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Journal Item

How to cite:

Hadler, K.; Martin, D. J. P.; Carpenter, J.; Cilliers, J. J.; Morse, Andrew; Starr, S.; Rasera, J. N.; Seweryn, K.; Reiss, P. and Meurisse, A. (2019). A universal framework for Space Resource Utilisation (SRU). Planetary and Space Science (Early Access).

Version: Accepted Manuscript

Link(s) to article on publisher's website:
http://dx.doi.org/doi:10.1016/j.pss.2019.104811

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PII: S0032-0633(19)30184-9
DOI: https://doi.org/10.1016/j.pss.2019.104811
Reference: PSS 104811

To appear in: *Planetary and Space Science*

Received Date: 30 April 2019
Accepted Date: 25 November 2019

Please cite this article as: K. Hadler, D.J.P. Martin, J. Carpenter, J.J. Cilliers, A. Morse, S. Starr, J. N. Rasera, K. Seweryn, P. Reiss, A. Meurisse, A UNIVERSAL FRAMEWORK FOR SPACE RESOURCE UTILISATION (SRU), *Planetary and Space Science* (2019), https://doi.org/10.1016/j.pss.2019.104811

A UNIVERSAL FRAMEWORK FOR SPACE RESOURCE UTILISATION (SRU)

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ABSTRACT

Space Resource Utilisation (SRU) or In Situ Resource Utilisation (ISRU) is the use of natural resources from the Moon, Mars and other bodies for use in situ or elsewhere in the Solar System. The implementation of SRU technologies will provide the breakthrough for humankind to explore further into space. A range of extraction processes to produce usable resources have been proposed, such as oxygen production from lunar regolith, extraction of lunar ice and construction of habitation by 3D printing. Practical and successful implementation of SRU requires that all the stages of the process flowsheet (excavation, beneficiation and extraction) are considered. This requires a complete 'mine-to-market' type approach, analogous to that of terrestrial mineral extraction.

One of the key challenges is the unique cross-disciplinary nature of SRU; it integrates space systems, robotics, materials handling and beneficiation, and chemical process engineering. This is underpinned by knowledge of the lunar or planetary geology, including mineralogy, physical characteristics, and the variability in local materials. Combining such diverse fields in a coordinated way requires the use of a universal framework. The framework will enable integration of operations and comparison of technologies, and will define a global terminology to be used across all fields. In this paper, a universal SRU flowsheet and terminology are described, and a matrix approach to describing regolith characteristics specifically for SRU is proposed. This is the first time that such an approach has been taken to unify this rapidly-developing sector.

Keywords: In situ resource utilisation, ISRU, space resources, SRU, space mining

1 INTRODUCTION

The use of in-space materials to provide life support, fuel and building materials has received significant attention in recent years (e.g. Crawford, 2015; Sanders, 2018). The production of oxygen on the Moon using lunar soil, or regolith, is of specific interest, since oxygen can be used to sustain human life and as fuel for further exploration. Furthermore oxygen is a major component of propellant for launch vehicles and other spacecraft, and comprises more than 40% of lunar regolith by weight (Schreiner et al., 2016), making it a prime in situ resource. Other chemical and mineral resources such as metals also may be considered valuable resources, particularly as they often are produced as by-products of extraction processes (e.g. Schwandt et al., 2012).

Several reduction processes have been put forward to produce oxygen from lunar regolith, the layer of unconsolidated rock fragments, minerals and glasses that covers the bedrock of the Moon. These processes include hydrogen reduction, carbothermal reduction, molten regolith electrolysis and molten salt electrolysis, as reviewed by Taylor and Carrier (1993) and Schwandt et al. (2012). Such processes cannot be carried out in isolation, however, and must be considered as part of a broader flowsheet, from excavation of the regolith to product storage and waste disposal.

