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Launch the Microbes: Making Methane for Deep-Space Exploration

Microbial action that makes methane for energy and plastic spare parts could be a solution when deep-space expeditions go far, far away from Earth.

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For Your Consideration

- How will we deal with food waste and human excrement during deep-space exploration?
- What technologies can sustain human life and mission operations using resources available on Mars or deep-space locations?
- What microbial functions may be useful for long-duration, deep-space exploration?

As NASA and private citizens such as Elon Musk consider astronaut-led long-duration missions into deep space, including exploring and living on Mars, many basic questions remain concerning the development of sustainable life-support systems. These expeditions must grapple with conducting routine operations without weekly, monthly or even yearly resupply from Earth.

Before such missions begin, fundamentals of survival need to be addressed. Can humans sustainably grow food; create needed materials, such as replacement parts for vehicles, scientific equipment or living quarters; and deal with generated organic wastes, such as leftover food or human excrement? Will the deep-space outposts always be close enough to the Sun to generate sufficient quantities of renewable energy via solar power? Making methane from the metabolism of several important microbes may be a solution.

From Waste Comes Methane and More

Sustainable nutrient cycling, i.e., cycling nutrients without loss to the environment, is essential as humanity expands further from our home planet and some key nutrients become less available. The generation of methane and nutrient cycling by anaerobic microbes, and microbial generation of bioplastics using methane gas, could address some of these challenges.

Microbes, the microscopic bacteria and archaea that are ubiquitous in all Earth environments today, continually generate energy or synthesize new cells by creating or breaking down chemical compounds, especially organics. Several microbially regulated biochemical reactions may be useful for sustaining human-led deep-space missions. Potentially one of the best is the degradation of organic compounds by anaerobic organisms such as hydrolyzers, acetogens and methanogens, processes that ultimately create energy-rich methane gas.[1]

The Earth's ecosystems, including the human body, are fueled by the cycling of nutrients, such as carbon, nitrogen and phosphorus. Nutrient cycling is tremendously complex and occurs in numerous ways on Earth, from physical or chemical weathering to processes mediated by microbial life.

Organic compounds, which are comprised of common elements such as carbon, nitrogen, hydrogen and oxygen, are the building blocks of life. Numerous biologically important organic compounds exist, including proteins (e.g., enzymes), fats and carbohydrates, which are found in all organic waste products, such as food waste and human excrement. Organic waste products invariably are created wherever humans exist and must be disposed of or treated.

For example, on Earth, waste streams from homes, restaurants and businesses are treated using a couple of different microbially mediated approaches. The far more common approach is aerobic treatment of wastewater. Microbes that consume oxygen treat wastewater in open-air environments over a broad range of temperatures.

While aerobic wastewater treatment is effective on Earth, it requires substantial amounts of energy to overcome low rates of oxygen transfer from atmospheric diffusion to effectively remove organic wastes from water.[2] These limitations make aerobic treatment a poor and likely unviable option for deep-space exploration and colonization.

Another approach is the treatment of organic waste streams via anaerobic microbes. The microbes degrade complex organic compounds in the absence of oxygen. Treating organics anaerobically has several potential advantages.

First, anaerobic treatment of organics has the potential to be energy-positive, defined as the potential to generate more energy than is required to operate the treatment system.[3] This feat is accomplished by creating methane-rich biogas as an end-product of the anaerobic microbial metabolism.[4] The produced methane in the biogas can be harnessed easily and converted into useable electricity.

Second, due to the lower energy available to anaerobic microbes, less overall biomass is produced, reducing the amount of waste biomass to manage, which may be advantageous under conditions of limited area such as future space colonies.

Anaerobic treatment of organic biosolids generated from aerobic wastewater treatment is commonly used at large wastewater reclamation facilities today. Direct anaerobic treatment of wastewater using biological reactors such as the anaerobic baffled reactor, and co-digestion of multiple organic waste streams including food waste and wastewater biosolids in large-scale anaerobic digesters, are promising areas of ongoing research for renewable energy generation.[5]

In addition to creating methane gas, anaerobic technologies further facilitate nutrient cycling. The resulting digested solids can be used as crop fertilizer, thereby putting nutrients back into the food chain.[6] These attributes make anaerobic treatment of organic waste streams a potentially viable option for deep-space exploration.

Do-It-Yourself Plastic

Beyond its use as an energy source, methane can be a source for bioplastic production in deep space. Methane gas serves as a substrate and electron donor for methanotrophic bacteria, which are ubiquitous on Earth. Under stressed conditions, e.g., when certain nutrients are not available, methanotrophs develop a carbon-based intracellular inclusion called polyhydroxybutyrate (PHB), which can be harvested and transformed into a biodegradable plastic.[7] Devices such as 3-D printers theoretically could mold PHB-based plastics to generate a number of useful parts or tools in deep space.

Further, PHB-based plastics degrade quickly in anaerobic digesters, while petroleum-based plastics take several hundreds to perhaps thousands of years to degrade and cycle nutrients back into the ecosystem. One can imagine a scenario where PHB plastic wastes are placed in an anaerobic digester that breaks down the biopolymer while generating methane gas. The methane in turn can be used to grow more methanotrophic bacteria and more PHB, creating raw material for bioplastics.

This "cradle-to-cradle" solution (as opposed to "cradle-to-grave" handling of wastes)[7] is the type of sustainable solution required by astronauts for long-duration, deep-space missions. Mango Materials, a startup company in Silicon Valley, is exploring efficient ways to mass-produce PHB-based plastics from methanotrophs and has a grant from NASA to explore methanotroph growth in space-like conditions.

Know Before You Go

Despite the promise of anaerobic microbial technologies, substantial challenges remain before they are viable for long-duration, deep-space missions. For example, questions remain concerning the viability of microbes traveling for long periods of time through space while being exposed to increased ultraviolet radiation. Further, additional study is required concerning the start-up and operation of biological reactors operated under deep-space conditions. Mars, for example, has a gravitational pull only 0.375 times that of Earth's gravity.

The function of microbes in lesser gravity, or no gravity at all, is a nascent area of research. Examination of full-scale anaerobic bioreactors is required before these reactors are deemed a reliable technology for deep-space exploration. Many other questions remain, and it is up to researchers knowledgeable in the fields of astrobiology, microbiology and biotechnology to develop solutions prior to implementing trusted microbial technologies in outer space.

Deep-space exploration is an ongoing mission set for NASA. Sustainable solutions to practical problems, such as generation of renewable energy, nutrient cycling and conservation, and the creation of replacement tools or repair parts, need to be developed before long-duration missions to Mars or beyond are truly feasible.

The metabolism of anaerobic microbes may hold the key to solving several of these challenges, but further research is required. Solutions to these challenges will be developed by not just those in academia, but those in the greater space community who have a more complete understanding of the challenges associated with operating in austere environments, including military space operations officers.

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