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THE ROAD LESS TRAVELLED: GREENHOUSES AND THEIR HUMANIZING SYNERGIES

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Co-authors Sandra Häuplik-Meusburger (architect and habitability researcher Vienna), Carrie Paterson (artist-researcher, Los Angeles), and Daniel Schubert (DLR-German Space Agency) consider the role of plants in long-term space missions historically since 1971 (Salyut 1) and propose design requirements for greenhouses and constructed environments given a range of plant-human relationships. Greenhouses in space will require advanced technical systems of automatic watering, soil-less cultivation, artificial lighting, and computerized observation of plants. In addition, functions discussed for plants in space habitats include physical/health requirements and human psychology, social cohesion, as well as the complex sensorial benefits of plants for humans. The authors cite recent research conducted by the German Space Agency (DLR) into the use of greenhouses in extreme environments to reveal the relative importance among of greenhouses for people living in isolated locations, and where greenhouses might factor into several strata of human health. In a recent design-in-use study of astronauts' experiences in space habitats discussed in *Architecture for Astronauts* (Springer Press 2011) it was found that besides the basic advantages for life support there are clearly additional 'side effects' for habitability and physical wellbeing. Other researchers have also documented that astronauts' experiences away from Earth extend beyond the scientific to include a strong spiritual, poetic and existential component, (1) though this has not been widely publicized by space programs and considered only minimally in programmatic requirements for space architecture. The authors have composed several key theses regarding the need to promote plant-human relationships in space, including areas where synergy and symbiosis occur. The justification is taken from A.) scientific research and astronauts' experiences as detailed in *Architecture for Astronauts*, B.) current findings by space programs about habitability issues, and C.) Paterson's investigation into the philosophical bases of horticulture within the thousands-of-years old traditions of *penjing* and *bonsai*. In terms of the latter, philosophical considerations will be introduced and discussed with references to philosopher of science Gaston Bachelard's examination of the poetic imagination. Together the authors demonstrate the necessity and technology requirements to include plants, greenhouses and environmental design for the purpose of humanizing the experience of space travel, preventing psychological crises, improving efficiency of life-support systems, promoting health and well-being of astronauts, and creating supportive environments for communities in space.

I. INTRODUCTION

On Earth, plants grow in different forms according to their natural environment. In extreme environments technology has to substitute for the Earth's natural conditions in order to allow plants to grow. One of the best-known and so-far largest endeavors of creating an artificial and closed-ecological biosphere is the Biosphere 2 project. In the longest mission eight people spent two years living in the sealed ecosystem, which eventually failed. Reported problems include troubles with CO2 and oxygen levels leading to an unbalanced fauna and flora, causing also interpersonal conflicts.

Artificial biospheres and greenhouses will be essential for future human space exploration and will be integrated into interplanetary and extra terrestrial planetary habitats. Near-future missions to the Moon offer a great potential for testing and evaluating these delicate systems. As space missions become longer, more arduous, or remote bases for long-term habitation on the Moon or Mars are designed, the effects of micro-gravity, how well different plants grow in space, and what kind of light they need will be important to discover.

Automatic systems for lighting and watering plants are a given in space; however, plants need constant monitoring by humans. They will, for example, monitor for changes in humidity, or the build-up of ethylene, which plants normally expel as a waste product and which is normally removed by atmospheric and weather conditions on Earth. (2 p. 184) These stresses on plants in the microgravity environment can be fatal. Even in an environment of nearly 100% humidity a plant may experience dehydration because in hypobaric conditions water escapes plants faster, causing them to close their stomata; they "react as if they are dying of thirst." (2 p. 188) Humans also have responsibility for plant reproduction, as studying the environmental effects on different plants over courses of generations helps to improve viability of seeds. Not until 2001, after close to thirty years of experimentation, did astronauts achieve a 70% + viability rate, with some early missions yielding only seeds and germs of wheat that were sterile. (2 pp. 181-184) Hybridization may be considered as a solution when space-born viable seeds are crossed with Earth strains as space-born seeds are sometimes genetically mutated as a result of their environment. (2 p. 185)

In addition to technical requirements for maintenance, trimming plants helps them stay healthy and for this they need human stewards. Cosmonaut Vladimir Kovalenok tended his onions by keeping rot at bay, trimming stalks that were unhealthy which promoted growth in the plant. He called his method the "simple peasant's way." (3) When dealing with more complex plants such as trees, flowers, and fruit bearing plants, some of which need constant pruning and care, the human-plant relationship is even more interdependent. In space the "success" rates of plants will be determined not simply by whether they live or die, but whether they have the possibility to thrive.

This paper concentrates on the plant-human relationship from a user-oriented point of view. It provides a short overview of the history of technical greenhouses in space, highlighting aspects that are related to the user. Key theses have been summarized regarding the plant-human relationship, finally resulting in a consideration of miniature landscapes through the case study of *bonsai* and *penjing* traditions.

II. MINI GREENHOUSES AND INDIVIDUAL GARDENS IN SPACE

Salyut 1 (launched April 1971) was the first space station that implemented a greenhouse—it was named *Oasis*. Since then, plant growth facilities were implemented in the later Salyut stations 4 (1974), Salyut 6 (1976) and Salyut 7 (1982); on Mir (in the module KRISTALL launched in 1990); and on the International Space Station. The US space laboratory Skylab (launched March 1973) only had an educational experiment with space grown rice seeds. (4)

Table 1 details the greenhouse facilities that have been used on-board particular space stations.

Small Plant Growth Facilities onboard SALYUT (1, 4, 6, 7) and MIR
Oasis 1 (Salyut 1): first plant growth system *Oasis 1M* (Salyut 4): improved water metering system *Oasis 1AM* (Salyut 6): designed for long duration missions *Oasis 1A* (Salyut 7): advanced lighting system *Malachite* (Salyut 6): ornamental plant culture system to provide psychological comfort *Fiton* (Salyut 6): greenhouse for onions and radish *Svetoblock* (Salyut 6): plant system that could be

mounted to a light in the cabin *Svetoblock-M* (Mir), *Svetoblock-S, Svetoblock-G* *Svet* (Mir): first joint Russian-US experiment *Magnetogravistat* (Salyut 7, Mir): greenhouse for wheat and flax *Biogravistat* (Salyut 7): greenhouse for lettuce *Vazon* (Salyut 6, 7 and Mir): system for the cultivation of bulbous plants without artificial lighting *Phyton* (Salyut 7): miniature growths system, first seed to flower produced on orbit.
Small Plant Growth Facilities onboard STS and ISS
Plant Growth Unit –PGU (STS): plant growth unit that fitted into a mid-deck locker on the Space Shuttle *Plant Growth Facility – PGF* (STS): improved lighting and control system *Astroculture System* (STS, Mir): closed chamber *Advanced Astroculture System* (ISS): student-designed experiment and commercial payload *Plant Generic Bioprocessing Apparatus – PGBA* (STS): included fluorescent lighting *Biomass Production System –BPS* (STS): developed for long duration missions *LADA* (ISS): modular type system MagISStra, Veggie and AstroGarden: as described below

