46th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria

Growing Plants from SEEDS on Mars for Supporting Human Exploration

Marco Volponi[1] and Jacopo Pisacreta[2]
SEEDS Master - Politecnico di Torino, Turin, 10129, Italy

Cesare Lobascio[3]
Thales Alenia Space, Turin, 10146, Italy

The paper presents the results of a study performed during the Project Work Activity by students of the 7th edition of the International Master Course in SpacE Exploration and Development Systems (SEEDS), born from a collaboration of Politecnico di Torino (Italy), Institut Supérieur de l'Aéronautique et l'Espace (ISAE-SUPAERO, Toulouse) in France and University of Leicester in United Kingdom (UK), with the partnership of European Space Agency (ESA) and Industries.

The study focused on the design of a Martian permanent human outpost and, among all the building blocks identified and designed, a Greenhouse (GH) module has been conceived, which objective was to be a plant growth facility to be integrated into a bio-regenerative life support system. Several trade-offs have been performed in order to evaluate possible design architectures, taking into account the cultivation methods, the selection of the crops and the diet composition.

Growth substrate (soil and soil-less cultures), lighting, pressure, temperature, atmosphere composition, waste treatment and robotic assistance have been subject of study, adopting environmental safety, robustness, maintenance easiness and effectiveness as figures of merit; different options of diet/crop combinations have been evaluated, progressively reducing the crops and the cultivated surface, in order to minimize the system needed and considering food integrations, via resupply, brought from Earth.

The last part of this study consisted in determining not only mass and power consumption of the module, but also to arrive to the module design concept and its integration into the overall outpost architecture; in doing so, the importance of the crew psychological health and of the possibility of using the GH as an initial test bed for further expansion was taken into consideration.

---

[1] Internship at Thales Alenia Space Italia, Space Flight Environment & Habitat, Domain Exploration and Science Italy, marco.volponi@gmail.com

[2] Internship at Thales Alenia Space Italia, System Architecture and Verification, Domain Exploration and Science Italy, j.pisacreta@yahoo.com

[3] Head of Space Flight Environment & Habitat, Domain Exploration and Science Italy, Thales Alenia Space Italia, Str. Antica di Collegno, 253, 10146 Torino, Italy, Cesare.Lobascio@thalesaleniaspace.com

Nomenclature

AEPS = *Autonomous Electric Power System*
ALTEC = *Aerospace Logistics Technology Engineering Company*
ATCS = *Active Thermal Control System*
BVAD = *Baseline Values and Assumptions Document*
C&DH = *Command and Data Handling*
CDRA = *Carbon Dioxide Removal Assembly*
ECLSS = *Environmental Control and Life Support System*
ESA = *European Space Agency*
ESM = *Equivalent System Mass*
EVA = *Extra Vehicular Activity*
FARM = *Food And Revitalization Module*
GH = *Greenhouse*
HEPA = *High-Efficiency Particulate Air*
HPS = *High Pressure Sodium*
ISAE = *Institut Supérieur de l'Aéronautique et l'Espace*
ISRU = *In-Situ Resource Utilization*
ISS = *International Space Station*
LED = *Lighting Emitting Diodes*
LMO = *Low Martian Orbit*
MAD = *Minimum Area Diet*
MAV = *Mars Ascent Vehicle*
MILESTONE = *Mars Initial Expedition TOwards a New Era*
NASA = *National Aeronautics and Space Administration*
NFT = *Nutrient Film Technique*
ORPHEUS = *Orbital Reconnaissance and PHobos Exploration by hUmanS*
PAR = *Photosynthetic Active Radiation*
PPF = *Photosynthetic Photon Flux*
SEEDS = *SpacE Exploration and Development Systems*
SLS = *Space Launch System*
TCCS = *Trace Contaminant Control System*
TRL = *Technology Readiness Level*
UK = *United Kingdom*
WRS = *Water Recovery System*

I. Introduction

THE next frontier of human space exploration is the exploration of Mars and the SEEDS (SpacE Exploration and Development Systems) Master course project for 2015 considered an initial human landing on the Martian surface. SEEDS VII is an international, multidisciplinary group comprised of students from both the Politecnico di Torino and the University of Leicester.

The SEEDS VII project covers the second step of Conquest by Humans of Mars in Five Steps, following the mission *Orbital Reconnaissance and PHobos Exploration by hUmanS* (ORPHEUS) developed by the SEEDS VI team (1). The proposed mission to accomplish this task is MILESTONE: *Mars Initial Landing ExpeditionS TOward a New Era*. A feasibility study is carried out for Mission MILESTONE, which is a short duration mission with the aim of establishing a long permanence outpost for subsequent exploration, and covers the descent to, survival upon and ascent from the Martian surface starting in a Low Martian Orbit (LMO). The project takes place over three stages: in Turin (Italy) working in collaboration with Aerospace Logistics Technology Engineering Company (ALTEC) and Thales Alenia Space, in Toulouse (France) with assistance from ISAE-SUPAERO, and in Leicester (United Kingdom) within the University of Leicester Space Research Centre.