The production of oxygen from lunar regolith by hydrogen reduction is a clear example of the need for integration through the entire process. Oxygen yields from the regolith have been shown to be related to the proportion of Fe^{2+} in the feedstock. Allen et al. (1996) carried out hydrogen reduction on a range of lunar mare, highland and pyroclastic glass samples, obtaining total O_2 yields of between 1.2% and 4.7% for Fe^{2+} contents of between 3.6% and 17.8%. They noted that there was no dependence of oxygen yield on sample maturity, and the order of efficiency of oxygen extraction, from highest to lowest, was from ilmenite, agglutinitic and pyroclastic glass, olivine, and pyroxene. Pyroclastic glasses were shown to be a potentially rich 'ore', producing yields of oxygen around 5%, although this is likely to be dependent on the FeO content of the glasses (Allen et al., 1996). The Fe^{2+} content in the regolith can be increased by increasing the ilmenite content through physical separation, known as beneficiation. Beneficiation, also called mineral processing, is used extensively at huge scale in the terrestrial mining industry to separate minerals of different type based on their physical properties. A study undertaken at a similar time by Chambers et al. (1995) concluded that beneficiated basalt regolith would provide the best yield of oxygen due to the higher ilmenite content, at 8-10%, compared to the 1-3% typically obtained from basaltic regolith. Subsequent studies have investigated the beneficiation of lunar regolith to improve ilmenite content (e.g. Li et al., 1999; Quinn et al., 2013), however currently there are no studies that link the performance of the beneficiation process with that of the hydrogen reduction process.

There are relatively few examples of large-scale trials of SRU technology that incorporate excavation and reduction. Those that exist have largely been the work of NASA (e.g. Sanders and Larson, 2011; Sanders and Larson, 2013; Lee et al., 2013), namely the field trials of the ROxygen and PILOT projects. These trials demonstrated the feasibility of SRU to produce oxygen. In a review on NASA's progress on lunar SRU, Sanders and Larson (2013) showed that technical developments had been achieved in the regolith reduction technology, in general increasing the Technology Readiness Level (TRL) by 2 points. Size separation and beneficiation of regolith prior to reduction had not seen any change in TRL, however, as it had been omitted from the field trials.

The need for integration of different units within the SRU flowsheet has highlighted critical differences between the fields of expertise involved. SRU brings together fields that have not previously collaborated, such as space systems engineers, chemical engineers, mining and mineral processing engineers and geologists, and it has become apparent that each sector has its own approach, objectives, and terminology. Furthermore, parameters that are critical to one sector (e.g. particle size distribution in beneficiation), are barely considered in other sectors (excavation and extraction).

In this paper, a framework for SRU is proposed that should be used by all researchers working on technical aspects of SRU. This is analogous to the Global Exploration Roadmap (2018), as developed by the International Space Exploration Coordination Group (ISECG), which brings together a consolidated view of exploration missions and plans of the participating agencies (Carpenter et al., 2016). The framework starts with a universal flowsheet, terminology, and an approach to characterising regolith for SRU processes. It is anticipated that this approach will bring together the different research fields to progress SRU towards implementation.

2 A UNIVERSAL FLOWSHEET

The use of flowsheets to describe processes and to assist in mass balancing is ubiquitous in mining processes, particularly in the beneficiation, or mineral processing, stages. They enable rapid evaluation of stream flowrates, assisting in process optimisation and troubleshooting. General flowsheets for SRU were introduced by Williams et al. (1979) to compare two cases to produce an ilmenite-rich product and a plagioclase-rich product; one in which the lunar ore is shipped prior to beneficiation and one in which the concentrated ore is shipped following beneficiation. More detailed flowsheets were then used to describe a proposed beneficiation process, comprising separation of the regolith by size, and by magnetic and electrostatic properties.

