DOI: 10.13009/EUCASS2022-6167

A Concept of Operations for a Sustainable Human-Centred Lunar Settlement by Integrating State-of-the-Art ISRU Technologies

Saanjali Maharaj⋆, Emily Nassar⋆, Rima Uraiqat⋆, Ketan Vasudeva⋆, Anne Jing⋆
⋆University of Toronto Aerospace Team (UTAT), Division of Aerospace Policy
4925 Dufferin Street, Toronto, Ontario, Canada, M3H5T6

Abstract

In-Situ Resource Utilisation (ISRU) has emerged in recent years as a consideration in upcoming space missions, such as NASA's Artemis Program, due to its potential advantages in supporting a sustainable human presence in space. This paper presents a Concept of Operations (ConOps) for a lunar ISRU system, emphasising the interfaces between the system, the human operators, and the lunar environment. A particular focus of this ConOps was the disposal of mining tailings to adhere to Article VII of the Outer Space Treaty.

1. Introduction

1.1 Motivation

In-Situ Resource Utilisation, or ISRU, may be defined as any hardware or operation that employs localised resources to enable the development of products and processes for robotic and human exploration [1]. Such technologies and processes may prove to be invaluable to the success of future long-term space exploration and colonisation missions, whereby space explorers will be unable to depend on a regular supply of primary resources (oxygen, air, water, food, etc.) from Earth, so they will need to leverage local resources to create sustainable habitats. To that end, NASA has already outlined proposals for such systems, most notably for the Artemis Lunar Base Camp planned for 2028 [2, 3].

One of the main challenges in lunar ISRU is the identification of suitable base locations according to the availability of local resources. For instance, NASA has outlined the Moon's South Pole as its current main target location for the upcoming Artemis mission due to the presence of lunar ice [3]. It has further identified both this ice and lunar regolith (composed of 40+% oxygen) as the main resources for potential ISRU applications [3]. These resources may be used to create oxygen and water for not only human consumption, but also propellant and fuel. The effective use of these materials would facilitate the establishment of a sustainable human presence on the Moon.

1.2 Research Objectives and Scope

The present work outlines a concept of operations (ConOps) with the primary objective of lunar ISRU focusing on water and oxygen to support a sustainable human presence. The safety of the operators and the sustainability of the habitat are prioritised in order to ensure the long-term success of the mission. The ConOps first establishes the relevant operational policies and the characteristics of the lunar operational environment. It then outlines the major components, interconnections, and interfaces interacting within the system. Furthermore, the paper describes the relevant user classes, summarises the system capabilities and performance characteristics, and presents a functional-flow block diagram.

This report emphasises the inclusion of the operators in the system. Although many ISRU technologies and lunar mission concepts have been proposed, there appears to be a gap in the research on how such technologies and concepts function in tandem with their operators. With this in mind, this work places a focus on tailing management technologies and the mitigation of risks to operators. By emphasising the safety of operators in the system, the aim of this paper is to promote the sustainability of the future lunar habitats.

DOI: 10.13009/EUCASS2022-6167

2. The State of ISRU

2.1 Review of Current and Upcoming ISRU Technologies

There are several existing proposals for ISRU technologies, mostly specific to Lunar and Martian environments. One such proposal in development by NASA is the Regolith-Based Volatiles Acquisition and Processing Technology [4], which involves drilling into water deposits on the Moon, Mars, or asteroids, to extract useful materials such as oxygen, potable water, and methane. The materials can then be used for propellant, life support consumables, and fuel cell reactants. NASA is developing both components and systems to facilitate extraction, storage, and transportation of resources with the ultimate goal of using them to maintain a sustainable human presence in space.

While this technology has not yet been implemented in space, there have been several analog field tests on Earth. In 2008, the first lunar ISRU surface operations analog field test was performed in Hawaii at a site developed by NASA, the Canadian Space Agency (CSA), and Germany's Deutsches Zentrum für Luft-und Raumfahrt (DLR) [5]. The goal of this test was to demonstrate the prototype hardware and operations for an end-to-end run of an integrated system with the following functionalities: excavating material, producing oxygen, and storing the product [5]. One prototype system was the Lockheed Martin Astronautics' Precursor ISRU Lunar Oxygen Testbed (PILOT), which uses a tumbling reactor to mix and heat the regolith [5]. The other prototype tested was NASA's ROxygen with a vertical reactor instead of a rotational one like PILOT. The vertical reactor is used in conjunction with fluidization and an internal auger [5]. In the test, PILOT completed six reactor operations while ROxygen completed five. Due to limited system verification prior to the analog field test, neither system successfully electrolysed the extracted water. However, when tested with deionized water, the other system functions were effective [5].

