IAC-14-A5.1.9

ARCHITECTURAL CONCEPTS FOR A LUNAR GREENHOUSE WITHIN THE MELISSAFRAMEWORK

Katarina Eriksson
Märka Design, Sweden, katarina@markadesign.se
Dr. Ondrej Doule
Florida Institute of Technology, Human-Centered Design Institute, FL, USA United States, odoule@fit.edu
Lucie Poulet
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany, lucie.poulet@dlr.de

This paper describes the space architecture research and rapid concept design of a large greenhouse module (GHM) for the extreme environment on the Moon, considering all aspects of construction and utilization from an architectural perspective. This study is made in the frame of the project "Greenhouse Module for Space System", led by the EDEN (Evolution Design of Environmentally-closed Nutrition- Sources) group of DLR Bremen for the ESA MELiSSA (Micro-Ecological Life Support System Alternative) project. This greenhouse module is one of the producer compartments of the MELiSSA loop, a regenerative closed system based on micro-organisms and higher plants to recycle organic wastes of the crew, revitalize the atmosphere, recycle water, and produce food. The greenhouse concepts are based on the required plant growth volumes for sustaining a crew of six on the Moon for two years. Three different concepts for external configuration are presented together with examples of how they can be outfitted internally with growth accommodations and supporting functional areas as well as space for accommodating subsystems. The greenhouse structures are composed of rigid, rigid deployable and flexible deployable components in different configurations, optimizing volume and mass, in three concepts demonstrating the principal differences between the structural concepts. The greenhouse subsystems are estimated based on currently available off-the shelf systems and the greenhouse operations consider both human and robotic greenhouse maintenance and are reflected in the architectural solutions. The interior layouts demonstrate different plant arrangements and different degrees of automation for compact placement of the plant growth structures, while allowing for reasonable working conditions for the astronauts. The three concepts presented in this paper are innovative outcomes of diverse requirements given by the MELiSSA project and provide different holistic views on the greenhouse design for extreme environments. They include all aspects of the space flight logistics, deployment and operations on the lunar surface and serve as preliminary architectural options for further evaluation of the different concepts.

I. INTRODUCTION

I.I Rational to grow plants on the Moon

Sustaining humans out of Low Earth Orbit (LEO) for several months has not been done yet. According to the NASA Advanced Life Support Baseline Values and Assumption Document [1], a two-year mission on the Moon (excluding travel, descent, and ascent time) would require 2.7 tons of dry food and 17 tons of water to sustain a crew of six astronauts. If we add up oxygen and hygiene water, we end up with a total of 57 tons of consumables necessary to sustain a crew of six on the Moon for two years.

Currently the maximum payload launch is reached by Delta IV Heavy with a capacity of 22.56 tons to LEO and 12.98 tons to Geostationary Transfer Orbit (GTO); and the future European heavy launcher should enable delivery of one to two tons of payload to the lunar surface [2]. With current launch systems it would thus require at least 27 launches to get all consumables to the Moon to sustain a crew of six for two years on the surface. Considering that the cheapest heavy launcher is the Chinese Long March 3B costing $11,538 per kg to GTO, launching all consumables from the Earth to the Moon is not an option [3].

A realistic solution would be to cultivate higher plants on site and combine them to regenerative life support systems, thus enabling regeneration of atmosphere and water. In addition to providing fresh food to the crew, with all the health benefits associated (vitamins, minerals), plants are very important for the crew well-being in isolation [4, 5] and non-edible parts of plants could also be used for manufacturing objects.

ESA and DLR have joined forces and are currently working on a common project aimed at estimating how much it would take in terms of energy & power, mass, crew time, and volume and how feasible it would be in terms of technology readiness level (TRL), risks, and complexity to deploy and operate a greenhouse module on the lunar surface. Previous studies are indeed based on technologies and data which are now outdated and so there is a need to reassess and update these variables to evaluate what it takes to grow plants on the Moon.

I.II Research Teams

The EDEN research group (Evolution & Design of Environmentally-closed Nutrition-Sources) of the German Aerospace Center (DLR) was founded in 2011 at the Institute of Space Systems in Bremen and focuses on Controlled Environment Agriculture (CEA) technologies for plant cultivation in greenhouse modules. Projects of the EDEN group range from the design of greenhouse modules for future space habitats to greenhouse module testing in Earth-analogue test sites (Antarctica).

The MELiSSA (Micro-Ecological Life Support System Alternative) system is conceived as a closed artificial ecosystem based on microorganisms and higher plants. The organic wastes (feces, urea, and inedible parts of higher plants) are broken down into nutrients necessary for the higher plants, which can then use up the carbon dioxide and produce oxygen, food and regenerate water. MELiSSA not only enables technology development for future regenerative life-support systems necessary on long-term manned space missions, but also enables to study and understand behavior of artificial ecosystems.

Märka Design is a graphic company targeting the space industry, and has previously collaborated on projects for bio-regenerative life support systems for lunar bases.

Florida Institute of Technology, Human-Centered Design Institute is representing know-how in the area of space architecture design for planetary, analog bases and self-deployable habitats.

I.III Pre-concept definition study

Three architectural greenhouse module concepts are presented in this paper, from which one will be chosen for further analysis and development in a concurrent engineering study during fall 2014.

The basis for the internal layouts is a detailed literature review and evaluation of existing concepts for space-adapted growth structures. The plant growing volumes and areas needed are based on NASA and ESA-MELiSSA plant growth data [6] [7]

The three architectural concepts presented are classified according to structural types:

- Inflatable
- Hybrid (combination of rigid, deployable and inflatable)
- Rigid

All structures are composed of rigid, rigid deployable or flexible deployable structures. The internal configuration of the structures including growth accommodation and fitting of subsystems is also addressed in this concept phase. Lastly, two different lighting options for plants, electrical and hybrid (a combination of electric and natural light), are compared.

II. CONTEXT/ASSUMPTIONS

II.I Requirements

The functional, performance, environmental and product assurance requirements for the greenhouse module are given in Table 1.

II.II System borders and main assumptions

A previous study on lunar environment (topography, illumination, temperature) determined that the greenhouse module would be placed on the rim of Preary crater, in the North Pole, between latitude 89.34 and 89.39 and longitude 126.21 and 131.09.

This study assumes that the greenhouse module is to be integrated into an already-established lunar base which relies on shelf food and a primary life-support system based on conventional Life-Support System (LSS) technologies prior to the deployment of the greenhouse module. The greenhouse module is part of the MELiSSA loop (Figure 1) which constitutes the primary life-support system of the habitat once operations within the greenhouse module are steady. The main tasks of the greenhouse module are the production, processing, storage, and distribution of crops, as well as revitalization of the atmosphere, and purification of water.