Table 1: Overview of greenhouse facilities used in space stations. Sources: (5) (6) (7) (8) (9)

A number of experiments with seeds and plants have been conducted, with the first plants carried to space in 1960 with Sputnik 4. (5 p. 3) However the first space-grown vegetables were reportedly eaten in 1975 onboard Salyut 4. During their mission the cosmonauts Vitali Sevastyanov and Pyotr Klimuk were given permission to eat some of the onion tubers. (10)

The first successful life-cycle from seed planted in orbit to flowering plant to producing new seeds was conducted in the growth chamber *Phyton* on Salyut 7. (9 p. 177)

Very early during the Salyut missions, astronauts experimented with plants and 'designed' their own little greenhouses. Robert Zimmerman writes that Salyut 6 cosmonaut Valery Ryumin "had a green thumb" and "turned the space station into a veritable jungle by growing [plants] in empty film cassettes, equipment casings, and food containers hung everywhere on the station's walls." (3 p. 3)

Salyut 6 and 7 cosmonauts even had multiple choices of greenhouses. Valentin Lebedev stayed 211 days on-board the Salyut 7 station and during his long-term stay he planted peas in *Oasis*, *Arabidopsis* in the *Fiton*, lettuce in the *Biogravistat*, tomatoes and coriander in the *Malakhit* and onions in a *Vazon*. (11 p. 169) (12)

Based on the many experiments with greenhouses, the Soviets recognized very early the psychological benefits of plants and designed a device "for the sole purpose of ornamental plant culture to provide psychological comfort to the cosmonauts in the interior of the station." (5 p. 187)

Img. 1 - Expedition 5 cosmonaut Victor Savinykh with plants onboard Salyut 6 (credit: Spacefacts, J. Becker).

Since then an international crew of astronauts have used a number of small greenhouses intended for growing vegetables and herbs.

<u>The *LADA System*</u>

Today the *LADA System* (Img. 1) is used on-board the International Space Station. It is a fully automated small greenhouse garden and was developed by the Space Dynamics Laboratory at Utah State University and the Institute of Biomedical Problems in Moscow. It has been used on-board the International Space Station (in the Zvezda module) since 2002. The system is as the size of a standard suitcase and includes a control module (24.1 x 17.8 x 24.1 cm).

One of the *LADA System*'s functions was to grow edible vegetables for the crew. Gail Bingham from

Img. 2 - Russian cosmonaut Sergei Volkov checks the progress of a growth experiment with the LADA-01 greenhouse in the Zvezda Module of the ISS. (credit: NASA)

Utah State University calls the *LADA System* "a salad machine." (3) (5 p. 7)

Besides the nutritional benefit, astronauts appreciated the activity itself. Space Dynamics Lab engineer Shane Topham recounted that following the Columbia disaster, "the crew members who were on the space station were obviously shaken up, and one of the things that the Russian space program did to try and calm them down was to assign them more crew time to gardening because they noticed it did have a calming effect." (13)

The *Astro Garden* and *Veggie System*

Three shuttle flights after the Columbia disaster, on STS-118 in August 2007 a small plant growth chamber was transported to space for an in-orbit experiment. The "*Astro Garden*" was designed as a kind of "hobby kit" where herbs, flowers, and vegetables could be grown and consists of a growth medium with watering valve and expandable plastic top to keep all parts of the garden enclosed. In parallel, the similarly designed "*Space Garden*" was made available to schools.

Astro Gardens are NASA's answer to the need for astronauts to have personal greenhouses. These serve not only as recreation. "During missions, astronauts often long for the tastes and smells of home," says the brochure distributed by the US government's *Astro Garden* developer. This was also confirmed by several astronauts interviewed by Haeuplik-Meusburger. (14) "Experiments involving plants have provided them with that important link back to Earth, and have made plants an important tool for their psychological well-being in space." (15)

Recently ORBITEC has been award with two NASA contracts to support the development and flight of *Veggie,* a deployable growth system to grow salad for long-term mission astronauts. (16)

Img. 3 - Veggie System to provide ISS astronauts with fresh salad (credit: Orbitec.com)

The MagISStra "Greenhouse in Space"

During the STS-120 mission ESA astronaut Paolo Nespoli conducted an experiment with a small educational greenhouse similar in design to the *Astro Garden*. Nespoli's "Greenhouse in space" project, proposed and conceived by ESA's Directorate of Human Spaceflight, was a fifteen week scientific experiment conducted in tandem with eight hundred schoolchildren aged between twelve and fourteen years old at Cite de l'espace in Toulouse France; ESA European Astronaut Centre, Cologne, Germany; ESA ESRIN, Frascati, Italy; and Ciencia Viva in Lisbon, Portugal. Observations were made about the germination and growth of *Arabidopsis thaiana*, a common flowering plant and model organism that has been studied in space since the first days of Salyut experiments. Nespoli's seeds germinated but quickly developed a potentially hazardous fungus necessitating they be disposed of; meanwhile on Earth, the children and a Mars500 crew completed their part of the mission with much more promising results. (17 p. 3)

One lesson from this milestone experiment suggests the benefits of performing greenhouse experiments in connection with diverse groups of people on Earth, rather than leaving an experiment vulnerable to the possibility of being completely ruined because of an accident or unforeseen issue in space. Imagine the disappointment of Soviet researchers when the first *Oasis* seeds from Salyut 1 were destroyed during the tragic decompression accident aboard Soyuz 11 that also sadly robbed them of their cosmonaut comrades.

Spontaneous Gardening: The Case of STS-61-A

Wubbo Ockels instigated an unplanned greenhouse activity during his mission on STS-61-A. In addition to the planned experiment with corn seeds he had ten extra seeds and made his personal greenhouse with a piece of plastic foam in a plastic bag with a zipper, and a knife for making holes into it. After a few days the leaves grew a few centimeters. He said that they had a "little party" and everybody ate a small amount of fresh food. The whole procedure of greenhouse making took him ten minutes. (18)

Ockels' innovation process confirms the importance and relevance of previous gardening activities of cosmonauts. As well, it indicates the immediacy of the growing environment and ease of incorporating plants into astronauts' daily lives, no matter if highly structured as part of experiments, or just for personal interest and health.

III. TOWARDS PLANETARY GREENHOUSES

Built greenhouses for Earth environments and extra-terrestrial greenhouses are fundamentally different. Depending upon the environmental conditions technical and scientific requirements will change. A greenhouse on the Moon will, for example, incorporate micrometeoroid and radiation shielding. Even if the facilities will have similar functions to Earth greenhouses, they will be designed according to the different gravity conditions.

Plants have been grown in micro gravity but never on a planetary body with the challenge of one-sixth Earth gravity on the Moon or one-third Earth gravity on Mars. From a scientific point of view it may be beneficial to observe how growth patterns of plants change under different gravity conditions. One might assume that having even a fraction of Earth's gravity would still result in positive effects for plants, which could be free-planted in soils in planetary greenhouses rather than always in limited sized containers where they can easily become root bound.