In 2010, a subsequent analog field test was carried out in Hawaii. The systems used in this test were the RESOLVE lunar polar resource characterization package, science instruments from CSA and NASA's Moon Mars Analog Mission Activity, as well as a mechanism for extraction using solar heating [5]. This analog field test proved much more fruitful than the first, as each individual system was functional, as well as the integration between the ISRU technology and the surface/transportation elements. In 12 operations, 28 g of oxygen was extracted via carbothermal reduction with a 9.6% average yield [5].

Looking ahead, NASA is investing in the Lunar Surface Innovation Initiative [6] under the Artemis mission. This initiative focuses on increasing the technology readiness level (TRL) of lunar ISRU technologies by building machinery and electronics that are functional in extreme environments such as cryogenic permanently shadowed craters, developing strategies to mitigate lunar dust, and carrying out surface excavation and manufacturing operations. The European Space Agency (ESA) also has a lunar ISRU demonstration in development, with a target date of 2025 [7]. As a part of the Roscosmos Luna-27 mission, ESA is contributing a robotic drill, called Prospect, which is equipped with several scientific instruments to acquire lunar samples, which may prove useful in determining the presence and accessibility of lunar water for future ISRU missions [8].

It is evident that the development of ISRU technologies has been steadily progressing over the past two decades. With the upcoming Artemis and Luna-27 missions, there is an even greater motivation to pursue these technologies to ensure that they are functional in future space missions.

2.2 Review of ISRU System Architectures

ISRU technologies can be organised into various systems to achieve the mission objectives. One such system architecture, explored by NASA, is a centralised system [2, 9], whereby excavation technologies are used to mine resources, such as lunar ice or regolith, from dig sites. The localisation and selection of these dig sites during the resource procurement process is of particular importance in any ISRU system [2, 10]. These raw resources are then transported to a central processing station, a key characteristic of the system architecture, where they undergo extraction processes to collect the valuable materials (such as water, hydrogen, oxygen, etc.).The goal of having one central station is to minimise the cost of expensive extraction methods by performing the task only once, but on an industrial scale. The resources are then injected into the habitat's ecosystem for human use.

An alternate configuration for an ISRU system is a decentralised system architecture, whereas resources are mined and extracted directly at the dig sites [2, 10]. The resources are then transported from these sites back to the habitat and injected into the habitat's ecosystem. Contrary to the centralised architecture, the combination of the mining and

DOI: 10.13009/EUCASS2022-6167

extraction processes is the defining characteristic of this system architecture. The key to the success of a decentralised ISRU system is low-cost resource extraction methods which can be reproduced at each dig site with low effort [2, 10].

2.3 Outstanding Challenges

Despite the continuous development of ISRU technologies and systems over recent years, particularly with the acceleration in human-focused space missions, significant challenges remain to be addressed before ISRU can be used ubiquitously and reliably to sustain human life in lunar environments. Two key opportunities for development lie in the management of mining tailings resulting from the extraction and utilisation of resources, as well as the interaction between human operators and ISRU systems with a focus on safety, as summarised below.

2.3.1 Mining Tailings Management

The extraction and utilisation of resources from lunar regolith, particularly water and oxygen, will inevitably lead to the production of mining tailings, encompassing debris, unwanted resources, and excess products, among others. Coupled with the unknown nature of the resources and their usability in human habitats, ISRU systems under development may require further considerations to better identify usable resources to limit the amount of tailings produced, and introduce novel approaches to manage the tailings [11, 12]. For instance, according to the ESA Space Resources Strategy, a key step in the early development of lunar habitats includes the identification of resources, and analysing their various characteristics [12]. Similarly, the development of technologies to mitigate dust and risks associated with regolith extraction and utilisation may prove to be of particular importance in reducing tailings produced in lunar environments [12].

2.3.2 Risk to Operators

Given that space environments generally pose significant risks for human operators, long-term operations on the lunar surface may present a new set of challenges, even with the incorporation of ISRU systems. Firstly, the absence of a protective atmosphere leaves the lunar-based systems vulnerable to radiation and other hazards, including physical objects ranging in size from minuscule dust particulates to larger asteroids and regolith material, which can pose significant risks to system components and human operators [13]. Lunar dust in particular has been shown to present significant challenges to both astronauts and various equipment due to its ubiquitous and adhesive nature [14].

The extreme lunar conditions also extend to the temperature variations experienced over the course of the Moon's rotation, where temperatures typically range between 100 K to 380 K [15]. Fundamentally, the key hazard to human operators can be attributed to the existing regolith on the lunar surface, as well as that generated during resource extraction and processing operations, which was previously shown to cause respiratory, ocular, and dermal complications for astronauts, particularly during the Apollo mission [13]. As such, the development of systems that allow for close human interactions, while ensuring safe operations and procedures may improve the versatility and safety of existing and proposed ISRU systems in space, and lunar environments more specifically.