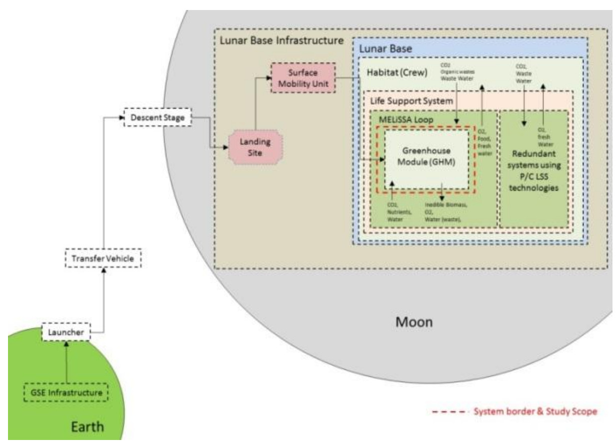

Figure 1: Greenhouse module system borders.

The main assumptions for this study are following:

• All necessary infrastructures (e.g. launcher, transfer vehicle, lunar base infrastructure) are present.

• Launch & ascent, planetary orbital & transfer phases as well as decent phase are out of scope of this study.

• The greenhouse module is integrated into the MELiSSA loop and therefore receives its inputs (water, CO_2, nutrients) from the loop and sends its outputs (harvested crops, inedible parts of the plants, O_2, fresh water) to the loop (Figure 1). In case of failure of the MELiSSA loop, the redundant LSS takes over and the greenhouse module exchanges CO_2, O_2, and water with it. Wastes from the plants are stored in a waste storage in this case.

• Overall wastes from the greenhouse module are managed by the MELiSSA loop. The greenhouse module does not include a waste management system, only a short-term waste storage.

• The seeds for the cultivation process will be part of the greenhouse module system from the beginning and will last till the end of the mission. No seed-to-seed production is foreseen during the mission.

• Thermal management is not part of the greenhouse module itself, it is performed by the habitat. The greenhouse module includes a thermal interface with the habitat for its own thermal regulation. However an emergency heat exchanger between the greenhouse module and the outside environment is included in case of extreme thermal load.

• The power generation is not part of the greenhouse module. It receives power from the habitat infrastructure. Only in case of extreme power demands, a separate power conversion unit will be considered.

• Food processing of raw crops is not part of the greenhouse module.

Class of requirement	Description
Required plant production	The greenhouse module shall produce the following crops: soybean, bread wheat, durum wheat, potato, lettuce, beet, rice The greenhouse module shall make available to the MELiSSA loop, on a monthly basis, the following dry mass of edible crops ± 10%: Soybean 25,000 g Durum wheat 31,000 g Bread wheat 33,000 g Potato 41,200 g Lettuce 1,000 g Beet 2,200 g Rice 38,000 g
Environmental requirements: Required growth conditions	**The greenhouse module shall provide the following environment to the crops:** **Illumination** Daylight levels of 250-600 µmol/m²/s Night levels 0 to 10 µmol/m²/s **Temperature** Air: controllable between 20°C and 30°C Water: controllable between 15°C and 20°C Absolute accuracy: ± 0.5°C **Flows** Air velocity 0.1-0.8 m/s Water supply in the roots 0.2 L/min **Nutrient solution** PH: 5.5 ± 0.5, EC: 1.9 ± 0.05 dS/m Dissolved Oxygen: 80 to 100% **Atmosphere** Pressure: 1010 mbar ± 20 mbar within 1 hour Relative Humidity: 50 to 85 % Composition: O_2: 20 ± 1%, CO_2: 300-2000 ppm, selectable and controllable during daylight levels, N_2: difference to 100% **Radiation** Absorbed dose by the plant 1000 µG/d (max)
External Environmental Conditions:	The product shall be designed and manufactured to withstand the following lunar environmental conditions: - Reduced gravity of the Moon: 0.167 g - Moon environmental pressure: 3.10^{-15} atm - Moon thermal environment, which temperatures on the ground are as follows: Dark side: 89 K; Illuminated side: 292 K. - Moon illumination environment (irradiation level and vector) at the selected location. - Moon radiation environment at the selected location.
Product Assurance Requirements	The greenhouse module shall operate at the selected location for not less than 24 lunar days (about two years).

Table 1: Requirements for the greenhouse module, ordered by class.

III. DESIGN REQUIREMENTS

The greenhouse module is a complex system integrated and stowed in a rocket payload shroud as a single payload. Based on requirements of this study and professional estimations based on human spaceflight standards for microgravity in NASA STD 3001 [8], NASA Integration Design Handbook [9] and numerous lunar structures concepts and studies (see [10, 11, 12, 13, 14, 15, 16, 17, 18, 19], [20, 21, 22, 23, 24, 25, 26, 27, 28, 29] and [30], the total required growth volume is 750 m^3 (table 2).

Species	Controlled Environment Area	Estimated support heights[mm]	Shoot zone [mm]	Root zone [mm]	Total height [m] (rounded)	Req. cultivation area incl. 5% margin for structure [m^2]	Overall volume needed , incl structure height and 5% margin for structure [m^3]
Bread wheat	1	230	725	65	1.1	185	203
Durum wheat	2	230	840	65	1.2	95	114
Potato	3	230	650	125	1.0	68	68
Soybean	4	230	1000	50	1.3	140	182
Lettuce	5	230	200	25	0.5	1.5	0.8
Beet root	5	230	300	25	0.6	4.5	2.7
Rice	6	230	800	125	1.2	150	180
Total						644	750

Table 2: The selected plants and their corresponding growth volumes and areas [6].

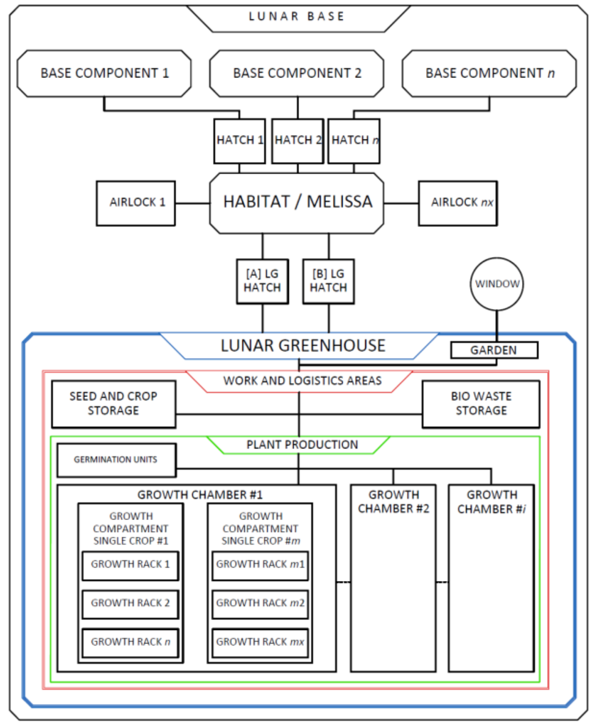

Figure 2: General operational and functional scheme of a GHM connected to a lunar base with emphases on the GHM components.

