PTMSS
Planetary & Terrestrial Mining Sciences Symposium

&

Space Resources Roundtable

Hosted by the Canadian Minerals and Metals Plan Secretariat

The Canadian Minerals and Metals Plan / Le Plan canadien pour les minéraux et les métaux

Financé par Ressources naturelles Canada / Funded by Natural Resources Canada

Canada

Virtual 2021

Global Perspectives

OUTCOME OF THE INTERNATIONAL IN SITU RESOURCE UTILIZATION (ISRU) GAP ASSESSMENT FOR EXPLORATION.

Gerald. B. Sanders[1] and Jorge Alves[2], [1]NASA, 2101 E. NASA Rd 1, Houston, TX 77058, gerald.b.sanders@nasa.gov, [2]ESA ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, jorge.alves@esa.int.

Introduction: The Technology Working Group (TWG) of the International Space Exploration Coordination Group (ISECG) is a worldwide agency-level group that leads the task of identifying technology gaps and the associated potential actions for closure in the scope of current and optional architectures within the Global Exploration Roadmap. In 2019, the TWG established a Gap Assessment Team (GAT) for the topic of In-Situ Resource Utilization (ISRU). To perform the assessment, a team was put in place with the objective to establish international dialogue amongst subject matter experts and deliver a coordinated assessment of the global knowledge gaps and associated technology needs within the ISRU value chain. Due to the cost (especially for launch) of interplanetary travel and especially to planetary surfaces, sustainable exploration activities can be achieved through ISRU in areas such as life support, propulsion, energy storage, in-space manufacturing and construction, radiation protection, and waste management. Infusing ISRU technologies and capabilities in the current architectures within the Global Exploration Roadmap can enable overall mission efficiency, towards sustainability and the establishment of space commercialization. Ultimately, the ISRU Gap Assessment was intended to inform agency decisions when considering investments is specific exploration technologies, while identifying potential collaboration opportunities. The final report was also intented to provide information to industry and academia on the current state of ISRU, areas of importance for future missions, and knowledge on development activities, facilities, and gaps that could help direct and focus future investments.

Report Content: The report provides a broad and comprehensive assessment of ISRU. Starting with defining the subject of ISRU, the report provides a taxonomy of the main ISRU areas (Consumable Production, Construction, and Manufacturing with ISRU-derived Feedstocks), and a functional flow diagram to allow readers to understand the content and interconnectivity of the functions and technologies. The report provides information on potential resources, products, and applications, strategic knowledge gaps, and how ISRU can be incorporated into mission phases for human exploration of the Moon and Mars. The report provides detailed assessments of recent development activities, available facilities and simulants to support development, and areas of activity and interest for each space agency. The report ends with an assessment of the gaps remaining, challenges, missions to address the challenges and implement ISRU, discussions on partnerships, public-puclic and public-private partnerships, private investment, policy and regulatory challenges, and key findings and recommendations. The full report can be found at: https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-Assessment-Report-Apr-2021.pdf

Key Findings:

- ISRU is a disruptive capability and requires an architecture-level integrated system design approach from the start.
- The most significant impact ISRU has on missions and architectures is the ability to reduce launch mass, thereby reducing the size and/or number of the launch vehicles needed, or use the mass savings to allow other science and exploration hardware to be flown on the same launch vehicle. The next significant impact is the ability to extend the life of assets or reuse assets multiple times.
- The highest impact ISRU products that can be used early in human lunar operations are mission consumables including propellants, fuel cell reactants, life support commodities from polar resources: highland regolith and water/volatiles in permanently shadowed regions (PSRs).
- Evaluation of human Mars architecture studies suggest that there is synergy between Moon and Mars ISRU with respect to water and mineral resources of interest, products and usage, and phasing into mission architectures.
- A significant amount of work is underway or planned for ISRU development across all the countries/agencies involved in the study, particularly in the areas of resource assessment, robotics/mobility, and oxygen extraction from regolith
- While it appears each country/space agency has access to research and component/subsystem size facilities that can accommodate regolith/dust and lunar vacuum/temperatures, there are a limited number of large system-level facilities that exist or are planned.
- While simulants are available for development and testing, greater quantities and higher fidelity simulants will be needed soon, especially for polar/highland-type regolith. Also, selection and use proper simulants is

critical for minimizing risks in development and flight operations.

- Technology and instrument development for Moon and Mars resource assessment and operations are underway, and several missions to begin surface and deep assessment of resources are in development, especially to obtain maps of minerals on the lunar surface, surface topography, and terrain features, or to understand the depth profile of water and volatiles.
- While there is significant interest in terrestrial additive manufacturing/construction development, development for space applications has been limited and primarily under Earth-ambient conditions.
- Further research, analysis, and engagement are required to identify synergies between terrestrial and space mining. Throughout the mining cycle and ISRU architecture, key areas for investigation include; dependence on remote, autonomous, and robotic operations; position, navigation, and timing systems; and energy technologies (e.g., small modular reactors and hydrogen technology).
- Stakeholder engagement is required between the terrestrial mining and space sectors to drive collaboration to identify and benefit from lessons learned from terrestrial innovations for harsh or remote operations.
- Long-term (months/years) radiation exposure limits for crew currently do not exist to properly evaluate radiation shielding requirements. These are needed to properly evaluate Earth-based and ISRU-based shielding options.