3. Proposed Operations Model of a Lunar ISRU System

The subsequent sections of this work comprise key elements of a Concept of Operations (ConOps) that provide an overview of the operational policies, system properties and interactions that may be of relevance when considering lunar ISRU systems.

3.1 Operational Policies

The 1967 Outer Space Treaty outlines the laws that apply to space exploration which are essential to consider in the development of an ISRU system. According to the Treaty, extractive activities are allowed on extraterrestrial bodies such as the Moon, but a question remains as to whom the extracted resources would belong. Ambiguities in ownership and collection requirements and regulations may also lead to potential conflicts in the future [16].

In particular, Article IX of the Outer Space Treaty states that "States Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose", meaning that any studies and

DOI: 10.13009/EUCASS2022-6167

exploration pursued in outer space should not in any way harm the celestial body in question [17]. Therefore, the system should safely extract the resources without adversely impacting the lunar environment.

Additionally, Article VII of the Outer Space Treaty affirms that "each State Party to the Treaty that launches or procures the launching of an object into outer space, including the moon and other celestial bodies, and each State Party from whose territory or facility an object is launched, is internationally liable for damage to another State Party to the Treaty or to its natural or juridical persons by such object or its component parts on the Earth, in air or in outer space, including the moon and other celestial bodies" [18]. Thus, in order to prevent damage to the Moon, Earth, or other celestial bodies, the proposed ISRU system must carefully consider mining tailings disposal.

In terms of operational constraints, there is still further progress to be made in the development of ISRU systems before they are ready to be implemented. An In-Situ Resource Utilisation Gap Assessment Report developed by a team of collaborators from NASA, ESA, DLR, and the CSA, among others, presents "cross cutting" challenges that should be controlled in order to ensure the reliability of ISRU systems during missions [19]. The challenges include but are not limited to power generation and storage, system autonomy, dust mitigation, as well as surface mobility and trafficability [19]. In fact, systems should be able to survive in the challenging environment in which they are implemented, while supporting processes requiring power. Similarly, an ISRU system should be able to function with minimal human assistance. This may be accomplished through the installation of hardware that could facilitate autonomous system maintenance and recovery procedures [19]. Finally, a system should also be mobile and functional on the types of surfaces expected to be encountered on a space mission.

3.2 Characteristics of the Operational Environment

With current technology, the Moon is not yet fit for a sustained human presence due to inhospitable thermal conditions, high-risk radiation and granular lunar dust [20]. For instance, the Moon's surface temperature varies from 100 K to 380 K depending on the time of day and location, which is not conducive to human survival. With a gravitational acceleration of 1.62 m/s^2, around 1/6 of Earth's gravitational acceleration, and a very low surface atmospheric pressure that approaches vacuum levels ($\sim 10^{-12}$ mmHg), additional measures are required to ensure the safety and operability of systems on the Moon [20]. Moreover, the lunar surface is constantly subjected to electromagnetic radiation, which may be dangerous in terms of human exposure and can damage and degrade materials.

However, the harsh environment does not prohibit human presence on the Moon. For instance, human presence may be maintained by mitigating lunar dust, providing protection from micro-meteoroid impact, and reducing astronaut exposure to radiation [21]. In addition, ISRU systems can support human presence on the Moon through the processing of lunar regolith to provide essential resources such as oxygen for life support and fuel, hydrogen for fuel and water production and metals for construction [20]. This can lead to a safer and more sustainable lunar environment for humans.

