MELiSSA

TECHNICAL NOTE

TECHNICAL NOTE 85.5

Higher Plant Chamber Prototype for the MELiSSA Pilot Plant: Detailed Design and Verification

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1. Introduction

Staff of the Department d'Enginyeria Química, Universitat Autònoma de Barcelona (UAB) and the Controlled Environment Systems Research Facility (CESRF) at the University of Guelph have been actively collaborating in an effort to integrate a Higher Plant Chamber (HPC) into the MELiSSA loop. Immediate goals are to integrate the HPC into the MELiSSA Pilot Plant (MPP) facility, located at UAB.

The main steps involved in HPC integration are:

- design of an HPC prototype, which is detailed in this technical note
- assessment of mass balance of the MPP including an HPC using data derived from empirical production trials for the purposes of sizing the HPC
- technical development and documentation of the prototype chamber
- development of dynamic models/control laws of gas exchange and nutrient uptake for MELiSSA candidate crops,
- formulation of local control algorithms for both the autonomous and integrated operation of the HPC within the Pilot Plant,
- construction of the HPC,
- connection of the gas, liquid and solid loops of MELiSSA to the HPC,

On the basis of the preliminary design document TN 75.3, this technical note further details the HPC prototype design in preparation for its construction.

2. HPC Prototype Definition and Design Justification

2.1. The MELiSSA Pilot Plant Facility

The laboratory volume devoted to the HPC in the new UAB facility is of 288 m^3 with a footprint area of 12 x 6 m and a height of 4 m. The infrastructure at UAB includes the key services listed below.

- Electrical power: tri-phasic/bi-phasic, 30 kW (28.5A), 220V, 50Hz
- De-mineralized and tap water lines
- Air conditioning equipment
- Chilled Water supplies, for HPC thermal control
- Gas lines: Compressed air, CO_2, N_2, O_2

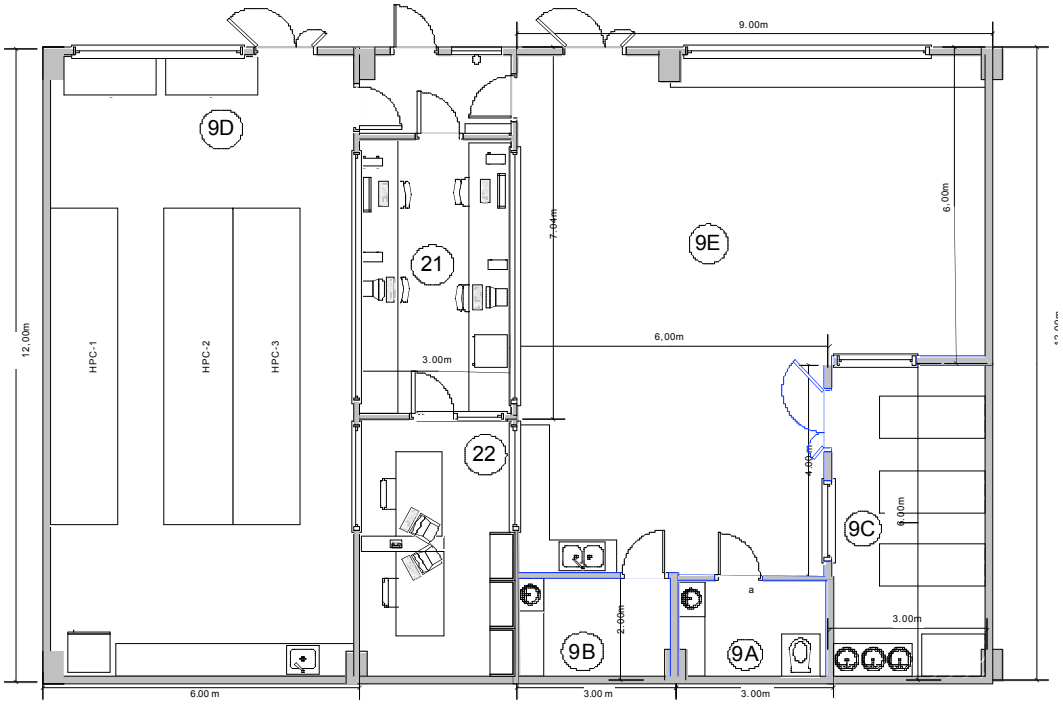


Figure 2.1-1. Higher Plant Compartment distribution in the UAB laboratory. The Higher Plants will be housed in Section 9D with a bay for analytical equipment housed at the bottom end of the room.

It is foreseen that in addition to the provisions at the MPP noted above, the HPC prototype will require additional research related infrastructure as follows:

- **Gas fueled hot water tank for thermal control of the HPC:** In the thermal control strategy hot water is to be pumped via a re-circulating loop into the radiator coil of the chamber. Capacity of this tank is being developed in consultation with an engineering firm concurrently with the specifications of the air handling system of the prototype. This design is being commissioned on a sub-contract basis and will form part of the final (as built) chamber design and operations document (TN , pending)
- **Laboratory work bench with sink.** One of the HPC room end walls should be fitted with a work bench which allows for tissue and sample preparation. The bench should have a 1m x 0.4 m stainless sink (or as close as possible) to accommodate cleaning of the hydroponics troughs (1 m x 0.2 m). The sink should be fitted with supplies for distilled and tap water and have storage underneath for micro-nutrient reagents and sample preparation equipment (vials, balance).
- **Drying Oven:** The determination of plant yield on a dry weight basis and the preparation of tissue samples will require an oven capable of drying a 1 m3 volume at 60 C for 5 days. Assuming staged culture, it is expected that 1 kg ± 500 g of biomass will be dried on every 10 days.

- **Analytical System Bay:** A storage cabinet will be required to house the IRGA/Paramagnetic CO_2 and O_2 analyzer and solenoids and pump for gas sampling.
- **Autoclave**
- **Provisions for control panel placement**
- **General Storage Facilities for relevant Harvesting/Preparation tools cited below**
- **Harvesting and Preparation Tools, including:**
    - Balance for dry and fresh weight masses and micro-nutrient/hydroponics salt measurement (500 g ± 0.01 Kg)
    - Bleach
    - Rockwool cubes (2 x 1 m^3 boxes)
    - Seed germination trays (consumable)
    - Solution stock storage tanks (2 x 50 L tanks with spigot, PP)
    - Solution transfer tank (1 x 200 L tank, PP)
    - Submersible pump (5 L min^{-1} or greater)
    - Cutting board, knife, scissors, paper towels, paper bags
    - Plastic vials, gas sampling tubes (for off-line VOC analysis)
    - Coffee grinder for tissue sample preparation
- **Additional Analytical Equipment, as required:**
    - Li-COR Leaf Area Analyzer (supplied)
    - GC/FID for off-line ethylene analysis
    - GC/MS for general off-line VOC
    - HPLC for hydroponics sample analysis (ions; F. Cl. NO_2, NO_3, PO_4, SO_4, Na, NH_4, K, Mg, Ca

The design presented in this documentation has been prepared according to the technical specifications provided as an appendix to the RFQ to the present contract. The design has been constrained by the UAB pilot plant facilities. A detailed description of adherence to the technical specifications wll be provided in the "as-built" design documentation and the results of the functinal tests.

2.2. Prototype Dimensions

At the MELISSA general working meeting held 29/30 November 2001, it was decided, initially, that three crops be selected for production trials within the MPP. The selected species were wheat (*Triticum aestivum* L.), lettuce (*Lactuca sativa* L. cv. Grand Rapids) and beet (*Beta vulgaris* cv. Detroit Medium Red). These crops are representatives of plants with varying harvest index (edible biomass/total biomass, dwb) and mineral composition. As such, they each provide a unique challenge to the first compartment of the MELiSSA loop.

From empirical productivity values obtained from controlled environment trials of beet and lettuce (CESRF) it was determined that 15m^2 of crop production space (5 m^2 per chamber) would suffice in meeting the biomass production target based on a 20% of one-person-day diet (edible dwb basis).

The details of the sizing calculations performed to determine the HPC prototype size are presented in TN 75.3 – Higher Plant Chamber Design.

The dimensions of the chamber are therefore determined as follows:

Table 2.2-1. HPC Prototype Dimensions

Dimension	Value
Total available production space	5 m^2
Chamber Length	5 m
Air lock length (each, including interior door)	0.50 m
Interior chamber/air-lock width	1 m
Exterior chamber width (maximum room access width)	1.3 m
Width of air handling envelope (total for both chamber sides)	0.10 m, 0.05 m each side
Chamber insulation width with aesthetic covering (each chamber side and trim)	0.20 m

According to the layout of the HPC prototype housing facility within the MPP, these dimensions would allow for a total end clearance of 12 – 6 m = 6 m (3 m either end, less benches and analytical system bay). The clearance on one side of the chamber may be seen in Figure 2.1-1. In the final proposed configuration, one long side of the chamber is exposed (to promote logistical tasks) and the other positioned against the facility wall or an adjacent HPC.

Additional space will be required to house the lighting system ballasts. Since remote ballasts will be employed, it is proposed that they be positioned on the upper side of the chamber, on the outer side of the lighting loft cover. The added width of the ballasts is expected not to exceed 0.30 m at a height of no less than 2 m from the floor.

2.3. Equipment Harmonization

Equipment procured for the HPC prototype will be in accordance with the MPP harmonization list presented below, with the exception of the HPC lighting system. The HPC lighting system will likely be supplied by P.L. Lighting Systems (Hortilux).

Table 2.3-1. Equipment Harmonization requirements for the MELiSSA Pilot Plant

Hardware type	Suppliers/reference
Programmable Logic Controller	Schneider/Quantum
Electrical connectors	Phoenix
Electrical cupboards	Rittal
Flow controllers	MKS
Lamps	Excluded for HPC
Port	Ingold
Tubing connections	Swagelok
pH-probe	Mettler-Toledo
O_2-probe	Mettler-Toledo
Electrical fuses, circuit breakers	Hager

2.4. HPC Prototype Power Budget

The HPC prototype design team is aware of the power availability in the MPP and has strived to make its economical use. The total budget for a single HPC prototype chamber is calculated as follows:

Table 2.4-1. Estimated HPC Prototype Power Budget

Hardware	Power Draw
HPS Lamps (600W, x 5 fixtures)	650 W x 5 = 3250 W
MH Lamps (400W, x 5 fixtures)	432 W x 5 = 2160 W
Internal air circulation fan (1500 L/ s)	2000W
Lamp loft circulation fan (2.5 m^3 / min)	1000W
Infra-Red and Paramagnetic Analyzer (CO_2, O_2	500W
UV/O_3 Disinfection system	970W
Irrigation pump	500W
Tray conveyer system	Manual
Misc. Sensors (pressure, EC, pH, temperature)	500W
Mass Flow Controllers (x 5)	50W
Computer and Monitor	500W
Power Consumption of Prototype	**11430 W**
Overhead (15% of total)	**1715 W**
Total Maximum Power Consumption of Prototype	**13145 W**

2.5. Materials

The materials used for construction of the chamber should be selected so as to minimize off-gassing. They should also be non-toxic to higher plants. A list of proposed materials and their possible uses is shown below. This list applies to wetted parts on equipment not specifically mentioned below.

Table 2.5-1. HPC materials, (1) Pure phenolic thermosetting resinous coating, (2) Fluoroelastomer heat resistant.

Chamber Part	Materials
Walls, floors, valves, air plumbing	Stainless steel 316
Roof, windows	Tempered glass
Liquid reservoirs and tubing	Polypropylene (PP)
Heat exchanger, motor parts, oxidation barriers	"Heresite"(1)
O-rings, solenoid seats	"Viton"(2)

2.6. Logistics

The chamber is designed so as to promote efficient horticultural practice while allowing for change out of technologies should there be a desire for an upgrade. Additionally, access doors have been included on the side of the chamber to facilitate chamber cleaning, diseased plant removal and other logistical tasks. Contact surfaces for the doors will be sealed with Viton gaskets. The end air locks of the chamber are also fitted with glove boxes allowing access into the air lock interior when its external doors are closed. The glove boxes should be positioned on the air lock access door so that the operator may easily reach across the air lock length (0,5 m).

2.7. Basic HPC structure

The chamber is proposed to have two access areas (air-locks) located at each of its ends. One is to be used in the seeding procedure and the other to be used in harvesting the mature plants. This configuration allows for a staged culture strategy and dampens the CO_2 sequestration dynamic associated with canopy development.

The hardware necessary for the operation of the chamber is proposed to be situated below the growing area and air locks so as to improve space utilization efficiency in the area dedicated to the HPCs within the Pilot Plant facility.

The prototype chamber is divided into five sub-systems (A100 – A500). These include the lighting loft (A100), the liquid sub-system area (A200), the air handling volume (A300), chamber access areas (A400) and the crop growing volume (A500) (Masot, 2004).

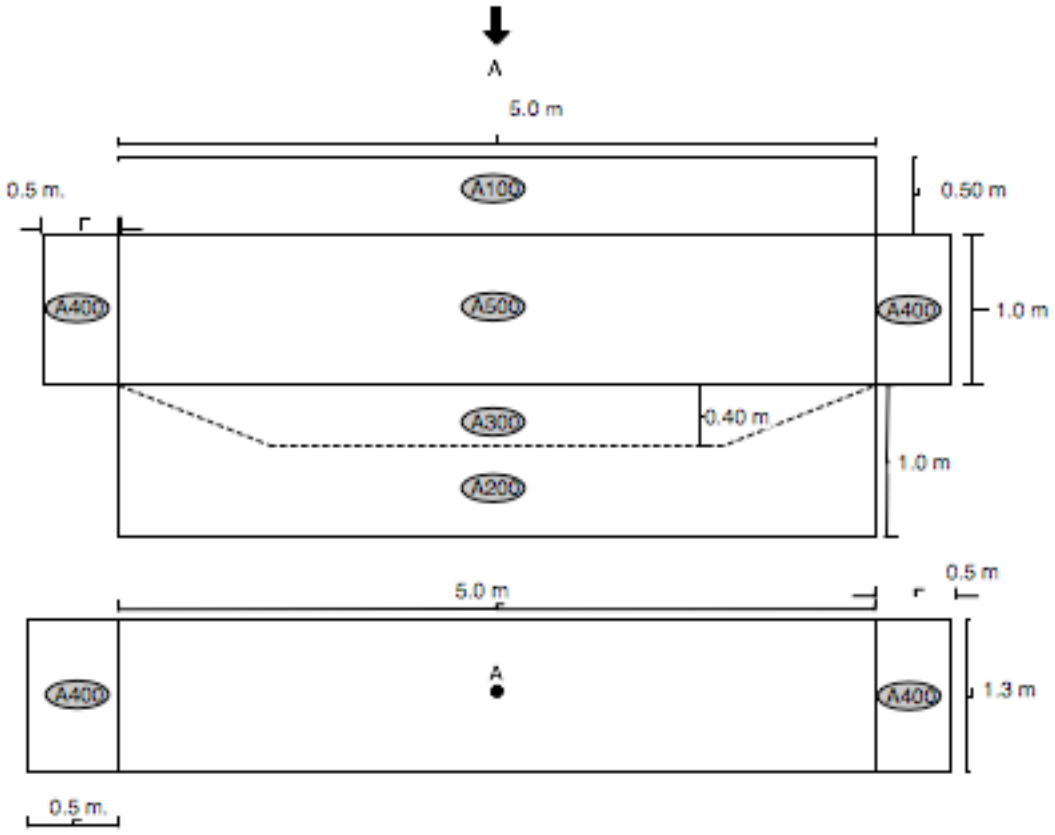


Figure 2.7-1. Schematic exterior view of the HPC prototype.

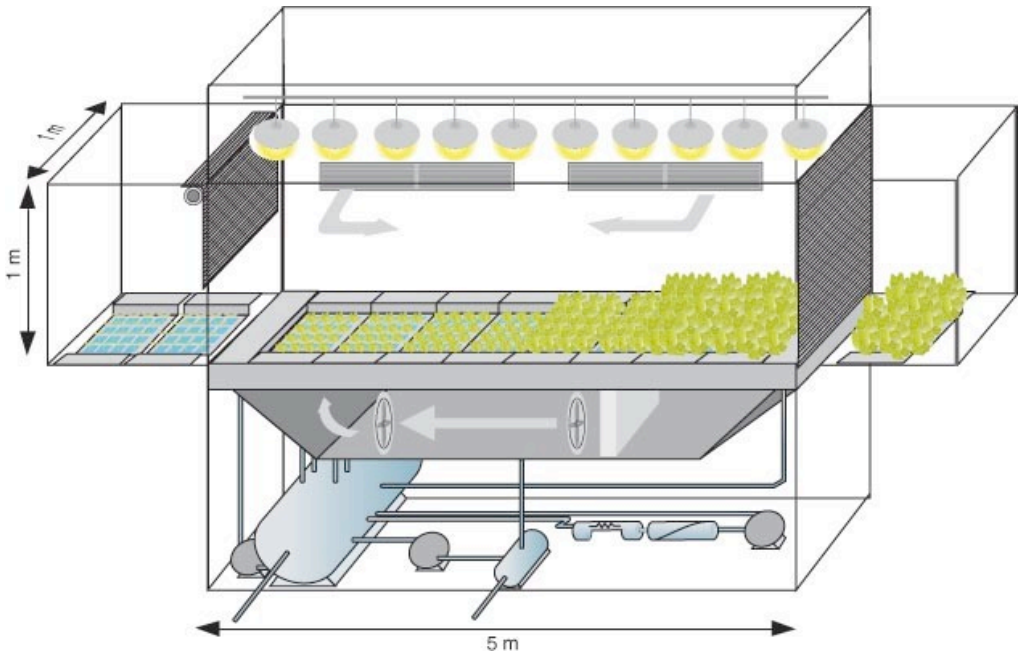


Figure 2.7-2. Diagrammatic representation of the higher plant chamber for integration into the Pilot Plant.

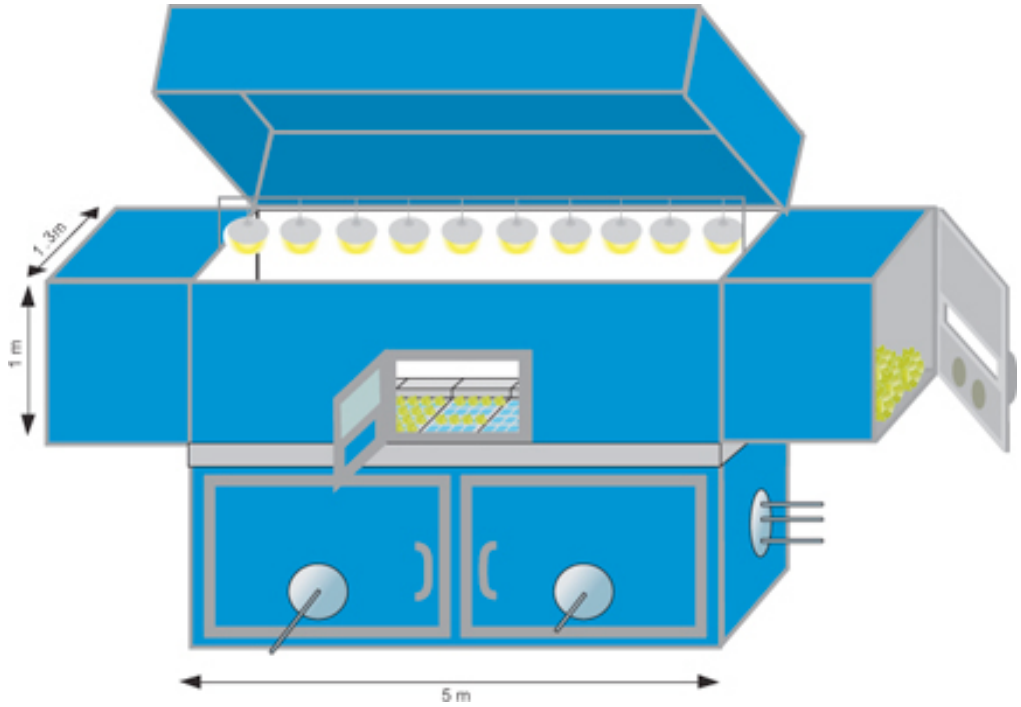


Figure 2.7-3. Diagrammatic representation - Exterior of the exterior of the higher plant chamber designed for integration into the MELiSSA Pilot Plant.

3. Functional Description of the Prototype

3.1. Atmospheric Control - Temperature, Humidity, Pressure and Composition

Air will be conditioned for temperature and humidity and re-circulated inside the chamber. Externally supplied chilled water and hot water are to be circulated through sealed and "heresite" coated (baked oxidation barrier) heat (cold and hot) exchange coils mounted in an internal plenum at the base of the chamber. Condensate from the chilled water coil will be collected on a slanted steel pan and collected and measured in a condensate collection reservoir (20 L reservoir volume). The condensate water may then be pumped back into the hydroponics reservoir and/or to the crew compartment of the MELiSSA loop depending on demand. Therefore, the condensate collection reservoir serves as a direct interface point between the HPC and the MEliSSA loop. Heresite coated fans and fan motors with silicone covered wiring are also mounted in the plenum and will distribute the air through ducts running the length and height of the chamber walls and into the chamber growing interior from outlets mounted an the upper interior wall. Modulated hot water and chilled water valves effect temperature and dehumidification control of the aerial environment. Hot water and chilled water will be supplied from services at the MPP. Humidification (when necessary) is achieved with measured injections of ultra pure atomized water using a fogging system. A source of de-ionized water within the MPP will be required for occasional (rare) humidification. The CESRF has found in its own experimental activity, that transpiration from the developing plant canopy is mostly sufficient in keeping the atmospheric humidity at levels near 75%.

