploration techniques and mission operations, reducing the risks and augmenting productivity of future missions to deep space and Mars*", comprises the establishment of a efficient frame for operations that favor international cooperation. This approach has already been taken on the ISS, which sets a good precedent for the future plans of the Lunar Gateway; however, there is no mission that has set a precedent to what will be encountered throughout the process of establishing a lunar settlement. Further development on this matter is needed not only to allow cooperation between nations, but also to open access to commercial actors. Table 11 lists the set of recommendations developed by the AMOOS TPR.

Table 11 AMOOS TP recommendations for OOS standards (International Space University, 2014)

Interface	Standardization Description
Mechanical/Docking	*"The servicer and the client shall be able to dock and undock autonomously through this interface without any human intervention. To ensure safety, the mechanical interface will need to meet certain stiffness and strength requirements related to the masses of the satellites."*
Component	*"There shall be an interface for the transfer of components such as batteries, propulsion modules, and solar arrays. Modular designs are encouraged to facilitate servicing."*
Electrical Load Transfer	*"The client satellite shall provide regulated direct current bus interface and grounding interface."*
Data	*"The client spacecraft shall use a common data interface connector and bus standard. Due to the large number of available connector and bus standards on the market, it is anticipated that the AMOOS spacecraft will need to be compatible with multiple connector and bus configurations."*
Fluid	*"Fluid interfaces shall incorporate sealing quick disconnects to minimize leakage during transfer operations and nominal operations."*

Table 12 below provides a brief explanation of the relevance to procure the development of standards for OOSs using the Lunar Gateway as a platform to facilitate its research.

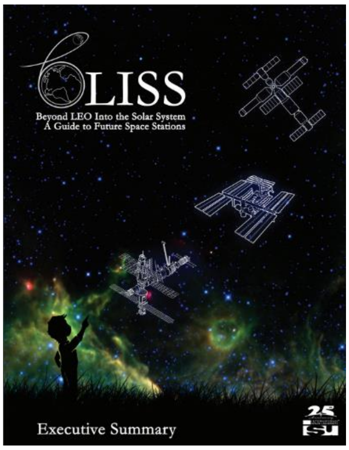
Table 12 Development of standards for OOS evaluation for implementation in the Lunar Gateway

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To develop a framework of standards for interface development and instruments operation for OOS on the Lunar Gateway	**Objectives:** • To facilitate technology development and transfer from cislunar space operability to lunar surface applications. • To secure interoperability of the Lunar Gateway's infrastructure for OOS by commercial actors and space agencies. • To reduce risks to mission success and hazards to crew's safety that could result from incompatibilities when operating OOS dedicated infrastructure on the Lunar Gateway.
Why is the Lunar Gateway the optimal facility for this instrument/research?	Before establishing permanent settlement on the Moon, further development of interface standardization needs to be accomplished within the lunar environment, which comprises cislunar space. Starting these efforts with the Lunar Gateway will provide the best platform to test the developed standards and facilitate their transfer for surface applications.

Although these recommendations are broad and lack a specific methodology as in how they could be developed, the fact that it covers at least one of the identified objectives of the Lunar Exploration Roadmap indicates that there might be valuable potential in them. In order to evaluate the feasibility of further developing this idea, a more detailed analysis is provided in the next section.

IV.VI BLISS: beyond LEO into the Solar System. A guide to future space stations

Under the premise that to expand human exploration of space it is necessary to go beyond LEO to perform science and technology demonstrations, the BLISS TPR starts by listing a set of lessons learned from the International Space Station's (ISS) operations to perform an analysis of what could be the future design drivers for a Next Generation Space Station (NGSS), to be implemented in 2025. From this, a guide based on a high-level matrix was developed, with the objective of providing guidance during the transition period from the decommissioning of the ISS to the put in service of a NGSS.



In terms of the science that can be made on board a NGSS, the BLISS report proposes an increment in the bandwidth for data downlink rate, since active payloads such as the Alpha Magnetic Spectrometer (AMS) require a very high bandwidth to transmit data from its measurements. At the same time, this raises the concept of an enhanced magnetic spectrometer, since the current one already carries out studies on cosmic particles that involve high statistics operations within an environment where the Earth's magnetic field affects their dynamics (Aguilar et al., 2002). While extrapolations from satellite observations could predict these particles' behavior in a different environment, it is logical that an instrument like this located in a more advantageous orbit, such as the cislunar space, could increase scientists' understanding of primary cosmic particles, primary antimatter and the nature of dark matter (AMS-02, 2019). Table 13 summarizes the science objectives of an instrument like this and the reasoning behind proposing its implementation in a NGSS like the Lunar Gateway.

Table 13 AMS-like experiment module evaluation for implementation in the Lunar Gateway

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: An upgraded AMS-like instrument will collect information from cosmic particles in a more exposed environment.	**Science Objectives:** To look for evidence of antimatter and to measure very high-energy radiation coming from distant celestial bodies, to understand its possible effects on life, in an environment free of Earth's magnetosphere (Ting, 2019).
Why is the Lunar Gateway the optimal facility for this instrument/research?	It has been identified that the Earth's magnetosphere and atmosphere safeguard humans and life in general against cosmic particles. By getting access to measurements of the cosmic particles interaction with the instrument without having the effects of our planet's magnetic field, better preventive design parameters can be implemented in spacecraft structures and manned spaceflight.

Another important consideration is the in-situ capability to perform analysis of experiments in an autonomous way to avoid dependence on sample return to Earth services and astronaut manipulation. Autonomy is a recurrent concept in several of the TPRs that were studied for this thesis and following the current trends and needs within the space sector, it results imperative to include this approach in every way possible for future implementation of these concepts.

For the science station of a NGSS, a variable gravity module or a free-flying microgravity research module for life sciences is proposed in the BLISS report as a key design driver to achieve more advanced results in biology related research. Nevertheless, considering the level of development of the existing proposed concepts for the Lunar Gateway, the integration of such a module may not be feasible for the initial operation stages of the Gateway. It might be feasible though, to evaluate the integration of this concept for a later stage after the scientific research activities start.

The concept of an on-orbit centrifuge laboratory has already been studied before to be implemented in LEO using CubeSats as test beds for scalable systems and from a low-cost approach, such as the Asteroid Origins Satellite I concept developed by the University of Arizona (Asphaug, Thangavelautham and Schwartz, 2018). Alien environment conditions, such as electrical conditions, atmospheric pressure and gravity could be simulated in this type of laboratories to test and validate scientific hypothesis regarding human adaptability in space and spacecraft performance. Based on this, Table 14 provides an introductory evaluation of the concept proposed by BLISS, its scientific objectives and relevance for implementation in the Lunar Gateway.

Table 14 Variable gravity module evaluation for implementation in the Lunar Gateway

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: A modular set of laboratories with a tether interface will allow more advanced research on the effects of microgravity and other alien environment conditions for life science, landing technology and surface mobility experiments.	**Science Objectives:** • To evaluate the effects of different gravity forces on biological phenomena, outside the effects of the Earth's magnetosphere. • To evaluate scalable technology for future surface exploration of Mars. • To validate models and simulations of hypotheses in planetary sciences and exploration engineering.
Why is the Lunar Gateway the optimal facility for this instrument/research?	Variations in microgravity conditions on LEO have significant effects on the science experiment results that have been obtained so far using the ISS as the research platform. Moving away from these variations will provide more accurate data regarding the effects of microgravity on different phenomena, as well as on exploration technology performance.

As proposed by Asphaug, Thangavelautham and Schwartz (2018), a first step towards implementing this concept would have to come from a CubeSat-like approach, which requires less budget but is also limited to a small internal volume (up to almost 2U in the AOS-I CubeSat concept) where experimentation can be performed. Nevertheless, these platforms could provide a more consistent link for hypothesis-testing in a beyond LEO environment.

IV.VII OASIS: Operations and Service Infrastructure for Space

As mentioned in this report's introduction and in other sections, space exploration efforts are still very limited by the mass that can be launched into space and our current dependency on Earth resources. OASIS proposes a network of spaceports that can provide resources to sustain long duration missions, with a joint use of ISRU

The proposed spaceports are divided into two main operating areas: LEO-stationed port supported by Earth supplies and a LEO-stationed port supported by Moon-based supplies, both of these planned to support a mission to Mars. A third optional node is also briefly mentioned, focusing on providing resupply services from a Phobos-based port to Mars. This is illustrated in Figure 13 below.

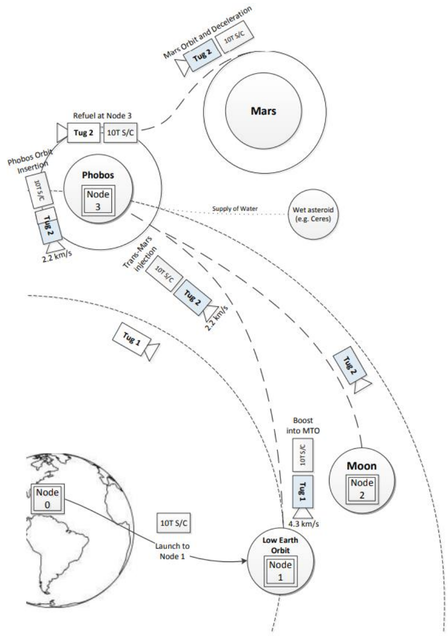


Figure 13 Schematic of the OASIS proposed concept for a phased mission to Mars (International Space University, 2012b)

However, the final proposed concept on this TPR is limited to a general description of why these specific spaceports would be relevant for the future exploration plans of Mars and the potential economic interest of commercial actors on resupply services offered at each of them. No novel or relevant scientific or technology concept is provided throughout the report, limiting itself to a general review of the existing technology that could be used to provide the launching services to set up the spaceport and to provide the tug services at each location. Even though on this report's abstract, it was mentioned that ISRU support would be included in the development of the proposed spaceports concept, no real evaluation of ISRU tehcnologies is provided, as it is also not done with any new approaches to integrate this type of resources for on-orbit servicing.

Based on this review, it was decided not to take this report to the next phase for concept feasibility analysis.

IV.VIII Access Mars: accessing cave capabilities establishing specific solutions

Even though this TPR was not initially identified as a candidate with potential valuable concepts for future lunar and cislunar missions, it was after identifying its focus on the use of lava tubes for future human settlements on Mars what flagged it as a potential bearer of ideas or concepts to look at, especially since it has been explicitly established on the Lunar Exploration Roadmap that characterizing an alien environment, its surface and subsurface interactions with robots and other instruments for exploration is of vital importance to allow a human settlement to develop in the near future.

Access Mars TPR assumes that as a predecessor to the proposed mission to Mars, the Moon was used as a testbed for the technology and ISRU methods included in its mission architecture. This assumption allowed the identification of potential valuable ideas to be done more objectively since a big part of the literature review and mission design are made taking into consideration existing and developing technologies for future lunar exploration activities. With this in mind, an interesting technology concept related to lava tubes recognition was identified: Quantum Well Infrared Photodetector (QWPD). Thermal sensors are key for remote sensing applications and have already been suggested as a good option for lava tubes identification on the Martian surface (Blamont, 2014), so precursor technology demonstration on the Moon would be a logical strategic step towards allowing habitation of Mars; ACCESS Mars proposes to have a satellite –based thermal sensor for cave detection, with a QWIP-based system to achieve a spatial resolution of 1 m, from a Martian orbit.

Transferring this concept for a lunar application could become feasible using the Lunar Gateway as the orbiting platform carrying the thermal infrared detection instrument. The LER identifies as a high priority investigation to understand volcanic processes on the Moon; to achieve this, science investigations will have to be performed from cislunar space and on the lunar surface.

ISRU is one of the main drivers to bet on the use of caves and lava tubes as habitats for future settlements; availability of ice and other resources that could be transformed into water, oxygen and propellant for other applications hold great promise to facilitate a future permanent human presence in other planets.

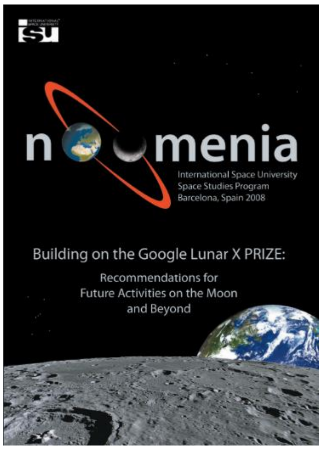
Cave localization through thermal detection could facilitate the identification of areas rich in resources with potential for other uses; however, a thermal model of a real cave still needs to be developed and spatial resolution in remote observations needs to be optimized before selecting the areas where robotic and crewed missions will start developing a permanent settlement.

Based on this preliminary analysis, it is proposed that the QWIP-based instrument for lava tube identification is taken further for a more detailed analysis on its feasibility and potential for future lunar missions. Table 15 below provides an initial analysis on the relevance of this concept for a potential implementation on the Lunar Gateway and its scientific impact.

Table 15 QWIP-based instrument for lunar cave characterization concept evaluation on relevance to the Lunar Gateway

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To provide data for direct detection of cave entrances and development of a thermal model of a lunar cave.	**Science Objectives:** • To further develop high thermal resolution instruments for future identification of lava caves on Mars. • To develop a thermal model of caves in other planetary surfaces for later application on Martian exploration. • Lava flows could contain well preserved paleoregoliths with different effects from solar wind. Mapping potential locations with lava tubes will facilitate mission planning for future in-situ studies of this material. ○ Studies on our Sun's superflares history and a better understanding of exoplanets characteristics can be developed from this investigations.
Why is the Lunar Gateway the optimal facility for this instrument/research?	Thermal resolution on this type of instruments has proven to have great potential to reach a high level, which could be enhanced by being located on an orbit closer to the subject of study. The Lunar Gateway can offer this platform, to either carry such an instrument as a permanent observation experiment, or by providing a launching platform for small satellites that could carry this instrument.

IV.IX Noumenia: building on the Google Lunar X Prize



This TPR focuses on developing a comprehensive overview of opportunities that could help maximize the benefits from executing and participating on the GoogleX Prize competition. Technical and legal challenges are briefly analyzed to generate a set of recommendations for the main stakeholders being affected the most by this competition, but the real focus of the study performed by the Noumenia team is on

However, one of its main takeaways is its focus on sustainability; in spite of being an initiative for technological development for future exploration of the

Moon, Noumenia suggests that the GoogleX Prize should broaden its scope to include a more sustainable approach to any development effort made by both, the participants and external stakeholders.

The most relevant recommendations and ideas proposed by the Noumenia team can be summarized on the following three points:

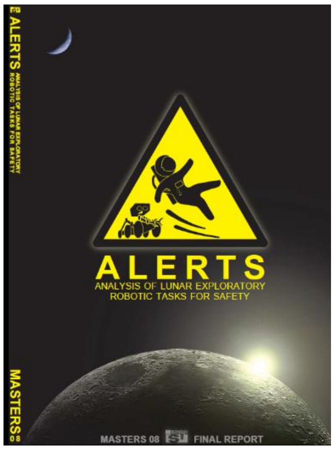
1. Bonus prize for utilization of technologies that have low impact on the lunar environment or that work as technology demonstration for environmentally friendly infrastructure for future exploration missions. This recommendation could have a potential positive impact by promoting investment in this type of technologies.
2. Raise awareness about the importance and potential of maintaining a sustainable mindset when planning and executing a mission in space for any purpose, normalizing this approach for any other activity related to space. This recommendation aims at using the GoogleX Prize to set a precedent on sustainable development in space for exploration purposes and integrate it as a main driver when designing missions.
3. Use the potential benefits from developing and using environmentally friendly technologies in space as a marketing strategy for sponsorship support.