The main issue on extra-terrestrial planets and moons is air pressure, the decrease of which can cause plants' internal regulatory systems to falter, as much as it makes the construction of greenhouses easier and cheaper due to the need for less material. In order for plants to thrive, species need to be selected that will able to do so in the oxygen-rich environments fit for humans. (2 pp. 186-187)

There are only select crops at the moment considered for long term space missions. "Ten pick-and-eat vegetable crops have been identified … [including] lettuce, spinach, carrots, tomatoes, green onions, radishes, bell peppers, strawberries, fresh herbs and cabbages." (19)

The goal to provide future astronauts on Moon or Mars bases with food that is nutritious and tasty is one of the most important motivators to explore greenhouse design. At the same time, volume and mass must be minimized for cargo transfers by using grey-water and composting systems. Not everything can be taken away from the bases and it would be too expensive and difficult to include the weight of extra fuel just to power waste materials off the Moon or Mars.

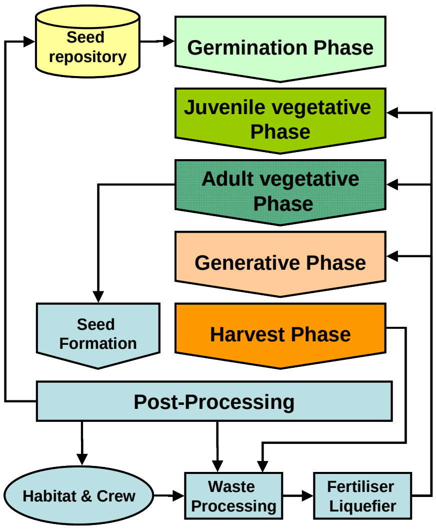
User-related aspects learned from previous space missions will apply toward planetary greenhouse design as well as experiences on Earth in remote locations such as Antarctic/Arctic research stations, oilrigs, tanker/research ships, military/summit base camps, and mining camps.

Research into use of greenhouses in extreme Earth environments is currently being undertaken by the German Space Agency (DLR). In the following two sections and illustrations, issues concerning plant life cycles and relevant system components are detailed.

Plant Life Cycle in a Technical Greenhouse

When considering higher plants for cultivation within a closed environment like a planetary greenhouse, several aspects need to be considered. First, a planetary greenhouse needs to provide each plant with an individually customisable set of environmental conditions (e.g. light, nutrient mixture, temp.), optimally controlled for each step of the plant life-cycle (Img. 4).

Out of a seed repository, a defined number of seeds (of one selected plant type) are taken in order to begin the growing cycle. The Germination Phase (G) of the plant usually takes place in a special climate controlled chamber with warm, high humidity conditions. Additional seeding illumination can be provided, as required by individual plant species.



Img. 4: Life cycle phases of plants

When the seed has developed its first cotyledons (germ layers) as well as first roots and is ready to begin with the first photosynthesis processes, it is implanted in the primary grow channel. During this Juvenile Vegetative Phase (J) the plant forms its first branches and leaves, and the root system is continuously evolving. The growing conditions required during this phase are high levels of air humidity, initial illumination and the first addition of low concentrations of nutrient mixtures. Most of the plant growth takes place during the Adult Vegetative Phase (A). Here the plant develops most of its branch and leaf system. The requirements for higher nutrient levels increase while requirements on air humidity levels decrease. During the Generative Phase (Ge) the plant develops one or more fruiting bodies. Requirements towards nutrient levels remain at high levels, while often the composition of the required mixture changes. Once the crops reach a certain level of readiness, the plants enter the Harvest Phase (H). This phase can be short (where all crops are harvested at one time) or an incremental harvest as fruit ripens.

Some plants skip the Generative Phase (Ge) because the edible crop is the leaves (e.g. lettuce). These plants, therefore, need to pass through the seed formation step in order to close the production loop. To accomplish this, some plants are taken out of the nominal production process and are cultivated separately in the seed formation growth unit. Here, the plants can accomplish their biological life cycle in order to produce new seeds that can be used to restock the seed repository. With relatively short mission durations in mind and considering the low mass and volume of some seeds (e.g. carrot has a Thousand-Seed-Weight [TSW] of ~11.5 g), it seems unnecessary to establish a seed formation growth unit (20). Nevertheless, for long mission durations and following the premise of closed-loop systems, the generation of new seeds becomes a necessity.

After a successful harvest the crops are relocated to the Food Processing Facility (FPF) where they are refined towards ready to use products. The FPF can be seen as an extended kitchen, where different production steps are executed (e.g. cleaning, cutting, peeling, extracting, disinfecting, sterilizing, boiling, drying, dehydrating, packing and storing). This way, the FPF functions as an interface between the in-situ greenhouse and the habitat, including the crew.

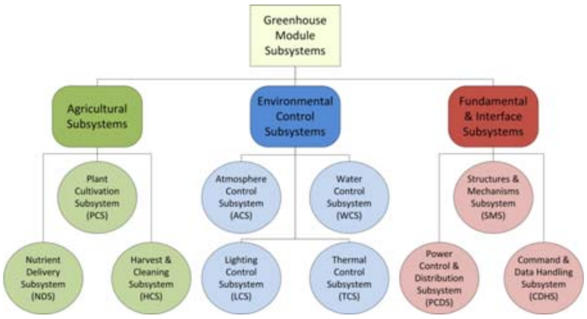
During this work phase, some seeds (e.g. wheat) are obtained from the fruit bodies, dried and stored in the seed repository so that they can be used for a new generation of plants. The remaining non-edible bio-mass is composted together with other bio waste materials of the habitat in order to produce new liquid fertilizer.

System Analysis for Planetary Greenhouses

Comparable to spacecraft, greenhouse modules can be divided into several subsystems. The selected approach detailed here (Img. 5) illustrates a fundamental classification of subsystems and their tasks.

The first group, the Agricultural Subsystems, encompass all subsystems directly related to the plants. In that group, the Plant Cultivation Subsystem (PCS) supports the plants during all development stages and contains the growth medium for the plants. The plants themselves and can be divided into root and shoot zone. The design of the PCS is directly affected by the selected plant cultivation method and growth medium. The PCS also has to ensure that the plants have stability in the growth medium and grow as desired.

The second branch of the Agricultural Subsystem, the Nutrient Delivery Subsystem (NDS), is responsible for the specialized mixture and storage of each plant's nutrient requirements. The nutrient solution has to be distributed to every plant in the greenhouse module in the desired amount and composition. Nutrient production can be part of the NDS of greenhouse modules, but usually this task is fulfilled by the waste treatment system of the habitat.



Img. 5: Possible subsystem overview of necessary subsystems

The task of the third branch, the Harvest and Cleaning Subsystem (HCS), is the provision of all tools and materials that are necessary for harvesting and cleaning the cultivated plants. Therefore, the HCS has to have a waste storage system to temporarily store the inedible parts of plants before they are distributed to the waste treatment system of the habitat. As the crop gathered from plants has to be packed after the harvesting and cleaning procedure, the HCS also has to provide the tools for the packaging. Afterwards the packed crop has to be stored, so the HCS has to provide storage volume as well as a refrigerator and a deep freezer for fast decaying crops.

