Departament d'Enginyeria Química
Escola Tècnica Superior d'Enginyeries
Universitat Autònoma de Barcelona
Tel.: 93.581.10.18 Fax: 93.581.20.13
08193 Bellaterra Spain

MELISSA

Memorandum of Understanding

ECT/FG/MMM/97.012

Contract Number: ESTEC/CONTRACT13292/98/NL/MV

Technical Note: 65.5

Higher Plant Chamber Preliminary Requirements Document

Version: 1

Issue: 5

MASOT, A.; WATERS, G; STASIAK, M; ALBIOL, J.; DIXON, M. GODIA, F.

September 2004

Document Change Log

Version	Issue	Date	Observations
Draft	0	17/02/03	Preliminary Version
Draft	1	07/06/03	First Version
Draft	2	01/10/03	Second Version
Draft	3	10/02/04	Third Version
Draft	4	28/04/04	Fourth Version
1	5	28/09/04	Final Version

Table of Contents

Nomenclature

DW: Dry weight

EC: Electroconductivity

ED: Edible biomass (DW; dry weight)

FM: Flowmeter

H: Height

HID: High Intensity Discharge

HPC: Higher Plant Chamber

HPS: High Pressure Sodium

INED: Inedible biomass (DW; dry weight)

L: Length

MCS: MELISSA control system

MELISSA: Microbial Ecological Life Support System Alternative

MH: Metal Halide

P: Pump

PAR: Photosynthetically Active Radiation

PPF: Photosynthetic Photon Flux

TN: Technical Note

UAB: Universitat Autònoma de Barcelona

UoG: University of Guelph

V: Valve

VOC: Volatile Organic Compound

W: Wide

1 INTRODUCTION

The MELISSA project (Microbial Ecological Life Support System Alternative), a micro-organisms and higher plants artificial ecosystem, is a tool for the development of regenerative life support systems for long term manned space missions.

The goal of the Pilot Plant, located at UAB, is to demonstrate the MELISSA loop concept. Consequently the closure of the loop has to be completed. In order to achieve this purpose, the integration of a higher plant compartment (HPC) is one of the next steps.

The design of the HPC, as a combination of several higher plant chambers, and its development taking into account its incorporation into the gas, liquid and solid loops are the main objectives of this step.

This technical note is devoted to the identification of the different functional, design and control requirements that the final HPC shall have. In these design requirements a preliminary sizing of the IVb compartment, considering the three plants already selected by the MELISSA partners, has been calculated and discussed.

Moreover, as the chamber has to be integrated into the MELISSA loop, the interconnection points with the other compartments, as well as the control parameters have been described and are listed in the requirements table. After approval of these general characteristics of the HPC by ESA, this technical note will be expanded with more detailed information about the HPC design in TN 75.3.

2 AVAILABLE FACILITIES

The laboratory area devoted to HPC in the new UAB facility is of 72 m^2 (12 x 6) and its height is approximately 4 m. The infrastructure includes some of the services listed below. For more detailed information see TN66.3.

- Electrical power: triphasic/biphasic, 30 kW (28.5A).
- Demineralised and tap water lines.
- Air conditioning equipment
- Gas lines: Compressed air, CO_2, N_2, O_2

3 CROP SELECTION

In TN46.2 an optimised menu was designed to supply the dietary requirements of a 6 member crew for a 10-day menu cycle. The crops were selected for their nutritional value, adaptability to closed environment culture, processing requirements, crop yield and physiological value. A list of 25 species, suitable to meet the dietary requirements of the crew while offer some variety, was selected. However, it had been decided in a MELISSA general working meeting (29/30 November 2001) that only three plants from the complete menu would be initially considered in the tests of the HPC. The selected species, which are wheat (*Triticum aestivum* L.), lettuce (*Lactuca sativa* L.) and beet (*Beta vulgaris*), are representatives of plants with a predominant composition in stems, leaves and roots respectively. Specific information on cultural management strategies in closed environments exists in the common literature for the three species, but as the data is collected from different sources, some discrepancies exist between their values. Although data presented below includes some non-consistent values, parameters selected to design the HPC will be from the same bibliographic source, whenever possible, and will be selected after a critical evaluation. Tables shown next contain some of the basic physiological parameters of those plant cultures.

PARAMETER	UNITS	VALUE	REFERENCES
Productivity:			
- Edible biomass: Dry basis	g dw/(m^2*d)	13.8 (11.50, 16.18)	Bugbee (2003)
Fresh basis	g fw/(m^2*d)	15.68 (13.07, 18.39)	calculated
Fresh basis H_20 content	%	12	Hanford, *et alt.* (2002)
- Inedible biomass: Dry basis	g dw/(m^2*d)	13.8 (11.50, 16.18)	calculated
Fresh basis	g fw/(m^2*d)	15.68 (13.07, 18.39)	calculated
Fresh basis H_20 content	%	12	calculated
-Total biomass (ed+ined)	g dw/(m^2*d)	27.6 (23.00, 32.36)	calculated
Harvest index(edible bio/total bio)	%	50	Bugbee (2003)
Carbon content	%	42	Wheeler, *et al.* (1995)
CO_2 uptake	mol/(m^2*d)	0.96	calculated
CO_2 uptake	g/(m^2*d)	42.24	calculated
O_2 production	mol/(m^2*d)	0.96	calculated
O_2 production	g/(m^2*d)	30.76	calculated
H_2O uptake /Transpiration	mol/(m^2*light·hours)	0.49	Hanford, *et alt.* (2002)
Time to harvest (Growth period)	d	65	Bugbee (2003)
Mature plant height	m	0.45	Bugbee (2003)
Density(initial/final)	plants / m^2	400	Bugbee (2003)
Photoperiod (light/dark)	h	24	Bugbee (2003)
PPF:	µmol/(m^2*s)	1000	Bugbee (2003)
Propagation	µmol/(m^2*s)	1000	Bugbee (2003)
Vegetative	µmol/(m^2*s)	1000	Bugbee (2003)
Flower Initiation	µmol/(m^2*s)	1000	Bugbee (2003)
Fruit/Seed	µmol/(m^2*s)	1000	Bugbee (2003)
PPF compensation point	µmol/(m^2*s)	20-40	theoretical
Minimum PPF range	µmol/(m^2*s)	250-450	theoretical
Temperature(light/dark)	ºC	23	Bugbee (2003)
Germination requirement	ºC	23	Bugbee (2003)
Vegetative	ºC	23	Bugbee (2003)
Flowering	ºC	17	Bugbee (2003)

Table 1. Wheat physiology parameters.

PARAMETER	UNITS	VALUE	REFERENCES
Productivity:			
- Edible biomass: Dry basis	g dw/(m^2*d)	1.68 (1.49, 1.88)	Waters(2002)
Fresh basis	g fw/(m^2*d)	34.88 (30.15, 39.54)	Waters(2002)
Fresh H_20 content	%	95.18	Waters(2002)
- Inedible biomass: Dry basis	g dw/(m^2*d)	0.54 (0.47, 0.59)	Waters(2002)
Fresh basis	g fw/(m^2*d)	6.86 (6.12, 7.48)	Waters(2002)
Fresh H_20 content	%	92.13	Waters(2002)
-Total biomass (ed+ined): Dry basis	g dw/(m^2*d)	2.22 (1.96, 2.47)	calculated
Fresh Basis	g fw/(m^2*d)	41.74 (36.27, 47.02)	calculated
Harvest index(edible bio/total bio, dwb)	%	76	calculated
Carbon content	%	40	Waters (2002)
CO_2 uptake	mol/(m^2*d)	0.074	calculated
CO_2 uptake	g/(m^2*d)	3.26	calculated
O_2 production	mol/(m^2*d)	0.074	calculated
O_2 production	g/(m^2*d)	2.37	calculated
H_2O uptake /Transpiration	mol/(m^2*light·hours	3.36	Waters (2002)
Time to harvest (Growth period)	d	45	Waters (2002)
Mature plant height	m	0.25	Waters (2002)
Density(initial/final)	plants/m^2	17.6	Waters (2002)
Photoperiod (light/dark)	h	14/10	Waters (2002)
PPF (seed to flower)	µmol/(m^2*s)	400-600	Waters (2002)
PPF compensation point	µmol/(m^2*s)	100	Waters (2002)
Minimum PPF range	µmol/(m^2*s)	250-450	Waters (2002)
Temperature(light/dark)	ºC	26/20	Waters (2002)
Germination requirement	ºC	4/4	Waters (2002)
Vegetative	ºC	26/20	Waters (2002)
Flowering	ºC	30/25	Langhans *et al* (1997)
Relative Humidity	%	70	Waters (2002)

Table 2. Lettuce physiological parameters.

PARAMETER	UNITS	VALUE	REFERENCES
Productivity:			
- Edible biomass: Dry basis	g dw/(m^2*d)	9.22 (8.05, 10.36)	Waters(2002)
Fresh basis	g fw/(m^2*d)	127.21 (110.36, 144.02)	Waters(2002)
Fresh H_20 content	%	92.75	Waters(2002)
- Inedible biomass: Dry basis	g dw/(m^2*d)	0.55 (0.49, 0.62)	Waters(2002)
Fresh basis	g fw/(m^2*d)	8.60 (7.20, 9.97)	Waters(2002)
Fresh H_20 content	%	93.6	Waters(2002)
-Total biomass (ed+ined): Dry basis	g dw/(m^2*d)	9.77 (8.54, 10.98)	calculated
Fresh Basis	g fw/(m^2*d)	135.81 (117.56, 153.99)	calculated
Harvest index(edible bio/total bio, dwb)	%	94.00	calculated
Carbon content	%	40	Waters (2002)
CO_2 uptake	mol/(m^2*d)	0.32	calculated
CO_2 uptake	g/(m^2*d)	14.08	calculated
O_2 production	mol/(m^2*d)	0.32	calculated
O_2 production	g/(m^2*d)	10.24	calculated
H_2O uptake /Transpiration	mol/(m^2*light·hours)	6.44	Waters (2002)
Time to harvest (Growth period)	d	54	Waters (2002)
Mature plant height	m	0.45	Waters (2002)
Density(initial/final)	plants/m^2	17.6	Waters (2002)
Photoperiod (light/dark)	h	14/10	Waters (2002)
PPF (seed to flower)	µmol/(m^2*s)	400-600	Waters (2002)
PPF compensation point	µmol/(m^2*s)	100	Waters (2002)
Minimum PPF range	µmol/(m^2*s)	250-450	Waters (2002)
Temperature(light/dark)	ºC	26/20	Waters (2002)
Germination requirement	ºC	4/4	Waters (2002)
Vegetative	ºC	26/20	Waters (2002)
Flowering	ºC	30/25	Langhans *et al* (1997)
Relative Humidity	%	70	Waters (2002)

Table 3. Beet physiological parameters.

The culture of the three species in a chamber is restricted due to the different photoperiod requirement of them.

4 FUNCTIONAL REQUIREMENTS

As previously mentioned the incorporation of the higher plant compartment in the MELISSA Pilot Plant, is one of the key steps to achieve the closure of the loop. The HPC has to be able to be integrated with the compartments in operation at the time of installation as well as to allow its operation in isolation. This way various experiments can be performed to test and validate the chamber after its installation or to produce higher plant biomass in different test conditions even if the loop is not in operation. For this reason its design will have to take into account all the gas, liquid and solid lines and flow regulation devices required for the mass transfers with the other MELISSA compartments. Besides the interconnection devices, the chamber will also be equipped with the required hardware necessary for the independent operation from the loop.

Furthermore, the chamber will allow to control key environmental conditions, as discussed more extensively in the control system description section, and allow the continuous monitoring of the plant culture evolution as well as the storage of the data obtained from the lighting, liquid gas and solid subsystem. The evolution of the plant culture can also be followed with video equipment that can be installed to allow stress image detection analysis.

5 DESIGN REQUIREMENTS

5.1 Sizing

As some constraints for the HPC design have been proposed in previous MELISSA meetings, different scenarios have been studied in order to size the culture chambers. As already mentioned, only three plants (wheat, lettuce and beet) of the whole initial menu will be initially considered. In addition to this it has been decided that the HPC biomass production shall supply around 20% of the daily human diet.

In order to feed 6 crew member for a 10 day menu cycle, an amount of 66,7 kg of dry edible biomass are required (Waters *et al.*, 2002). This means that 1.1 kg of dry biomass per person and day shall be supplied to cover the dietary requirements.