All these recommendations are meant to be implemented on an early phase of the planning activities for the next editions of the competition and also as an immediate action during the on-going efforts related to this initiative's objectives.

Since these recommendations do not fall within the defined scope of this thesis, no further analysis will be performed on them; however, the relevance of this TPR's content to future collaboration between agencies and private entities for space exploration development could be further evaluated under a scope that is more focused on partnerships and legal frameworks development.

It is, however, been identified as a high priority to a sustainable development of a permanent human presence on the Moon to maximize the commercially driven activities within a well-defined legal and scientific framework.

IV.X ALERTS: Analysis of Lunar Exploratory Robotic Tasks for Safety



The future establishment of a permanent human settlement on the surface of the Moon is becoming more feasible thanks to the renewed efforts made by NASA and private entities; however, before achieving this milestone, several precursor missions will have to be performed to help adapt to the hostile lunar environment. Team ALERTS report focuses on developing a set of recommendations to increase astronaut crews’ safety when performing future exploration activities on the lunar surface. Such recommendations are based on the premise that, by implementing a robotics assistance approach, astronauts’ and the mission’s safety itself will be increased, and by doing so, so will do the capacity to establish permanent human settlements on the Moon.

Just as it is done on Earth, robotic technology is used to assist humans on difficult and demanding tasks usually with the same objective of preventing people from dangerous situations and to make processes and operations more efficient. If robotics technology on Earth is to be transferred to space applications, especially for a Cislunar spacecraft or lunar surface activities, a key factor needs to be considered to increase the feasibility of automating tasks in space: multitasking. However, this ability to deal with several taks at the same time comes with potential risks for the human crew that would be either executing the tasks or interacting with the robotic support. This Team Project suggests tackling this challenge through a synergic approach using the Peer to Peer Human-Robot Interaction (P2P-HRI) technique.

The P2P-HRI concept focuses on the development of key tools and techniques to enhance human-robot teams’ productivity through spatial awareness, communication process improvement and advanced user interfaces. The main target areas for applications are crew exploration vehicles, lunar surface systems and all the preparing activities for a permanent settlement deployment (Fong et al., 2006).

The latest available analysis on this concept was published in 2006, but its relevance to the current needs for robotics support in lunar exploration missions is still of high relevance, which is why further research and development should be considered within the immediate action plans of NASA and other relevant actors. Table 16 below provides a brief initial analysis on this concept’s relevance to lunar surface missions and potential implementation on cislunar and lunar surface space.

Table 16 P2P-HRI concept evaluation on relevance to future lunar missions

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To improve human-robot collaboration in tasks performed in space, in an effective, efficient and flexible way.	**Science Objectives:** • To develop robust and efficient communication between operating entities (robots and astronauts) in an independent-from-ground-control scheme, supported by an universal operating system. • To develop a more detailed model of human behavior to be implemented as a computational cognitive architecture for robot adaptation. • To develop a system for human-robot interaction measurement and evaluation to be homologated in all space exploration activities.
Why is the Lunar Gateway/Lunar surface the optimal facility for this instrument/research?	Prior to its implementation on the lunar surface, this concept will have to be validated in a space environment under simmilar conditions to the ones that will be encountered on the Moon, especially those related to communication processes and microgravity effects on the human element during maintenance and inspection activities. The Lunar Gateway offers the perfect environment for this with its key location on cislunar space and the communication challenges that will be encountered there.

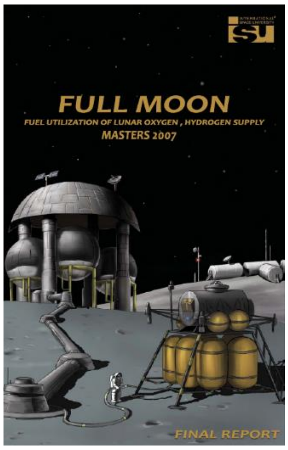
IV.XI DOCTOR: developing on-orbit servicing concepts, technology options and roadmap

The DOCTOR TPR focuses on providing an interdisciplinary review of on-orbit servicing challenges to generate a roadmap with a near-, mid- and far-term vision on feasible missions using the ISS as a base platform to provide inspection, maneuvering and mannipulation services. The topic of on-orbit servicing is approached as a preventive element for potential future space debris and facilitating spacecraft routine operations and, possibly, manufacturing.

As a result of this study, a Feasibility Matrix to assess different missions' feasibility was developed, providing a gap analysis from a policy, economic and technical perspective. The mission scenarios that were subject of analysis for this matrix were formulated based on three types of on-orbit services mentioned previously: inspection, manipulation and maneuvering. However, the main constraint of the proposed concept missions is that all its assumptions and recommendations are outlined around very specific characteristics and conditions of the ISS, making it difficult to transfer the rationale behind each aspect to the Lunar Gateway unless it is assummed that simmilar conditions and infrastructure will be available on this new platform.

The main contribution of this report is the mission architecture development of an on-demand robotic Orbital Replacement Unit (ORU) exchange mission, which consists on a complex servicing spacecraft that would provide OOS to spacecraft on GEO after piggybacking to GTO. However, since this concept focuses on developing a specific spacecraft to provide these services on GEO to a market that's already existent, it is considered as non-relevant for this thesis scope to further develop research recommendations and feasibility analyses on it, as neither the Lunar Gateway nor the lunar surface represent a key element for a potential future development platform.

IV.XII Full Moon: storage & delivery of oxygen and hydrogen



How do we stay on the Moon? This is the opening question under which team Full Moon develops its report, focusing on the gaps regarding research on ISRU storage and delivery infrastructure concepts that could allow the future development of a supply station of oxygen and hydrogen on the Moon (International Space University, 2007b). Keeping in mind that the ultimate goal of the current lunar-related efforts is to permanently stay on the surface of the Moon, two main drivers are addressed as the main "consumers" of the delivery and storage services: life support systems and propelling for surface transportation.

According to NASA's ISRU Implementation Lifecycle chart (Figure 14) these services would be located within the mid-term (highlighted in green text, under green arrow) phase of the ISRU activities development plan and are key to proceed with the actual mining operations that would provide the required resources to allow a permanent and sustainable presence on the lunar surface.

Based on this and the Feed Forward Goal C described on Table 1, to prepare for future exploration of Mars it is necessary to address this need from an early stage of the lunar exploration planning activities. From the analyses made to different options for storage and transportation of resources on the Moon, team Full Moon concluded that the best option for storage are Al-Li alloy tanks, for which further research on an optimal design and material technology needs to be performed, while for the transportation system, the top three candidates for further future development were: ballistic rockets, ballistic-wheeled-walkers and surface pipelines.

From this results, it is proposed that a more detailed analysis on the feasibility of both solutions is performed on the comign section of this report. For this, an initial analysis on their relevance is provided on Table 17 below.

Table 17 Al-Li storage devices and ballistic-like transportation system relevance to lunar surface studies

STATEMENT	INSTRUMENT/CONCEPT DETAILS
Function Statement: To provide a safe and efficient way of storage and transportation for consumables and resources on the lunar surface, potentially between different locations.	Science Objectives: • To define the safest alloy of materials for storing consumable resources for human sustenance on the lunar surface. • To study the effects of high radiation levels on Al-Li alloy storage devices. • To study the effects of lunar dust abrassion on Al-Li alloy storage devices. • To study the effects of prolongued interaction between stored resources in microgravity on Al-Li alloy storage devices. •
Why is the Lunar Gateway/Lunar surface the optimal facility for this instrument/research?	The expected behavior of the materials from which the storage containers will be made can only be determined by direct exposure to the real environmental conditions that will be encountered on the lunar surface. Transportation systems, although highly relevant for a late-term phase of the lunar exploration plans, can only test their technology for future applications on other planets, like Mars, by operating on precursor missions, which in this case would be the Moon. Complementary to this, expected consumption of resources, both in power and fuel, can only be validated by in-situ operation of the technology.

Figure 14 ISRU implementation life cycle (adapted from (Sanders, 2018))

- Define end-goals for resource utilization
- Perform initial feasibility study
- Evaluate candidate sites
- Perform initial cost analysis
- Weigh alternatives
- Go/No-Go decision
- Elaborate and define Plan Program

- Global Resource Evaluation
- Site Selection
- Characterization of potential sites
- Identify and verify potential resources

- Estimate size of resources reserves
- Obtain samples of resources and test for quality
- Geotechnical characterization of mineral resources
- Identification of different potential uses and users of resources
- Assess potential return on investment

- Hardware scalability demonstration
- Extraction and storage operation and processes demonstration
- Evaluation of processing options

- Selection of mining site
- Environmental analysis
- Development of required power sources
- Design of required transportation and communication infrastructure
- Development of contingency plans

- Development and set up of required infrastructure
- Preparation of landing site and roads for transportation
- Construction of processing facilities

- Perform first excavation
- Extraction of resources
- Management of operations
- Perform maintenance activities as needed

- Processing of extracted resources
- Transfer of processed resources for supply operations
- Recycle of waste and byproducts

- Export resources from site
- Processing of resources into final product
- Delivery to end users

IV.XIII Luna Gaia: a closed loop habitat for the Moon

The main concept that is proposed by this TP is a closed-loop system called Luna Gaia Life Support System (LuGaLiSus), which is the result of a combination of two experimental concepts: Bios-3, developed by the Russian Academy of Sciences, and MELiSSA, developed by ESA. This hybrid system (shown in Figure 15) was estimated to have a 90-95% efficiency as a closed-loop system, with the food production subsystem and contamination control contingencies being the least developed areas of this concept.

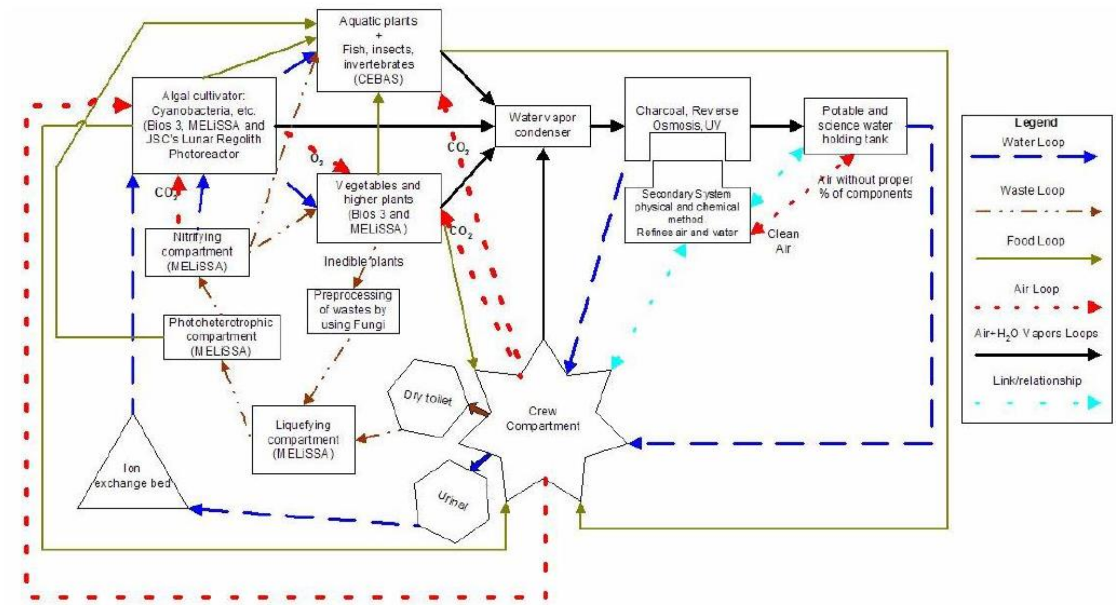
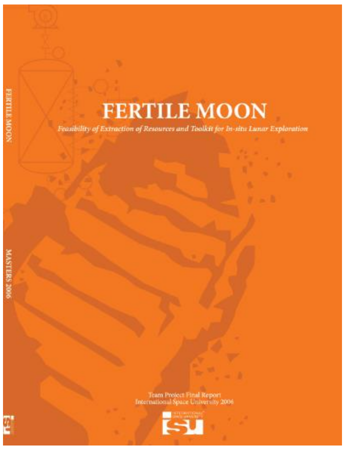


Figure 15 LuGaLiSus concept block diagram (International Space University, 2006b)

Another downside of the analysis performed by team Lunar Gaia is the lack of considerations on specific key parameters for the type of containers for the consumable resources, as it is still uncertain to what extent lunar environment conditions can affect them and, in consequence, alter the consumables.

Nevertheless, the LEAG has identified the need to develop life support systems for exploration activities on planetary surfaces as a high priority area, which is why this concept will be taken further for a feasibility analysis on the coming section. At the same time, the previously presented concept of an air revitalization device for life support (Starport I TPR, Table 9) will be merged on the feasibility analysis of this concept to provide a more comprehensive evaluation for their future implementation.

IV.XIV FERTILE Moon: feasibility of extraction of resources and toolkit for in-situ lunar exploration



Just as it has been approached by previously reviewed TPRs, FERTILE Moon bases its study on the premise that, in order to expand a permanent human presence to the Moon, it is necessary to maximize the benefits of ISRU. However, FERTILE Moon recognizes that ISRU technologies development still needs to mature and be further researched on for a real implementation on the lunar surface.

The scope of this report is limited to the development of a computational model tool to evaluate the feasibility of ISRU from an interdisciplinary approach, meaning that political, legal, ethical, economic and technology aspects are integrated within the model to provide a holistic evaluation of the provided input. From the demand input provided by the user, an Excel+Visual Basic code determines a suitable

However, several assumptions were made by the FERTILE Moon team for the creation of the software algorithms, especially in the subsystems where there is a big gap between predictions and simulations, and proven technology results. These areas include life support systems, transportation operations from Earth to the Moon (and vice versa), and ISRU processes, such as extraction and transformation of local resources. Because of this, the results offered by the proposed concept contain inaccuracies and do not make this a suitable tool to make objective decisions.

Although there is potential and value on the FERTILE software concept, it was considered that a higher priority should be given to focus and develop ISRU technology and precursor related activities first, as well as the individual subsystems of a closed-loop life support system. For this reason, no further analysis on this concept´s feasibility will be performed for this thesis, although it is recommended that the idea presented by this TPR is reevaluated at a later phase of the lunar exploration surface missions.

IV.XV METZTLI: an International Space Station approach to lunar exploration

This TPR developed a top-level analysis on how to use the ISS as a platform to initiate lunar exploration activities once it starts its process of end-of-life. Because of this scope, many of the evaluated challenges on this matter are limited to orbital mechanics and operations of the ISS, making it irrelevant to the scope of this thesis.