Key Recommendations

- It is recommended that countries/agencies focus on the defined Strategic Knowledge Gaps that have been identified as high priority for each of the 3 human lunar exploration phases described. Early emphasis should be placed on geotechnical properties and resource prospecting for regolith near and inside permanently shadowed regions.
- Since the access and use of in-situ resources is a major objective for human lunar and Mars exploration and the commercialization of space, locating, characterizing, and mapping potential resources are critical to achieving this objective. A focused and coordinated lunar resource assessment effort is needed
- While short-duration lunar surface crewed missions can be completed with acceptable radiation exposure risk, it is recommended that long-term exposure limits be established and radiation shielding options be analysed as soon as possible to mitigate risks for sustained operations by the end of the decade.
- Long-term sustained operations will require a continuous flow of missions to the same location. Dedicated plume-surface interaction analysis and mitigation technique development are recommended, and establishment of landing/ascent pads be incorporated into human lunar architectures as early as possible
- Wear and thermal issues associated with lunar regolith/dust may be a significant risk to long-term surface operations. Coordination and collaboration on dust properties/fundamentals, and mitigation techniques and lessons learned are highly recommended. This effort should also involve coordination and collaboration on the development, characterization, and use of appropriate lunar regolith simulants and thermal-vacuum facility test capabilities and operations for ground development and flight certification.
- To maximize the use of limited financial resources, it is recommended that the ISECG space agencies leverage the information presented in the report as a starting basis for further discussions on collaborations and partnerships related to resource assessment and ISRU development/operations.
- Collaboration and public-private partnerships with terrestrial industry, especially mining, resource processing, and robotics/autonomy are recommended to reduce the cost/risk of ISRU development and use. This includes establishment of an international regulatory framework for resource assessment, extraction, and operations, which are necessary to promote private capital investment and commercial space activities.
- The sustainable development aspects of the ISRU activity are recommended to be taken into account from the start of activity planning for the surface exploration of Moon and Mars.
- Aspects of reusing and recycling hardware are recommended to be taken into account from the design and architecture phase of mission planning. This will contribute to minimizing the exploration footprint (e.g. abandoned hardware) and therefore key towards sustainability.
- To accelerate the development of key technologies, close knowledge gaps, and expedite testing/readiness, it has been seen that the use of unconventional models, such as government-sponsored prize challenges can be effective innovation catalysts operationalizing the above recommendations, and ultimately, bringing ISRU to the Moon and onwards to Mars.

Acknowledgement: The authors of this abstract want to recognize and thank the members of the ISRU Gap Assessment Team for their hard work and dedication in supporting assessment and writing the final report. The study involved 49 members from 11 space agencies and 4 additional government agencies over a two year effort.

THE EUROPEAN SPACE RESOURCES INNOVATION CENTRE – ESRIC. M. Link [1], B. Lamboray [2], [1]European Space Resources Innovation Centre (mathias.link@esric.lu), [2]European Space Resources Innovation Centre (bob.lamboray@esric.lu)

Introduction: In 2016, Luxembourg launched the Space Resources.lu initiative with the aim to promote the peaceful ex-ploration and sustainable utilisation of space resources for the benefit of humankind. The initiative puts a particular emphasis on economics, research, education as well as legal aspects related to space resources.

With the support of the Luxembourg Government, the Lux-embourg Space Agency ("LSA") is committed to support research activities connected to the utilisation of space re-sources and develop new capabilities as well as critical tech-nologies in close collaboration with industry and public re-search.

The European Space Agency ("ESA") developed in 2019 an innovation-driven Space Resources Strategy. It is following a mission-orientated innovation approach applied to the chal-lenge of sustained and sustainable human presence in space.

In line with the objectives of the SpaceResources.lu initiative, ESA's Space Resources Strategy and considering the growing international interest in space resources, LSA established in 2020 the European Space Resources Innovation Centre ("ESRIC") in cooperation with the Luxembourg Institute of Science and Technology (LIST), and in a strategic partnership with ESA.

LSA and ESA include R&D and technology maturation, as well as partnership and business creation as part of their core strategic activities. ESRIC is thus conducting activities in the following four areas.

Research – This includes the implementation of ground-based research and advancement of technologies used across the whole value chain of space resources utilisation. The centre is hosting a Space Resources laboratory that is open to academia and industry from Europe and beyond.

Business – This includes the setup of commercial partnerships and a specific support programme for start-ups targeting ac-tivities related to space resource utilization.

Knowledge Management – This includes the monitoring of progress in research, technology, economics and legal aspects related to space resources.

Community Management – This includes the establishment of a network and broad collaborations with other relevant Euro-pean and international organizations with key expertise in space resources related fields.

As the Moon is of global strategic interest, ESRIC's activities will initially be centred around the use of lunar resources for the production of hydrogen, oxygen and metals as well as products and services relevant for sustainable lunar surface activities.

From the scientific, technical and business activities running at the centre, ESRIC has the ambition to become a central place in Europe, with international reputation, for advancing the field of space resources utilisation.

Together with European space and terrestrial industry, the centre will drive technology innovation and open new oppor-tunities in the short, medium and long term.

OVERVIEW OF NASA'S IN SITU RESOURCE UTILIZATION TECHNOLOGY AND MISSION PLANS.

G. B. Sanders[1], [1]Affiliation NASA, 2101 E. NASA Rd 1, Houston, TX, 77058. gerald.b.sanders@nasa.gov

Introduction: The National Aeronautics and Space Administration (NASA) has been directed to send astronauts back to the lunar surface and begin a sustainable human lunar exploration program in the 2020's, and to lead the first human exploration mission to the Mars surface in the 2030's. A major objective of NASA's Moon to Mars exploration program is to understand and characterize the resources that exist at these destinations, and to learn how to utilize these resources for sustained human exploration and the commercialization of space. This ability, commonly known as *In Situ* Resource Utilization (ISRU), involves any hardware or operation that harnesses and utilizes local resources to create products and services for robotic and human exploration. A major focus of ISRU is the production of mission critical consumables, such as rocket propellants, life support consumables, and fuel cell reactants. These ISRU-derived products make up a significant fraction of the mass launched from Earth, are critical to mission success, and can reduce the cost for reusable transportation. Another major objective is the ability to perform construction and manufacturing from in situ-derived materials to create and expand on the infrastructure needed for sustained surface and space operations. To achieve ISRU objectives, NASA is developing technologies and systems, and initiating missions that will find, measure, and harness the resources of the Moon and Mars for science, human exploration, and eventually commercial space advancement. This endeavor is led by NASA's Space Technology Mission Directorate (STMD) in coordination with the Science and Human Exploration and Operations Mission Directorates (SMD and HEOMD).