FUNCTION	**Area [m^2]**	**Volume [m^3]**
Growth area		
Production unit	644	750
Germination unit	58	21
Garden	25	70
Total growth area, excl. garden	702	743
Total growth area, incl. garden	727	813
Subsystems*	20	84
Supporting functions		
Storage*	12	33
Work areas	18	54
Logistical paths etc. **	128	650
Storage and work areas total	58	137
Supporting functions total	188	440
Total, for required functions	805	1037
Total including logistics estimate	935	1637

Table 3: Total areas and volumes intended for each GHM component.

Notes: Areas for growth include a 5% margin, work areas 20% and volumes for storage and systems include a 10% margin.
*In the case of storage and subsystems, the occupied volume rather than floor area is the interesting number, since they can be stacked in different configurations and the surface area is highly dependent on the specific shape of each system part or storage space. The number stated is a "placeholder" to account for the fact that it will take up some area since the systems are not designed at this point.** Rough order of magnitude (ROM) estimate as a first baseline, since this will depend on layout and will be minimized compared to the growth volume.

III.I Plant production

The greenhouse module is composed of a germination unit, a plant production unit, a temporary storage area, a work area and a garden.

Seeds are initiated in the germination unit and seedlings are kept there until they are mature enough to be transplanted into the plant production unit. This unit can be connected to a seeding station work area where the seeds are planted, or to the growth chambers.

The plant production unit is the main component of the greenhouse module and where plants are grown for most of their growth cycle until harvest. It is composed of several individual walk-in growth chambers, each of them providing specific environmental conditions (temperature, humidity, CO_2 level) for a given species, because plants are cultivated in monocultures. Each growth chamber is divided into several growth compartments, providing a given light condition, corresponding to a given growth phase (young plant, mature, flowering, ready for harvest). Crops are grown continuously so there are plants in each stage of growth at any time.

External structures provide natural divisions into individual growth chambers but in some cases further internal divisions have to be considered to accommodate for smaller volumes of mono-culture.

Racks, shelves and growth trays

Plants are grown hydroponically in trays on parallel shelves. This choice was made to limit complexity and mass addition compared to moveable shelves. The height of the shelf depends on the height of the fully grown plant; it is thus species-dependent. Lighting is optimized for the specific species and placed on top of each growth shelf. and sensors help adjust the temperature and humidity.

The racks and growth trays and their sizes are standardized for easier handling, storing, transportation and manufacturing.

The growth trays are 50 x 60 cm (width x depth), placed in shelves 60 cm deep, placed along the walls or in double rows so that each shelf can be reached from each side. The size is based on human reach envelope, and general ergonomics to enable handling when carried or lifted, whether it is by a human or a robot.

The height requirements of the plants and the standardized rack shapes make the smallest "building blocks" cuboids of different heights. Thus the interior layout is not always designed in what at first sight might seem to be the most volume-efficient way.

This also means that the required floor area in addition to the total volume becomes a driving requirement.

III.II Storage

Storage area is needed for temporary storage of edible plant parts and inedible plant waste for a given number of days before transportation to the other parts of the MELiSSA loop and the habitat of the lunar base. The volume of the storage area is based on a first estimation of the plant parts compacted after harvest, based on the growth volume. Since there is no seed-to-seed production, the seed stock shall last two years. Growth trays are also kept in storage between use cycles.

III.III Functional and logistic areas

Work areas are designated to operational and logistics tasks of the crew or robotic systems. A robotic aid and some degree of automation are assumed, which also requires some space. The astronauts need a certain work envelope and there has to be enough space between the racks and in other translational paths for growth trays and robotic aids to be moved around. Standardization of lunar man-rated systems is not in place and therefore terrestrial standards are employed regarding anthropometric requirements. Paths between growth racks are 55 - 80 cm, based on Neufert (90 cm) [31] and downsized to a minimum according to human anthropometry. While the atmosphere, temperature and lighting in the growth chambers are optimized for the specific plant, the work areas should be adjusted for human conditions. The work areas consist of a quality control unit, pre-processing (seeding), post-processing (harvesting, tray cleaning, and sterilization), and maintenance. They can also partly function as logistics areas. The partial gravity of the Moon should be considered as this means lower requirements on load-bearing structures and easier vertical translation for the astronauts. There is little experience of moving in partial gravity but it is expected that the bouncing walk will favor a higher ceiling [32], which however has to be traded against the increase in volume this would incur. The logistics areas also include two hatches between the greenhouse module and the rest of the base: one for people and edible crop to the habitat, and one for the waste to the other compartments of the MELiSSA loop. Each subsystem for water, power and air will be connected separately to other LSS compartments. Within the greenhouse module there are airtight doors between each compartment to keep optimal environmental conditions within each compartment as well as to limit any potential contamination.

Robotic aid

A robotic aid [33] is assumed to help the astronauts to some degree, for manipulation, harvesting and for placing and removing growth trays in the racks, as well as post-harvest tasks. A robotic system will minimize the number of heavy lifts, especially important since a large number of the shelves have to be above reach height. There are two options for harvesting; either harvest in the growth chamber or at the post-processing station. In either case both the crop and the growth trays have to be transported to the post-processing station from the growth chamber. Transport of trays and crop to the post-processing station will be easier if the harvest is done completely or partly in the growth chamber, than if the full growth tray with fully grown plants has to be moved. On the other hand, the robotic aid and other tools have to be kept in the growth chamber or brought there, and the working conditions for the astronauts have to be considered from an ergonomic point of view. A combination of harvest in the chamber and at a designated harvesting station is also a possibility. In the case of potatoes for example, crops can be removed from the growth tray to facilitate transport; then at the work station a more specified robotic aid removes the edible potatoes from the inedible leaves.