The chamber will be fitted with two 200 litre double sealed Teflon bags (or similar bladder material) positioned in the base of the chamber. The Teflon bags serve as a passive approach to atmospheric pressure management in the chamber since they will expand or contract with variable atmospheric volume within the chamber growing interior as associated with programmed diurnal temperature fluctuations. The bags will each be connected via manifolds to the chamber growing volume using a 50 mm diameter stainless steel tube. The total temperature range influencing gas volume in the chamber represented by a single bag capacity of 200 L (nominally filled at 100L) is about $\pm$6 degrees. The total capacity of the two bladders together amounts to a volume change associated with $\pm$12 degrees.

The computer controller will maintain internal chamber CO_2 concentrations during the day-light hours so that any net carbon gain by the stand through photosynthetic activity is compensated for by injections from an external CO_2 tank. The tank may be commercially available bottled CO_2 or a reservoir of CO_2 collected from other MELiSSA compartments. The input of CO_2 into the chamber from the intermediate reservoir therefore represents another primary interface point between the MPP and the HPC. The details of this interface connection are provided in the section below.

The net carbon gain of the developing crop will be determined using a compensation technique. The volume and duration of CO_2 injections from external tank or intermediate reservoir to maintain demand levels within the growing area will be used to estimate day time Net Carbon Exchange Rate (NCER) of the developing canopy. During the dark period it will not be possible to remove CO_2 produced by the respiring canopy and so the difference in observed CO_2 and demand will be used to determine stand respiration rates (expressed as negative NCER). The signed integral of NCER estimates over a 24 hour period (in moles C), yields daily carbon gain (DCG). DCG is a model predicted output of the Thornley model of photosynthesis, described in greater detail below.

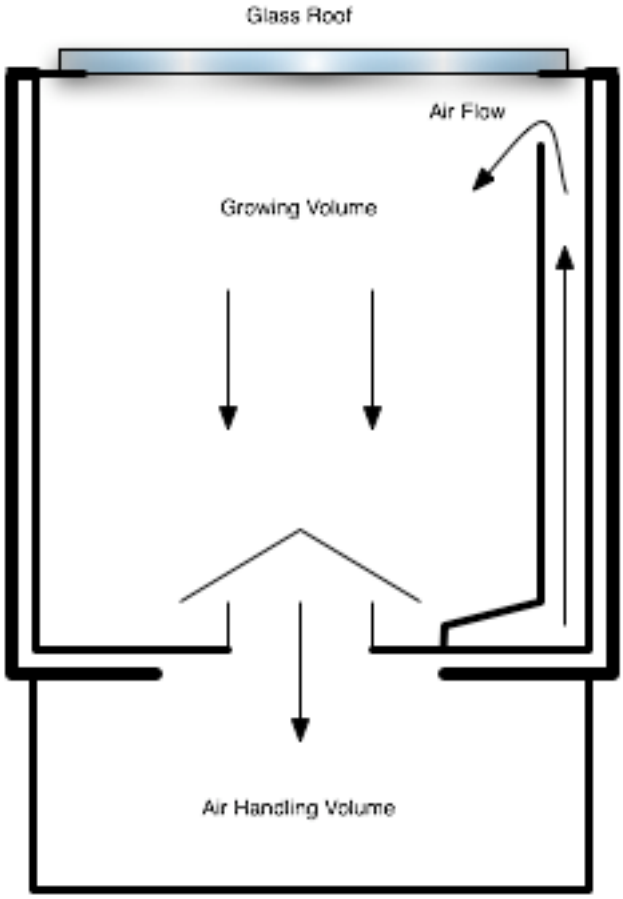


Figure 3.1-1. Representation of the air flow patterns within the prototype. Air moves through a plenum positioned on one of the side walls of the chamber and through vents (louvers) positioned on the upper side of the growing volume. Return is through vents positioned below the hydroponics tray support (trays not shown).

3.2. Hydroponics System Operation

The nutrient requirements for the plants are supplied in a hydroponics medium stored in a polypropylene nutrient solution reservoir mounted on the underside the chamber. The solution is pumped into the chamber to the head of sloped stainless steel troughs (trays) using a water cascade system. The trays are 1 m long and 20 cm wide (outer edge) each and are oriented along the width of the chamber (perpendicular to their line of travel on the conveyer system). The chamber has a total length of 5 m and can therefore accommodate up to 25 trays. The trays will be designed to accommodate a variety of root media as a substrate for the hydroponics solution including Rockwool©, expanded clay (Lecca©) and newly developed biodegradable and inert media. The solution drains from each tray into a common collection trough via gravity. The collection trough (5m in length) then returns the solution back to the nutrient reservoir. The condition of the solution with respect to pH and electrical conductivity is monitored and adjusted continuously through measured injections of acid, base and/or various nutrient mixes. For more details on the operation of the hydroponics system, readers are referred to the typical operational scenarios described in the section below.

3.3. Lighting System Operation

The plant growth chambers will be equipped with 5 pairs of 600W HPS and 400W MH lamps externally mounted overhead to provide illumination through a 10 mm tempered glass roof. Initially static ballasts will be used. This means that light intensity can not be attenuated through power supply regulation to the ballasts. Therefore, light intensity control will be discrete with binary (on/off) operation of the lamps to achieve desired illumination levels. More details on the lighting system operation area provided below.

4. HPC Prototype Technical Specifications

4.1. Chamber Access System

Access to the chamber growing area is gained through i) air-locks positioned at both chamber ends and ii) hinged doors positioned along the length of one side (exposed) on the chamber. The air locks are designed to reduce atmospheric leakage or cross contamination between the chamber interior and exterior during seeding and harvesting procedures. On the interior side of the air-lock is a rolling door. The door is activated by relays to allow for remote opening or closing when the exterior air-lock door is closed. The steps to be taken in the seeding and harvesting procedure are outlined in the section below, including a description of a manual procedure involving the purge of the air lock with nitrogen gas. The exterior air lock doors will be opened manually and will be fitted with gaskets and bolts/wing nuts to ensure a seal against the exterior chamber wall when not in use.

During periodic cleaning of the HPC, the side doors may be opened to access the depths of the chamber interior. These doors will be opened manually and will be fitted with gaskets and bolts/wing nuts to ensure a seal against the exterior chamber wall when not in use. The height of each side door is proposed to be 0.6m with the width not to exceed clearance between chambers within the MPP (i.e.: 0.6m). The chamber access system is represented in the diagrams below.

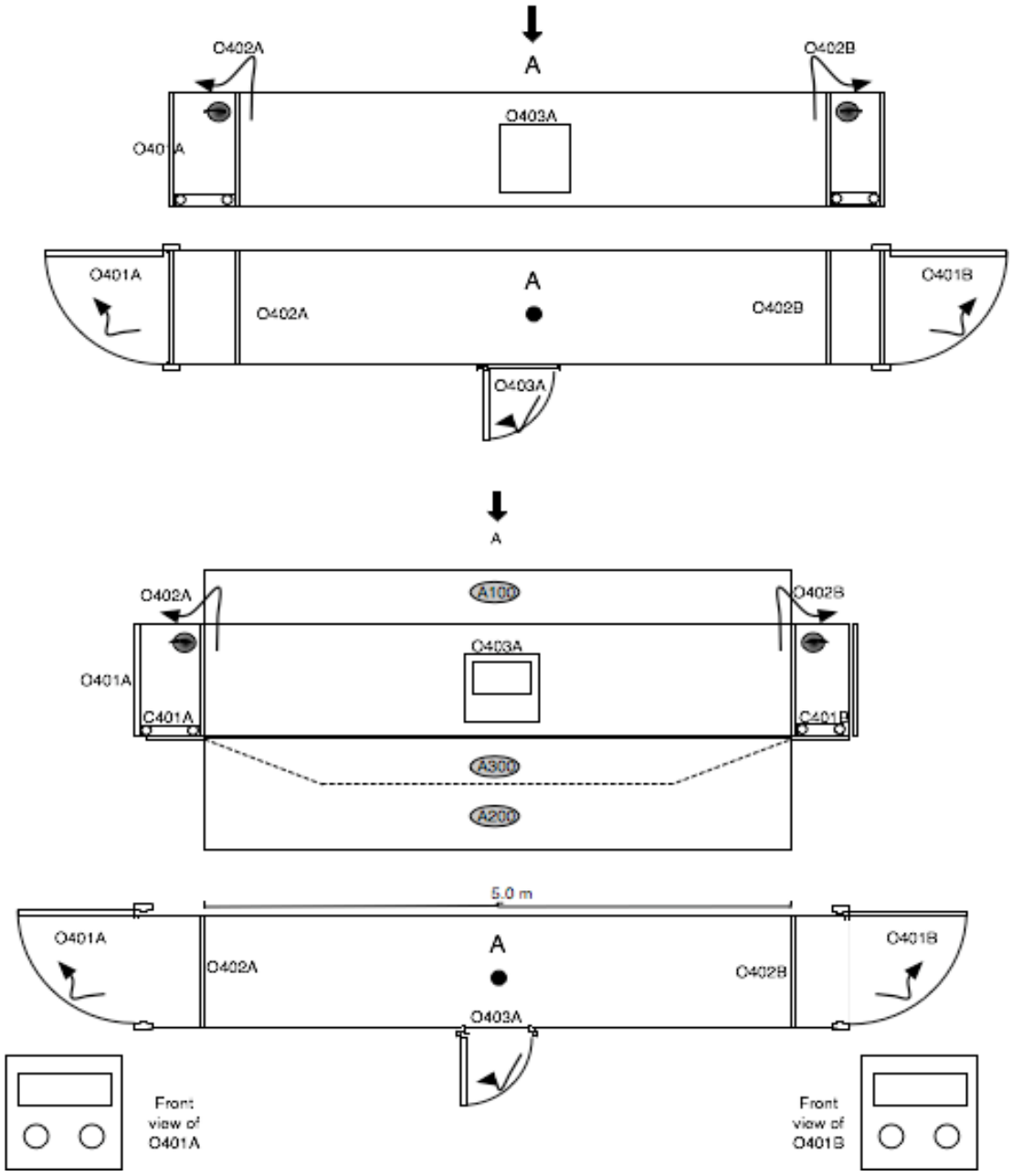


Figure 4.1-1. Schematic of the HPC access air locks (Masot, 2004).

4.1.1. Interior Air Lock Door Control

Below is a diagrammatic representation of the control loop for operation of the interior air-lock doors. The interior doors are activated manually by a relay switch.

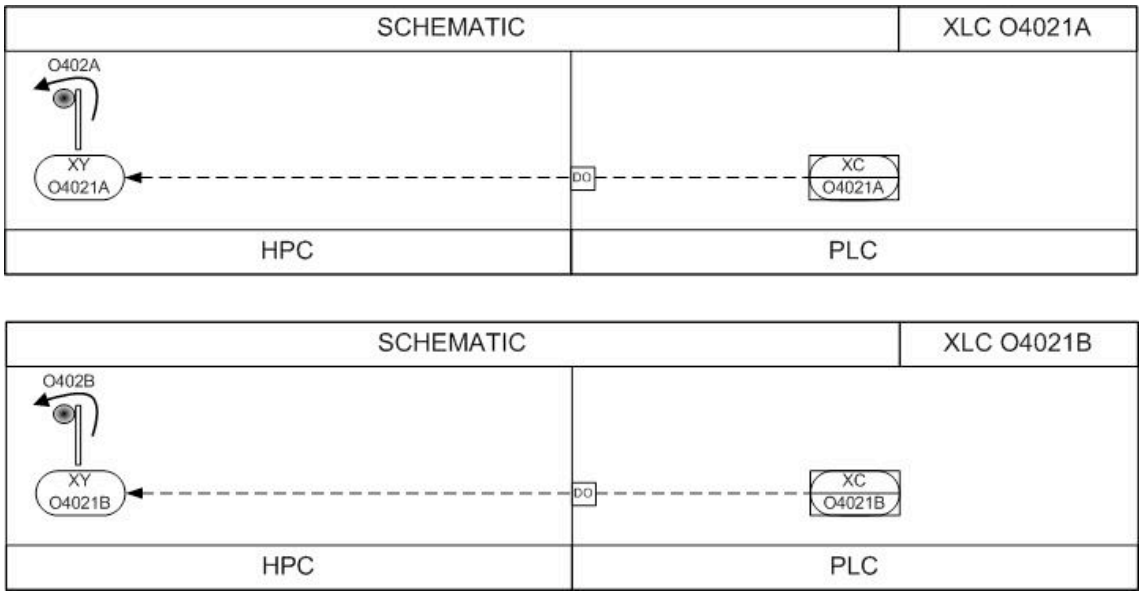


Figure 4.1-2. Control loop schematic for operation of the internal air lock doors (Masot, 2004).

Control Group Identifier: XLC 04021A, XLC 04021B

Objective: Open/close interior air-lock doors

Description of the Control Loop:
Relays are used to trigger the opening or closing of the interior air-lock doors. The doors will roll upon themselves using a motor. No formal feedback control loop is envisioned.

Equipment

Hardware	Reference
Rolling door with motor	O402A, O402B

Instrumentation and Signals:

Instrument	Reference	Signal
Relays	XY O4021A, XY O4021B	2 x DO

4.1.2. Air Lock Purge Control

Below is a diagrammatic representation of the control loop for purge of the interior air-lock volume.

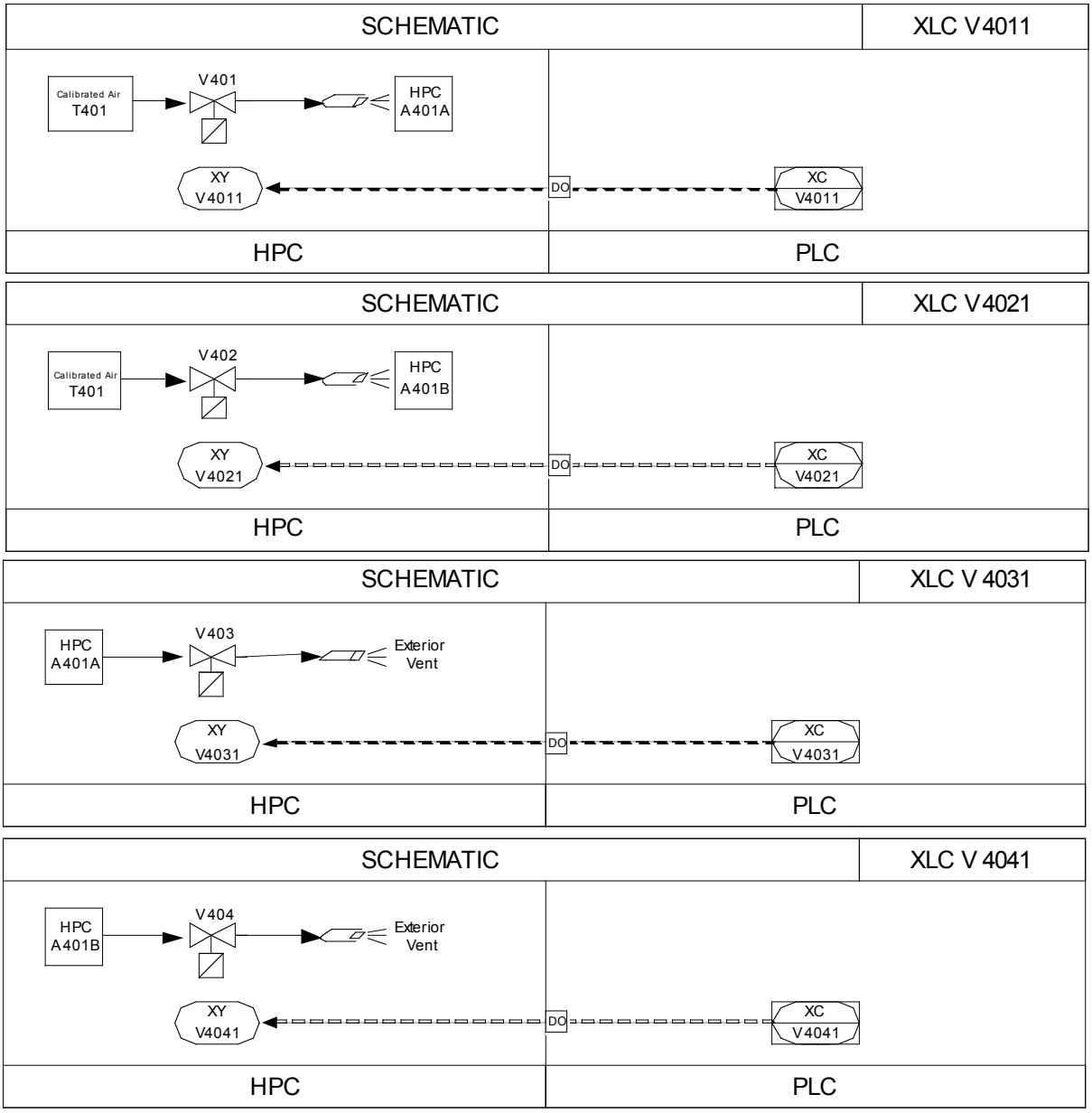


Figure 4.1-3. Control loop schematic for gas purge of the air locks (Masot, 2004).

Control Group Identifier: XLC 04011, XLC 04021, XLC 04031, XLC 04041
Objective: Purge the air locks after the seeding and harvesting procedures.

Description of the Control Loop: After opening the air locks (A401A and A401B) a relay is activated (XYV4011) to allow for the injection of calibrated air mixture equal to the chamber interior control values (1000 ppm CO_2, 21% O_2, balance N_2) (T401) through

a metering valve (V401/V402). Simultaneously the valve allowing venting of the air lock atmosphere is opened (V403/V404).

Equipment

Hardware	Reference
Planting Air-Lock N_2 Purge valve	V401
Harvesting Air-Lock N_2 Purge valve	V402
Planting Air-Lock Vent valve	V403
Harvesting Air-Lock Vent valve	V404

Instrumentation and Signals:

Instrument	Reference	Signal
Relays	XY V4011	DO
Relays	XY V4021	DO
Relays	XY V4031	DO
Relays	XY V4041	DO

4.2. Lighting system

The selection of the artificial lighting system proposed for the prototype chamber is based on a number of factors including emission spectral quality, light intensity (photosynthetic photon flux, PPF), crop growing area, mounting height and characteristics of the reflector. The proposed lighting system is also designed to promote flexibility in its use. The external mounting of the lamps and ballasts allows for more rapid lamp and reflector change-out and re-distribution. The mounting of the lamps on the chamber exterior reduces heat load and allows for the incorporation of a lighting loft cooling system. Either neutral density screening or variable intensity discharge lamps could be used to control light intensity. The design team is continuing to investigate the possibility of variable intensity, high pressure discharge bulbs for the purpose of controlling gas exchange in the HPC but for now proposes a combination of binary (on/off) control and manually introduced neutral density screening to attenuate light intensity when needed.

4.2.1. Light Intensity Measures

Photosynthetically Active Radiation energy (PAR) is in the 400 to 700 nanometer (nm) wavelength range. The unit of Photosynthetic Photon Flux (PPF) is expressed as micromole photons in the PAR range per second per meter square (μmole s^{-1} m^{-2}). The following are conversion factors for lux (lx) and PPF.

Table 4.2-1. Conversion factors used for PPF and LUX conversion for various lighting sources (Apogee Instruments, 2006)

PPF (μmol m^{-2} s^{-1}) to LUX	
Sun	54
Fluorescent white lamp	74
HPS	82
MH	71
LUX to PPF (μmol m^{-2} s^{-1})	
Sun	0.0185
Fluorescent white lamp	0.0135
HPS	0.0122
MH	0.0141

For a combination of 600W HPS and 400W MH, the weighted conversion factor from Lux to PPF may be determined as follows:

60% x 0.0122 + 40% x 0.0141 = 0.01296

where the percentage weightings are derived from the relative power rating of the HPS and MH lamps.

4.2.2. Choice of Lamp Type

High Pressure Sodium (HPS) Lamps

The high-pressure sodium lamp has a transparent discharge tube filled with a gas and sodium mixture (the conductor.) An electric current vaporizes the conductor causing it to glow, which results in the emission of light and heat. The ballast (a current regulating device) is required to limit and stabilize the current passing through the lamp, greatly reducing the loss of energy in the form of heat. The ballast also prevents overdriving of the lamp, resulting in longer lamp life.

HPS is the most energy efficient lamp for greenhouse lighting. About 30% of the electric energy input is converted into PAR, compared to 6.7% for incandescent lamps. Only 14%

of the light energy is in the waveband between 400 and 565 nm, and most of the rest in the region up to 700 nm, providing maximum plant growth. The rest is converted into heat energy.

The useful life of HPS lamps is twice that for Metal Halide (MH). The light output during the lamp life will drop less than 10%.

Metal Halide (MH) Lamps

Metal Halide lamps produce a whitish light that closely resembles the spectrum of daylight. A MH lamp has a transparent discharge tube filled with a mixture of gas and metal salts of halogens (the conductor.) An electric current vaporizes the conductor causing it to glow, which results in the emission of light and heat.