According to these data, the daily productivity of the HPC shall be 222.3 g of dry edible biomass.

In the following paragraphs the HPC sizing and plants distribution description will be done and discussed for different scenarios.

Total productivity and harvest index are the only bibliographic values used for the sizing, since the other values are either fixed for each case (for example the even distribution of an item in the chamber such as the either edible material (ED), the inedible material (INED) or the growing area) or easily calculated from the previous ones.

Since it's preferable to select data from the same bibliographic source all data used are from University of Guelph references (Waters, Cloutier), except for wheat total productivity that is the one reported by Bugbee. The rest of the reference data given in the tables provide an approximation of the possible range of variation of the data used for the design.

As initial starting point, the 222.3 g edible dw/d can be taken. Assuming that this productivity has to be reached, two different options are possible. On one hand, it can be considered an even distribution among the three chambers of the edible biomass, which means 74 g ED/d of each crop per chamber. The table below shows the production area required (excluding air-lock), calculated using the data shown in tables 1, 2, and 3 (A list of Productivity sources investigated in the course of this work package is given in Appendix B).

			Harvest index	Productivity	Area
	g ED/d	gINED/d	gED/(g total)	g ED/(m^2*d)	m^2
WHEAT	74.0	74.0	0.5	13.80	5.4
LETTUCE	74.0	23.4	0.76	1.68	44.0
BEET	74.0	4.7	0.94	9.22	8.0
Total	**222.0**	**102.1**			**57.4**

Table 4. HPC sizing with even distribution of edible biomass (scenario 1).

Analysing the data obtained, an area of 57.4 m^2 is required to achieve an equal edible distribution. It can be seen that about a 77% of the growing area is lettuce culture due to its low productivity.

Nevertheless, 72% of the inedible biomass produced per day is wheat, which is not the most desirable conditions for first compartment inlet, since its degradation efficiency of certain compounds, mainly is fiber and lignin, present in high quantities in the non edible part of the wheat is not optimal.

As another option, an even inedible biomass distribution can be considered, so that the inlet in the first compartment can have a more uniform mixture composition.

			Harvest index	Productivity	Area
	g ED/d	gINED/d	gED/(g total)	g ED/(m^2*d)	m^2
WHEAT	11.2	11.2	0.5	13.80	0.8
LETTUCE	35.4	11.2	0.76	1.68	21.1
BEET	175.4	11.2	0.94	9.22	19.0
Total	**222.0**	**33.6**			**40.9**

Table 5. HPC sizing with even inedible biomass distribution (scenario 2).

In this scenario the production area is reduced to 40.9 m^2, but while lettuce and beets have reasonable percent of total area (51.6% and 46.4% respectively), wheat represents 2%. Furthermore, beets produce the 79% of the edible biomass, which leads to a non-equilibrated human diet.

Fixing a chamber area and evaluating the biomass production, different approaches to plant distribution can be done. Assuming that one chamber of 5 m^2 is devoted to each plant and taking into account the same productivities and harvest index as before, the results obtained are:

	Area (m^2)	g ED/d	%ED/d	g INED/d	%INED/d
WHEAT	5	69.0	55.9	69.0	92.5
LETTUCE	5	8.4	6.8	2.7	3.6
BEET	5	46.1	37.3	2.9	3.9
Total	**15**	**124**	**100.0**	**75**	**100.0**

Table 6. HPC sizing with even crop area distribution (scenario 3).

The calculation of the different percentages of the edible and inedible biomass is described for wheat case in detail. As commented above, the area is fixed to 5 m^2, so multiplying this value by edible specific productivity reported in previous tables (13.8 gED/m^2d), the edible of wheat per day is obtained (69.0 gED/d). Then, the inedible daily production of wheat is calculated with the harvest index.

As shown in the table, not only the edible biomass produced per day is lower than the required by a human daily diet, but also almost all the inedible part is generated by wheat. The high content of fiber in the non edible part of wheat is probably not the best option for the C-I tests.

The analysis of the different approaches and consideration of the different advantages and disadvantages does not allow reaching a definitive conclusion with the available data. Therefore, in order to proceed with a preliminary design able to support the higher plant cultures of the Pilot Plant and obtain further data it was decided in collaboration with the University of Guelph to use scenario 3 to progress with the chamber design description in this technical note. Therefore it is proposed to build one or several HPC with 5 m^2 of growing area each and the capability to accommodate any one of the different plant cultures and postpone the decision of the type of plants that will be planted inside according to future Pilot Plant productivity requirements.

5.2 Materials

A close environment implies the accumulation of certain compounds, which even at low concentrations can be toxic to plants. This is the reason why it is important to minimize the contamination of the entire MELISSA loop and the HPC. According to this the materials used for the HPC are chosen specifically and a control contamination control has to be implemented. Therefore, materials used shall be selected to be compatible with higher plants and to avoid environmental contamination, so biocompatible and non-off gassing ones are the most suitable. This fact leads to a limited list of potential materials to be used. A proposal of different materials and its possible uses is shown in table 7 (Stasiak, 2002):

PARAMETER	MATERIALS
Walls, floor, valves, plumbing...	Stainless Steel 316
Roof	Tempered Glass
Tubing, gas expansion bladders	Teflon
Tubing, valves	Polypropylene
Heat exchange, motor parts, ox	"Heresite" (1)
O-rings, solenoid seats	"Viton" (2)
Sealant	Silicon sealant (Dow-Corning RTV 732)

Table 7. HPC materials
(1) Pure phenolic thermosetting resinous coating
(2) Fluoroelastomer heat resistant

In addition to the desirable properties commented before, the interior finish shall provide a uniformly high reflection of the light source in order to have a proper distribution of the radiation energy.

5.3 Basic HPC structure

Depending on the chamber design, access areas will be defined. The final design of the HPC isn't decided yet, but a different proposal from the currently plant chambers in UoG was discussed and proposed as pre-design in the recent UAB/UoG exchange meetings. A basic scheme of this design is depicted next.

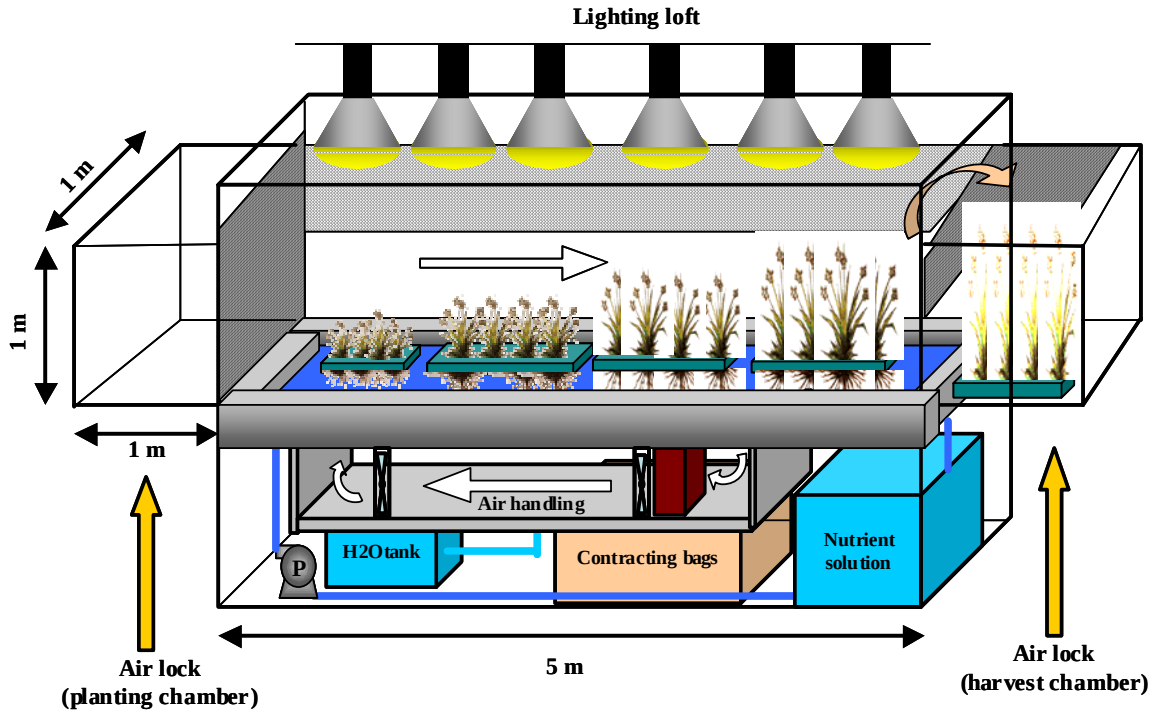

Figure 1. Diagrammatic representation of higher plant chamber for integration in a human life support system.

This chamber has two access areas located at each of its sides. One is to be used in the seeding procedure and the other one to harvest the mature plants. This configuration allows to implement a staggered culture procedure and also a good gas closure avoiding any gas loses, since while planting or harvesting the access zones can be independent from the rest of the chamber with an air-lock system defined more detailed in section 5.4. Furthermore, these access areas avoid the exchange of air between interior and exterior of the HPC avoiding gas contamination caused by external pathogen. It is foreseen to introduce another method to further decrease the possibility

of contamination, such us an air filter after closing the external doors and before opening the internal ones.

The hardware necessary for the chamber plant operation such as nutrient solution tank, pumps, water condensed tank and other instrumentation will be situated below the growing area to reduce the space occupied outside the chamber limits.

As it was commented before, chamber dimensions shown in figure 1 was depicted taking the production area required for scenario 3, where there is a plant chamber of 5 m^2 (excluding air-lock) devoted to each one of the three species selected. Thus, distribution of these chambers in the new laboratory can be the one proposed next.

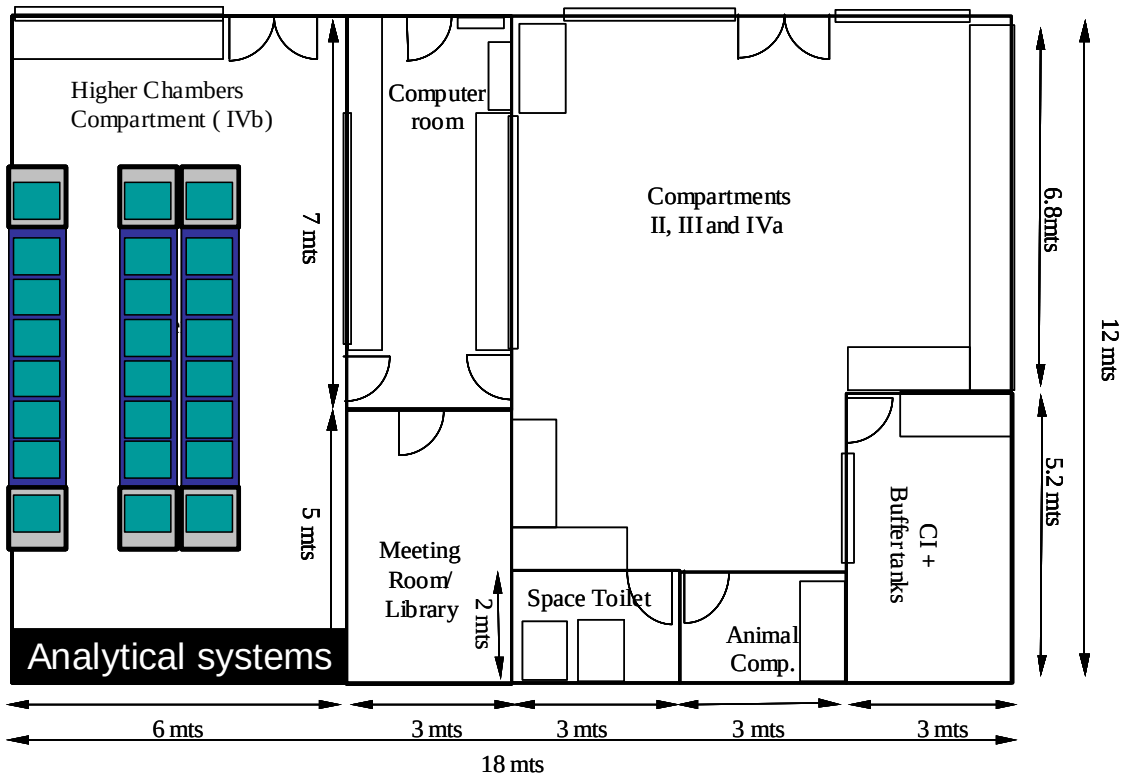

Figure 2. Higher Plant Compartment distribution in the UAB laboratory.