The second group of subsystems, the Environmental Control Subsystems, maintains all environmental conditions, which are required either by humans or plants. The optimal growth environment is especially necessary for the plants to achieve a high yield. Usually the subsystems of this group are combined in the ECLSS of the spacecraft, but it is suitable to split the functions into different subsystems when analyzing greenhouse modules. Here, the Atmosphere Control Subsystem (ACS) monitors and controls the humidity, the composition and the pressure of the air. It also has to filter the air and assure circulation through the whole greenhouse module. Humidity and air composition have an especially great impact on the growth rate of plants. Usually, the ACS of greenhouse modules is connected to the ECLSS of the habitat to allow gas exchange.

The Water Control Subsystem (WCS) monitors and regulates the water distribution and water quality. The main task of the WCS is the delivery of the desired amount of water to every plant in the greenhouse module to achieve an optimal growth rate. Water quality is also important for the growth rate of plants. The WCS of greenhouse modules have a connection to the water management system of the habitat, therefore, the WCS must be capable of storing a defined amount of water for cases of emergency.

The task of the Lighting Control Subsystem (LCS) is to provide and maintain the illumination of the greenhouse module. Lighting for the crew who work there must also be considered. The plants need specific lighting for an optimal growth rate, which depends on the light spectrum, the light intensity and the illumination phases. Required lighting conditions differ between plants species, so consequently the LCS has to provide the optimal lighting conditions for each plant species for the maximum yield. When the greenhouse module uses the sun as a light source, the LCS has to regulate the irradiation of the sunlight.

In spacecraft, the Thermal Control Subsystem (TCS) maintains the temperature of all components at every time of the mission within their limits (21). The TCS of greenhouse modules has to fulfill the same functions, where the critical elements for the TCS are the plants. Different plant species have specific requirements for temperature requiring different temperature zones in the greenhouse module. The TCS has to maintain the requirements of each zone. The thermal insulation of the greenhouse module is also part of this subsystem, which has to ensure that the heat loss to the environment and to other parts of the habitat is as low as possible to reduce the energy demand of the TCS. Depending on the lighting source, special cooling devices are necessary to protect the plants from overheating.

The third group of subsystems, the Fundamental and Interface Subsystems, constitute the framework of the greenhouse module. The functions of the Structures and Mechanisms Subsystem (SMS) of greenhouse modules and spacecraft are similar. According to (22), the SMS is the mechanical support of all other subsystems and its structures have to withstand all applied loads during the whole mission as well as serve the function of radiation shielding. Furthermore, the SMS is responsible for all mechanisms used in greenhouse modules. Unlike the electrical power system (EPS) of spacecraft, the Power Control and Distribution Subsystem (PCDS) of greenhouse modules does not generate or store electrical power, it only controls and distributes the electrical power provided by the electrical power system of the habitat (23). The PCDS has to supply each of the other subsystems with the voltage they need, to assure the subsystems can work as desired. In case of emergency, greenhouse modules can contain batteries or other power supplies. The power demand of greenhouse modules depends on the power consumption of the other subsystems; in general the Environmental Control Subsystems have the highest demands, especially lighting (LCS).

The Command and Data Handling Subsystem (CDHS) of greenhouse modules has to fulfil the same functions as in every spacecraft: receiving, validating, decoding and distributing of commands to other subsystems, and gathering, processing and formatting of data as well as data storage. Security interfaces and computer health monitoring are also functions of the CDHS (24). In order to maintain optimal growth conditions for plants in greenhouse modules, the CDHS has to interpret the signals of several sensors to send suitable commands to each subsystem. The higher the level of automation of the greenhouse, the higher is the complexity of the CDHS. When the CDHS is a physical part of the greenhouse module, it has to be protected against the high humidity and temperature inside the greenhouse.

The Human Factor: Personal use of greenhouses

While the incorporation of time saving technical systems will be important for the smooth operation of greenhouses, personal use of greenhouses in individual areas of the structure will also prove beneficial for recreation and relaxation, and thus overall mission success. While crew time needs to be minimized for regular maintenance of edible plants and to keep basic life sustaining elements available, recreational plant caretaking may be allowed more time (depending upon the preferences of the crew). However, this time should not be essential to the physical health of crew members, and rather should be akin to pruning, which can be endeavored within a window of time for plants' overall wellbeing.

Many people find gardening and plant maintenance to be calming and soothing. Also space-travelers confirm

Img. 6 Antarctic Research Station WHERE WHEN view by artist Connie Samaras

the importance of tending plants to keep themselves occupied during their free time and to encourage interaction of the crew with living beings in a technologically mediated habitat. (14) This effect is measurable in that the difference in brain activity is significant between the high frequency beta waves of rational thought necessary for day-to-day work operations and the slower alpha and theta waves produced by repetitive activities conducted in a relaxing way, such as planting seeds, watering, and tending to plants. (25 p. 80)

Areas for personal use of greenhouses that go beyond maintenance can also be incorporated into the architecture of planetary greenhouse environments. Planetary greenhouses can command a larger total footprint than the economy of a space capsule and can be integrated within the living environments in various ways; for example, to mediate views to the outside planetary surfaces, to provide sheltered "homey" environments rich with fresh oxygen where social activities might occur, or provide alternate work and exercise environments. As on Earth, it will be important for people living in remote and enclosed spaces to feel there is some choice of location for activities such as eating, work, rest/relaxation and exercise.

Future goals

To have a garden in space is deeply connected to dreams of finding life on other planets, and even sentient life. NASA Ames planetary scientist Chris McKay, who has long been an advocate for planetary exploration in order to further astrobiology, will support a new project, *Lunar Oasis*. This venture of private corporations intends to grow the first plant on the Moon. "The first plant to grow from seed and complete its life cycle on another world will be a significant step in the expansion of life beyond the Earth," McKay is quoted on the Odyssey Moon Ltd. website. "The sooner we do it the better," the scientist says. (26) Clearly McKay is pointing to a benchmark; much like having the first animals and then humans orbit the Earth, the first plant grown in space heralds a paradigm shift—the dawn of a new Garden.