About 55% of the light energy of a 400W MH lamp falls in the waveband of 400 - 565nm. The highest radiant energy peaks fall in green and orange wavebands. MH lamps have a wider spectrum than mercury or sodium lamps, because they contain metal salts of halogens, which include fluorine, chlorine, bromine and iodine. They are less energy efficient and have a shorter life-span than HPS. However, compared to lighting with fluorescent tubes, fewer fixtures are required making MH lamps more cost-effective.

MH lamps serve a distinct purpose in the scheme of supplemental greenhouse lighting. They can be combined to work in tandem with other light sources, such as HPS lamps, for particular applications such as growth rooms without sunlight where a complete light spectrum is required for balanced plant growth.

A comparison of the spectral output of three lamp types compared to sunlight is provided below. Our team's earlier research with Microwave lighting systems within the SEC2 chambers has determined that the microwave lamp system will be too unreliable for inclusion in the MPP HPC Prototype.

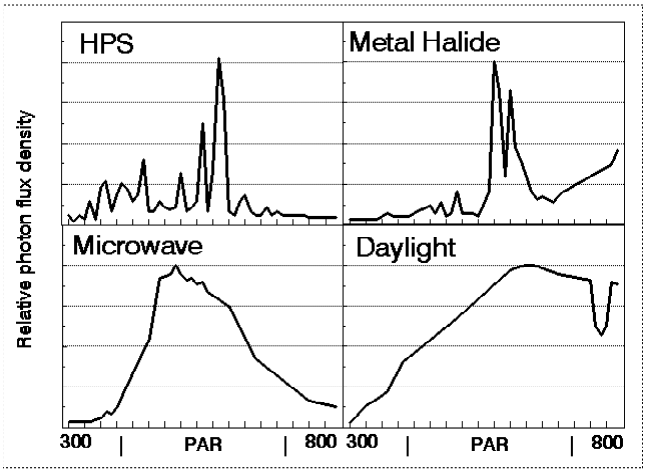


Figure 4.2-1. Relative spectral output of various lamp types in the PAR range.

Remote Fixtures and Ballasts

In remote fixture systems, the ballast is located on the ground outside the chamber, or in commercial applications, between the crops (and used as a heating source) (P.L. Lighting Systems, 2005). Only the lamps themselves, equipped with reflectors, are suspended over the chamber. The absence of the ballast over the crop results in reduced shading and heat load to the chamber. This configuration also minimizes the infrastructure required to support the lighting system over the growing area.

Light Emitting Diodes

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 used. As the LED technology improves, it may be possible to remove the conventional lighting systems from the HPC and replace them with panels of^2 LED arrays. This step should be considered only after experience has been gained in operation of the prototype under conventional lighting systems.

Recommended System: Remote Fixture HPS and MH

It is recommended that a combination of HPS and MH lamps targeting a lighting intensity at bench height of greater than 400 µmol m^{-2} s^{-1} PAR be used.

A remote ballast lighting system may accommodate up to 2 bulbs with reflectors (eg. Hortilux Maxima Reflector) per m^2 given the power availability within the MPP. Assuming lighting pairs (strings) consisting of one each of 600 W HPS and 400 W MH lamps, 5 x 1000 W pairs could be positioned overhead. Power requirement for lighting

will be therefore up to 5.5 kW per single chamber assuming a peak power draw at the plug allotment of 10%.

The figure below depicts the lighting loft with the MH and HPS lamps. The full complement of ballasts is not shown as they will be positioned on the upper and outer side of the lamp loft cover. Fans with appropriate ducting leading to the air cooling system of the MPP are positioned in the loft to prevent lamp over-heating. The lighting loft may be covered with a steel box lid with hinges or a lightweight reflective canopy for ease of access. Air exchange may freely occur in the loft to promote cooling.

The diagram below depicts the anticipated light intensity using the P.L. Lighting System lamps PL2000 600 W HPS Remote and PL2000 400 W MH Remote. The calculations of uniformity in the illumination field were conducted using software designed and operated by P.L. Lighting Systems (Hortilux) and is specific to their lamp and reflector combination. Provisional guarantee is provided by P.L. Lighting Systems regarding such predictions.

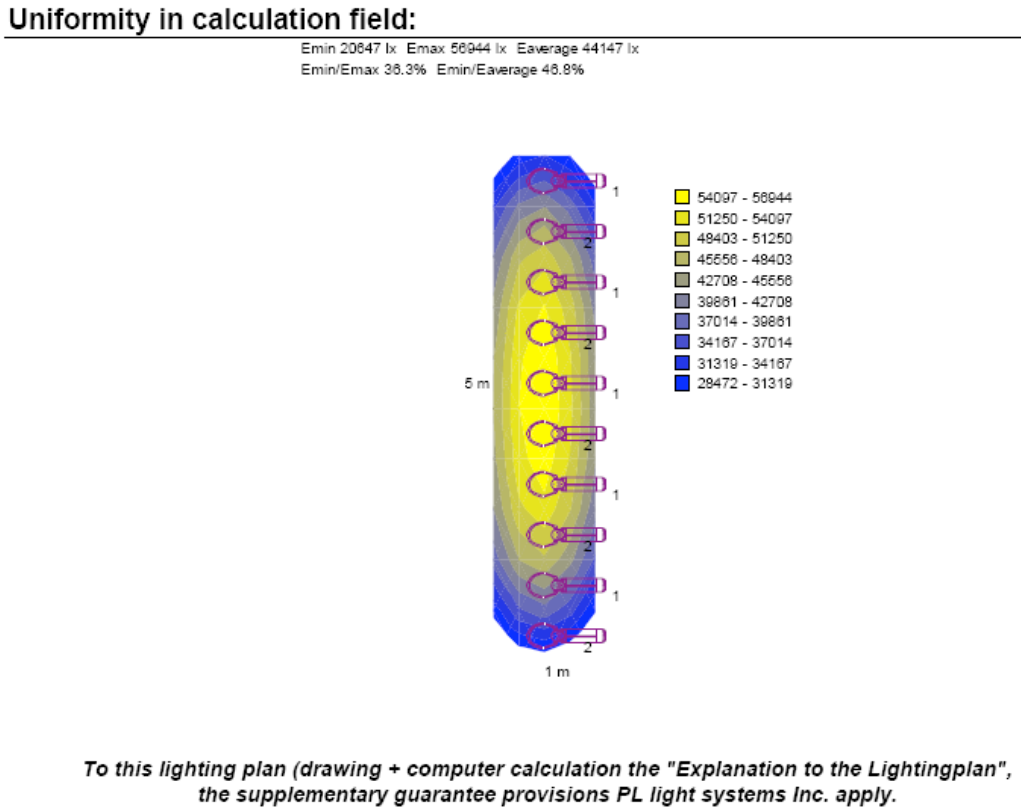


Figure 4.2-2. HPC lamp configuration. Lamp 1 refers to the HPS and Lamp 2 refers to the MH lamps. The diagram above does not accurately predict the placement of the lamp ballasts which are remote and to be positioned on the exterior of the lamp loft cover.

4.2.3. Operation and Control of the Lighting System

This section provides a summary of the major operational and control requirements for the lighting system. The lighting loft and lamps are designated as A100. In the description below it is assumed that 2 HPS-MH lamp pairs are used per m^2. Under this configuration 5 lamp banks (MH-HPS pairs) are identified. The lamps will be positioned in the lighting loft at least 30 cm above the glass roof of the chamber. This will allow for the introduction of neutral density screens under the lamps to manually attenuate light intensity, if so desired.

4.2.4. Light Intensity Control

In the case of fixed ballasts which are not dimmable, control of the lighting system intensity is limited. A relay switches each lamp bank on or off, depending on the desired intensity. It is proposed that each HPS-MH pair be wired as a separate 'lamp string' (i.e. strings consist of a MH and HPS lamp pair and are designated as Strings A through E). In this case, discrete changes in light intensity may be had in 20% increments (i.e. 5 control strings) from off to maximum intensity. An added benefit is that this approach may afford the control of gas exchange in each age class of a staged cropping scenario since the strings will be mounted, roughly, directly overhead of the age classes (assuming 5 age classes of a crop are represented in the chamber).

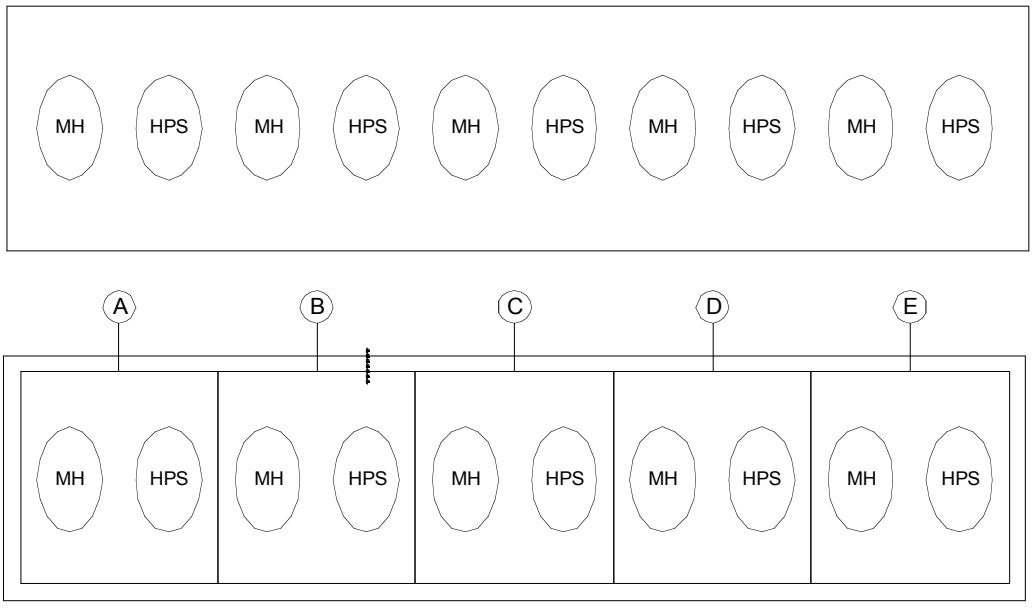


Figure 4.2-3. Lamp distribution in the lighting loft and binary control scenario (Masot, 2004)

The proposed control scenario for the lighting system is represented diagrammatically below. Below each HPS-MH pair (strings A-E) will be PAR sensors. Depending on the desired light intensity (i.e. that predicted from the HPC control law based on the Thornley photosynthesis model) each lamp string will be triggered on/off.

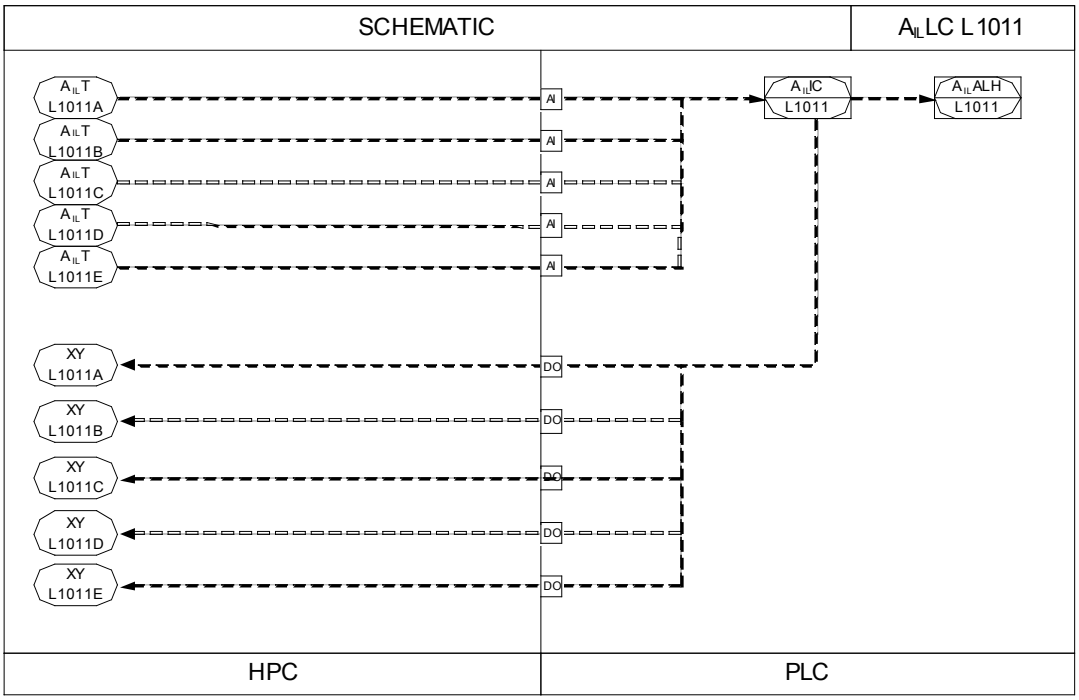


Figure 4.2-4. Light intensity control schematic (Masot, 2004)

Control Group Identifier: A_{IL} LC L1011

Objective: Turn on/off lamps positioned above chamber

Description of the Control Loop:

Output from PAR (A_{IL}T L1011A-E)) sensors positioned in the chamber is directed to the PLC through AI interfaces. If the light intensity is at desired levels no action is taken. If light levels are too high, additional banks (A to E) may be turned off through outputs to relays XY L1011A-E.

Equipment:

Hardware	Reference
5 HPS Lamps+5MH Lamps	L101

Instrumentation and Signals:

Instrument	Reference	Signal
PAR Sensors	$A_{IL}T$ L1011A-E	5 x AI
Relays	XY L1011A-E	5 x DO

4.2.5. Lighting Loft Temperature Control

Four temperature sensors will be positioned in the lighting loft to measure its temperature. In the event that the loft is too hot, air will be circulated through the loft to promote cooling. Coolant air may be drawn from the overhead ventilation to the HPC housing room at the MPP or the ambient air in the HPC housing area. Proposed air exchange rates are on the order of 1 m^3 / s. In most operational scenarios (i.e. full light intensity) the air circulation will be continuous. Because of the potential for light attenuation through a water barrier positioned underneath the lamps and the added load bearing capacity required for the glass roof, it is not suggested that a water bath be used for cooling. The design team recognizes that optimal cooling of the lamp loft will be required so temperature increases in the plant culture area are minimized.

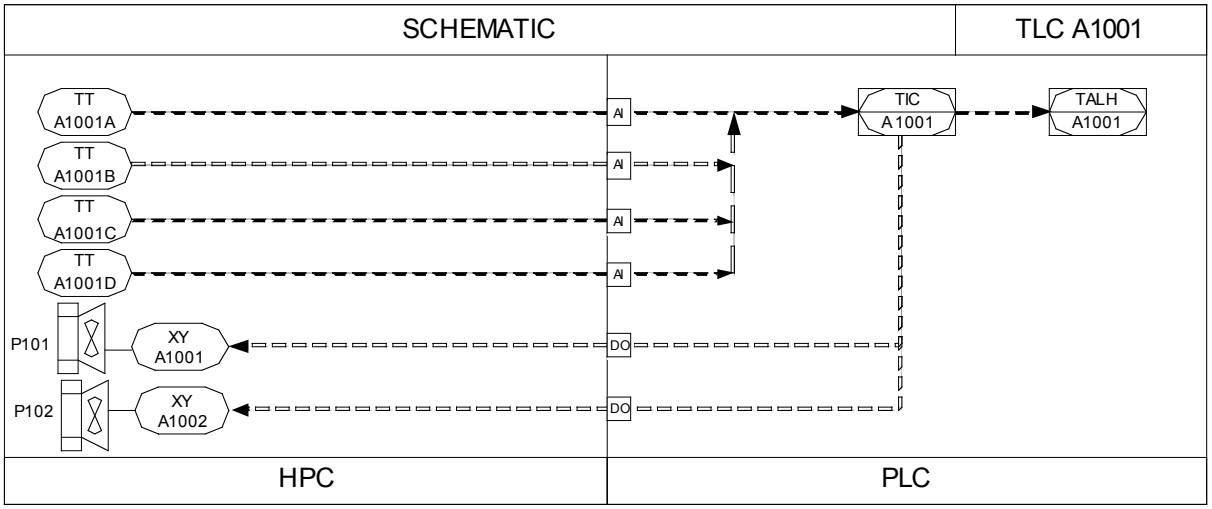


Figure 4.2-5. Control loop schematic for lighting loft temperature (Masot, 2004)

Control Group Identifier: TLC A1001

Objective: Maintain the temperature in the lighting loft at a set point (25 °C) so that temperature increases in the plant culture area are minimized.

Description of the Control Loop: Forced air circulation in the bank should be used. The air introduced into the loft (A100) comes directly from the air input into the laboratory and circulated using two two-speed fans running at half speed (P101, P102). Air is rejected to the handling system of the laboratory. Four temperature sensors (TT A1001A-D) are positioned in the lighting loft area. The sensor signal is sent to the controller which will turn on/off the exchange fan. An alarm is indicated when temperatures in the lighting loft exceed 35 °C.

Equipment:

Hardware	Reference
Lighting Loft	A100
2 x two speed Fans and vent with ducting	P101, P102

Instrumentation and Signals:

Instrument	Reference	Signal
Temperature thermocouple	TT A1001A-D	4xAI
2 x Fan Relays	XY A1001, XY A1002	2 x DO

4.3. Liquid subsystem

Crops will be grown in hydroponics using a Nutrient Film Technique (NFT). In this method, a thin film of nutrient solution, which is always in contact with the plants, flows through a channel that contains the plant roots. The trays span with the width of the chamber and are sloped on at a 2% grade. Basic schemes of the plant NFT trays and the HPC liquid loop are depicted in the figures below.

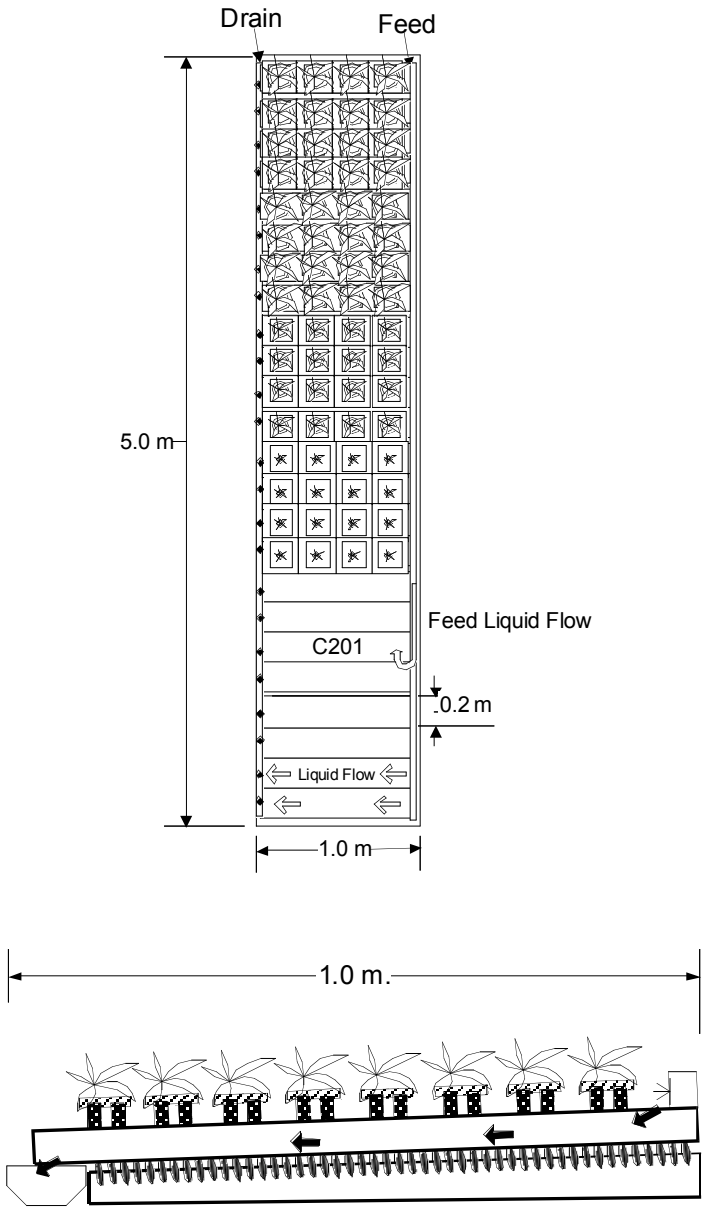


Figure 4.3-1. Representation of the growing trough distribution and in side profile.

The nutrient solution will be pumped (P201) from the external reservoir (T201) into the chamber in steel tubing to the head of sloped, one meter long, troughs (C201) spanning the width of the chamber. A water cascade system will be used to deliver solution at the tray heads. The water cascade system consists of a single solution distribution line spanning the 5 m length of the chamber. At distances along this main line corresponding to the heads of the stainless steel troughs will be mounted a t-fitting having an open top. While ensuring the main distribution line is level, the water flow from each t-fitting is directed into the head of each trough. The solution flow rate into the trough is therefore

passively regulated. The trays are free to move on the conveyer will positioned under the fittings. The diagram below represents the water cascade approach.