III.IV Astronaut Green Garden

As mentioned, the garden is an optional feature. It would provide a space for some additional plants in smaller portions for added flavor and variety such as herbs and tomatoes, and the lettuce and beetroot would be grown there. It would add to the required volume (and hence mass) but this should be weighed against the benefits of astronaut psychological wellbeing and the possibility of added nutritional value and better flavored food. A little deployable pond can provide fish production for added nutritional value, and serve as a garden feature.

The entire garden settings should support psychological and recreational needs of the astronauts.

A window is an optional component as windows are one of the main psychological benefactors in a secluded and confined habitat. Preferably the window should face the Earth for the same reasons. An alternative option is a virtual window based on a system of mirrors or digital displays to mitigate structural or radiation protection issues, which provides the same kind of effect but not to the same degree. Virtual windows can also be used as complement to one or few real windows.

III.V Subsystems

The subsystems volume requirement is based on ESA's Closed Loop Food System Final Report [33] to get a first rough order of magnitude (ROM) estimate of the required space for them until each subsystem is designed specifically. They are up-scaled linearly, and 10% volume margin is added, which should give a conservative baseline figure for a ROM value. Since the subsystems are not designed at this stage they are seen as black boxes and used as "placeholders" for occupied volume in the interior layouts rather than exact placement. The subsystems are made up of atmosphere control system, lighting (mainly included in the growth support structure), nutrient delivery subsystem (water and nutrients), robotic arm/aid and control and warning systems.

IV. GREENHOUSE MODULE CONCEPTS

The structural configuration of the greenhouse module depends on the mass and size payload capacity of the dedicated launcher, settlement deployment strategies, operational preferences and the overall lunar base plan. Following concepts are presented as standalone modules that can be integrated to an assumed existing lunar base system and are to some extent scalable based on requirements on launcher or internal volume.

The launchers that were considered and will be available in the near future for the greenhouse transport to the lunar surface include American Space-X Falcon Heavy (53 tons to LEO) [34], Russian Angara (67 tons to LEO) [35] rocket. It is presumed that a heavy lift launcher capable of carrying a 50 ton payload to LEO will be sufficient to deliver 10 tons to the lunar surface in equatorial location and a lighter payload to polar locations on the Moon [10]. Smaller launchers such as the European Ariane or American Delta IV Heavy would be capable of carrying around 20 ton payloads to LEO where it would connect with a trans-lunar injection stage in order to deliver approximately 10 tons of payload to the lunar surface. This is the framework, 10 tons to the lunar surface is the assumed mass for the presented modules.

The greenhouse module is designed to support six people. Modular configuration of lunar settlements should enable interconnection of multiple modules or connection of single modules to lunar infrastructure as required.

IV.I Inflatable

Architectural concept and structure

The main principle of this configuration is the utilization of an inflatable structure in the shape of a torus that deploys around the module's vertical core, covered with regolith. The inflatable structure is divided into six parts, ("petals"), where the walls between the petals function as a structural, internal pressure load-bearing system, but also as separation walls, enabling operation of the petals independently in case of potential off-nominal scenarios happening in the other petals.

The suitable geometry of a twice divided torus was inspired by volumetric efficiency from nature (optimum surface tension) and by existing space architecture projects utilizing a rigid core and surrounding inflatable structure [20], [10].

The structure is composed of thin multilayer structure composed of a load-bearing structure, a backup load-bearing structure, an atmosphere holding bladder and a sensory network system. The structure is covered with thin anti-abrasive fabric on the top, anchored to the lunar regolith and providing a barrier for the lunar regolith compacting process.

Each concept requires access ports for connecting with the lunar base and its systems. The inflatable concept is equipped with two deployable/inflatable airlocks reaching out from the rigid core (
Figure 3).

A system of light collectors or photovoltaic system can be part of the pre-integrated greenhouse module. Light collectors are depicted on top of the structure on
Figure 3 on the right.

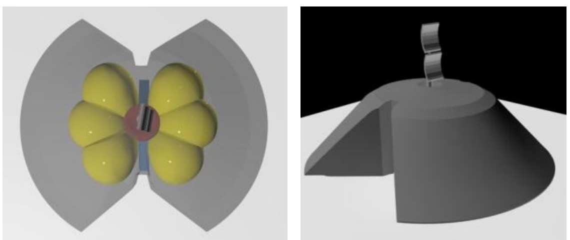

Figure 3: Inflatable concept - inflatable structures depicted in yellow, rigid core in red. Deployable greenhouse structure is covered by regolith (on the right).

The six "petals", each of them being a growth chamber with access from the rigid, central core, are partially pre-integrated with horizontal structures such as floors and shelves including necessary infrastructure for water, air and electricity (Figure 4). They are divided in levels, each of them being a growth compartment. Further division within one level to create more than one growth compartment is also possible.

<u>Internal arrangements - fixed shelves</u>

The work areas and storage are in the core. The work areas, (19.8 m^2 with a ceiling height of 2.5 m), are on the bottom floor to co-utilize the work area/work envelope with logistics paths. Storage, (100 m^3, including subsystems) and a germination unit, would be on upper levels, requiring a small platform lift.

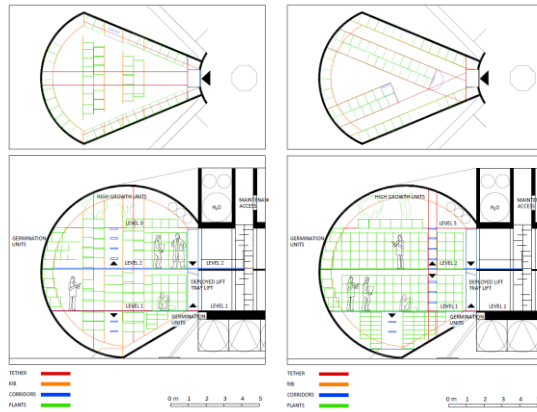

Figure 4: Two internal layout options for the Inflatable Concept including a possible structural configuration of the inflatable interior. Both options are based on tension tethers and ribs that are kept in position by internal overpressure. (Design and models by O. Doule, FIT, HCDi)

An option without floors in the petals is also possible, if the robotic aid moves up and down along the racks and collects the growth trays etc. Ladders along the racks would enable astronauts to reach the higher levels, but solid floors make it easier to work, and minimize risk of a falling accident. Floors also enable stacking of the shelves in more options since they do not have to be stacked on each other. The ratio between growth volume and total volume is 750 m^3 to 2070 m^3, i.e. 0.36.

