# ESTIMATING THE SCALE OF SPACE RESOURCE UTILISATION (SRU) OPERATIONS TO SATISFY LUNAR OXYGEN DEMAND

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## ABSTRACT

The production of oxygen from lunar regolith is analogous to metal production from ore in a terrestrial mine. The process flowsheets both include excavation, haulage and beneficiation of the regolith or ore to provide the feedstock for the chemical extraction of oxygen or metal. The production rate of oxygen depends on the mass rate of regolith treated and the efficiency of converting the regolith to oxygen. To date, the development of Space Resource Utilisation (SRU) has been concerned with the technological development of the process, particularly the excavation and oxygen extraction. However, the required operating mass rates of the mine operation and the oxygen extraction stage have not been considered in any great detail.

Previous estimates of mining scale for lunar oxygen production are reviewed, and converted to a comparable regolith mining rate of kg/h. Beneficiation of the regolith before oxygen extraction is considered, and the effects of pre-sizing and removal of a specific component, agglutinates, are considered. The oxygen yield and operational availability are also included. It is estimated that the minimum mining rate to produce 1000 kg of oxygen per annum is at least five times higher than previous estimates, 30 kg/h, for equivalent efficiency assumptions.

Monte-Carlo simulations were performed for statistical confidence in the estimates of the mining mass rate and the required oxygen extraction feedstock rate. To be 95% confident that the 1000 kg/y $O_2$ will be met, the designed mining rate should be at least 65 kg/h, and the beneficiated feedstock rate 16 kg/h.

This study has revised and increased the estimate of the lunar regolith mining scale required for the production of a given amount of oxygen. It has also estimated the mass rate of feedstock required for oxygen extraction, if the regolith is first beneficiated.

The findings have a significant impact on the practical implementation of lunar mining and oxygen extraction, particularly the process design and whether the operation will be by batch- or continuous processing. The mass scale and beneficiation approaches bring terrestrial mining and processing concepts to SRU, and for the first time estimates the effect that regolith beneficiation and uncertainty have on the estimated scale of both the mining and extraction operations.

*Keywords: Space resources, space mining, SRU, ISRU, lunar mining scale, Moon feedstock tonnage*

# 1 INTRODUCTION

Lunar SRU was proposed by Carr (1963) during the Apollo era as a way to reduce launch mass and the dependency on Earth. Research in this field peaked first in the early 1970s at the height of the Apollo programme, and then again in the early 2000s following the announcement of the (now defunct) Constellation Program. With the recent advent of space privatisation and investment, and NASA's commitment to return astronauts to the Moon by 2024 (NASA, 2019), SRU is once again coming to the forefront of space sector research and development.

The commodities of interest are oxygen and water, both of which have numerous economic and technological applications. In a recent and comprehensive report, Kornuta et al. (2019) estimated that the demand for lunar water could be as much as 2450 t/y, including water required on the lunar surface (150 t/y), for fuelling missions to Mars (180 t/y) and for transporting propellant to LEO (1880 t/y). Furthermore, it is reported that 1000 kg $O_2$ will be required per year for life-support purposes on the Moon (Lee, Oryshchyn et al. 2013). In order to design suitable technologies and processes for producing a given target quantity of oxygen, the scale of the regolith mining and oxygen extraction operations must be established.

While the use- and business cases for lunar SRU have been well-considered, the scale of mining operations required to produce the projected amount of oxygen (1000 kg/y, following Lee, Oryshchyn et al., 2013) has received less attention. The scale of operations is critical as this defines the technology and scheduling requirements of the whole process, for example whether to operate on a continuous basis or a batch basis.

To estimate the scale to produce a specified target of 1000 kg/y of $O_2$, the efficiency of the reduction reactor must be taken into account, in addition to possible upstream beneficiation of the regolith into a more efficient oxygen extraction feedstock. These mass rate estimations are standard mass balancing procedures carried out in terrestrial mining operations.

## 1.1 Mine Operations

The extraction of space resources follows the same basic flowsheet as that of terrestrial mineral extraction. This is shown in Figure 1. In terrestrial mining, the operations are mining, beneficiation (mineral processing) and smelting. Beneficiation is the process in which particles in a feedstock (ore or regolith) are separated based on some material property, including size, density, conductivity, magnetism and surface chemistry.

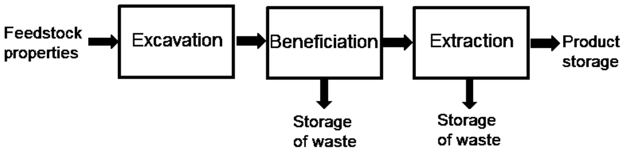

**Figure 1: Universal flowsheet for SRU processes, from Hadler et al. (2019)**

There are several, critical, differences between terrestrial operations and those for space resources, namely the environmental differences (low gravity, vacuum and no available water for transport and separation of particles), fault tolerance levels and system design. On Earth, processing operations are overseen by teams of operators, to resolve frequent interruptions in operation caused by the handling of large streams of slurry with variable feed properties. The flowsheets are typically complex, to enable one, or several, products to be produced to a target specification. For space resources, reliability and process simplicity must be taken into account, in addition to process optimisation.