If it was necessary to have a bigger production area (20 m^2) another plant chamber can be easily incorporated beside the right wall.

5.4 Air-lock system

After considering different configurations for the air-lock system such us the use of manipulation gloves to allow proper operation or use of specialized automation system like a robotic arm, the air-lock system has been designed.

As the closure of the chamber is an important requirement, this side-opening access doors will have interior lock sheeting made of polypropylene that ensure a better insulate.

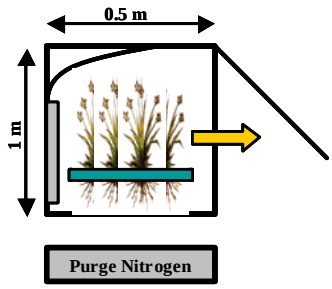

Figure 3. Air-lock system.

As it's depicted in the picture, the dimensions of this air-lock system are 1m (W) x 0.5m (L) x 1m (H) at each end, which represent 1 m^3 per chamber. This air-lock-system will be the subcameras where the seeding and the harvest will take place. Pressure regulation and purge of this area can be done with nitrogen gas.

Furthermore, the HPC will be equipped with 5 doors more distributed along the sidewalls of the chamber (1 door/m chamber length) to allow maintenance and supervision of the culture. The dimensions of this side doors will be 0.6m (W) x 0.6m (H). The specific design of the side doors will be elaborated in TN73.5. This configuration allows seeing the culture opening only the external door and avoiding the gas exchange between internal and external atmosphere.

Further considerations such as a possible extension of hydroponics trays from interior of the chamber to the air-lock region for atmospheric seal or the possibility to disassemble this air-lock area for access can be considered.

5.5 Lighting subsystem

As light is the only energy source for the plants growth and development, it is one of the most important factors regarding to crop yield. Thus, the selection of the

artificial lighting system shall be made taking into account some parameters such as photosynthetically active radiation (PAR), photosynthetic photon flux (PPF), spectral emission and conversion efficiency which will determine the type of lamp required. (Langhans *et al*., 1997).

Photosynthetically active radiation (PAR) describes the radiation contributing to the light reactions and is generally accepted to be comprised of a range wavelength between 400 and 700 nm (visible spectrum). Although this is a commonly used term, PPF also refers to the light absorbed by the plants and used for photosynthesis expressed in $\mu mol/m^2$ s, and is also quite often found in literature. Due to that plants absorbs specially the blue wavelengths (440-460 nm) for photosynthesis and the red ones (600-700 nm) for maturation, flowering and germination, the type of light source selected shall provide a broad spectrum to which the plants are well adapted. In addition, the conversion efficiency of electricity into radiant energy and the direction of this energy onto the plant canopy, determines the efficiency of the type of lamp.

Thus, different kind of lamps needs to be studied. Incandescent lamps are rich in red wavelengths, but have low conversion. Fluorescent lights have a spectrum that generally matches the requirements of plants. High-intensity discharge (HID) lamps, such as metal halide (MH) and high-pressure sodium (HPS), produce PPFs greater than incandescent and fluorescent lamps. Microwave lamps have not only a good spectrum, but also a good efficiency although they seem to have low reliability (Langhans *et al*., 1997).

While modern advances in Light Emitting Diode (LED) technology have rendered the diodes themselves more efficient, when one considers the reduced delivery capacity compared to HPS or MH lamps and the inefficiency of the LED lighting system ballasts (transformer), it is recommended that more conventional lamp types (MH, HPS) be considered.

After evaluating different types of lamps the HPS and MH have been selected, because they not only supplies a broad spectrum, but also a light intensity between 0 to 1000 $\mu mol/m^2$ s at bench height (1 m from lamps with dimmable ballast) which satisfies the photosynthetic photon flux absorbed by the plants. Moreover, the power consumption is less than other models. Further, these lamps have dimmable light ballasts to provide a range of light intensities for control.

Regarding to this, a combination of HPS (600W) and/or MH (400W) lamps that can provide a maximum of 2 kW per m^2, would be a good choice for a reliable lighting system in the HPC. As the production area is firstly considered to be 5 m^2, which leads to a lamp bank with at maximum of 20 lamps per chamber (2 HPS 400W and 2 MH 400W lamps per square meter) situated in the lighting loft (see figure 1). Thus, power requirement for lighting is up to 12.5 kW per single chamber (considering a safety factor of 1.25). More typically and certainly more practical is the use of 1 lamp of each type per m^2 giving a total of 1 kW intensity. This would reduce the power consumption to 5 kW per chamber. This shall be considered as a reasonable target for lighting configuration.

Lamps shall be controlled (on/off) to provide the photoperiod required by the plants.

In order to remove high heat load of the lighting system, a cooling coil must be considered. One possibility is to design an independent cooling coil, as well as a fan for the lamp loft external to the chamber (option A). Another possibility is to remove the heat in the same way that is done in the laboratory ventilation system (option B). This system takes air from the exterior, flows through a heat exchanger installed in the ventilation system of the building (with a 4 ºC cold water line), introduces the fresh air into the laboratory (or into the HPC) and goes back to the exterior through an air line, which collects all the warm air from the different labs. In this case, as the air comes always fresh from the exterior, its temperature is often lower than if the air were recirculated constantly through the lighting loft, which would have a higher temperature due to the air is not coming fresh from the exterior but recirculated through the lamp bank. Thus, it seems that if the inlet air stream comes from exterior (option B) with a cooler temperature than if it was recirculated (option A), the capacity required by the cooler will be smaller for option B. The design of the cooling coil and the possibly needed hardware for water condensation treatment will be elaborated in TN73.5.

A diagrammatic representation of the lighting loft and two possible options for its cooling coil (A, B) are depicted in figure 4.

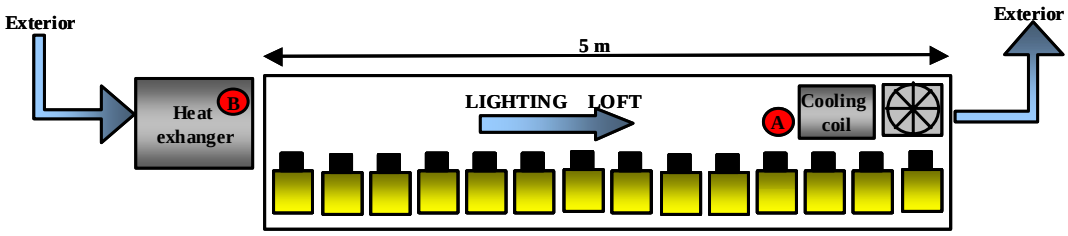

Figure 4. Lighting loft basic structure.

5.6 Liquid subsystem

Plants are grown hydroponically using a nutrient film technique. In this method a thin film of nutrient solution, which is always in contact with the plants, flows through channels that contains the plant' roots.

The nutrient solution is stored in a 300-litre Teflon or steel reservoir (0.63m[W]x0.95m[L]x0.63[H]) located outside of and below the chamber and accessible for maintenance. In the same way, the tank has the base opened to drain the liquid when necessary.

A basic scheme of the liquid subsystem is depicted in figure 5.

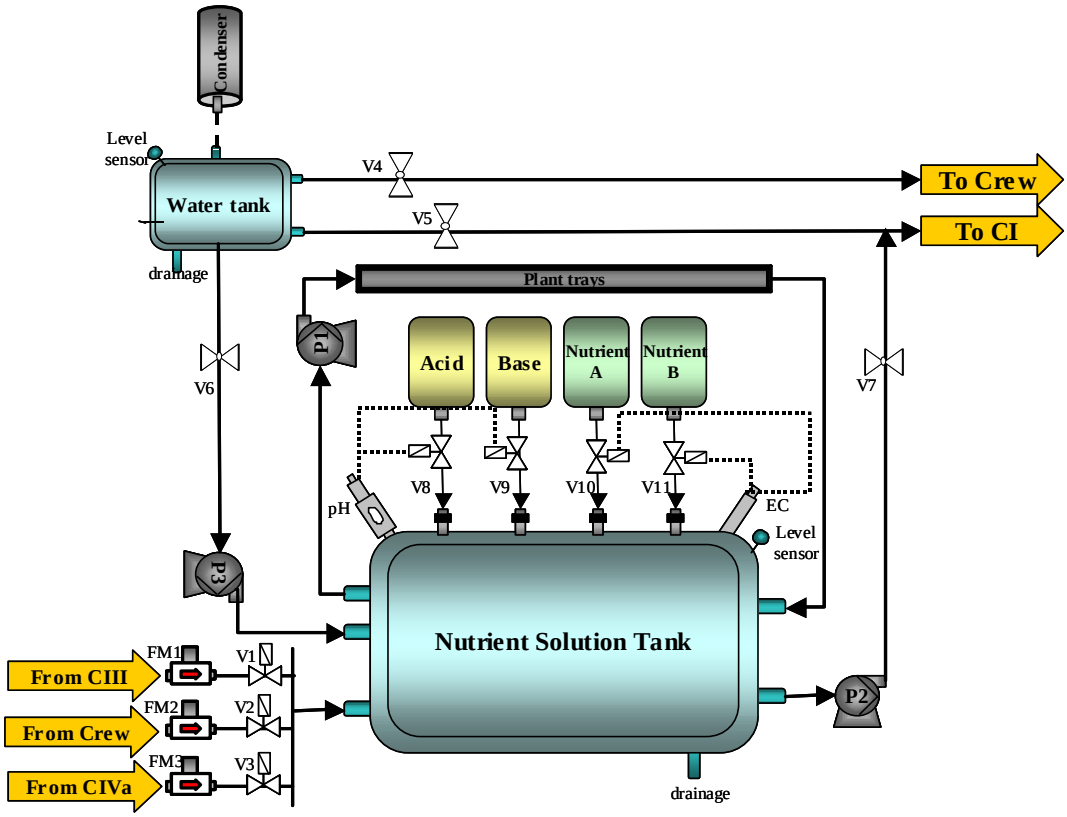

Figure 5. HPC Liquid subsystem (V=valves, FM=flowmeter, P=pump)

The nutrient solution is pumped from the external reservoir into the chamber in Teflon (or polypropylene) tubing to the head of rays with a 24 hour duty cycle pump (P1) situated outside the chamber. The one metre wide troughs, of which there will be a variable number in each chamber depending on the schedule of planting is designed to accommodate a variety of root media as a substrate for the hydroponic solution. These include rockwool, lecca (expanded clay particles), silica sand, and glass etc. Gravity assists the return of the solution to the external reservoir. As it is desirable to adapt the distance between the light source and the plants, the trays will be adjustable.

A water tank shall be foreseen where the water condensate from the aerial environment is gravitationally collected.

In order to determine the capacity of this water tank a preliminary calculation of the water transpirated by the plants have been done. Area calculated in the different scenarios (see crop selection section) multiplies the bibliographic values of the water uptake of each specie.

The results obtained are shown in the next table.

	Water uptake	Area (m^2)			Water uptake (kgH_2O/d)		
	kg $H_2O/(m^2d)$	1	2	3	1	2	3
WHEAT	0.21	5	1	5	1.1	0.2	1.1
LETTUCE	0.85	44	21	5	37.3	17.9	4.2
BEET	1.62	8	19	5	13.0	30.8	8.1
Total		**57**	**41**	**15**	**51.5**	**48.9**	**13.4**

Table 8. Water uptake (condensed water) for scenario 1, 2 and 3.

As it can be seen in the table, the amount of water condensed can range between 13.4-51.4 L H_2O/d depending on the operational conditions, so a tank between 15-55L shall be designed. Moreover, the condensate stored in the water tank is provided with a tipping bucket system for measuring condensate production rates.

The pH and EC of the hydroponic solution are controlled continuously. A pH sensor located in the nutrient tank sends the pH value measured to the controller, which decides the necessity to inject acid or basic solution stored in externally mounted reservoir tanks. The global salt composition of the nutrient solution is measured by an electroconductivity sensor and it is adjusted to the desired value injecting concentrated nutrient solution stored in external reservoir tanks A and B. The proportion between the

solutions A and B is fixed and they are in different tanks due to storage requirements for high concentrated salt solutions in order to avoid precipitation. Further considerations about more specific ion sensors shall be done.

Additionally, the liquid flow rate and the level of the tank shall be controlled by means of pumps located at the input and output the tank lines. In the same way, the flow rate and the level of the evapotranspiration tank must be controlled.