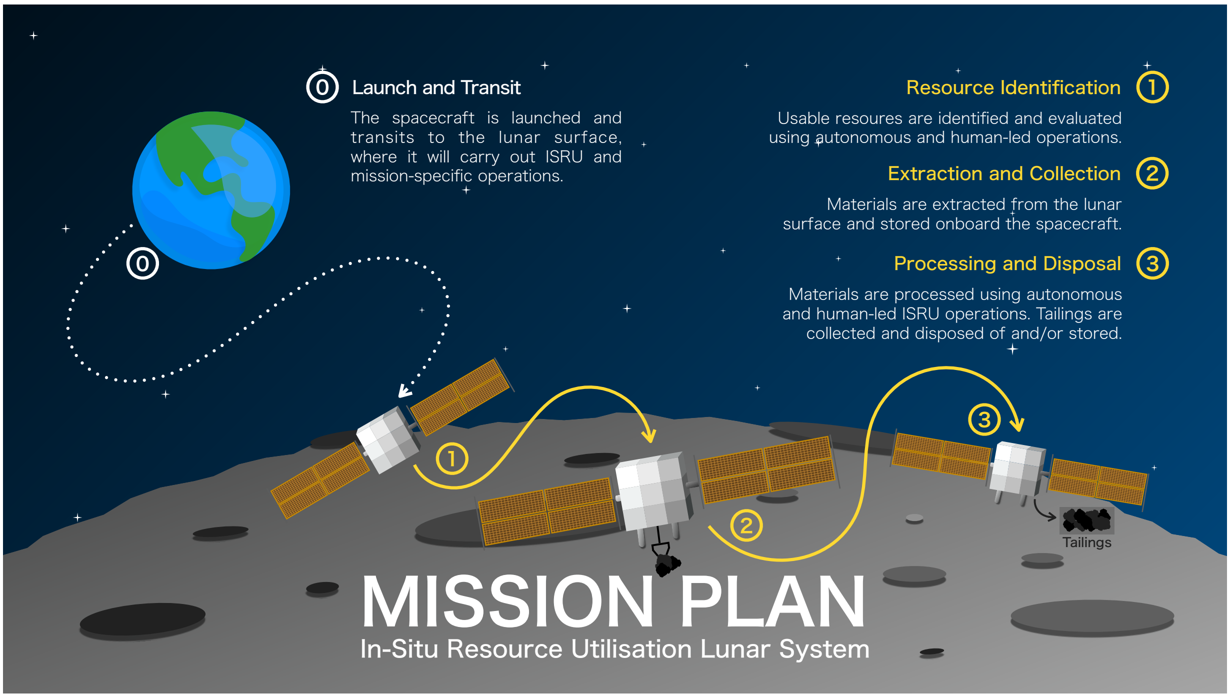
3.3 Major System Overview and Components

Lunar systems, particularly those geared towards employing ISRU technology as part of sustainable human habitats, can vary in complexity and functionality. This section aims to present an overview of a lunar ISRU system that incorporates sustainability and the safety of operators, beginning with a simplified Mission Level Block Diagram (MLBD) depicting the various stages of a lunar ISRU mission, as well as a summary of key system components and interconnections.

3.3.1 Mission Level Block Diagram (MLBD)

The following Mission Level Block Diagram (MLBD) presents a simple overview of a proposed lunar-based ISRU system. Each of the three main steps (identification, extraction and collection, as well as processing and disposal) are illustrated in sequential order, with additional details provided with respect to operations involved. Note that the launch and transit stages of the mission are shown in the diagram for clarification purposes, and are both out of the scope of this paper. As such, out of scope stages are shown in white, whereas steps of significance are shown in yellow.

DOI: 10.13009/EUCASS2022-6167



The spacecraft is launched and transits to the lunar surface, where it will carry out ISRU and mission-specific operations.

Usable resoures are identified and evaluated using autonomous and human-led operations.

Materials are extracted from the lunar surface and stored onboard the spacecraft.

Materials are processed using autonomous and human-led ISRU operations. Tailings are collected and disposed of and/or stored.

Figure 1: High-level Mission Level Block Diagram (MLBD) for proposed lunar ISRU system

3.3.2 Mission Level Interface Diagram

To model the interfaces and interconnections between the elements within the system, an interface diagram is presented in Figure 2, which illustrates the mechanical, control, and software (sensing) interfaces and connections between the physical ISRU system, the human operators, and the lunar environment. Note that this diagram does not include any external systems, including the ground station or other local systems that may be based on the lunar surface. Any material, data, or thermal interfaces are also outside the scope of this diagram.