For any SRU process on the Moon, Mars or any other body, the material flow can be described by the flowsheet in Figure 1. This universal flowsheet comprises three key stages; excavation, beneficiation and extraction. This is analogous to many terrestrial mining operations, where the process stages are mining, mineral processing and smelting. Much of the SRU-related research to date has focused on the final stage, the production of oxygen by regolith reduction, for example. Extraction of any valuable commodity, however, requires a suitable feedstock. Such a feedstock must be predictable and consistent in terms of composition and physical properties. This enables the extraction processes to be optimised in recovering and transforming the valuable resource and for it to be autonomous or controlled effectively.

The production of a consistent feedstock will require beneficiation. Beneficiation increases the mass fraction of the component of interest (e.g. ilmenite, or specific mineral particle size range) in the feedstock by removing other components that are less useful or may interfere with the subsequent extraction. This must be accounted for in the overall SRU process chain, or flowsheet. For extraction processes that do not require beneficiation, the transfer of material from the excavation system to the extraction process must still be designed.

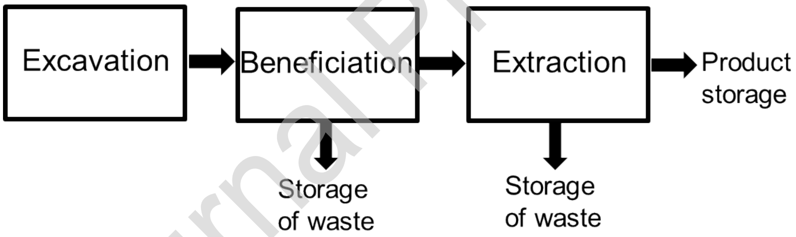

Figure 1: Universal flowsheet for SRU processes

The universal flowsheet in Figure 1 highlights the need to consider upstream processes in the calculation of mining scale, but also for comparison of different processing options. An example of this can be taken from the work of Chambers et al. (1995), in which calculations are given for the mass of feedstock required to produce 1 t oxygen. The beneficiated basaltic regolith is shown to yield 10% oxygen, compared to 3.1% oxygen for the non-beneficiated basalt, therefore it is suggested that 10 t of beneficiated feedstock is required compared to 32.3 t to produce the oxygen. While this is true for the final extraction stage, when the entire flowsheet is considered, the material rejected in beneficiation must be taken into account in the total mass flow, in order to allow a complete comparison of the two systems.

The performance of each downstream stage is dependent on the preceding operation. The decision on the arrangement and scheduling of the excavation, stockpiling and processing, in addition to product and waste storage, must take into account the interaction between the stages. Variability and target production rates will define the process parameters, as in terrestrial mining (Lotter et al., 2018).

At present, the reduction of lunar regolith using hydrogen has been the most widely studied of the oxygen production techniques (Schwandt et al., 2012), with the variation in oxygen production by regolith type (e.g. mare, pyroclastic glasses) being studied by Allen et al. (1996) and Chambers et al. (1995). The beneficiation of lunar regolith to increase ilmenite content to improve the oxygen yield from hydrogen reduction is the most widely studied beneficiation strategy for lunar regolith (Rasera et al., 2019). As further research is carried out on the operating sensitivity of other reduction processes and the need for beneficiation is established (e.g. size separation of fine and coarse particles; to account for the variability of the regolith composition), the universal flowsheet will provide the foundation for fair and robust comparison.

Furthermore, by mapping existing research onto the universal flowsheet, weaknesses in the knowledge and technology base can be identified. One such area is size separation; many reduction studies have been carried out using limited size fractions (e.g. Allen et al., 1996; samples were screened at 1 mm), as have many beneficiation studies (e.g. Agosto, 1983; Li et al., 1999; Trigwell et al., 2013). The effect of particle size on the reduction process has been largely overlooked. Clark et al. (2009), for example, describe a single field test that treated a lunar simulant sample (JSC-1A) in the PILOT hydrogen reduction system. The trial produced close to 1% by mass water. This translates into an oxygen yield from regolith of 0.88%, assuming a 100% conversion and gas recovery during the subsequent water electrolysis. The experimental system suffered numerous complications; some of these issues were attributed to the large proportion of very fine particles in the feedstock. By specifying the feedstock conditions to the final extraction stage, the beneficiation stage can be defined, and the appropriate research and process design carried out.