Lunar Resources for ISRU: For simplicity, lunar resources under consideration for ISRU are divided into two broad categories: regolith and water/volatiles found in permanently shadowed regions (PSRs) of the lunar poles. Lunar regolith can be divided into two broad categories as well: highland and mare types, with potential additional constituent resources such as pyroclastic glasses, KREEP (potassium, rare earth elements, and phosphorous), and solar wind implanted volatiles. Regolith at the lunar polar regions is primarily highland-type regolith, which is mostly anorthite minerals and extremely iron-poor. Both highland and mare type regolith are great resources for oxygen and metals; oxygen is over 40% by weight (wt%) in lunar regolith minerals (mostly silicates). While orbital data provides clues about the possible water and volatile resource content and distribution in the PSRs, the only 'ground-truth' data that exists today is from the analysis of the plume created by the Lunar Crater Observation and Sensing Satellite (LCROSS) impact in 2009. The LCROSS plume (analyzed by A. Colaprete) was estimated to have 5.5 wt% water and lower concentrations of other volatiles such as hydrogen, carbon monoxide, hydrogen sulfide, ammonia, and others. Spectral modeling by Li (2018) shows that some ice-bearing pixels may contain ∼30 wt % ice mixed with dry regolith**.**

ISRU in Human Lunar Exploration: NASA's human lunar exploration program, known as Artemis (the sister of Apollo in Greek mythology) and led by HEOMD, is a multi-phased robotic and human exploration activity. The initial phase is primarily aimed at sending the first women and next man to the lunar south pole, with the goal of achieving this by 2024. This phase of exploration also includes orbital and surface robotic missions for science, technology development, and resource assessment. The next phase of human lunar exploration is aimed at demonstrating and building capabilities for longer duration lunar surface exploration missions, and to demonstrate technologies, capabilities, and operations that will be needed for the first human mission to Mars. This phase will include the use of unpressurized mobility platforms, robotic and human science tools and experiments, payload offloading and deployment systems, and initial surface power, habitat, and pressurized mobility assets. Throughout the initial phase and into the next, a major objective for ISRU is the assessment, characterization, and mapping of the lunar resources, especially the water/volatile resources in the PSRs.

Oxygen and Water Mining Strategies: Oxygen (and metals) in lunar regolith and water and other volatiles in PSRs provide both benefits and risks for developing and incorporating ISRU systems into future human missions.

Water is an amazing resource and product. On its own, water can be used for crew support, plant/food production, and is an excellent radiation shield material. Water can also be converted into oxygen and hydrogen which can be used for propulsion and fuel cell power systems. The oxygen can be used for crew breathing and the hydrogen can be used with other carbon resources to make plastics and other hydrocarbons. Water is also easily transportable to other locations for processing. However, there is significant uncertainty in the form, concentration, and distribution of water in PSRs, and the technologies to locate and process material in PSRs to extract water are immature. Also, the extremely low temperatures in the PSR and ability to generate or transfer energy into the PSR are significant challenges.

Oxygen on its own is also a very good resource and product. It can be used for crew breathing and provides 75 to 80% of the propellant mass needed for reusable chemical propulsion systems, so it still provides tremendous mass/cost savings compared to bringing oxygen for ascent vehicles and hoppers from Earth. Technologies for lunar excavation and oxygen extraction from mare regolith have also been demonstrated for short periods of time and subscale production rates under terrestrial environment conditions. However, significant work is required for operating under lunar conditions for months/years with abrasive lunar regolith, and with highland-type regolith.

Because of the significant benefits and advantages that water resources can provide for human mission architectures and future commercial activities in space, NASA's strategy for developing ISRU is to 'Lead' with developing technologies and performing missions to find, characterize, and use water resources at the poles of the Moon, while 'Following' with development of technologies and missions for excavating and extracting oxygen from lunar regolith. Which path will eventually lead to ISRU utilization and commercial operations will depend on the results of ground development and flight missions.

ISRU Ground Development and Flight Missions: Technology development for ISRU is primarily the responsibility of the STMD in NASA. Within STMD, ISRU resource processing technologies fall under the In-Situ Propellant and Consumable Production (ISPCP) project. Excavation and surface construction technologies fall under the Advanced Materials, Structures, and Construction (AMSC) project. To develop technologies and capabilities for future missions, STMD has a broad range of programs, known as the Technology Pipeline, which allow for requests for technology development from the extremely low Technology Readiness Level (TRL) all the way to flight demonstrations. Each of these programs focus on different TRLs, areas of interest, and proposers (industry, academia, and/or government). Since scientific and human exploration of the lunar surface involves multiple technical disciplines and surface assets, the STMD initiated the Lunar Surface Innovation Initiative (LSII) and the Lunar Surface Innovation Consortium (LSIC) to help focus development activities across the Technology Pipeline, and with external participants and partnerships. The LSII and LSIC covers technology development for six major surface exploration aspects: ISRU, Surface Excavation and Construction, Sustainable Power, Lunar Dust, Extreme Access, and Extreme Environments.

As with any new technology, before it can be utilized in a mission-critical role for human spaceflight, it needs to have undergone significant ground development as well as demonstrated its performance in the actual flight environment. To achieve the end goal of using ISRU products for mission-critical applications, STMD has initiated a conservative ground development and flight demonstration strategy for ISRU. This strategy incorporates a four-stage approach:

I. Extensive ground testing at mission-relevant scale under flight environmental conditions and analogue operation conditions,
II. Direct measurement of resources and demonstration of critical technologies in flight,
III. Demonstration and validation of ISRU systems and products at relevant mission scale to extend or enhance a robotic and/or crewed mission (i.e. pilot operation), and
IV. Utilization of ISRU systems and products in a mission-critical role.