Nevertheless, there is an entire section of this report focused on studying lunar exploration as a vessel to establish a framework for future planetary exploration activities, as well as to analyzing the challenges that will be encountered when developing a lunar outpost; unfortunately no concept or idea to tackle those challenges is proposed, limiting the content to a brief outline of a proposed phased-timeline for lunar exploration development.

The initial phases of this proposed timeline recommend performing early investigations on Earth, on relevant areas that have already been mentioned in previous sections, such as:

- Closed habitat operations
- Social and psychosocial human aspects
- Operations and control
- Robotic and automated processes
- Surface issues
- Infrastructure aspects

From the completion of this phase, the timeline moves towards performing scientific research on LEO, to then move to cislunar space and finally reach the surface of the Moon to concentrate on ISRU research and development. Finally, build-up activities for a lunar outpost begin, relying on robot and technology demonstration missions

It is evident that, despite the different time at which this project was developed, well-thought recommendations were generated using relevant supporting material since the proposed timeline follows a similar flow as the one that is currently under development with NASA and other spacefaring actors. However, no further review or analysis needs to be made on the Metztli TPR as no relevant novel concept or idea is mentioned nor formulated within it.

IV.XVI LunAres: international lunar exploration in preparation for Mars

For the development of this TPR, it was assumed that the complexity of the mission preparation to go to the Moon and to Mars can be set at the same level based on the fact that most of the technology gaps that need to be addressed to perform surface exploration activities on both places has still to go under in-situ testing validation. Besides, following a logical sequence, to perform the validation missions on the Moon before reaching Mars, would allow to achieve higher robustness in the technology required for the Martian environmental conditions.

Similar to the case of the Metztli TPR, this TPR does not offer any new approaches to tackle the challenges for lunar and Martian exploration missions; however, this TPR offers a comprehensive overview of mission enabling elements to go from lunar surface activities to Martian ones. In addition to this, a selection of the best elements suitable for evaluation on the Moon are identified and listed in a prioritized manner, which can be used to validate, compare and enrich the feasibility analysis that is performed on this thesis.

Interestingly, a similar approach was used by the LunAres team to identify the best candidates before the prioritization process. By identifying the elements that would be better evaluated on Earth, LEO, the Moon and Mars, a list with 45 top-level categories relevant to lunar surface demonstration was generated. To prioritize them, a weighed evaluation was performed considering the following criteria: performance

- Safety
- TRL
- Cost
- Policy implications
- Sustainability
- Scientific value.

For future reference and comparison with the results of this thesis, the prioritized list of categories generated by the LunAres TPR is included in the Appendix section, *A.I Prioritized list of categories and enabling elements for evaluation on the Moon*, of this report.

IV.XVII Autonomous Lunar Transport Vehicle (ALTV): providing a link for scientific research

The ALTV TPR proposes a concept of an autonomous lunar vehicle for transportation, thought to operate between two bases on the surface of the Moon, one located in Shackleton Crater and the other in Tsiolkovsky Crater. The initial cargo requirement was set to 550 kg, crew included if applicable.

After performing a comprehensive feasibility evaluation of different approaches that could be used for the final concept of the vehicle, the ALTV team chose to use a rocket-propelled ballistic hopper over wheeled vehicles, tracked vehicles, screw-driven buoyant vehicles walking-type vehicles and mechanical hoppers.

As mentioned before (*IV.XII Full Moon: storage & delivery of oxygen and hydrogen*) on the introductory analysis of TPR Full Moon's concept of a ballistic-like transportation system, it is pertinent to elaborate on future research that could make this concept feasible for future exploration activities on the surface of the Moon; therefore, although no initial analysis on the relevance of this specific concept is performed on this subsection, it should be noted that a more detailed analysis and further recommendations for a future implementation will be provided on the coming section.

V. Feasibility Study on Selected Concepts

As mentioned in previous sections, a feasibility study was performed on each of the selected concepts to produce a final list with the ranking of the most relevant ones, as well as to outline a set of recommendations for each of them. The methodology used for this study is explained on section *II.II Feasibility Study & Prioritization Process.*

The intention of this section is to evaluate how feasible it would be to implement the selected concepts during future lunar and cislunar missions, as well as to provide a prioritized selection with recommendations for further research.

V.I Scientific Prioritization Criteria

In the coming subsections, feasibility and prioritization assessments will be performed on the selected concepts. For the prioritization of the concepts, the following three-level approach was used, following a similar approach as that proposed by the LEAG (Table 18). This criterion is indicated with a purple diamond on a high to low scale.

Table 18 Scientific Prioritization Criteria (adapted from (Lunar Exploration Advisory Group, 2013)*)*

Priority Level	Description
High	• Concept is essential to develop and progress significantly in exploration activities and habitat establishment. • Advancement on scientific knowledge is greatly facilitated by the concept. • Greatly benefits from lunar/cislunar infrastructure and/or shows promising performance only on the lunar surface or cislunar space.
Medium	• Could be considered as high priority with sufficient investment.
Low	• Concept is not essential to develop and progress significantly in exploration activities and habitat establishment, but It would be good to develop it. • Concept moderately contributes to scientific knowledge. • Could be done/developed more efficiently on other locations.

V.I The Power Cell Concept: Solar Power Satellite and Concentrated Solar Power

In order to establish infrastructure with growing capability on the lunar surface, it is necessary to tackle the limitations that energy production bring to surface mission operations. Mobile operations and transportation of goods and equipment will require a distributed power transmission infrastructure, adapted to the lunar environment and non-dependent of Earth's resources and supplies.

Apart from representing a key step towards facilitating long-term human presence on the Moon, depending on the scheme under which power generation and distribution services are developed for the lunar surface, these activities could also represent a commercial opportunity for private partnerships.

Based on the relevance of these technologies development to the current exploration roadmaps and the previously mentioned objectives for research and development, the following time phasing and prioritization rationales are proposed in Figure 16. Next to the each of the proposed phases for future development, a brief recommendation for the corresponding investigations to undertake or technologies to develop and test is provided.

According to the objectives and challenges identified by the LEAG, power is one of the main prerequisites in terms of available infrastructure, not only for a lunar settlement to happen, but also to allow many other investigations to be developed, mainly in the areas of communications, lunar surface observation and lunar-based Earth observation.

Using the ranking tables defined on section *II.II Feasibility Study & Prioritization Process,* the final evaluation to rank the overall relevance of the concept can be provided on Table 19 below.

Table 19 The Power Cell concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL	Although some individual technologies have been developed and tested, none of the proposed technologies has been tested in space. The integration of the technologies has not been tested either and remains as concept formulation.	2	-	7	14
Technical	Operational Efficiency	Concept is not passive, and requires power to operate.	1	4	5	65
	Autonomy	Concept requires human intervention for its operation and maintenance.	1	3		
	Safety	• Concept does require human intervention and/or robotic assitance for its setup (1 pt). • Concept is not made of hazardous materials but malfunction could endager crew's safety (1 pt).	2	2		
	Adaptability	Concept can be studied, in a different scale, during experimentation on the Lunar Gateway.	2	1		
Economic	Cost	A cost breakdown for a 10-year mission is provided in the Lunar Night Survival TPR and the forecasted sum required for System upkeep falls within NASA's FY 2020 budget. Further analysis on this is required.	2	-	3	6
Policy/Legal	Conflict with Treaties/Conventions	The use of nuclear technology in space questions applicability of the Outer Space Treaty and Moon Agreement.	1	-	1	1
					Total Score	**86**

From these considerations, a time phasing with recommendations for further research and activities required for this concept's development, as well as a prioritization indicator derived from the Lunar Exploration Roadmap are provided on Figure 16.

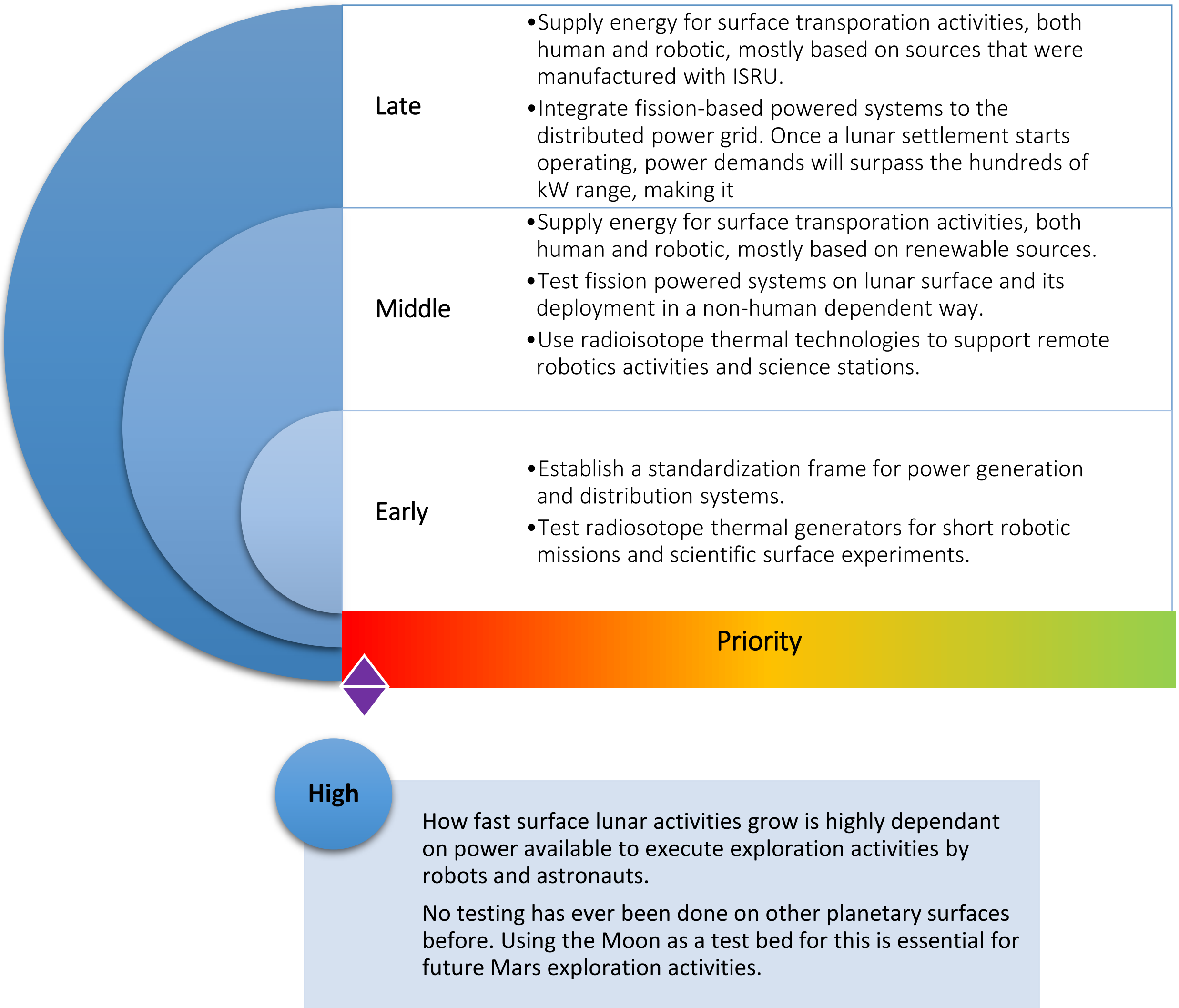


Figure 16 SPS & CSP concepts time phasing and prioritization rationales

Other recommendations

So far, current investigations regarding power generation on other planetary surfaces are limited to fission power systems testing on the lunar surface, radioisotope thermal generators and rechargeable energy storage technologies, especially for stays throughout lunar nights (Lunar Exploration Advisory Group, 2013). Based on this research, it is recommended that the approach adopted by "The Power Cell" concept be further developed, focusing on the following areas:

- **High efficiency PV systems:** current PV technologies are barely reaching a 50% efficiency under simulated environments and controlled testing, so it is difficult to rely on PV systems as a main power source for future lunar applications. Nevertheless, PV technologies show promising future applications as supporting power sources on surface operations. One of the experiments selected for the coming lunar flights is focused on evaluating advanced photovoltaic technology for high voltage consumption on the lunar surface, suggesting that it will be worth evaluating the implementation of "The Power Cell" concept in a later phase of the establishment of a lunar settlement. Meanwhile, according to Herasimenka, Fedoseyev and Reginevich (2019) two major roadblocks need to be addressed to allow PV technologies to be used in a GW-scale: reducing the cost of launching the required mass for their deployment by a factor of 100, which could be achieved via reusable rockets, and reducing the cost of solar cells themselves by a factor of 100 as well, this by advancing the development of thin silicon technology, which, at least in theory, has proven to be the most cost-efficient option for high-power applications in space.
- **Dynamic heat engines integration:** Stirling engines are the most efficient heat-dependent system for electricity generation available at the moment. NASA has already studied this technology through their Advanced Stirling Radioisotope Generator (ASRG), which transforms thermal energy, coming from a plutonium-238 radioisotope into mechanical energy, to finally transform it into electrical energy (Wilson and Wong, 2014). The use of radioisotope thermal generators for small remote stations with a low power demand (approximately >1 kW) could greatly benefit scientific investigations from a medium phase of the lunar exploration activities and help diversify the different power sources that could be used at different locations, specially at those where sunlight is not present on a continuous basis.

  A key consideration related to this technology and to its successful implementation is automation. As it is also with most of the technology concepts being evaluated for future exploration missions, the least dependent a system is on human intervention, the less associated risks it will bring for astronauts and the faster the pace of expansion for lunar outposts could be.
- **Develop support technology from ISRU:** thermal wadis have been proposed as a more sustainable alternative for thermal protection on the lunar surface by using modified regolith as a thermal mass supported by a solar energy reflector, as shown in Figure 17. In areas where heat leaks can be fatal for continuous operation, such as with small rovers located in equatorial regions, this concept could allow them to cope more efficiently with the low temperatures and to keep rover development

costs low by staying within the standard hardware configuration instead of adding to the thermal protection mass to ensure proper operation (Balasubramaniam et al., 2009).

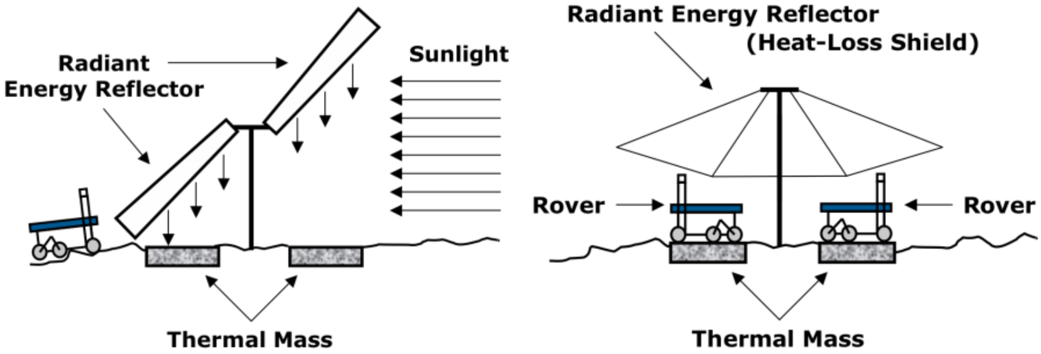


Figure 17 Thermal wadis concept

The last measurements made on lunar regolith were performed during the Apollo program, and they showed that this material does not have a high thermal diffusivity (about 6.6 x10^{-9} m^2/s) (Balasubramaniam et al., 2009), meaning that, by itself, lunar regolith cannot store thermal energy very efficiently. To improve this, it is necessary to process the regolith through an external process, such as: sintering, melting and solidifying, incorporating high-thermal conductivity materials or through thermo/electrochemical processes to reduce regolith's thermal-contact resistance.