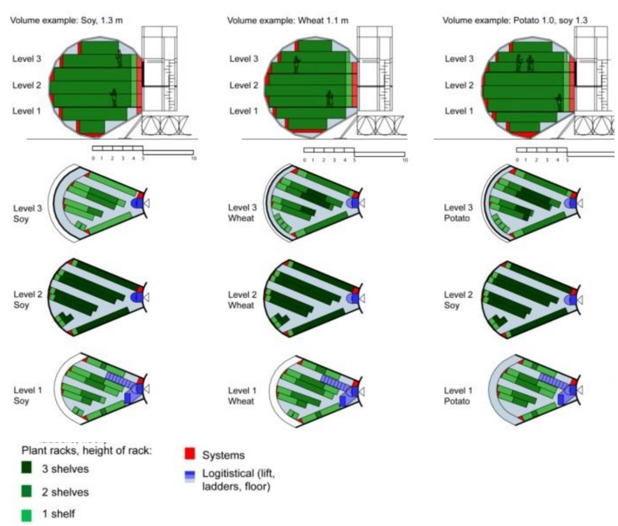

Figure 5: Example of distribution of growth racks in one petal/growth chamber, in three different plant combinations.

IV.II Hybrid

Architectural concept and structure

The combination of deployment with a mechanical arm that can later on serve as a main system operator, deployable structures and inflatable structures is presented in the Hybrid concept. The system provides two independent tori with racks on two main levels and pre-integrated water, air, electricity infrastructure.

The system is deployed in sequence, one torus after the other. The structure is covered by lunar regolith in the final phase of construction. The structure is lower than the Inflatable option due to its volume distribution in two smaller diameter tori. Each torus has a small internal core with a deployable robotic arm for automated maintenance of the plants. The uninterrupted internal volume of the torus allows for variety of arrangement for an automated system that would spin around the central core if each torus (see Figure 6).

Two access ports are place on the core opposite of each other for access to the rest of the lunar base. The top center of the rigid core provides possibility for placement of a solar concentrator or photovoltaic system for light collection, or power generation independently of the lunar base infrastructure.

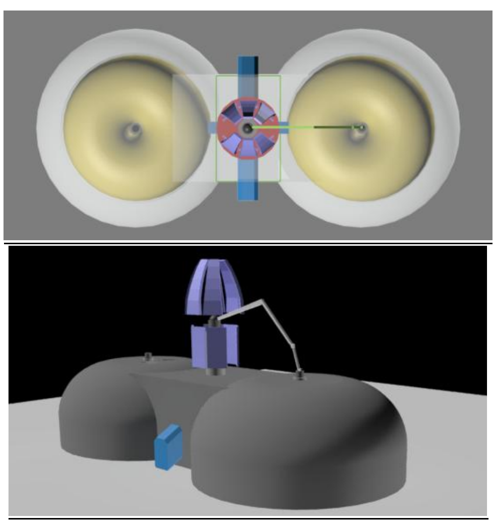

Figure 6: Hybrid concept composed of two inflatable tori. Inflatable structures are depicted in yellow on the top image. The bottom represents pre-fabricated deployable system covered by regolith shell.

Internal arrangements

The Hybrid concept could in principle be outfitted either with fixed or rotating racks. In case of the rotating racks, a "carousel" is the method, with the racks fitted to the hub of the "wheel". The work areas, germination unit and storage are in the core. The work areas are on the bottom floor to co-utilize the open areas with translational paths. The working area is minimized to 14 m^2. An upper "floor" with 1.3 m ceiling height contains 34 m^3 of storage. This volume-optimized version does not include a garden.

Calculations were also made with fixed racks and it was found that even with a volume increase by 16% there is not enough area for all plants. Thus fixed shelves are discarded for this concept.

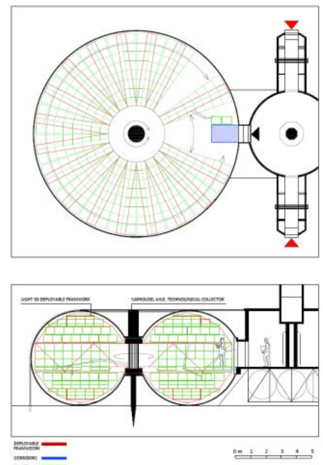

Figure 7: Hybrid Concept interior layout option showing the rotating shelves system. (Design and models by O. Doule, FIT, HCDi)

The torus is divided into 11 pie-shaped racks, leaving about 9.5 m^2 of working area closest to the entrance hatch. Each rack is divided into 4 levels of growth shelves. The ratio between growth volume and total volume is 750 m^3 to 1200 m^3, i.e. 0.625.

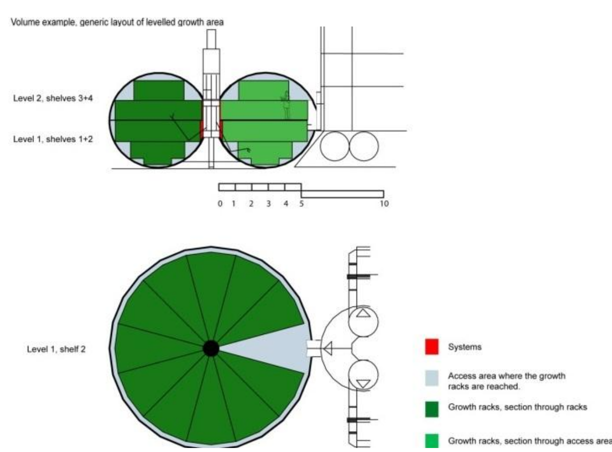

Figure 8: Distribution of growth racks in one torus, illustrating the principal layout of movable racks in a carousel system. The access area (light blue) has to be emptied when the carousel is turning. After the turning, two new racks can be reached. The access

area also has a horizontal communication to the lower levels, mainly for robotic access.

IV.III Rigid

Architectural concept and structure

A fully rigid modular structure with telescopically deployable components is presented as the third option suitable for the lunar greenhouse module. The greenhouse depicted in Figure 9 is composed of 18 hexagonal telescopic components (HTC) covered by regolith shell. This configuration that volumetrically corresponds to options Inflatable and Hybrid would require at least 3 times more launches. In one launch six telescopic chamber components would be delivered to the Moon.

