The Metalysis-FFC-Cambridge process for the efficient production of oxygen and metals on the lunar surface.
B. A. Lomax[1], M. Conti[2], N. Khan[2], M. D. Symes[1]; [1]University of Glasgow, UK; [2]Metalysis, UK.

Introduction: Oxygen will undoubtedly be one of the most valuable resources in a self-sustaining space economy. As the largest weight component of any bi-propellant rocket, an efficient and plentiful source of liquid oxygen (LOX) on the lunar surface would reduce the reliance on mass transported from Earth. In-space lunar refueling would impact not only lunar surface operations, but also activities in cis-lunar space, and deep-space missions.

While evidence is growing for ice deposits in the permanently shadowed craters at the lunar poles [1], the form, quantity, and accessibility of this resource remains unknown. The lunar regolith, on the other hand, is ubiquitous across the entire lunar surface and contains 40-45 wt% oxygen. Additionally, the lunar regolith contains a range of other elements that can be used to produce useful metals and alloys in-situ. Developing a single process that can efficiently extract the oxygen from regolith and produce useful materials will have a significant impact on the space resource economy. In this scenario, a process capable of both could operate synergistically with water extraction operations, should the lunar ice deposits prove to be a viable resource for oxygen. Furthermore, technology developed on the lunar surface that can produce metals and alloys is applicable to future Mars mission architectures, where processes that only produce oxygen become redundant in favor of simpler methods utilizing the Martian atmosphere.

The FFC-Cambridge process: The Fray-Farthing-Chen (FFC)-Cambridge Process has been suggested as an efficient method for the production of both oxygen and useful materials from lunar regolith. The FFC-Cambridge process was invented at the end of the 1990s as a direct electrochemical method for producing metals from the corresponding metal oxides in molten salt [2]. At temperatures where the $CaCl_2$ salt is molten and can facilitate the transport of ions, approximately 900 °C, the metal oxide feedstock remains in the solid state throughout the entire process.

The metal oxide, which in the past has been in the form of a sintered pellet, forms the cathode and is electrochemically deoxidized to produce metal and oxygen ions:

$$\text{Cathode: } MO_x + 2xe^- \rightarrow M + xO^{2-}$$

In the terrestrial context, a carbon-based anode facilitates the removal of oxygen from the system in the form of carbon dioxide and carbon monoxide. In the lunar context an inert anode can be employed to directly produce oxygen:

$$\text{Anode: } 2O^{2-} \rightarrow O_2 + 4e^-$$

Some previous work has been done to investigate the reduction of lunar regolith using the FFC-Cambridge process [3]. The primary focus of this was the utilization of lunar ilmenite as a feedstock; however, this process is distinguished by the fact it has the ability to remove 100 % of the oxygen from lunar regolith in the solid state, regardless of composition. Additionally, in the early years of this technological innovation, many aspects that would be relevant to a large-scale lunar operation were not yet proven.

Recent developments: In the almost two decades since this novel process was first reported, significant progress has been made in developing this technology. Metalysis (UK) have successfully scaled-up and commercialized the production of a number of metals and alloys. Innovations in the process have been made to allow for the production of metal powders for additive manufacturing, aerospace and automotive applications directly from powder oxide feedstock.

Current work: The current research investigates the reduction of lunar regolith with the FFC-Cambridge process, applying the processing innovations of the Metalysis. Maximizing efficiency, in terms of quantity of oxygen extracted and the functionality of materials produced versus energy consumption and process complexity are key goals. The processing knowledge gained in the years of terrestrial technology development will inform the design of a process that has the ability to be scaled up and operate sustainably and autonomously on the lunar surface.

References: [1] Li, S et al. (2018) *PNAS, 115 (36)*, 8907-8912. [2] Chen, G. Z. et al. (2000) *Nature, 407*, 361-364. [3] Schwandt, C. et al. (2012) *Planetary and Space Science, 74*, 49-56.

Research Support: This research is supported by Metalysis and by ESA's Network/Partnering Initiative.