## 1.2 Oxygen Production from Lunar Regolith

While over 20 technologies have been proposed for this step (Taylor and Carrier, 1993), the four main contenders being considered by NASA and ESA are (in order of increasing oxygen yield): Hydrogen reduction of ilmenite (<2% yield; Lee, 2013); carbothermal reduction of silicates and iron oxides (~10% yield; Muscatello and Gustafson, 2010); molten regolith electrolysis (estimated to be 20-40% yield, Schreiner, 2015); and, molten salt electrolysis, also known as the FFC Cambridge process (up to

100% recovery; Schwandt et al., 2012). Of these technologies, hydrogen reduction has received the most attention, and its working principles are well-characterised.

The hydrogen reduction of regolith is primarily dependent on the ilmenite content (Schwandt et al., 2012), according to the following reactions:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O \tag{1}$$

$$H_2\mathrm{O} \rightarrow H_2 + 0.5O_2 \tag{2}$$

While the FeO component of ilmenite is preferentially reduced, oxygen can also be extracted (with varying efficiencies) by the reduction of $\mathrm{TiO_2}$, plagioclase, olivine and pyroclastic glasses (Chambers et al., 1995).

Each hydrogen reduction reactor has been designed to operate with an ideal feed. There is, however, comparatively little research on how these feeds would actually be produced in situ, and how this would feed into the reactor. For example, a design patented by Gibson and Knudson (1996) requires a feed comprising 80-90 wt% ilmenite and ferrous agglutinates, sized to 20-200 μm, in order to operate at the highest oxygen production efficiency. While they do discuss the needs and requirements for magnetic, electrostatic and size separation steps, such technology has yet to be developed for lunar applications.

### 1.3 Regolith Variability

Lunar regolith contains around 40% oxygen, however this is bound in minerals. Of the minerals on the Moon, ilmenite ($\mathrm{FeTiO_3}$) is one of the most attractive for SRU applications, as it is relatively abundant, easily processed and has a high oxygen yield (Chambers et al., 1995). The maximum mass of $\mathrm{O_2}$ that can be produced for 1 kg of ilmenite is 105 g by stoichiometry; a theoretical maximum yield of 10.5%.

Two of the most significant uncertainties in the SRU flowsheet are the material properties and the spatial variability of the regolith. According to Schreiner, Dominguez et al. (2016), this has impeded the rigorous engineering design of reactors, transport mechanisms and excavation technologies. They collated thermo-physical properties of regolith, reporting average contents of $TiO_2$ of 8.5% for high-Ti Mare, 2.9% $TiO_2$ for low-Ti Mare and 0.5% for Highlands regolith. The Highlands regolith dominates the lunar surface, accounting for 84% of the nearside and 99% of the farside (Heiken et al., 1991). The bulk density of regolith lies between 1500 kg/m$^3$ for the top 15 cm to 1790 kg/m$^3$ at around 60 cm depth (Schreiner, Dominguez et al., 2016). It should be noted that the $TiO_2$ exists typically in the mineral form of ilmenite ($FeTiO_3$), however titanium dioxide content is often cited in the literature as an analogue.

Lunar simulant JSC-1A has a $TiO_2$ content of approximately 1-2% (Schwandt et al., 2012). Clark et al. (2009) describe a single field test that treated a JSC-1A sample in the PILOT hydrogen reduction system. The single successful trial produced close to 1% by mass water. This translates into a conversion of regolith to oxygen of 0.88%, assuming a 100% conversion and gas recovery during the subsequent water electrolysis. It is of interest that the experimental system was not straightforward and suffered numerous practical complications. It appears that at least some of these issues can be attributed to the large proportion of very fine particles in the feedstock.

The variability in the $TiO_2$ content of 17 lunar maria was reported by Sato et al., (2017), where the average was 3.9% $TiO_2$. The highest $TiO_2$ content was reported for Mare Tranquillitatis at 12.6%, with an average of 6.4% $TiO_2$. The authors highlighted that many of the maria had $TiO_2$ levels below the detection limit (~2%), and also that there was great variability. It is suggested that older maria have greater variability.

A comprehensive petrological and geochemical study of 12 particles from the Apollo 12 soil samples is presented in Alexander et al. (2014). The samples are all of low-Ti basalts (i.e. 1-6% $TiO_2$), with an ilmenite content ranging from 0.2% to 7.3%.

The variability of the feedstock, and the subsequent effect on processing, is a feature of both terrestrial and space resource extraction. The estimation of mining and extraction rates can therefore be performed in two ways. First, by using the average properties of the regolith, a single estimate is obtained, and which can be altered by changing the process variables, such as particle sizing and decontamination to assess the range. Second, this can be repeated by taking also the regolith property variance into account and performing numerous Monte-Carlo simulations, where many estimates are made by repeatedly drawing from the property and variable distributions. This yields a confidence estimate for the predictions, which is useful for mission-critical production of oxygen. Both these approaches will be used here.

### 1.4 Objectives

While a great deal of research effort has been allocated to the technologies that produce oxygen in situ, the feed preparation stage has generally been oversimplified or overlooked entirely. The preparation of a suitable feedstock for a given reduction process, hydrogen or otherwise, will directly impact the design of the reduction technology, and will govern the scale of the mining operation itself.

Here, we consider two lunar oxygen production facilities, each capable of generating 1000 kg/y of oxygen via a hydrogen reduction process. The first uses a regolith run-of-mine feedstock that has been well characterised, and the second uses a variable feedstock with regolith from various locations. For each of these facilities, the impact of feed preparation, namely sizing and decontamination, on the overall scale of the mine are evaluated.

## 2 METHODOLOGY

The estimation of the scale of a mine depends on a number of variables. For lunar applications, the estimation equations are most appropriately scaled to the mass rate of oxygen required.