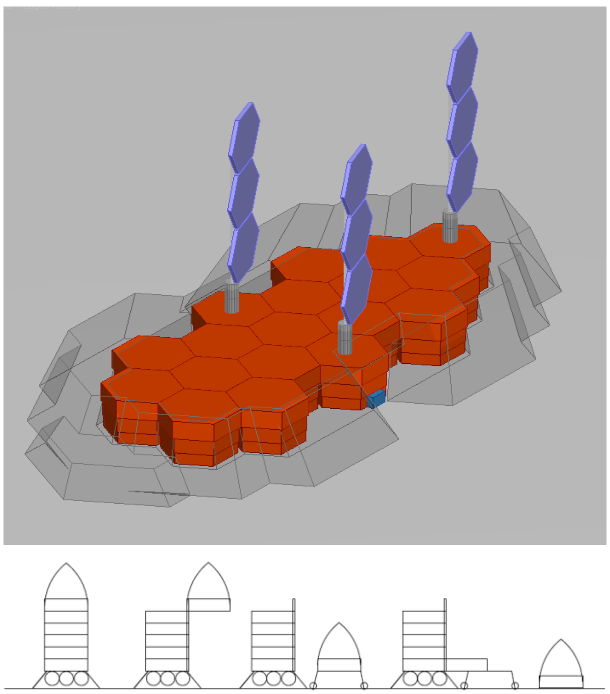

Figure 9: Rigid concept composed of hexagonal telescopic components and covered by regolith shell (top). Scheme of the deployment (bottom).

Although this concept requires multiple launches, its structures are very simple, utilizing a vertical sliding mechanism for its deployment and the universal lunar surface vehicle Athlete that is being developed by NASA. The hexagonal shape of the components allows for unlimited growth of the greenhouse system and also for pre-integration of all required technical infrastructure, subsystems or functional elements inside the un-deployed components. The Rigid concept as presented in Figure 9 allows for stowing of hexagonal solar concentrators or photovoltaic system allowing for light or power autonomy.

Internal arrangements

Presented here are two suggestions for layout of the growth structures, with different volumes of plants as a result. The first growth compartment module has one door and an automated carousel system. The second one has two entrances and a system of parallel racks that are movable on tracks for a compact accommodation. The total volume of one growth compartment module is 50 m^3. The total volume of the whole greenhouse module depends on the number of growth compartment used, about 20-27 HTCs to fit all plants, depending on the configuration. The two-door type have to be used for passage to other growth compartments, the one-door type can only be used at the perimeter of the greenhouse module. One or more modules are used as hubs and work area with a floor area of 16 m^2 each.

HTC 1: (1 entrance; carousel): 37.5 m^3

HTC 2: (2 entrances; parallel, movable racks): 28 m^3

HTC 3: (2 entrances; movable racks in half circle): 26 m^3

They can be arranged in different combinations and the six of the first delivery can constitute a first functional entity that can then be expanded on in steps until it fulfils the requirements for the whole greenhouse.

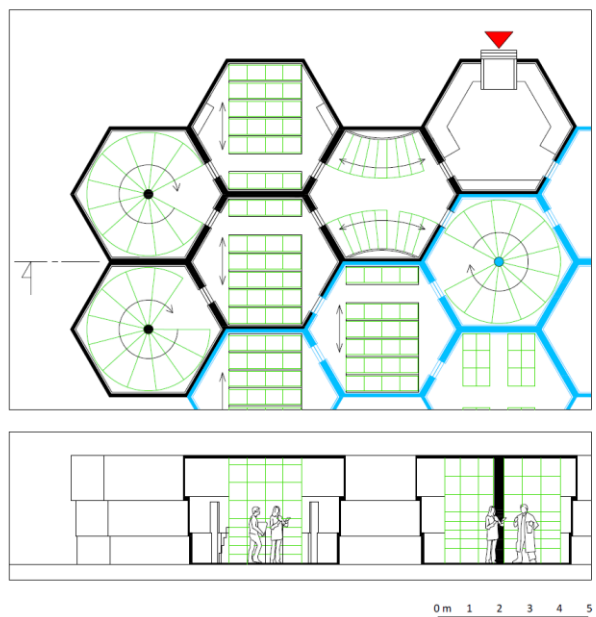

Figure 10: Rigid concept internal configuration provides a possibility of utilizing modular design and producing modular plant bed units. Both fixed and movable shelves systems are possible. . (Design and models by O. Doule, FIT, HCDi)

V. Lighting Options

Three types of lighting are available to implement in the three architectural concepts previously presented:

natural lighting, relying solely on the Sun, electrical lighting, relying on white LED lights, and hybrid lighting, a combination of both natural and electrical lighting.

The illumination characteristics at the chosen location are following [36]:

- The average solar illumination over a year is 84% at surface level and reaches 86.6% at 10 m above the surface.
- There are 323.7 to 326.4 Earth days of sunlight per year at surface level (328.8 to 333.9 Earth days at 10 m above ground level) and 38.9 to 41.5 Earth days of darkness per year at surface level (31.4 to 36.4 Earth days at 10 m above ground level).

Since these concepts are all covered under sintered regolith for radiation protection, in the case of natural illumination, Sun is collected with giant parabolic mirrors and transmitted via fiber optics to the growth chambers of the greenhouse module, using a system similar to the Optical Waveguide (OW) developed by Physical Sciences, Inc. [37, 38]. In order to gather the most light, collectors are placed 10 m above the ground. There is a total of 31.4 to 36.4 days of darkness per year and maximum length of darkness periods are about 1 Earth day. Thus the natural lighting system will in any case need to have an electrical back-up lighting system, which in practice makes it a hybrid lighting system. Calculations and results for the hybrid and the electrical system are presented. We consider the worst case scenario, in which the lighting system needs to provide 600 μmol/m^2/s over 641m^2 during a 16-hour photoperiod.

V.I Full electrical option

The white LEDs currently have an efficiency of 33% [39]. The assumptions are following:

- The growth chamber and the power management and distribution system are both 85% efficient [40].
- The electrical energy needed to evacuate 30 BTU of heat is 1 kWh.
- The efficiency of the solar cells is 21% and they can utilize the whole Sun's spectrum and incident sunlight of 1366 W/m^2.
- Batteries charge during the 8 hours of plants' night period (no power needed for lighting), thus covering the energy demand of the LED for half the photoperiod (8 of the 16 h). The photovoltaic arrays thus need to be dimensioned for an eight-hour photoperiod, plus 20% of margin.

Table 4 gives the required electrical power and energy needed to power the white LEDs and to evacuate the generated heat. The total photovoltaic arrays area needed is 810 m^2.

Lighting	
Electrical Power needed for lighting (kW)	353
Electrical Energy for lighting per day (kWh)	5650
Area of photovoltaic arrays for lighting (m^2)*	739
Cooling	
Electrical Power for cooling (kW)	29
Electrical Energy for cooling per day (kWh)	462
Area of photovoltaic arrays for cooling (m^2)*	71
Total	
Total Electrical Power needed (kW)	382
Total Electrical Energy needed per day (kWh)	6112
Total area of photovoltaic arrays (m^2)*	810

* 20% margin included

Table 4: Electrical power and energy needed for lighting and cooling the LED lighting system.