The most sustainable approach to this concept then, would be to implement the thermal mass production process through solar sintering, since no alteration to the native lunar environment would be made. However, for purposes of efficiency and mission success assurance, it would be convenient to perform more research on materials that can be brought from Earth to enrich the regolith and achieve a highly efficient thermal mass while maintaining low-invasive profile on the lunar environment.

These variations can be evaluated through a trade-off analysis during mission design, since two main constraints will have to be weighed in when deciding the best approach for energy storage in a future lunar outpost: the location of the outpost itself and the initial launch mass. As for the initial launch mass, it is still uncertain the capabilities that will be available for the first missions targeting the set up of the first outpost; however, regarding the potential location for the outpost, Shackleton Crater's rim, on the lunar south pole, has been suggested as the best candidate to perform the initial mission towards establishing a permanent human settlement.

If it would be the case that the rim of Shackleton Crater was to be the final destination for the coming lunar missions, thermal studies performed by Balasubramaniam et al. (2009) suggest that the use of thermal wadis can provide a 50 K margin for thermal protection, allowing teleoperated rovers to operate for a longer period despite the lunar nights.

Finally, considering that a thermal wadi is a stationary thermal energy source and that rovers that would use them would spend a considerable amount of time on them, it might be useful to integrate extra features to the wadi, such as batteries, to make the most out of its time of operation and to solve as many needs as possible without depending on external sources or human intervention (Johnes et al., 2011).

Another way in which ISRU can support power generation systems is by providing spares or even manufacturing parts of "The Power Cell" subsystems, such as the PV cells.

- **Develop power-beaming technologies from cislunar space to lunar surface:** this recommendation involves de use of the Lunar Gateway during the early phases of lunar exploration missions to test power beaming technologies within cislunar space at first, to later test the beaming process onto the lunar surface. A similar approach was proposed by Deyoung and J., in 1989, having as a key element a spacecraft in a Low Moon Orbit providing power to a lunar base via laser beams. However, considering the current plans to send humans to the lunar surface by 2024, a good precursor experiment for future power-beaming technology testing could be through the use of a small rover that could be powered by a laser-beaming source once the Lunar Gateway starts operating.
  It is difficult to define a clear mission architecture that involves this technology due to the uncertainty about the science that will be performed during the coming mission to the Moon in 2024. However, with the recently announced Lunar Surface Instrument and Technology Payloads Call, it makes sense to reconsider adding a precursor experiment for laser-beamed power systems in the next lunar flights.

Taking into consideration that the location with better chances to welcome a future lunar settlement is the Moon's south pole, and that this area benefits from an almost continuous sunlight, the challenge to provide power for future operations on the lunar surface lies on the efficiency of PV technologies and the integration of other sources, such as nuclear reactors and lunar-orbiting power beaming. Nuclear fission reactors are not considered within the feasible options based on the current budgetary constraints and lack of a solid international regulation on the use of these technologies in space. Therefore, it is essential to consider the potential of a system that can beam energy to the lunar surface, from a lunar orbit, assuming that the Space Launch System will allow to carry the required mass to set up such a system at an early stage. Figure 18 shows an orbital solar power system concept, which would orbit at 3000 kilometers in a polar orbit and which would be able to fit in the SLS for an easy deployment on the lunar surface.

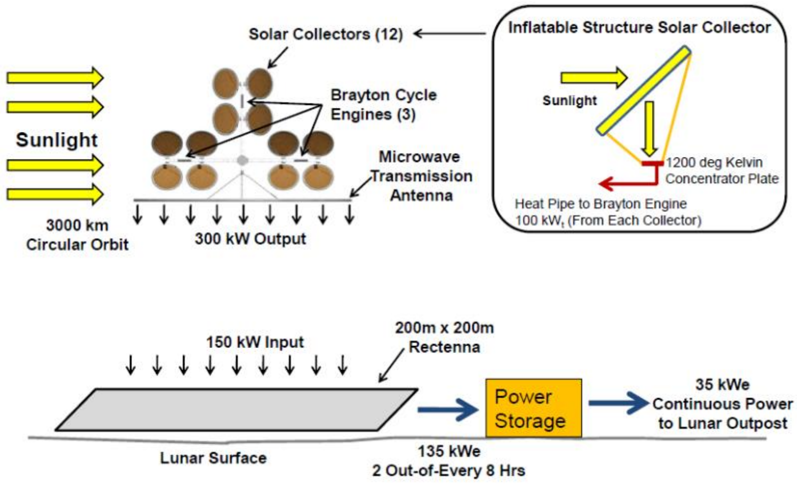


Figure 18 Orbital Solar Power System concept developed by Johnson (2017).

From these considerations, it is safe to establish that "The Power Cell" concept is of high relevance and priority for future surface lunar missions. Not only has the need for a reliable and robust power source been identified by NASA, but it is also convenient that the amount of research done on power systems' development allows for technology demonstration in space to be performed soon.

There is still, however, some debate about the technology readiness level of the previously mentioned concepts. Table 20 provides a brief overview of how an orbital solar power system compares to another promising concept mentioned before: The Concentrating Solar Power system. Whether one or the other are ready to be tested on the lunar surface is still uncertain; what cannot be denied is the fact that the whole Power Cell concept holds promise that should be reevaluated with further research in the points listed before.

Table 20 Comparison between Solar Power Satellites and Concentrating Solar Power systems (adapted from Smitherman, 2013)

Segment	Solar Power Satellite Concept	Concentrating solar Power System	Notes
Technology Readiness Level	5	9	CSP is operational on Earth, space operations are still to be validated. SPS individual technologies are rated from TRL 2-9.
Space-Based Systems Area (Collector plus Transmitter)	5.15 km^2 with potential reduction to 3.17km^2	0.00 km^2	SPS area reduction depends on PV array efficiency improvements from 30 to 50%.
Ground Receiver Type	Rectenna	Heliostats with Power towers	Internal heating of rectennas resulting from microwaves is a main constraint for SPS systems.
Receiver Collection Area	10.00 km^2	15.15 km^2 with a potential reduction to 4.82 km^2	CSP potential area reduction depends on future power tower efficiency improvements.
Total System Area	15.15 km^2 with potential reduction to 13.17 km^2	15.15 km^2 with a potential reduction to 4.82 km^2	Significant potential improvements can be achieved for CSP systems.
Receiver Land Area	34.00 km^2	90.87 km^2 with a potential reduction to 28.4 km^2	Despite the fact that the land area for CSP systems is about three times larger than that of SPS systems, a significant reduction can be achieved through efficiency improvements.
Total End-to-End efficiency	14.79% with potential improvement to 24.65%	4.83% with potential improvement to 15.18%	SPS efficiency is much better than CSP systems.
Power Output from Collector	202 W/m^2 with potential upgrade to 337 W/m^2	66 W/m^2 with potential upgrade to 208 W/m^2	More than two times of power output is offered by SPS systems over CSP¨systems.

V.II Starport I's Radiation Shielding Concept

Consistent with the previously mentioned Goal-SCI-D, which is centered on using the Moon as a unique research tool for its hazardous environment, Starport I's concept of a radiation shield would satisfy possible investigations about the effects of radiation on the lunar surface on biological systems.

The concept that Starport I TPR presents consists on a triple-layered aluminum shield, with an additional water layer and a triple layer of tantalum, as depicted on Figure 19. The tantalum layers would provide protection against x-rays, while debris protection is also encouraged by proposing to ad to extra layers of Kevlar between the central layer and the outer ones.

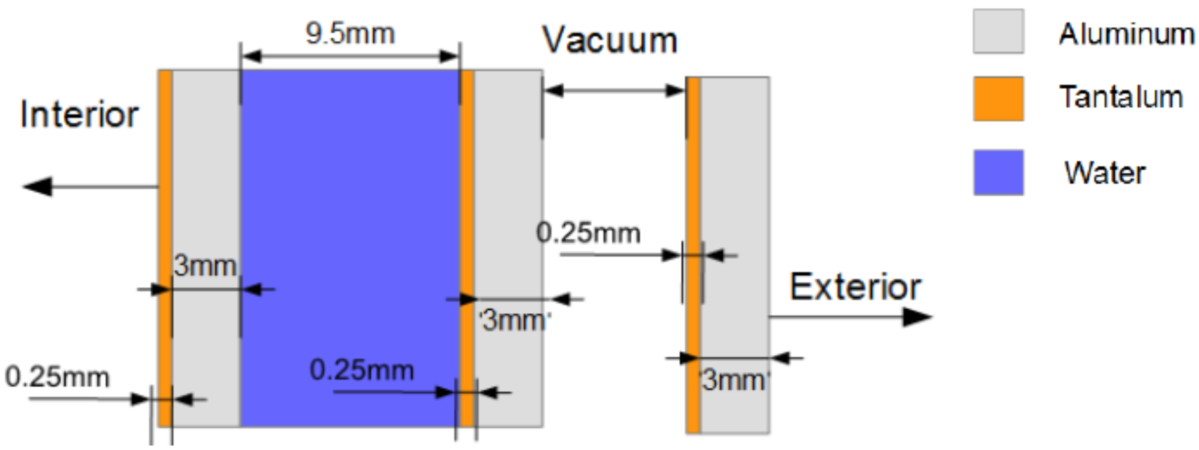


Figure 19 Starport I's radiation shielding concept, cross section view

Although this concept sounds reasonable, it is based on the assumption that a future lunar habitat would be built with rigid structures, which has not yet been defined within the current exploration plans. However, it is worthy to evaluate the different applications that the development of such a concept could facilitate.

This concept has not been tested yet, although some of its components have been extensively researched on and even tested in space. Such is the case of Kevlar, which under ESA's sponsored program ALTEA-shield, was tested in the Columbus modulus of the ISS. From this investigation, it has been found that Kevlar's performance is comparable to that of polyethylene (Narici et al., 2017).

Using the ranking tables defined on section *II.II Feasibility Study & Prioritization Process,* the final evaluation to rank the overall relevance of the concept can be provided on Table 21 below.

Table 21 Starport I's Radiation Shielding concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL		2	-	7	14
Technical	Operational Efficiency	Concept is passive, does not require power to operate.	2	4	5	120
	Autonomy	Concept does not require huan intervention for its operation.	3	3		
	Safety	• Concept does require human intervention and/or robotic assitance for its setup (1 pt). • Concept is not made of hazardous materials (3 pt).	3	2		
	Adaptability	Concept can be used to perform other experiments, studies where the science objectives focus on evaluating radiation effects on biological subjects.	2	1		
Economic	Cost	No data of the actual cost that this concept's development would represent has been defined, but considering its impact on payload mass cost, given the fact that all the materials would have to be launched to the lunar surface, the lowest grade is awarded.	1	-	3	3
Policy/Legal	Conflict with Treaties/Conventions	No identified legal conflict	2	-	1	2
					Total Score	**139**

From these considerations, a time phasing with recommendations for further research and activities required for this concept's development, as well as a prioritization indicator derived from the Lunar Exploration Roadmap are provided on Figure 20.

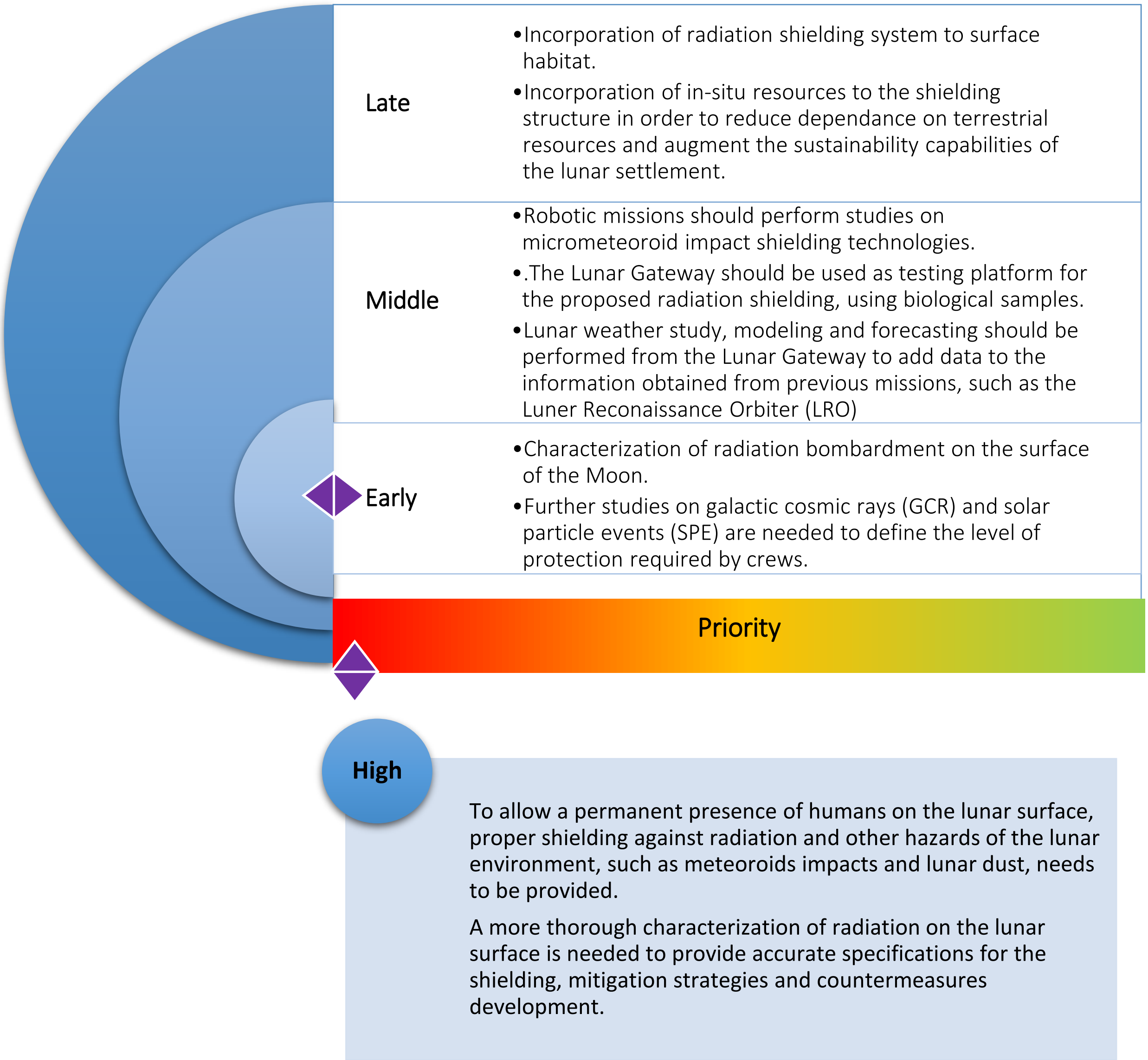


Figure 20 Starport I's radiation shielding concept time phasing and prioritization rationales and recommendations

Other recommendations

Given the fact that the current state of this concept lies on the early phase of its potential development, the following recommendations are provided for further research:

- **Recommendation 1:** Radiation also needs to be quantified inside caves or lava tubes if a robotic mission is ever sent towards those sites in order to have a more objective evaluation of whether these should still be considered as good candidates for future habitats, as they could provide natural protection against prolonged exposure to radiation.