3 A UNIVERSAL TERMINOLOGY

In developing a framework for SRU, it is apparent that a clearly defined set of terms is required to describe the efficiency of a process. This is important for comparing the performance of different processes, in addition to enabling calculation of likely throughputs, which will define the requirements from the upstream processes of excavation and beneficiation. Many different terms are used in the SRU literature, unfortunately they are neither consistent nor clearly defined. Here, a selection of terms that can be applied to any SRU system is proposed, many of which are taken from the terrestrial mining industry. It should be highlighted that the key to clear use is to define the reference point, for example 'per t of regolith excavated' or 'per t regolith feed into extraction'. This will enable complete mass balancing for all materials across the flowsheet.

3.1 REGOLITH EXCAVATION

Terms such as resource and ore have established and fixed definitions in the terrestrial mining sector (e.g. Wills and Finch, 2015). Some common terms are:

Resource: A concentration of minerals in a form and amount that economic extraction is currently or potentially feasible.

Reserve: The part of a resource that can be economically and legally extracted under current circumstances.

Ore: The material that contains economically extractable minerals or metals. Ores are typically composed of valuable material (minerals and/or metals), non-valuable minerals (called gangue) and waste rock. Waste rock does not undergo processing. The objective in the beneficiation stage is to separate the desired component in the ore from the associated gangue (undesired) component.

For SRU, and specifically any process that is treating regolith, there may be a requirement to remove a fraction of the surface material to access subsurface material. The removal of surface material in this way must be accounted for in planning, and is referred to as the strip ratio:

Strip Ratio: Mass of surface regolith removed per unit mass of regolith ore.

Furthermore, in excavation, the operations of loading and hauling regolith to the processing site will require a *mine scheduling* approach to maximise efficiency.

The regolith will be excavated and transported to a stockpile or directly to the processing section, following which beneficiation is likely to take place prior to the final extraction step.

3.2 REGOLITH PROCESSING

For terrestrial mining operations, mineral processing comprises two key stages; liberation of the minerals from the ore by comminution (crushing and grinding) and physical separation (concentration) of the desired minerals from the non-valuable or unwanted minerals. As the size of the lunar regolith is already fine, no comminution is required, therefore the focus is on separating the minerals, components or size fractions as required by the downstream extraction process.

No physical separation is perfect; unwanted waste (gangue) minerals pass into the product stream and desired mineral particles are lost to the waste stream. To account for this misreporting of particles, in terrestrial mineral processing, the terms recovery and grade are used, as follows:

Recovery: Mass of product produced (e.g. O_2) per mass of product in feedstock (e.g. O_2 in regolith into beneficiation process)

Grade: Mass of product (e.g. ilmenite in feedstock) per mass of stream (e.g. total mass of feedstock)

The product streams from beneficiation are typically termed *concentrate* (for the product) and *tailings* (for the waste). Enrichment ratio can be used to describe by how much the beneficiation process has concentrated the species of interest. This is less commonly used in terrestrial processing than grade and recovery.

Enrichment ratio: Grade of given species in outlet of process as a ratio of the grade of the same species into the process (e.g. ilmenite content in product of beneficiation as a ratio of the ilmenite content in the feed to beneficiation).

In the extraction stage, the terminology is taken from standard terms used in chemical reaction engineering:

Refresh ratio: Mass of fresh reactant required (e.g. H_2) per mass of product produced (e.g. O_2).

Conversion: Mass of reactant consumed (e.g. H_2) per fresh reactant input.

An example of the use of refresh ratio is given by the work of Stenzel et al. (2018) on carbothermal reduction of regolith. Yields of 2 m^3 CO_2 were reported from an initial regolith mass of 100 kg, for 1.6 kg of carbon fresh feed. No details are given on the pressure and temperature for the CO_2, but if standard atmospheric conditions are assumed, this represents a yield of O_2 of 2.8%, with a refresh ratio of 0.57.