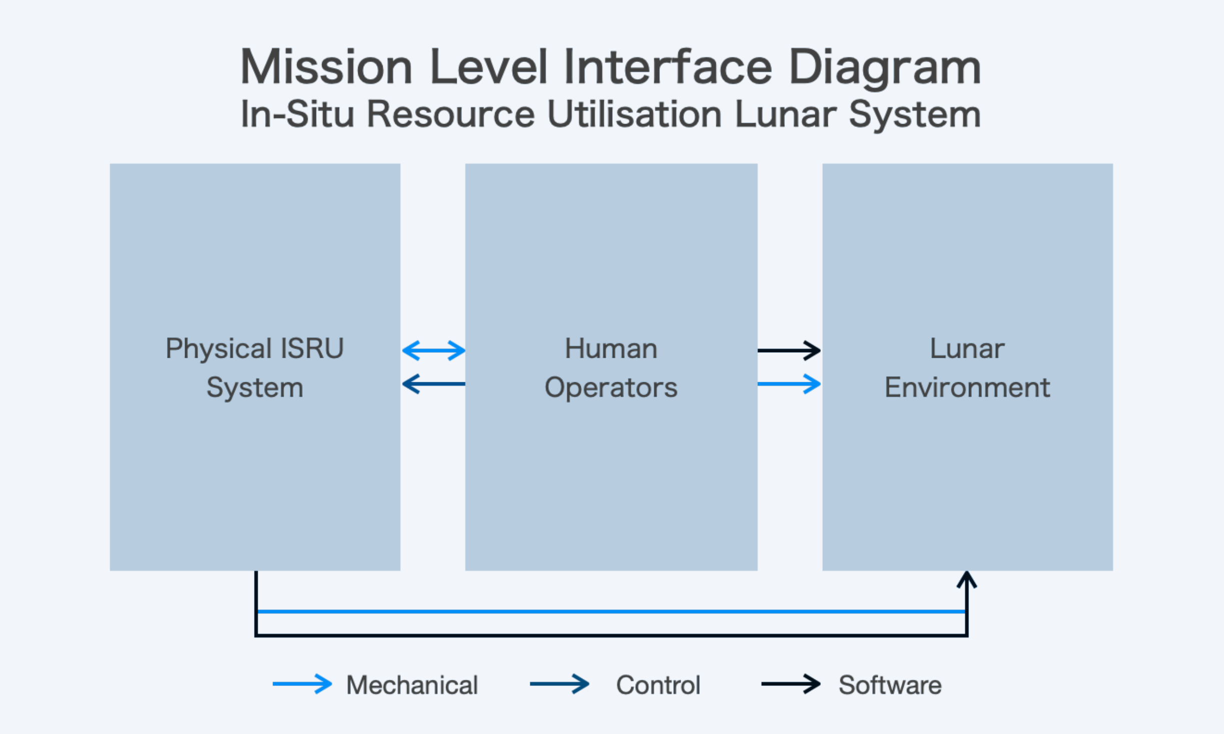


Figure 2: High-level Mission interface block diagram for proposed lunar ISRU system

DOI: 10.13009/EUCASS2022-6167

Table 1: A summary of system interfaces

Interface	Description
Physical ISRU System + Human Operators	*Mechanical:* Human operators interact with the physical structure and other mechanical aspects of the ISRU system, and the physical system supplies the human operators with resources and life support materials.
Physical ISRU System + Human Operators	*Control:* The human operators contribute to the control of the physical ISRU system by providing commands, among others.
Physical ISRU System + Lunar Environment	*Mechanical:* The lunar environment provides the raw materials required in the ISRU process, while the ISRU system disposes of and controls the tailings on the lunar environment.
Physical ISRU System + Lunar Environment	*Software:* The physical ISRU system relies on software and sensing to survey and map the lunar surface and environment.
Human Operators + Lunar Environment	*Mechanical:* Human operators may interact directly with the lunar regolith and environment, which may involve directly collecting resources from and studying the lunar surface to identify potential resources for use.
Human Operators + Lunar Environment	*Software:* Human operators may rely on sensors in the identification of usable resources, or potential hazards on the lunar surface and the general environment.

3.4 User Classes

As the purpose of this work is the definition of interactions between many agents in excavation and lunar base technologies, it is important to explicitly define the users acting within the system. These definitions assume a general excavation technology pipeline whereby raw materials are mined and processed in order to be inserted into a lunar habitat's life support ecosystem (whether the system is centralised, decentralised, etc.).

Ground Control Crew: Ground control will be responsible for the oversight of the excavation processes. Ground control will also be involved in supporting large-scale operational or physical changes to the lunar base system.

Lunar Habitat Crew: The lunar habitat crew will be responsible for bridging the gap between ground control and the lunar environment, intervening if necessary according to emergency procedures. The habitat crew will also be the direct recipients of the processed mined materials as it is injected into the habitat ecosystem.

3.5 System Capabilities

The proposed system shall have the following capabilities in order to accomplish the primary mission objective, this being lunar ISRU for water and oxygen to support a sustainable human presence:

- Collect raw material from lunar surface
- Process lunar material to extract water and oxygen
- Dispose of tailings safely i.e. in accordance with Operational Policies and Constraints described in Section 3.1
- Transit between collection site, processing site, disposal site
- Communicate with lunar base station to send data and receive commands
- Support nominal operations throughout the mission with emergency procedures in place for failures
- Integrate with systems for application of extracted products (eg. propulsion systems, life support systems)

DOI: 10.13009/EUCASS2022-6167

3.6 Performance Characteristics

The performance of proposed ISRU systems can be defined based on the specific requirements of the mission, as well as any applicable constraints and parameters within which the system must operate. Table 2 below summarises some performance characteristics of relevance to lunar ISRU systems, with particular emphasis on resource selection, extraction, and utilisation. Note that the scope of this performance analysis is greatly limited to the ISRU components of the system, and does not incorporate other important mission characteristics, such as propulsion, transit to the lunar surface, thermal requirements, launch requirements, and system lifespan, among others.