The Mission MILESTONE feasibility study focuses on the mission stages from LMO onwards only, and does not carry out a detailed investigation into the Earth-Mars transit. A 180 day transit is assumed each way, with the intention of residing on the surface for 60 days. As the mission is intended as a precursor to exploration missions, it is focused on the establishment of a habitable environment to ensure the supply of sufficient resources required to sustain human life. As the first human expedition on the Martian surface, the primary objective of Mission

MILESTONE is the assembly of a complete base, a first step towards a longer presence of mankind on Mars. The outpost is formed of a number of main building blocks: a habitable module, a laboratory, a greenhouse (subject of this paper), an In-Situ Resource Utilization (ISRU) system and a power plant. A pressurized rover is intended to allow for exploration in future missions, a Mars Ascent Vehicle (MAV) to leave the surface of the planet, three communications satellites and an Earth return vehicle are placed in Martian orbit. The outpost architecture is complemented by a node and the extra vehicular activity (EVA) module.

The number of modules with a given function can be increased, taking into account redundancy considerations, on a case by case basis (see Figure 1). The outpost is sized for future 500 day scientific and exploration missions that will consist of crew which varies from 6 to up to 12 people, during the rotating period. While the outpost is intended to be largely self-sufficient in order to reduce burden on the launch system, there will be some reliance on Earth resources, with each crew bringing certain consumables.

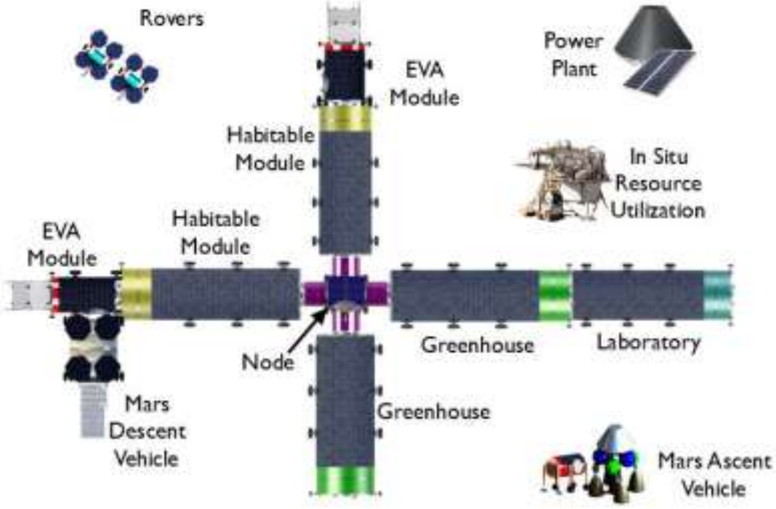

Figure 1. MILESTONE Outpost

During this first manned mission to the Martian surface there will be also technology demonstrations, increasing technology readiness levels for the benefit of future missions. Mission MILESTONE will be an early stage mission, which will create an outpost on Mars for further human exploration by subsequent missions. This was determined to be the most cost-effective method: since a substantial outpost would be required to sustain human life on Mars, a multi-mission outpost is designed to allow sufficient time for experimenting to build a future permanent outpost.

The mission will take the form of a split mission, with the cargo modules being launched in two windows in 2039 and 2041, and the crew being launched in 2042. The cargo modules will be collected at the outpost location autonomously by the rovers, prior to the crew launch. There will be a total of 15 launches, with 8 Heavy and 7 Super Heavy launches, considering 3 launch bases in different locations around the world and as baseline launchers the Space Launch System (SLS) 2B and the Falcon Heavy by SpaceX, underling the mandatory international environment for such an ambitious mission. The crew of MILESTONE will undertake a 60 day stay in the Martian environment, which includes the transits to and from Low Mars Orbit.

The main objectives of the crew phase of Mission MILESTONE are to assemble the outpost and to conduct scientific activities and exploration, including demonstrating in-situ resource utilization and food production. A large outpost has been designed, as a key objective of Mission MILESTONE is to provide a habitable environment sized for a long-duration future mission. The landing site for the mission is Amazonis Planitia, in a region centered on 15N, 155W and at an elevation of -3.5 km MOLA (2). The region is thought to be a Noachian impact basin, with Hesperian lava flow and most recently an Amazonian surface (3), with around 6% water content (4). The region is of geological interest, and also has a volcanic history which may have caused fossils or extant life to be pushed closer to the surface (3).

II. Greenhouse Module

The Greenhouse Modules (see Figure 2) have been introduced mainly for the sake of future missions: in fact, the greenhouse is convenient against carrying food from Earth only after an extend permanence on the Martian surface. So, its benefits will become evident after some long permanence missions; nevertheless, it will guarantee a solid base for investigating the growth of plants on another planet, a key point for a sustainable planet colonization. In addition, access to plants has been shown to have psychological benefits for the crew members (5).

A. Greenhouse Layout and Structure

The greenhouse modules share the same primary and secondary structure with the Habitable Module: the section of the internal volume has a hexagonal shape, with a maximum height of the ceiling of 2.3 m and a floor dimension of 4 m. In addition it has also a tertiary structure which consists in a series of four racks, extended for all the length of the rigid part, separated by two corridors, in order to guarantee accessibility for both the crew and a servicing robot. The driving factor for the size is the cultivable surface: in fact, the configuration assumes an average height available to each plant of 58 cm, obtained adding 20 cm to the average plants height. As explained in the following sections, a great deal of effort was put to reduce the surface, arriving at a total of two GH with 93 m^2 of cultivable surface each.