IV. KEY THESES TO CREATE HUMANIZED GREENHOUSE DESIGN

Following a review of past greenhouse designs and users' experiences, the authors have itemized the benefits of integrating greenhouses into the space habitat design process for humans as follows:

IV. I. Humans need plants to maintain health, both biological and psychological

Dr. Fred Davis, AgriLife Research Faculty Fellow at the Texas A&M University, researches low-pressure controlled food production environments for NASA. He commented that for astronauts "just biting into something with some turgor [ie. skin membrane] to it, and not having a diet limited to reconstituted foods has important psychological benefits." (27)

Davis reports that a greenhouse at a U.S. Antarctic base which supplies salad bowl crops is "one of the most popular places on the base, where crew members will retreat from the cold, white, barren, snow-capped landscape to recharge, rest and nap in hammocks stretched across the green visual of live, growing, green plants." The mental image is almost Edenic with all "those bright, light colors, aroma, texture and flavor of plants." Davis concludes, "Small wonder that the greatest pastime in the U.S. is gardening. It will also be an important activity as humankind colonizes space during the 21st Century." (27)

In contrast to the current strategy not to bring strong smells in space in order not to disturb other crewmembers, the introduction of recognizable scent and tastes is being considered. (28) (14 p. 185, 195) One obvious way to do this is through food. "Anecdotal reports state that healthier and tastier foods will decrease the stress often experienced by the crew. This suggests that taste, menu variety and an array of textures, colors and flavors can contribute to the psychosocial wellbeing of the crew." (19)

The experience of micro-gravity causes blood to pool in the head and chest, and sinus cavities to fill with fluid, creating congestion and hindering the sense of smell. (29) The same mechanism may also affect astronauts' taste buds, along with other factors like the sterility of the cabin environment, creating a need for sauces and spices to make food palatable and interesting. (28)

Food systems in space have changed to a large degree over the past years. While for the early astronauts "food was just taking medicine" now astronauts are experimenting with "space-cooking" in order to increase the variety. (14 p. 213, 218) Vickie Kloeris, manager of ISS food systems at the NASA Johnson Space Center in Houston says, "Food is a comfort that [the astronauts] would like to feel they have some input on or some control over…. [It's] psychological—I don't know if we've flown anyone to the station who hasn't been concerned about their food." (28)

Early during the Salyut missions it was learned that plants and dealing with the greenhouse had a positive psychological effect on cosmonauts. During the Salyut and Mir era, to boost morale and fight against loneliness or depression, surprise leisure activities were organized for the crew from the ground and gifts were sent with the Progress freighters. (7) In 1979, the Salyut 6 cosmonauts Valery Ryumin and Vladimir Lyakhov received flowering tulips and a kalanchoe plant growing in a *Vazon* as a gift. (11 p. 155) According to Zimmerman, they were so happy they gave the plant a name: "life tree." (3)

Anecdotal references show that besides their regular duties, astronauts also enjoyed doing experiments with plants and observing them grow. One of the Salyut cosmonauts placed his sleeping bag next to an *Oasis* greenhouse, in order to see the plants progress immediately after waking up. During the Shuttle-Mir missions Mike Foale seemed not only to like the plant experiments, for him it was a "very encouraging" activity, as he reported after the seeds he had planted showed sprouts with leaves. (14 p. 213) (30 p. 82)

Rationale for integration and benefits

Using vegetables and herbs in space can increase the variety of menus available to astronauts. The possibility to personalize food in taste and texture provides choice, which is key to human psychological health. The integration of key vegetables and fruits like tomatoes, spinach and strawberries provide extra nutrients that are absorbed differently than supplemental vitamins. An increase in natural fiber will also benefit human digestive systems.

Documented testimonials about how noxious space capsules can smell suggest plants have another important function for humans in space. Plants that suggest "freshness" can normalize the environment of astronauts on long-term missions and deal with a certain amount of indoor "air pollution" cased by humans themselves. We must remember the early days of space travel through the words of Apollo 15's Jim Irwin, who attested, "I began to smell like a restroom…. It got so I couldn't stand my own company." (1)

Additionally, it will be worthwhile to experiment with growing medicinal plants and herbs for stress relief and common ailments—chamomile, mint, lavender, echinacea, and yarrow being just some of the many—or aloe vera for wound care, and others for pain relief from illness or injury. Pharmaceuticals have greater strengths, but every chemical ingested by a human in space potentially makes its way back to many through the closed loop system; in which case, metabolized organics may be preferable. In other instances, a person simply having the choice of remedies may feel better due to our strong belief systems that are key to maintaining holistic wellness.

Plants mitigate toxicity and can contribute to the health of humans not only in terms of direct ingestion but also just in their passive existence. Spider plants, ferns and other species absorb volatile organic compounds which can be of harm to humans, can cause allergies, and which are commonly given off by glues, resins, rubbers, and various materials that may be used in the construction of long-term space flight architecture or planetary habitats. Air filtration systems in enclosed modules are of utmost importance; however, within close range of immediate sources of potential toxicity, plants can help stay off negative effects.

IV.II. Humans develop relationships with plants, and through plants, to each other

Individually owned plants can provide companionship and comfort to an individual spacefarer in ways unique to that person. On Salyut 1, the first flax seed sprouts were tended to devotedly by crew members Viktor Patsayev and Vladislav Volkov. “These are our pets,” were Patsayev’s words. “They are our love,” said Volkov. (3)

Humans benefit when they have time away from the heavily structured regimen of the spacefarer’s workload. (26 p. 137) Integration of plants on spacecraft provides the possibility for free-time activity that is personal, quiet, but also contributes to the social fabric of the ship or colony. Kanas and Manzey report that territorial behavior can result if private spaces are not adequate when people are living long-term in confined spaces and under “prolonged isolation.” (30 p. 134) Each astronaut having his or her own little “plot” of land could be an effective countermeasure and promote crew cohesion by differentiating personal spaces from community gardens.

In long-term space missions or on Moon or Mars bases, there will be more down time than experienced so far by astronauts. Short flights have meant astronauts are too busy for activities. Notes Oliver, “After labouring across twenty feet of open space to retrieve an experiment package from an inert Agena rocket, Gemini 10 astronaut Michael Collins imagined what he might have said about the experience: ‘*I found God outside my spacecraft.* Wrong, I didn’t even have time for look for Him.’” (1)

The contemplative aspect of life with plants can be seen as a compliment to basic human need for connection to living things. Oliver reports that astronauts primed for spiritual experiences through their former activities and frames of reference were changed by their experiences in space. (1) The question remains open as to what influence space gardening might have; the realization of the Earth as a whole is a common point of epiphany and it changed several astronauts’ futures when they returned to Earth. (1) Kanas notes people have become “more humanistic, religious, or spiritual after observing the oneness of people on Earth or the infinity of the Cosmos.” (31 p. 160)

In his 2010 TED talk “Calculus in Architecture,” international renowned architect Greg Lynn started his lecture referring to nature as an example of “good architecture.” Architects, designers and engineers have studied principles in nature in order to find innovative solutions over centuries. The research fields of bionics and biomimetics, wherein systems and design solutions from nature are studied in order to develop innovative technical and engineering solutions, is widely recognized and has growing interest.

Humans have long been fascinated with plants’ physical forms, and specific plants have given rise to human cultures—as the basis for rituals, traditional foods, decoration, and perfumes, all of which bond communities—as well as architecture, from the traditional Nipa hut made of palm fronds to the form of the Acanthus plant on the capitals of Corinthian columns, later substituted with ears of corn when Americanized.