Table 2: An overview of ISRU system performance characteristics

Characteristic	Description	Performance Criteria
	Resource Selection and Utilisation	
Usability	The applicability of a material for various functions (e.g. propulsion)	Materials that can be used for multiple functions are preferred
Purification and Processing	The amount of purification and processing required for a material	Less material purification and processing is preferred
	Resource Collection	
Complexity	The amount of effort (e.g. number of steps in the process, power required) required to carry the material from the extraction site	Less effort and operational complexity is preferred
Resource Type	The type of material (e.g. metal, rock) being extracted and its phase	A greater variety of materials extracted and collected is preferred
Storage	The type of structure(s) required to store collected resources, characterised using volume and infrastructure complexity	A greater volume and simpler infrastructure is preferred
	Resource Extraction	
Accessibility	The complexity of the process (e.g. number of steps) required to access the material from the lunar surface	Fewer steps and more direct access to resources is preferred
Efficiency/Yield	The number of iterations required to extract a specific volume/mass of material from the lunar surface	Fewer iterations per operation is preferred to allow for a greater volume to be collected during the mission's lifetime
Consistency	The uniformity in the amount and quality of resources extracted	More consistent and uniform operations are preferred
Quantity	The amount of material that can be extracted during one operation	A greater volume of material extracted per operation is preferred
	System Operations	
Power Requirements	The amount of power required to keep equipment operational	Lower power consumption is preferred, but more power stored on board is preferred

DOI: 10.13009/EUCASS2022-6167

Characteristic	Description	Performance Criteria
	System Operations	
Mass Requirements	The amount of mass allocated for all components and subsystems	Larger mission mass constraints to increase functionality, and lighter components are preferred
Volume Requirements	The amount of volume allocated for all components and subsystems	Larger volume constraints to increase functionality, and more compact components are preferred
System Redundancy	The ability of the system to resume operations in the case of a component failure or malfunction	Increased system redundancy and risk mitigation is preferred
	System Sustainability	
Mining Tailing Management	The method(s) by which tailings is disposed of and/or stored once resources have been processed	Management methods that can handle large amount of tailings safely [1] are preferred
Debris Mitigation	Amount of debris produced through extraction and collection	Less debris generation and/or more effective protection strategies (e.g. shielding) is preferred
	Operator Interactions	
Safety	A measure of risks that human operators may be subject to while interacting with the system or lunar environment	More thorough risk assessment and decreased hazard levels are preferred
Accessibility	A measure of the ease of use and operability of the system to human astronauts and operators	More intuitive and accessible system design is preferred
Automoation	The number of operations that can be performed without human intervention (i.e. autonomously)	More automation is preferred to ensure accuracy and mitigate environmental risks
	Compatibility with the Lunar Environment	
Thermal Compatibility	The ability for the system to operate within the Moon's temperature ranges	Optimal operability in a wider temperature range is preferred
Resistance to Radiation	A measure of the system's resistance to radiation through the use of tools like reflective paints	Greater protection against radiation is preferred to protect electronic equipment and human operators
Resistance to Debris	A measure of the damage caused by debris and dust to the system	A greater resistance, and less damage to the system due to debris, is preferred

---

[1] Please refer to Section 3.1 for additional clarification on safety requirements

DOI: 10.13009/EUCASS2022-6167

3.7 Functional-Flow Block Diagram (FFBD)

The high-level functions of the proposed system are illustrated in a functional-flow block diagram (FFBD) below. The purpose of this diagram is to chronologically outline the steps involved in the process in the broadest sense in Level 0, which are then broken down further in Level 1.

