Bioreactor Design for Enhancing bio-ISRU for Lunar Colonization. A. Fallahi and D.J. Bayless, Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, 400 W. 13th St., Rolla, MO 65409 afallahi@mst.edu, dbayless@mst.edu

Introduction: Bio-based life support systems (BLSS) enhanced using lunar regolith and other in-situ resources could provide a useful tool in supporting the Artemis objective of sustaining human presence on the moon. Such systems (bio-ISRU) have potential to produce food and oxygen while recycling wastewater and carbon dioxide in support of human habitation. Because of that potential, bio-ISRU has been studied for mineral absorption and growth rates using cyanobacteria, a phototrophic bacteria that can be used as a food source or supplement, grown lithographically on wetted lunar regolith [1-4]. While data indicate potential for growth augmentation in cyanobacteria with bio-ISRU, a number of practical issues remain, including how to scale any system to levels needed for bio-life support, overcoming cultivation limitations due to regolith particle size variability, reducing energy and water requirements, and minimizing the cost and payload requirements for implementation.

Background: work with multiple cyanobacterial strains – including Chroococcidiopsis, Gloeocapsa, Phormidium, and Anabaena – indicated lithotrophic growth on basalt and anorthosite, both representative of lunar mare and highlands materials [2]. The results indicated bioweathering caused by the cyanobacteria increased dissolved concentrations of Ca, Mg, Fe, Mn, K, and other elements essential for metabolic activity. Their study also confirmed that many cyanobacteria exhibit extreme desiccation tolerance. Billi et al. [3] showed that *Chroococcidiopsis sp. 029* can grow both planktonically and as biofilms in water containing lunar highland simulant or water released minerals, without the need for fully soluble nutrient formulations. Biomass yields reached 40–50% of standard BG 11 controls using only regolith or mineral leachate supplemented with nitrate. *Chroococcidiopsis* overcame its lack of nitrogen fixing capability with urea, including diluted synthetic human urine, as an N source, coupling crew waste streams and bio ISRU biomass production. Additionally, Leapaldt et al. [5] showed that Synechococcus PCC 8806 accumulates Fe, Zn, Cu, Mn, and P at levels exceeding 1000× the surrounding medium, and that biotically precipitated carbonates exhibit even higher enrichment factors.

Opportunity: Given its potential, focus must turn to the practical engineering of BLSS. Sustained cyanobacterial growth for BLSS will require water, soluble species of nitrogen, phosphorous, and potassium, as well numerous minerals in trace quantities, inorganic carbon and photosynthetically active radiation (PAR). While water may eventually be extracted from in-situ resources on the moon, it will likely need to be delivered (as payload) to the colony for an unspecified amount of time. Further, once a source of water is established without delivery from Earth, it still will need to be managed carefully as a scarce resource. Soluble nitrogen, phosphorous, and potassium are found in human wastewater, but will require some degree of treatment and supplement in a lunar-based BLSS. Inorganic carbon will be supplied or supplemented via human respiration, and PAR will be primarily delivered from solar photons, with some artificial augmentation needed in the dark period of lunar rotation. The limitations of payload and available lunar base footprint will also necessitate careful design of a BLSS to minimize water usage and loss, material weight, maximize growth surface area for the given footprint available, and optimize available solar PAR for photosynthesis.

Current Work: The use of wetted woven-fiber membrane substrates for growth of cyanobacteria for carbon recycling dates to 2001 [5]. Integration of the vertical membrane substrate bioreactor system with cyanobacterial growth for lunar BLSS was considered in 2005 [6]. This bioreactor system minimizes water consumption by growing the cyanobacteria in mats wetted by thin films suspended to membranes saturated with growth media. By suspending the membrane film between a water supplying header and a collection system, significant weight is avoided when to compared to other aquatic systems, such as tubular or raceway bioreactors.

Previous work by Bayless found that using dispersed particles ranging in size from 45-75 microns in BG-11 media with a composition approximating “average” lunar regolith, growth density of the cyanobacterial mat visually increased compared to untreated BG-11. This is shown in a comparison of the darkness of the cyanobacterial mat between Figure 1 (with simulated regolith) and Figure 2 (using only BG-11) in the following.

Figure 1. *Cyanobacterial mat after 5 days of growth using BG-11 and dissolved lunar regolith simulant*

Figure 2. *Cyanobacterial mat after 5 days of growth using BG-11 without lunar regolith simulant*

While no analysis of the mineral content of the mat was performed, it was theorized that the increased mineralization due to the cyanobacteria increase mineral deposits on the membrane substrate and enhanced capillary distribution of the media through the mat.

The current design, shown in Figure 3, is undergoing growth testing. It design provides advantages of vertical mat growth, which increases surface area per unit footprint, decreases weight and payload requirements, allows better distribution of growth media and also allows for the ability rotate areas of the mat into and out of direct sunlight throughout the lunar day. The design also allows for conversion to artificial PAR during the lunar night.

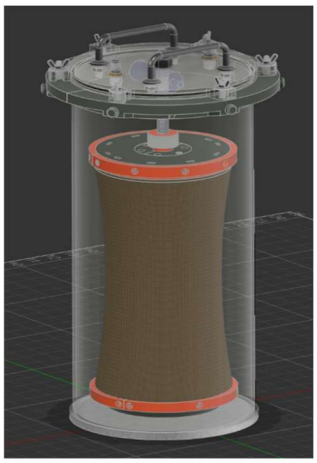

Figure 3. *Cylindrical membrane bioreactor design for potential lunar deployment*

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