Two different operation ways of the higher plant compartment have to be considered. The liquid subsystem explained above is common in both cases, but the difference come up when HPC operates isolated or interconnected with the other MELISSA compartments, which is commented next and referenced to figure 5.

5.6.1 HPC operation: isolated

In this case the nutrient solution is prepared in the laboratory and then pumped into the external nutrient tank, from where the recirculation operation mode described before starts.

Then, the water collected from the plants' transpiration, is pumped (P3) to the hydroponics reservoir in order to maintain a constant liquid volume in the liquid subsystem. However, as the plants uptake nutrients from solution, the concentration diminishes and it's necessary to add an amount of concentrated nutrient solution. To control the composition of the flow, the electrical conductivity (EC) is measured with a sensor located in the nutrient tank and the measure value is sent to the control system, which regulate the valves situated in the concentrated nutrient tanks (V10, V11). In the same way pH is measured with a pHmeter and controlled by the addition of acid or base by means of regulation of the electro valves V8 and V9.

The nutrient solution used by plants is the same for the three species selected and is a modified half-strength Hoagland with nitrate as the only N source (Hoagland *et al*., 1950).

The composition of this media is reported in table 9.

COMPOUNDS	CONCENTRATION mmol/l
$Ca(NO_3)_2.4H_2O$	3,62
$FeCl_3$	0,025
$MgSO_4.7H_2O$	1
KNO_3	5
$NH_4H_2PO_4$	1,5
$(NH_4)_2SO_4$	1
H_3BO_3	0,02
$MnSO_4.H_2O$	0,005
$ZnSO_4.7H_2O$	0,0035
$CuSO_4.5H_2O$	0,0008
$H_2MoO_4(85\%MoO_3)$	0,0005

Table 9. Nutrient solution composition

However, a solution with a variable nutrient composition is also possible.

5.6.2 HPC operation: interconnected with the MELISSA loop

The nutrient solution used when the chamber is operating interconnected with the MELISSA loop is different from the one reported in table 9, so a general overview of the liquid loop evolving compartment IVb is described next.

The chamber nutrient tank will receive a mix of the liquid outflow from compartment III (V1) and the effluent from the crew urine degradation (V2). If nitrite is found in excess in the outlet flow of compartment IVa (V3), it is possible to add it to the HPC (Albiol *et al.*, 2002). The control of the pH and nutrient composition of the hydroponic tank can be controlled either with this effluent, which is rich in nitrogen and minerals, or with the addition of acid (V7), base (V8) or concentrated nutrient solution (V9, V10) like in the HPC isolated operation described above.

The nutrient solution, as a mix of effluents from different MELISSA compartments, is pumped (P1) to the trays and returned back to the nutrient solution tank as in the isolated operation mode.

Depending on the inlet liquid flow and the water evapotranspirated flow different situation must be taken into account. When the nutrient solution tank inlet and the water evapotranspirated flow are the same, then condensed water will be use mainly by the crew as drinking water (V4).

However, when the nutrient solution tank inlet is higher than the water uptake by the plants, then part of the solution recirculated through the trays is pumped (P2, V7) to compartment I, which can be diluted with part of the condensed water (V5). Moreover, the condensed water is interconnected with the nutrient solution tank (P3) and its flow can be regulated (V6) to maintain a constant volume.

A general view of the whole loop can be seen in figure 6. For a more extensive liquid loop description and overview see TN.62.3.

5.7 Gas subsystem

Some parameters concerning the gas environment (atmospheric regeneration, air handling and gas leakage) are commented first. Then, as some differences exist depending on the mode of operation, the chamber working isolated or evolving the whole loop are described separately.

5.7.1 Atmospheric regeneration

The process of photosynthesis, in which CO_2 is chemically fixed, while O_2 is released, results in the regeneration of the atmosphere.

A basic determination of the net exchange rate can be done using the total daily biomass yield. First of all it is assumed that 40% of total biomass is carbon, then 0.4 multiplies the total production rate and the obtained result is converted to CO_2 moles removed from the atmosphere. Finally, the consumption of CO2 per day can be calculated with the area per crop. In addition to this, the O_2 production can be found easily, though the ratio of net O_2 evolved by the crop and CO_2 consumed oscillates around 1:1. (Waters, 2002)

The following table shows the daily CO_2 consumption of the different scenarios described in section 5.1, calculated as mentioned above.

		SCENARIO 1	SCENARIO 2	SCENARIO 3
	mol $CO_2/(m^2 d)$	mol CO_2/d	mol CO_2/d	mol CO_2/d
WHEAT	0.96	5.15	0.80	4.80
LETTUCE	0.07	3.26	1.56	0.37
BEET	0.32	2.57	6.07	1.60
Total		**10.97**	**8.43**	**6.77**

Table 10. CO_2 daily consumption in the three different scenarios.

Liquid loop

GM: Grinding and mixing

SLSS: Solid liquid separation system

Aquanitra: Nitrate Analyser

Aquamonia: NH_4^+ Analyser

UF: Ultrafiltration unit

BF: Buffer tank.

GC: Gas Chromatograph

Main liquid lines
Sampling lines
Food and organics lines
NH_4^+ -Urea lines

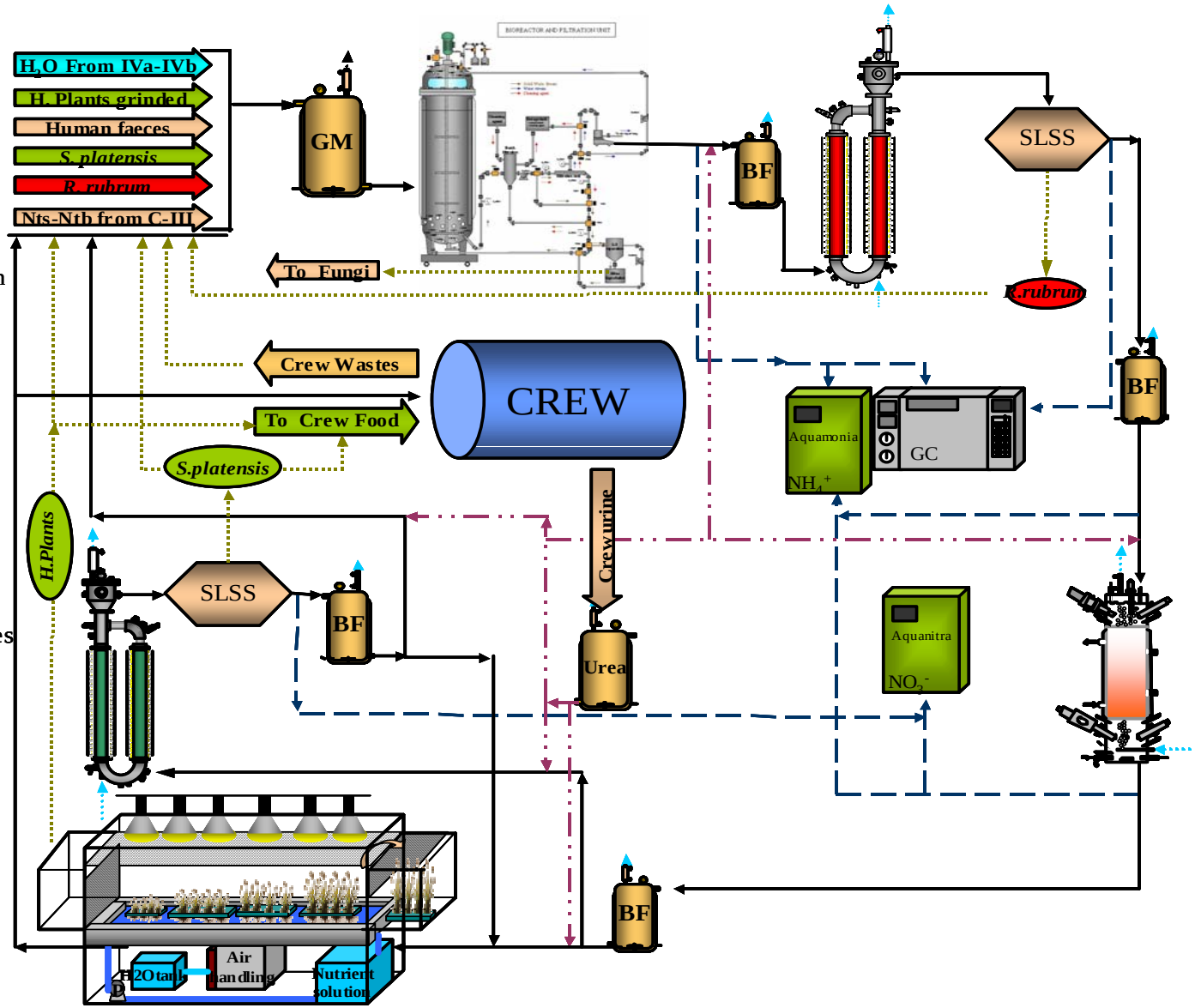

Figure 6. MELISSA Pilot Plant Liquid Loop

5.7.2 Gas leakage: insulation

Independently of the final design, the leakage of gases such as CO_2, O_2 and light is an undesirable situation. Therefore the chamber shall be built as sealed as possible in order to minimize the transfer of gas in or out of the HPC. Moreover, a good insulation will allow a better closure of the MELISSA loop. In fact this is the reason why a reliable air-lock system must be designed.

As a reference point, a loss no more than 10 μmol/(mol CO_2 min) at a differential of 500 μmol/mol CO_2 between the chamber and the surrounding air is suggested for controlled CO_2 studies. (Langhans *et al.*, 1997). Another possibility to control the closure of the chamber is to ensure that the leakage is less than 2% per day based on the driving gradient of 2000 ppm CO_2.

Taken into account these two references the HPC will be test by the manufacturer at the HPC delivery and by the operator every time a new culture is start to evaluate that its loses are less than 10 μmol/(mol CO_2 min) at a differential of 500 μmol/mol CO_2 and lees than 2% per day based on the driving gradient of 2000 ppm CO_2. The equipment necessary for this test is the same that the one use to control the CO_2 concentration inside the HPC.

5.7.3 Air handling

In order to supply CO_2 to the plants, to maintain a minimum vertical or horizontal temperature gradient and to evacuate heat from the chamber, an air circulation system is required. Thus, air shall be conditioned for temperature and humidity and re-circulated inside the chamber.

Neither too high nor too low airflow rates are desirable, thus the air can damage the plants or can create preferential flow paths leading to a partially increase of temperature respectively. Therefore, a range of air velocity between 0.1 and 1 m/s (Barta *et al.*, 1996) will be enough for good uniformity without damaging the plants. As a recommended value an air velocity of 0.36 m/s can be chosen (Langhans *et al.*, 1997).

In order to provide this internal air circulation (one air exchange per minute) two fans with motors shall be located in the sub chamber bay. The volume of the chamber considered includes 5 m^3 of growing volume and some volume of mechanical plenum (excluding airlock) leading to a >5 m^3/min air exchanging.

A basic representation of the airflow direction inside the chamber is depicted in figure 7.

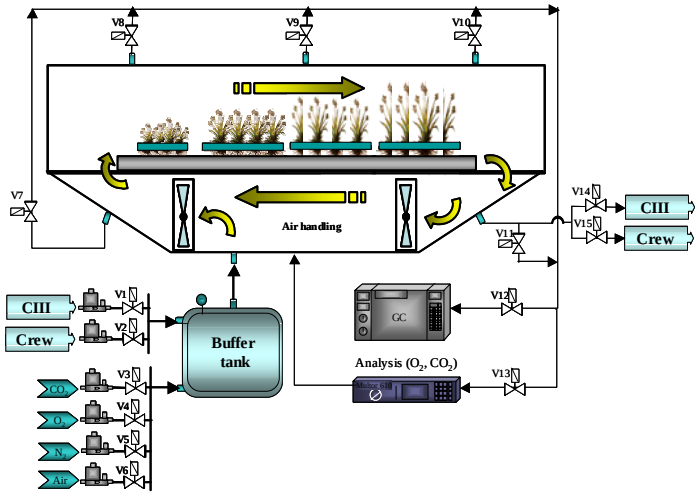

Figure 7. HPC Gas subsystem

5.7.4 HPC operation: isolated

When the chamber is working in isolation the air composition is regulated with injections of gases from the laboratory lines, such as the CO_2 management to have a CO_2 enriched atmosphere. Thus, all the gas lines (CO_2 O_2, N_2, air) will be interconnected either directly to the air-handling area in the chamber or to a buffer tank to ensure the homogeneity of the gas mixture. The flow of this gas lines will be measured with flowmeters and controlled with electrovalves.