B. Growth Considerations

1. Growth Mechanism

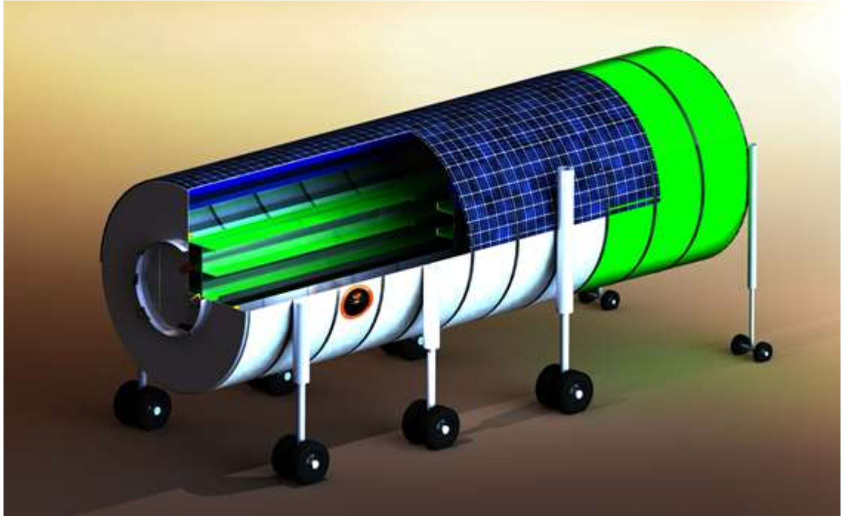

Figure 2. Greenhouse Rendering

The greenhouse will use a hydroponic growth system, specifically the nutrient film technique (NFT). In NFT, plant roots are kept in contact with a small amount of water (a few cm of depth), which is constantly cycled around the system. It has been found that it is possible to grow most crops with NFT, including potatoes which usually require a solid growth substrate to grow successfully (6). The benefit of NFT is that the steady stream of water and nutrients past the plant roots allows them to absorb as much water as they require. Since the greenhouse will be deployed on the planetary surface, a gravity-assisted system will be employed, in which the water/nutrients flow through the plant system assisted by gravity before returning to a liquid tank, where additional nutrients can be introduced before the liquid is recycled through the plants.

2. Nutrient Management

In order to ensure correct growth of the crops in the greenhouse, an enriched nutrient solution will be introduced into the water flowing around the hydroponic system. These nutrients can be added in the form of salts by means of diluted solutions, namely an initial ionic solution (more diluted) and replenishment ionic solutions (nutrient solution ionic composition can be monitored so to minimize nutrient solution unbalances that would lead to early disposal), such as those listed in the National Aeronautics and Space Administration (NASA) Baseline Values and Assumptions Document (BVAD) (7).

3. Illumination

For the lighting system three solution have been taken into account:

- High Pressure Sodium (HPS) Lamps: they are the most common light source for gardeners, as they have a high output of photosynthetic active radiation (PAR) (8). They also have a high electrical efficiency, but they have a low portion of blue (400-500 nm) light compared to natural sunlight (8). The conversion coefficient for a typical HPS lamp from lm/m^2 to $\mu mol\ m^{-2}\ s^{-1}$ is 0.012 (9), and its lifetime is 20000 h (5).
- Fluorescent Tube: these are low pressure gas discharge lamps, that typically use mercury vapors to produce visible light. For the Grow Fluorescent Tubes, properly tailored to emit radiation useful for plant photosynthesis, has a lm/m^2 to PAR conversion coefficient of 0.029 (9) and a maximum lifetime of about 30000 h (5).
- LED: this light source have been recently increasing in popularity for plant growth as the small diodes can be placed close to the plant canopy and be used to apply narrow-band light spectra to the plants (8). LEDs have the highest efficiency of illumination systems; we have used data from a commercial LED

illumination system designed for greenhouses (10): a lamp of 150 W, which weights 10 kg, has a PAR output of 1180 µmol m^{-2} s^{-1}, which corresponds to 7.867 µmol m^{-2} s^{-1} W^{-1}. The expected lifetime is greater than 100000 h and can be dimmed up to its 10% power (11).

Table 1. Lighting Comparison. *In order to estimate the Power Specific Illuminance, a distance from the plant of 60cm has been chosen (the same for the statistics for the LED lamp), and a solid angle of π.*

	Power specific Luminous Flux (lm/W)	**Power Specific Illuminance (lm/m² W)**	**Spectrum Efficiency Coefficient (lm/m² to µmol $m^{-2}s^{-1}W^{-1}$)**	**Photosynthetic Photon Flux (PPF) (µmol $m^{-2}s^{-1}W^{-1}$)**	**Power Consumption per Area (W/m^2)**
HPS	150	132.6	0.012	1.59	502
Fluorescent tube	104	92.2	0.029	2.68	299
LED				7.87	102

From Table 1, LEDs emerge to be the lowest power consuming option. As they are also the most reliable solution, they allow the frequency of lighting to be tailored to ensure optimum crop growth, they have the least massive and the longest lifetime (which means less spare parts and fewer repairs), thus they have been chosen as the best option for artificial illumination.

4. Irrigation System

NFT systems require a large amount of water circulation: from Earth-based studies (12), a water flux of 1 l/min per channel has been found to be appropriate. It has been estimated to have 0.6 channels/m² of cultivable surface, each with a length of 9 m.