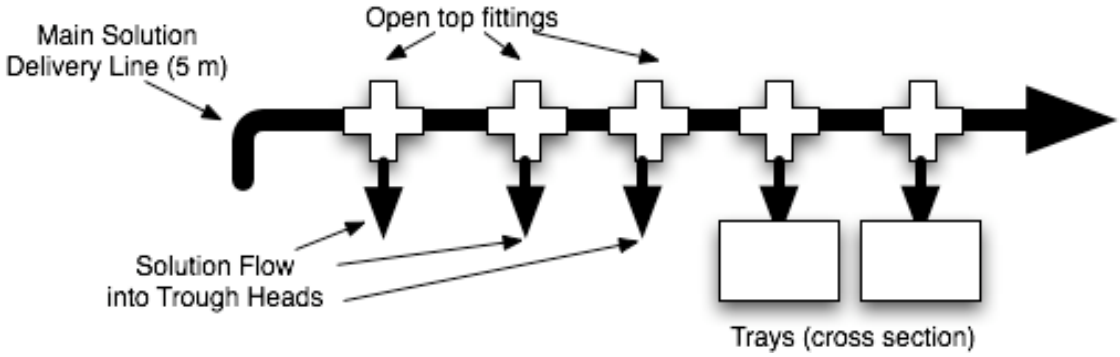


Figure 4.3-2. Representation of the water cascade approach. The main irrigation line is fitted with open topped t-fittings along its length corresponding to the distances between troughs. Solution flows through the main line and out of the bottom of the t-fittings. The top of the t-fittings are left open so that the flow rates into the troughs are regulated passively.

The troughs will be 0.20 m in width (outer edge) and will rest on a support rack with wheels (conveyer). The trays are connected on their lateral side and will be moved manually down the length of the chamber during the harvesting and seeding procedures using a winch and pulley system. The direction of tray movement on the conveyer is perpendicular to the direction of solution flow (i.e. along the long axis of the chamber). The trays may accommodate a variety of root media as a substrate for the hydroponics solution. These include Rockwool©, Lecca© (expanded clay particles), silica sand, and glass beads. Gravity assists the return of the solution to the external reservoir via a separate collecting trough (C202) which runs the length of the chamber (5 m). The individual hydroponics trays feed into this common 5 m length collection trough.

A condensed water tank (T202) is used to collect condensate from the air handling system. When the chiller is activated for chamber temperature control, atmospheric water vapour will condense on the coil and be collected in a trough positioned underneath. Gravity assists the feed of condensed water to the condensate collection tank. This condensate water may then be pumped from the collection tank into the nutrient reservoir or out of the HPC to the compartments of the MELiSSA loop requiring fresh water (i.e. crew).

Under autonomous operation compensatory nutrient addition to the hydroponics reservoir is handled by metered injections from nutrient stock containers (T205 and T206). The stock containers can contain any desired mix at concentrations usually in excess of 100x reservoir strength. An Electrical Conductivity (EC) sensor is positioned in the nutrient tank and the controller regulates the metered gravity feed of concentrated stock to the hydroponics reservoir to meet EC demand levels. Two stock reservoirs are used to

prevent precipitation of salts. Stock reservoir A contains, most commonly, calcium nitrate and reservoir B contains the balance of solution salts. Since both stock reservoirs are at the same concentration relative to the reservoir, a low EC reading will indicate the equal volume injection from both stock reservoirs. In the same way pH is measured with a pH meter positioned in the tank and is controlled by the metered gravity drain of acid or base (T203 and T204). The nutrient solution tank will have also a dissolved O_2 sensor ($A_{O2}T$ T201)

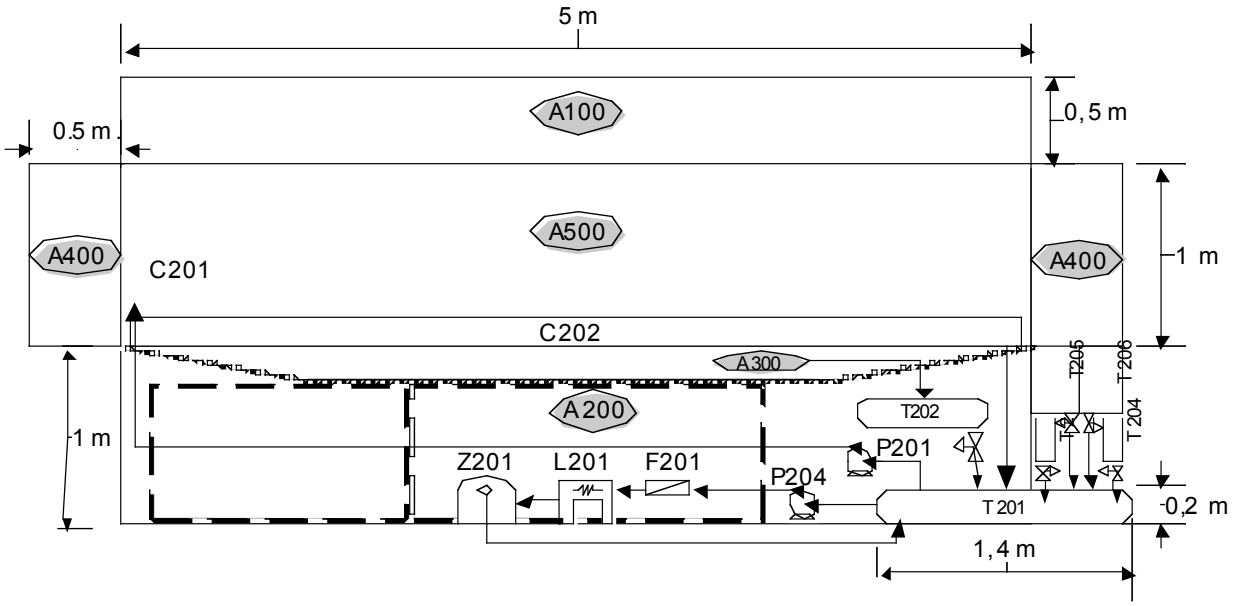


Figure 4.3-3. Representation of the HPC liquid sub-system. The growing troughs, C201, is behind C202 in this profile view. Dotted lines indicate the position of the access panels in the chamber belly.

Under autonomous operation the nutrient solution used to culture the plants will be crafted in the laboratory. The nutrient solution used by plants is similar for the three species selected and is a modified half-strength Hoagland with nitrate as the primary N source. Details on the methods of creating the nutrient solution is provided in the section dealing with typical operational scenarios below.

Under integrated operation the HPC will receive a mix of the liquid outflow from compartment III and, possibly, the effluent from the crew urine degradation. If nitrite is found in excess in the outlet flow of compartment IVa, it is possible to add it to the HPC. The control of the pH and nutrient composition of the hydroponics tank can be controlled either with this effluent, which is rich in nitrogen and minerals, or with the addition of acid, base or concentrated nutrient solution as described for the operation of the HPC in isolation, as noted above.

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

4.3.1. Hydroponics Reservoir Pump

This section provides the control loop schematics for operation of the main reservoir-to-tray irrigation pump (P2021).

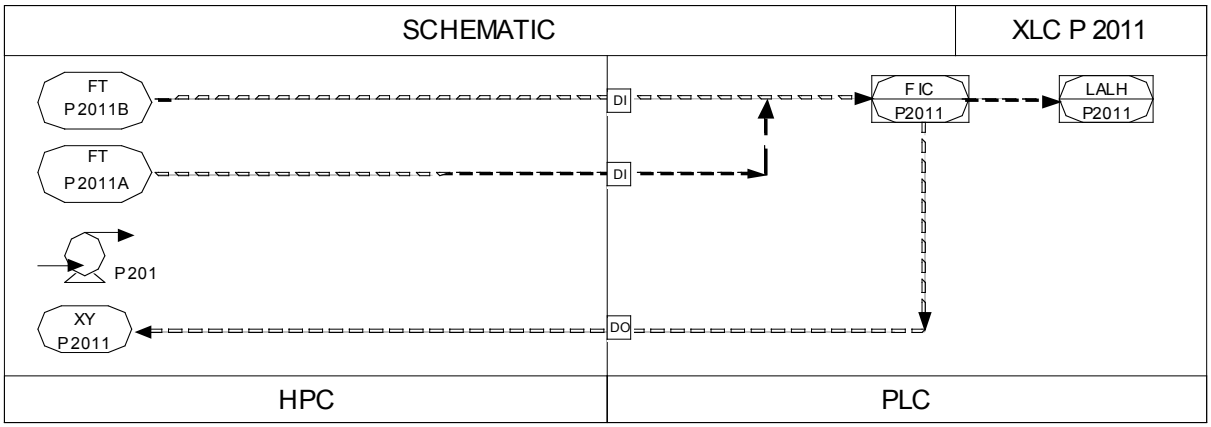


Figure 4.3-4. Control loop schematic for hydroponics plumbing and pumps (Masot, 2004)

Identification: XLC P2011

Objective: Switch on nutrient reservoir pump (P201)

Description of the Control Loop:
In the case of this control loop the main irrigation pump (P201) will be operated continuously. Two flow sensors, one (FT P2011A) located between the reservoir pump (P201) and the growing trays (C201) and another one (FT P2011B) between the collecting tray (C202) and the input to the reservoir tank will indicate a tray overflow if the difference between input and drain flows is positive. In this case the reservoir pump (P201) will be deactivate.

Equipment:

Hardware	Reference
Main Irrigation Pump	P201

Instrumentation and Signals:

Instrument	Reference	Signal
Flow sensor	FT P2011A-B	2xAI
Main Irrigation Pump Relay and Motor	XY P2011	DO

4.3.2. Control of pH in the Solution

This section describes the control loop required to achieve acceptable ranges of pH within the hydroponics solution reservoir.

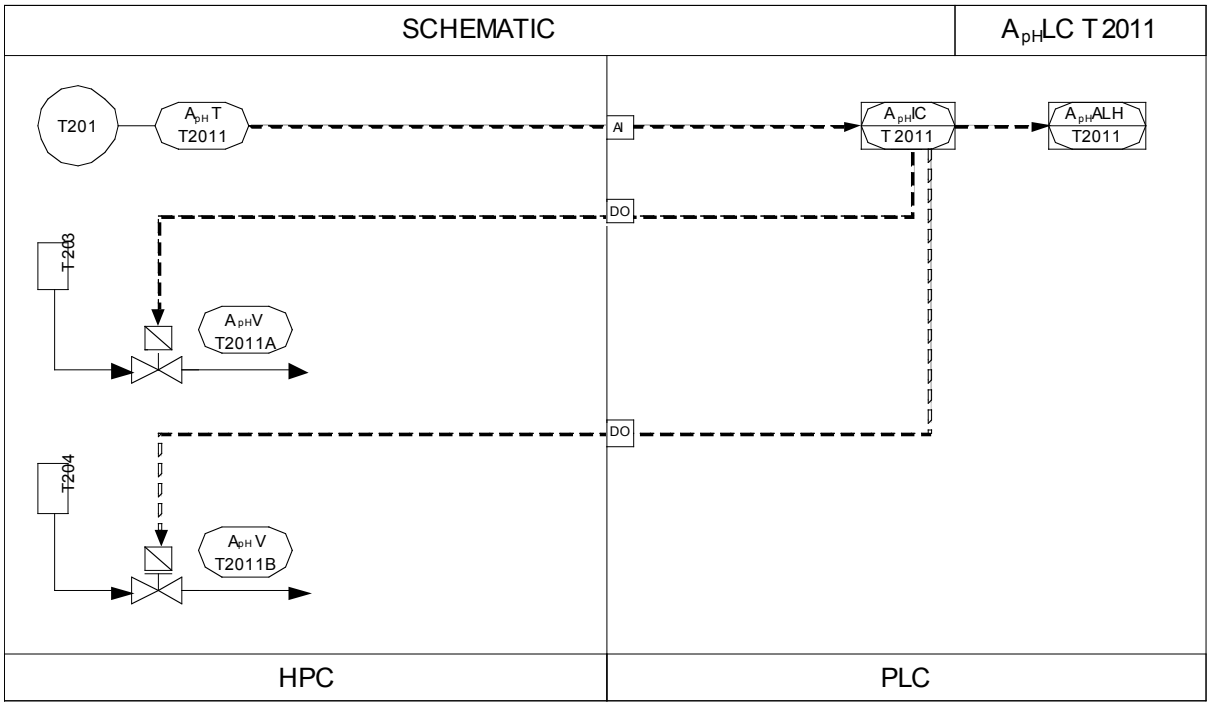


Figure 4.3-5. Control loop schematic for control of pH in the hydroponics solution (Masot, 2004)

Control Group Identifier: A_{pH} LC T2011

Objective: Control of the nutrient solution pH in the reservoir to a set point within the range of 4.5 and 6.0.

Description of the Control Loop: An in-line pH sensor (A_{pH}T T2011) measures the solution acidity and a signal is sent to the controller. When this value deviates from the set point the controller sends a signal to regulate pH. Acid and base stock solutions reside in tanks resting above the nutrient solution reservoir (T203 and T204). In the case of a

solution which is too basic, the controller directs a solenoid valve associated with the acid tank ($A_{pH}V$ T2011A) and stock acid drains (H_3PO_4) by gravity into the reservoir. Likewise, if the solution is too acid, a mass flow controller ($A_{pH}V$ T2011B) connected to a base stock tank regulates base (usually KOH) to drain into the reservoir. Gravity drives fluid flow through the valves and the controller records how much time the valve is open, in order to calculate the amount of acid or basic solution added with a previous calibration of the drain.

Equipment:

Hardware	Reference
Acid tank	T203
Base tank	T204

Instrumentation and Signals:

Instrument	Reference	Signal
pH Sensor	$A_{pH}T$ T2011	AI
Acid Stock solenoid valve	$A_{pH}V$ T2011A	DO
Base Stock solenoid valve	$A_{pH}V$ T2011B	DO

4.3.3. Control of Electrical Conductivity in the solution

The following section describes the control loop required to keep hydroponics solution levels at electrical conductivity (EC) levels that are appropriate for plant culture. The EC setpoint will depend in the solution composition/formulation used and is usually around 1900 $\mu S^{-1}m^{-1}$.

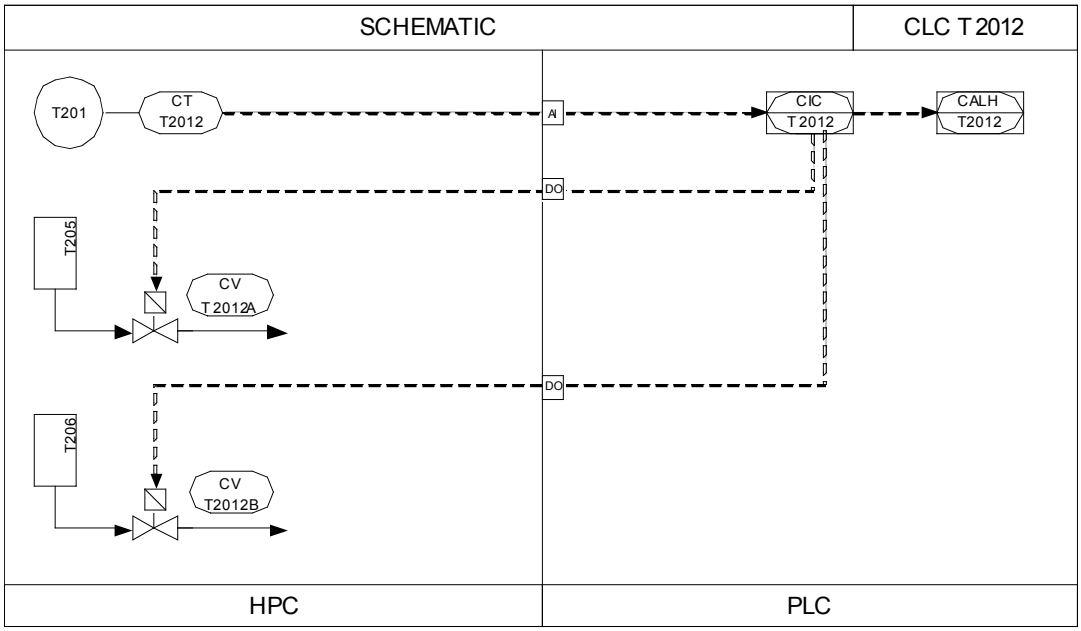


Figure 4.3-6. Control loop schematic for electrical conductivity control in the hydroponics reservoir (Masot, 2004)

Identification: C LC T2012

Objective: Control of the nutrient solution electrical conductivity within an acceptable range (1 – 2 S m^{-1}) with the injection of nutrient stock solutions into the nutrient reservoir.

Description of the Control Loop: Output of the EC sensor is used to control the solution nutrient concentration through the injection of stock solutions (A and B) when EC levels fall below demand. The injection of the stock solutions is done in proportion to each other to maintain the desired composition. If EC is outside the acceptable range an alarm is indicated. Injections of concentrated stocks from tanks T205 and T206 (A and B) is by gravity assist and is regulated by metered solenoid valves (CV T2012A-B).

Equipment:

Hardware	Reference
Stock A Tank	T205
Stock B Tank	T206

Instrumentation and Signals:

Instrument	Reference	Signal
EC Sensor	CT T2012	AI
Stock A solenoid valves	CV T2012A	DO
Stock B solenoid valves	CV T2012B	DO

4.3.4. Control of Nutrient Solution and Condensate Water Levels

This section describes the control loops necessary to mediate injections from the condensate tank into the MELiSSA loop (crew) and the feed of MELiSSA loop liquid effluent into the HPC hydroponics reservoir.

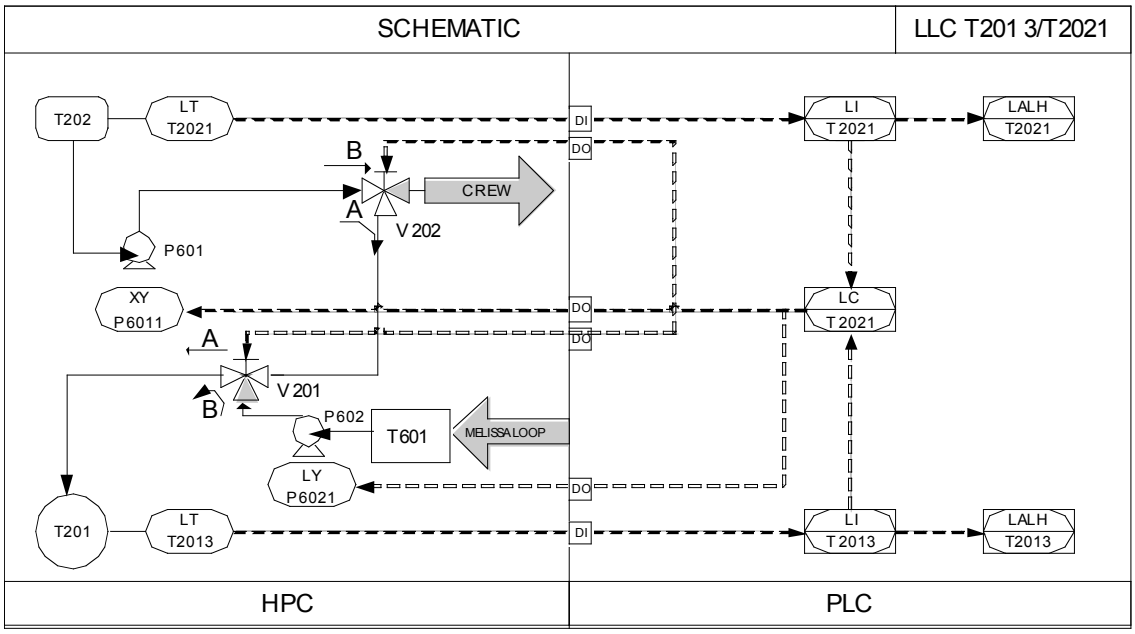


Figure 4.3-7. Control loop schematic for nutrient solution and condensate water levels (Masot, 2004).

Identification: LLC T2013, LLC T2021

Objective: Maintain the nutrient solution reservoir at volumes greater than 10% (20 L) capacity and less than 90% (180 L) capacity and condensate water volumes greater than 10% (1 L) of the condensate tank's capacity and less than 90% of the condensate tank's capacity (9 L).

Description of the Control Loop: Nutrient solution levels in the tanks are measured with float sensors positioned at 90% and 10% of the tanks' volume. The level sensor for the main hydroponics reservoir is identified as LT T2011. The level sensor for the condensate collection reservoir is identified as LT T2021.

When the chamber is operating in autonomous mode, the condensate collection tank (T202) is used as a source for water replenishment to the nutrient solution reservoir (T201). When the condensate tank volume is greater than 90% capacity or the volume of the nutrient solution reservoir is less 10% capacity (as indicated by output from sensors LT T2011 and/or LT T2021) a metering pump (P601) is activated and water is transferred to the nutrient solution reservoir (V201 and V202 in position A). The metering pump

(P601) is shut off when the volume of condensate water is less than 10% of the tank's capacity (level sensor off) or when the reservoir is at 90% capacity.

When the chamber is in connected to the pilot plant loop, water from the loop (or from the MPP de-ionized water supply) is passed to the nutrient solution reservoir using a pump designated as P602 and through valve V201 in position B. The output from the condensate tank is passed to the crew compartment using pump P601 and valve V202 in position B. When the chamber is operating in interconnected mode, the shadowed arrows are in operation as described above.