Then air is continuously circulated through the chamber with the airflow depicted in figure 7. Several samples are taken from different parts of the chamber and flows either to the CO_2 and O_2 analyser and then returned to the chamber or to the gas chromatograph. In this way the air composition (O_2, CO_2, N_2, VOCs such as ethylene and other compounds) is measured and the atmosphere environment control can be done.

The flow of the chamber samples is regulated with electrovalves, which are located in the air-handling input (V6), along the chamber (V7, V8, V9) and in the air-handling output (V10).

The internal temperature and dehumidification of the aerial environment can be controlled by the modulation of the chilled water and steam valves. Externally supplied water and steam may be circulated through sealed and "heresite" coated (baked oxidation barrier) heat exchange coils mounted in an internal plenum at the bottom of the chamber. Condensate from the chilled water coil may be measured and collected in a condensate reservoir. Heresite coated fans and fan motors with silicone covered wiring shall also be mounted in the lower plenum and distribute air through stainless steel ducts with baked enamel louvers.

Humidification control of the aerial environment is achieved with measured injections of ultra pure (>10 mega ohm) atomised water in stainless steel plumbing.

The pressure can be controlled passively with expanding and contracting bags depending on the changes in the internal or external pressure and temperature. Each chamber may be fitted with up to ten 200 litre double sealed Teflon liners manifold on a 50 mm diameter stainless steel tube which protrudes through the rear wall of the chamber. This provides a total expansion volume potential of 2.0 m^3 $\pm$1.0 m^3. Given the approximate 12.5 m^3 internal volume of the chamber, this represents about 16% $\pm$8.0% volume expansion/contraction in response to possible temperature fluctuations inside the chamber. The total temperature range influencing gas volume in the chamber represented by this capacity is about $\pm$10 ºC. The contracting bags will be located in the mechanical plenum below the growing area.

5.7.5 HPC operation: interconnected with the MELISSA loop

The recirculation of the air inside the chamber, the sample points, and the pressure control are the same as in the isolated operation mode. The difference is that the gas inlet comes from the other MELISSA compartments (CIII, crew) instead of the laboratory gas lines. Moreover, the outlet of the HPC is sent to the aerobic compartments.

However, when the chamber is connected with the whole loop, two different configurations can be considered.

In the first one, the O_2 and CO_2 from the HPC are separated and stored independently in buffer tanks. In this way, the compartments do not mix its own gas compositions, leading to a more controlled situation (see figure 8a).

In the second one, there isn't any gas separation device, so the gas line from the chamber flows to the consumer compartments, which are the nitrifying C-III one and the crew compartment (Pérez et al., 2002) (see figure 8b).

Therefore gas connections have to be foreseen to allow the operation in any one of those alternative configurations. A general overview of the gas loop is depicted next and more complete description about gas loop can be found in TN62.4.

5.8 Solid subsystem

Plant biomass will be harvested manually and manipulated to separate the edible and the non-edible parts of the plant.

The edible biomassa to be use in crew compartment and the non-edible biomass to be used in CI or for analysis will be stored in a fridge for short term or freeze dried if stored for long term. Otherwise biomass will be discarded as UAB organic waste.

5.9 Cooling subsystem

Some factors such as radiation heat load, wall and floor area, volume, growing area temperature and ambient temperature will determine the capacity of the condenser unit as well as compressor and motor cooling size. Thus, when all this different parameters will be known an accurate calculation of the cooling capacity can be done.

However, two different cooling coils have been already identified and commented in previous sections of this technical note. One is necessary to remove the heat produce by the lighting loft and another one to control the chamber interior temperature with the heating coil. Depending on the final selected pump model for pumping the hydroponic solution from the nutrient tank to the trays, an extra cooling for the nutrient pump will be considered.

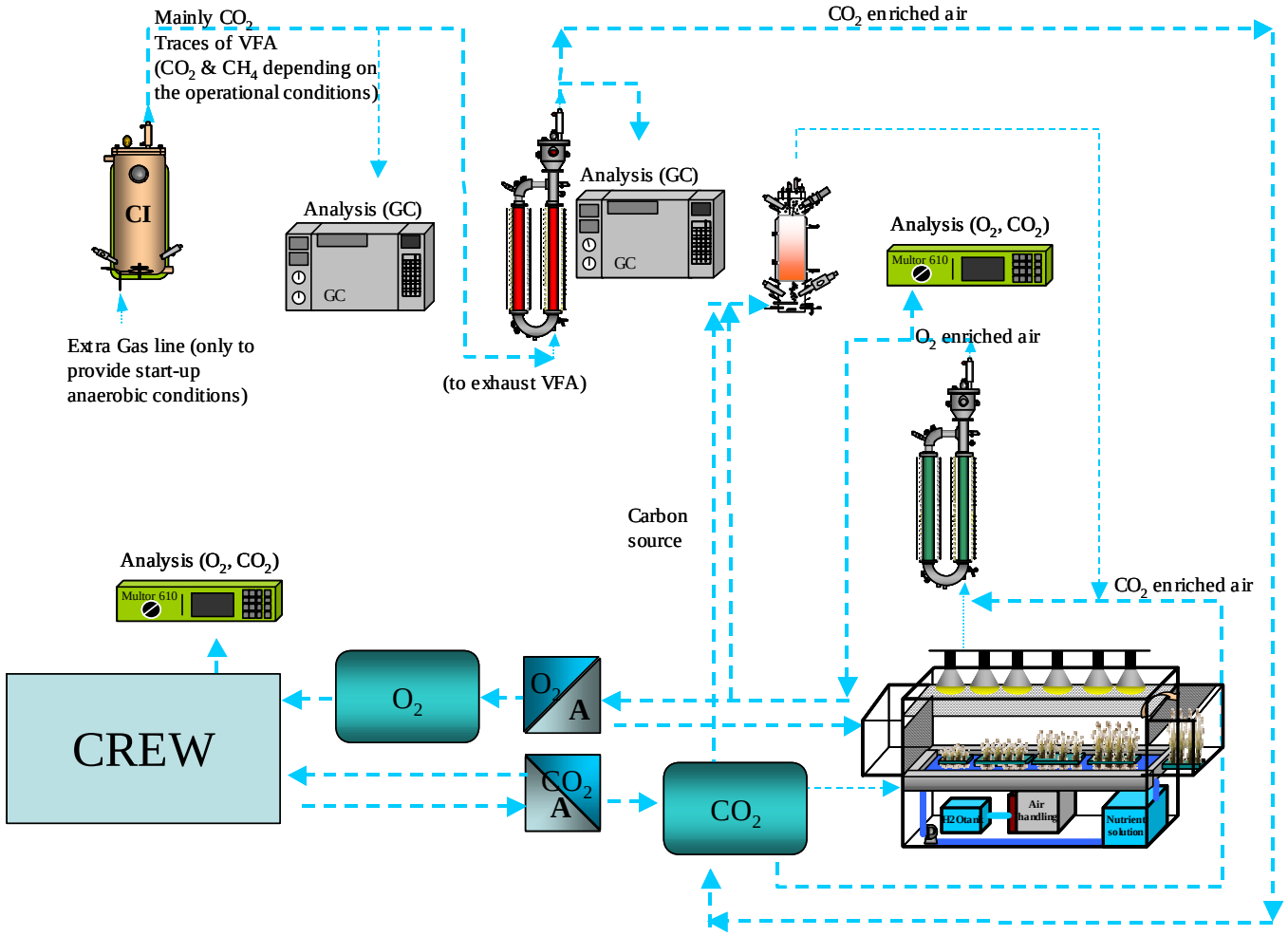

Figure 8a: MELISSA Pilot Plant Gas Loop

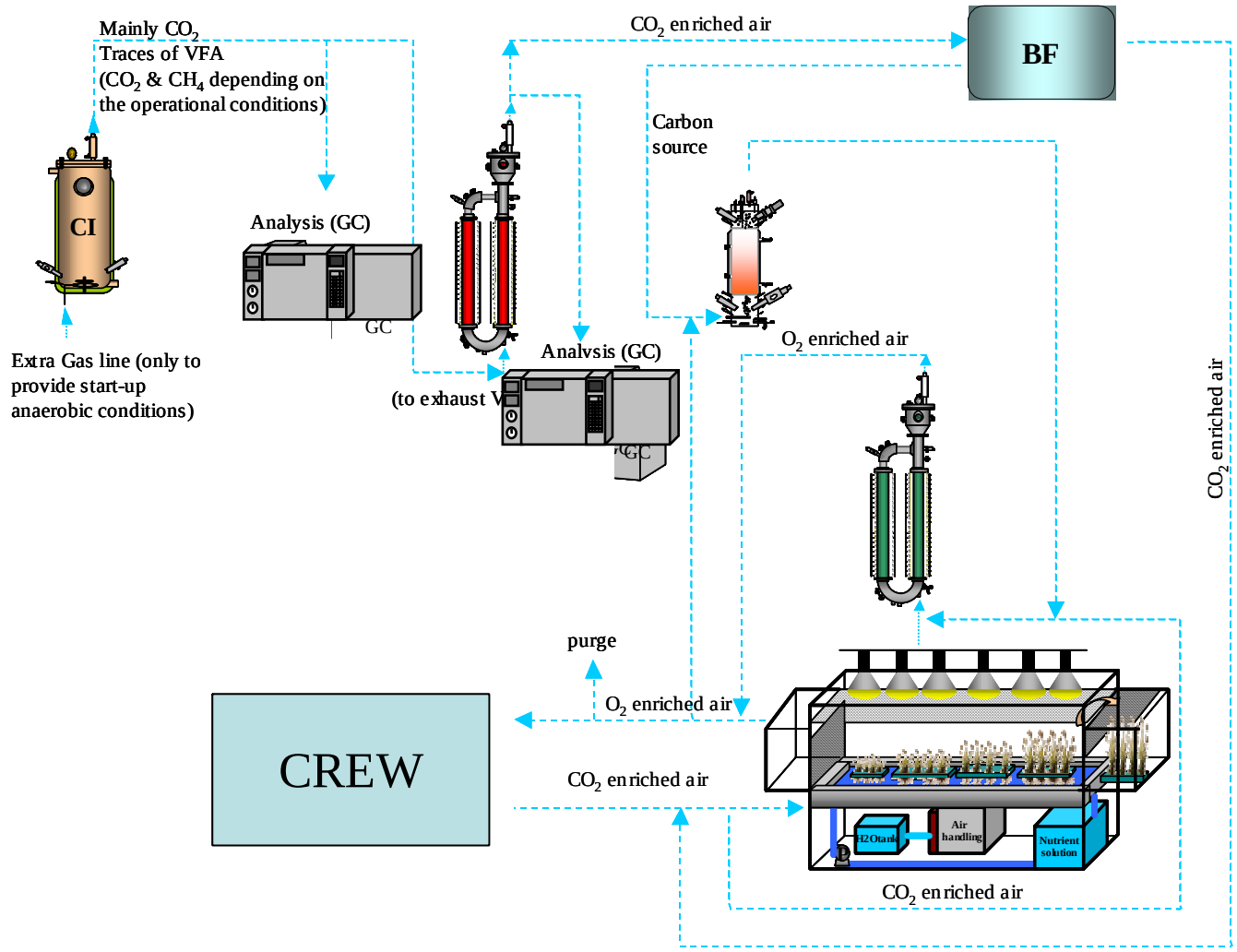

Figure 8b: MELISSA Pilot Plant Gas Loop

6 CONTROL SYSTEM REQUIREMENTS

The higher plant compartment is operated and characterised through different parameters that are controlled or measured. In the following a general description of this control system, including the variables to measure and control and the interface with the MELISSA global control system is done.

6.1 Interface with existing control system

The HPC control system must provide some measured parameters to the MELISSA control system (MCS), so that the operation of the whole loop can be coordinated. The objective of the MCS is to optimise the operation of each compartment using the information collected, which consists in the data received from the sensors and compared to the values expected from the mathematical models.

Therefore, it is necessary that the HPC have to supply all the required information about its operation to the MCS. Additionally it has to accept the MCS operation commands and according to this its operation has to change. This is the general procedure adopted for all the compartments. In order to have homogeneity in the different control devices and software, the MELISSA groups devoid to its control have selected the hardware and software to be used in all compartments. The HPC has to adhere to this standard. The controllers to be installed in the HPC have to be 'Schneider Quantum PLC' the characteristics of which are described below:

Schneider Quantum PLC (CPU Ref. 140CPU43412A) with an Ethernet module (Ref. 140NOE77101).