V.II Hybrid option

It is assumed that the collectors follow the Sun during a lunar day and that the conversion from solar irradiance to photon flux approximately is 1W/m^2 = 4.57 μmol/m^2/s [41]. The reference system is a space-adapted optical waveguide, 77% efficient [40]. The collectors transmit the photosynthetically active radiations (PAR) part of the Sun's spectrum (400 – 700 nm) via fiber optics to the growth chambers. Including a 20% margin, the solar collectors need to cover an area of 300 m^2 (Four ten-meter diameter parabolic mirrors) in order to provide sufficient lighting to the growth chambers. The remaining part of the spectrum is used to produce electrical power, stored in batteries, which is utilized to power up the LED lights during darkness periods. The batteries need to cope with one full day of darkness, so they need to have a storage capacity of at least 6112 kWh, or 7334 kWh with 20% margin. Solar irradiance without PAR is 850 W/m^2, which gives 179 W/m^2 generated with 21%-efficient solar cells. Adding a total of 30 m^2 of photovoltaic cells to the collectors would enable to generate 129 kWh per day (24 hours). Since the average long total daylight period varies between 170 and 180 days, the batteries could charge during 80 days in a row and thus store 10320 kWh, from which 7224 kWh would be usable, assuming batteries with 70% efficiency. This is more than enough energy to power the white LEDs and their cooling system for one day of darkness.

V.III Comparison of the two lighting options

Table 5 summarizes the main features of the electrical and hybrid lighting options. The hybrid option requires less daily energy for lighting and cooling, which results in smaller area of photovoltaic arrays needed. In case the energy is provided by another source than photovoltaic arrays, the hybrid option requires deploying a larger area to collect sunlight than the electrical option, which increases complexity and risk of failure. But the electrical option would put a power burden on the power source of the habitat. In terms of Technology Readiness Level (TRL), LEDs have already been tested on the International Space Station to grow plants [42], whereas the hybrid system was only prototyped on Earth [37]. The hybrid system works with two different technologies and thus has intrinsic redundancy. The lower energy needed to operate the system, the smaller area of photovoltaic arrays needed and the redundancy make the hybrid option the better choice for plant lighting in the greenhouse module.

	Electrical	**Hybrid**
Total surface needed (m^2)	810	330
Daily lighting energy (kWh)*	5650	573
Daily cooling energy (kWh)*	462	47
Redundancy	No	Yes
TRL	8 – 9	6 – 7

* average on one year

Table 5: Summary of the comparison between the two lighting options

VI. CONCLUSION

In this paper three different options for the conceptual design of a lunar greenhouse module have been presented. The three concepts can be used as a baseline for further comparison and evaluation and be further developed in future iterations. The three options represent completely different settlement deployment strategies that have to be evaluated against the overall lunar base/settlement deployment strategy prior to the final configuration selection.

Therefore, prior to final concept selection, a mission strategy for the whole base construction, lunar urban and landscape planning, and planetary protection, has to be thoroughly identified and described. Especially the base layout and all its components must be well defined before engineering of the greenhouse module is initiated. The greenhouse module architecture is also dependent on geographical location, on morphology of the terrain, geology of the regolith bed and local resources it should use, if any.

The availability or absence of a lunar spaceport will also determine how the greenhouse module is deployed and if and how it is transported on the surface. The two inflatable or partly inflatable concepts presented are designed as for pinpoint landing which means that all surrounding infrastructure would have to be protected against regolith ejecta. The third concept presented utilizes the NASA Athlete platform for transport and deployment of the hexagonal base components.

The settlement construction and urban strategy development will largely determine whether a single module with radial deployment (Inflatable option) is more suitable than one with multiple cores (Hybrid) or if a cluster (Rigid) configuration of the greenhouse module is preferable.

A lunar base can also be used as a test-bed for a Mars base. The risk related to operations and communications is much lower since the Moon is just a couple of days away from Earth but the environmental conditions are harsher and more extreme compared to Mars (i.e., lower gravity and near vacuum on the Moon less similar to terrestrial conditions than environment on Mars and provide much less protection against dangerous solar and cosmic radiation). It can also be used for testing astronaut psychology and general health in a full scale "test", with the isolation and confinement as well as many operational features similar to a life on Mars (the need for a confined habitat, life-support system, the need for EVAs etc.).

VI.I Next steps

Evaluation of which concept that seems most promising should be performed depending on the overall mission scenario. Universal architecture is always more complex and difficult to develop as it has to cope with unpredictable but probable scenarios.

The selection will be based on the following criteria: energy, mass, volume, crew time, TRL, risk/reliability, complexity, and psychology. In particular the following aspects will need to be evaluated:

- Ease of integration in an overall mission architecture
- Ease of integration in the system architecture
- Modularity and compatibility with established lunar base systems
- Complexity of the systems (risk of failure and its implications
- Degree of automation
- Working conditions for astronauts
- System safety
- Time required for deployment
- Operational convenience (internal and external)

During the fall of 2014 the EDEN team will continue the process of selecting the most promising concept and further develop the design.

REFERENCES

[1] A. J. Hanford, "Advanced Life Support Baseline Values and Assumptions," NASA/CR-2004-208941, August 2004.

[2] J. Starke, "Human Mission to Moon, Final Architecture review," ESA-ESRIN, 2009.

[3] Futron Corporation, "Space Transportation Costs: Trends in Price Per Pound to Orbitv1990-2000," Madison, WI, 2002.

[4] S. Bates, V. Gushin, M.D., G. Bingham, A. Vinokhodova, J. Marquit and V. Sychev, "Plants As Countermeasures: A Review Of The Literature And Application To Habitation Systems For Humans Living In Isolated Or Extreme Environments," *Habitation*, vol. 12, pp. 33-40, 2010.

[5] S. Haeuplik-Meusburger, C. Paterson, D. Schubert and P. Zabel, "Greenhouses and their humanizing synergies," *Acta Astronautica*, vol. 96, pp. 138-150, 2014.

[6] S. Sasidharan, "MELiSSA reference crop data," ESA, 2013.

[7] Deutsches Zentrum für Luft und Raumfart, DLR, "Greenhouse Module Concepts," DLR, Bremen, 2014.

[8] NASA, "NASA Technical Standard, NASA SPace Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health (Superseding NASA-STD-3000 Vol1 and Vol2)," NASA, Washington, DC 20546-0001, 2011.