In Stage I, NASA will fund develop and advance technologies, subsystems, and systems that will acquire and process lunar simulants into mission products at relevant mission scales and under lunar vacuum and thermal environments. In Stage II, NASA will utilize orbital and lander missions to better understand the resources on the Moon, especially lunar polar water and volatile resources that are needed to support technology development and eventual site selection for long-term human surface operations. It is anticipated that early lander missions will be aimed at obtaining critical data on lunar regolith and environmental properties that were not obtained from the previous Apollo and Lunar Surveyor missions. Stage II will also perform proof-of-concept and risk reduction demonstrations of critical ISRU technologies and concepts that are most dependent on interacting with lunar regolith and/or need to interact with large amounts of lunar regolith under lunar surface conditions to validate longevity and robustness. The end-to-end demonstration in Stage III at relevant mission scale will be critical for full utilization of ISRU capabilities and products in mission critical roles and for commercial operations to be successful in Stage IV.

Resource characterization and technology demonstration missions will be performed throughout the 2020's with the pilot plant demonstration aimed for operation by 2030. Resource characterization missions have already started. The Lunar Reconnaissance Orbiter continues to provide critical lunar information. Several cubesats related to understand water/volatiles in PSRs are scheduled for the first Artemis I mission in

2022. Finally ground truth information will begin to be taken by the PRIME-1 technology demonstration mission in 2022 and the VIPER mobile resource assessment mission in 2023.

Synergetic Material Utilization – Combining ISRU and ECLSS

Paul Zabel[1]

[1]Institute of Space Systems of the German Aerospace Center (DLR), Head of Synergetic Material Utilization research group, Robert-Hooke-Str. 7, 28359 Bremen, Germany, paul.zabel@dlr.de.

Introduction: Sustaining exploration of the solar system requires a large amount of material and an even larger amount of propellant to transport this material out of Earth's gravity well and onwards to its destina-tion. Despite recent advances in lowering the launch costs by applying methods such as reusability of the launch system, transferring material from Earth to space is still very costly with several thousand to tens of thousands Euro per kilogram into a low-earth orbit and transportation to Moon and Mars cost-ing a multitude of that. Although, current predictions foresee a further reduction in launch costs in the near future to tens of Euro per kilogram [1], each kilogram of material transported from Earth to LEO remains valuable and when transported to Moon or Mars the value is even higher.

Human space exploration requires a significant amount of resources such as food, water and oxygen. Waste products such as metabolic waste, polluted water and carbon dioxide are produced by the as-tronauts. Life support engineers are developing systems and processes to recycle and to regenerate as many resources as possible, also known as 'closing the loops', in order to reduce the material supplied from Earth to enable sustainable human space exploration of the solar system.

Our solar system is full of resources that potentially can be exploited to greatly reduce the material re-quired to be launched from Earth. Among these resources are water ice, hydrates, metals, regolith, rare earths, chemical compounds, volatiles and rare isotopes. Utilizing space resources would enable e.g. propellant production, in-space manufacturing or the construction of large structures which would oth-erwise be very expensive or not possible at all with material launched from Earth.

The concept of Synergetic Material Utilization (SMU) combines In-situ Space Resources Utilization (ISRU) and Environmental Control and Life Support System (ECLSS) engineering approaches to lower the material supply required from Earth.

In 2021 a research group was founded at the German Aerospace Center's Institute of Space Systems in Bremen, which focuses on the Synergetic Material Utilization concept.

Synergetic Material Utilization Concept: ECLSS and SRU are two space engineering fields with increasing importance in the future to enable sustainable exploration of the solar system. In both fields processes and techniques are applied to ex-tract, produce, utilize, consume and regenerate resources albeit with different purposes. The goal of ECLSS engineering is to enable human survival in space with as little resources as possible in order to reduce cost for resupply from Earth. SRU on the other hand uses local resources to produce a wide range of materials for different applications, but also with the goal of reducing the cost of launching the material from Earth.

Despite the similarities among both fields, ECLSS and SRU scientists and engineers often disregard the other research field. Almost all case studies of near-term SRU rely purely on robotics and automation without the assistance of humans on-site. Often the presence of humans is rejected with the argument regarding the costs involved of setting up the required ECLSS infrastructure. ECLSS case studies of fu-ture Moon or Mars space exploration systems, on the other hand, mostly neglect the utilization of local resources because of the fixation on regeneration and the 'closing the loop' principle, but also by using the cost argument for setting up a SRU infrastructure.

Synergetic Material Utilization is the approach of combining ECLSS and SRU engineering in order to exploit the many synergies among both fields to enable sustainable exploration of the solar system.

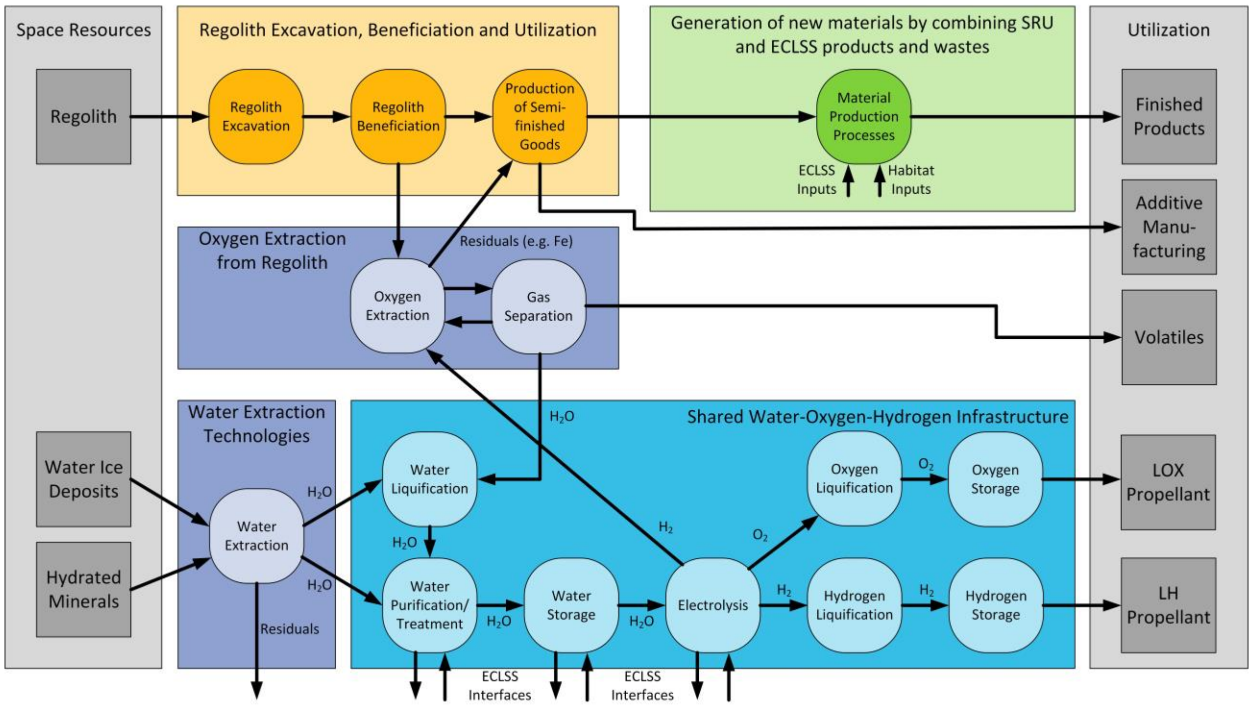
Synergies between ECLSS and SRU are:

- Shared processes and technologies,
- Common materials processed,
- Common products generated,
- Cross-utilization of products and resources,
- Combination of materials from various sources.

Planned Activities of the SMU Research Group at DLR: The SMU research group at the DLR Institute of Space Systems was established in 2021 with approval of the Director of Space Research of DLR. This research group focuses on the combination of SRU technologies with life support systems and processes in order to exploit synergies. Thus, a holistic approach for resources management during future space exploration missions is persecuted.

Concrete activities for the next 3-4 years are technology developments for regolith beneficiation, oxygen extraction from regolith and water extraction for in-situ propellant production. These developments are complemented by a system study for a shared water-hydrogen-oxygen infrastructure with ISRU and ECLSS elements for a future habitat and by concept studies for the in-situ production of new materials based on ISRU and ECLSS products.

The schematic below illustrates how the different topics of the research group are connected to each other and also where the interfaces with the ECLSS and habitat are.



References:

[1] Jones, H. W. (2018), 'The Recent Large Reduction in Space Launch Cost', *48th International Conference on Environmental Systems, 8-12 July, Albuquerque, New Mexico*.

International Outer Space Law and the Mining of Space Resources: Ambiguities and Opportunities. V. Oosterveld[1] and E. Steyn[2], [1]Faculty of Law and Institute for Earth and Space Exploration, University of Western Ontario, 1151 Richmond St., London, Ontario, Canada, N6A 3K7, vooster@uwo.ca, [2]Faculty of Law and Institute for Earth and Space Exploration, University of Western Ontario, 1151 Richmond St., London, Ontario, Canada, N6A 3K7, esteyn2@uwo.ca.

Introduction: The extraction and utilization of space resources is fast becoming a reality. The international space law framework provides opportunities for the space mining sector, but the ambiguities inherent in this law also create key questions. This presentation will set out and examine three main ambiguities in international space law as it relates to space mining. First, it will consider the question of how international law addresses the extraction of space resources from their original location on a celestial body. Second, it will discuss whether mining activities on celestial bodies can be carried out in accordance with the non-appropriation principle in Article II of the Outer Space Treaty (OST). Finally, it will reflect on the applicability of international environmental law norms to space mining. This presentation will conclude by examining the adequacy of current efforts to clarify international space law as it applies to space resource extraction.

Extraction of Space Resources: The extraction of space resources for the purpose of terrestrial or in-space utilization has been considered at domestic law but is unsettled as a matter of international space law.[1] The OST uses the phrase 'exploration and use' in its terms, for example in Article I with the reference to 'free for exploration and use by all States' and Article II with 'by means of use'. The word 'use' indicates that using space resources was within the contemplation of the drafters of the OST, and thus not prohibited.[2] However, does 'use' include non-scientific commercial uses?[3] If so, what is the extent of use permitted? Space resource extraction on the scale currently under consideration raises some crucial questions, including the contrasting rights of the non-mining countries to explore and use that area of space intact.

Another central legal question is whether there are any rights to the resources extracted that vest in countries or private entities. The diplomatic history of the OST indicates that perhaps this point was deliberately left ambiguous during the drafting in order to gain support across countries. In the world of diplomacy, this is referred to as constructive ambiguity – constructive at the time of the treaty adoption so as to gain agreement, but ambiguous now in terms of legal application.

The official position of the United States is that the removal of the space resources from being *in situ* allows the granting of ownership rights. Under the US interpretation, the non-appropriation prohibition does not extend to governmental or private ownership of resources once they are removed from the celestial body.[4] The United States has adopted domestic legislation to reflect this: the SPACE Act of 2015 indicates that private US companies have rights to all resources extracted and removed from the celestial body.[5] Other jurisdictions have subsequently adopted similar domestic laws. However, there are contrary country views, leading to nongovernmental attempts to ascertain or articulate the law on the removal and use of space resources.[6]

Space Mining Activities and Non-Appropriation: There is a legal tension in the simultaneous application of Article I of the Outer Space Treaty (OST), on the right of countries to freely explore and use space and to have free access to all areas of celestial bodies, and Article II of the OST when considering space mining. Article II states: 'Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means'. No territorial claims are permitted in space by countries or non-governmental entities. During the drafting of the OST, all negotiating states felt that this was the best guarantee of the peaceful use of outer space, and a similar idea had been used several years earlier to resolve territorial disputes in Antarctica.[7]

Article II raises, but does not answer, the issue of whether the extraction of space resources amounts to national appropriation. The United States has opined that space resource extraction from celestial bodies does not amount to national appropriation, reinforcing this view through section 10 of the 2020 Artemis Accords, which states that the 'extraction of space resources does not inherently constitute national appropriation under Article II of the Outer Space Treaty'. This appears to be a very careful compromise among the Artemis Accord states. Other countries are of the view that space resource exploitation may contravene Article II, particularly where title to the resources is granted through domestic law.[8] Given the differences of opinion, this ambiguity in the OST requires urgent resolution at the international level.