For detailed description of the liquid interfaces between the MPP and the HPC readers are directed to the section on Interface Descriptions below.

Equipment:

Hardware	Reference
Condensate pump (metering)	P602
Loop to reservoir pump (metering)	P601
3-Way Valves	V201, V202

Instrumentation and Signals:

Instrument	Reference	Signal
Level sensor for reservoir	LT T2013	DI
Level sensor for condensate	LT T2021	DI
Condensate pump relay	XY P6011	DO
Loop to reservoir pump relay	XY P6011	DO
Flow valves	V201, V202	DO

4.3.5. Ultraviolet and Ozone System for Solution Contaminant Control

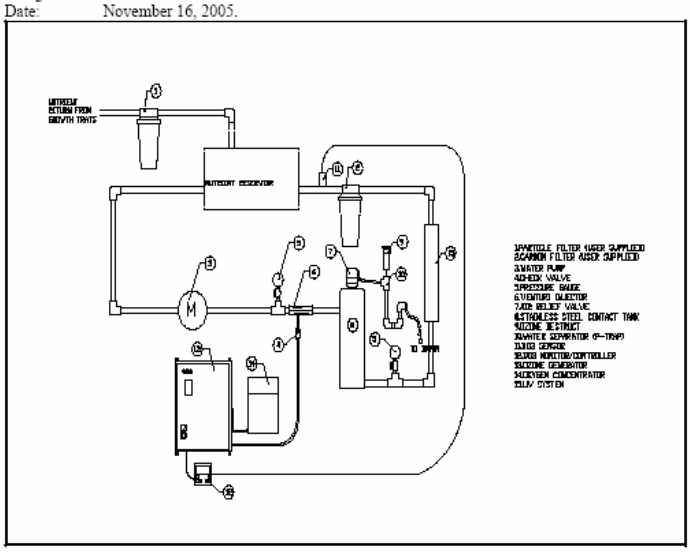
Ultraviolet radiation is to be used as a germicidal agent in the HPC prototype. The dosing of the nutrient solution with wavelengths of UV radiation between 200 – 300 nm is effective at inactivating micro-organisms by altering key metabolic enzymes and nucleic acids. Care must be taken to replace the UV lamps on a regular basis since the bulbs tend to degrade, resulting in a lowered dose. Chelating agents also tend to be susceptible to UV destruction and as such – iron, manganese, magnesium and calcium may precipitate from solution. Proper replacement of the precipitated ions and cleaning of residues on the lamp are prescribed. Additionally an ozone system will be employed on the same by-pass loop to further aid in solution disinfection. The ozone system will target residual concentrations of ozone in solution of between 0-2 mg/L. A feedback control system will be required to maintain ozone concentrations in the hydroponics reservoir at acceptable levels.

A diagrammatic representation of a preliminary design for a combination ozone and UV disinfection systems is provided in the diagram below. This design was prepared for the CESRF team at UoG by one of its current industrial research collaborators in the application of such technologies in hydroponics solution remediation (PRTI Inc.). The design includes and ozone trap to prevent the atmospheric accumulation of ozone gas. It is likely that the final design will replace the ozone monitor/controller (Part #12) with the higher level HPC controller and the water pump (Part #3) will be repositioned upstream of the UV system and directly connected to the nutrient reservoir.

Below is a diagrammatic representation of the control loop required for the UV and Ozone disinfection system.

MELiSSA (Micro-Ecological Life Support System Alternative) Higher Plant Compartment sanitation and oxygenation loop design.

Prepared for: Thomas Graham (Controlled Environment Ststems)
Design: Alternative 1
Date: November 16, 2005.



Bill of Materials – Major Components Nutrient Disinfection System
11-16-05

- **Ozone Generator (Item 13)**
- **Oxygen Concentrator (Item 14)**
- **Dissolved Ozone Monitor/Controller and Sensor (Items 11 and 12)**
- **Ozone Destruct (Item 9)**
- **P-Trap Water Separator (Item 10)**
- **Air Relief Valve (Item 7)**
- **Venturi Injector, Kynar (Item 6)**
  Model to be determined based upon output capacity of the pump, and expected pressure loss across Carbon Filter (Item 2)
- **Stainless Steel Contact Tank (Item 8)**
- **Ozone Gas Check Valve (Item 4)**

Figure 4.3-8. Preliminary design for the UV/Ozone disinfection systems to be installed on by-pass of the hydroponics system.

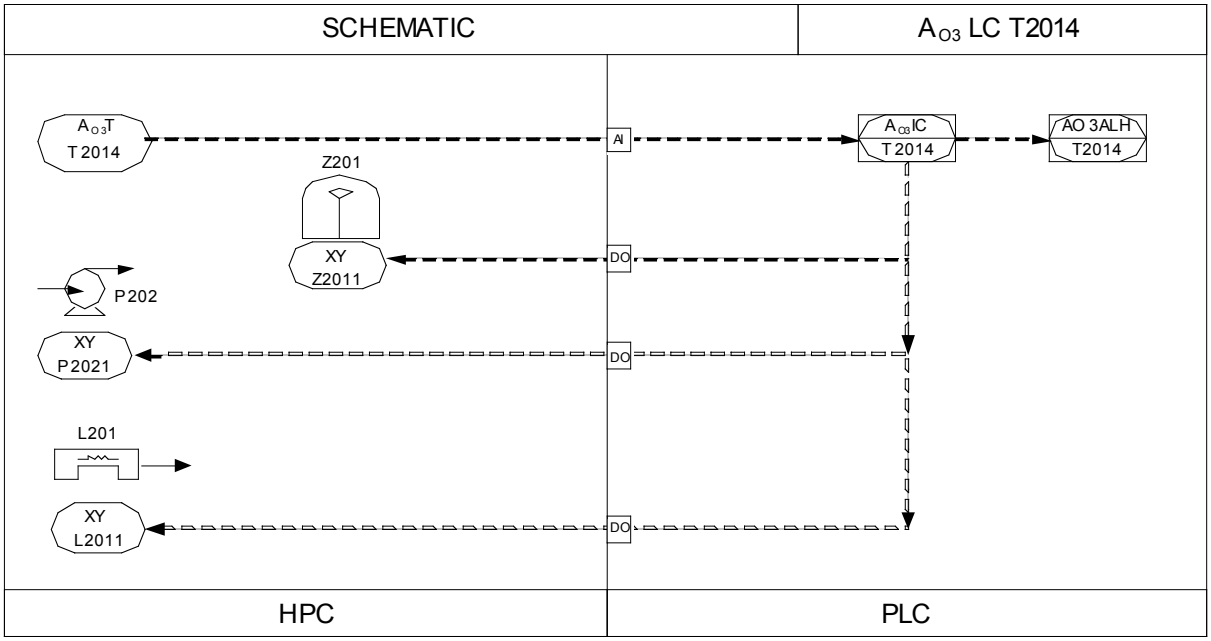


Figure 4.3-9. Control loop schematic for the ultraviolet and ozonation sterilization system.

Identification: AO_3LC T2014
Objective: Turn on sterilization loop bypass pump (P202), ozonation system (Z201) and UV lamp system (L201)
Description of the Control Loop: This is not formally a control loop but is a relay for the on/off operation of a UV situated in the nutrient pump lines.

Equipment:

Hardware	Reference
Filter	F201
UV Lamp	L201
Ozonation System	Z201
Sterilization by-pass loop pump	P202

Instrumentation and Signals:

Instrument	Reference	Signal
Ozone Sensor	A_{O3}T T2014	AI
Ozone generator relay	XY Z2011	DO
UV lamp relay	XY L2011	DO
Sterilization loop by-pass pump relay	XY P2021	DO

In the case of the control loop (A_{O3}LC T2014) for the operation of the O_3/UV sterilization system by-pass pump (P202), an ozone sensor will regulate the on/off operation of the by-pass pump and the ozone generator (Z201) if solution ozone levels in the hydroponics reservoir are low, as indicated by sensor AO_3T T201. An alarm is also indicated if ozone levels are high or low (A_{O3}ALH T2014). The controller will also turn on the UV lamp system for concurrent disinfection.

4.4. Atmospheric Control

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 should be conditioned for temperature and humidity and re-circulated inside the chamber.

In order to provide an internal air circulation of one air exchange per minute two fans with motors should be located in the sub-chamber bay (A300). The volume of the chamber considered includes 5 m^3 of growing volume and some volume of mechanical plenum (excluding airlock) leading to a required >5 m^3/min air exchange capacity.
A basic representation of the airflow direction inside the chamber is depicted in the figure below.

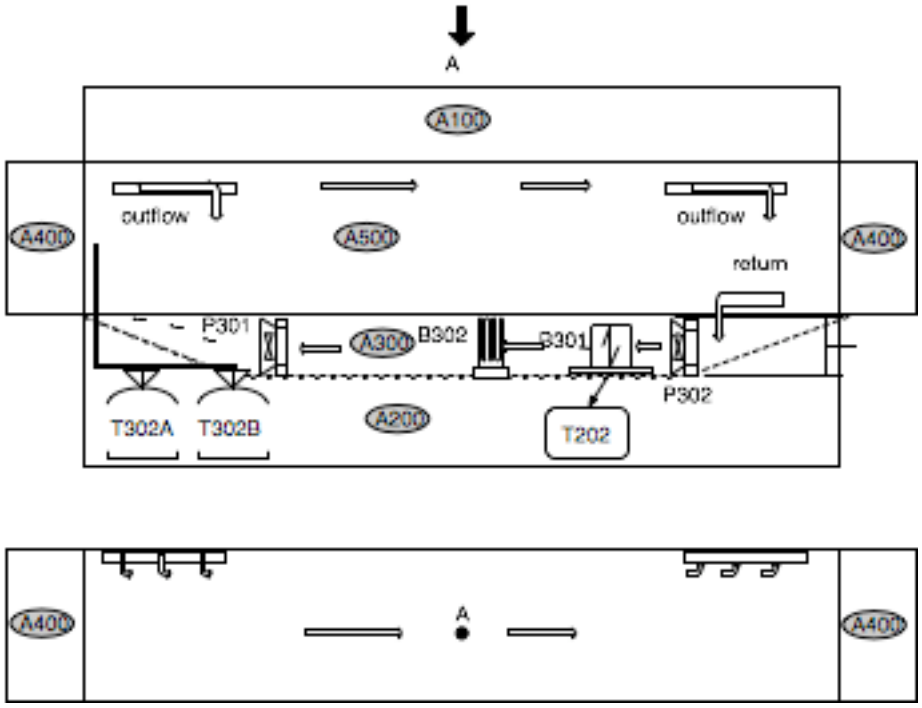


Figure 4.4-1. Air circulation patterns and handling system for the prototype chamber (Masot, 2004).

When the chamber is working in isolation/autonomous mode the air composition is regulated with injections of gases from laboratory lines. In the case of CO_2 management, compensatory injections for photosynthesis are required. All the gas lines (CO_2 O_2, N_2, air) will be interconnected directly to the air-handling area in the chamber. Mass flow controllers will be employed to regulate CO_2 levels at demand.

Air is continuously circulated throughout the chamber with the airflow depicted in the figure above. Several samples for analysis are automatically taken from different parts of the chamber. In this way the air composition (O_2, CO_2, N_2, VOCs such as ethylene and other compounds) is measured and controlled.

In the case of its operation integrated with the rest of the MELiSSA loop, air circulation inside the chamber remains the same. In the case of integrated operation however, the gas inlet originates from other MELISSA compartments (CIII, crew) instead of the laboratory gas lines. Moreover, the outlet of the HPC is sent to the aerobic compartments.

Under integrated operating conditions, two different gas handling configurations can be additionally considered. In the first case, the O_2 and CO_2 from the HPC are separated and stored independently in buffer tanks. In this way, mixing of gas compositions among compartments is minimized. This leads to a greater flexibility of atmospheric control in each compartment. In the second case, it is assumed that there is no gas separation device and so the gas line from the chamber flows directly to the consumer compartments (C-III, crew compartment) (Pérez *et al.*, 2002).

Thermal control is achieved using radiator coils mounted under the chamber. Chamber air is circulated around the radiator which is fed by laboratory hot water and chilled water supplies. In cooling the chamber, chilled water flows through the coil causing the condensation of atmospheric water vapour. The collected condensation is either returned to the hydroponics reservoir or is used by another MELiSSA compartment (i.e. potable water for crew). Humidification of the chamber is handled by injections of purified water vapour into the chamber atmosphere.

The specifications for air handling equipment was determined in consultation with Richard Elliot of Constant Temperature Control. The requirements for air handling are summarized below.

Table 4.4-1. Air Handling Equipment Requirements for the HPC

Parameter	Value
Chilled water flow rate into coil (assuming 8°C entry from MPP)	0.57 L/s
Hot water flow rate into coil (assuming x°C entry from MPP)	0.23 L/s
Hot water boiler (54 kW based on a single	18.0 kW per chamber

hot water boiler for 3 chambers total)	
Air circulation fan speed	1500 L/s

4.4.1. Control of Air circulation fans

The diagrams below represent the control loop required for turning on the two air circulation fans.

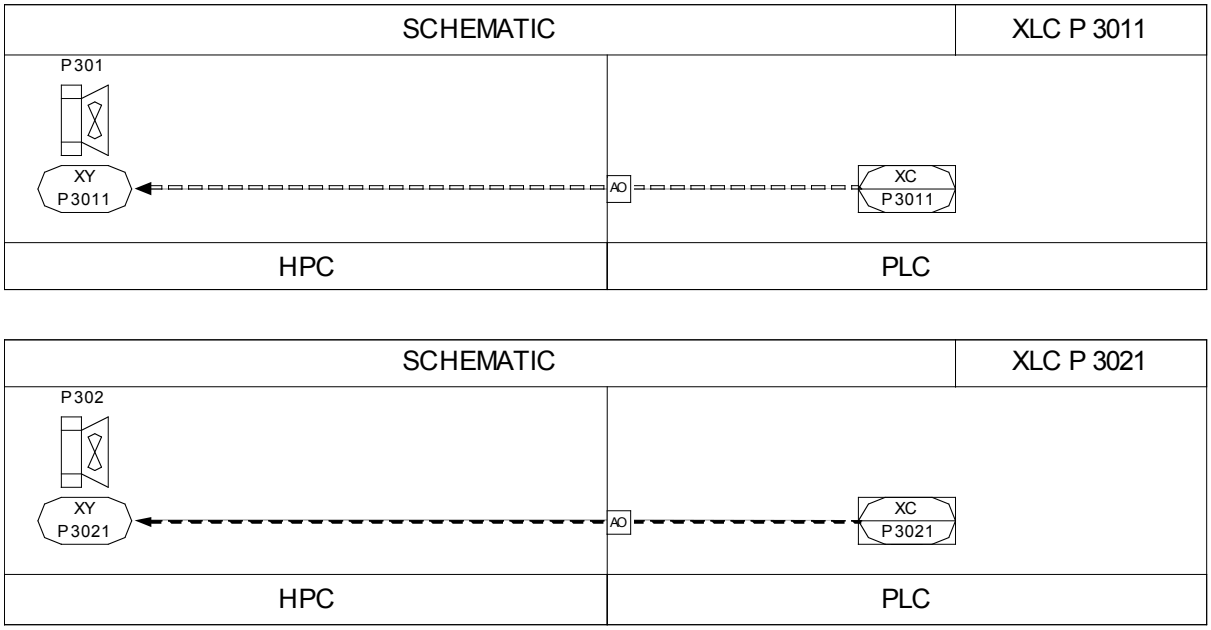


Figure 4.4-2. Control loop schematic for air circulation fans (Masot, 2004)

Identification: XLC P3011, XLC P3021

Objective: Maintain internal air circulation of the plant chamber and minimize internal gradients in atmospheric conditions

Description of the Control Loop: The internal air circulation fans are in continuous operation in the chamber and as such, no formal feedback control loop is defined.

Equipment:

Hardware	Reference
Fans	P301, P302

Instrumentation and Signals:

Instrument	Reference	Signal
Fan relays and motor	XY P3011, XY P3021	2x AO

4.4.2. Temperature and Humidity Control

The diagrams below represent the control loop required for temperature and humidity control in the chamber.

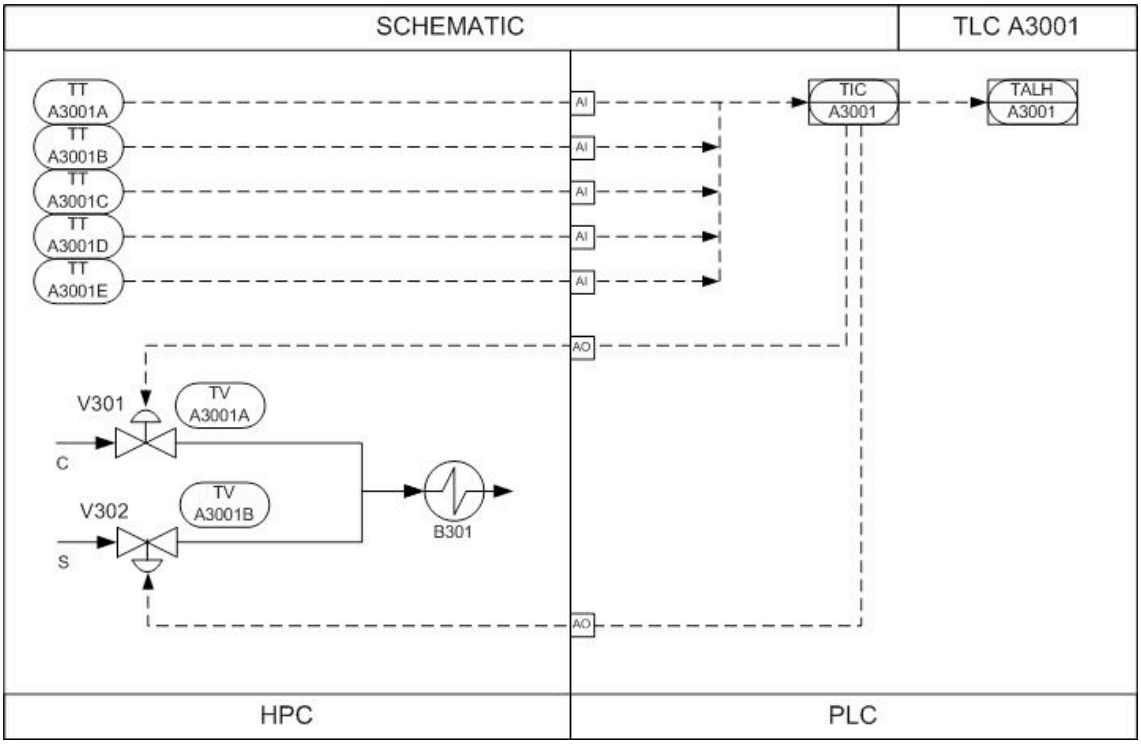


Figure 4.4-3. Control loop schematic for air temperature control (Masot, 2004)

Identification: TLC A3001

Objective: Maintain internal chamber temperature and humidity at desired set points. The set points for temperature and humidity are within the range of 10-30 °C and 50-85% RH respectively. Control may also be achieved using vapour pressure deficit (VPD).

Description of the Control Loop: Temperature control in the higher plant chambers is maintained with the use of a heat exchange coil (B301) connected to hot water and chilled water lines. Five temperature sensors positioned in the interior of the chamber growing area are used (TT A3001A-D), 3 measuring the atmosphere and 2 in the hydroponics channels . If chamber temperature is above demand set points chilled water

(c) is passed through the coil. In the event that the chamber temperature is below set points hot water (s) is passed through the coil. The entry of hot water or chilled water into the heat exchange coils is regulated by valves (V301 and V302) mounted on each line.

Equipment:

Hardware	Reference
Heat exchange coil	B301
Regulatory Valves	V301, V302
MPP supplied chilled water/hot water lines	c, s

Instrumentation and Signals:

Instrument	Reference	Signal
Temperature sensor	TT A3001A-E	5x AI

The diagram below represents the control loop for humidity control in the chamber.

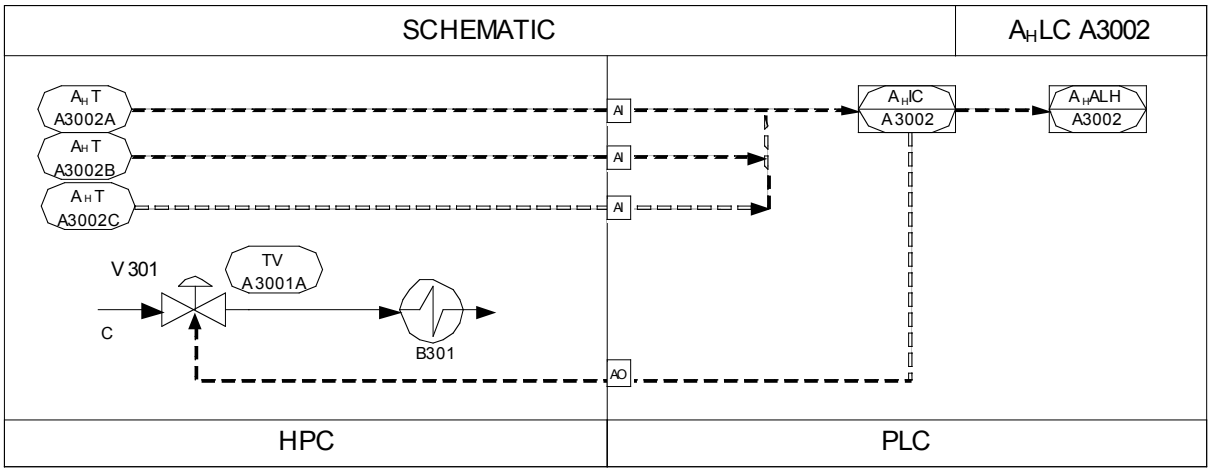


Figure 4.4-4. Representation of the control loop for chamber humidity control.