Plants have been described by poetry, music and math (from the golden mean to fractals). Plants have also played an important role in the history of human aesthetics. Thus, greenhouses in space can form an interface with other leisure forms like music, art and literature. The use of plants historically as metaphor, from the complex Victorian language of flowers, to the Japanese haiku, provide endless examples of culture manifesting through the observation of nature. Inspirations for poetry and philosophy come close on the heels of this type of activity. Including specific plants on space missions that have unique properties like scents, or aesthetic forms, or particular cultural meanings to people who are part of the journey can only benefit the community as a whole.

Rationale for Integration

There is a demonstrable need for communal greenhouses as well as personal "green" spaces: humans like to take care of plants, the smell of plants is connected to memories and emotions, plants are aesthetically pleasing and connect people to specific instances of their cultural or family background. Plants provide unique spaces for meditative and relaxing thoughts, and the oxygen-carbon dioxide exchange between humans and plants makes them ideal for integration in exercise locations. With special attention paid to allergies and potential negative interactions between plants and humans, the optimal "greenscaping" of space architecture can take place. Plants and humans collaborate in the health of space-faring environments.

Future investigations

Support systems for plants have to be highly regulated and consistent. Space Shuttle and ISS experiments in astroculture confirm that efficient lighting systems in red and blue LED's are best for seed germination. (2 p. 184) Some seeds grown in space have proven to be potentially more robust when brought back to Earth, having experienced slight genetic modifications. (2 p. 185) Plants with short life cycles like *Arabidopsis* are favored for study because of this; a wide variety of others should be identified.

The vegetable kingdom contains plants like algaes that hold the promise of alternative energy, and nutrient-dense food. Fungi might be useful in a different manner as they can very quickly and efficiently decompose waste products into rich fertilizers. Some molds and fungi, however, can pose a threat to human health, and are difficult to control sometimes necessitating the eradication of the affected plant. Taking experience from Earth, the spread of a communicative disease among plants poses a danger and therefore having diverse strains of crops rather than monocultures seems preferable. Biological treatment options should be explored to reduce the use of unnecessary fungicide chemicals.

IV.III Technical space is 'humanized' by plant-human relationships

Stimuli

Highly technical spaces are aesthetically neutral, supremely functional, "cold" (devoid of personalization), and often visually crowded. Plants add natural colors without over-saturating such spaces. The Soviet stations Salyut and Mir space station integrated a muted color system to mimic Earth orientation (walls and ceiling), but also to improve mood. "A limited variety of color of medium brightness and saturation" are recommended by NASA, according to Kanas, including "cinnamon, beige, cream, maize, straw, ivory, pale yellow, and blue." (30 p. 135)

Technical spaces demand certain kinds of attention due to instrumentation, rigid operational systems, and surfaces that are highly specialized. Plants can "humanize" these spaces because they are not functions of human will but symbiotic partners. Vladimir Gushin, a psychologist at Russia's Institute for Biomedical Problems stated in an interview, "Confinement on the space station isn't the problem, it's a lack of stimuli…. Plants are one of the opportunities that makes [astronauts] feel something is changing, that nature is with them, a piece of earth is with them…. That gives them the feeling … of Earth, of life. From this [perspective], nothing can substitute for plants." (13)

Time

Plants are connected to all aspects of human culture and language. Michael Pollan in *The Botany of Desire: A Plant's-Eye View of the World* (2001) details plants that have adapted to integrate into human life in such an intertwined way as to make themselves indispensible—specifically, apples, tulips. marijuana, and potatoes. Which plants will be necessary and desired for our habitation of outer space?

Metaphors generated from the vegetable kingdom relate to our reproductive capacity and life cycle: a child grows "like a bean sprout;" a young woman "blossoms;" we are in the "autumn" of our lives as we age; and as for the next generations being like their ancestors, it is said "the apple doesn't fall far from the tree." The ancient Maya were "the people of the corn." Which plants will become the choice metaphors for those who live outside Earth's orbit?

The answer may lie in one of the most important and obvious, but perhaps overlooked aspects of plants in space. They have the ability to mark time, though it is "slow time." Away from normal diurnal cycles and in the absence of seasons, plants provide an important measure for human life. It is already determined that twenty-four hour schedules result in better crew performance and health due to maintenance of circadian rhythms (31 p. 137); but in long-term space missions we must also be concerned with yearly cycles.

Because plants are constantly changing, mute but alive, they need human attention in a very different way than a machine does. The environment provided by technology has been designed by humans, but the plant is designed by another force. This in itself provides a necessary contrast to human fantasies of ultimate control. In this way, plants provide a reminder of humility and therefore as a side effect may also improve sociability among people.

Habitability

The unique physical requirements put on a greenhouse design for space architecture have to allow optimum production of food, fresh water and oxygen and include vital recycling processes to minimize waste production, while providing maximum crew mental health benefits with minimum mission costs. This calls not only for new technologies to stand up to these needs, but offers likewise the possibility to design an alternative greenhouse system combining agricultural and gardening requirements in the most effective ways.

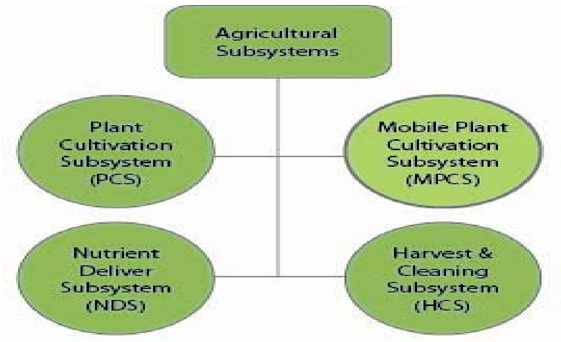
In this sense, greenhouses in space are a chance to revise on a design-level the relationship between mankind and nature, which on Earth is determined by conflicting design-philosophies, requirements and expectations of how humans should relate to nature. When designing those growing chambers for space habitats one could think of a piece of cultivated land, combining the art of gardening in its artistic and pastime expression and the art of horticulture for pure productivity—a combination that can be found in traditional rural agriculture. (6)

In the paper "Greenhouse design integration benefits for extended spaceflight," Haeuplik-Meusburger, Peldszus and Holzgethan have touched upon the topic of Japanese design philosophies and listed several design integration concepts, as follows: (a) Surrogate views through "green" windows, (b) Spatial enhancement: stretching the view using illusion and perspective, and (c) Individual interaction through modular growth units. (6)

In extreme environments, where the inclusion of windows means a potential risk for human beings in the habitat, "surrogate windows," such as an integrated greenhouse like the *Veggie System* (item a) can add to habitability. An adequate living representation of nature (flora and possibly fauna) in isolated environments such as space habitats could be of utter importance on long-term missions to Mars, where the visual connection to planet Earth will be no longer possible.

Furthermore, habitat designers can use greenhouses to add additional viewing layers and create sightlines that can enlarge the perceived space (item b). Kanas reports that such additions can psychologically "compensate for the effects of the otherwise decreased range of environmental cues in a space habitat." (31 p. 135)

The combination of individual mobile growth units (c.) with a larger greenhouse facility can further enhance the living conditions. Those mobile greenhouses could also be used to provide food supplement in pressurized rovers. Individual mobile units could also possibly act as countermeasures for psychological problems. We therefore propose an addition to the classification of greenhouse subsystems as proposed in Img. 4—the 'Mobile Plant Cultivation Subsystem (MPCS) (Img. 7).



