SUSTAINABLE OXYGEN EXTRACTION FROM LUNAR REGOLITH VIA MOLTEN SALT ELECTROLYSIS.

F. J. Guerrero-Gonzalez[1,2], Mateusz L. Donten[2,] and Philipp Reiss[1], [1]Technical University of Munich, Lise-Meitner-Str. 9, Ottobrunn, 85521, Germany, f.guerrero@tum.de, [2]Maana Electric SA, Foetz, 3895, Luxembourg.

Introduction: Molten Salt Electrolysis (MSE) has emerged as one of the most promising technologies for extracting oxygen and metals from lunar resources. The process relies on the electrochemical reduction of regolith minerals in a bath of molten salts at temperatures below 1000 °C. During electrolysis, metal cations are reduced at the cathode while oxygen anions migrate to the anode and are oxidized to gaseous O_2.

In contrast to thermochemical processing routes that typically target only specific compounds present in lunar regolith, MSE is largely landing-site agnostic, as it can electrochemically reduce the broad range of minerals contained in regolith [1]. Compared to other alternative processing routes, such as molten regolith electrolysis or vacuum-thermal decomposition, MSE operates at significantly lower temperatures, reducing energy demand and minimizing thermal wear on equipment.

Among different MSE approaches, Hall–Héroult (HH)-style electrolysis is particularly relevant. The HH process, originally developed for aluminum production from Al_2O_3, is based on the dissolution of oxides in molten fluoride electrolytes. Despite its already demonstrated potential as an industrial process, two major technology gaps remain before HH-style MSE can be transferred to lunar regolith processing. The first challenge is identifying fluoride electrolyte compositions suitable for sustainable operation. Electrolytes must remain stable over a wide electrochemical window so that all metal cations in regolith can be reduced without decomposing the salt itself. If this condition is not met, bath poisoning and accumulation of undesired species may occur, altering the thermophysical properties of the melt.

The second major challenge involves developing stable oxygen-evolving anodes. Conventional aluminum electrolysis relies on carbon anodes that are consumed during operation. In the context of space resource utilization, however, oxygen is the desired product. Therefore, the anode must remain chemically stable in harsh molten-salt environments while facilitating the oxidation of O^{2-} ions to O_2 gas.

Temperature strongly influences both technology gaps. High operating temperatures accelerate corrosion of candidate anode materials, while also affecting electrolyte stability and oxide solubility. Conversely, lowering the temperature can reduce thermal wear and energy demand but may also increase melt resistivity and reduce oxide solubility.

For this reason, understanding the role of temperature in both cathodic reduction and anodic oxidation processes is essential.

Cathodic reduction process: An important advantage of HH-style electrolysis is the ability to selectively deposit metals at the cathode. Such selectivity could replace extensive beneficiation and refining steps when targeting specific metals or alloys [2].

Silicon represents a relevant proof-of-concept metal for demonstrating this selectivity, given its abundance in lunar regolith.

We have evaluated the effect of temperature on the cathodic deposition of silicon in two fluoride electrolyte systems: FLiNaK and eutectic LiF–CaF_2. These salts are of interest because they provide electrochemical windows large enough to reduce all metal cations present in lunar regolith while having low melting points of 454 °C and 770 °C, respectively [2].

Electrolysis was performed over a temperature range of 700 °C to 1000 °C using lunar anorthosite simulants as feedstock. Since the melting point of silicon (1412 °C) exceeded the operating temperature of the electrolytes, Si was reduced at the cathode in the solid state, yielding cathodic products that typically appeared as porous metallic deposits. Such morphology is consistent with the solid-state nature of silicon deposition under these conditions. However, the deposited material was strongly influenced by temperature. Lower operating temperatures negatively affected deposition kinetics and silicon product quality.

Anodic oxidation process: Several classes of materials have been proposed as candidates for oxygen-evolving anodes, including metals and alloys, ceramic oxides, and cermets. However, material corrosion processes in molten fluoride environments, including oxidation, dissolution, and halogenation, remain major challenges. These degradation mechanisms are thermally enhanced at high temperatures. As a result, lowering the operating temperature is widely considered a key strategy for improving anode material durability [3].

Although noble metals have been typically disregarded as oxygen-evolving materials due to their excessive cost, they are a potentially viable alternative for extraterrestrial oxygen evolution. Gold has been demonstrated to evolve oxygen in fluoride melts [4] and be compatible with lunar regolith simulant electroreduction [5] at temperatures around 800 °C. Temperature constraints arise from this material choice since the melting point of gold is 1064 °C. The use of this material for oxygen evolution in molten fluoride systems must, therefore, operate far below this temperature limit to remain mechanically stable.

We have evaluated the effect of temperature on the degradation of oxygen-evolving gold anodes in similar fluoride electrolyte systems to those used in the cathodic deposition experiments. Electrolysis was also performed over a temperature range of 700 °C to 1000 °C using lunar anorthosite simulants as feedstock. The observations made during these experiments represent a necessary step toward defining operating conditions suitable for sustainable oxygen evolution in lunar regolith electrolysis.

Conclusion: For the cathodic reduction process, alkali (FLiNaK) and alkaline earth fluoride (LiF–CaF_2) eutectic electrolytes that provide electrochemical windows large enough to reduce all compounds present in regolith are preferred within the investigated temperature range. However, excessively lowering the operating temperature can negatively influence deposition kinetics and the quality of cathodic deposits.

For the anodic oxidation process, gold represents a pragmatic candidate for oxygen-evolving electrodes in early mission implementations. Gold is chemically simple, resistant to halogenation in fluoride melts, and has already been demonstrated to evolve oxygen in low-temperature molten-salt environments compatible with regolith electroreduction.

Overall, the operating temperature of HH-style electrolysis systems must be selected to remain compatible with both cathodic reduction and anodic oxidation processes. This requires identifying electrolyte compositions and operating temperatures that simultaneously support efficient metal deposition while maintaining the chemical stability of anode materials.

References: [1] Schlüter L. and Cowley A. (2020) *Planet. Space Sci., 181*, 104753. [2] Guerrero-Gonzalez F.J. et al. (2025) *ICES-2025-441*. [3] Padamata S. K. et al. (2023) *J. Electrochem. Soc., 170*, 073501. [4] Massot L. et al. (2007) *J. Electroanal. Chem., 606*, 17–23. [5] Maes M. (2024) *PhD Thesis*, Université Paul Sabatier Toulouse III.