HYDROGEN REDUCTION OF ILMENITE FOR THE PRODUCTION OF OXYGEN AND METALS FROM LUNAR REGOLITH: CURRENT RESEARCH AT ESRIC. D. Harries[1], A. Maulu[1], E. Scolan[1], T. Schild[1,2], A. Yerzhankyzy[1], K. Hadler[1], B. Lamaze[2], M. Conti[2], [1]European Space Resources Innovation Centre (ESRIC), Luxembourg Institute of Science and Technology (LIST), 41 rue du Brill, L-4422 Belvaux, Luxembourg (dennis.harries@esric.lu), [2]European Space Research and Technology Centre (ESTEC), European Space Agency (ESA), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands.

The production of oxygen and metals from the lunar regolith has been the focus of significant and growing research interest over the last 20 years. In-situ production of water and oxygen is seen as being the first critical step towards sustainable space travel, reducing the reliance on materials from Earth. Here, we focus on hydrogen reduction of lunar minerals to extract oxygen and produce metals and will update on ESRIC's current work and research objectives.

Reduction of the lunar regolith using hydrogen is one of several technologies proposed to extract oxygen bound in the minerals that make up the lunar surface – in this case mainly from ilmenite, $(Fe,Mg)TiO_3$ [e.g, 1,2]. While it is not new, it has fallen out of favor in comparison with technologies that potentially produce higher oxygen yields, such as molten salt or molten regolith electrolysis. Despite its low yields with raw regolith (typically about 1 % w/w O_2), it continues to be of interest due to its relative simplicity and the potential to enhance yield via regolith beneficiation. ALCHEMIST-ED is a large-scale demonstrator of a hydrogen reduction system designed and build by Space Applications Services and Metso:Outotec [3] under contract with ESA and currently being commissioned at ESRIC. The TRL-4 system accepts up to 1.4 kg solid mass charge and utilizes an externally heated fluidized bed reactor coupled to gas recycling. Following initial commissioning tests, the ALCHEMIST-ED will be used to enhance our understanding of this system in order to improve extraction efficiency and to optimize the end-to-end process. Central research questions to be considered are:

Thermodynamics of the reduction. The influence of water separation on the chemical potential of the gas driving the reduction needs to be understood, i.e., high H_2O/H_2 ratios (high fO_2) drive the reaction away from reduction and, hence, water needs to be removed efficiently through condensers and/or adsorption.

Reaction pathways and kinetics. Depending on the thermodynamics, temperature, and microstructures of the solid products, the reduction rates may vary over orders of magnitude. Proper reaction progress models (i.e., core-shell geometries, anomalous diffusion, rate models) and size dependencies need to be established.

Energy and power demands. The reduction process needs to be optimized with respect to duration and extent of the reduction reaction. Here, the understanding of reaction kinetics and the trade-off between increasing thermodynamic driving forces and investing in water separation efficiency are crucial.

Beneficiation of the feedstock. Because ilmenite is the main mineral that can be reduced by hydrogen, the low oxygen yield with respect to raw regolith requires enrichment of ilmenite through size- and material-selective separation. The physical beneficiation of the feedstock therefore is crucial, and solid understanding of the separation processes under challenging conditions (dry, low gravity) needs to be obtained.

Fidelity of regolith simulants. Technological knowledge at low TRL requires extrapolation and de-risking to transfer it to the lunar environment. Regolith simulants may contain undesired hydrous minerals that release water during the high-temperature processing and bias the understanding of water production through reduction [3]. Iron(III) minerals absent on the Moon but present in terrestrial simulants, e.g., magnetite or hematite exsolution in ilmenite, are of additional concern, because their reduction to may lead to overestimation of reaction rates and yields.

Qualitative and quantitative impurity assessment. The utilization of water/oxygen extracted during the reduction process imposes purity constraints on the final product, e.g., for electrolysis. Due to the heterogeneous nature of the feedstock, contaminants are generated in the process, e.g., H_2S from troilite, FeS, or HCl from chlorapatite, $Ca_5(PO_4)_3Cl$. Understanding of the reactions and the contaminant levels in the product are required to optimize the process, e.g., through pre-reduction beneficiation and post-reduction purification.

Separation and utilization of by-products. Metallic iron and other solid by-products (e.g., Ti oxides) are of interest for downstream utilization. They need to be separated and refined to interface with the relevant technologies, e.g., metal 3D printing. Currently, this is studied at ESRIC also for metal separates obtained from FFC molten salt regolith reduction, which will allow a better understanding of the potential trade-offs among both approaches.

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