- **Recommendation 2:** The same recommendation applies to regions near/or at the poles, especially since the potential existence of valuable resources at those sites remains a driver for their exploration.
- **Recommendation 3:** Polyethylene has been recognized as a suitable standard option for solid shielding structures, but Kevlar has already proven its capability to perform at the same level. More experiments need to be made with Kevlar to measure its radiation dose reduction capability under different configurations.
- **Recommendation 4:** The use of water as radiation shielding should be further studied, focusing on a synergic use of the shielding structure to provide life support services as well.
    - ISRU should be considered an enabling path for allowing multiple applications of water, for its use in a terrestrial-dependent way does not make this feasible, in terms of cost and required infrastructure.
- **Recommendation 5:** To further develop this concept, the use of novel materials, besides the already proven Kevlar, should be studied. Some candidate materials that could substitute the proposed layers are:
    - **Palladium/Silver:** these materials hold potential for radiation shielding applications because of their ability to store high levels of hydrogen; however, no concrete studies have been performed on this matter and need to be addressed. Another downside of these is the associated cost of production and high atomic mass.
    - **Nano-carbons:** these materials' strength comes from their versatility in applications, for they can be used in composite structures, fuel cells and hydrogen storage. This last property is probably a valuable research focus, since H_2 retention can increase radiation shielding effectiveness.

      Amongst the disadvantages that need to be addressed for future space applications are its flammability and cost of production.
    - **Metal Hydrides:** these materials are considered good candidates to optimize GCR dose reduction, with a performance comparable to that of polyethylene. Some of their disadvantages are that they can be flammable and reactive to water.

      Nevertheless, there is potential value in studying these materials' performance in space, since their low cost and chemical properties suggest a double use in fuel cells.

V.III LuGaLiSus System Concept

As mentioned before, this concept uses as baseline systems MELiSSA and Bios-3; the first one, for its efficient use of cyanobacteria and plants to provide food and manage waste recycling, while the second was selected for its approach on air and water closed loops. Regarding waste management processes in this concept, physico-chemical systems are proposed as an initial step before implementing supportive bio-regenerative systems (See *Figure 15 LuGaLiSus concept block diagram* (International Space University, 2006b)for concept reference).

Also, as mentioned before, and based on the air revitalization deficiencies of the LuGaLiSuS concept, a special focus on the air revitalization system proposed on the Starport I TPR is made on this section for the evaluation of the concept's ranking.

An overall TRL of 4 has been given to the MELiSSA system (Lasseur, 2017), but a detailed TRL evaluation of individual subsystems can be found on Appendix *A.II MELiSSA's Planned Roadmap.* Similarly, Bios-3 system can also be graded with a TRL of 4 based on the experimental activities that were carried out for its development and testing. This, unfortunately, does not mean that LuGaLiSus can be graded with the same TRL. While this concept is based on the integration of two other systems with tested technology, the integration itself of such technologies has not been tested yet, but rather stayed as a speculative formulation of potential successful operation. Based on this, a TRL of 2 is awarded to this concept.

Table 22 summarizes the relevant criteria evaluation to rank this concept's relevance and feasibility for future implementation during lunar missions.

Table 22 LuGaLiSuS concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL		2	-	7	14
Technical	Operational Efficiency	Concept is not passive, and requires power to operate.	1	4	5	65
	Autonomy	Concept requires human intervention for its operation and maintenance.	1	3		
	Safety	• Concept does require human intervention and/or robotic assitance for its setup (1 pt). • Concept is not made of hazardous materials but malfunction could endager crew's safety (1 pt).	2	2		
	Adaptability	Concept can be used to perform other experiments, studies where the science objectives focus on evaluating life support systems for biological subjects during experimentation on the Lunar Gateway.	2	1		
Economic	Cost	No data of the actual cost that this concept's development would represent has been defined, but considering it integrates existing technology or under current development, a neutral grade is awarded.	2	-	3	6
Policy/Legal	Conflict with Treaties/Conventions	No identified legal conflict	2	-	1	2
					Total Score	**87**

From these considerations, a time phasing with recommendations for further research and activities required for this concept's development, as well as a prioritization indicator derived from the Lunar Exploration Roadmap are provided on Figure 21.

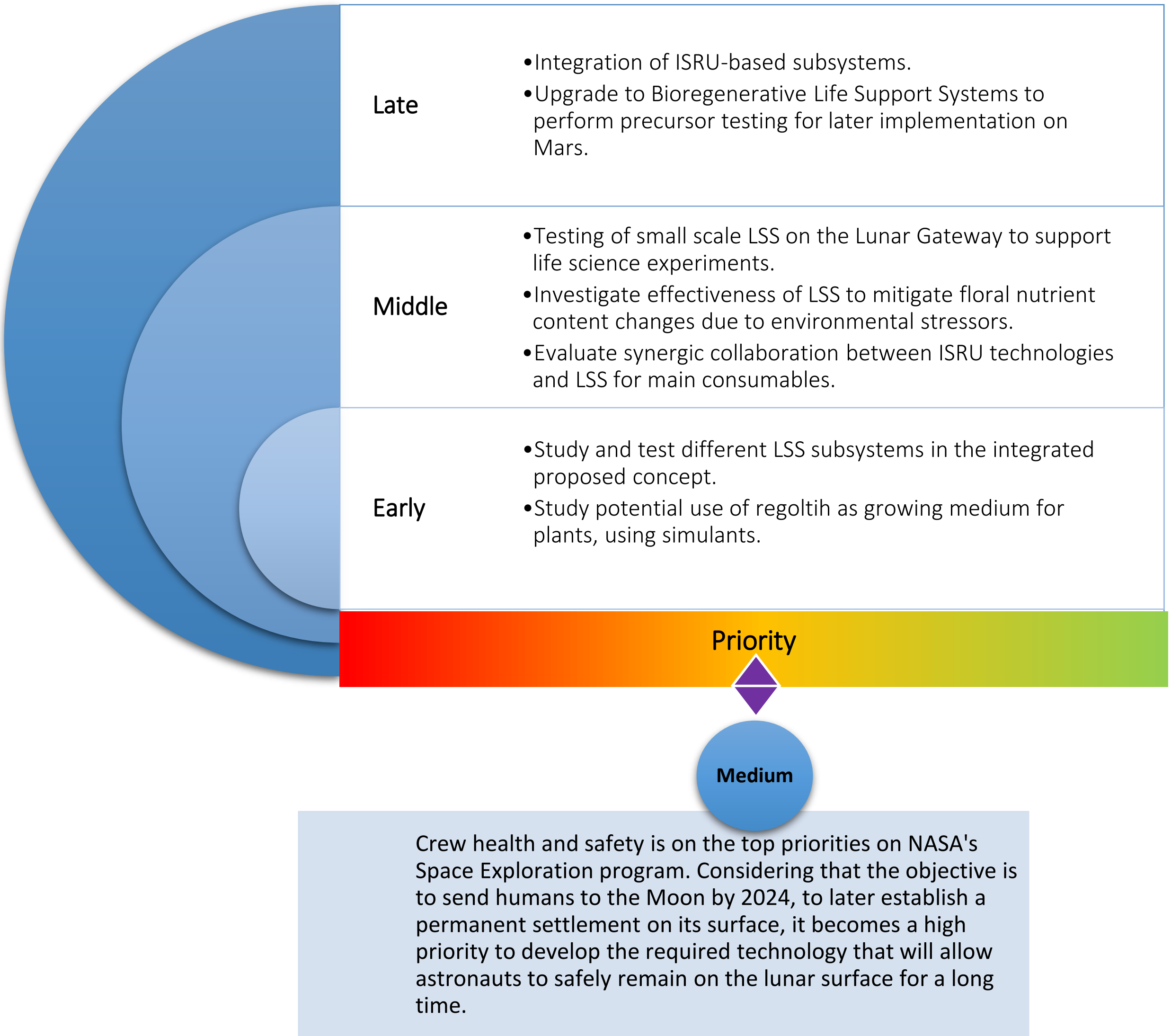


Figure 21 LuGaLiSuS concept time phasing and prioritization rationales and recommendations

Other recommendations

- **Recommendation 1:** Smaller scale LSS should be tested on the Lunar Gateway, specially to develop powered systems and automated operations for a later transfer into lunar surface operations.
  - Bioregenerative Life Support Systems' challenges: Study of damages on algae due to long-term exposure to radiation: this research can be conducted on the Lunar Gateway; Chlorella vulgaris and Nostoc sphaeroides have been proposed as good candidates for a study like this (Niederweiser et al., 2018). A down-scaled LSS is required to perform this

research. This is a high priority research due to the lack of knowledge we have on bioregenerative life support systems and its relevance to achieve the ultimate goal of permanently settling on the Moon. Efficient implementation of this approach would have a positive impact on mission cost reduction and development of sustainable capabilities.

- **Recommendation 2:** Waste management subsystems need further development under close-to lunar environment conditions. Successful technologies for this application have already been developed, but under gravity-dependent constraints (the Trash to Gas system, (Meier and Hintze, 2018)). The Lunar Gateway can help assess long duration space travel waste management and reutilization, under micro gravity conditions.
    - Thermochemical processes are of high relevance and should be considered a priority for this research.
- **Recommendation 3:** Regarding the use of cyanobacteria for oxygen regeneration, more research is needed on the efficiency that can be obtained from using Arthrospira platensis and Chlorella in co-habitation. This is mid-term priority area for research, although it is recommended that early experiments are performed on the Lunar Gateway to leverage from the unique environmental conditions that it will provide.
- **Recommendation 4:** Food source propagation and augmenting the nutritional value that can be obtained from them needs further investigation as the timeline moves towards the establishment of a lunar settlement. Precursor research, as it has been done on LEO with the ISS, should be performed as a priority on the Lunar Gateway. This will accelerate technology scalability for surface applications.
- **Recommendation 5:** Human interaction with this system was one of the downsides that lowered its overall ranking grade. Crew interaction for operation and maintenance has to be reduced, therefore, further research on automation of LSS is needed in the early term.
- **Recommendation 6:** ISRU integration to LSS is required to move towards a sustainable presence on the Moon. Research on water and oxygen generation is needed in the early/mid-term.

V.IV Plasma Drill Concept for Deep Lunar Studies

In a joint effort between Zaptec Inc., a Norwegian oil & gas company and Shackleton Energy Company (SEC), a U.S. lunar mining company, the concept of a plasma drill for future deep-drilling missions on asteroids, the Moon and Mars is being developed. Although little technical specifications have been provided regarding this concept´s operation, it aligns with the LER's objectives and this thesis' focus on scientific opportunities for future missions on the Moon, favoring its feasibility evaluation.

Other than its capability to drill to up 2000 m in depth, using 2 kW of power and weighing approximately 440 kg, no other data is available for this concept (see Figure 22 for sizing reference). Nevertheless, the principle of operation suggests that multiple related science and technology investigations can be derived from the proposed plasma drilling concept.

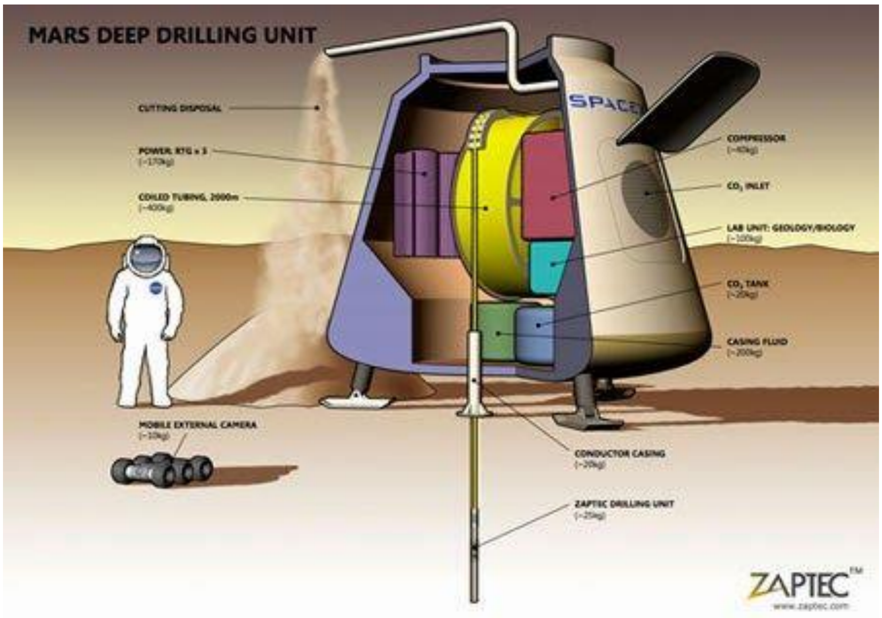


Figure 22 Zaptec's Plasma Drill concept. Power transformer designed to fit inside SpaceX Dragon capsule (Zaptec Inc., 2018)

Table 23 summarizes the relevant criteria evaluation used to rank the feasibility and relevance of this concept for future lunar missions.

Table 23 Plasma Drill concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL		3	-	7	21
Technical	Operational Efficiency	Concept is not passive, and requires power at high rates to operate (2kW) .	1	4	5	90
	Autonomy	Concept requires does not require human intervention for its operation and maintenance.	2	3		
	Safety	• Concept does not require human intervention for its setup (2 pt). • Concept is not made of hazardous materials but malfunction could endager crew's safety (1 pt).	3	2		
	Adaptability	Concept only has one specific use; however, the electronic transformer powering the drill could be used for other purposes on the lunar surface. The drilling unit could piggy back other experiments/instrumentation to the lunar surface..	2	1		
Economic	Cost	No data of the actual cost that this concept's development would represent has been defined; the lowestl grade is awarded.	1	-	3	3
Policy/Legal	Conflict with Treaties/Conventions	No identified legal conflict	2	-	1	2
					Total Score	**116**

Key investigations that need to be addressed before, during and after this concept's development are outlined in Figure 23, with a general recommendation for time phasing and scientific relevance, these under the assumption that the plasma drill concept is implemented. More detailed recommendations that are not based on that assumption, for potential research, are provided after.