- Allow redundancy in CPU by mounting in different racks two CPU configurations and I/O modules need to be mounted separately using RIO (Remote Input Output) bus.
- CPU is an Intel 80486 at 66Mhz, integrates 2 MB of user memory, 896KB for programs and co-processor is installed.
- It is programmable through IEC languages collection (5 of 5 supported) using Concept 2.5 software.
- Around 6000 analog I/O per CPU.
- Allow communication through Industrial Ethernet network devices.
- It takes 13 to 48 ms of switchover after a fault detected in a CPU.
- Execution times from 0.1 to 0.5 milliseconds per 1000 instructions.
- HMI terminals can interact with any PLC connected to the network.

The controllers will be accessed via the software 'iFix' from Intellution, already available in the Pilot Plant.

6.2 Parameters to be monitored

Monitored variables are listed below and in the requirements table. Characteristics such as range, maximum, minimum, temporal average, accuracy, sampling frequency of each monitored variable shall be determined though some are already proposed. All this data must be transmitted and stored for a proper control of the different factors.

Description	
Alarm	A
Pump Power	PP
Regulated Valve	RV
Sensor	S
Analogical input	AI
Analogical output	AO
Digital input	DI
Digital output	DO

Table 11: Description abbreviations used in table 12, 13 and 14.

In the following tables different characteristics of the measured variables concerning the isolated and interconnected operation of the HPC are specified. It is stated the variables description, including the devices involved and its types of signals (see the abbreviations used in table 11), the operation and measurable range, and the instrumentation's location.

Firstly, the monitored variables concerning the isolated operation of the HPC are described and associated in the different control loops (thick line), which have been explain in their corresponding subsystem and are summarized in the section 6.4 (table 12). The table include the variable description, the operation range (which refers to the usual operation range of the equipment in the HPC), the measure range (which refers to the minimum and maximum limits for the measure of the equipment) the corresponding units and the location.

Description			Operation Range	Measure Range	Units	Location
Air temperature	S	AI	10-40	0-150	ºC	Inside HPC
	A	DO				Panel control
Air velocity	S	AI	0.15-0.5	0-5	m/s	Inside HPC
	A	DO				Panel control
Pressure	S				KPa	Inside HPC
	A					Panel control
PPF	S	AI	0-1500	0-2000	$\frac{mols}{m^2 s}$	Inside HPC
	A	DO				Panel control
Humidity	S	AI	50-95	0-100	% H_2O	Inside HPC
	A	DO				Panel control
Irrigation flow rate	S	AI				Inside HPC
	PP	DO				Panel control
Temperature	S	AI	30-40	0-150	ºC	Nutrient solution
	A	DO				Panel control
Temperature	S	AI	4-15		ºC	Heat exchange system
	A	DO				Panel control
Steam flow rate	S				l/h	Heat exchange system
	RV	AO	0-100	0-100	%	Steam line
Chilled water flow rate	PP	DO			l/h	Heat exchange system
	RV	AO	0-100	0-100	%	Chilled water line
pH	S	AI	5-7	0-14		Nutrient solution
	A	DO				Panel control
Acid flow rate	S	AI			l/h	From acid tank to nutrient tank
	PP	DO				
	RV	AO	0-100	0-100	%	
Base flow rate	S	AI			l/h	From base tank to nutrient tank
	PP	DO				
	RV	AO	0-100	0-100	%	
Electroconductivity	S	AI	1-3	0-5	mS	Nutrient solution
	A	DO				Panel control
Ions composition	S	AI				Nutrient solution
	A	DO				
A solution flow rate	S	AI			l/h	From A tank to nutrient tank
	PP	DO				
	RV	AO	0-100	0-100	%	
B solution flow rate	S	AI			l/h	From B tank to nutrient tank
	PP	DO				
	RV	AO	0-100	0-100	%	
Liquid level	S	DI		0-100	% v/v	Nutrient solution tank
Nutrient flow rate	S	AI			l/h	From nutrient tank to trays
	PP	DO				
	RV	AO	0-100	0-100	%	
Water level	S	DI		0-100	% v/v	Evapotranspiration water tank
Liquid flow rate	S	AI			l/h	From water tank to nutrient tank
	PP	DO				
	RV	AO	0-100	0-100	%	
CO_2 composition	S	AI	500-2500	0-3000	ppm	Inside HPC
	A	DO				Panel control
	RV	AO	0-100	0-100	%	CO_2 gas line
O_2 composition	S	AI	20-25	0-100	%	Inside HPC
	A	DO				Panel control
	RV	AO	0-100	0-100	%	O_2 gas line
VOCs (Ethylene)	S	AI	<40	0-100	ppb	Inside HPC
	A	DO				Panel control

Table 12: Measured variables in the HPC

Secondly, the measured variables due to the plant chamber interconnection with the MELISSA loop are described for the liquid and gas loop. As the inputs to the HPC are the outputs from other compartments or buffer tanks, some parameters (1) are optional for the CIVb, thus its value can be received from the system control instead of being measured twice (table 13, 14).

Description		Signal	Operation Range	Measure Range	Units	Location
Liquid flow rate	S	AI			l/h	From water tank
	RV	AO	0-100	0-100	%	to MELISSA loop
Liquid flow rate	S	AI			l/h	Liquid input
	RV	AO	0-100	0-100	%	from MELISSA loop
$N\text{-}NH_4^+$ composition	S	AI			ppm	Liquid input from MELISSA loop
	A	DO				Panel control
$N\text{-}NO_3^-$ composition	S	AI			ppm	Liquid input from MELISSA loop
	A	DO				Panel control
Temperature(1)	S	AI		0-150	ºC	Liquid input from MELISSA loop
	A	DO				Panel control
pH(1)	S	AI		0-14		Liquid input from MELISSA loop
	A	DO				Panel control

Table 13: Measured variables due to the liquid loop interconnection

Description		Signal	Operation Range	Measure Range	Units	Location
Gas flow rate	S	AI			l/h	Gas input from
	RV	AO	0-100	0-100	%	MELISSA loop
CO_2 composition (1)	S	AI			ppm	Gas input from MELISSA loop
	A	DO				Panel control
	RV	AO	0-100	0-100	%	CO_2 gas line
O_2 composition(1)	S	AI			%	Gas input from MELISSA loop
	A	DO				Panel control
	RV	AO	0-100	0-100	%	O_2 gas line
VOCs (Ethylene) (1)	S	AI			ppm	Gas input from MELISSA loop
	A	DO				Panel control
Gas flow rate	S	AI			l/h	Gas output
	RV	AO	0-100	0-100	%	from MELISSA loop
CO_2 composition	S	AI			ppm	Gas output from MELISSA loop
	A	DO				Panel control
	RV	AO	0-100	0-100	%	CO_2 gas line
O_2 composition	S	AI			ppm	Gas output from MELISSA loop
	A	DO				Panel control
	RV	AO	0-100	0-100	%	O_2 gas line
VOCs (Ethylene)	S	AI			ppm	Gas output from MELISSA loop
	A	DO				Panel control

Table 14: Measured variables due to the gas loop interconnection

A quantity estimation of the analogical/digital inputs/outputs can be done taking into account all the control requirements defined above.

	AI	AOI	DI	DO
Alarm	-	-	-	23
Pum Power	-	-	-	8
Regulated valve	-	17	-	-
Sensor	34	-	2	-
Total	**34**	**17**	**2**	**31**

Table 15: Control signals required

6.3 Sensors

The choice of sensors will be affected by the final control system design, including not only the ones necessary for the chamber but also for the interconnections with the MELISSA loop. Further sensor descriptions will require information about the measured variable.

A preliminary list of the type of sensors required is:

-Temperature

-Humidity

-Pressure

-pH

-EC

-Ion sensors (ISFET)

-Liquid flow rate

-Liquid level

-Light (PPF)

-Gas flow rate

-CO_2

-O_2

-Ethylene

-VOCs

6.4 Parameters to be controlled

As explained above, the HPC shall be able to change some parameters according to MCS or chamber control system commands. An identification of the different controlled variables, which have been already explained in its corresponding subsystem, is detailed in the following.

- *Light intensity*

The light sensor will send the value to the controller and this will act upon a light regulator. Besides, the controller will switch on/off the illumination system to provide the photoperiod required by the plants.

- *pH*

Upon the value of pH sent by the pH sensor the controller will inject acid or base solution regulating its valves.

- *Electrical conductivity*

The controller will add a fixed proportion of concentrated nutrient solution A and B to control the EC value sent by the EC sensor.

- *Tanks liquid level of the hydroponic system*

A level sensor will send the value of the nutrient tank level to the controller, which will regulate the pumps flow.

- *Temperature and relative humidity*

The controller will received the value from the temperature and humidity sensor and will regulate the chilled water and steam valves of the heat exchanger or will inject of ultra pure (>10 mega ohm) atomised water.

- *Gas concentration*

A gas analyser sent the gas composition (CO_2, O_2) and the controller adjust it by means of gas flow controllers connected either to the laboratory gas lines or to the MELISSA gas lines from other compartments.

7 REFERENCES

Albiol, J.; Creus, N.; Perez, J.; Montras, A.; Masot, S; Godia, F. (2002) Pilot Plant Liquid Loop Review. Technical Note62.3. ESTEC/ CONTRACT13292/ 98/ NL/ MV.

Barta, D.J.; Henninger, D.L (1996) Johnson Space Center's Regenerative Life Support Systems Test Bed. *Advances in Space Research*, **18**, pp.211-221

Both A.J., Leed A.R., Goto E., Albright L.D., and Langhans R.W., "Greenhouse spinach production in an NFT system," *Acta Horticulturae*, 440, 1996187-192.

Bugbee B.; Salisbury F. (1988) Exploring the Limits of Crop Productivity I: Photosynthetic Efficiency of Wheat in High Irradiance Environments. *Plant Physiology*, **88**, 868-878.

Bugbee, B. (2003) http://www.usu.edu/cpl/research_dwarf.htm,

Cloutier, G.; Dixon, M.; Hunter, J.B.; Olabi, A. (2001) Area Requirements for Biomass Production Units (BPUs) Including current MELISSA Candidate Crop. Technical Note 46.2. ECT/FG/MMM/97.012

Creus, N. (2003) Estudi d'un bucle de bioreactors pel desenvolupament d'un sistema de suport de vida biològic. . Ph.D. Dissertation Universitat Autònoma de Barcelona, Spain .

Gòdia, F., Albiol, J., Creus, N., Perez, J., (2001) Preliminary Review of the Pilot Plant Integration Loop," European Space Agency Technical Note, ES-MELiSSA TN 47.3 ECT/FG/MMM/97.012.

Hanford,A.J.; Ewert, M.K.; Henninger,D.L. (2002) Advanced Life Support Baseline Values and Assumptions Document (JSC47804). Crew and Thermal Systems Division. NASA B. Johnson Space Center. Houston, Texas.

Hoagland, D. R.; Arnon, D. I. (1950) The Water Culture Method for Growing Plants without Soil. California Agricultural Experiment Station Circular 347.

Langhans, R.; Tibbits, T.(1997) Plant Growth Chamber Handbook. Project NCR-101, Controlled Environment Technology and Uses. ISSN: 0361-199X.

Mortensen, L. M., (1994) "Effects of Elevated CO_2 Concentrations on Growth and Yield of Eight Vegetable Species in a Cool Climate," Scientia Horticulturae, Vol. 58, pp. 177-185.

Pérez, J.; Albiol, J.; Creus, N.; Montras, A.; Masot, S.; Gòdia, F. (2002) Pilot Plant Gas Loop Review. Technical Note 62.4. ESTEC/ CONTRACT13292/ 98/ NL/ MV.

Poughnon, L. (1997). Including of a HIgher Plants Chamber in the MELISSA Loop: Descri`tions of an HPC for MELISSA Loop Steady State Simulations. Technical Note 32.3. ECT/FG/CB/95.205

Sionit N., Strain B.R., and Flint E.P., (1987) "Interaction of temperature and CO_2 enrichment on soybean: photosynthesis and seed yield," Canadian Journal of Plant Science, 67, 629-636.

Stasiak, M. (2002). Effect of Inner Canopy Irradiation on Plant Productivity in a Sealed Environment**.** Phd Thesis. University of Guelph, Canada.