The final, and most widely used, term is yield. It is defined as follows:

Yield: Mass of product produced (e.g. O_2) per mass of feedstock (e.g. regolith into beneficiation)

It can be related to any stage of the flowsheet, allowing the comparison of different technologies or operating conditions.

This list of terminology is not exhaustive, but these terms are the fundamental basis for SRU systems design. If the wider SRU communities are to communicate their findings effectively, this terminology (and others, as required) must be adopted and used consistently. Using terms that are standard within established industrial processes will encourage transfer of knowledge between terrestrial and space resource communities.

As each stage of the flowsheet will incur losses and inefficiencies, comparison between the technologies can be carried out more effectively when a common set of terminology is applied.

4 CHARACTERISING REGOLITH COMPOSITION FOR APPLICATION IN SRU

Lunar regolith has been analysed in many different ways. The lunar samples that have been returned to Earth have been comprehensively characterised in terms of their particle size distribution, modal mineralogy and chemical composition (Heiken et al., 1991). The specific measurements depend on the focus of the study and the properties determined for one particular sample may differ significantly from other types of regolith and other landing sites. This often has the consequence that the complete sample properties have not been collated as a single source.

For SRU process design, it is essential that the complete composition of the regolith is known, ideally on a particle-by-particle basis. This is analogous to mineralogical analyses used in terrestrial mineral extraction processes (e.g. Fandrich et al., 2007; Ntlhabane et al., 2018; Lotter et al., 2018), which describe the individual particle composition and mineral distribution, size-by-size.

This collated mineralogical and size information allows identification of size fractions and minerals of interest, and which materials must be targeted in order to optimise the extraction stages. The importance of this is two-fold; first it allows the efficiency of the extraction step to be optimised, and secondly, it defines the requirements of the excavation and beneficiation stages.

For SRU process design, a broad characterisation of the regolith in terms of size distribution and composition can be made. As an example, consider the properties of lunar sample 71061,1, which is regarded as a typical Apollo 17 mare soil (Heiken, 1975). In the detailed table from Heiken (1975), the sample has been divided into 12 size classes, and 21 components. It is notable that not all size classes have equivalent component information.

For first stage process design, this detailed information can be simplified into fewer size classes and combined components, to produce a component-size matrix, an example of which is shown in Table 1. This retains the key information, but allows rapid assessment of the most important mineral and size classes. The matrix breakdown and detail level will depend both on the sample and the process.

In Table 1 the particle size classes are guidelines, divided broadly into fines (<45 μm), coarse (>1000 μm), and two broad size classes (45 to 90 and 90 to 1000 μm) that contain the key components.

Arranging the properties in such a matrix allows clear identification of size fractions or material types that are of value, or that can be considered as waste or deleterious to the downstream process. Glass beads, for example, have been shown to produce favourable yields of oxygen in hydrogen reduction (Allen et al., 1996)), however can fuse at high temperature (1100 ^{o}C), adhering strongly to the reactor walls (Allen et al., 1994).

SIZE (μm)	**<45**	**45-90**	**90-1000**	**1000 to 10000**
Mass (%)	30.2	11.4	26.2	23.0
Agglutinates	17.1	14.1	10.3	0.0
Glass	0.0	26.7	15.6	0.0
Basalts	0.0	11.4	38.1	100.0
Breccia	0.0	3.4	7.0	0.0
Other minerals	0.0	37.2	26.0	0.0
Ilmenite	0.0	5.3	3.0	0.0
Other material	82.9	1.5	0.3	0.0

Table 1: A simplified version of Table 4a in Heiken (1975)

Ideally, the variability in regolith properties will also be available, so that confidence intervals can be ascribed. The average and possible ranges of size fractions and minerals properties ultimately define the detailed process design, and allow sensitivity analyses of the extraction stage to feedstock properties, as discussed in Cilliers et al. (2019). Such data is available, for example the Lunar Sourcebook (Heiken et al., 1991) details the modal (volume %) abundance data in the 90 to 1000 μm size fraction of representative soils (Table 7.2 therein, originally from Simon et al., 1981). This allows the variability to be described statistically.