The Water Recovery System (WRS) for the greenhouse is sized in accordance to the one flying on the International Space Station (ISS) and has a total mass of 922 kg, a power requirement of 1.5 kW. An increased efficiency of water recovery is assumed, since it mainly manages condensation of the transpiration moisture of the plants[4]. Part of the water input is absorbed by the crops while growing, and forms both edible and inedible water content (7); the rest of the water is then transpired by the crops. As the waste management system also recovers a large amount of water during the incineration of the unedible biomass (14.5 kg/day), only 31.2 kg/day are required to be introduced from an external source.

Due to the use of a hydroponic growth medium, water is a critical component in the greenhouse and it is necessary to provide a number of buffers: a tank in which the nutrient solution can be mixed with water before being circulated; the "in-use" tank, containing the daily water usage. It is assumed that cleaning flushes will be carried out at regular intervals, fully removing and replacing the water in the NFT system. Each greenhouse will have a tank of half the computed size for redundancy and efficiency. A second tank will be considered as a water buffer, if the in-use water were to become contaminated in any way, and will store water for 60 days of operations and two flushes. A third tank will also be provided in which water can be purified before being returned to the other tanks. This water will be stored as radiation protection around the habitable modules.

5. Atmosphere Management

The atmospheric composition (79% N_2, 21% O_2, 500 ppm CO_2, $p = 10^5$ Pa) of the greenhouse will be the same as for the rest of the outpost to increase the ease of movement for the crew and to allow for a consistent air system throughout the outpost. The CO_2 depletion and the O_2 increase is balanced with the help of the Waste Management system.

The system is sized considering a steady state mode of operation and the eventual buffers are located in the ISRU facility, which also compensates possible over production and needs of oxygen and carbon dioxide. Obviously, the system will face variations, even daily, of air composition, thus it is foreseen to have an O_2 removal system to stabilize the internal atmosphere environment of the outpost.

---

[4] A gravity assisted system is thought to be used here, but the utilization of the ISS WRS is considered to be a conservative approach.

6. *Robotic Assistance*

A dexterous multifunction robot is planned in each module to partially automate the operations to be performed in the greenhouse, from planting of the seeds to moving the plants from germinator trays to growing trays, to help in checking the growth and maturation of the fruits. It is also envisaged to help humans in harvesting the crops and disposing of non-edible parts of the plants. The robot could be fixed to a telescopic tube which could move along rails on the ceiling, so it can operate together with humans, without mutual hindrance.

7. *Waste Management*

The configuration of the Waste Management system of the greenhouse is depicted in Figure 3 and its budgets are reported in Table 2 (13)' (14). The system will be capable of managing both the greenhouse waste stream and the O_2 produced by the crops to restore some of the CO_2 necessary to the growth chamber. The waste management system is composed by: i) a sterilizer, where the biomass wet base and the habitable module waste dry base are treated; ii) a drier, where the majority of water is recovered; iii) a condenser, that condenses water removed in the drier; iv) a sizer, for reducing the waste size; v) a batch incinerator, which burns the resulting dry mass; vi) a filter assembly; vii) a storage tank for the ashes.

The by-products of combustion are ashes, which are collected in containers, and a mixture of hot gases. The noxious gases are extracted (mainly NOx and particulates), hot flux is returned to the drier, water to the condenser and carbon dioxide is fed back to the growth chamber of the greenhouse.

Table 2. Properties of the Waste Management System

Mass [kg]	Volume [m³]	Power [kW_e]	Cooling [kW_{th}]	ESM [kg]
982	9.2	5	4.6	1800

It is worth noting that the heat coming from the incinerator will be used to feed the drier, thus this heat will be transferred to the condenser, so in the overall computation they will be accounted as 2 kW_{th}. The overall cooling power required is therefore 4.65 kW_{th}.

The system will be capable of using both the greenhouse waste stream and the O_2 produced by the crops to restore some of the CO_2 in the growth chamber.

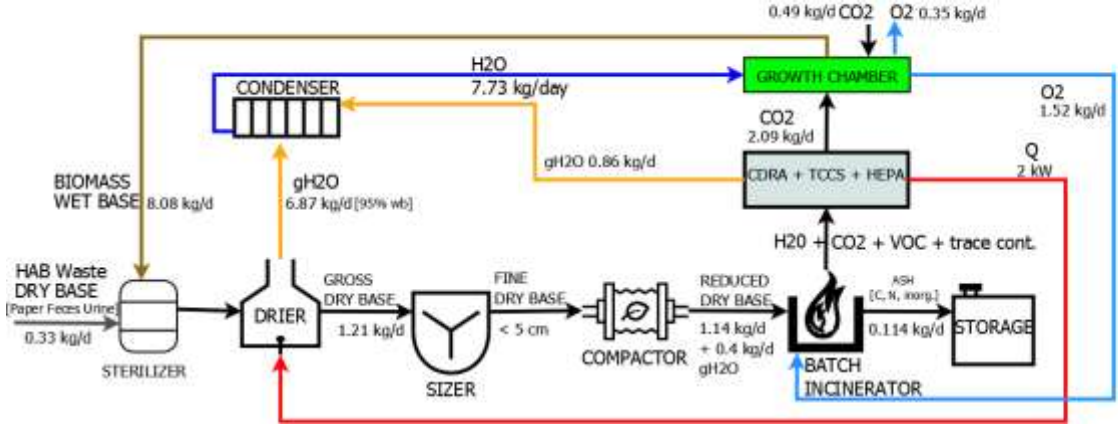

Figure 3. Waste management system schematics. *All the numbers are computed considering one Greenhouse's products and half the waste stream coming from the Habitable module.*

The waste management system will be capable of treating a part of the waste stream coming from the habitation module, mainly the dried faeces, urine and toilet paper produced by a crew of 6 members. In the oxidation reaction, the amount of carbon is computed assuming the dry biomass composed of 50% carbon, and then summing one half of the habitation module waste stream, i.e. accounting for two identical greenhouses.

