MYCOTECTURE OFF PLANET: FUNGI AS A BUILDING MATERIAL ON THE MOON AND MARS.

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Introduction: A turtle carries its own habitat. While reliable, it costs energy and is not adaptable to the environment. NASA makes the same trade-off when it transports habitats and other structures needed to destination. Astronauts stayed on the lunar surface for up to 75 h (Apollo 17), with the lunar module doubling as a habitat. An example of the "build it on Earth, launch it into space" approach is the Habitat Demonstration Unit (HDU) Deep Space Habitat, developed by the Habitat Systems Project (NASA AES). It has a composite fiberglass resin-infused shell attached to eight steel ribs, providing living and working space for four. Even with advanced materials, it weighs >14,000 kg (~466 kg/m^2 living space), leading to high launch costs. Upmass and resupply will result in reduced surface operations, greater mission risk, loss of productivity and psychological stress.

In contrast, a bird builds its home at destination using sustainable manufacturing and in situ materials. In this vein, NASA's Centennial Challenges program ran a 3D printed Habitat design challenge for the Moon, Mars and beyond [1]. Top designs used ISRU, focusing on agglutinated regolith or frozen water. Requirements included a vapor barrier, and a robotic infrastructure for preparing the site, gathering regolith and building. While regolith and ice have advantages as building materials and are compatible add-ons to our concept, regolith alone has disadvantages including rigidity, poor thermal insulation, potential mineral/chemical toxicity and incompatibilities, and a dedicated infrastructure required for production of both [2].

Vision: In a NASA Innovative Advanced Concepts (NIAC) Phase 1 study, we introduced the concept of structures grown by fungal mycelial at destination (Fig 1). Mycelial materials are thermal insulators, fire resistant, and unlike plastics and glues, do not outgas. They are more flexible and ductile than regolith alone. The density and material properties are tuned during production. The material could be used dry, wet, frozen with water or as part of a self-produced biocomposite which would allow such enhancements as radiation protection and a vapor seal. Even better, it is self-replicating so the habitat could be extended at a future date, and thus also be self-repairing. Some form of this material could be used for a habitat at destination, furniture, storage, additional buildings, and the shell of multiple rovers. As a standalone material or in conjunction with agglutinated or sintered regolith, a mycotectural building envelope could significantly reduce the energy required for building because in the presence of food stock and water it would grow itself. After the arrival of humans, additional structures could be grown with feedstock of mission-produced organic waste streams including inedible plant or soil components, or human waste. When protected, the mycomaterials can have a long life, but at the end of its life cycle the material could be become fertilizer for mission farming or production of new mycomaterials.

Figure 1. Mycotecture habitat on Mars (redhouse).

Radiation has been considered a "showstopper" for human missions, but some black fungi not only survive, but may thrive in space radiation [3]. We could supplement our mycomaterials with either bioengineering of the mycelia to bind materials such as metals as we did in Phase 1, or with bacteria with which they would form a mutualistic relationship. These bacteria could supplement the structural integrity of the mycotectural envelope through bio-mineralization, polymer production or filament formation. Alternatively, they could act as an intelligent input (biosensor) in the mycomaterial synthesis process detecting pressure and flaws in the mycotectual structural integrity by measuring mechanical strength, and reporting anomalies through color change or fluorescence. Autotrophs could provide to, and receive from, the fungal mycelia, essential metabolites to speed up the growth of the structure.

Mission architecture: (1) Before launch, a plastic inflatable is seeded with dried fungal mycelia and algae or cyanobacteria and deflated for launch. The shell allows for liquid water and meets planetary protection protocols for Mars. A concentrated nutrient solution will de-risk the mission. (2) At destination, the inflatable is deployed to the surface, water brought from Earth or collected at destination is added to the inflatable to activate the algae and fungi. (3) The algae grow during daylight, converting sunlight, CO_2 and water into biomass as well as producing O_2 which inflates the structure. The fungi use the O_2 and biomass to grow, providing structural integrity. The structure will be heated to allow growth during the lunar night. Ideally the structure will be complete during this time allowing the heat of the lunar day to bake the structure adding rigidity. If the growth cannot be completed during lunar night, cooling will be needed for thermal stability during the day until the structure is grown.

Progress to date:

Inflatable. Moonprint solutions built a 4x4 m inflatable prototype (Fig 2). The internal dropstitching allows the inflatable to maintain shape as well as providing scaffolding for the fungi to grow on.

Figure 2. Prototype of inflatable (Moonprint).

Architectural. A 4x4 m prototype has been grown separate from the inflatable. In addition, the use of "sand towers" or "sand bricks", and concept that can be extended to use on lunar or Martian regolith, has been tested. Cyanobacterial/fungal biocomposites were made and tested for their mechanical properties (Fig. 3).

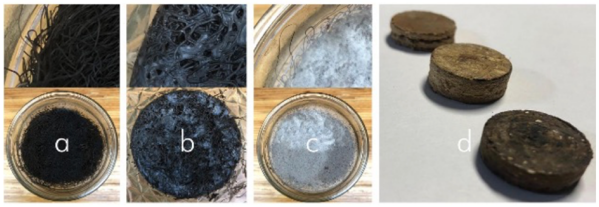

Figure 3. Bio-composites grown by redhouse. a) Dried *Nostoc flagelliforme* (diazotrophic cyanobacterium) in a sterilized glass jar. b) hydrated *N. flagelliforme* inoculated with *A. oryzae* liquid culture. c) fully colonized composite. d) compressed composites that are structural and insulative. Note: similar samples by redhouse achieved 30 MPa compression strengths.

Materials testing. Materials testing was begun on fungal samples and biocomposites grown in the lab, as well as those exposed to the planetary simulator at McMaster University.

Benefits to NASA and the broader aerospace community: If we succeed in developing a biocomposite material that can grow itself, we will provide NASA with a radically new, cheaper, faster, more flexible, and lighter material for habitats for extended duration lunar and Mars missions, as well as furniture and other structures. While our habitat shell is designed to be inert, we can envision its extension into a living state participating actively in waste recycling, oxygen production, and detoxification similar to a living roof. Such living architecture was demonstrated by a five-story Bio Intelligent Quotient building in Germany **[4]** showing that this approach can scale. Other ISRU building proposals suggest agglutination of regolith, which could be done by fungal mycelia. In Phase 1 we demonstrated growth of mycelium on regolith simulant with added nutrients.

Terrestrial spin-offs: The building processes to be developed in Phase 2 may have profound effect on the building industry. This is responsive to the UN Sustainable Development Goals 9, 11, 12 **[5].** The building industry is responsible for 40% of Earth's carbon emissions. The concept of a rapidly deployable, self-building self-healing structure potentially with embedded biosensors and is biodegradable and emits no toxic volatiles, is appealing. The commercial sector is exploring insulation and packing materials, but with the addition of our new feedstocks, scaffold, and embedded sensing capabilities, they could be more useful. We are currently exploring the use of mycotecture to increase sustainability in the award-winning Basque restaurant, Azurmundi.

Acknowledgments: We grateful for support from NASA's NIAC program. This research is also funded by Northern Bridge Consortium as part of the Hub for Biotechnology in the Built Environment (HBBE), and by the group Bio-Futures for Transplanetary Habitats.

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