Stasiak M., Cote R., Dixon M.A., and Grodzinski B.L. (1998), "Increasing plant productivity in closed environments with inner canopy illumination," *Life Support and Biosphere Science*, 5, 175-181.

Waters, G.C.R. (2002) Dynamic modelling of the higher plant chamber as a component of bioregenerative life support systems. PhD Thesis. University of Guelph, Canada.

Wheeler,R. M.; Mackowiak, C. L.; Stutte, G. W.; Goins, G.D., Ruffe, L.M.; Sager, J.C.; Hinkle, C.R.; Knott, W.M (2001) A Crop Handbook for Advanced Life Support Systems: Observations and Recommendations from the Kennedy Space Center Breadboard Project. National Aeronautics and Space Administration, J.F.K Space Center, Florida.

Wheeler, R. M.; Mackowiak, C. L.; Stutte, G. W.; Sager, J. C.; Yorio, N. C.; Ruffe, L. M.; Fortson, R. E.; Dreschel, T. W.; Knott, W. M,; Corey, K. A. (1995) "NASA's Biomass Production Chamber: A Testbed for Bioregeneerative Life Support Studies", *Advances in Space Research*, **18**, pp.215-224

Wheeler, R. M., Mackowiak, C. L., Sager, J. C., and Knott, W. M., (1994) "Gas Exchange Characteristics by Lettuce Stands in a Closed, Controlled Environment," *Journal of the American Society of Horticultural Science*, Vol. 119, No. 3, , pp. 610-615.

Wheeler, R. M., Tibbitts, T. W., and Fitzpatrick, A. H., (1991) "Carbon Dioxed Effects on Potato Growth Under Different Photoperiods and Irradiance," *Crop Science*, Vol. 31, No. 5, pp. 1209-1213.

Wurr, D. C. E., Hand, D. W., Edmondson, R. N., Fellows, J. R., Hannah, M. A., and Cribb, D. M., (1998) "Climate Change: A Reponse Surface Study of the Effects of CO_2 and Temperature on the Growth of Beetroot, Carrots and Onion," *Journal of Agricultural Science*, No. 131, pp. 125-133.

8 APPENDIX A: REQUIREMENTS TABLE

In order to describe the requirements and to define the acceptance criteria for each one, different verification methods would be used and explained next.

Analysis (A): Variables, which are calculated or obtained by analytical process of the results of partial test.

Design Review (R): Parameters which can neither be tested nor affect directly performances such as material selection.

Inspection (I): Non functional characteristics of the equipment (dimensions, devices description…)

Test (T): Functional variables analysis which requires starting up the devices and submitting them to artificially condition.

The requirements are described not only in a verifiable form, but also in a quantitative way. For this purpose, the following acronyms have been used:

TBC: To be confirmed

TBD: To be defined

Req. Nº	Description	Verif.	Comments.
	REQUIREMENTS TABLE		
	8.1 Functional requirements		See section 4
8.1.1	The HPC has to be able to operate interconnected to the MELISSA loop or in isolation.	T	
8.1.2	The HPC shall be tested and validated after its installation in isolation and interconnected.	T	
8.1.3	The HPC gas, liquid and solid lines and flow devices required for the interconnection with the MELISSA loop will be designed according to other compartments sizing.	T	
8.1.4	Instrumentation required for the isolated operation will be included.	T	
8.1.5	The HPC shall allow controlled environmental conditions	T	
8.1.6	The HPC shall allow the monitoring and the storing of the internal environmental conditions data (aerial and root parameters)	T	
8.1.7	The HPC shall allow installing video equipment for stress image detection analysis.	T	
8.1.8	A culture of the plants and the continuous monitoring of their evolution shall be performed in a proper way	T	

Req. Nº	Description	Verif.	Comments.
	8.2 Design requirements		See section 5
	8.2.1 Sizing		See section 5.1
8.2.1.1	The HPC shall produce 20% of a daily human diet, which is 222,3 g dry biomass.	T	
8.2.1.2	A standard chamber of 5 m^2 (scenario 3) will be built. TBC	I	
	8.2.2 Material		See section 5.2
8.2.2.3	Materials will be chemical inertness (to study effectively VOC evolution).	D	
8.2.2.4	Materials will be bioresistant	D	
8.2.2.5	Materials will be sterilizable.	D	
8.2.2.6	Interior material will have a uniform coating with high reflection of the light source.	D	
8.2.2.7	The material shall be inert to water, chemical and microbial attack.	D	
	8.2.3 Basic HPC structure		See section 5.3
8.2.3.1	The HPC will have 2 access areas for seeding and harvesting.	I	
8.2.3.2	The two access areas will be independent from the growing area to avoid gas loses.	I	
8.2.3.3	Growing area dimensions will be: 1m[W]x5m[L]x1m[H].	I	
8.2.3.4	The number of chambers to built will be: 3 or 4 -only 3 in operation at the same time (15m^2 growing area)	I	

Req. Nº	Description	Verif.	Comments.
	8.2.4 Air-lock system		See section 5.4
8.2.4.1	Two air-lock systems will be located at each extreme of the HPC	I	
8.2.4.2	The external access doors of the air-lock system will be side opening.	I	
8.2.4.3	The interior lock coating will be made of polypropylene to ensure a good insulation.	R	
8.2.4.4	Air-lock dimensions will be: 1m[W] x 0.5m[L] x 1m[H].	I	
8.2.4.5	Pressure regulation and purge of the air lock can be done with N_2.	T	
8.2.4.6	Five access doors will be located on the sidewalls along the HPC	I	
8.2.4.7	Side doors dimensions will be: 1m[W] x 1m[H].	I	
8.2.4.8	The hydroponics trays can be extended from the chamber interior to air lock area.	T	
8.2.4.9	The air-lock area can be disassembled.	T	
	8.2.5 Lighting subsystem		See section 5.5
8.2.5.1	Maximum energy power provided per area will be: 2 kW/m^2	T	
8.2.5.2	Lighting power requirement per chamber will be: 12.5 kW	T	Security factor: 1.25
8.2.5.3	Lamps selected are a combination of HPS (600W) and MH (400W).	I	
8.2.5.5	Number of lamps per chamber will be 10 HPS and 10 MH.	I	
8.2.5.6	PPF, PAR, spectral emission and conversion efficiency of the lamps selected shall be defined. TBD	R	
8.2.5.7	PPF supplied by lamps: 1000 μmols/(m^2 s)	T	One-meter from lamps.

Req. Nº	Description	Verif.	Comments.
8.2.5.8	A cooling coil and a fan have to be designed to remove the heat load of the lighting loft. TBD	I	See figure 4
8.2.5.9	Light shall be controlled (on/off) and dimmable (if possible) to provide the photoperiod required by plants and different light intensities. .	T	
	8.2.6 Liquid subsystem		See section 5.6
8.2.6.1	Plants are grown hydroponically using a nutrient film technique.	R	
8.2.6.2	Hydroponics solution is stored in the nutrient solution tank.	I	
8.2.6.3	Nutrient solution shall be homogenized inside the nutrient tank.	T	Stirring
8.2.6.4	Nutrient solution tank volume: 300L	I	
8.2.6.5	Nutrient solution tank dimensions: 0.63m[W]x0.95m[L]x0.63m[H]	I	
8.2.6.6	Nutrient solution tank location: outside and below the growing area.	I	
8.2.6.7	Nutrient solution tank material: Teflon or steel	R	
8.2.6.8	Nutrient solution tank drainage shall be designed. TBD	I	
8.2.6.9	Nutrient solution pump must have a 24h-duty cycle TBD	T	
8.2.6.10	Trays description TBD	I	Dimensions, material…
8.2.6.11	Trays will be adjustable to adapt the distance between light source and plants.	T	
8.2.6.12	Condensed water is stored in a water tank.	I	
8.2.6.14	Experimental condensate production rate is measured with a tipping bucket system located in the condensed water tank.	T	

Req. Nº	Description	Verif.	Comments.
8.2.6.15	Condensed water tank volume: 15-55 L TBD	I	
8.2.6.16	Condensed water tank dimension: TBD	I	
8.2.6.17	Condensed water tank location outside and below the chamber TBC	I	
8.2.6.18	Condensed water tank material: Teflon or steel	R	
8.2.6.19	Condensed water tank shall be designed. TBD	I	
	• **HPC operation: isolated**		See section 5.6.1
8.2.6.21	The nutrient solution prepared externally will be pumped with an external pump into the nutrient solution tank.	T	
8.2.6.22	The condensate water is pumped (P3) into the nutrient solution tank.	T	See figure 5
8.2.6.23	The nutrient solution used is a modified half-strength Hoagland solution.	T	See table 9
	• **HPC operation: interconnected with the MELISSA loop**		See section 5.6.2
8.2.6.24	The chamber nutrient tank will receive a mix of the liquid outflow from CIII, crew and CIVa. The quality of the mixture will be evaluated by the controller using the values measured at the output of the mentioned compartments. TBC	T	See figure 5,6
8.2.6.25	The nutrient solution is recirculated (P1) through the trays as in the isolated operation mode.	T	See figure 5
8.2.6.26	The condensed water will be used mainly by the crew.	T	See figure 5, 6
8.2.6.27	The condensed water can be returned to the nutrient solution tank	T	See figure 5

Req. Nº	Description	Verif.	Comments.
8.2.6.28	The liquid outlet from the chamber can be diluted by condensed water and be sent to CI.	T	See figure 5, 6
8.2.6.29	All the piping for the liquid loop must be designed and can be identified in figure 5.		
8.2.6.30	Number of pumps in the liquid loop: 3 TBD	I	See figure 5
8.2.6.31	Number of valves in the liquid loop: 11 TBD	I	See figure 5
8.2.6.32	Number of flowmeters in the liquid loop: 3 TBD	I	See figure 5
8.2.6.33	The ranges of the flowmeters and capacity of the pumps will be selected based on input/output flow range from the MELISSA compartments TBD	T	
8.2.7	**8.2.7 Gas subsystem**		See section 5.7
	• **Atmospheric regeneration**		See section 5.7.1
8.2.7.1	A basic determination of the net exchange rate is calculated using the total daily biomass yield.		
8.2.7.2	The daily CO_2 and O_2 molar flows range between 7.09-12.6 mol/d each	T	
	• **Gas leakage: insulation**		See section 5.7.2
8.2.7.3	The chamber shall be built as sealed as possible.	T	
8.2.7.4	The maximum leakage allowed will be: 10 μmol/(mol CO_2 min) at a differential of 500 μmol/mol CO_2 between the chamber and the exterior.	T	
8.2.7.5	The maximum leakage allowed will be: 2% per day based on the driving gradient of 2000 ppm CO_2.	T	

Req. Nº	Description	Verif.	Comments.
	• **Air handling**		See section 5.7.3
8.2.7.6	An air circulation system is required to remove heat and maintain internal temperature.		
8.2.7.7	Two fans will provide this air circulation.	T	
8.2.7.8	The air flow direction inside the chamber is depicted in figure 6.		
8.2.7.9	Air velocity shall range between 0.15 and 1 m/s.	T	
8.2.7.10	Internal air circulation shall provide one chamber gas volume exchange per minute: $>5m^3$/min	T	
	• **HPC operation: isolated**		See section 5.7.4
8.2.7.11	Laboratory gas lines (CO_2, O_2, N_2, air) will be interconnected either to the air-handling area or to a buffer tank.	T	See figure 7
8.2.7.12	Air is continuously recirculated inside the chamber.	T	See figure 7
8.2.7.13	Number of air sample points in the HPC: 5	I	See figure 7
8.2.7.14	Sampling gas line for gas chromatograph analyses is required	T	See figure 7
8.2.7.15	Sampling gas line for CO_2/ O_2 analyses is required	T	See figure 7
8.2.7.16	Pressure is controlled passively with expanding/contracting bags.	T	
8.2.7.17	10 pressure bags of 200L with a total expansion volume potential of 2 $m^3 \pm 1$	T	
	• **HPC operation: interconnected with the MELISSA loop**		See section 5.7.5
8.2.7.18	Gas lines from crew and CIII will be interconnected either to the air-handling area or to a buffer tank.	T	See figure 7