Thus each greenhouse produces 1.87 kg/day of O_2 and the incineration process will need 1.52 kg of it to burn all the fuel coming from the waste streams. The system will be able to recover 7.73 kg/day of water and will produce 2.09

kg/day of CO_2. Nevertheless, when the crew is taken into account, the system is not fully balanced as there is a lack of oxygen.

Considering two greenhouses, the remaining oxygen of up to 0.7 kg/day will help to reduce the ISRU production requirements. The growth chambers will need a total amount of 5.16 kg/day of CO_2 and the burning process will produce 4.18 kg/day of it. The plants will still need an additional 0.98 kg/day of CO_2, which can potentially come from the crew respiration (around 6 kg/day of CO_2 is produced).

The system will be capable, through the trace contaminant control system (TCCS), the carbon dioxide removal assembly (CDRA) and the high-efficiency particulate air (HEPA) filter subsystems, to separate the noxious gas stream (mainly NOx and particulate) and CO_2 processing the flux coming from the incinerator stage and allowing for the recirculation of the heat flux and water whilst the CO2 is adsorbed by the CDRA system and desorbed to the growth chamber, as can be seen in Figure 3.

The produced ashes amount to 0.114 kg/day, and at the end of the 500 days mission it is expected to have to store around 58 kg of them. In the future, it would be beneficial to introduce nutrition recovery from the ashes, rich in nitrates, and to develop a system to recover N_2 from the harmful NOx.

8. *Storage*

In order to minimize crop mutation due to the Martian environment, it was decided that all seeds required would be brought from Earth. All crops would therefore be first-generation Martian crops, with no use of seeds produced (other than for scientific experiments). The total storage required is 42 kg, which provides enough crops for 6.72 crew members for 500 days (which accounts for crew cross-over time for the long duration mission), including the mass of potato seeds. Freezing was chosen as storage means because it is a power and mass-efficient method of storage, and also causes minimal physical changes to the food produced.

III. Crew Diet

In order to size the greenhouse, it was necessary to determine the diet for the astronauts, as different crops have different space and water requirements. To do this, the NASA guidelines were consulted, from which it was determined that each crew member requires approximately 3000 kCal, 400 g carbohydrate, 100 g fat and 120 g protein. Requirements were also determined for the vitamin and mineral inputs, which was used to ensure that the crew would not develop any serious deficiencies during their mission.

Two versions of each diet were included: one in which everything required (other than the olive oil) is grown in the greenhouse; and a second one, labelled as *Reduced*, in which wheat, rice and beans are brought dried from Earth, rather than being grown on Mars. This decision was made on the basis that these crops are resource demanding, requiring a large area, a lot of water and complex post processing, yet they are low volume and long-life when dried and therefore relatively easy to deliver.

Diet 1: FARM (SEEDS II)

SEEDS II included a greenhouse in their lunar outpost, Food And Revitalization Module (FARM), and produced a number of different diets for comparison as part of their investigation (1). The quasi-full diet was the most complete of their diets, relying as little as possible on food being brought from Earth. This diet was modified slightly, mostly through the inclusion of olive oil in order to increase the fat provided, as the diet had too little fat in comparison with the recommendations.

The Reduced version of this diet requires 370 g of food per person per day to be shipped, which totals to 1227 kg for the equivalent mission of 6.72 crew members for 500 days.

Diet 2: SEEDS VII

As a comparison to the FARM diet, a diet was created with the aim of providing as close to 100% of the food requirements solely from crops that could be grown in the greenhouse, and with a lower requirement on delivered food for the reduced version.

The shipping requirement for the Reduced version of the SEEDS VII diet would be 220 g per crew member per day, totaling to 753 kg for the total equivalent mission.

Diet 3: Minimum Area Diet

As a final comparison, a diet was generated which would require the smallest area of greenhouse, so called Minimum Area Diet (MAD). This was created with the inclusion of a number of high calories foods, such as bresaola, tuna ("under oil"), salame Milano and chocolate.

Each astronaut would eat 2.2 kg of food a day: in the full version of this diet, 210 g of this food are provided from Earth; in the Reduced equivalent 560 g of food are provided. The total food required to be delivered in the Reduced diet totals to 1875 kg.

Table 3. Comparison of the different diets (Wet Masses indicated)

Crop	FARM [g/d]	SEEDS VII [g/d]	MAD [g/d]
Cabbage	372	220	220
Carrot	372	300	100
Chard	61	200	0
Celery	372	220	100
Dry bean	61	100	200
Green onion	61	100	50
Lettuce	200	100	50
Onion	39	80	50
Pea	50	50	50
Peanut	122	150	0
Pepper	122	220	220
Radish	122	120	120
Red beet	61	110	110
Rice	50	40	50
Snap bean	0	150	150
Soy bean	56	20	0
Spinach	0	80	0
Strawberry	122	220	220
Sweet potato	61	320	0
Tomato	372	220	220
Wheat	261	70	120
White potato	250	230	200
Olive Oil	30	25	60
Bresaola	0	0	20
Tuna ("under oil")	0	0	50
Salami Milano	0	0	40
Chocolate	0	0	40
TOTAL	**3217**	**3350**	**2230**

A. Budgets and Trade-offs

These different diets were compared using the Equivalent System Mass (ESM), a value which takes into account a number of factors such as the volume required and power consumption of each diet; this was used to decide on the final diet for the crew.

