



# The production of oxygen and metal from lunar regolith

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## ABSTRACT

The present article summarises the various methods that have been, and still are, explored for the production of oxygen from lunar materials. These include the classical concepts based on chemical reduction with hydrogen or methane, vapour phase pyrolysis, sulphuric acid treatment, and molten oxide electrolysis. Our main focus in this paper is on a novel approach developed at the University of Cambridge that employs molten salt electrochemistry to achieve the combined winning of oxygen and metal from solid lunar materials of varying composition. This makes the Cambridge process attractive because it will work equally well in mare as in highland regions. We also discuss the implications of the recent apparent discovery of water ice at the poles of the Moon and conclude that, even if this discovery is confirmed, it will nevertheless be desirable to provide oxygen at non-polar localities, and the Cambridge process is a strong candidate for achieving this.

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## 1. Background and introduction

An extended human presence on the Moon is likely to be beneficial for both scientific and economic reasons (e.g., Spudis, 1996, 2005; Crawford, 2004; Crawford et al., in this issue). It is clear that this aspiration will need to be supported through significant progress in in-situ resource utilisation (ISRU) (e.g., Taylor and Carrier, 1993; Baird et al., 2003; Sen et al., 2005; Anand et al., in this issue). In an effort to prepare for a return to the Moon in the foreseeable future, as well as to enable further space travel to Mars, NASA defined a set of specific targets (NASA, 2007a, 2007b). These include the identification and characterisation of lunar resources; the demonstration of ISRU concepts, technologies and hardware; the use of the Moon for operational experience and mission validation for Mars; the development and evolution of ISRU capabilities to enable lunar exploration; and the use of ISRU for space commercialisation.

The most important goal of ISRU is arguably the generation of oxygen from lunar materials so that human life may be sustained long-term and an oxidant for rocket fuel may become available (e.g., Taylor and Carrier, 1993). Producing oxygen on the Moon,

instead of supplying it from Earth, would give rise to massive cost savings, and NASA specified its initial target as the annual production of 5 t of oxygen by the year 2022. Another key aspect of ISRU is the production of metals from lunar materials so that a lunar infrastructure may be established. It would hence be advantageous to have a process that allows for the production of both oxygen and metal.

The objective of the present article is to summarise and assess the main methods that have been under consideration for the extraction of oxygen from lunar materials. The classical concepts of hydrogen and methane reduction, vapour phase pyrolysis, sulphuric acid treatment, and molten oxide electrolysis are briefly reviewed; and a novel process developed at the University of Cambridge is described in some detail which employs molten salt electrochemistry to win oxygen and metal simultaneously from solid lunar feedstocks.