Identification: A_HLC A3002

Objective: Maintain internal chamber humidity at desired set points. The set points for humidity are within the range of 50-85% RH. Control may also be achieved using vapour pressure deficit (VPD) as the input signal.

Description of the Control Loop: Humidity control is integrated with the temperature control loop because of its dependence on temperature. Three aspirated humidity sensors are positioned throughout the interior of the chamber. Atmospheric water vapour is condensed at the heat exchange coil whenever chilled water is passed through the coil.

Instrumentation and Signals:

Instrument	Reference	Signal
Humidity sensor	A_HT A3002A-C	3x AI

4.4.3. CO_2 Control

The diagram below represents the control loop for CO_2 control within the HPC.

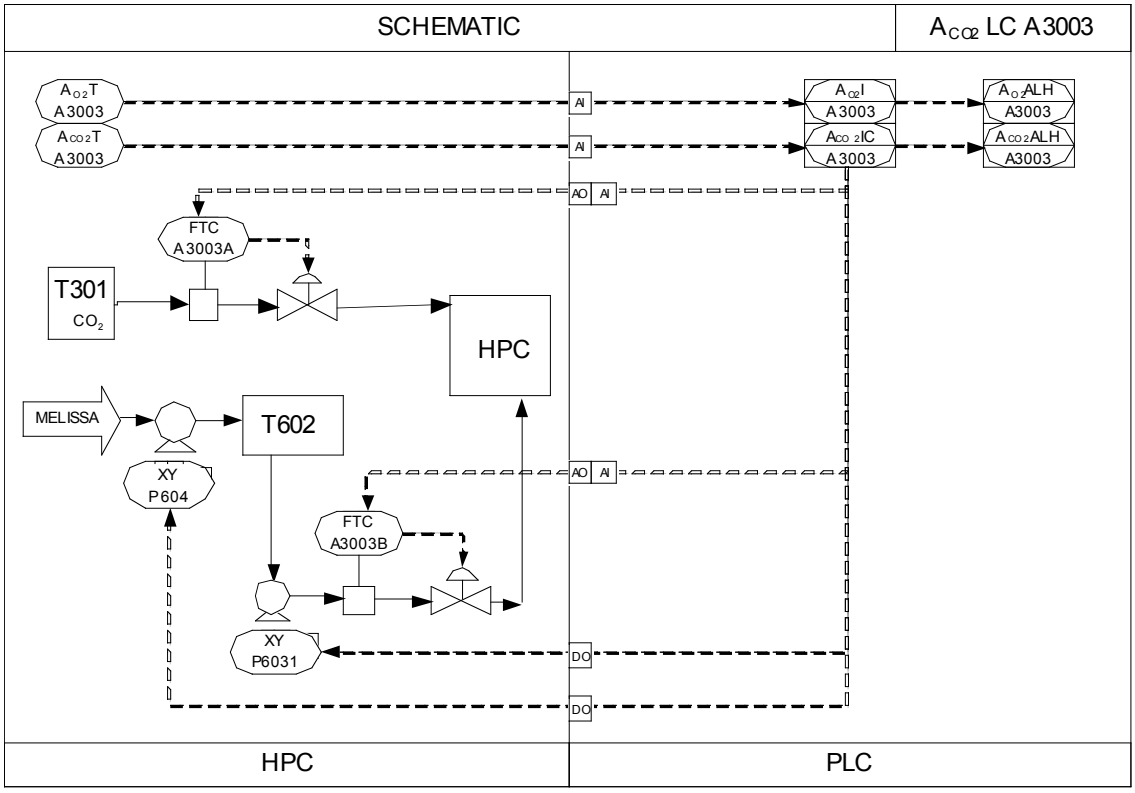


Figure 4.4-5. Control loop schematic for CO_2 levels (Masot, 2004)

Identification: A_{CO2}LC A3003

Objective: Maintain CO_2 concentration in the higher plant chamber at demand levels (typically at concentrations of 1000 μL L^{-1})

Description of the Control Loop: A CO_2 (A_{CO2}T A3003) and O_2 (A_{O2}T A3003) analyzer (Infra-red Gas Analyzer and Paramagnetic Analyzer, respectively) are used to determine the atmospheric concentrations of these gases inside the plant chamber and pass their signal to the controller. The controller, in turn, responds by opening a mass flow

controller having a programmable/controllable flow rates. The photosynthetic rate is determined from the rate of injection of CO_2 into the plant chamber during daylight hours. If the CO_2 concentration is above demand levels no action is taken since the plant canopy will remove the excess CO_2 in time during daylight. During dark hours, the CO_2 concentration in the chamber is allowed to increase due to plant respiration.

If the chamber is operating in autonomous mode, the source of the CO_2 is from a pressurized bottle and so a pump is not required on the injection line. In integrated operation the source of the CO_2 is from the MELiSSA loop via a gas mixing tank (T601) fed by a pump (P603). A second pump (P604) is required to inject CO_2 enriched air into the plant chamber from the mixing tank if it is not under pressure. Control of O_2 concentrations is not achieved in the chamber but levels are measured.

Equipment:

Hardware	Reference
Gas mixing tank	T601
Mixing tank feed pump (from MEliSSA Loop)	P603
CO_2 injection pump	P604
CO_2 Bottle	T301

Instrumentation and Signals:

Instrument	Reference	Signal
CO_2 mass flow/sensor controller	FTC A3003A	AI/AO
CO_2 mass flow sensor/controller	FTC A3003B	AI/AO
Infrared Gas Analyzer (IRGA) calibrated for CO_2	$A_{CO2}T$ A3003	AI
Paramagnetic Analyzer calibrated for O_2	$A_{O2}T$ A3003	AI
2 Pump relay	XY P603, XY P604	2xDO

4.4.4. Pressure Control

Pressure control in the chamber is passive. Expansion bladders having a total volume capacity of 200L are required. These bladders will be positioned under the chamber and will expand and contract with changing chamber volumes precipitated by programmed diurnal temperature fluctuations. The expansion bags are connected to the interior chamber volume via a manifold.

Additionally, to prevent air accumulation in the headspace of the hydroponics reservoir, associated with growing tray drainage, a pressure equilibration line must be connected to the chamber interior.

Equipment:

Hardware	Reference
2x Teflon expansion bags (0.45m diameter, 1.25 m length) Total Volume = 200 L each	T302A-B

4.5. Equipment List and Specifications

The following tables summarize the equipment requirements for the HPC. Equipment is listed by HPC area (A100-500) and wherever possible the equipment specifications are provided.

Table 4.5-1, Equipment list and specifications for the HPC

Equipment/Part	Quant.	Identification	Specifications
A100			
5 HPS Lamps 600W + 5 MH Lamps 400W	10	L101	PL 2000 with remote ballasts (Hortilux), 400V, 50Hz wired to tri-phase supply
Support frame for lamps	1	N/A	Steel support beams
Light intensity sensor (PAR)	5	$A_{IL}T$ L1011A-E	LI-190SL Quantum Sensors calibrated for artificial light
Temperature sensor	4	TT A1001A-D	Thermisters
Fans and vent	2	P101, P102	1 m^3 /s, two speed, both running at half speed
Lamp loft cover	1	N/A	Steel cover with hinges
Glass Roof	1	N/A	1 cm (0.4") thick, tempered/laminated glass (sectioned)
A200			
Hydroponics plumbing	30 m		12 mm (sub-lines), 25 mm main, OD, PP and
Hydroponics troughs, channels	30	C201	PP, 20cm wide, 1m long
Collecting/return trough	1	C202	PP 10cm wide, 5 m long
Nutrient solution reservoir	1	T201	PP, 200L
Condensate collection tank	1	T202	PP, 20L
Irrigation pump	1	P201	10 L / min
pH sensor	1	$A_{pH}T$ T2011	Mettler-Toledo
Acid stock tank	1	T203	Steel, 20L (TBD)
Acid drain solenoid valve	1	$A_{pH}V$ T2011A	Normally closed
Base stock tank	1	T204	Steel, 20L (TBD)
Base drain solenoid valve	1	$A_{pH}V$ T2011B	Normally closed
EC sensor	1	CT T2012	TBD
Nutrient Stock A Tank	1	T205	Steel, 20L (TBD)
Nutrient stock A solenoid valve	1	CV T2012A	Normally closed
Nutrient Stock B Tank	1	T206	Steel, 20L (TBD)
Nutrient stock B solenoid valve	1	CV T2012B	Normally closed

Flow sensors	2	FT P2011A-B	Propeller type
Hydroponics reservoir level sensor	1	LT T2013	TBD
Condensate reservoir level sensor	1	LT T2021	TBD
3-way solenoid valve	1	V201, V202	TBD
Ozone sensor	1	$A_{O3}T$ T2014	TBD
Ozonation System	1	Z201	TBD
UV Lamp	1	L201	TBD
Sterilization by-pass pump	1	P202	TBD
Filter solution	1	F201	TBD
Dissolved oxygen sensor	1	$A_{O2}T$ T201	TBD
A300 and A500			
Air circulation fans	2	P301, P302	1500 L / s (maximum), dampers directing flow to side plenum
Temperature Sensors	5	TT A3001A-E	Vaisala
Chilled water mixing valve	1	V301	TBD
Hot water mixing valve	1	V302	TBD
Heat/Cool radiator	2	B301, B302	TBD
Humidity sensors	3	A_HT A3002A-C	Aspirated humidity sensors, Vaisala
Infrared Gas Analyzer for CO_2	1	$A_{CO2}T$ A3003	0-3000 ppm
Paramagnetic oxygen analyzer	1	$A_{O2}T$ A3003	0-25%
Mass Flow Controller	2	FTC A3003A-B	TBD
CO_2 Supply Tank	1	T301	Calibrated CO_2 supply tank
Teflon expansion bags	2	T302A-B	200L each
Plumbing	30 m	N/A	0.63 cm (1/4") OD, steel
Tray conveyer	1	C501	TBD
Air flow vents	10	O501A-J	TBD
A400			
Air Lock	2	A401A, A401B	0.5 m x 1m x 1m, x 0.63 cm thick 316 Stainless Steel
Exterior Air Lock Door with glove box access and window	2	O401A, O401B	1m x 1m x 1m x 0.63 cm thick, 316 Stainless Steel
Interior Air Lock Door with motor	2	O402A, O402B	Rolling Door (TBD)
Air Lock Conveyer	2	C401A, C401B	TBD
Air Lock Gas Purge Tank (Nitrogen or calibrated	1	T401	Calibrated nitrogen or air gas cylinder with regulator and two way splitter

air)			
2-way solenoid valve	4	V401, V402, V403, V404	Electronic valve for gas purge servicing both air locks (split) including vent
Gas line plumbing	10 m	N/A	6 mm OD, steel
A600 – MPP Interface to HPC			
Condensate to MPP metering pump	1	P601	TBD
Intermediate solution tank – MPP to HPC	1	T601	TBD
MPP to solution reservoir metering pump	1	P602	TBD
Gas Mixing tank from MELiSSA loop	1	T602	TBD
MPP to mixing tank vacuum pump	1	P603	TBD
Mixing tank to HPC vacuum pump	1	P604	TBD

Requirements for equipment with specifications yet to be determined will be determined in collaboration with the chamber shell contractor and will form the basis of TN 85.71.

A summary of the control requirements for the HPC is provided in the table below. The control system for the MPP should be based on the Schneider PLC as is consistent with Table 2.3-1.

Table 4.5-2. Summary of control requirements for the HPC

AREA	EQUIPMENT	AI	AO	DI	DO	TOTAL
A100	L101	5			5	10
	A100	4			2	6
	Total A100	**11**			**2**	**15**
A200	T201	4		1	5	10
	T202			1	2	3
	L201				1	1
	Z201				1	1
	P201				1	1
	P202				1	1
	P203				1	1
	P204				1	1
	Total A200	**4**		**2**	**13**	**19**
A300	A300					17
	P301					1
	P302					1
	Total A300	**13**	**4**		**2**	**19**
A400	O402A,B				2	2
	Total A400				**2**	**2**

5. Chamber Interface with the MPP

The major points for the HPC are described below for the gas, solid, liquid and utility interfaces.

5.1. Liquid Interface

The liquid interface between the HPC and the MPP is in the form of collected condensate feed (T202) to MELiSSA compartments requiring fresh (potable/condensate) water. The feed of potable water is through pump P601 (metering pump).

Additionally, outflow from upstream compartments (II and III) is interfaced to the HPC from an intermediate tank. The intermediate tank will allow for metered injections of MELiSSA effluent to the HPC hydroponics reservoir. The requirements for nutrient solution amendment depend on the quality and composition of the effluent and the desired feed concentration of the hydroponics solution. Feed from the intermediate solution tank (T601) is through metering pump P602. The specifications (sizing) of this tank and pump will be determined in consultation with MELiSSA partners who have characterized the effluent composition.

5.2. Solid Interface

The solid interface between the HPC and the MPP is in the form of harvested inedible biomass leading to Compartment I and edible biomass leading externally from the MPP (to humans). No special equipment is required for this interface other than a drying oven and, perhaps, a grinder for tissue preparation.

5.3. Gas Interface

Connection of the MPP to the HPC is through an intermediate gas mixing tank (T602). This tank serves to concentrate CO2 outflow from the MELiSSA compartments and feed to the HPC. Gas out-streams from the MPP are pumped to the common interface tank (T602) through a vacuum pump (P603) and a second vacuum pump (P604) and mass flow controller from the mixing tank to the HPC (FTC A3003B). Additionally, the O2 enriched atmosphere of the HPC may feed directly to the MPP by metered injection. In the case, a flow through HPC is not envisioned (i.e.: intermediate injections from the HPC to the MPP).

5.4. Utility Interfaces

The HPC lighting system will be hardwired to tri-phasic supply of the MPP at 50Hz and 380V. All other equipment will be wired to the wall supply. Cold water and hot water lines are also required to feed the HPC directly from the MPP for temperature control through regulator valves (V301 and 302).

6. Control Law and Expected Performance of the HPC

Recent advances have been made in the use of the Thornley canopy photosynthesis model which is an extension the rectangular hyperbola model (Thornley and Johnson, 2000). In collaboration with ESA-ESTEC, the Thornley model has been coded in EcosimPro software and the predicted responses have been compared to empirical carbon exchange data collected in the SEC-2 chambers in 2004 (Ordóñez *et al.*, 2004; Favreau *et al.*, 2005). Results indicate that the Thornley model is superior to the Modified Energy Cascade Model reported upon in the cited papers. Higher plant modeling efforts for space-related applications have been limited within NASA to the Modified Energy Cascade (MEC) model by Cavazzoni (Cavazzoni, 1999). However, the predictive control strategy that has been foreseen for MELiSSA imposes additional constraints to the model. A first principles model is therefore necessary to extend the capabilities of the control law to operational points beyond the limits of historical on-the-ground research. This allows a more effective control and the development of an adequate optimization strategy.

Thornley and Johnson's work proved to be a very valuable source of information. All the aspects of the growth of plants are reviewed, giving mathematical models for photosynthesis, leaf growth, respiration, light interception, temperature effect, transport processes, root growth, and transpiration. Although not all the models proposed are based on physiology, a first principles model is proposed for photosynthesis, which is the main process driving plant growth.

6.1. Models of Gas Exchange of the HPC

The transport of CO_2 into the leaf interior is governed by the pathway conductance. Equations 8.1.1 and 8.1.2 are established considering that, at equilibrium, the diffusion rate of CO_2/O_2 into/from the leaf must be equal to the photosynthesis rate (in congruent units)

$$P_n = \frac{C_a - C_i}{r_{dc}} \qquad \textbf{Equation 6.1.1}$$

$$P_n = \frac{O_i - O_a}{r_{do}} \qquad \textbf{Equation 6.1.2}$$

Equations 8-1 and 8-2 variables have the following meaning:

P_n: Net photosynthesis rate
C_a: CO_2 concentration in the ambient air
C_i: CO_2 concentration in the leaf
r_{dc}: CO_2 diffusion coefficient from air to leaf
O_a: O_2 concentration in the ambient
O_i: O_2 concentration in the leaf
r_{do}: O_2 diffusion coefficient from leaf to air

In a simplified model of the Calvin Cycle, it is supposed that an enzyme X is activated by light. Its activated form, X*, fixes CO_2 into the carbohydrate recovering its original form. A constant dark respiration rate is assumed. Considering these three reactions as equilibrium reactions with equilibrium constants k_1, k_2 and k_3 respectively;

$$P_n = \frac{\alpha \cdot I \cdot \left(\frac{C_i}{r_x} - \frac{O_i}{r_p} \right)}{\alpha \cdot I + \frac{C_i}{r_x} + \frac{O_i}{r_p}} - R \qquad \textbf{Equation 6.1.3}$$

α, r_x, and r_p are constants derived from the equilibrium constants, the depth of the leaf (h), and the total concentration of enzyme X_0 (X_0=X+X*). This is:

$$\alpha = h \cdot k_1 \cdot X_0; \quad r_x = h \cdot k_2 \cdot X_0; \quad r_p = h \cdot k_3 \cdot X_0$$

R is the respiration rate and is treated below.

Given the respiration rate and the boundary conditions (light intensity, O_2 and CO_2 concentration in the atmosphere) equations 8.1.1, 8.1.2 and 8.1.3 allow solving the system for P_n, C_i and O_i.

The leaf photosynthesis model has to be extended to canopy level. Assuming a high planting density, the canopy can be considered as a murky medium. The light attenuation through a murky medium follows a Beer-Lambert law (exponential decay), given by equation 8.1.4.

$$I(l) = I_0 \cdot \frac{k}{1-m} \cdot e^{-k \cdot l} \qquad \textbf{Equation 6.1.4}$$

where:

I(l): Light intensity at leaf area index l
I_0: Light intensity at leaf area index 0 (top of the canopy)
l: Cumulative leaf area index
k: extinction coefficient
m: transmission coefficient

The leaf area index (l) represents the density of leaves in the canopy (measured as m^2 of leaf over m^2 of ground). It is supposed to be null at canopy height, and the sum of all the leaf areas at ground level. The light is thus attenuated while absorbed by the leaves. The extinction coefficient *k* is related to three parameters: the leaf transmission coefficient *m*, and two geometrical parameters ξ and ζ related to the leaf distribution and inclination within the canopy respectively (equation 8.1.5)

$$k = (1 - m) \cdot \xi \cdot \zeta \qquad \textbf{Equation 6.1.5}$$

The knowledge of the light distribution within the canopy allows the integration of the leaf photosynthesis to obtain the total photosynthesis in the canopy;

$$P = \int_0^l \left[\frac{\alpha \cdot I_0 \cdot e^{-k \cdot l} \cdot \left(\frac{C_{bs}}{r_x} - \frac{O_{bs}}{r_p} \right)}{\alpha \cdot I_0 \cdot e^{-k \cdot l} + \frac{C_{bs}}{r_x} + \frac{O_{bs}}{r_p}} - R \right] \cdot dl \qquad \textbf{Equation 6.1.6}$$

Although a constant dark respiration could be assumed, the reproduction of the experimental results required the introduction of a respiration model. The approach consists of separating the respiration into two components. The first component is known as “growth respiration” and it is proportional to the photosynthesis rate, while the second component is the so called “maintenance respiration”, and is proportional to the total biomass,

$$R = k_p \cdot P_n + c \cdot W \qquad \textbf{Equation 6.1.7}$$

where:

R: Respiration
P_n: Net photosynthesis rate

W: Canopy dry mass

The three sub-models presented above allow the implementation of a canopy model whose results will be compared against experimental data. Three additional parameters are needed to evaluate the leaf area growth from the net photosynthesis: the specific leaf area (m^2 leaf / g leaf), the carbon content of the plant (g C / g plant), and the percentage in weight of leaves in the plants.

$$\frac{dl}{dt} = \frac{P \cdot L_{plant} \cdot SLA}{C_{leaf}} \quad \textbf{Equation 6.1.8}$$

where:

l: Leaf area index
P: Photosynthesis rate
L_{plant}: Leaf content of the plant (% in dry weight)
SLA: Specific Leaf Area (m^2 leaf / g leaf)
C_{leaf}: Carbon content of leaf (% in dry weight)

Empirical data were used to validate the Thornley model with initial inputs of canopy density, initial leaf area, light intensity as a function of time, and the atmospheric conditions (pressure, temperature, atmosphere composition). The results of the comparison are shown in the figures below.