The data from NASA BVAD (7) was used to calculate ESM and factors such as the water, carbon dioxide, PPF and area requirements for different plants. The detail of the formulas used can be found in Appendix A.

Table 4. Parameters for confronting different diets

Parameters	FARM	FARM Reduced	SEEDS VII	SEEDS VII Reduced	MAD	MAD Reduced
Cultivated Area (m2)	576	429	566	459	351	162
GH Cult. Volume (m3)	294	210	295	233	167	63
Water per day (kg/d)	2152	1037	1602	1116	1184	348
O2 per day (kg/d)	16.6	10.0	16.1	12.2	10.2	3.3
CO2 per day (kg/d)	22.9	13.8	22.2	16.8	14.0	4.5
Inedible Dry Mass (kg/d)	7.94	4.38	7.67	5.59	4.98	1.41
Ined. Water Content (kg/d)	71.5	39.4	69.0	50.3	44.8	12.7
Inedible Total Mass (kg/d)	79.4	43.8	76.7	55.9	49.8	14.1
PPF per day (mol/d)	21895	11059	16278	11585	11900	3840

From these values, power and mass were estimated, using formula and assumptions found in Appendix A.

Table 5. Diets final trade-off

Parameters	FARM	FARM Reduced	SEEDS VII	SEEDS VII Reduced	MAD	MAD Reduced
Total food to transport (kg)	0	1227	84	753	706	1875
Mass of Tertiary Structure (kg)	7062	5264	6939	5624	4302	1984
Mass of lighting system (kg)	3851	1945	2863	2038	2093	676
Mass of pump (kg)	35	26	34	28	21	10
Mass of nutrients (kg)	2318	1466	2281	1785	1494	640
Mass of robots (kg)	2362	1760	2321	1881	1439	663
Mass of Waste Mgmt (kg)	982	982	982	982	982	982
Mass of Fire D&S (kg)	1123	809	1127	895	646	253
Total Mass (kg)	17648	13321	16542	13841	11485	6789
ESM volume (kg)	5103	3678	5123	4070	2938	1149
ESM power (kg)	5676	3134	4383	3266	3298	1377
TOTAL ESM	**28512**	**20292**	**26414**	**21536**	**18099**	**9686**

From this trade-off the Minimal Area Diet was chosen, and the values derived from it are the base of the sizing of all the GH subsystems.

IV. Results & Conclusions

A. Contingency Considerations

Before sizing the greenhouse, a 15% margin was applied to the surface required for production. This is intended to take into account the uncertainties of growing plants on another planet, an operation never tried before. Under optimal lighting and nutrient conditions, the actual yield of plants can be boosted by up to 10% (7). This, combined with the margin, has been assumed as enough to compensate for possible complications.

Since out the energy amount, 76% is provided by the food brought from Earth, the following plan for contingencies has been chosen:

- double the food to be brought from Earth;
- use the nominal surface to be cultivated, but split in two greenhouse modules;
- bring from Earth the same type and amount of food the greenhouse is designed to produce in a month, lyophilized, as an emergency buffer for 1 month.

With this configuration, the volume and mass are kept to the minimum, and in the worst case scenario (complete stop of the production of both greenhouse modules), the crew has 30 days of eating a normal diet to repair the failure. The system is therefore two-failure tolerant. It is also thinkable, even if is like a life-or-death compromise, that in case of unrecoverable loss of both the greenhouse modules, the crew could wait for the subsequent launch window (which is up to two years) eating only the food brought from Earth together with vitamins and minerals.

The values of this system configuration, per greenhouse module, are shown in Table 6:

Table 6. Characteristics of each greenhouse module

Cultivated Area (m^2)	93.0	**Inedible Dry Mass (kg/d)**	0.81
GH Cultivated Volume (m^3)	36.2	**Inedible Water Content (kg/d)**	7.28
Water per day (kg/d)	200	**Inedible Total Mass (kg/d)**	8.09
O_2 per day (kg/d)	1.88	**Edible Water Cont. (kg/d)**	6.30
CO_2 per day (kg/d)	2.59	**PPF per day (mol/d)**	4165

B. TRL Roadmap

A number of critical technologies need to be developed in order to make possible the realization of the Greenhouse module for the MILESTONE Mission. Following the NASA and ESA Technologies Roadmaps (15)’ (16) and assessing the Technologies Readiness Level (TRL) to date, a list of these necessary technologies is presented in Table 7.

Table 7. TRL Roadmap

Enabling Technology	Description/ Capability Performance Goal	Current TRL
Waste management/batch incinerator	Recycling and disposal of organic waste from the greenhouse and future integration with human waste.	3
High Efficiency LEDs	High efficiency LEDs for providing light at optimal plant growth.	6
Greenhouse tending robotic arm	Robotic arm for planting seeds, checking the “vegetable readiness level” and harvesting crops. Able to manipulate growing trays position and move around the module.	3
Oxygen Removal System	System for removal of oxygen produced in excess from the greenhouse and for purging oxygen from the outpost during unmanned operation.	3

C. Greenhouse Overall Mass and Power Budgets

In the following figures the overall budgets for the Greenhouse subsystems are presented. Figure 4 shows the mass budget. It is clear how the reliance on supplies brought from Earth is still the main component of the system, meaning the needs of further development with the aim of reaching the self-standing status required by a possible future colonization of Mars.