A related question is whether mining activities amount to national appropriation through the reality of operation. For example, the Artemis Accords recognize that national activities on the Moon will require close coordination, including through the creation and honouring of safety zones. However, international law does not provide clear guidelines at present as to whether request-based entry to safety zones prevents them from being considered national appropriation through use, and whether there is a size or time limit on safety zones above which they will be considered as a form of appropriation. Additionally, there are live questions as to how safety zones fit with Article I of the OST to freely explore and use space.

International Environmental Law Norms: The final question explored in this presentation is whether and how international environmental law norms apply to space resource extraction activities. Article III of the OST provides that 'States Parties to the Treaty shall carry on activities in the exploration and use of outer space, including the moon and other celestial bodies, in accordance with international law'. When the OST was adopted, terrestrial international environmental law was relatively undeveloped. However, since then, this area of international law has significantly expanded. Certain aspects of international environmental law have already been applied in space law. For example, the 'no harm' principle is reflected in the aims of the space debris mitigation guidelines.[9] This is the obligation of countries to ensure that activities within their control respect the environment of areas beyond national control, including space. However, there is no clear articulation of the scope of international environmental law norms that apply to space resource extraction.[10] This presentation will consider the overarching international environmental law norms that are likely to apply to these activities.

Conclusion: The existing international space law framework created by the OST appears to provide some guidance for the legal extraction of resources in space, thereby creating opportunity for space mining. However, there are crucial ambiguities that require urgent international resolution in order to ensure certainty in the planning and operation of these activities.

References:

[1] Fabio Tronchetti states: "The legal status of extraterrestrial resources is a highly controversial topic. Indeed international space law lacks clear and internationally accepted rules governing their removal and use" at F. Tronchetti, 'Legal Aspects of Space Resource Utilization' in F. von der Dunk and F. Tronchetti, *Handbook of Space Law* (2015), 769-813 at 788.

[2] S.W. Anderson, K. Christensen and J. LaManna, 'The Development of Natural Resources in Outer Space' (2018) *Journal of Energy & Natural Resources Law* 227-258 at n. 96.

[3] There is consensus that scientific use is permitted: Tronchetti, *supra* note 1 at 788.

[4] See Anderson et al., *supra* note 2 at 783 outlining that US position on resource rights.

[5] US *Commercial Space Launch Competitiveness Act, 2015*, § 51303 Asteroid resource and space resource rights: 'A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained, including to possess, own, transport, use, and sell the asteroid resource or space resource obtained in accordance with applicable law, including the international obligations of the United States.' Tronchetti has commented that this might amount to appropriation 'by other means', prohibited by Article II of the OST: Tronchetti, *supra* note 1 at 792.

[6] Contrary country views have been expressed in the legal committee of the UN Committee on the Peaceful Uses of Outer Space: see the reaction of developing economies and parties to the Moon Agreement in response to the US legislation, described by F. Lyall and P. Larsen, *Space Law: A Treatise*, 2nd ed. (2018) at 185. For nongovernmental discussions, see the Vancouver Recommendations on Space Mining (2020): http://www.outerspaceinstitute.ca/docs/Vancouver_Recommendations_on_Space_Mining.pdf, and Hague Building Blocks for the Development of an International Framework on Space Resource Activities: https://www.universiteitleiden.nl/en/law/institute-of-public-law/institute-of-air-space-law/the-hague-space-resources-governance-working-group.

[7] Lyall and Larsen, *supra* note 6 at 167-8.

[8] For consideration of this issue, see Lyall and Larsen, *supra* note 6 at 185.

[9] For the application of this principle, see J. Su, 'Control over activities harmful to the environment' in R. Jakhu and P.S. Dempsey, *Routledge Handbook of Space Law* (2017), 73-89 at 75.

[10] However, authors have identified certain international environment law principles as relevant to lunar exploration and space mining, such as the precautionary principle: Su, *supra* note 9 at 89. Note that Lyall and Larsen indicate that 'it would be wrong to consider the law of the space environment as something sepa-

rate, distinct and different from the concepts of terrestrial environmental law': *supra* note 6 at 245.

SPACE MINING AND THE EVOLUTION OF INTERNATIONAL SPACE LAW. M. de Zwart[1] and S. Henderson[2], [1]The University of Adelaide (Adelaide Law School, The University of Adelaide, S.A. 5005, Australia; melissa.dezwart@adelaide.edu.au), [2]The University of Adelaide (Adelaide Law School, The University of Adelaide, S.A. 5005, Australia; stacey.henderson@adelaide.edu.au).

Introduction: In recent years, there has been a dramatic increase in investment in space mining activities, many of which are led by commercial space actors. The current international legal framework for space resource extraction and utilization is sadly lacking, which leads to commercial uncertainty and increases the risk associated with investment in such endeavours. The foundational space law treaty governing activities in outer space – *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (‘*Outer Space Treaty*’)[1] – applies to all space activities, whether carried out by a government space agency or private actor. Yet, the *Outer Space Treaty* contains no explicit mention of space resources or space mining. The *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* (‘*Moon Agreement’*)[2] does explicitly address space resources but is binding on very few States Parties and is not reflective of customary international law. In light of this gap in international space law, States have forged a path ahead by passing their own domestic legislation relating to space resources, and by entering into a series of bilateral agreements with other States that address space resources, such as the Artemis Accords. This paper explores the impact that these actions by States are having on the future evolution of international space law relating to space resources, and calls for greater certainty in the law relating to space mining.

International Space Law Framework: International space law is comprised of five treaties. The most significant of these is the *Outer Space Treaty* which entered into force in 1967. The other four treaties build upon the foundations of the *Outer Space Treaty*.

Outer Space Treaty. This treaty was negotiated at the height of the Cold War and when only two space actors existed: the United States of America, and the Union of Soviet Socialist Republics. The *Outer Space Treaty* is silent on space resources – it neither explicitly permits nor prohibits mining activities in space. However, several of its Articles are relevant for space mining activities.