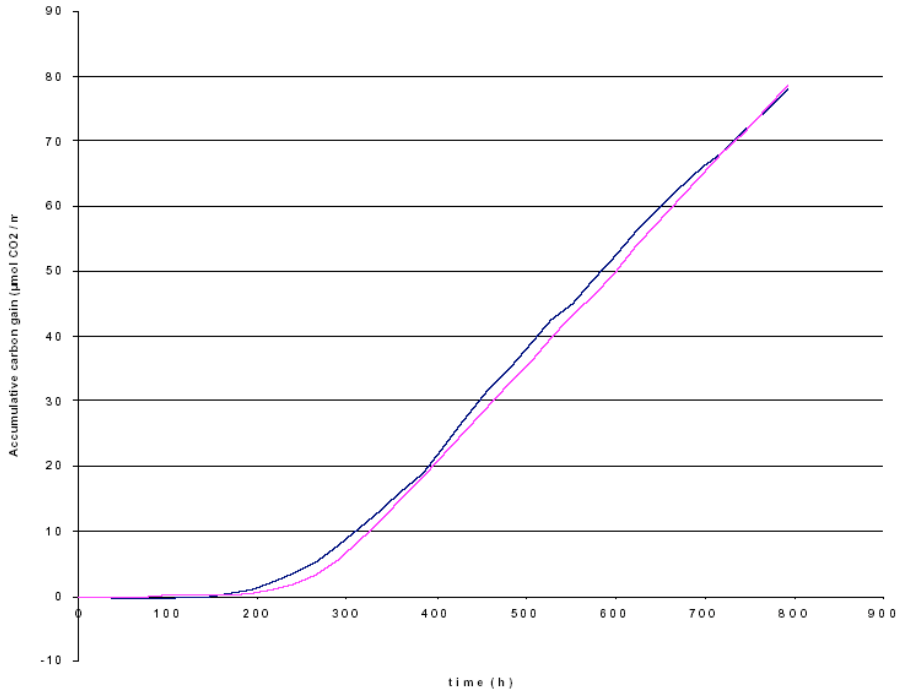


Figure 6.1-1. Comparison between lettuce experimental results (blue) and simulation results (pink) - Accumulated Carbon Gain (mol C)

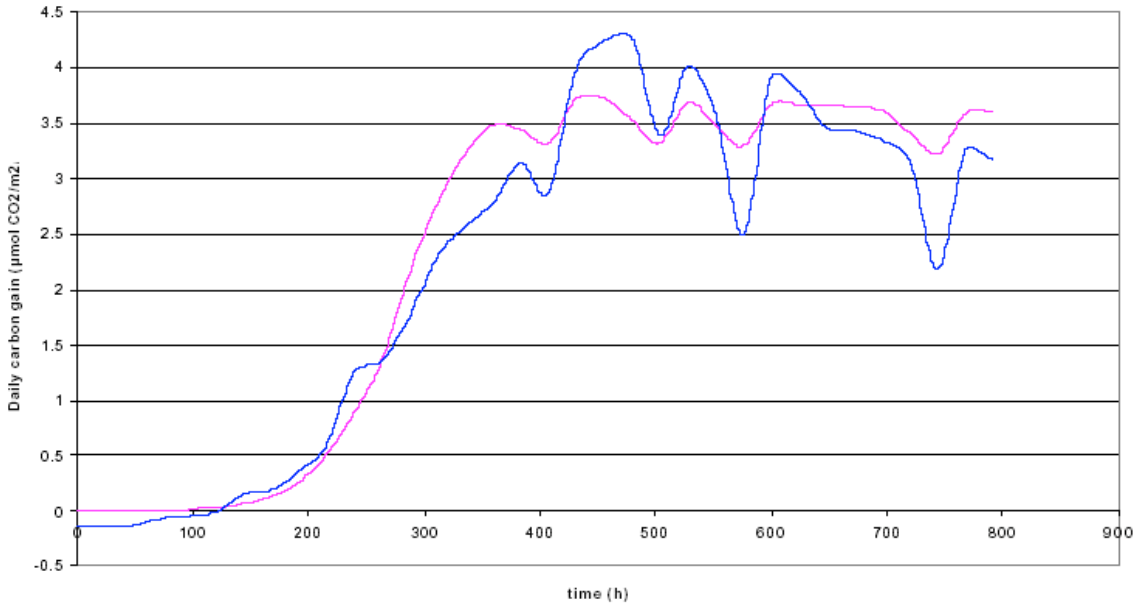


Figure 6.1-2: Comparison between lettuce experimental results (blue) and simulation results (pink) - Daily Carbon Gain (mol C / d)

The table below show the results of the tuning, giving the values for the parameters resulting from the fitting exercise.

Table 6.1-1. Lettuce model parameters

Parameter	Value	Units
C	1000	ppm
O	21	%
I_0	$7.5\ 10^{-4}$	m^2 leaf / m^2
α	$4.5\ 10^{-8}$	kg CO_2 / J
k_p	0.005	No units
c	$5.0\ 10^{-8}$	s^{-1}
k	0.9	No units
m	0.1	No units
rdc	25	s / m
SLA	225	m^2 / g
L_{plant}	95	%
C_{leaf}	40	%
rdo	50	m^2 $kgO_2/kgCO_2/g$
rp	$1.67\ 10^4$	s / m
rx	5	s / m

The model was also compared to experimental trials with beet. Results are shown in Figure 6.1-3 and Figure 6.1-4. shows the values of the parameters which resulted from fitting the beet model to experimental data. Table 6.1-2 presents estimations of model parameters for fits on beet experimental data.

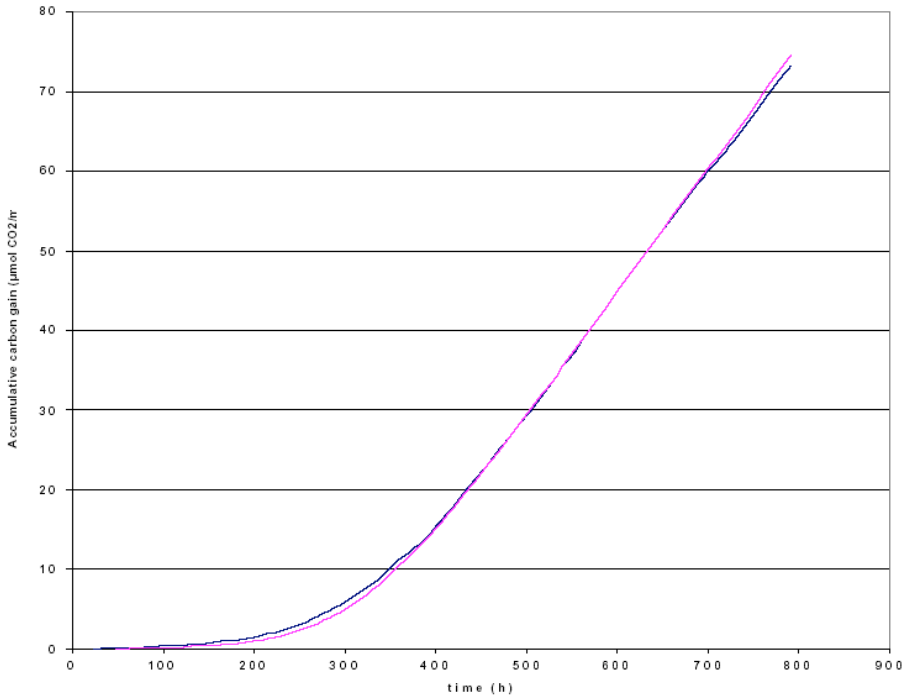


Figure 6.1-3: Comparison of beet experimental results (blue) with simulation results (pink) - Accumulated Carbon Gain (mol C)

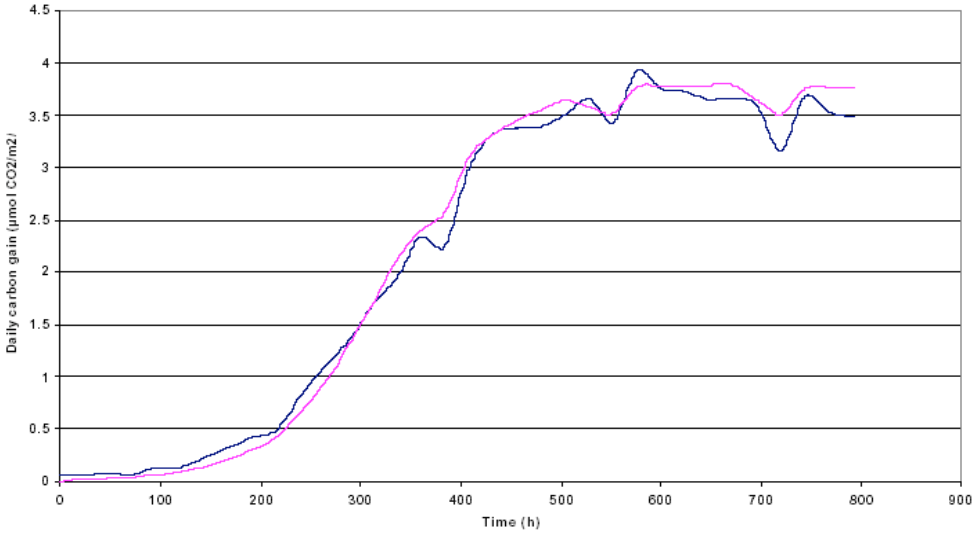


Figure 6.1-4: Comparison of beet experimental results (blue) with simulation results (pink) - Daily Carbon Gain (mol C / d)

Table 6.1-2. Beet model parameters

Parameter	Value	Units
C	1000	ppm
O	21	%
I_0	$5.0\ 10^{-3}$	m^2 leaf / m^2
α	$3.2\ 10^{-8}$	kg CO_2 / J
k_p	0.12	No units
c	$5.5\ 10^{-9}$	s^{-1}
K	0.9	No units
m	0.1	No units
rdc	24	s / m
SLA	110	m^2 / g
L_{plant}	50	%
C_{leaf}	40	%
rdo	50	m^2 $kgO_2/kgCO_2/g$
rp	$1.82\ 10^4$	s / m
rx	3.45	s / m

Despite the fact that the model implemented is at an early stage of development, preliminary results indicate a good performance as shown by the ability to reproduce independently derived experimental results. Several capabilities remain to be added to the model including i) temperature dependence, ii) carbohydrate partitioning models, iii) water uptake, and iv) the ability to simulate staged and integrated canopies.

6.2. Models of Nutrient Uptake by the HPC

Under closure of a hydroponics system it has been found that ion imbalances may result from the indiscriminate control capability afforded by conventional electrical conductivity and pH feedback sensing. Since both commercial greenhouse and advanced life support systems target closure of the hydroponics loop, compensatory nutrient addition to the crop root zone needs to be balanced by uptake. While the design team are also investigating the role of specific ion sensing technologies such as in-line HPLC and ion-specific electrodes, there is the parallel development of predictive models of nutrient uptake that can be integrated into a model and sensor driven control system. An advantage of working in sealed environments is that canopy gas exchange may be readily monitored with conventional gas analysis equipment. This gives rise to opportunity for correlating canopy photosynthetic activity with nutrient uptake. Ideally, mass dynamics in closed environment system designed for life support could be expressed as a function of a single variable, Net Carbon Exchange Rate.

The theory of steady state nutrition, as proposed by Ingestad and Agren (1988) provides a mechanism by which dynamics in nutrient uptake may be predicted from the carbon exchange of plant canopies. The theory, originally developed for aspen (populus

tremuloides), proposes that the relative growth rate (RGR) of plant stands and the relative nutrient uptake rate (RUR) of a given nutrient are equivalent. Ingestad and Agren (1988) explain that the theory of steady state nutrition holds if two conditions are met i) the relative proportions of different plant parts (tuber, roots, flowers etc.), whose mineral concentrations may differ, remains constant during the period of study and ii) the nutrient composition of each different plant part must itself remain constant or the relative proportions of the plant parts adjust to offset any mineral changes. It is very difficult to confirm adherence to steady state nutrition using mineral analysis of plant parts and tissues. First, high numbers of plants must be cultured to generate sufficient biomass for destructive growth analysis and secondly, plant parts must be harvested at regular intervals in order to assess any drift in tissue concentrations as a result of departures in steady state theory.

It can be shown that non-destructive estimations of crop RGR can be determined from NCER as follows:

$$RGR(t) = \frac{NCER(t)}{\int_{t=0}^{t} NCER(t) \cdot dt}$$ **Equation 6.2.1**

where NCER(t) is an instantaneous estimate of plant Net Carbon Exchange Rate at any age t. Ingestad and Agren's (1988) concept of steady state nutrition states that Relative Nutrient Uptake Rate (RUR) is equivalent to RGR. Under the assumption of steady state nutrition, the ion uptake rate, $U\tilde{\eta}(t)$ may be estimated by non-destructive means as follows:

$$U\eta(t) = \frac{NCER(t)}{\int_{t=0}^{t} NCER(t) \cdot dt} \cdot \int_{t=0}^{t} U\eta(t) \cdot dt$$ **Equation 6.2.2**

where $U\tilde{\eta}(t)$ is the instantaneous uptake rate of any ion,$\tilde{\eta}$, at time t.

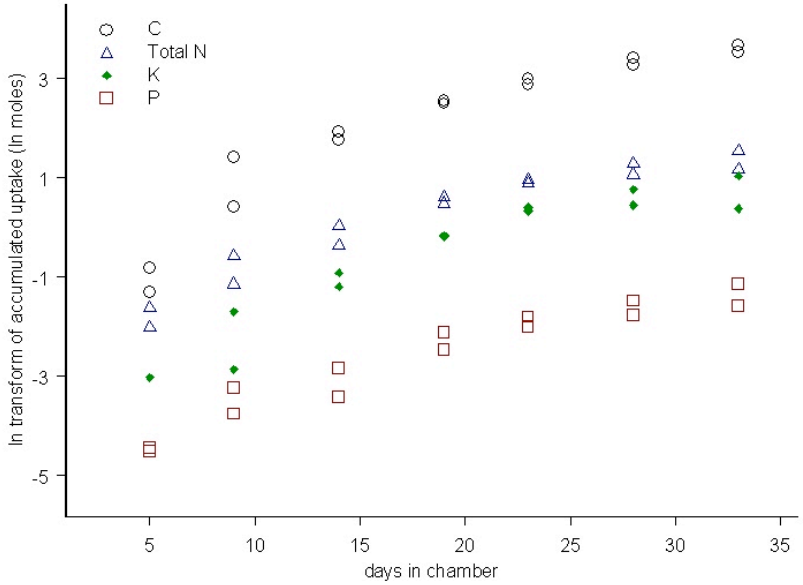


Figure 6.2-1. Patterns of the ln transform of nutrient uptake for beet canopies grown in a sealed environment chamber.

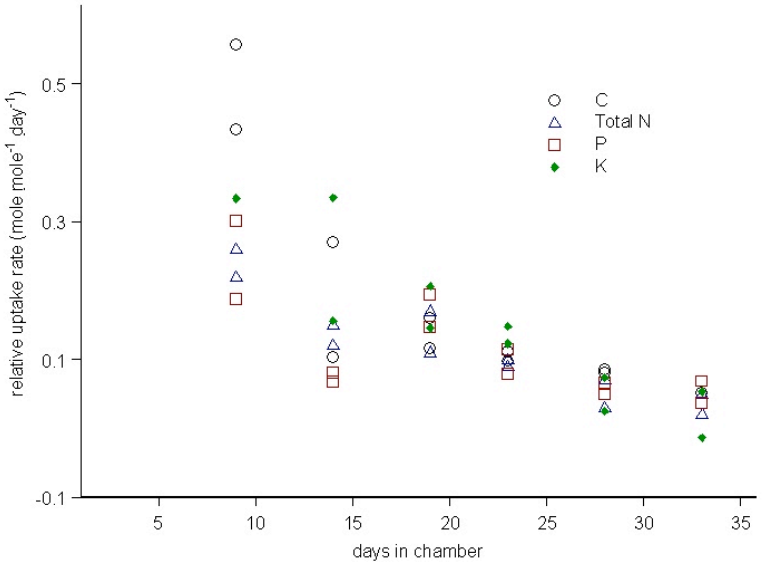


Figure 6.2-2. Relative nutrient and carbon uptake for beet canopies grown in a closed environment

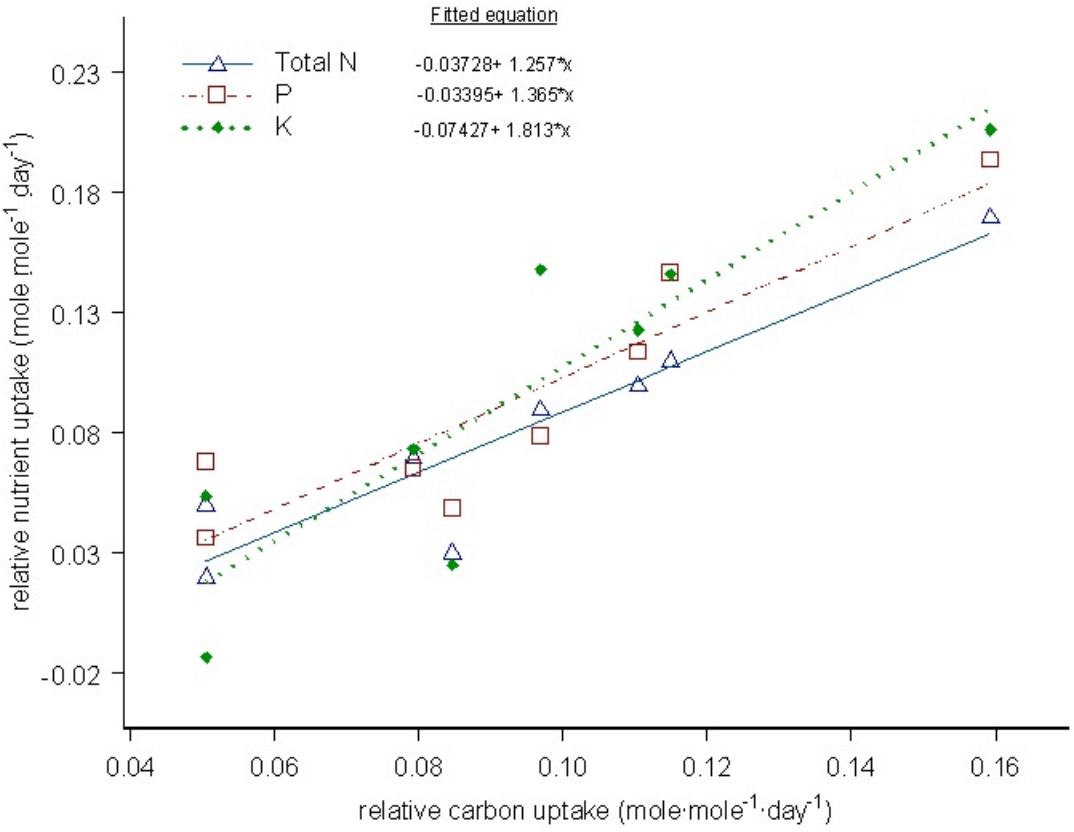


Figure 6.2-3. Reltaionships between relative nutrient uptake rate and relative carbon uptake rate derived from NCER analysis.

Preliminary analysis of the data presented above indicates that congruence between the stand RGR and RUR as postulated in may hold. While there exists for each experiment conducted in 2004 nutrient uptake and gas exchange data much of them remain to be analyzed. Work on the application of steady state nutrition to model driven control of hydroponics solution will continue using NCER as the main predictor and by linking the canopy photosynthesis models described above to ion uptake dynamics.

7. Other Design Considerations

In addition to the structural and control loop requirements of the chamber noted above the following considerations should also be made.

7.1. Aesthetics

The chamber should have an exterior colour of ESA blue. All internal parts should be constructed of inert materials. Air locks and glove boxes shall be constructed of tempered glass. Appropriate electrical and plumbing tracking should be used.

7.2. Transportation and HPC construction on Site

No single dimension of chamber should components should exceed the Pilot Plant Site loading dock clearance. It is proposed that the HPC be constructed, initially at the CESRF inside a shipping container in order to facilitate easy transfer to the Pilot Plant Facility. Once at UAB, the prototype may be disassembled in place.

7.3. Labour Requirement

The current chamber design relies on labour for staged culture management, planting and harvesting. No mechanized systems are proposed to be included in the initial prototype.

7.4. Future Cropping Systems

The chamber has been design to accommodate, with a sample change out of the hydroponics system, additional cropping systems such as Deep Water or Aeroponics. Additionally, sufficient room has been allotted for a change of crop type.

8. Anticipated Chamber Operational Procedures

8.1. Objectives in Chamber Use

The purpose of experiments conducted with the HPC prototype operating in autonomous mode may include the continued empirical validation of mechanistic models predicting Net Carbon Exchange Rate (NCER) in staged cultures, the analysis of environmental conditions impacts on tissue mineral, proximate and fibre contents. The dynamics in evapo-transpiration, and nutrient uptake may also be quantified from analysis of the hydroponics solution. The chamber may be used in integrated mode for the analysis of mass exchange dynamics at the water and gas interfaces with the MPP. These studies might include the determination of CO_2, O_2 and nitrogen exchange. The chamber also provides an avenue to investigate the logistical aspects of crop production and operation of the chamber in integrated fashion.

The typical operation and maintenance procedures described below are for the chamber's operation in autonomous mode. Many of the methods will be common under operation in integrated mode but special attention to management of the interfaces needs to yet be determined. This task will be completed when more information is known about the outflow of the MELiSSA compartments downstream of the HPC.