[9] N. Handbook, "Human Integration Design Handbook," NASA, Washington DC, 2010.

[10] O. Doule, E. Detsis and A. Ebrahimi, "A Lunar Base with Astronomical Observatory," in *41st International Conference on Environmental Systems (ICES)*, Portland, 2011.

[11] H. Benaroya, Lunar Settlements, Boca Rota: Taylor & Francis, 2010.

[12] S. Howe and I. Gibson, "MOBITAT2: A Mobile Habitat Based on the Trigon Construction System," in *2nd International Space Architecture Symposium*, San Jose, 2006.

[13] S. Howe och B. Sherwood, Out of This World: The New Field of Space Architecture, AIAA, 2009.

[14] S. Howe, G. Spexarth, L. Toups, R. Howard, M. Rudisill and J. Dorsey, "Constellation Architecture Team: Lunar Outpost "Scenario 12.1" Habitation COncept," in *Twelfth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments*, Honolulu, 2010.

[15] J. C. Mankins, "Modular Architecture Options for Lunar Exploration and Development," in *International Astronautical Congress*, Rio de Janeiro, 2000.

[16] E. Seedhouse, Lunar Outpost, Springer-Verlag GmbH, Praxis, 2008.

[17] D. K. Bodkin and K. J. Bocam, "A human Lunar Surface Base and Infrastructure Solution," in *2nd International Space Architecture Symposium*, San Jose, 2006.

[18] SICSA, "The Manned Lunar Outpost (MLO): NASA/USRA -Sponsored Study," SICSA, Houston, 1989.

[19] M. Robert, "Inflatable Habitation for the Lunar Base," NASA Johnson Space Center, Houston, 1993.

[20] O. Doule, "Mars Base 10 – A Permanent Settlement on Mars for 10 Astronauts," in *39th International Conference on Environmental Systems*, Savannah, 2009.

[21] H. Benaroya, "An Overview of Lunar Base Structures: Past and Future," in *AIAA Space Architecture Symposium*, Houston, 2002.

[22] J. K. Kennedy, L. Alexander, R. Landis, D. Linne, C. Mclemore and E. Santiago-Maldonado, "Human Exploration Destination Roadmap," NASA, 2010.

[23] L. Mulugeta, O. Doule, D. Bodkin, D. Jagula, L. Qémet, M. Turnock, A. Chan, R. Chasseigne, M. Demel, J. Hochstein, A. Oprong and J. Salazar, "Astronaut Safety on the Moon," *Space Times*, vol. 48, no. 3, pp. 4-8, 2009.

[24] B. Sherwood, "Lunar Architecture and Urbanism 2nd edition," in *35th International Conference on Environmental Systems*, Rome, 2005.

[25] D. Smith och G. Woodcock, "Lunar Surface Systems and Operations for an Early Human Oupost," i *Space Technology and Applications International Forum*, Arlington, 2008.

[26] T. Wilson and W. K.B., "Regolith Sitnering: A SOlution to Lunar Dust Mitigation?," in *36th Annual Lunar and Planetary Science Conference*, League City, 2005.

[27] L. Taylor and T. Meet, "Micorwave Sintering of LUnar Soil: Properties, Theory and Practice," *Journal of Aerospace Engineering*, vol. 15, no. 3, pp. 188-196, 2005.

[28] O. Doule, K. Errikson, D. Platt and V. Šálený, "Sinterhab v2," in *64th International Astronautical Congress*, Beijing, 2013.

[29] O. Doule, B. Imhof, W. Hohender, A. Aablo, C. Welch, V. Šálený, M. Ilzkovitz, J. Gancet och P. Weiss, "Self-deployable Habitat for Extreme Environments - Innovative Architecture Test-bed for Terrestrial and Space Applications," i *64th International Astronautical Congress*, Beijing, 2013.

[30] T. Rousek, K. Eriksson and O. Doule,

"SinterHab," *Acta Astronautica,* vol. 74, pp. 98-111, 2012.

[31] P. Neufert, E. Neufert, B. Baice and N. Walliman, Neufert Architects' Data, Oxford: Blackwell Science Ltd, 2000.

[32] H. Benaroya och L. Berhold, "Engineering a lunar base," *Acta astronautica,* vol. 62, pp. 277-299, 2008.

[33] NTE, TNO, VDD, UGent, "CLOSED LOOP FOOD SYSTEMS ST9.1 Final report, ST9-0000-TN-027-NTE," ESA, 2005.

[34] Space-X, "Falcon Heavy," 2013.

[35] A. Zak, "Sodruzhestvo," Russianspaceweb.com, 2013.

[36] E. Mazarico, G. Neumann, D. Smith, M. Zuber and M. Torrence, "Illumination conditions of the lunar polar regions using LOLA topography," *Icarus 211,* pp. 1066-1081, 2011.

[37] J. Cuello, D. Jack, P. Sadler and N. T., "Hybrid Solar And Artificial Lighting (HYSAL): Next-Generation Lightning Strategy For Biorenerative Advanced Life Support," *SAE Technical Paper series,* no. 1999-01-2104, 1999.

[38] T. Nakamura, J. A. Case and M. Mankamyer, "Optical waveguide solar lighting system for space-based plant growing," *The American Society of Mechanical Engineers, NY,* pp. 347-358, 1996.

[39] J. A. Nelson and B. Bugbee, "Supplemental greenhouse lighting: Return on Investment for LED and HPS fixtures," July 2013. [Online]. Available: http://cpl.usu.edu/files/publications/factsheet/pub__4964212.pdf. [Accessed 26 September 2013].

[40] T. Nakamura, Interviewee, *Hybrid systems and illumination on the Moon.* [Interview]. 17 September 2013.

[41] Environmental Growth Chambers, "Lighting Radiation Conversion," Environmental Growth Chambers, [Online]. Available: http://www.egc.com/useful_info_lighting.php. [Accessed 10 July 2013].

[42] J. C. Maida, C. Bowen and C. Wheelwright, "Solid State Light Evaluation in the US Lab Mockup," NASA/TM-2009-214784, 2009.

[43] E. Koh, "Pasona O2," Tokyo, 2008.

[44] Lundqvist, "Lundia Stal," Lundqvist Inredningar, Stockholm, 2013.

[45] NASA, "The ATHLETE Rover," NASA Jet Propulsion Laboratory, 2013.

[46] K. J. Kennedy, "Lessons from TransHab," in *AIAA Space Architecture Symposium*, Houston, 2002.

[47] A. J. Hanford, "NASA Advanced Life Support Baseline Values and Assumptions Document," Purdue University Purdue e-Pubs, Purdue, 2006.