From Figure 5 it is worth noticing how the illumination system is the most power demanding. Even if cutting edge technologies have been used, the chart shows clearly that further studies are needed in this area, since power is a precious and scarce resource for Space Exploration.

Table 9. Power Budget

Subsystem	Power (W)
ECLSS	2370
ATCS	578
C&DH	39
GH Subsystem	21700
Total	**24700**

Table 8. Mass Budget

Subsystem	Mass (t)
Primary Structure	13.1
Secondary Structure	1.45
ECLSS	3.20
ATCS	2.29
AEPS	1.62
C&DH	0.021
GH Subsystem	7.16
Total	**28.9**

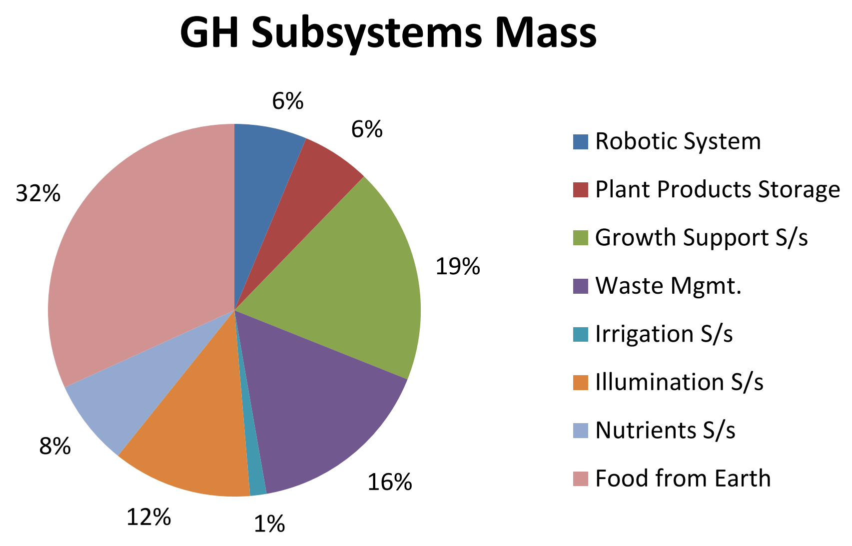

Figure 4. Greenhouse Mass Budget

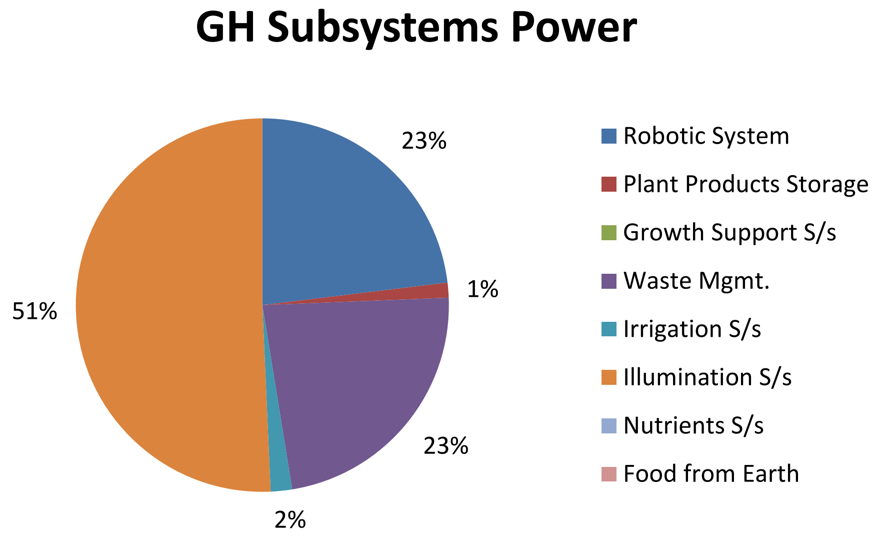

Figure 5. Greenhouse Power Budget

D. Conclusions

During two of the six months of the SEEDS Master, we managed to design a GH module for the MILESTONE Mission following a pre-Phase A study approach. Through deep and detailed analyses we assessed the possibility of such a project, underlining the main issues, developing a credible system. Where the technologies unavoidably needed were absent or immature we assessed the plan to bring their TRL to be flight ready.

Now we leave this project in the hands of the SEEDS VIII team, sure that they will exploit its potential to continue the pursuit of Mars Colonization.

Appendix A

Diet Parameters

The effective number of crewmembers takes into account for the superposition of two subsequent mission crews during the rotation period. It follows:

$$n_{CM}^{eff} = \frac{(t_{miss} + t_{rot})n_{crew}}{t_{miss}} = 6.72\,.$$

The total cultivable surface can be obtained as:

$$S = n_{CM}^{eff} \sum_{i}^{plant\ types} f_i \frac{1}{p_i}$$

where f_i is the food need per crew member per unit time and p_i is the edible fresh biomass production, per unit surface per unit time.