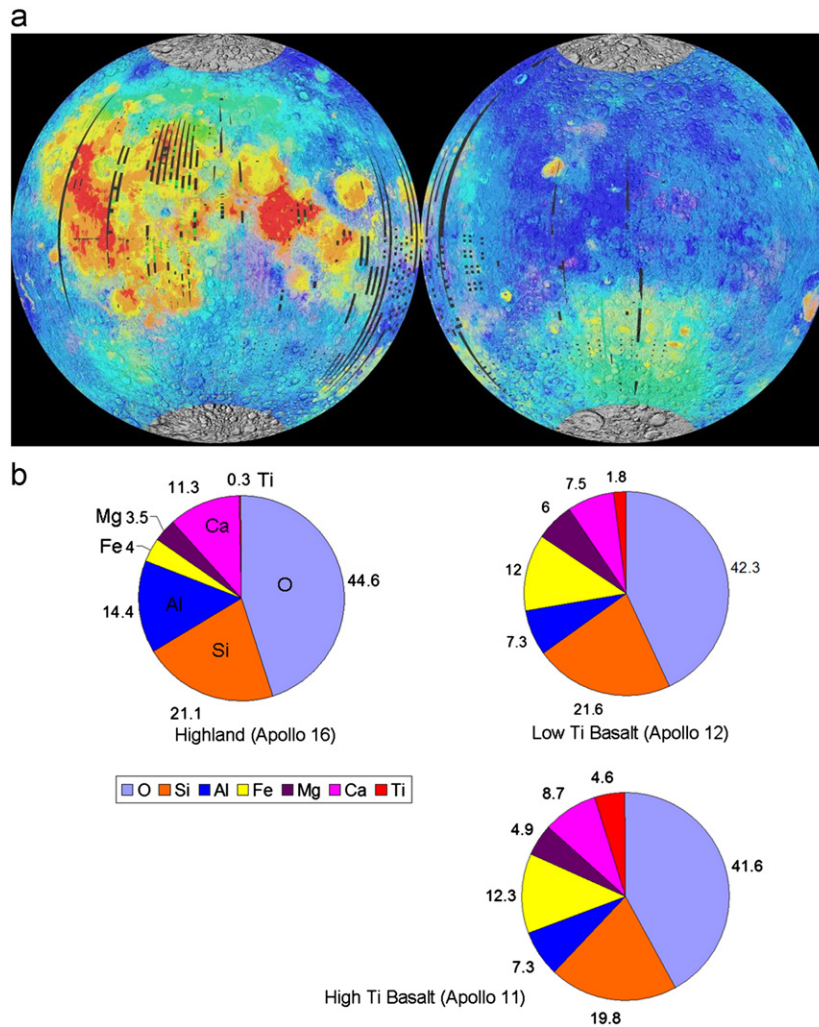
## 2. Lunar geology

The surface of the Moon consists of two main geological units. One is the ancient, light-coloured lunar highlands; the other is the darker, lunar mare ('seas') filling the large impact basins located mainly on the nearside. The chemical compositions of the lunar regolith occurring in these units have been derived from soil samples taken in the Luna and Apollo missions as well as from

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**Fig. 1.** (a) Distribution of rock types on the nearside (left) and the farside (right) of the Moon. Blue: anorthositic highlands; yellow: low-Ti basalts; red: high-Ti basalts. The large yellow/greenish area in the southern hemisphere of the farside is the South Pole-Aitken Basin, and the colours mostly reflect the more Fe-rich nature of the lower crust exposed by the basin rather than basaltic material (Spudis et al., 2002; image courtesy of Paul Spudis). (b) Chemical compositions of lunar highland minerals (Apollo 16), low-Ti basalts (Apollo 12), and high-Ti basalts (Apollo 11). (Diagrams based on data from Stoesser et al. (2010)).

remote sensing measurements (Heiken et al., 1991; Jolliff et al., 2006). The compositions are summarised in Fig. 1.

The lunar highlands are composed of predominantly anorthositic rocks and contain more than 90% by mass plagioclase in the form of calcium-based anorthite ( $\text{CaAl}_2\text{Si}_2\text{O}_8$ ) and small quantities of magnesium- and iron-bearing minerals such as pyroxene ( $(\text{Mg,Ca,Fe})\text{-SiO}_3$ ) and olivine ( $(\text{Mg,Fe})_2\text{SiO}_4$ ); and the lunar mare is composed of basaltic lava flows which contain varying proportions of plagioclase, pyroxene and olivine as well as ilmenite ( $\text{FeTiO}_3$ ) (e.g., Heiken et al., 1991). Depending on whether the titanium dioxide ( $\text{TiO}_2$ ) content in the basalts is above or below 6% by mass, these are further subdivided into ‘high-Ti’ and ‘low-Ti’ (Neal and Taylor, 1992).

ISRU studies are usually performed with geochemical simulants for lunar regolith. Simulant JSC-1 (NASA, 2005) has a composition approximating that of the lunar mare samples, and the more recent simulant NU LHT (NASA, 2008; Stoesser et al., 2010) has a composition approximating that of the anorthositic highlands. Other factors in the design of lunar simulants are the particle size distribution, the extent of particle agglomeration, and the content of glassy phase. The compositions of the two simulants are given in Table 1.

The south polar highlands in the vicinity of the Shackleton crater are considered to be an ideal location for the return to the Moon. This area provides almost permanent daylight throughout the year,

**Table 1**

Chemical compositions of lunar simulants JSC-1 (NASA, 2005) and NU LHT (NASA, 2008). Composition ranges are given for JSC-1 to reflect the slightly varying specifications for this material.

Oxide	JSC-1, % by mass	NU LHT, % by mass
$\text{SiO}_2$	46–49	46.7
$\text{Al}_2\text{O}_3$	14.5–15.5	24.4
$\text{CaO}$	10–11	13.6
$\text{MgO}$	8.5–9.5	7.9
$\text{Na}_2\text{O}$	2.5–3	1.26
$\text{K}_2\text{O}$	0.75–0.85	0.08
$\text{TiO}_2$	1–2	0.41
$\text{MnO}$	0.15–0.20	0.07
$\text{FeO}$	3–4	–
$\text{Fe}_2\text{O}_3$	7–7.5	4.16
$\text{Cr}_2\text{O}_3$	0.02–0.06	–
$\text{P}_2\text{O}_5$	0.6–0.7	0.15

which is favourable for both illumination and generation of solar electricity, and will thus facilitate extended periods of residence. The south polar highlands are predominantly of an anorthositic nature (Spudis et al., 2008), and this impacts on the selection of a suitable ISRU process.

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