PLANTS IN LONG TERM LUNAR EXPLORATION

Robert J. Ferl[1,2] and Anna-Lisa Paul[1], [1]University of Florida, Program in Plant Molecular and Cellular Biology, and [2]Interdisciplinary Center for Biotechnology Research. Gainesville, FL 32611. alp@ufl.edu , robferl@ufl.edu.

Introduction- Science and Exploration Rational: Plant are complex eukaryotic organisms that share fundamental metabolic and genetic processes with humans and all higher organisms, yet their sessile nature requires that plants deal with their environment by adaptation in situ. Thus plants have evolved to deal with environmental change and stress by responding with changes in metabolism in order to meet the challenge – rather than behavioral modification of their environment. This makes them ideal reporters of the biological impact of their environments. Plants are therefore very well suited for biological experiments to and on the moon and other extraterrestrial environs.

Plants can make the transit spaceflight journey within the stasis of the seed, under complete vacuum and extremely low temperatures. Seeds have been to and returned from lunar orbit during the Biostack experiments of the Apollo era, and even during those very early baseline exposure experiments, seeds provided fundamental insights into radiation exposure in the circumlunar environment.

Given the extraordinary developments in modern molecular biology, as well as the current and continued emphases in eukaryotic genomics, developmental and molecular genetics, truly insightful experiments that address fundamental questions about biological adaptation and responses to extreme extraterrestrial environments can be answered using plants.

Plant biology experiments are scalable over a wide range of lunar environments that should be examined for biological impact. Vairables include atmospheric com-position and pressure, transit and in situ radiation, gravity, and exposure to local resources such as regolith. Plant biology experiment payloads are also scalable over a wide range of engineering and mission profile constraints. In a seriously constrained scenario, a few watts of power and a few cubic centimeters would allow examination of growth, development over several critical stages and gene expression in 10s of plants - all within the course of a single lunar day. In a less constrained scenario, plants could be exposed to lunar regolith and a variety of mitigation technologies to enhance survivability and examine suites of in situ biological responses. In all of these scales and scenarios, the seeds produced from the plants contain the biological readout of the experiment, safely in a quiescent and stable stasis for later analysis.

The plants to populate early and mid lunar experiment would also be genetically engineered to be biological sensors (bio-sensors) of their environment. Plants engineered with Green Fluorescent Protein (GFP) reporter genes can be designed to respond to a variety of stimuli can be monitored telemetrically, and biological data collected in the form of digital images. Switching between nor-mal lighting and that which facilitates the observation of GFP expression, would enable observation of both the general condition of the plants as well as monitoring of the development of fluorescent signals that records a specific molecular biological response to a specific feature of the lunarenvironment.

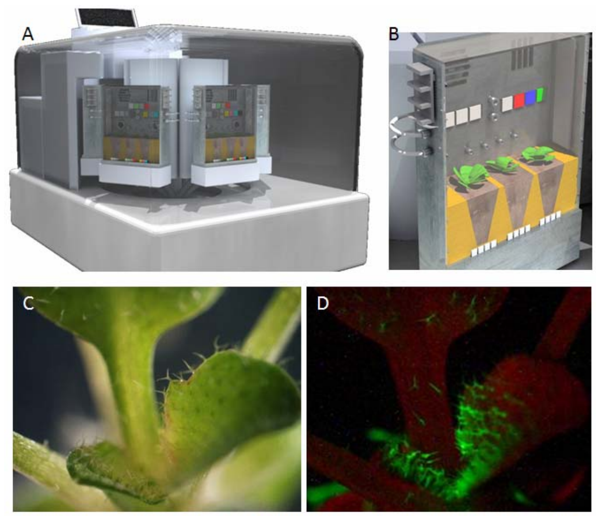

Figure 1. A model of a plant biology payload module for a Lunar Lander. A) illustrates how growth pods might be arranged around a central hub for regolith deposit and mediation and photography. B) a close-up showing plant growth in regolith and the photographic surface with color targets. C and D) a close view of the apex of an Arabidopsis plant engineered with a GFP biosensor to respond to low oxygen, photographed in white light (C) and photographed in 488nm light to show extent of GFP expression (D).

