METHANE PRODUCTION FROM CARBONACEOUS CHONDRITES USING ELECTROMETHANOGENESIS.

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Introduction: One of the first potential uses of space resources is obtaining propellants [1]. Carbonaceous chondrites are known to contain both water ice and carbon compounds , which have been demonstrated to be extractable by heating [2]. The output of this process contains both water vapor and CO_2 [2].

While water itself can be used as propellant directly, it can also be electrolyzed to form hydrogen and oxygen for bipropellant rocket engines. To maximize energy density, using methane instead of hydrogen would be preferred. The products from the heat treatment of asteroids (water and CO_2) could be used for the production of methane.

One way to produce methane from CO_2 is using hydrogen-utilizing methanogenic archaea known as hydrogenotrophic methanogens. Compared to abiogenic production of methane – which often requires high temperature, high pressure, metal catalysts and large volumes of hydrogen gas – biogenic production of methane by methanogens is much more kinetically favorable under conditions relevant for space explorations. Laboratory cultivation of hydrogenotrophic methanogens is typically performed with hydrogen in the headspace. Relatively recently, however, bioelectrochemical reduction of CO_2 has been proposed as a promising methane production mechanism [3]; this process is called electromethanogenesis. A biological system can also be modified to produce more complex organics, such as plastics.

We are developing a method to apply this concept of electromethanogenesis to in situ propellent production during asteroid explorations by using starting materials extracted from carbonaceous chondrites (water and CO_2). Electromethanogenesis would be especially well suited for space utilization, since it allows an efficient supply of reducing power for a large population of methanogens in the form of electricity instead of hydrogen. The same approach would also work in other scenarios, such as producing methane on Mars.

Experimental systems: We have been cultivating methanogens in two different types of bioelectrochemical systems (BES), with and without a proton exchange membrane (see Fig. 1). In a membraneless BES, carbon cloth or carbon brush electrodes are submersed in a methanogen medium with CO_2 in the headspace and a constant voltage difference (0.7V) is maintained between electrodes. A variation of the setup contains a proton exchange membrane and an air-exposed anode, with AQDS (Anthraquinone-2,6-disulfonate) as an electrom mediator and operated by in-house built potentiostats. In this membraneless BES setup, the cathodes were operated at -0.6 to -0.7V with respect to Ag/AgCl reference electrode. The starting inoculum may be a pure culture of methanogen (*Methanosarcina barkeri*) or enrichments of methanogenic communities from anaerobic sediments.

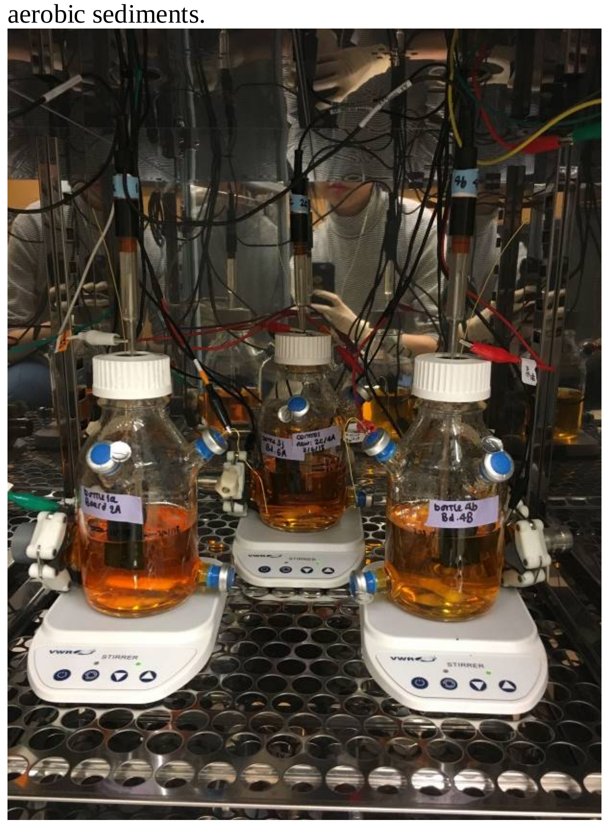

Fig.1 Three biolelectrochemical cells operating in a thermostat. This design uses a nafion proton exchange membrane and an air electrode as anode.

During the experiments, growth of methanogens is monitored by visually investigating biofilm development on the cathode and by quantifying methane production using gas chromatography.

The current system has been used as a proof of concept for methane production and we have designed a second system to optimize methane production rates.

Results and discussion: We have successfully cultured methanogens and produced methane in our proof-of-concept BES. Thus far, the fastest methane production rate we have observed was 8 mL/day for a 500 mL container bottle. For practical use, this rate must be increased by several factors of magnitude. Larger scale system are known to produce 0.28 L of methane per L of culture in a day [4], but these system have also not been optimized for large scale propellant production.

We have observed methanogenesis in both pure cultures of *Methanosarcina barkeri* and in enrichment cultures containing various anaerobic bacteria and archaea. These include microorganisms that belong to the phyla Firmicutes, Proteobacteria, Euryarchaeota, Bacteroidetes, Chlorobi and Chloroflexi, based on 16S rRNA analysis.

Experiments this far indicate that the BES performance is limited by the electrode area and the system geometry. This has lead to a new BES design using carbon felt electrodes in a 3D printed holder, which minimizes inter-electrode distance and maximizes ionic conductivity with minimum direct liquid flow between the electrodes. This setup is expected to significantly increase methane production rates in a small volume, representing the best case scenario.

Conclusion: We have demonstrated methane production from resources relevant for carbonaceous chondrites. Further experiments are underway to optimize the system for more rapid gas generation by finding the optimal electrode configuration and bacterial/archaeal strains.

The viability of this approach for in situ resource utilization still remains to be seen and optimization is required to determine the maximum methane production rates by this system and the upper limit of methane that can be produced from a limited quantity of other starting materials, such as salts.

References: [1] Lewis, John S.*Asteroid Mining 101: Wealth for the New Space Economy*. Deep Space Industries, (2014) . [2] Zacny K. et al. (2016) *AIAA SPACE 2016, AIAA SPACE Forum*, AIAA 2016-5279. [3] Cheng S. et al. (2009) *Environmental Science & Technology*, 43, 3953–3958. [4] Cusick R. D. et al. (2011) *Appl. Microbio. and Biotech.*, 89, 2053–2063.