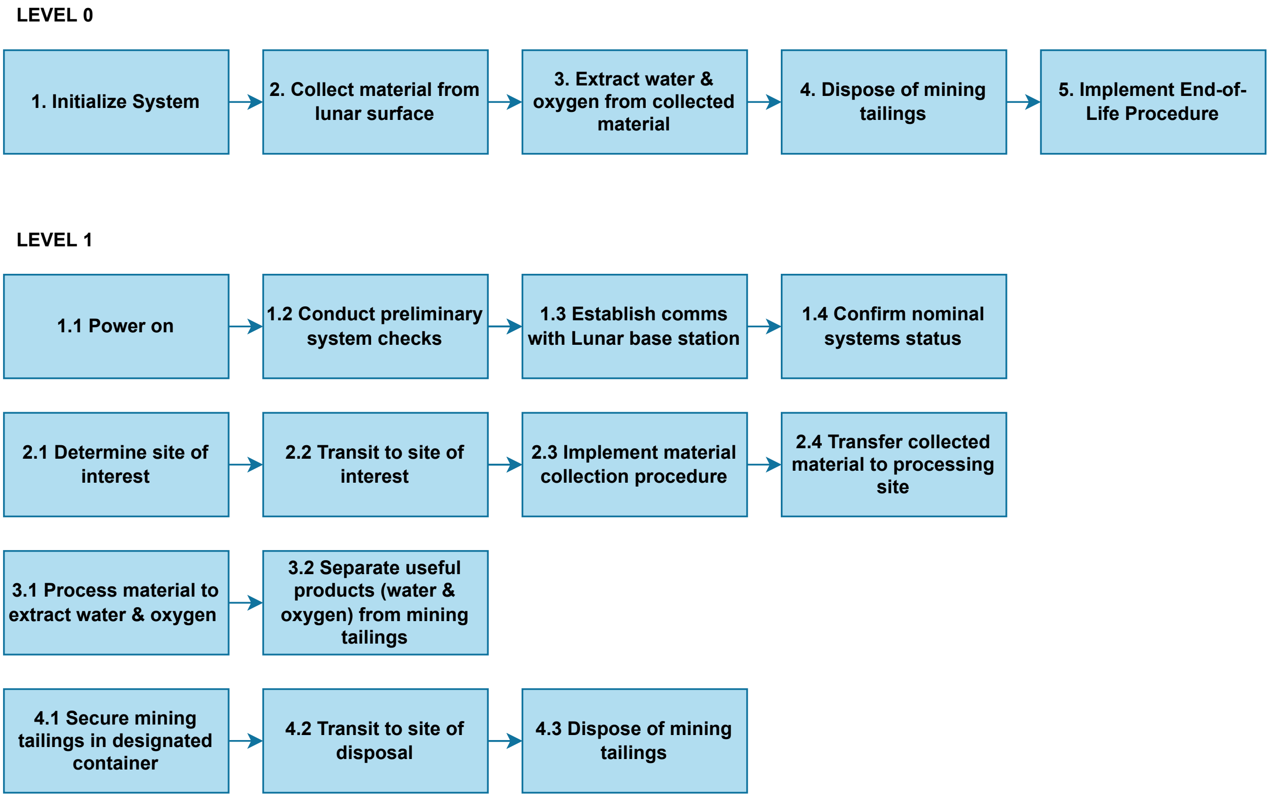


Figure 3: Functional-flow block diagram for proposed lunar ISRU system

4. Conclusion

ISRU technologies and processes prove to be potentially critical in the success of long-term space exploration and colonisation. They allow for travellers to lessen their dependence on Earth for essential necessities. The present work has established and outlined characteristics of an optimal lunar operational environment. Foremost, technologies should be able to safely extract resources without negatively impacting the lunar surroundings. Operationally, technology should manoeuvre on all types of terrains. Although the moon is not, naturally, a suitable candidate for maintaining human habitation, it can be achieved by processing the lunar regolith and extracting it to provide essential resources. Summarising these constraints, a Mission Level Block Diagram (MLBD) depicting the various stages of a lunar ISRU mission was developed. To accomplish primary objectives, the system has capabilities such as water and raw material collection, communication, and safe mining tailings disposal. Finally, a functional-flow block diagram was developed to chronologically outline the procedure. It is anticipated that this work may provide a framework for future ISRU missions that emphasises sustainability and operator safety.

5. Acknowledgments

We thank the University of Toronto Aerospace Team (UTAT) for facilitating the authorship team's formation. We are also grateful to our advisors, Professors Christopher Damaren and Jonathan Kelly from the University of Toronto Institute for Aerospace Studies (UTIAS), and Dr. Cameron Dickinson from MDA, for their guidance and feedback. We acknowledge Yi Qiao (Cindy) Chen for her contributions to the team in developing the abstract and for her leadership in the early stages of research. Last but not least, we wish to thank the organizers of the European Conference for Aeronautics and AeroSpace Sciences for providing us a space to share this research.