The fraction of time that the complete oxygen production operation is in production is called the *operational availability* and must be taken into account when estimating the regolith mining mass rate required and the feedstock mass rate required to the oxygen extraction process. Operational availability will depend on, for example, the availability of energy, light, temperature limitations and shift working practices.

The oxygen extraction process treats a feedstock. This feedstock is the product from the beneficiation stage (Figure 1). If there is no beneficiation stage, the oxygen extraction feedstock is the same as the mined regolith.

The mass rate of feedstock required (kg feedstock/h) for oxygen extraction can be estimated from the mass rate of oxygen required (kg oxygen/h), divided by the yield of oxygen from the feedstock (kg oxygen/kg feedstock) and the operational availability:

$$Mass\ rate\ of\ feedstock = \frac{Mass\ rate\ of\ Oxygen}{(Oxygen\ Yield * Operational\ Availability)} \tag{3}$$

The mined regolith may be beneficiated, for example, to remove first particles that are too fine and too coarse, and subsequently, specific deleterious components such as agglutinates. The removed material is the regolith waste. The mass rate of mined regolith required to meet the required feedstock mass rate is determined by the fraction of the mined regolith that is not removed by beneficiation.

$$Mass\ rate\ of\ mined\ regolith\ = \frac{Mass\ rate\ of\ feedstock}{(1 - Mass\ fraction\ of\ regolith\ waste)} \tag{4}$$

These two equations can be extended to include any beneficiation processes, for example that may be mineral specific, or using different operational availabilities for the mining and beneficiation and oxygen extraction stages.

In order to estimate the mining scale for lunar oxygen production from regolith, the efficiency of the reactor and the resultant yield of oxygen must be considered, but also the effect of beneficiation on the mining rate required, the oxygen yield, and the operational availability.

Previous studies have addressed several of these aspects in their mine scale estimations (for example Linne et al., 2015 and Williams et al., 1977). Linne et al. (2015) consider that 1000 kg of oxygen will be required annually in an early outpost for life support closure only (as did Lee, Oryshchyn et al. 2013), and as much as 10 000 kg oxygen per year to supply a full scale, permanent site.

Linne et al. (2015) estimate the mining scale required based on 1000 kg/y of oxygen and assume that the full mined regolith can be used in a hydrogen reduction process, as Clark et al. (2009) tested experimentally on JSC-1A. As noted, this may cause significant operational problems and system reliability and efficiency are likely to improve with a feedstock from which has removed both the very fine and coarse particles. Further, Linne et al. (2015) assume that the oxygen yield from maria is 4%. The $O_2$ yield is a most important variable in determining the mine scale, as shown in Equation 3. Considering the average mare $TiO_2$ content was found to be 3.9% (Sato et al., 2017), 4% $O_2$ yield is a relatively high estimate (Chambers et al., 1995). Linne et al. (2015) also assume a 70% available operation time, based on a solar-power-driven outpost near the southern poles with up to 90% daylight. Using 4% oxygen yield and 70% operational availability, this yields a required feedstock mass rate of 4.1 kg/h (Equation 3). Since un-beneficiated regolith is used as the feedstock, the mined regolith mass rate is also 4.1 kg/h (Equation 4).

Williams et al. (1977) quantify the efficiencies required of theoretical beneficiation stages by specifying the mineralogical content (% $TiO_2$) of both the mined regolith (13% $TiO_2$) and that of the oxygen extraction feedstock (48.1% $TiO_2$). Williams et al. (1977) estimate a working year of 3700 hours (42.2% operational availability). They assume an optimistic 8% oxygen yield, therefore requiring a feedstock mass rate of only 3.4 kg/h to produce 1000 kg $O_2$ annually (Equation 3). A mass balance shows that to increase the $TiO_2$ concentration 3.7 times from mined regolith to feedstock requires 73% of the mined regolith tonnage to be rejected as waste. Their predicted required mined regolith rate is therefore 12.6 kg/h (Equation 4).

As noted previously, the mined regolith and oxygen extraction feedstock mass rate estimates here are all scaled to the same required oxygen mass rate of 1000 kg/y or 0.114 kg oxygen/h.

The estimated 12.6 kg/h regolith mined mass rate of Williams et al. (1977) is almost double the 6.8 kg/h of Linne et al. (2015), at an equivalent 42.2% operational availability. However, as a result of the increase in oxygen yield from regolith beneficiation, the Williams et al. (1977) oxygen extraction feedstock mass rate is only 3.4 kg/h. This has tremendous implications for the design of the complete oxygen production flowsheet, from mine to oxygen product. In particular, halving the required furnace capacity has significant energy and mass benefits, but these may be offset by the large increase in the required mine scale.

It is evident that the impact of regolith beneficiation on oxygen production must be examined in greater detail.

This study estimates the oxygen extraction and regolith mining scales required to produce 1000 kg/y of oxygen, considering:

- Regolith particle sizing, and the effect of removing the fine and coarse materials that are likely to cause blockages, material handling issues and dust.
- Regolith decontamination.
- Oxygen yield from regolith (conversion efficiency).
- Operational availability.

# 3 MINE SCALE ESTIMATION: SPECIFIC REGOLITH COMPOSITION

The first estimations establish the mine scale for a given specified feedstock that takes into account variation in the beneficiation stage and oxygen yields.

As an exemplar of a mined lunar material that could be used as a feedstock, consider sample 71061,1, which is regarded as a typical Apollo 17 mare soil (Heiken, 1975). The soil property data were collated into a number of size classes and component classes to highlight the key groups that will be considered.