In practice the plant growth payload would have a series of modules in which plants would be exposed to various aspects of the planetary environment as appropriate, with the size and number of modules being determined by the engineering trade space and mission profile. Gravity would be an inherent component of the lander environment, as would be the incident radiation that penetrated the lander hull. Regolith collected by a robot arm and returned to the growth space in a potential experiment variable that offers tremendous potential returns.

Extended Lunar Exploration and Habitation: Plant biology payloads are both a fundamental test of biological survival outside the terrestrial environment as well as a technical and programmatic step in the development of advanced plant-based life support systems to support human exploration. Potential toxicity issues will be addressed directly, in situ and in concert and context with the suite of environmental impacts present on the lunar surface. If, for example, plants can be grown safely in regolith, then the use of regolith within human rated habitats becomes much more tenable and plants can then be used for the capture of in situ resources and the movement of those resources into the habitation environment.

Virtually all scenarios for the long-term habitation of orbital or extraterrestrial structures involve plants as important parts of the containerized environment that would support human beings [1]. Plants have been envisioned as integral components of long-term bioregenerative life support systems for decades [2-4] and, by extension, essential components of efforts to establish larger-scale, controlled ecosystems on extraterrestrial surfaces. The interrelationships between plants and animals are completely complementary: plants recycle human wastes and provide human nutrients, while humans recycle plant wastes and provide plant nutrients.

Within the last 10 years, major advancements have been made in our understanding of how plants respond to unique and challenging terrestrial environments, and how they can be utilized to gather vital information on the biological impact of unique environments on humans as well. The advantages of using plants for investigating the effects of lunar environments and lunar transit journeys on biology are similar to the general arguments put forth for the study of plants in spaceflight and other extraterrestrial environments [5]:

- Plants are highly responsive to gravity, radiation, temperature, and pressure.
- Well developed plant models are available for study (e.g. the Arabidopsis thaliana genome has been sequenced and other plant genomes are complete or in progress).
- Plants are amenable to genetic engineering and can be developed into highly sensitive indicators of radiation damage and other environmental stresses, or altered to accommodate limits imposed by the space environment.
- There are no regulatory restrictions on the use of plants as experimental subjects, making them ideal biological subjects for robotic missions.
- Plants can be stored and transported in a dormant state as seeds, providing a low mass, low volume, highly reliable source of biological material for life support research.
- The supporting mass for the growth and monitoring of Arabidopsis (NASA's model specimen plant) is minimal. Plants can be grown to maturity in less than cc's of soil, and with a corresponding low volume of water. In addition, Arabidopsis flourishes in, low energy LED lighting.
- Seeds can be surface sterilized, thereby conforming to planetary protection guidelines as well as preventing ambiguous results that could arise from a contaminating terrestrial microorganism.
- The life support requiremtne and the psychological well being of the crew will be enhanced by crew interaction with plants as indicated by reports from returning astronauts.

Both spaceflight and ground-based studies with plants have set the stage for integrating plants into Lunar missions as biosensors and as a means to survey generational effects on a higher eukaryote. The genomic response of Arabidopsis to spaceflight suggests that although plants can adapt to the spaceflight environment, their global patters of gene expression are altered to cope with the novel environment [5]. The same is true of an environment that we may adopt in the process of establishing research stations or outposts on the moon, such as a low pressure environment of altered gaseous composition and limited radiation protection. Arabidopsis responds, for example, with great sensitivity to reduced atmospheric pressures, and reducing the pressure by just one fourth (from 101kPa at sea level to 75 kPa, a pressure also adopted by the space shuttle for EVAs) evokes a significant change in the gene expression profile of Arabidopsis. However, Arabidopsis can thrive at significantly lower pressures (10 kPa) while inducing and repression a huge host of genes that regulate their metabolic adaptation to that environment [7,8].

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