A UNIVERSAL FLOWSHEET AND TERMINOLOGY FOR IN SITU RESOURCE UTILIZATION (ISRU)

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Introduction: In Situ Resource Utilization (ISRU) has the potential to be the breakthrough technology that enables the further exploration of space by humankind.

The use of in-space materials to provide water, fuel and building materials reduces significantly the launch mass, but also presents a multitude of challenges in numerous areas. These range from uncertainties in the mineralogical and physical characteristics of the local regolith [1] to the development of processes and associated technologies that are reliable under extreme environmental conditions, including varying temperatures, low gravity and abrasive dust [2].

The production of oxygen on the Moon using lunar regolith has received significant attention in recent years [3], since it can be used both to sustain human life and as fuel for further exploration. Furthermore oxygen is a major component of launch vehicles, spacecraft and lander masses, but comprises more than 40% of lunar regolith by weight [4], making it a prime in-situ resource. Other chemical and mineral resources such as metals and rare gases also may be considered valuable resources, particularly as they often are produced as by-products of extraction processes (e.g. [5]).

While a range of extraction processes to produce usable resources have been in development for some time, practical and successful implementation of ISRU requires that all the stages of the extraction flowsheet are considered. This requires a complete mine-to-product type approach, analogous to that of terrestrial mineral extraction.

A key high-level challenge is the unique cross-disciplinary nature of ISRU; 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 a universal framework, on which the different processes and systems can be mapped, in order to identify gaps in the knowledge and to progress the field towards implementation. In this paper, the foundations of this universal framework are presented.

A Universal Flowsheet: Much of the ISRU-related research has, to date, focused on specific processes for extraction of oxygen, for example hydrogen reduction of lunar regolith (e.g. [6]). 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 most efficient in recovering and transforming the valuable resource and to be autonomous or controlled effectively.

The production of the necessary, consistent feedstock is likely therefore to 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 ISRU process chain, or flowsheet.

Each extraction process can be described by a single, overall flowsheet, which is given in Fig. 1. This universal flowsheet comprises three key stages; excavation, beneficiation and extraction. This is analogous to terrestrial mining operations.

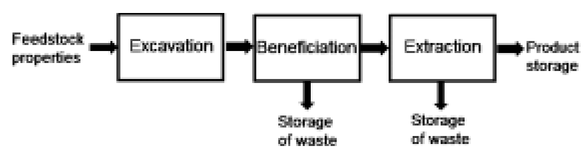

Figure 1: Universal flowsheet for ISRU processes

There is great benefit in mapping existing research onto the universal flowsheet, so as to identify weaknesses in the knowledge and technology base.

For ISRU to become a reality, all stages of the flowsheet must be integrated and function in the given environmental conditions (i.e. the planetary surface of interest).

A Universal Terminology: In developing a framework for ISRU, 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, and therefore defining requirements from the upstream processes of excavation and beneficiation. Many different terms are used in the literature, unfortunately they are neither consistent nor clearly defined.

The following key definitions are proposed:

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

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

Grade: Mass of product (e.g. O_2 in feedstock) per mass of stream (e.g. total mass of feedstock)

Enrichment ratio: Grade of given species in outlet of process as a fraction of the grade of the same species into the process

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

Conversion: Mass of product produced as a fraction of the mass of reactants consumed.

This list of terminology is not exhaustive, but these terms are the fundamental basis for ISRU systems design. Further, some terms are more applicable to certain stages of the flowsheet; e.g. *grade* and *enrichment ratio* are more appropriate to beneficiation, while *refresh ratio* and *conversion* are applicable to extraction (Fig. 1).

If the wider ISRU communities are to communicate their findings effectively, this terminology (and others, as required) must be adopted and used consistently.

Future Outlook: The aim of this work is to ensure that meaningful advances in ISRU are made, and that the process is considered as an entire system.

The Universal Flowsheet and Terminology are the beginning of this unified framework.

However, they must become the ISRU standard, and be consistently extended, to bring together effectively the research in this relatively new field.

In the next phase of development, the physical characteristics of local materials, specifically lunar regolith, will be defined in the context of ISRU feedstock.

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