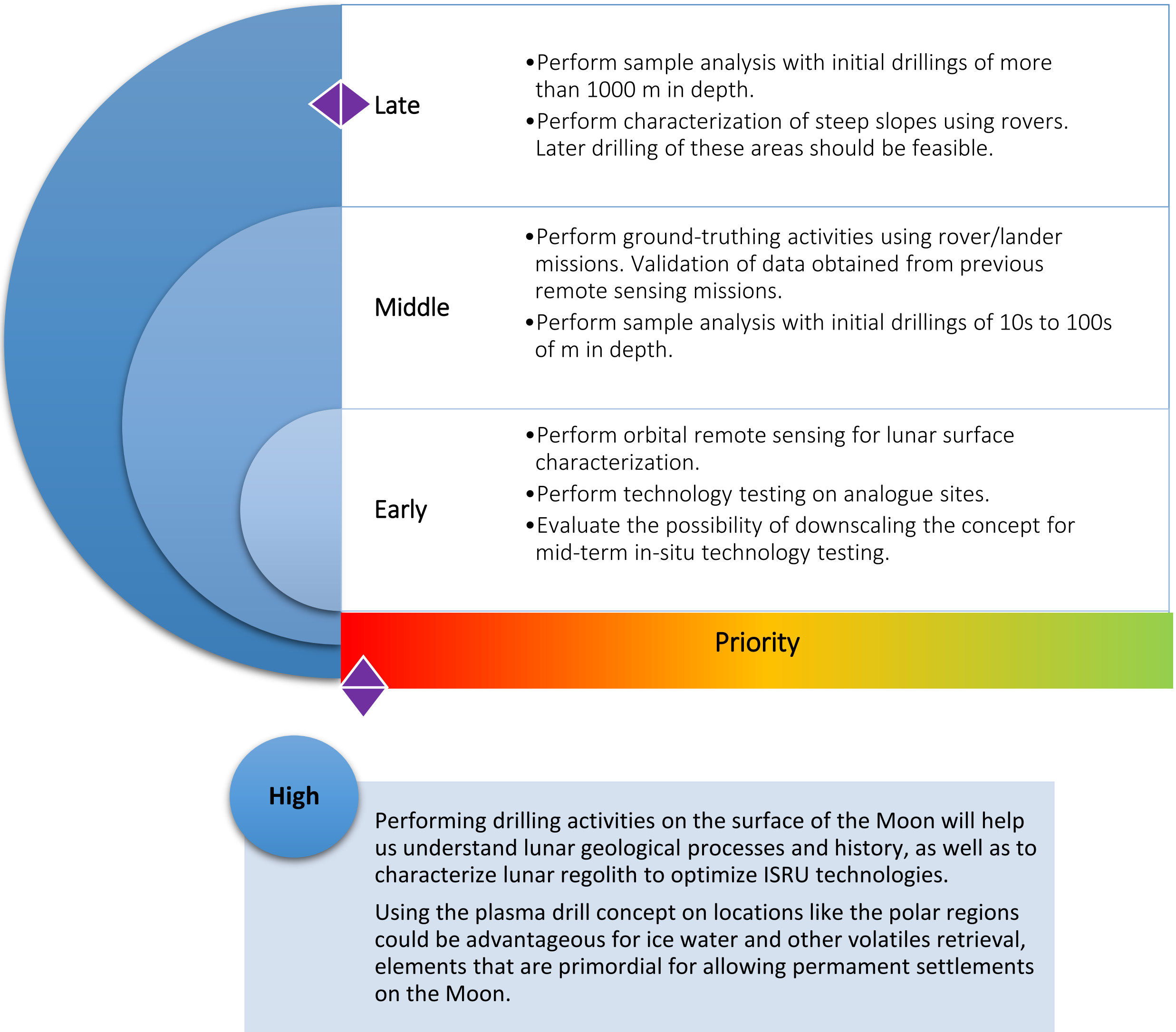


Figure 23 Plasma Drill concept time phasing and prioritization rationales and recommendations

Since this concept's implementation corresponds to a mid to late-term, some of the following recommendations are focused on the research that could be done once the technology is developed.

Other recommendations

- **Recommendation 1:** Study compressed CO_2 gas circulation processes for powdered sample retrieval during drilling activities.
- **Recommendation 2:** Study new approaches to reduce and optimize the current mass of the drilling system. Since the drilling capability is power-dependent, and the transformer designed for this concept is meant to provide 2kW of power, it would be reasonable to reduce the drilling capability for early phases of the exploration activities to reduce the power segment's mass and increase the concept's feasibility.
- **Recommendation 3:** Study the option of testing a down-scaled version of the concept through an early lunar lander or rover mission.
- **Recommendation 4:** Study and characterize the different layers of regolith. During late phases this could be done on different locations using rover support. This investigation will help determine the following gaps in lunar science:
    - Transport mechanisms of volatiles: lateral and vertical mixing of regolith understanding will help us know more about the Moon's subsurface composition and the history of the Sun's activity.
    - Space weathering throughout time: solar wind and radiation, micrometeorite impacts cosmic radiation have shaped the Moon's regolith composition, so different variations could offer potential for different applications.
    - Geotechnical properties of regolith: key for structural applications in habitat or other infrastructure construction.

V.V Development of Interface and Operation Standards for OOS

In line with Goal-FF-B, an interesting idea was identified in the AMOOS TPR: the standardization of interfaces and operations for OOS. It is necessary to define a structure that allows strong international cooperation, with a cost-effective approach. The ISS has been used as a test platform for establishing multi-lateral cooperation for space centered activities; however, with the coming execution of lunar missions and the planned construction of the Lunar Gateway, it becomes necessary to rethink and redefine an efficient administrative structure for the collaborations to come. In this case, the focus of the idea lies on On-Orbit Services and the need to establish interface standards to facilitate interoperability between the (now) more varied space community. Cooperation between space agencies and private companies is a key element that will make the coming missions to the Moon a reality. Table 24 and Figure 24 below, provide a feasibility assessment, time-phased suggested proceeding and scientific prioritization.

Table 24 Interface and Operation Standards for OSS concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL	Operations on the ISS work as benchmark for this concept's development	3	-	7	21
Technical	Operational Efficiency	N/A .	1	4	5	100
	Autonomy	Once defined, this standards will apply to all activities related to OOS from the Lunar Gateway and similar spacecraft.	2	3		
	Safety	• Good development and definition of this concept will directly impact on safety for crew and infrastructure.	4	2		
	Adaptability	Concept can be used as baseline to develop other standards.	2	1		
Economic	Cost	No data of the potential cost of this concept's development has been defined, but it should not affect the current budget.	2	-	3	6
Policy/Legal	Conflict with Treaties/ Conventions	No identified legal conflict, although an official international framework is required for the creation and implementation of standards.	2	-	1	2
					Total Score	129

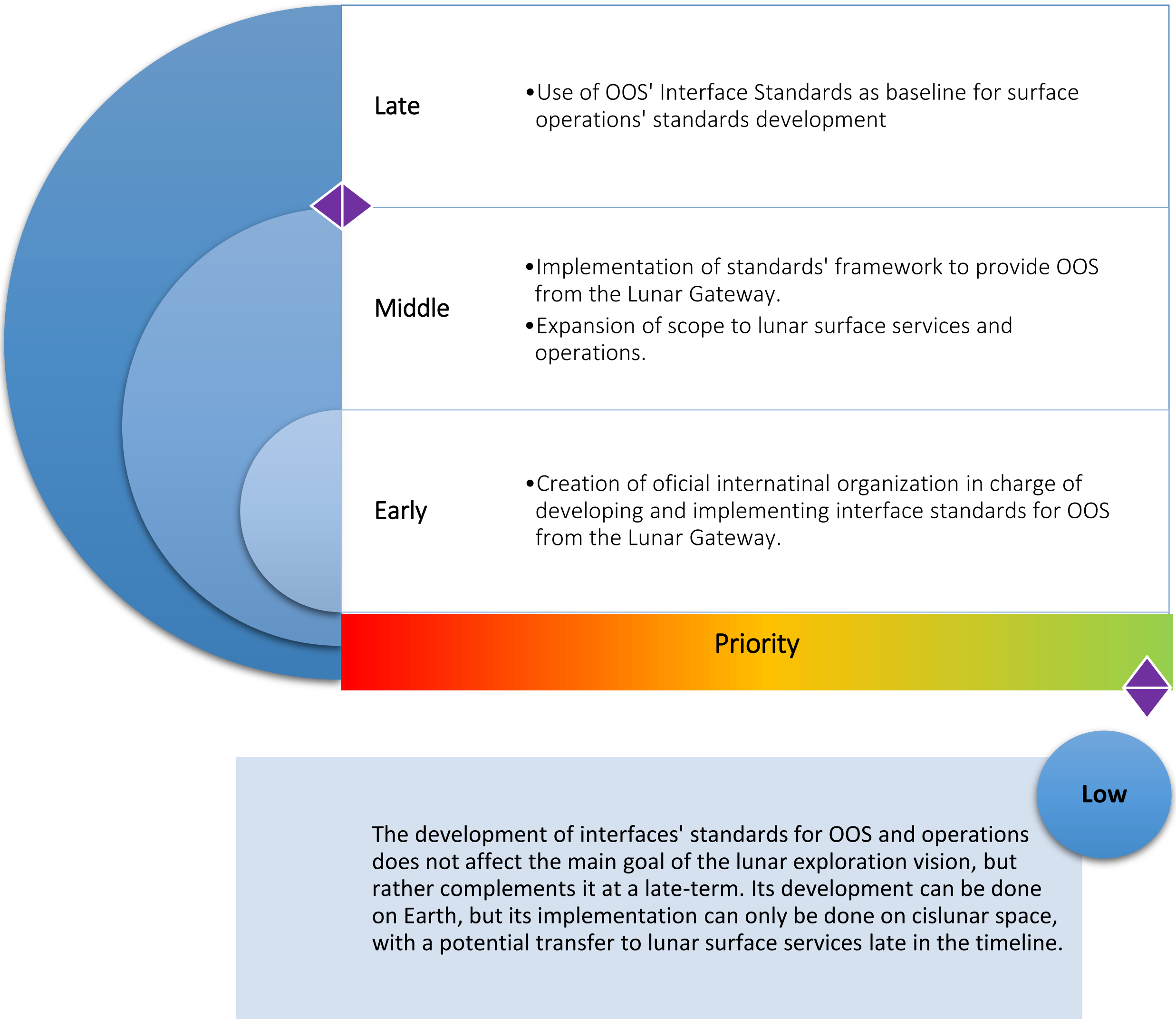


Figure 24 Development of interfaces and operations standards for OOS concept time phasing and prioritization rationales

As mentioned at the beginning of this chapter, if a concept or idea could be better developed in a location different than the lunar surface or the Lunar Gateway, then a low priority level would be awarded to it. Nevertheless, it is important to start considering the various gaps that exist due to the lack of a standard framework for interfaces and operations for OOS. The following recommendations are outlined with the intention of filling those gaps and facilitate the future development of the proposed idea.

Other recommendations

- **Recommendation 1**: As stated by Coutinho and Welch (2018), new standards for interfaces should be driven by inclusivity, interoperability and commercial viability. These three principles should always be followed for any standard defined for cislunar/lunar surface interface.
- **Recommendation 2:** A methodology to define interfaces' standards for use on cislunar space (on the Lunar Gateway) and on the lunar surface, needs to be established in an international cooperative effort.
  - All actors involved in the current lunar missions' activities have to be involved in the process of defining these standards, and special consideration should be given to the possible creation of a Standard Development Organization (SDO) solely focused on operations on cislunar and lunar space. The suggested actors to be involved in this process are:
    - Space agencies
    - Industry and Academia
    - Industrial Associations
    - Moon Dedicated Associations
    - SDOs (Coutinho and Welch, 2018)
- **Recommendation 3:** The OOS that would be provided from cislunar platforms need to be clearly defined in order to identify all the interfaces that require standardization.
  - Functional systems need to be defined from the services that are intended to be provided. This will provide a clearer idea of the required interfaces.
    - Human-computer interface: definition of a standard language for operation.
    - Data interface: depending on the use/service being provided by the instrument on the Lunar Gateway, a standard protocol for data prioritization needs to be established.
    - Power interfaces: human safety standards need to be defined, as well as electromagnetic compatibility and electrical loads requirements.
      - Direct current and grounding interface standards need definition.
    - Mechanical interfaces: safe docking/undocking procedures between client satellite and provider platform need to be defined to ensure that interfaces meet mechanical requirements.

V.VI AMS-like experiment module evaluation

Although the BLISS TPR does not propose the use of this instrument per se, it does mention that its implementation on the ISS has been of high relevance to further advance in the field of radiation mitigation countermeasures, and has also represented a defining constraint for data downlink due to the amount of information generated by its operation. From this premise and its recognized relevance by the LEAG as an investigation worth including in the plans of future lunar exploration, this concept is evaluated for lunar surface implementation feasibility and potential future research for its continuous development. Table 25 below provides a feasibility assessment for a later ranking of the AMS-02-like instrument concept.

Table 25 AMS-02-like instrument concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL	Operation on the ISS work as benchmark for this concept's future development for lunar surface implementation	5	-	7	35
Technical	Operational Efficiency	The baseline power consumption is set at 2 kW	1	4	5	95
	Autonomy	This instrument does not require human intervention for its operation.	2	3		
	Safety	No hazards from instrument operation and composition.	4	2		
	Adaptability	Concept has a very specific purpose.	1	1		
Economic	Cost	The total cost of the AMS-02 experiment went up to 2 billion USD (Musser, 2011). No projection for its lunar implementation is available ; the lowest grade is awarded.	1	-	3	3
Policy/Legal	Conflict with Treaties/ Conventions	No identified legal conflict.	2	-	1	2
					Total Score	135