It is highly likely that some regolith pre-treatment will be required to reduce operational problems primarily associated with dust and abrasiveness. These pre-treatment (beneficiation) stages will reduce the mass of feedstock available for oxygen production, and therefore increase the required mine scale.

**Table 1: Collated properties of lunar sample 71061,1, data from Heiken (1975), converted from volume % to weight %. Note that material coarser than 10 mm constitutes 9.4% of the sample mass, all of which is assumed to be basaltic.**

| | **SIZE (μm)** | **<45** | **45-90** | **90-1000** | **1000-10000** |
|---|---|---|---|---|---|
| | Total Mass Fraction | 30.2% | 11.4% | 26.2% | 22.8% |
| Mass Fraction (in size range) | Agglutinates | 12.0% | 9.9% | 6.9% | 0.0% |
| | Glass | 0.0% | 23.8% | 13.3% | 0.0% |
| | Basalts | 0.0% | 13.0% | 41.5% | 100.0% |
| | Breccia | 0.0% | 3.5% | 6.9% | 0.0% |
| | Other minerals | 0.0% | 39.6% | 26.4% | 0.0% |
| | Ilmenite | 0.0% | 8.6% | 4.7% | 0.0% |
| | Other material | 88.0% | 1.6% | 0.3% | 0.0% |

## 3.1 Particle Size

It will be necessary to remove material that is either too coarse or too fine, to reduce possible blockages, equipment damage and dust issues during materials handling and oxygen extraction. The regolith material greater than 1 mm constitutes 32.2% (22.8% is 1 mm to 10 mm and 9.4% greater than 10 mm) of the total mass (Table 1). It is considered difficult to size efficiently dry particles below 90 μm (Kelley, 2007), and this is considered the minimum size that can be processed. The material finer than 90 μm constitutes 41.6% of the total mass.

From Table 1, it can be seen that removing both the coarse (>1 mm) and fine (<90 μm) fractions eliminates 73.8% of the mined regolith as waste and leaves only 26.2% of the mass for further processing. The process step of sizing alone will increase the mine scale almost fourfold from mine scale estimates that propose utilising the full regolith size distribution.

## 3.2 Decontamination

Agglutinates are considered the most abrasive part of the feedstock and should not be handled extensively, as it will rapidly cause extensive equipment wear. Furthermore, the glass fraction is likely to cause issues in the high-temperature furnace due to sintering (Allen et al., 1994). It is considered possible theoretically to remove both the agglutinates and glass particle types selectively by using shape-selective techniques, however these are yet to be developed.

Using the data in Table 1, agglutinate decontamination will reduce by a further 6.9% the sized regolith mass available for oxygen extraction. Pre-sizing the mined material and then removing the agglutinates reduces the proportion of mined regolith available for oxygen production to 24.4% of the total mined mass. Removing also the glass fraction (13.3%) will reduce the useable part of the regolith to 20.9% of the total mined regolith.

An additional benefit of sizing and removing both glass and agglutinates is that the ilmenite content is increased from 2.2% in the full size distribution up to 5.9% in the remaining sized and decontaminated fraction. The effect on the mass fraction remaining and the ilmenite proportion can be estimated by assuming a perfect separator that removes only non-ilmenite minerals, as shown in Table 2.

**Table 2: The effect of increasing the ilmenite content from 4% to higher values on the mass fraction of mined regolith available for oxygen extraction by removing additional constituents from the 90-1000 μm fraction.**

| **Components Removed** | **Ilmenite content** | **Remaining Mass %** |
|---|---|---|
| Agglutinates | 5.0% | 26.0% |
| Glass + Agglutinates | 5.9% | 20.9% |
| Glass, Agglutinates + Basalts | 12.2% | 10.0% |
| Glass, Agglutinates, Basalts + Breccias | 14.9% | 8.2% |

It can be noted that the effect of selective mineral upgrading on the mine scale is significant, and that even a modest doubling of the proportion of ilmenite in the feedstock for chemical extraction (from 5.9% to 12.2%, for example) will halve the mass remaining as feedstock (from 20.9% to 10.0%) and therefore double the mine regolith mass rate required. The impact of the ilmenite content on the oxygen yield must therefore be very significant to offset the increase in the amount of regolith that will be required.

We will not consider further in this paper the effect on the mine scale of selectively upgrading specific minerals.

### 3.3 Operational Availability

As mentioned, Linne et al. (2015) estimate and use a 70% operational availability of the mining and extraction operations. They consider the use of solar energy that is supplied from an outpost located near the southern pole with up to 90% daylight. This places a significant constraint on the mine location. Williams et al. (1977) estimate a 3700 h work year based on the lunar day/night cycle, a loss of two shifts in each lunar day, and 7.5 production hours per 8 h work period. This corresponds to 42.2% operational availability and has been considered as the baseline in this study.

### 3.4 Mine Scale

NASA's ROxygen demonstration reactor, for example, employs hydrogen reduction. Experiments on small-scale reduction systems showed the yield of $O_2$ produced from lunar regolith simulant to be 1-2% (Lee, Oryshchyn et al., 2013). The authors noted that at temperatures of over 800 $^{\circ}$C, clumping of regolith particles was observed, which may result in improper mixing and sintering, fouling permanently the reactor. In larger-scale experiments, the $O_2$ yield was 0.2-0.5% by mass; the decrease in yield was attributed to issues associated with scaling the benchtop design, in particular with the heat transfer to the reactor.