DOI: 10.13009/EUCASS2022-6167

References

[1] G. B. Sanders, “Mars ISRU: State-of-the-Art and System Level Considerations,” Keck Institute of Space Science (KISS), Jun. 2016. [Online]. Available: https://kiss.caltech.edu/workshops/isru/presentations/Sanders.pdf

[2] J. E. Kleinhenz and A. Paz, “Case Studies for Lunar ISRU Systems Utilizing Polar Water,” Sep. 2020. [Online]. Available: https://ntrs.nasa.gov/citations/20205007966

[3] G. B. Sanders, “NASA Lunar ISRU Strategy,” Luxembourg, Oct. 2019. [Online]. Available: https://ntrs.nasa.gov/api/citations/20190032062/downloads/20190032062.pdf

[4] L. Hall, “Overview: In-Situ Resource Utilization,” Apr. 2020. [Online]. Available: http://www.nasa.gov/isru/overview

[5] G. Sanders and W. Larson, “Progress made in lunar in-situ resource utilization under nasa’s exploration technology and development program,” *Journal of Aerospace Engineering*, vol. 26, 04 2012.

[6] L. Hall, “Lunar Surface Innovation Initiative,” Oct. 2019. [Online]. Available: http://www.nasa.gov/directorates/spacetech/Lunar_Surface_Innovation_Initiative

[7] “ESA - Exploration of the Moon - In-Situ Resource Utilisation (ISRU) Demonstration Mission.” [Online]. Available: https://exploration.esa.int/web/moon/-/60127-in-situ-resource-utilisation-demonstration-mission

[8] “ESA - Exploration of the Moon - About PROSPECT.” [Online]. Available: https://exploration.esa.int/web/moon/-/59102-about-prospect

[9] S. Indyk, “Planetary Volatiles Extractor (PVEx) for In Situ Resource Utilization (ISRU),” Columbia, MD, Nov. 2016. [Online]. Available: https://pdfs.semanticscholar.org/2647/23812adf167dd558ba9fe2ad99bc49394ff6.pdf

[10] G. B. Sanders and W. E. Larson, “Progress Made in Lunar In Situ Resource Utilization under NASA’s Exploration Technology and Development Program,” *Journal of Aerospace Engineering*, vol. 26, no. 1, pp. 5–17, Jan. 2013. [Online]. Available: https://ascelibrary.org/doi/10.1061/%28ASCE%29AS.1943-5525.0000208

[11] J. Carpenter, R. Fisackerly, and B. Houdou, “Establishing lunar resource viability,” *Space Policy*, vol. 37, pp. 52–57, Aug. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0265964616300315

[12] “ESA Space Resources Strategy,” May 2019, publisher: European Space Agency (ESA). [Online]. Available: https://sci.esa.int/documents/34161/35992/1567260390250-ESA_Space_Resources_Strategy.pdf

[13] N. Khan-Mayberry, “The lunar environment: Determining the health effects of exposure to moon dusts,” *Acta Astronautica*, vol. 63, no. 7-10, pp. 1006–1014, Oct. 2008. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0094576508001239

[14] T. J. Stubbs, R. R. Vondrak, and W. M. Farrell, “Impact of Electrically-charged Dust on Lunar Exploration,” Kauai, Hawaii, USA, Sep. 2005. [Online]. Available: https://www.nasa.gov/centers/johnson/pdf/486014main_StubbsImpactOnExploration.4075.pdf

[15] M. B. Garrison and D. H. Nguyen, “Thermal Considerations for Designing the Next Lunar Lander,” in *AIP Conference Proceedings*, vol. 880. Albuquerque, New Mexico (USA): AIP, 2007, pp. 35–42. [Online]. Available: http://aip.scitation.org/doi/abs/10.1063/1.2437438

[16] M. Wall, “Moon Mining Idea Digs Up Lunar Legal Issues,” Jan. 2011. [Online]. Available: https://www.space.com/10621-moon-mining-legal-issues.html

[17] L. d. G. Matignon, “The legal status of planetary rovers - Space Law,” Mar. 2019. [Online]. Available: https://www.spacelegalissues.com/space-law-planetary-rovers-and-their-legal-status/

[18] The United Nations, “Outer Space Treaty,” publisher: United Nations Office for Outer Space Affairs. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

[19] International Space Exploration Coordination Group, “In-Situ Resource Utilization Gap Assessment Report,” Tech. Rep., Apr. 2021. [Online]. Available: https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-Assessment-Report-Apr-2021.pdf

DOI: 10.13009/EUCASS2022-6167

[20] D. Beale, “Chapter 5: The Lunar Environment and Issues for Engineering Design,” publisher: Auburn University. [Online]. Available: https://www.eng.auburn.edu/ dbeale/ESMDCourse/Chapter5.htm

[21] E. J. Faierson and K. V. Logan, “Potential ISRU of Lunar Regolith for Planetary Habitation Applications,” in *Moon: Prospective Energy and Material Resources*, V. Badescu, Ed. Berlin, Heidelberg: Springer, 2012, pp. 201–234. [Online]. Available: https://doi.org/10.1007/978-3-642-27969-0_9