Under Article I, outer space, ‘including the Moon and other celestial bodies, shall be free for exploration and use….and there shall be free access to all areas of celestial bodies’. Article II of the *Outer Space Treaty*, which is sometimes simply referred to as the principle of non-appropriation, poses the biggest potential challenge to space mining activities. Article II provides: ‘Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means’. This is not in any way restricted to government space mining activities; the prohibition applies equally to commercial space mining activities. Through space mining activities, there can be no appropriation of any celestial bodies. However, it is unclear whether a distinction can be drawn between appropriation of the celestial body as a whole, and appropriation of resources once they have been extracted from the celestial body.

Moon Agreement. For the 18 States Parties to the *Moon Agreement* there is an additional lawyer of international law to be navigated.

Article 11 of the *Moon Agreement* is most significant in this context. It restates the principle of non-appropriation from the *Outer Space Treaty*, identifies the Moon and its natural resources as ‘common heritage’, and requires the establishment of an international regime ‘to govern the exploitation of the natural resources of the Moon as such exploitation is about to become feasible’. Article 11(7) provides that: ‘The main purposes of the international regime to be established shall include:
(a) The orderly and safe development of the natural resources of the Moon;
(b) The rational management of those resources;
(c) The expansion of opportunities in the use of those resources;
(d) An equitable sharing by all States Parties in the benefits derived from those resources, whereby the interests and needs of the developing countries, as well as the efforts of those countries which have contributed either directly or indirectly to the exploration of the Moon, shall be given special consideration’.

While the majority of the States who are party to this treaty have limited, or no, space capabilities, for others, being bound by the *Moon Agreement* has the potential to dramatically restrict the development of a domestic space resource industry.

Domestic Legislation: The United States was the first country to introduce domestic legislation relating to space mining and the ownership of extracted space resources. The 2015 *Space Resource Exploration and*

Utilization Act, which forms Title IV of the *Commercial Space Launch Competitiveness Act*, gives US citizens engaged in commercial space mining the right to 'possess, own, transport, use, and sell the asteroid or space resource obtained in accordance with applicable law, including the international obligations of the United States'. The US laws essentially grant property rights over extracted space resources [3]. The United States is not a party to the *Moon Agreement*, and as such is under no international obligation in relation to the establishment of an international regime governing space resources.

Luxembourg followed the lead set by the United States when it introduced similar legislation in 2017, with the United Arab Emirates close behind.

Bilateral Agreements: The Artemis Accords are a series of bilateral agreements entered into between NASA and other countries as part of the US' Artemis Program. While some of the principles in the Artemis Accords merely reflect obligations contained in the *Outer Space Treaty*, others reflect a particular US interpretation of international space law and are far more controversial [4]. Among the more controversial principles in the Accords are the right to extract and use celestial bodies' resources for commercial purposes (section 10) and the right to establish 'safety zones' to avoid interference with nominal operations (section 11). The Artermis Accords pose a unique challenge to countries such as Australia, which have signed up to the Accords and are also States Parties to the *Moon Agreement*.

Conclusion: Recent developments in domestic legislation and bilateral agreements indicate a trend towards increased freedom to engage in space resource extraction and utitlisation for commercial gain. The current international space law regime needs to evolve in order to keep up with this thriving industry to ensure that an appropriate balance can be struck between commercial interests, security of the space domain, and the preservation of space for all humanity.

References:

[1]*Outer Space Treaty* (1967). [2] *Moon Agreement* (1984). [3] Su, J. (2007) *IntlCompLQ, 66*, 992. [4] Tronchetti, F. and Liu, H. (2021) *AJIA*, 2.

A DEEP DIVE INTO NASA'S 3D PRINTED HABITAT CHALLENGE: EXPLORING HOW PRIZE CHALLENGES COMPLEMENT AN ORGANIZATION'S INNOVATION EFFORTS. A. Vrolijk[1] and Z. Szajnfarber[2], Department of Engineering Management and Systems Engineering, The George Washington University, 800 22nd Street NW, Washington, DC 20052, USA. [1]avrolijk@gwu.edu, [2]zszajnfa@gwu.edu.

Introduction: Prize challenges—one of several open innovation tools—are catalysts for innovation. Here, teams of "solvers" compete to achieve, or beat, technology performance goals set by an organization—the "seeker" [1]. These non-traditional participants often deliver novel solutions to the seeker, and some solutions surpass the state-of-the-art [2], [3]. In turn, the solvers compete for an attractive (monetary) prize—the incentive to participate and do well [4]. In short, a challenge can prompt a dedicated effort from a broad range of individuals, meet or surpass technical performance goals, and have a significant impact within the focal domain.

Technical organizations—both firms and government agencies—want to reap these benefits in their domains. As such, they are increasingly using challenges to help address problems that are core to their mission(s) [5], [6]. With this increased popularity, scholars are calling for a better understanding of how the contest fits into the organization's innovation efforts [7]. Practitioners starting their own challenges echo this concern: they need this information to deploy this tool effectively [8].

We took a step in that direction by unpacking the life cycle of one prize challenge. Between 2015 and 2019, we studied National Aeronautics and Space Administration (NASA)'s 3D Printed Habitat Challenge (3DPH), part of NASA's Centennial Challenges Program (CCP)'s portfolio. In this work, we describe how the challenge benefited NASA's planetary additive construction efforts in useful ways. From these case study data, we inductively construct a framework of *what* challenge benefits occur *when*. Our work aims to help seekers plan and execute future innovation contests, fully taking advantage of this important innovation tool.

Setting, Data, and Method: We studied the 3DPH Challenge, considered one of NASA's most complex—and successful—prize challenges run to date. Through a $2 million prize, it aimed to advance additive construction[1] technology, moving NASA closer to producing viable habitats on planetary surfaces. We chose to study 3DPH because it encapsulated several successes: it addressed important NASA priorities; it connected NASA to large, non-aerospace firms interested in the subject matter; it allowed diverse SMEs to collaborate on shared interests; it resulted in useful solutions; and it infused outcomes into ongoing NASA projects. Understanding what made these successes possible will allow us to build theory to support future challenge activities.