As noted by Linne et al. (2015), maximum yields of 2% to 4% oxygen mass to regolith mass have been demonstrated for high-iron mare soils (McKay and Allen, 1996). The $O_2$ yield given a particular grade of ilmenite in the feed is arguably the greatest unknown in the reduction process, thus a range of values are considered here.

The experimental hydrogen reduction results of Allen et al. (1994) for various lunar soil samples were published originally as the weight-% of $Fe^{2+}$ and the oxygen yield. The results include the allocation of

$Fe^{2+}$ to different feed constituents, including ilmenite. Figure 2 provides an interpretation of those data in terms of ilmenite grade versus oxygen yield.

It has been assumed that the data follow a linear trend for total oxygen production versus grade, as was used by Chambers et al. (1995), and is shown on Figure 2. There is significant scatter, however additional, comparable data of oxygen yield versus ilmenite grade for the hydrogen reduction of lunar regolith (or simulants) are not readily available.

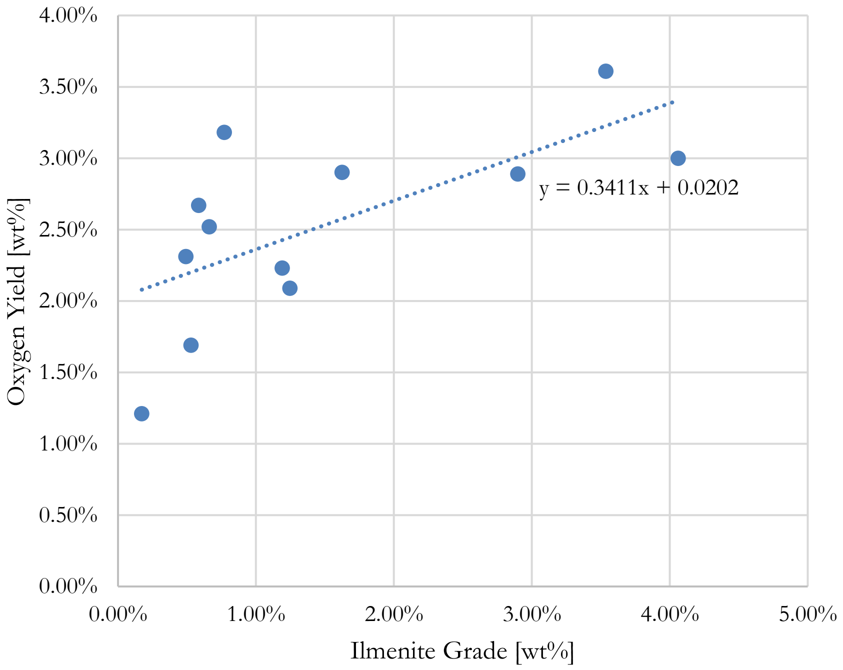

**Figure 2: Oxygen yield from a given grade of ilmenite in a hydrogen reduction cell. Adapted from Allen et al. (1996).**

Table 3 presents the expected mine scale based on the data and equation derived from the experimental work of Allen et al. (1996, Figure 2) and the degree of beneficiation as presented in Table 2. While this method is approximate, this analysis does highlight the appreciable impact of $O_2$ yield on the capacity and throughput of the reduction technology, and the scale of the required mining operation.

**Table 3: Analysis of mine scale for an annual output of 1000 kg $O_2$ as a function of ilmenite grade and oxygen yield, showing also the feedstock rate to the reduction process. Note that following the 'As Mined' data, the remaining data assumes the feed has also been sized to the 90-1000 μm fraction.**

| | | | Linear Approximation from Allen et al. (1996) | | | |
|---|---|---|---|---|---|---|
| **Components Removed** | **Ilmenite Grade [wt%]** | **% of Mined Material Remaining after Beneficiation** | **Oxygen Yield [wt%]** | **Total Regolith Required [t/year]** | **Mining rate required [kg/h]** | **Reduction process rate [kg/h]** |
| As Mined (no sizing) | 2.2% | 100.0% | 2.77% | 36 | 9.8 | 9.8 |
| Agglutinates | 5.0% | 26.0% | 3.73% | 103 | 27.9 | 7.3 |
| Glass + Agglutinates | 5.9% | 20.9% | 4.03% | 119 | 32.1 | 6.7 |
| Glass, Agglutinates + Basalts | 12.2% | 10.0% | 6.18% | 162 | 43.7 | 4.4 |
| Glass, Agglutinates, Basalts + Breccias | 14.9% | 8.2% | 7.10% | 172 | 46.4 | 3.8 |

It is notable from Table 3 that beneficiation of the regolith to increase the ilmenite content increases significantly the mined tonnage rate required, but reduces also the feedstock mass rate for the reduction process. This is an important trade-off that has not been considered in detail previously. An oxygen-producing reduction furnace treating less than half a kilogram per hour of high-grade, sized feedstock will be smaller, lighter and less energy intensive than one treating a kilogram per hour of unsized regolith. The associated mining and beneficiation processes must handle a five time greater tonnage rate, although probably at a lower energy intensity and technical complexity. This is a complex technical and economic trade-off.

The mining rates estimated in Table 3 can be compared with previous studies. Linne et al. (2015) estimate a mining rate of 6.8 kg/h at 42.2% operational availability and 4% oxygen yield. The mine scale required when first removing the glass and agglutinates is almost five times higher (32.1 kg/h), while the oxygen extraction feedstock rate is, of course, the same.