Req. Nº	Description	Verif.	Comments.
8.2.7.19	HPC gas outlet will flow to aerobic compartments (CIII, crew)	T	See figure 7, 8
8.2.7.20	Air-flow direction inside the chamber and sampling is analog to the one in the isolated operation mode	T	See figure 7
8.2.7.21	Two different configurations one including O_2 and CO_2 buffer tanks and another considering direct gas interconnection with the HPC are under study.		See figure 7, 8a, 8b
8.2.7.22	Gas pipeline from O_2 and CO_2 buffer tank to chamber must be defined TBC	I	
8.2.7.23	Gas pipeline from HPC to O_2 and CO_2 buffer tank must be defined TBC	I	
8.2.7.24	Gas pipeline from HPC to compartment III and crew must be designed	I	
8.2.7.25	Gas pipeline from crew compartment to HPC TBC	I	
8.2.7.26	Compressors required for all the gas piping must be identified TBD	A	
	8.2.8 Solid subsystem		See section 5.8
8.2.8.1	Plant biomass will be harvested manually and manipulated to separate the edible and non-edible parts.	I	
8.2.8.2	Biomass will be stored in a fridge for short term and in a freeze dried form for long term	I	
	8.2.9 Cooling subsystem		See section 5.9
8.2.9.1	Condenser capacity TBD	A	
8.2.9.2	Compressor size TBD	A	

Req. Nº	Description	Verif.	Comments.
8.2.9.3	A cooling coil to remove heat from the lighting loft must be designed. TBC		
8.2.9.4	A cooling coil to compensate heat discharge from the nutrient tank pump must be designed. TBD		
8.2.9.5	A cooling coil to control interior temperature must be designed. TBD		
	8.3 Control system requirement		See section 6
	8.3.1 Interface with existing control system		See section 6.1
8.3.1.1	The HPC control system has to send selected data to the MELISSA control system (MCS) in order to coordinate the operation of the whole loop	T	
8.3.1.2	The HPC has to be able to change is operation according to the MCS commands.	T	
8.3.1.3	The controllers to be installed in the HPC have to be 'Schneider Quantum PLC' CPU Ref. 140CPU43412A) with an Ethernet module (Ref. 140NOE77101).	R	
8.3.1.4	The controllers will be accessed via the software 'iFix' from Intellution, already available in the Pilot Plant.	R	
	8.3.2 Parameters to be monitored		See section 6.2
8.3.2.1	The maximum, minimum, temporal average, measurement range, accuracy, sampling frequency of each measured variable shall be recorded in the control system database.	A	See table 12, 13, 14
8.3.2.2	The devices required by each monitored variable shall be defined (sensor, regulated		See table 12, 13, 14

Req. Nº	Description	Verif.	Comments.
	valve, alarms, pumps…)		
8.3.2.3	Air temperature day/night will be measured	T	See table 12
8.3.2.4	Air velocity will be measured	T	See table 12
8.3.2.5	Pressure will be measured	T	See table 12
8.3.2.6	PPF will be measured	T	See table 12
8.3.2.7	Humidity day/night will be measured	T	See table 12
8.3.2.8	Irrigation flow rate will be measured	T	See table 12
8.3.2.9	Hydroponics solution temperature will be measured	T	See table 12
8.3.2.10	Steam flow rate will be measured	T	See table 12
8.3.2.12	Chilled water flow rate will be measured	T	See table 12
8.3.2.13	pH of nutrient solution will be measured	T	See table 12
8.3.2.14	Acid flow rate will be measured	T	See table 12
8.3.2.15	Base flow rate will be measured	T	See table 12
8.3.2.16	Hydroponics solution electroconductivity will be measured	T	See table 12
8.3.2.17	Hydroponics solution ions composition will be measured TBD	T	See table 12
8.3.2.18	A solution flow rate will be measured	T	See table 12
8.3.2.19	B solution flow rate will be measured	T	See table 12
8.3.2.20	Level in the nutrient tank will be measured	T	See table 12
8.3.2.21	Nutrient flow rate will be measured	T	See table 12
8.3.2.22	Level in the evapotranspirated water tank will be measured	T	See table 12

Req. Nº	Description	Verif.	Comments.
8.3.2.23	Liquid flow rate will be measured	T	See table 12
8.3.2.24	CO_2 composition inside chamber will be measured	T	See table 12
8.3.2.25	O_2 composition inside chamber will be measured	T	See table 12
8.3.2.26	VOCs (Ethylene) inside chamber will be measured	T	See table 12
8.3.2.27	Liquid flow rate from water tank to crew compartment will be measured	T	See table 13
8.3.2.28	Liquid flow rate from CIII and crew compartment to HPC will be measured	T	See table 13
8.3.2.29	$N\text{-}NH_4^+$ composition in MELISSA liquid input to HPC will be measured	T	See table 13
8.3.2.30	$N\text{-}NO_3^-$ composition in MELISSA liquid input to HPC will be measured	T	See table 13
8.3.2.31	Temperature in MELISSA liquid input to HPC TBC will be measured	T	See table 13
8.3.2.32	pH in MELISSA liquid input to HPC TBC will be measured	T	See table 13
8.3.2.33	Gas flow rate in the gas line from MELISSA to HPC will be measured	T	Two different gas interconnections options are currently under study (see 5.4)
8.3.2.34	CO_2, O_2, ethylene composition in the gas line from MELISSA to HPC will be measured	T	See table 14
8.3.2.35	Gas flow rate in the gas line from HPC to MELISSA will be measured	T	See table 14
8.3.2.36	CO_2, O_2, ethylene composition in the gas line from HPC to MELISSA will be measured	T	See table 14
	Analogical/Digital inputs/outputs required (TBC)		See Table 15
8.3.2.37	Number of analogical inputs: 34	I	
8.3.2.38	Number of analogical outputs: 17	I	

Req. Nº	Description	Verif.	Comments.
8.3.2.39	Number of digital inputs: 2	I	
8.3.2.40	Number of digital inputs: 31	I	
	8.3.3 Sensors		See section 6.3
8.3.3.1	As many sensors shall be placed as necessary to reach the scientific and engineering goals of the research facility. A preliminary list of different types of sensors required for the HPC is shown next:		Table 12, 13,14
8.3.3.2	-Temperature	I	Table 12,13
8.3.3.3	-Humidity	I	Table 12
8.3.3.4	-Pressure	I	Table 12
8.3.3.5	-pH	I	Table 12,13
8.3.3.6	-EC	I	Table 12
8.3.3.7	-Ion sensors (ISFET)	I	Table 12
8.3.3.8	-Liquid flow rate	I	Table 12, 13
8.3.3.9	-Liquid level	I	Table 12
8.3.3.10	-Light (PPF)	I	Table 12
8.3.3.11	-Gas flow rate	I	Table 12, 14
8.3.3.12	-CO_2	I	Table 12, 14
8.3.3.13	-O_2	I	Table 12, 14
8.3.3.14	-Ethylene	I	Table 12, 14

Req. Nº	Description	Verif.	Comments.
8.3.3.15	-VOCs	I	Table 12, 14
	8.3.4 Parameters to be controlled		See section 6.4
8.3.4.1	Air temperature and dehumidification is controlled by the modulation of the chilled water and steam valves (heat exchanger)	T	
8.3.4.2	Humidity control is achieved with measured injections of ultra pure atomised water.	T	
8.3.4.3	pH of nutrient solution is controlled by injections of acid and basic solutions.	T	
8.3.4.4	EC of nutrient solution is controlled by injections of concentrated nutrient solutions	T	
8.3.4.5	Nutrient solution flow rates are controlled by electrovalves	T	
8.3.4.6	Level in tanks (for condensed water and nutrient) is measured with a level sensor and controlled by means of pumps located in the input and output of the tank.	T	
8.3.4.7	Gas composition (CO_2, O_2, Ethylene) is controlled by injections of laboratory gas lines or other compartments gas effluents	T	
8.3.4.8	PPF can be controlled regulating lamps light intensity.	T	

9 APPENDIX B: SOURCES OF PRODUCTIVITY DATA

Summary of Higher Plant Productivity Data Collected from Empirical Trials and Bibliographic Review Compiled by G. Waters, UoG

The higher plant productivity data presented in Figure 2 cannot be assessed in the context of crop productivity on a g edible biomass m^{-2} day^{-1} basis. The numbers are expressed on a g dry matter per day basis and are not standardized on a per area basis. Further, there seems to be a discrepancy between sets of productivity data used among MELiSSA TNs.

The following tables summarize data obtained empirically and from literature review. These tables allow for comparison of productivity data and attempt to develop mean values to be employed in future studies. Whenever possible, it is suggested that the empirical data from the University of Guelph be used in studies relating to the pilot plant as the environment conditions used in their generation will be similar to those attainable in the pilot plant facility. Further, the candidate crop list used in simulation studies should include beet, as it is a candidate crop for the first integration tests to be performed at the pilot plant at UAB.

Crop	Density (plants m^{-2})	PPF (µmol m^{-2} s^{-1}) PAR	Photo-period (h)	Temperature ^{o}C (day/night)	Edible Biomass (g $plant^{-1}$, dw)	Harvest Index (%)	Days to Harvest	Crop Productivity (g edible dw m^{-2} day^{-1})	Source
Beet	17.6	600	14	26/20	28.3	94	54	9.22	Waters (2002)
Lettuce	17.6	600	14	26/20	4.3	77	45	1.68	Waters (2002)
Soybean	39.2	1000 – 1200 at mid canopy	18/8* and 12/12	24/18	6.1	19	119	2.01	Stasiak (2002)

Table 16. Empirical Data Collected at the University of Guelph CES research facility * A photoperiod of 18/8 h (day/night) was used for the first 8 weeks of production followed by a photoperiod of 12/12 hrs thereafter.

Crop	Density (plants m^{-2})	PPF (µmol m^{-2} s^{-1}) PAR	Photo-period (hrs)	Temperature ^{o}C (day/night)	Edible Biomass (g $plant^{-1}$, dw)	Harvest Index (%)	Days to Harvest	Crop Productivity (g edible dw m^{-2} day^{-1})	Source
Beet	39	700	14	18/18	25.5	98	84	9.0	Wurr *et al* (1998)
Lettuce	30.4	640	16	17/11	6.4	94	26	3	Wheeler *et al* (1994)
Onion	76.2	640	16	17/11	16.8	66	93	13.8	Mortensen (1994)
Potato	5.88	800	12	16/16	383.3	79	90	25.0	Wheeler *et al* (1991)
Rice	235	1000	12	31	10	47	110	10.0	Bugbee (website)
Soybean	24	600	9	26/20	76	45	90	20.3	Sionit *et al* (1987)
Spinach	39	600	16	24/18	12.8	74	33	15.1	Both *et al* (1995)
Tomato	Aprx. 8	600	16	26/22	Indeterminate	36	117	8.0	Bugbee (2003)
Wheat	400	1000	24	23/23	2.24	50	65	13.8	Bugbee (2003)

Table 17. Bibliographic Review of Productivity Data

Crop	PPF (mol m^{-2} day^{-1}) PAR	Photo-period (h)	Temperature ^{o}C (day/night)	Harvest Index (%)	Days to Harvest	Crop Productivity (g edible dw m^{-2} day^{-1})	Source
Beet	17	16	23/23	65	38	6.5	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Lettuce	17	16	23/23	90	28	6.57	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Onion	17	—	—	80	50	9.0	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Potato	28	12	20/16	70	132	21.06	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Rice	33	12	28/24	30	85	9.07	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Soybean	28	12	26/22	40	97	4.54	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Spinach	17	16	23/23	90	30	6.57	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Tomato	27	12	24/24	45	85	10.43	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7
Wheat	115	20-24	20/20	40	79	20.00	Hanford (2002; BVAD, Table 4.2.6 and 4.2.7

Table 18. Productivity data taken from the Baseline Values and Assumptions Document (BVAD)

Crop	Crop Productivity (g edible dw m^{-2} day^{-1})	Source
Beet	-	-
Lettuce	6.0	Gòdia (2001); Creus (2003); Poughon, (1997)
Onion	22.5	Gòdia (2001); Creus (2003); Poughon, (1997)
Potato	33.0	Gòdia (2001); Creus (2003); Poughon, (1997)
Rice	4.0	Gòdia (2001); Creus (2003); Poughon, (1997)
Soybean	15.0	Gòdia (2001); Creus (2003); Poughon, (1997)
Spinach	21.0	Gòdia (2001); Creus (2003); Poughon, (1997)
Tomato	18.0	Gòdia (2001); Creus (2003); Poughon, (1997)
Wheat	33.0	Gòdia (2001); Creus (2003); Poughon, (1997)

Table 19. Values for Productivity TN 32.3