We conducted a longitudinal field study of this challenge. This inductive approach gave us the tools to develop a strong understanding of the context and capture the relevant data [9]. We observed the challenge's events, interviewed CCP staff and subject matter experts (SME) integral to the challenge, and drew on the relevant project documents. With these data in hand, we relied on qualitative research techniques to triangulate the challenge benefits among the different pieces of data and synthesize a framework that can apply outside of our research context [10].

3DPH's Fit with NASA's Existing Efforts: The 3DPH was not NASA's first, or only, additive construction effort. Teams at NASA's Marshall Space Flight Center (MSFC) and NASA's Kennedy Space Center (KSC) had been independently pursuing this capability for several years before the prize challenge started. These SMEs were crucial in shaping the direction and planned outcomes of the challenge, and their buy-in was important to its success within NASA.

The two teams differed in printing methods and materials. At MSFC, the In-Space Manufacturing (ISM) team joined the U.S. Army Corps of Engineers (USACE) and other partners to form the Additive Construction with Mobile Emplacement (ACME) project, a follow up to previous additive construction activities at MSFC. Here, the partners found an overlap between printing temporary housing for the U.S. Army and the planetary structures required by NASA. Their focus was on demonstrating large scale structures. To accomplish this, they used a gantry style robot that printed with Portland cement.

At KSC, the Swamp Works lab led a broad partnership pursuing a variety of approaches that could work on a variety of planetary surfaces. One approach focused on polymer concrete feedstocks: using plastics to bind, extrude, and layer regolith into the desired shapes. SMEs thought this approach would be beneficial for both Earth and planetary surface applications: recycling thermoplastics would support sustainability

[1] Additive construction uses additive manufacturing processes and knowledge as well as specialized feedstocks to construct large-scale infrastructure: "3D printing" for e.g., roads, berms, or single story houses.

efforts as well as cut down on the mass needed to establish a human presence on the Moon or Mars. Their printer architecture was a robotic arm.

The MSFC and KSC teams integrated the most important areas for additive construction development based on the agency's existing efforts. The challenge would address three technical priorities (see Table 1): new feedstock materials, autonomous operations, and robotic architecture required for large scale structures. Success for 3DPH, then, meant achieving technical outcomes that contributed to the teams' additive construction work. It also meant showing that the CCP could successfully accelerate early-stage technology development in areas relevant to NASA.

Table 1: Focus areas addressed in the 3DPH Challenge [11]

Technical Priorities	**Performance tested in**		
	Phase 1	***Phase 2***	***Phase 3***
3D printed habitat designs	Architectural concept		Virtual model
Feedstock development		Feedstock recipe and print demonstrations	Feedstock recipe and print demonstrations
Autonomous operations		Print demonstrations (semi-autonomy)	Virtual model and print demonstrations
Large scale printing			Virtual model and print demonstrations

Preliminary Results: We coded the challenge's benefits to NASA's additive construction SMEs along two categories: the *network benefits* strengthened the NASA's links to relevant domains, and the *technology benefits* helped them make progress on areas of technical uncertainty. Network benefits included building connections to individuals and organizations in non-traditional domains, raising the visibility of additive construction, and forming new partnerships after the challenge. Technology benefits included reducing the innovation costs through partnering, absorbing new solutions, and spurring non-domain development. We then coded these according to what challenge stage they occurred in: formulate, solve, review, or absorb.

Conventional prize challenge wisdom would have expected these benefits to be realized when the solutions are received and judged. Instead, the benefits of the challenge were realized across the 3DPH life cycle. In fact, we found that more kinds of benefits occurred *outside* of the solution review stage than *within* it. It indicates that NASA SMEs benefited from all stages of the challenge, and casts the importance of the other stages of the challenge in a new light.

We also found that the source of the benefits was not always the solvers. During the formulation of the 3DPH Challenge, all benefits stemmed from non-solvers: companies and organizations that were interested in the problem, interacting with the NASA SMEs as sponsors and/or experts in related domains. It is only in later stages that the benefits stemmed from the connections to solvers and their solutions.

Our results reinforce the challenge as a tool to broadly serve the organization's needs. Here, our work recognizes the crucial role of the seeker in the challenge's success in providing value for the organization. Our contribution to this discussion is a clearer picture of *what* benefits occur *when*. With this, future seekers can gear their organization to more fully take advantage of the benefits that the innovation contests can offer.

References: [1] C. Terwiesch and Y. Xu, Management Science, vol. 54, no. 9, pp.1529–1543, Jul. 2008. [2] L. B. Jeppesen and K. R. Lakhani, Organization Science, vol. 21, no. 5, pp. 1016–1033, Oct. 2010. [3] L. Kay, R&D Management, vol. 41, no. 4, pp. 360–377, Sep. 2011. [4] L. Brunt, J. Lerner, and T. Nicholas, The Journal of Industrial Economics, vol. 60, no. 4, pp. 657–696, 2012. [5] J. L. Gustetic, J. Crusan, S. Rader, and S. Ortega, Space Policy, vol. 34, no. Supplement C, pp. 11–17, Nov. 2015. [6] H. Lifshitz-Assaf, Administrative Science Quarterly, vol. 63, no. 4, pp. 746–782, Dec. 2018. [7] Z. Szajnfarber, L. Zhang, S. Mukherjee, J. Crusan, A. Hennig, and A. Vrolijk, IEEE Transactions on Engineering Management, pp. 1–15, 2020. [8] Z. Szajnfarber and A. Vrolijk, Systems Engineering, vol. 21, no. 1, pp. 47–58, 2018. [9] K. M. Eisenhardt, M. E. Graebner, and S. Sonenshein, Academy of Management Journal, vol. 59, no. 4, pp. 1113–1123, Jul. 2016. [10] M. B. Miles and A. M. Huberman, SAGE, Jan. 1994. [11] A. Vrolijk and Z. Szajnfarber, CESUN Conference. 6, 2021.