Such collated composition matrices can be used to compare samples from different regions, or variability within the same region, but also to generate greater integration between geological knowledge of the proposed orebody and the processing. In terrestrial mining, this bridge between geology and processing is termed *geometallurgy*; a field developed in recent years to promote better integration across the mining supply chain in order to optimise operations (e.g. Philander and Rozendaal, 2011; Tungpalan et al., 2015). This is essential for process design and operation, to effect the efficient engineering of SRU mining, beneficiation and extraction.

5 APPLICATION OF FRAMEWORK FOR RESEARCH STRATEGY

In order for SRU to become an integrated, unified field, the framework proposed in this paper must become the standard. One of the key benefits of considering the process in this 'mine-to-market' approach is that gaps, either in knowledge or in technology, can be identified readily, and the appropriate research strategy defined. For example, based on the framework presented in this paper, the following example research questions must be addressed:

- What is the mass distribution and variability of different regolith components by class, size and deposit?
- How well do different reduction processes perform for non-beneficiated regolith? How do they perform if some beneficiation (size or material type) is carried out?
- How do the refresh ratios (i.e. amount of fresh reactant required) vary by extraction technique and with feedstock variability?
- Do fine particles need to be removed before reduction?
- How do different components, such as agglutinates, affect processing?

The framework is intended to promote collaboration across the disciplines working in this new field, to bring together those with space systems expertise and terrestrial mining expertise.

6 CONCLUSIONS

The use of space resources to produce consumables, such as oxygen, is a field that is of increasing interest and importance. It brings together a wide range of sectors, many of which have not previously worked together, including the space and mining industries. As the technology for space resource utilisation (SRU or ISRU) advances, so too does the need for integration of all stages of processing, from excavation to product storage. This 'mine-to-market' integration is similar to that required by the terrestrial mining industry.

For meaningful advances towards implementation of SRU technology, a universal framework is required that will enable integration, but also comparison of different processing routes. In this paper, the foundations of this framework are presented, using a universal flowsheet, terminology and a matrix approach to describing regolith composition specific to SRU. Terms such as yield, conversion and recovery are defined, and described in the context of the universal flowsheet. The matrix of the regolith composition considers the content of different components of interest, agglutinates for example, in a range of size fractions to assist in determining the optimal feedstock for extraction. This defines the requirements of the excavation and beneficiation stages.

Use of such a framework will enable gaps in the knowledge base, and in the existing technology, to be identified. In turn, this will guide the research strategy. This paper is the first time that such a framework has been proposed in this dynamic field. Use of common frames of reference will have a transformative effect on the progress of space resource utilisation research towards implementation on the Moon, Mars or other bodies.

Acknowledgements

This is a product of the ESA Topical Team on ‘A complete resource production flowsheet for lunar materials’.

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16th September 2019

To: The Editor
Planetary and Space Science

Dear Editor,

RE: PSS_2019_142; A UNIVERSAL FRAMEWORK FOR SPACE RESOURCE UTILISATION (SRU)

On behalf of my co-authors, I can confirm that there are no conflicts of interest related to the preparation or publication of this paper.

Yours Faithfully,

KHadler

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A UNIVERSAL FRAMEWORK FOR SPACE RESOURCE UTILISATION (SRU)

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RESEARCH HIGHLIGHTS

- For SRU to progress towards implementation, integration between disciplines is required
- The first step is to define a standard flowsheet and terminology
- Terms such as yield, recovery and conversion are defined for SRU
- A matrix for characterisation of regolith feedstock is developed