Williams et al. (1977) estimate a mining rate of 12.6 kg/h at 42.2% operational availability and 8% oxygen yield. To upgrade the $TiO_2$ fraction, they reject 73% of the mined material as waste, an amount comparable to sizing the regolith and removing the agglutinate fraction. They assumed, however, an 8% yield from the hydrogen reduction step. With a lower $O_2$ yield (3.73%), their mining rate is less than half the estimate (27.9 kg/h) in Table 3.

It is of interest that the required mining mass rate increases linearly, while the required oxygen production feedstock mass rate decreases linearly (Figure 3), since the $O_2$ yield has been linearly correlated to the feedstock $TiO_2$ content. This implies that reducing the oxygen production feedstock mass rate by increasing the feedstock $TiO_2$ content will also increase linearly the required mining rate. This allows optimisation of the power, mass and design of the oxygen extraction flowsheet.

It is evident from these estimates that the required lunar mining mass rate, for even limited oxygen production, may be significant. The mine mass rate depends on the combination of assumptions made about the regolith size range used, any decontamination or selective upgrading and the operational availability. There is also a balance between the oxygen extraction feedstock mass rate and the mining mass rate that allows optimisation.

In the following section, a statistical estimation will be used to estimate the confidence levels in the required feedstock rate and mining rate to produce 1000 kg/y oxygen.

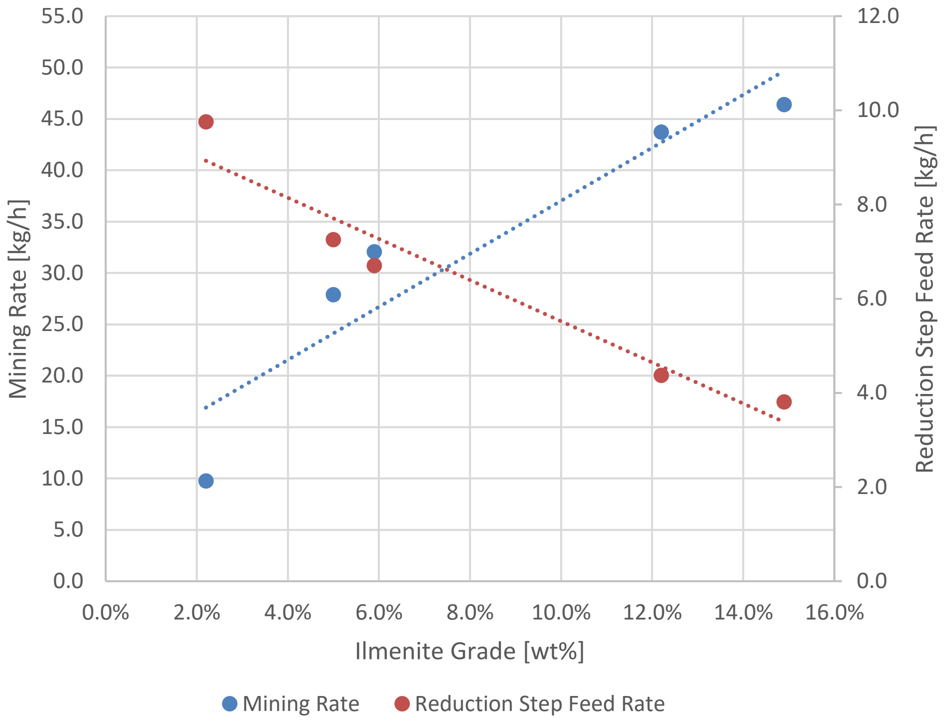

**Figure 3: Regolith mining mass rate and reduction step feed rate versus ilmenite grade.**

# 4 MINE SCALE ESTIMATION: VARIABLE REGOLITH COMPOSITION AND OPERATING CONDITIONS

In the calculations above, the very specific properties of lunar regolith sample 71061,1 were used to estimate the mine scale. The size distribution and proportion of agglutinates varies across the Moon, however. In order to estimate more comprehensively the range of mine scales that are likely, Monte-Carlo simulations were performed, using a range of values and their distributions.

Monte-Carlo simulations make repeated, random draws from known distributions of variables and combine them to make a prediction. This is repeated a large number of times to generate a probability distribution of the likely outcome. The results can be interpreted as the confidence that can be placed in the predicted value.

## 4.1 Particle Size

The size range between 90 μm and 1 mm is well characterised for many lunar samples. It is also considered to be a range likely to reduce operational problems caused by very fine or coarse regolith.

The mass fraction of regolith between 90 μm and 1 mm was estimated from distributions compiled by Phinney et al. (1977), and Heiken et al. (1991) for the Apollo samples. They note that some statistical descriptions can be made, and that most mean grain sizes fall between 45 and 100 μm.

Interpolating from the graphical lunar soil size distributions reported (Phinney et al., 1977), the fraction of regolith in the 90 μm to 1 mm size range varies from approximately 36% to 48%, or an average of 42% ±6%. For the Monte-Carlo simulations, it is assumed that the distribution of the mass fraction of regolith between 90 μm and 1 mm is normal and that the 6% mass range describes ±2 standard deviations (encompassing 95% of the sample means).

## 4.2 Agglutinate Decontamination

Heiken et al. (1991, Table 7.2) report the volume percent of agglutinates for the 90 μm to 1 mm material for fourteen lunar samples, representative of each Apollo mission. The data was collated and the average and standard deviation were calculated. Since the density of each component reported was not known, the mass and volume percentages were considered equivalent.