The total volume, water consumption, oxygen production, CO_2 consumption, inedible dry and fresh masses and total PPF can be obtained from the following formula, substituting X_i with the proper quantity, per unit surface per unit time:

$$X_{TOT} = n_{CM}^{eff} \sum_{i}^{plant\ types} f_i \frac{1}{p_i} X_i$$

The values for the X_i were taken from the tables 4.97, 4.98, 4.99 and 4.100 of the NASA BVAD (7).

Power

The power of the lighting system and the water circulation were estimated using commercial products as guidelines (OSRAM-SYLVANA Zelion® HL LED (10) and Pentax CM50); the Waste Mgmt was fixed to 5kW at this stage and the robots mass was taken from the NASA BVAD (7).

Mass

The *Total Food to be shipped from Earth* mass was calculated in each diet, assuming to substitute the wet masses of wheat, rice and beans with their dry ones; the mass of the *Tertiary Structure* was estimated using Bartscher Shelving System Kit 2 (shelves of aluminium and copolymer) as a guideline, plus polymer channels for the NFT system.

The mass of the *Lighting System* was sized on the commercial lamps we based on (10), as well as the *Irrigation System*; the mass of the *Nutrients* was calculated from the data taken from NASA BVAD (7), like for the mass of the *Robots*. The *Fire Detection and Suppression System* was sized accordingly to the analog designed for the rest of the MILESTONE outpost.

The Equivalent System Mass (ESM) was also calculated taking data from the NASA BVAD (7), specifically the *Volume ESM* using the Unshielded Inflatable Volume parameter.

Acknowledgments

First of all, we want to thank SEEDS organization and the Politecnico di Torino for setting this Master several years ago and continuing to develop it with the same passion and rationality; this was also made possible thanks to ALTEC and Thales Alenia Space Italia, ISAE-SUPAERO and University of Leicester, with their hospitality and technical support.

A special thanks goes to our friends and master comrades, with whom we shared laughs and tears: Marco Baldelli, Samuel Brown, Alberto Ferrero, Oliver Hardy, Rachel Henson, Lorenzo Menghini, Gerard Moreno-Torres Bertran, Silvio Silvestrelli, Ameer Zailani.

Last but not the least, a mention is needed to the Compagnia di San Paolo, which supported us financially through a scholarship.

References

1. *Concept of a Lunar FARM: Food and revitalization module.* **Finetto, Claudio, Lobascio, Cesare and Rapisarda, Alessandro.** s.l. : Acta Astronautica, 2010, Vol. 66.

2. **NASA.** The Mars Orbiter Laser Altimeter (MOLA). [Online] August 2015. http://mola.gsfc.nasa.gov/images.html.

3. **Fuller, Elizabeth R. and James W., Head III.** *Amazonis Planitia: The role of geologically recent volcanism and sedimentation in the formation of the smoothest plains on Mars.* s.l. : Journal of Geophysical Research, 2002.

4. **Arizona, University of.** Data from 2001 Mars Odyssey Gamma Ray Spectrometer. [Online] August 2015. http://phoenix.lpl.arizona.edu/images/Mars_Full_Planet_Water_Map.jpg.

5. **Hublitz, Inka.** *Engineering concepts for inflatable Mars surface greenhouses.* s.l. : Division of Astronautics, Technische Universität München, Germany.

6. *Crop productivities and radiation use efficiencies for bioregenerative life support.* **Wheeler, R M, et al., et al.** s.l. : Advances in Space Research, 2008, Vol. 41.

7. **Anderson, Molly S, et al., et al.** *Life Support Baseline Values and Assumptions Document.* s.l. : NASA, 2015. NASA/TP-2015-218570.

8. *Role of Hydroponics and Aeroponics in Soilless Culture in Commercial Food Production.* **Lakkireddy, K K R, Kasturi, K and Sambasiva Rao, K R S.** 1, s.l. : Research & Reviews: Journal of Agricultural Science & Technology, 2012, Vol. 1.

9. *A review on plant without soil - hydroponics.* **Sardare, Mamta D and Admane, Shradda V.** 3, s.l. : IJRET: International Journal of Research in Engineering and Technology, 2013, Vol. 2.

10. **Osram Sylvania.** ZELION® HL Horticulture LED Grow Light Fixtures. [Online] Osram Sylvania, 2013. [Cited: September 09, 2015.] http://www.osram-americas.com/en-us/products/display-optic-specialty-lighting/Pages/ZELION-HL-Horticulture-LED-Fixtures.aspx.

11. Zeoponics . *Zeomin Australia.* [Online] [Cited: April 16, 2015.] http://zeomin.com.au/zeolite-applications/zeoponics.

12. Issue 01: NFT Culture. *Hydroponics.* [Online] [Cited: 04 24, 2015.] http://www.hydroponics.com.au/issue-04-nft-culture/.

13. **MAXWELL, Sabrina and DRYSDALE, Alan E.** *Asssessment of Waste Processing Technologies for 3 Missions.* s.l. : SAE Technical Paper, 2001.

14. **VEROSTKO, Charles, et al. .** *Solids Waste Processing and Resource Recovery for Long-Duration Missions–A Workshop.* s.l. : SAE Technical Paper, 2001.

15. **NASA.** NASA Technologies Roadmap. [Online] 2015. http://www.nasa.gov/offices/oct/home/roadmaps/index.html.

16. **ESA.** ESA TRL Roadmap. [Online] 2015. http://www.esa.int/Our_Activities/Space_Engineering_Technology/Latest_edition_of_Europe_s_technology_master_plan_published.