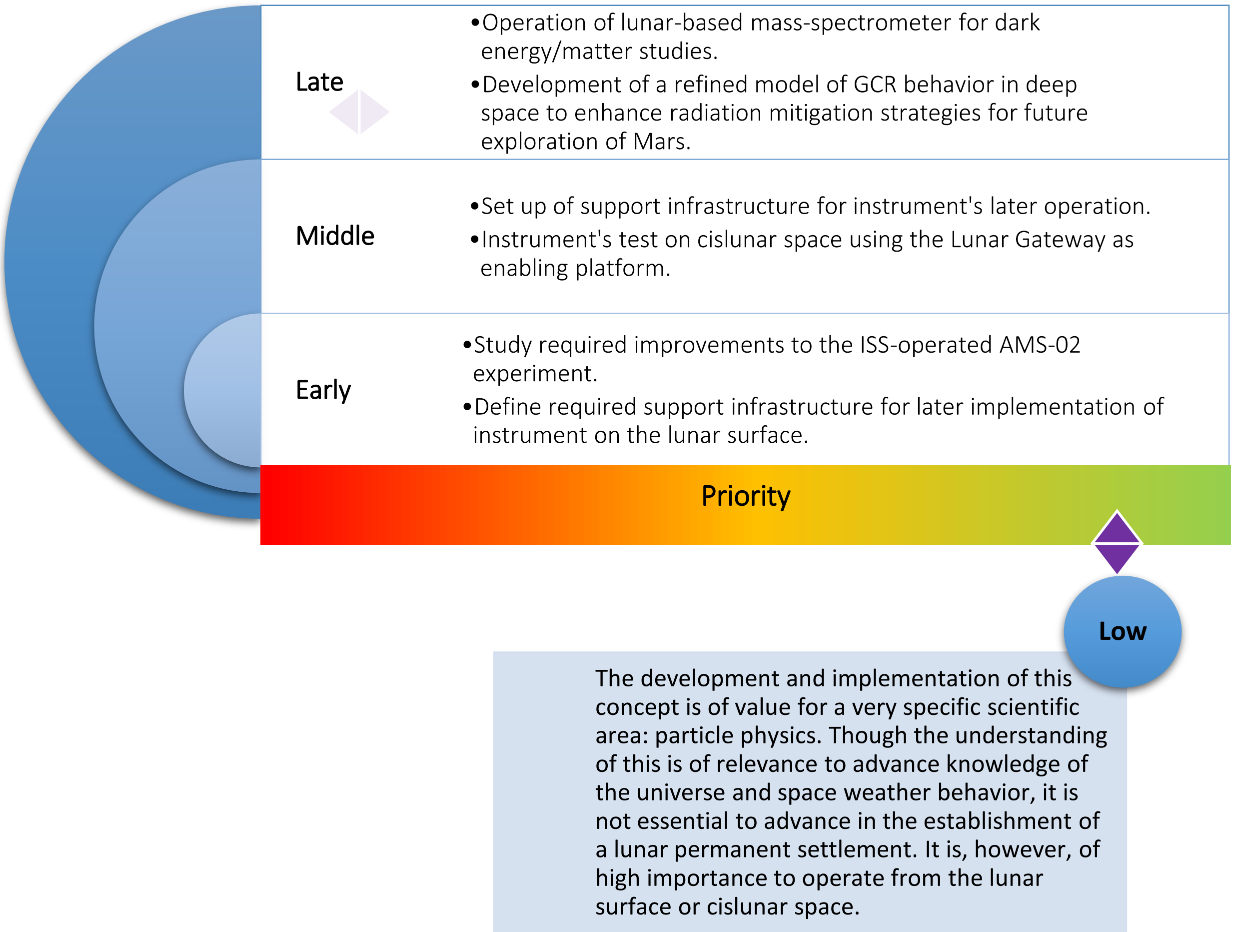


Figure 25 AMS-like concept time phasing and prioritization rationales and recommendations

Other recommendations:

- **Recommendation 1:** Research on an optimized power consumption of this instrument is required to successfully transfer the technology to the lunar surface (limited resources).
- **Recommendation 2**: a downscaled version of the instrument should be studied for potential testing on the Lunar Gateway.
- **Recommendation 3:** Cloud computing capabilities for the Lunar Gateway need to be studied and planned or implementation in a late term to avoid bandwidth saturation through downlink operations.

V.VII QWIP-Based Instrument for Lava Tube Identification

The use of caves and lava tubes as habitats for future human settlements has been proposed based on the multiple benefits their natural characteristics could bring to counteract the hazardous conditions of alien environments: high levels of radiation, dust, micrometeoroids' impacts and extreme temperatures are the most popular. On the other hand, there could be valuable deposits of local resources inside caves and lava tubes that could be used for consumables production through ISRU and even to perform studies on their composition and historical evolution, increasing our understanding of space weather phenomena and lunar history.

Despite the advantages that the use of these places could bring to the future of lunar exploration, work still needs to be done on efficient technologies for identification of these structures, being spatial resolution one of their main constraints. Quantum Well Infrared Photodetector technology for thermal sensors could fill this need, which is why further research and development is needed. Table 26 below summarizes the feasibility assessment for this concept.

Table 26 QWIP-based instrument evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL	Thermal camera was tested during RRM3	8	-	7	56
Technical	Operational Efficiency	Low power consumption (Keesey, 2018)	2	4	5	115
	Autonomy	This instrument does not require human intervention for its operation.	2	3		
	Safety	No hazards from instrument operation and composition.	4	2		
	Adaptability	Concept has a very specific purpose.	1	1		
Economic	Cost	Low cost for instrument development	2	-	3	6
Policy/Legal	Conflict with Treaties/ Conventions	No identified legal conflict.	2	-	1	2
					Total Score	179

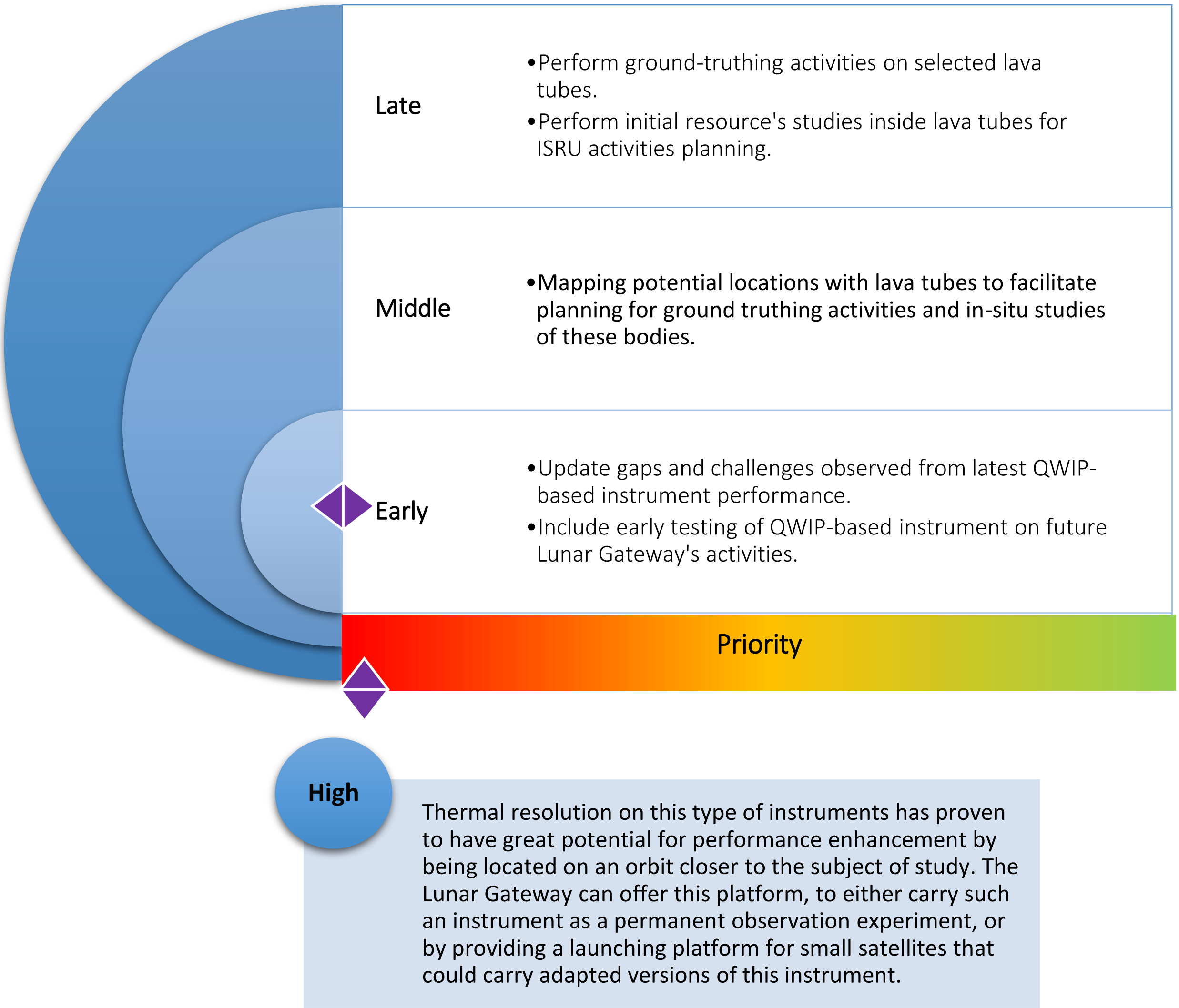


Figure 26 QWIP-based instrument for lava tube identification concept time phasing and prioritization rationales

Other recommendations

- **Recommendation 1:** Ground-truthing through gravimetry studies in a middle-term phase when the first robotic missions are sent to the surface of the Moon. A gravimetry experiment can be performed with the aid of small rovers since, unlike GPR, it does not require a lot of power to operate. Seismic dynamics on the Moon would be better understood through studies using this technique since not only can lava tubes be characterized with it, but a wide variety of other subsurface features as well, such as deposits of ice and buried impact craters. Results from this research can help develop cave thermal models.

- **Recommendation 2:** Perform research on strained layer superlattice technology to enhance thermal detection at higher temperatures without compromising the power budget of the instrument.
- **Recommendation 3:** As mentioned before, data processing for this instrument's readings tends to complicate as the resolution increases, requiring more efficient data processing. Research is required on computing systems that can provide image and video processing on-orbit, such as hybrid computers to control the instrument and process readings simultaneously or using data processing support from the Lunar Gateway.

V.VIII P2P-HRI Concept

The P2P-HRI concept aims at enhancing human-robot interaction by developing key tools and techniques for spatial awareness, communication processes and user interfaces. The main target areas for applications are crew exploration vehicles, lunar surface systems and all the preparing activities for a permanent settlement deployment (Fong et al., 2006).

This concept's relevance to the future needs for robotics support in lunar exploration missions is of high relevance, which is why further research and development is needed in the short term.

Table 27 below provides a feasibility assessment on this concept's relevance to lunar surface missions and potential implementation on cislunar and lunar surface space.

Table 27 P2P-HRI concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL	Studies have been conducted in simulated environment.	5	-	7	35
Technical	Operational Efficiency	Non-dependent on power.	2	4	5	120
	Autonomy	This concept is highly relevant to developing autonomy within robotic responses when interacting with humans..	2	3		
	Safety	Development of concept is focused on increasing safety. (2 pt) No hazardous materials related to concept's development/implementation (2 pt)	4	2		
	Adaptability	Concept is intented to adapt to all types of activities involving human-robot interaction.	2	1		
Economic	Cost	Low cost for concept's development	2	-	3	6
Policy/Legal	Conflict with Treaties/ Conventions	No identified legal conflict.	2	-	1	2
					Total Score	179

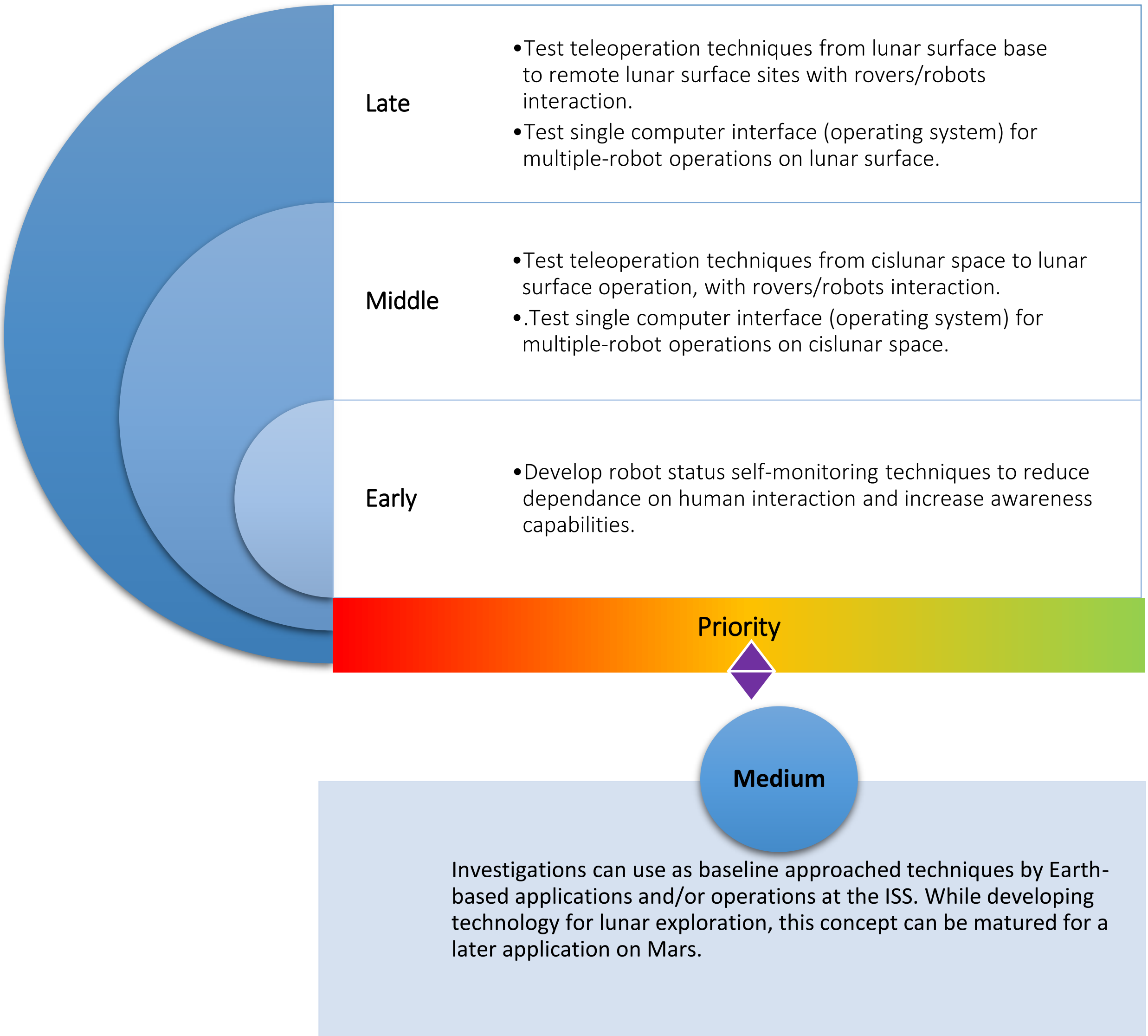


Figure 27 P2P-HRI concept time phasing and prioritization rationales and recommendations

Other recommendations

- **Recommendation 1:** Develop a standardized operation system that works as the interaction framework for direct human-robot interactions and teleoperated ones.
- **Recommendation 2:** Redefine required components for a standardized operating system, such as:
    - Task, Resources, Interaction and Context Managers.
- **Recommendation 3:** Identify potential communication challenges, such as time delays or mission duration to develop countermeasures protocols and use them as baseline for further development of autonomy.
- **Recommendation 4:** Monitoring task completion and result evaluation has been identified by Fong et al. (2006) as one of the main challenges faced by human-robot interaction; research is needed in the area of cognitive modeling for the robotic segment, aiming to implement artificial intelligence approaches to monitor when a task is being executed and then completed.
- **Recommendation 5:** Moving towards a standardized development in space exploration activities, it is necessary to enhance existing voice to action interfaces, for which more research is needed, accompanied by ground testing on simulated environments.
- **Recommendation 6:** Develop measurement techniques to evaluate how efficient and effective is the human-robot interaction for both, simulated and real environments.

V.IX Ballistic Lunar Hoper Transportation System

To provide a safe and efficient way of storage and transportation for consumables and resources on the lunar surface, potentially between different locations, the concept of a ballistic lunar hopper was proposed in two of the reviewed TPRs. Despite the potential of this concept for future exploration applications, information about studies and development of subsystems and the system is scarce and limited.