Img. 7 – Mobile Plant Cultivation Subsystem

The emptiness of space can be psychologically difficult as detailed in Kanas, *Space Psychology and Psychiatry*. A type of anxious depression can manifest—"Long Eye Syndrome"—where someone gazes out of the window back toward Earth for long periods of time. (31) One can only guess that on a mission to Mars such a condition would become more extreme as the planet recedes into an unimaginable distance. One could also argue that this distress is not truly befitting psychiatric definition, for it is not a *mental illness* but is rather an understandable state of *melancholia*, one of the primary generative conditions of the poetic imagination.

The experiences of greenhouse systems, especially from a user-oriented point of view have led to the formulation of some key theses in order to create functional and humanized future greenhouse systems (cf. 6, 11). The case study of *bonsai* and *penjing* in Section V. represents a mini-garden solution to the condition by enabling the expression of poetic thought in personally specific ways by individual members of the crew and providing the buffer of a 'window' of green life between the astronaut and the immensity of outer space.

IV.IV Plants provoke the imagination: Poetic vs. rational/scientific thought

Historically astronauts have rated art "activities" lower in importance than communication with Earth and keeping up with world events, according to Kanas. (31 p. 158) But art forms that are a cross with gardening activities may make more sense to include on space missions than traditional art forms. It is worth noting that on Mir in 1993 the sculpture *Cosmic Dancer,* sent into space as "an aesthetic contribution to the astronauts' living quarters" by the artist Arthur Woods, featured the bright yellow-green colors of nature to contrast with the Mir interior. (32) Also Valentin Lebedev (Salyut 7) said: "Many little details, such as photographs … flowers, and green plants in the garden, turn this high-tech complex into our warm and comfortable, if a little bit unusual, home." (12)

To best understand the place and benefits to the lives of astronauts of plant-inspired art, we look to the French philosopher of science, Gaston Bachelard and two of his most important works, "The Experience of Space in Contemporary Physics" and *The Poetics of Space*. Where do reason and science meet the imagination—"a cosmic force"? (33 p. xiii) For Bachelard, they join in the "material imagination," which germinates from "images of matter" and the sense of "permanency present in things." (33 p. xiii)

Contemplation is a key activity in this state of mind. The 'seeds' born in moments of *deep-looking* (creating alpha brain waves) or *daydreaming* (creating theta brain waves) give rise to instantaneous images, which Bachelard defines as poetic because they simply appear. These images have no historical antecedent of thought, emerging suddenly and as whole images. Bachelard contrasts poetic thought with scientific rationalism, which necessitates building upon past knowledge using logic in order to think through the next steps in a developing chain of discoveries. Poetic thought comes from a different place—it is as isolated as the Earth itself seen out the window of the space module, surrounded by emptiness and vastness, and in this, Bachelard writes, there can be an "ecstasy" found in its newness, "a sudden salience on the surface of the psyche." (34 p. xv) The inherent nature of the poetic is its surprise.

For the astronaut, the surprise of poetic thought—like the moment of a seed's germination—would be a key counterbalance to the routines of space life, to boredom (31 p. 137) and the doldrums, an antidote to the quiet internal suffering of being a human contained in such a small space. Through poetry, there is expansion of thought, as in the works of astronaut Dr. Story Musgrave: "... Sculptured by the seasons, listening to Nature's reason, Grew I, rooted in the ether." (35)

The poetic image is fleeting; it appears from a wellspring of the imagination and marks the mind in a manner akin to the process of making a solargram (Musgrave: "The Sun and I streaking across the sky." (35)—the poetic image is both the flash of brilliance and the object registered indelibly on the imagination. What is this image? What is this object? And can a plant provide such a location for it to become?

V. SYSTEM INTEGRATION AND CASE STUDY: *BONSAI* AND *PENJING*

While the Plant Cultivation Subsystem (PCS) supports the plants during all development stages and contains the growth medium for the plants in the main chamber, its mobile version (MPCS) supports the same activities when separated from the main chamber. The greenhouse system can host individual and mobile greenhouses together and, when connected, the MPCS is part of the automated system. This option is important because of human-related aspects. In case the crew is on a rover mission, is sick, busy with a pressing or emergency matter, or in between regular maintenance schedules, the MPCS is no extra work.

While these mini-greenhouses can host different kinds of plants, depending upon individual preference, we propose The Bonsai Case study to examine how plants grown and cared for in the stable automatic conditions of the PCS could then be separated as a module for personal use. When the astronaut uses the MPCS, he or she is responsible for all matters of care and feeding of the plant/s. The benefits for long-term space travel of the MPCS will be explained in the following sections with context given to the way and personal plants have been cultivated in Asian cultures for centuries.

The Art of Bonsai

The traditional Japanese and Chinese art forms of *bonsai* and *penjing* feature miniaturized landscapes, either as a single potted tree ("*bonsai*"), or a naturalistic scene, featuring rocks and varying sizes of trees in forests. Through these gardens the eye plays with the illusion of distance while exploring the real vicinity of the dwarfed tree or landscape.

Not only do the histories of these art forms tell us something about human imagination, but due to the size of their realization, the practice could be incorporated into space programs and inform requirements for greenhouse design and MPCS modules.

Paterson has become a participant-observer over two years of study with *bonsai* master Roy Nagatoshi in Sylmar, California and her continued maintenance of thirty self-designed *bonsai* trees and *penjing* landscapes, committing several hours a week to watering, pruning, designing, propagating, potting and overall tree health, as well as studying the history of *bonsai*. Through social relationships formed in Nagatoshi's workshops with other participants, additional advice, skills, and knowledge have been attained to reinforce the following observations.

The art of *bonsai* is the creation of aesthetically pruned trees, as in the slender single trunk *Bunjin* style, rarely found in nature, or forests of trees, both deciduous and evergreen. It is an illusionistic art, and relies on the power of human psychological projection to imagine the small tree/s isolated in a pot/display as if they were full scale.

Penjing, an ancient Chinese art of creating miniature potted landscapes including moss, rocks, different sized trees, environmental effects, and even statuary, works also with the tropes of miniature. Like *bonsai* forests, *penjing* landscapes feature complete worlds, a collective of moments in nature. The pieces come together like a puzzle, consolidating into a singularity.