An average of 66.6% of the total mass of the 90 μm to 1 mm fraction remained after agglutinate decontamination, with a standard deviation of 12.6%. The distribution of values is assumed to be lognormal to eliminate negative values.

## 4.3 Operational Availability

The operational availability estimate of 42.2% by Williams et al. (1977) was used as the mean of a lognormal distribution. Without any further knowledge of the lunar operating conditions, a standard deviation of 2.5% was assumed.

### 4.4 Oxygen Yield

The data from Allen et al. (1996) were used as the basis for the oxygen yield. The data in Figure 2 and the linear regression indicate a relatively weak dependence of oxygen yield on ilmenite content. For the Monte-Carlo simulations the ilmenite content is not considered as a variable, and the average and standard deviation of the oxygen yield are from the experimental values reported by Allen at al. (1996).

The mass of oxygen per mass of regolith into the reduction process was therefore assumed to have a mean of 2.5% and a standard deviation of 0.7%, lognormally distributed to eliminate negative yields.

Table 4 summarises the assumptions made for all the variables considered in the Monte-Carlo simulations.

**Table 4: Summary of Monte-Carlo variables and distributions.**

| Variable | Average | Standard Deviation | Distribution | Reference |
|---|---|---|---|---|
| Size mass fraction (90-1000 μm) | 42.0% | 3.0% | Normal | Clark et al. (2009) |
| Fraction post agglutinate removal | 66.6% | 12.6% | Lognormal | Heiken et al. (1991, Table 7.2) |
| Oxygen yield | 2.5% | 0.7% | Lognormal | Allen et al. (1996) |
| Operational availability | 42.2% | 2.5% (approx.) | Lognormal | Williams et al. (1977) |

### 4.5 Mine Scale

The mine scale estimated directly from the mean values of all the variables in Table 4 yields an estimate of approximately 40 kg/h of regolith to be mined to produce 1000 kg/y $O_2$. This corresponds well with the regolith mass rate estimated for lunar sample 71061,1 above, which yielded an estimate of 57.5 kg/h, for a slightly lower (2%) oxygen yield.

The Monte-Carlo simulations were run 10000 times. First, each variable was varied individually, to assess the magnitude of its effect and to determine which variable had the largest influence on the range of estimates.

A simulation output is shown in Figure 4Figure 5 and Figure 5, where all the four variables were randomly sampled simultaneously. The figures show the results in two ways, as fractional and cumulative probabilities. The fractional probability shows the shape of the probability distribution of the predicted regolith mining rate required (kg/h). The most likely rate is 40 kg/h, which corresponds to using the means of all the variables. There is a long tail of predictions of high mining rates. Figure 5 shows the confidence that can be placed in the predictions. There is only a 47% confidence that a 40 kg/h mining rate will produce 1000 kg per year of oxygen, but a 90% confidence that a regolith mining rate of 63.9 kg/h will deliver the required $O_2$ rate.

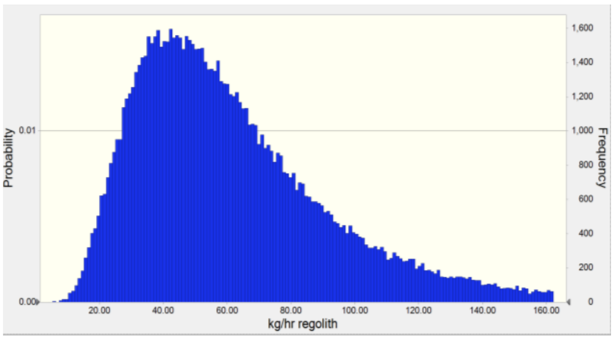

**Figure 4: The range of estimates of mining scale for varied regolith properties, operational availability and $O_2$ yields**

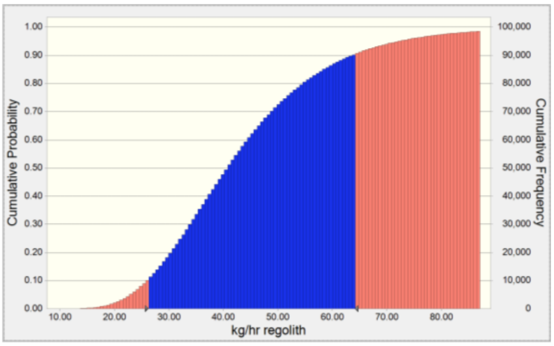

**Figure 5: The mining scale for varied regolith properties, operational availability and $O_2$ yields as a cumulative frequency of estimates**

The results taken from the simulation of each variable individually, and all variables simultaneously are summarised in Table 5.

**Table 5: Summary of Monte-Carlo results for the variables in Table 4 individually and combined, showing the cumulative fraction of estimates.**

| | **Confidence in Estimation of Mining Rate (kg/h)** | | | |
|---|---|---|---|---|
| **Variable** | **10%** | **25%** | **75%** | **90%** |
| Size mass fraction (90-1000 µm) | 30.9 | 34.7 | 44.7 | 50.0 |
| Fraction post agglutinate removal | 35.5 | 36.9 | 40.6 | 42.6 |
| Oxygen yield | 28.3 | 33.4 | 48.4 | 57.1 |
| Operational availability | 35.9 | 37.2 | 40.4 | 41.8 |

| | | | | |
|---|---|---|---|---|
| All variables simultaneously | 26.5 | 32.6 | 51.8 | 63.9 |

It can be observed that the interquartile range (25% to 75%) is widest for oxygen yield, and shows that gaining confidence in technology to produce, consistently, high yields of oxygen will significantly lower and narrow the mine scale estimates. Sizing, agglutinate removal and operational availability produce similar interquartile estimates. This highlights the importance of quantifying the performance of the hydrogen reduction process, and its performance variability to varying feedstock properties.