Table 28 below shows the feasibility assessment made on the concept, while Figure 28 describes a time-phased set of recommended actions for this concept's development and implementation, followed by other recommendations for future research.

Table 28 Lunar Ballistic Hopper Vehicle concept evaluation for ranking

Criteria	Parameter	Justification/Comments	Score	Individual Weight	Overall Weight	Final Score
Scheduling	TRL	Studies, modeling and simmulations have been conducted	3	-	7	21
Technical	Operational Efficiency	Highly dependent on power and could consume high levels of resources.	1	4	5	65
	Autonomy	Human interaction required for operation	1	3		
	Safety	Human interaction required for operation and set up until automation is achieved (1pt) Danger of malfunction of propulsion system represent a hazard (1 pt)	2	2		
	Adaptability	Concept is intented to adapt to different activities and has potentiall to downscale for other applications	2	1		
Economic	Cost	No cost for development and implementation has been identified.	1	-	3	3
Policy/Legal	Conflict with Treaties/ Conventions	No identified legal conflict.	2	-	1	2
					Total Score	91

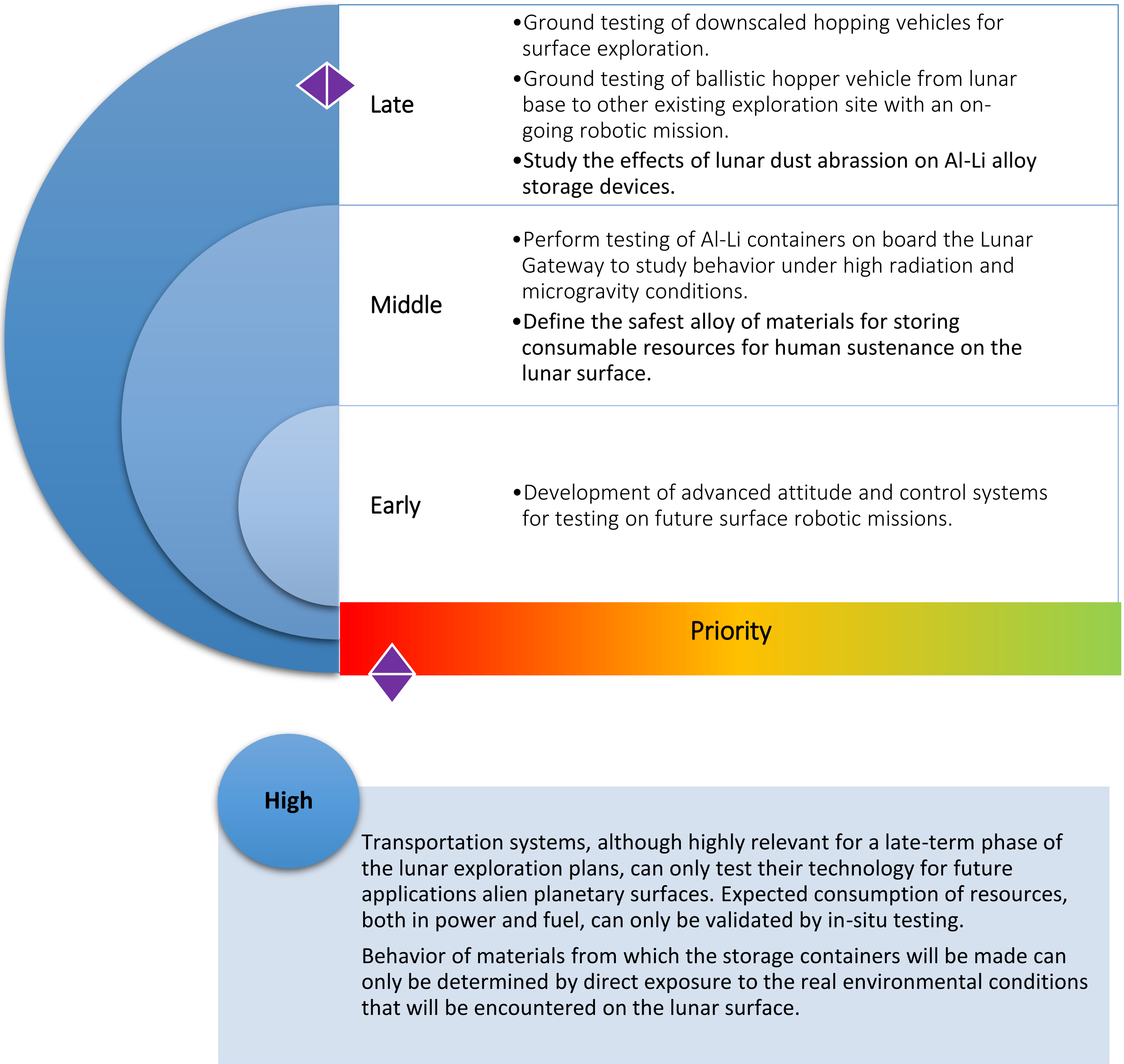


Figure 28 Ballistic Lunar Hopper concept time phasing and prioritization rationales and recommendations

Other recommendations

- **Recommendation 1:** Perform further research and simulations on possible maneuvers at lift-off and landing to economize on fuel consumption, as suggested by Middleton, Paschall II and Cohanim (2010).
- **Recommendation 2:** Increase guidance computing capabilities to support non-crewed operation of hopping vehicles. This will allow for size and mass reduction of the overall system.
- **Recommendation 3:** Perform research on advanced paired control moment gyros for development of automatic attitude and control system operation.
- **Recommendation 4:** Research on how to downscale this concept for short-distance transportation, small sample return, mapping and ground-truthing activities inside lave tubes, for example would be appropriate for implementation at a medium-late phase of the lunar exploration timeline. Shape of the downscaled concept should be adaptable to the unknown terrains inside the lava tubes; spherical propelled hoppers, as suggested by Thangavelautham et al. (2017), could be a good approach.

V.XI Prioritized List of Most Relevant Concepts

As a result of the analysis and discussion presented in the previous sections, a list with the most promising concepts and ideas was developed, and an initial feasibility study for each of them was performed. Table 29 summarizes the selected concepts for further research and development, as well as the top-level criteria that were considered to outline the future steps that will be required to mature the idea/concept and finally implement it in future lunar and cislunar missions.

Table 29 Summary of selected concepts for further research and development

Concept	Criteria				Total Score	Ranking
	Scheduling (TRL)	Technical	Economic	Policy/Legal		
Starport's Radiation Shielding	14	120	3	2	139	**3**
LuGaLiSus System	14	65	6	2	87	**8**
The Power Cell	14	65	6	1	86	**9**
Plasma Drill	21	90	3	2	116	**6**
Development of interfaces' standards for OOS	21	100	6	2	129	**5**
AMS-like instrument	35	95	3	2	135	**4**
QWIP-based instrument	56	115	6	2	179	**1**
P2P-HRI concept	35	120	6	2	163	**2**
Ballistic Hopper	21	65	3	2	91	**7**

VI. Performance to Plan

To evaluate the level of compliance of this report with the proposed objectives in the Project Plan, a *Performance to Plan* table (Table 30) is used, where each objective is given a *"Fully compliant", "Partially compliant" or "Non-compliant"* mark depending on the achievements made at the end of this project.

Table 30 Performance to plan evaluation

Objective ID	Description	Compliance	Corresponding Chapter
Objective 1 (O1)	To formulate a prioritized list of TPs with technological and non-technological concepts and ideas of potential high value to NASA's and the international community's Lunar/Cislunar mission planning.	*Fully compliant*	Chapter 5
Objective 2 (O2)	To identify and categorize potential high value technological and non-technological concepts and ideas from these TP reports and assign a level of feasibility to each.	*Partially compliant From the original list of 28 TPRs, the two more recent once had to be left out due to lack of time to review them.*	Chapter 5
Objective 3 (O3)	To determine a select number of the most promising concepts and ideas for further research, and formulate an outline for a subsequent research phase	*Fully compliant*	Chapters 4 & 5
Objective 4 (O4)	To identify the concepts and ideas, from the final list, that are relevant for development on the Lunar Gateway or on the lunar surface.	*Fully compliant*	Chapter 4

VII. Conclusion & Recommendations

This chapter presents the concluding remarks the author has identified as relevant throughout the development of this thesis. Defining the thesis plan from an early stage of the research was crucial for the achievement of the proposed objectives, although several adjustments to the original time line of the project had to be made to match the external responsibilities of the author.

One of the main challenges for this thesis' development was the implementation of an appropriate methodology to gather the available information in the form of Team Project Reports and analyze it for a later identification of the reports with the most valuable and relevant content for evaluation. Through a careful revision of lunar-related titles and quick reading of the available Executive Summaries, a total of 141 TPRs were reduced to a list of 28 reports with potential relevant content.

After applying the first filter, a thorough revision of 26 of the 28 selected reports was made. The two most recent titles had to be left out due to the stage of the analysis at which the author was when the two reports were made publicly available. Nevertheless, the author recommends thorough revision of these titles is made by interested parties due to their high relevance to future lunar and cislunar missions, especially in the areas of sustainability and space commercialization.

Before analyzing the selected reports to find relevant ideas or concepts, it was necessary to establish why it is important, at this time, to go back to the Moon. To define this, a brief explanation of the current context is provided on Chapter III, emphasizing the relevance and value of In-Situ Resoure Utilization and the need to develop related technologies, the unique capabilities that can be leveraged from using the proposed Lunar Gateway as a platform for science and technology development,and finally, establishing the key role that lunar missions are playing in paving the road towards the future exploration of Mars.

From the revision of the 26 selected reports, a brief summary of the 19 most relevant was developed and included in Chapter IV, as an initial justification to why the final concepts were selected. From these 19 titles, 9 final concepts were selected, some of them overlapping from different reports. In this regard, and contrary to what the author believed was a good first indicator of the relevance of the reports to this thesis, in some cases the description of the reports' scope and general concept turned out to be irrelevant or of low value to this thesis' objectives, which resulted in a reduced number of titles to be evaluated for feasibility and adaptability to the Lunar Gateway and future surface activities on the Moon.

After identifying the most promising concepts for future Lunar and Cislunar missions, with a relevance for the future development of the Lunar Gateway and the scientific activities to be performed by astronauts in future missions on the lunar surface, an assessment of each of these ideas was performed following a quantitative, qualitative and weighted approach. Through the evaluation of four main criteria (Technical, comprising operational efficiency, safety, autonomy and adaptability, TRL, Economic impact and Legal impplications), each of the identified concepts were ranked and assessed as to which should be the next steps to take into consideration in order to further develop them for a future implementation in lunar missions.

After performing the feasibilty assessment on the final 9 concepts, a ranked list of the most feasible ones for future implementation on lunar missions was generated. From this list, it becomes evident that the more defined is the objetive and application of the concept, and the more specific is the outline for its possible development, the best ranking was obtained by the concept. When the concept is more complex, and proposes the development of several subsystems and use of low TRL technologies, the final ranking in the feasibility list goes lower. On the other hand, to generate the list of recommendations for further research it was found that the least developed the concept was, the more recommendations could be formulated.

It is evident that, thorughout time, ISU's TPRs have become more relevant to the current lunar exploration plans from a technological, scientific and policy point of view; however, there has been a tendency to focus more on the possible actions to be taken in policy and cooperation matters, which, despite offering fresh and innovative solutions to the current state of the space sector, lacks a real leverage as to actually being able to execute the provided recommendations. Because of this, it is recommended that whenever a Team Project is based on the development of a technology or scientific concept, a more detailed analysis of its future development is performed to make it more feasible for private companies and space agencies to build on their findings and propositions.

It was interesting to find that no dust mitigation concepts or ideas were found during the revision of ISU's previous TPRs when more research is needed on this topic to allow further development of surface instrumentation for ISRU and to support robotic missions. Similarly, no relevant research was found in the area of Data Science applications for space; as reviewed on this thesis, there is a need to develop more autonomous technologies to reduce risks and hazards to astronauts and infrastructure, so it should be considered as high priority to include this topics for future research focus of TPs at ISU.

The Lunar Eploration Roadmap has identified a clear set of scientific goals to pursue through technology and scientific experiments' development. Despite the emphasis made on lunar environment and geotechnical caracterization as high priority goals, as well as on technologies that will allow a self-sustained presence on the Moon, the author considers that the development of standards and legal frameworks should be awarded a high priotrity level as well despite the lack of dependency on using the lunar and cislunar space as platforms for una optimal development. In the end, their use will be required on those sites and will determine how fast and effectively the exploration roadmap moves forward.

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Appendices

A.I Prioritized list of categories and enabling elements for evaluation on the Moon

Adapted from International Space University, (2004).

Rank	Category	Enabling Element
1	Psycho-social Factors	Conflict resolution
2	Extra-vehicular Activities (EVA)	Advanced planetary suit capability
3	Guidance, Navigation and Control	Precision landing
4	Transportation	Soft landing
5	Medical issues & human physiology research	Isolation-related medical strategies (critical care requirements: pregnancy, death)
6	Medical issues & human physiology research	Radiation management
7	Psycho-social Factors	Crew workload and spare time
8	Psycho-social Factors	Psychological countermeasures and treatment
9	Psycho-social Factors	Group structure and interactions
10	Habitation (Mars surface)	Airlocks
11	Guidance, Navigation and Control	Surface navigation and localization
12	Medical issues & human physiology research	Surface stay countermeasures
13	Environmental Shielding	Regolith, caves (radiation)
14	Medical issues & human physiology research	Prophylactic medical and surgical measures
15	Operations	Maintenance and repair
16	Crew Rescue, Safety & Survivability	Emergency training
17	Crew Rescue, Safety & Survivability	Safe Heaven
18	Science	Planetary science (geology, astrobiology)
19	Transportation	Human transport
20	Communication	Earth-Mars relay satellites
21	Extra-vehicular Activities (EVA)	Decontamination
22	Medical issues & human physiology research	Reduced gravity medical procedures (including diagnostics and treatment)
23	Planetary Protection	Containment
24	Planetary Protection	Sterilization
25	Planetary Protection	Procedures for human missions
26	Habitation (Mars surface)	Pre-deployed habitat
27	In-Situ Resource Utilization (ISRU)	Water extraction from surface
28	Operations	Construction
29	Science	Life sciences (human physiology, plant growth)
30	Power Generation & Storage	Nuclear reactor
31	Operations	Contingency training
32	Medical issues & human physiology research	Sexual management strategy
33	Operations	Skills training
34	Habitation (Mars surface)	Advanced construction materials
35	Life Support Systems (LSS)	On-board salad machine
36	Operations	Mission control aspects
37	Life Support Systems (LSS)	Food production and storage
38	Habitation (Mars surface)	Inflatable structures
39	Crew Comfort & Welfare	Surface stay
40	Propulsion	Nuclear thermal propulsion
41	In-Situ Resource Utilization (ISRU)	Propellant production from ISRU
42	Habitation (Mars surface)	Living, working area, greenhouses
43	Life Support Systems (LSS)	Low pressure greenhouse
44	In-Situ Resource Utilization (ISRU)	Construction from ISRU
45	Propulsion	Advanced chemical production

A.II MELiSSA's Planned Roadmap

Obtained from Lasseur's (2017) presentation to JAXA.