Miniature forests

Miniaturization is a privileged activity for the philosophical investigation of the world, as seen when one reads Bachelard. Revealing his personal exploration of its effects on the psyche, he writes, "To have experienced miniature sincerely detaches me from the surrounding world, and helps me to resist dissolution of the surrounding atmosphere." Miniature is both a release for the observer, and something that keeps "dissolution" or evaporation of the self/context at bay. He continues, "Miniature is an exercise that has metaphysical freshness; it allows us to be world conscious at slight risk. And how restful this exercise … can be! For miniature rests us without ever putting us to sleep. Here the imagination is both vigilant and content." (34 p. 161)

Bonsai, penjing and miniaturization in general are perfect art forms to be used by the space farer. Bachelard: "When we examine images of immenseness, [we find that] tiny and immense are compatible. A poet is always ready to see large and small." He then quotes *Cinq grandes odes* by Paul Claudel, who "in his cosmogony was quick to assimilate the vocabulary—if not the thinking—of contemporary science." Claudel: "Just as we see little spiders or certain insect larvae hidden like precious stones in their cotton and satin pouches / In the same way I was shown an entire nestful of still embarrassed suns in the cold folds of the nebula." Bachelard compares the agility of the poet to seeing simultaneity "through a microscope or a telescope." (34 p. 172)

Forests are also privileged sites for Bachelard, who considers them almost as paralleling the infinity of outer space in their "immediate immensity." (34 p. 186) Reverie, deepness and intimacy all exist in the forest at the same time for one who wanders through. There is silence, age and history there, and the thought of other creatures, invisible to the eye, sharing the space.

Bachelard's writings are from the late 1950's, the first space age, but reflect critically now on the project of people who want to extend life on Earth beyond, and to find out who and what else might be living "out there." The forest itself is an apt metaphor for the space wherein the astronaut ventures, a "vast" space—says Bachelard, we should take care to pronounce the long-"a" very carefully—through which calm also radiates, like a breath. (34 p. 197)

Img. 8 – Miniature forest of pomegranate and Chinese elm ("Root over Rock") in front of window on the Kibo Laboratory, ISS (image and bonsai forest: C. Paterson)

Care of *bonsai* in space

More can be explored within the art forms of *bonsai* and *penjing*, but this must be done in greenhouse environments designed for extra-planetary missions. Bonsai only need attention at intervals. After wiring a bonsai it needs time to grow into the set form. For juniper trees this is about one year, for example. In that interval, the bonsai tree is an object of decoration as much as it is a living creature. Yet its foliage needs routine maintenance several times a year (to be reduced) so that the tree puts its energy into continuing the desired growth pattern. For deciduous trees, time is needed to let the tree grow new branches, which have to be clipped regularly after two buds appear. This creates the desired ramification effect so that the tree's branches are complex, like a full-grown tree.

Several interesting issues present themselves for both the larger MPCS design and smaller detachable PCS systems, including how one might design a tree differently in micro-gravity, using certain tree types like elms that have photophilic root systems and could therefore be planted in various types of containers, facilitating the use of hydroponic systems or vacuum-forced water feeding systems to emulate gravity. Light sources, normally considered as coming from above, might need to be below, if the stability of a light table and more light intensity is desired. It is clear this is more complicated in the MPCS as a battery energy source would be required. The nutrients necessary for optimal plant health, as well as cures for plant ailments, will also be unique to the outer space environment. In MPCS modules feeding tubes would have to integrated into the design.

Traditional ceramic pots, as much a part of the aesthetic creation as the tree itself, will be too heavy for space travel. However, waste products (sludge) if freeze-dried to kill bacteria, could serve as a nutrient-rich container that could also be worked by hand as if it were clay. These forms made by astronauts into individualized MPCS components could have additional aesthetic interest. The Japanese dried clay-like Akadama soil, which holds water near roots without drowning them as dirt can, could be substituted with a more lightweight version, an "aeroclay" (freeze-dried clay), requiring technical experimentation at zero or micro gravity.

Because *bonsai* is a difficult art to master, and takes many years of observation and experimentation, astronauts or test subjects committed to the exploration of the idea would probably have to start years in advance. This would create another continuity between a person's life at home and his or her life beyond Earth's orbit, with positive implications for post-mission readjustment.

A view toward the future

Each part of a forest, or the mere fact of a "tree," has a reference in the memory and experience of the astronaut, However, Bachelard distinguishes the poetic image from memory in an important way. Memory is attached to specifics of the past, of lived life, of inherited space. As poetic images, *bonsai* and *penjing* materialize not the past as much as the future—the miniaturized, stylized tree in space becomes not an echo of the Earth left behind, which may cause sadness, regret, or fear. Rather it is a place always of the future—it can be changed, it will grow, it will become. As anyone who has worked with *bonsai* will understand, the art form is a constant exercise in patience and vigilance. The trees are sculpted in stages and one has to endeavor to see the tree as it *will be* years into the future, not how it looks in the present.

Habitability issues in man-made extra-terrestrial environments do not just demand technical or architectural responses, but also consideration of the unique philosophical, emotional, existential and aesthetic conundrums of living and being human in the most extreme circumstances of limitation. Having hope in the future of a plant, no matter how small, to look forward to its growth, its change and to be a collaborator with the tree in bringing about a future poetic image, is what makes these art forms particularly appropriate for inclusion on long term space missions and in extra-planetary habitats. They look to the future, like a "Memory Game" card that waits to meet its double, somewhere in the mind.

VI. CONCLUSION: HUMANS NEED PLANTS TO SURVIVE OUTSIDE EARTH

No matter how "remote" the locations for test greenhouses are on Earth, plants therein ultimately have a utilitarian function because they are understood in relationship to the plants located just miles away in contiguous environments. In space, on the contrary, there is a paradigm shift—plants are now traveling companions that are possibly even born in space, part of the effort to migrate terrestrial life away from the planet. The stakes are higher for keeping plants alive and cultivating their bounty. There is more potential emotional attachment to plants in space due to their potential loss and, in the case of *bonsai* or *penjing* landscapes, the fact they are irreplaceable. As such, advanced and multi-functional greenhouse systems have to be well tested before they are incorporated into the space program—not having something at all is different than having a vital system functioning and then losing it. The effects of such "system failure" especially in MPCS, where one astronaut is ultimately responsible, could be psychologically troubling.

We might also consider a few science fiction scenarios while thinking about the future of greenhouses in space. The genetic similarities between plants and humans are not so great as to preclude some kinds of creative hybridization. Plants can preserve or carry fragments of human DNA as demonstrated by bioartist Eduardo Kac in his work *Natural History of the Enigma* first exhibited in 2009. Kac has created a genetically engineered flower he calls an "Edunia," a cross between himself and a petunia. The flower expresses an isolated gene from Kac's DNA in its red veins. This gene is "responsible for the identification of foreign bodies." He remarks, "In this work it is precisely that which identifies and rejects the *other* that I integrate." (36) The artwork poses many questions about the perceived boundaries of human life and our cohabitation on the planet with the vegetable kingdom.

In the event of non-human viability, plant-human hybrids could colonize another planet, or live in space with robotic assistance as emissaries of Earth life. Douglas Trumbull's 1972 film *Silent Running* does an excellent job of visualizing the latter complete with Joan Baez lyrics to accompany the protagonist in his regular walks through the large garden dome he tends orbiting Saturn.

To close with a contemporaneous quote from Joni Mitchell, "We are stardust, we are golden. We are billion year old carbon, and we got to get ourselves, back to the garden."

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