When designing a lunar oxygen production facility on which will depend the survival and transport of humans, a high confidence level of adequate scale is essential. For a 90% confidence that the mine rate will be adequate, a mine must be designed to produce at least 63.9 kg/h of regolith. This is almost double the estimate not taking the variance into account. For a 95% confidence, this increases to 72.6 kg/h. These Monte-Carlo simulation estimates are orders of magnitude greater than the bare minimum that is obtained from single point calculations without taking onto account the variance.

### 4.6 Hydrogen Reduction Scale

The scale of the reduction operation is also required to design the complete oxygen production flowsheet from mine to product. The average size distribution and agglutinate content for a range of lunar samples was used to calculate the mine rate. Comparable data for ilmenite content was not available to relate it to the oxygen yield and the latter was treated as an independent variable in the Monte-Carlo simulations to estimate the scale required of the reduction stage.

The average scale of the reduction operation to produce 1000 kg/y $O_2$ can be estimated from the mean values of the oxygen yield and the operational availability as 10.8 kg/h. This is in the range of values estimated for lunar sample 71061 in Table 3, but here not taking into account the effect of ilmenite concentration on the oxygen yield.

The Monte-Carlo simulation was run 10000 times. First, the operational availability and oxygen yield were varied individually to assess the magnitude of their effects and to determine which of these two variables had the largest influence on the range of estimates. Thereafter, they were varied simultaneously.

The results taken from the simulation of each variable individually and both simultaneously are summarised in Table 6.

**Table 6: Summary of Monte-Carlo results for the variables in Table 4 individually and combined, showing the cumulative fraction of estimates.**

| | **Confidence in Estimate of Reduction Rate (kg/h)** | | | |
|---|---|---|---|---|
| **Variable** | **10%** | **25%** | **75%** | **90%** |
| Oxygen yield | 7.9 | 9.3 | 13.5 | 16.0 |
| Operational availability | 10.1 | 10.4 | 11.3 | 11.7 |
| Both variables | 7.8 | 9.3 | 13.6 | 16.1 |

It can be observed that the interquartile range (25% to 75%) is widest for oxygen yield, and shows that gaining confidence in technology to produce, consistently, high yields of oxygen will significantly lower and narrow the reduction process scale estimates.

From the Monte-Carlo simulations under the assumptions made, there is a 90% confidence that a reduction rate of 16.1 kg/hr of feedstock, produced from sized and decontaminated regolith, will deliver the annual requirement of 1000 kg of $O_2$. This increases to 17.9 kg/h for a 95% confidence level.

# 5 IMPACT ON SRU FLOWSHEET

The mining rate estimates are significant. The estimated minimum lunar mining mass rate of 30 kg/h will require substantial infrastructure and logistics. If the range of possible values is considered, this rate is likely to be more than double to have sufficient confidence in the estimate, at least 65 kg/h.

The required mining mass rate determines whether the mineral sizing and decontamination can be performed in batches, or as a continuous process. This has very significant design implications. A batch process design may allow integration of mining and sizing equipment, so that the majority of the unwanted material is rejected at the mining stage. This will reduce significantly the tonnages that must be transported from the mine to the centralised beneficiation and extraction points. Continuous operation may require satellite operations to prepare the feedstock, which is then transported, possibly to a single extraction point. In both cases, operation may have to pause during the lunar night.

The specific details of the process engineering clearly depends significantly on the regolith tonnage rate that has to be mined, sized, beneficiated and transported.

Considering the reduction stage to produce oxygen, there is evidence that the oxygen yield is enhanced when the ilmenite concentration in the feedstock is increased. This is an effect of sizing and agglutinate decontamination of the mined regolith, but can also be further enhanced by mineral beneficiation. This reduces significantly the mass scale of the reduction process, but increase the mined tonnage required. This aspect of the overall oxygen production flowsheet will require significant further investigation, as the relative scales will require optimisation to determine the most efficient combination.

# 6 CONCLUSIONS

This study has produced a range of possible values for the lunar regolith mining rate required. Estimates were based on data from lunar samples, and reasonable assumptions from terrestrial mining and the hydrogen reduction extraction process.

The estimated minimum mining rate required is approximately 30 kg/h, which is as much as five-fold higher than previous estimates. Monte-Carlo simulations were performed to take into account uncertainty in the values. These indicated that to have 95% confidence that adequate $O_2$ will be produced, the required mining mass rate is likely to be as high as 65 kg/h. The mining mass rate is important for process design, as at some point the beneficiation process may be more efficient if designed as a continuous rather than batch operation.

The impact of ilmenite content on oxygen yield is significant, as it determines both the increase in the mine tonnage required and the decrease in tonnage to be treated during the reduction stage. More accurate estimates can be made once there is greater confidence in the oxygen yields from various beneficiated feedstocks, as well as the requirements of alternative reduction processes. This is probably the source of the greatest uncertainty, and which can only be reduced by further experimentation.

In the mining scale estimate above, no allowance has been made for activities such as preparing the mine area by removing boulders, smoothing out small craters and preparing roadways. It is estimated that such activity could add a significant burden to the mining tonnages that must be planned for.

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