The methods described below are similar in operation to the SEC and hypobaric chambers at the CESRF.

8.2. Operational Length

The study periods for staged culture within the CESRF chambers have lasted as long as 160 days in the chamber for beet (CESRF-GW1204) and 80 days in the chamber for lettuce (CESRF-GW0106). It is important to note that UoG-CESRF studies conducted within the CESRF chambers to date have been with periodic hydroponics solution dump and replacement. We believed that this would more closely approximate 'ideal' nutrient composition under the conditions of specific ion control since re-circulating systems controlled through EC/pH sensing result in the disproportionate supply of some ions to the crop root zone. Additionally, the CESRF chambers had to be opened to facilitate staged culture.

Given the design provision for end air-locks, the prototype may accommodate staged culture under sealed atmospheric conditions for durations even longer than those completed within CESRF. However, particular attention must be paid to the potential for micro-organism proliferation in re-circulating hydroponics solutions. The chamber therefore includes an ozone/UV disinfection system which may help to control populations and extend the functional life of the closed trial.

8.3. Chamber Operating Procedures

8.3.1.Chamber Start-Up and Functional Verification

Chamber start-up begins with a functional test of the chamber components by sub-system using. A test profile of demand conditions in the chamber may be created in the control system to verify correct functioning of the atmospheric control system and parts. A typical test profile would cycle the chamber through a range of set-points throughout a 24 hr period. An example of such a profile is outlined below.

Table 8.3-1. Typical demand set-points for HPC operation verification tests.

Parameter	Demand Set-Point	Part Verification
Temperature	30 to 10 °C (5 °C intervals)	Chiller/hot water valves, radiator/air circulation efficacy, temperature sensor functioning
Lighting	0, 25, 50, 75 and 100% of full intensity	Lamp/ballast operation, attenuation capability, light sensor function
Humidity	60%, 75%, 90%	Humidification valves, condenser efficacy
CO_2	1000 ppm	Mass flow controller operation, IRGA, leakage assessment
O_2	21%	Mass flow controller operation, O_2 analyzer, leakage assessment

Following activation of the air circulation fans in both A100 and A500 and the air handling monitoring, control and handling system operation the hydroponics system components may be verified including the calibration of the stock/acid/base feed lines and valves.

8.3.2. Leakage Test

Following equipment start verification a 48 hour leak test should be completed using CO_2 as a marker gas. The chamber should be operated at the temperature and humidity conditions of the pending experiment (new test profile) but the CO_2 demand should be set to 1500 ppm. The CO_2 injection systems should remain on during equilibration and once

demand levels are reached shut-off. The leakage rate may de determined from the slope of the decay profile in CO_2 over time bracketing the intended CO_2 concentration for the experiment. The leakage rate is used as a correction term in the calculation of net carbon exchange rate.

8.3.3. Solution Preparation

The chamber design allows for the use of a common nutrient solution (single reservoir) feeding all age classes of the crop in staged culture. Studies using the nutrient solution formulation tabled below have been successfully used in staged culture of beet and lettuce with periodic solution dumping. Alternate formulations may indicated depending on the crop and objectives of the study.

Table 8.3-2. Typical hydroponics nutrient solution used in HPC studies.

Component	Mol. Wt. (g)	Feed Strength (mM)
Stock A		
$Ca(NO_3)_2 \cdot 4H_2O$	236.16	3.62
Stock B		
$MgSO_4 \cdot 7H_2O$	246.48	1
KNO_3	101.1	5
$NH_4H_2PO_4$	115.08	1.5
$(NH_4)_2SO_4$	132	1
Micronutrients		
$FeCl_3$ (DTPA)	162.20	0.025
H_3BO_4	61.83	0.02
$MnSO_4 \cdot H_2O$	169.01	0.005
$ZnSO_4 \cdot 7H_2O$	289.54	0.0035
$CuSO_4 \cdot 5H_2O$	249.68	0.0008
H_2MoO_4 (85%MoO3)	161.97	0.0005

The feed strength (hydroponics reservoir concentration) is provided in concentrated forms through tanks A and B. Calcium nitrate (Stock A) is separated from the remaining components in Stock B to prevent precipitation. The EC level of freshly made solution is used to define the demand levels for control. Solution composition may be maintained with metered injections from stock reservoirs at concentrations ranging from 100 to 250x those of the feed. Appropriate measures to prevent precipitation of chelated metals may be necessary in the presence of an operating UV system since chelating agents are susceptible to destruction with UV irradiation.

The initial (fresh) solution may be crafted with reagent or greenhouse grade fertilizer salts with appropriate off-line composition analysis. It should be crafted at feed strength in a 200 L tank and then pumped into the reservoir.

8.3.4. Germination, Emergence, Thinning, Planting and Harvesting

Seeds are generally subjected to a period of vernalization at cool (4°C) temperatures and high humidity in a paper lined Petri dish for a period of 48 to 72 hrs. Seeds are transferred to Rockwool cubes or flats thoroughly rinsed with distilled water and placed under cover beneath a suitable lighting source. The seeds are watered regularly (daily) with water and diluted feed stock solution. After emergence, plants are thinned from the Rockwool to the desired planting number and the covers, used to promote high humidity, are removed. Rockwool and trays for germination may be readily obtained from local suppliers. For the purposes of creating a germination area within the MPP an HPS or fluorescent lamp suspended over the seedlings at growing room temperature (20-25°C) will usually suffice. Plants are transferred to the chamber for inclusion in the staged culture after a period of 20 days, or after there has been sufficient root exposure and true leaf emergence. Following true leaf emergence, the seedlings are moved into the chamber.

The transplantation of the seeds in the chamber may be done as follows:

- Ensure interior air lock door seal at the harvesting end of the chamber
- Activate relays for opening the exterior air lock door
- Place up to two growing troughs with seedlings placed at the proper density into the air lock, with the tray and chamber long dimensions perpendicular to each other
- Slide the troughs onto the air lock conveyer
- Close the exterior air lock door and ensure seal
- Purge the air lock volume with nitrogen gas or a calibrated air stream by activating a solenoid valve connected to the gas tank regulator
- Open the interior air lock door
- Using the air-lock glove box, fasten the newly introduced troughs to those already on the conveyer
- Open the harvest air lock interior door
- Using the winch and pulley system, move the connected troughs along the conveyer into the harvest air lock (2 troughs at a time)
- Using the glove box of the harvest air lock, disconnect the harvested troughs from the conveyer line
- Close the interior door of the harvesting air lock and ensure seal
- Open the exterior door of the harvesting air lock and remove troughs and plants
- Prepare plants for tissue analysis (part separation, leaf area, drying and grinding)

8.3.5. Management of the Staged Cultures

The maintenance of a staged culture requires the regular seeding, thinning and harvesting of the crop. Typically, a ten day staged planting interval is used. For a crop with a grow-out period of 60 days, a total of 7 seed groups will be actively growing, including the dishes for vernalization. In the diagram below, seed groups 4 through 1 would be resident in the chamber and seeds groups 5 and 6 remain in the germination area. Seed group identification should be the ordinal of its date of germination, as is in the diagram below.

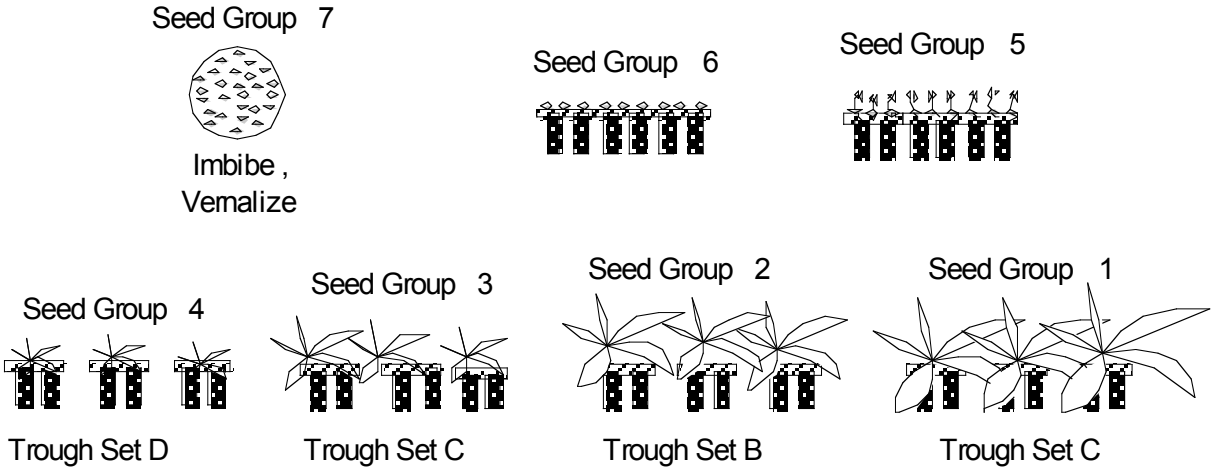


Figure 8.3-1. Profile diagram of seed groups and trough sets used in the staged planting trials as would be achieved on Day 60 of a staged culture experiment.

8.3.6. Analysis of Net Carbon Exchange Rate

The computer controller of the SEC-2 chambers maintains CO_2 concentrations at demand levels during day-light hours through the automated injection of CO_2 from a bottle store and a mass flow controller. Output from the mass flow controller/meter are used to estimate net carbon gain of the developing crop stands using a compensation technique. The computer controller maintained internal chamber CO_2 concentrations during the daylight hours so that any net carbon gain by the stand through photosynthetic activity was compensated for by injections from the gas external tank. The volume and duration of CO_2 injections were used to estimate day-time NCER. During the dark period it was not possible to remove CO_2 from the chamber to achieve static conditions, and as such, the difference in observed CO_2 and demand concentrations was used to calculate dark period respiration (negative NCER). The sum of these signed NCER estimates over a 24 hour period (in moles C), yielded daily carbon gain (DCG).

9. Maintenance Plan

9.1. Chamber Cleaning

Prior to the start of a study, the chamber growing troughs, side walls and drains should be cleaned. Ozonated water or a dilute (1%) bleach solution may be used. The major tasks are outlined below.

- Wipe interior surface parts with the cleaning solution.
- Pump cleaning solution should be pumped through the hydroponics system for at least 3 hours. The hydroponics system may then be rinsed with fresh water. The 200 L PP tank may be used for this purpose.
- The condensate collection and nutrient and acid/base stock reservoirs should be autoclaved prior to experiment start.

9.2. Regular Chamber Maintenance Procedures

Prior to the start of any production trial a chamber start-up procedures detailed above shall be performed. This includes the running of;

- Functional verification of major parts (lights, pumps and conveyer)
- Control system test with a test-profile (see Table 8.3-1)
- Chamber leakage test
- Visual inspection of chamber components (corrosion, tightness of fittings, evidence of leakage points

The infrared gas analyzer for CO_2 and the paramagnetic analyzer for O_2 should be calibrated bi-weekly. Calibration is generally done using a zero gas (nitrogen) and a span gas (usually 2500 ppm CO_2, certified). The oxygen sensor calibration may be conducted using a zero (nitrogen) and span gas (30% O_2, certified). An automated calibration system should be built into the control system.

The EC sensor and may be calibrated using three points. Serially diluted hydroponics stocks will suffice. The pH sensor should be calibrated using three points using buffers having a pH of 3, 7 and 9. Calibration may be completed once at the start of a study. Humidity and temperature sensors will generally require only occasional calibration. Light intensity sensors should be returned to the manufacturer for calibration.

The flow rates of acid, base and stock solutions into the reservoir using the gravity drain approach should be quantified and calibrated so as to derive a conversion between valve opening time and the volume of flow from the stocks into the reservoir. Since the head pressure will influence the drain rate from these stock reservoirs, the calibration of flow

rate shall be conducted over a range of reservoir volumes. Check must be made so as to ensure stock/acid/base volumes in their respective tanks are at acceptable supply levels.

9.3. Equipment Warranty

Extended warranties will be solicited from manufacturers for parts costing more than $5000 CDN or those part of the chamber shell.

Table 9.3-1. Equipment planned to be included in chamber warranty

Chamber Shell Components [1.]		
Equipment/Part	Quantity	Identification
Fan and vent	1	P101
Lamp loft cover	1	N/A
Glass Roof	1	N/A
Hydroponics troughs, channels	30	C201
Collecting/return trough	1	C202
Nutrient solution reservoir	1	T201
Tray conveyer	1	C501
Air circulation fans	2	P301, P302
Air flow vents	10	O501A-J
Air Lock	2	A401A, A401B
Exterior Air Lock Door with glove box access and window	2	O401A, O401B
Interior Air Lock Door with motor	2	O402A, O402B
Air Lock Conveyer	2	C401A, C401B
Analytical Equipment [2.]		
Equipment/Part	Quantity	Identification
Ozonation System	1	Z201
UV Lamp	1	L201
Infrared Gas Analyzer for CO_2	1	$A_{CO2}T$ A3003
Paramagnetic oxygen analyzer	1	$A_{O2}T$ A3003

[1.] Maximum attainable warranty of chamber shell components shall not comprise more than 5% of total chamber shell cost

[2.] Maximum attainable warranty on Analytical equipment shall not comprise more than 5% of their component costs.

10. Logistics Plan

10.1. Chamber Construction Sequence

The proposed sequence of chamber construction is as follows:

1. Finalize air handling unit design and specification in consultation with local sub-contractor (Constant Temperature Control). This process includes;
    a. Determination of air flow requirements
    b. Placement of radiator, condensate collection troughs, fans and vents within chamber plenum, temperature and RH sensors
    c. Sizing of the radiator and air circulation fans
    d. Calculation of the chilled and hot water flow rates into the radiator
    e. Calculation of the MPP hot water tank sizing requirement
    f. Assessment of the predicted temperature homogeneity within the chamber
2. Ordering of minor chamber parts
3. Design and construction of HPC prototype shell with cub-contractor including set-up of a contract for further design and provision of:
    a. Air handling equipment
    b. Air-locks and end wall glove boxes
    c. Tray conveyers
    d. Detailed 3-dimensional and shop drawings
4. Functional verification of parts on arrival
5. Integration of chamber parts
6. Functional verification of the chamber

Details on the proposed chamber test plan are provided in the section below.

10.2. Chamber Transport to the MPP

Transport of the prototype chamber will be within a standard shipping container. Once on the UAB site the chamber will enter the MPP facility through courtyard glass doors. The chamber will require re-assembly of the lighting loft and cover, and the air locks at the MPP site. Other functional equipment should arrive at the MPP assembled/fixed to the camber. Connection of sensors and power supplies will be required upon arrival on at the MPP followed by a functional verification of the prototype in accordance with the details to be presented in TN 85.10.

11. Prototype Test Plan at the CESRF and MPP

Following functional verification of each chamber part, the following steps will be taken to ensure chamber compliance.

1. **Determination of Control Capability.** Following chamber assembly and functional verification of the plant parts, the control system performance will be tested using the test-profile described in Table 8.3-1.
2. **Determination of Chamber Leakage.** It is envisioned that a series of three chamber leakage tests be performed initially with a leakage test during all subsequent experiment start-ups. This leakage test will be in accordance with that described in Section 8.3.2.
3. **Performance of the Chamber in Batch Culture of Lettuce.** Following the successful results of the chamber leakage tests a batch culture of lettuce will be conducted for a period of 40 days. The batch test will be used to validate the dynamics in NCER as predicted by the Thornely model and ensure proper chamber operation (set-point maintenance).
4. **Performance of the Chamber in Staged Culture with Lettuce.** Following the successful results of the chamber leakage tests and the batch culture of lettuce, a stage lettuce production trial will be conducted for a period of 60 days. The staged test will be used to validate the dynamics in NCER as predicted by the Thornely model and ensure proper chamber operation (set-point maintenance) with particular emphasis on the tray conveyer system and air-locks.

Following these tests, which will be performed in accordance with the typical chamber operation strategies outlined in Section 8, the chamber will be readied for shipment to the MPP.

Following arrival at the MPP the chamber will subjected to test procedures similar to those outlined above. The details of this test-plan will be provided in TN 85.10.

12. References

De Chambure D. Test report of respiratory activity of rats fed on Spirulina enriched diets; 1992; ESA-TEST Report YCV/93.2DDC.if.

Dixon M.A.; Grodzinski B.; Cote R., and Stasiak M. Sealed environment chamber for canopy light interception and trace hydrocarbon analyses. Advances in Space Research. 1997; 24(3):271-280.

Favier-Teodorescu L.; Pons A., and Poughon L. Stoichiometric analysis of *R. rubrum* growth on different carbon substrates. MELiSSA Technical Note 45.4. 1999; ESA/ESTEC/Contract 13323/98/NL/MV.

Favreau M., Rodriguez A., Ordóñez L., Waters G.C.R., 2005. *Application of the Non-Rectangular Hyperbola Model to Lettuce and Beet Crop,* Society of Automotive Engineers (SAE) Technical Paper, 2005-01-2823.

Ganong W.F. Review of medical physiology. New York, ESA: Ed Lange Medical Publications; 1976.

Hermans V. and Demey D. MELiSSA demonstration reactors. MELiSSA Technical Note 43.2. 1999; ESA/Contract 12922/98/NL/MV.

Perez J. Utilización of Nitrosomonas y Nitrobacter en forma de biopelícula para la nitrificación biológica de lecho fijo: Thesis Universitat Autònoma de Barcelona; 2001.

Masot A. Anàlisi i disseny del Compartiment de Plantes Superiors d'un Sistema de Suport de Vida Biològic. Master Thesis. Universitat Autònoma de Barcelona; 2004.

Ordóñez L., Lasseur Ch., Poughon L., Waters G.C.R., 2004. *MELiSSA Higher Plant Compartment Modeling Using EcosimPro*, Society of Automotive Engineers (SAE) Technical Paper 2004-01-2351.

Vernerey A. Conception controle et fonctionement d'un photobioreacteur pour la culture en mode continu de la cianobacterie Spirulina platensis: Universitat Autònoma de Barcelona; 2000.

Waters, G. C. R.; Masot, A.; Albiol, J.; Dixon, M. A., and Gòdia, F. Static Mass Balance Studies of the MELiSSA PIit Plant: Integration of a Higher Plant Chamber. Society of Automotive Engineers, Tehcnical Paper Series. 2004; (2004-01-2579).

Waters G.R.; Olabi A.; Hunter J.B.; Dixon M.A., and Lasseur C. Bioregenerative food system cost based on optimized menus for advanced life support. Life Support and Biosphere Science. 2002; 8(#3/4):199-210.

13. Acknowledgements

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Appendix 1 - Instrumentation and Control Loop Nomenclature

EQUIPMENT
All equipment for the HPC are labeled as EK00, where:
E: Equipment type, see table 17.1
K: Number corresponding to the HPC area where the equipment is located, see table 17.2
00: Sequential digit that indicates similar equipment inside the same HPC area.

E	Explaination
A	HPC area
B	Condenser, Resistance
C	Chanel, Conveyor
F	Filter
H	Hydroponics Troughs
L	Lamp
O	Open, acces door
P	Pump, Fan, Compressor
T	Tank

Table A.1 Acronyms used for equipment identification.

K	Area of HPC
1	Lighting Area (A100)
2	Liquid Area (A200)
3	Air Handling Area (A300)
4	Acess Areas (A400)
5	Growing Area (A500)
6	MPP Interface Area (A600)

Table A.2.- Acronyms list used for the different HPC sub-systems area.

Example #1: T202.- Tank (T) located in liquid sub-system area (2), the second (02) that appears.

CONTROL LOOPS
Control loops are specified as X LC EK00N, where:
X: Controlled variable, see table 12.3
LC: Control Loop

EK00: Equipment or area at which the control loop is associated
N: Control loop number related to an equipment or area.
Table A.3.- Acronyms list used for control variables and instrumentation, proposed by ISA (Instrument Society of America)

LETTER	Control Variable (X)	Type (Y)
A_Z	Analized Variable (1)	Alarm
C	Conductivity	Controller
F	Flow	
H		High (2)
I		Indicador
L	Level	Low (2)
P	Pressure	
R		Regulation
T	Temperature	Transmitter (3)
V	Viscosity	Valve
X	Motor Order (On/Off)	
Y		Contact/Relay

(1) Where Z indiques analized parameter (H: Humidity; IL: Light intensity; pH; CO2; O2; etc.)
(2) If corresponds to open/close equipment, High means open or almost open, and Low means Closed or almost close.
(3) Transmitter refers to the equipment constitued by transductor or sensor and transmitter itself.
Example #2: AIL LC L1011: First (1) control loop (LC) for light intensity (AIL) of the lamps (L101).

INSTRUMENTATION
Instrumentation located within the HPC and associated with a control loop is described as XY EK00NA, where:
X: Controlled Variable, see table 17.3
Y: Instrumentation type, see 17.3
EK00: Equipment or area at which is associated.
N: Control loop number related to an equipment or area
A: Optional. Sequential letter, which identifies the doubled instrumentation in the same control loop.

Example #3: AILT L1011A: First (A) transmitter (T) for light intensity (AIL) in the first (1) control loop for lamps (L101).

Examples #4 A_{IL}IC L1011: Indicador (I) and Controller (C) for light intensity (AIL) in the first (1) control loop for lamps (L101).

Example #5: A_{IL}ALH L1011: Alarm (A) Low/Highv (LW) for light intensity (AIL) in the first (1) control loop for lamps (L101).