M ELiSSA

Technical Note

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DETAILED DESIGN OF THE HIGHER PLANT CHAMBER

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1 Introduction

Staff of the Department d'Enginyeria Química, Universitat Autònoma de Barcelona and the Controlled Environment Systems Research Facility (CESRF) at the University of Guelph has 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 goal of the MPP is to demonstrate the MELISSA loop concept and to achieve the integration and closure of MELiSSA compartments. Inclusion of an HPC customized for the Pilot Plant is one of the next steps towards this goal.

The main steps involved in HPC integration are:

- design of an HPC prototype,
- 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,

Over the contract period, work has focused on the collection of baseline productivity data for the HPC operating at the Pilot Plant scale. The SEC-2 chambers at CESRF were used specifically for this purpose. Gas exchange and nutrient uptake data of candidate crops grown in both batch and staged culture have been used in the assessment of mass balance of the MPP. Results indicate that an HPC having about 5 m^2 of crop production area would be sufficient. Empirical trials conducted in the SEC-2 chambers are at this same scale and therefore provide valuable information to the HPC integration team. Work also continues on the use of empirical data collected at this scale to validate models of canopy carbon exchange. This task is in support of the formulation of local control algorithms for the HPC.

2 HPC Sizing for the Pilot Plant

2.1 Methods Used in the Collection of HPC Sizing Data

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.

Since the November 2001 MELiSSA meeting, the UoG has been involved in the collection of baseline data sets for two of the three candidate crops; beet (*Beta vulgaris* cv. Detroit Medium Red) and lettuce (*Lactuca sativa* L. cv. Grand Rapids). Empirical production trials have included replications in batch culture (single seeding date) using either a deep water or an NFT hydroponics system. The deep water culture trials were conducted in 2002 at a lower planting density than those reported for NFT (17.6 and 24 plants m^{-2}, respectively). Since these NFT data, collected in 2004, are used to scale the HPC for the Pilot Plant a description of the methodology used to collect them is warranted. Additionally, data sets have been collected in the SEC-2 chambers for beet and lettuce under staged (multiple seeding dates) culture. These experiments were run in either 2004, 2005 or 2006.

The 2004 data set was collected from three production trials of each crop at the full canopy (120 plants per chamber) scale. All experiments were complete by August 2004. The data set includes Net Carbon Exchange Rate (NCER) and nutrient uptake for a developing canopy, stand level NCER as a function of both light intensity and crop age and photosynthetic responses to CO_2 and light intensity at the leaf scale. A summary of the available data sets and key variables collected to date may be found in the Table 2.1.1, Table 2.1.2 and Table 2.1.3. All experiments were conducted in the SEC-2 chambers at the UoG CESRF.

Table 2.1.1. Experimental data available to date relevant to HPC sizing and control algorithm development. DW = Deep Water Culture, NFT = Nutrient Film Technique, LD=Low Density at 17.6 plants m^{-2}, HD=High Density at 24 plants m^{-2}, DCG=Daily Carbon Gain. The most recent data are those designated as GWXX04, where XX represents the month of experiment start.

Crop	Culture	Density	Replication ID	Data Collected
Beet	Batch, DW	LD	GW0402a - Beet-Batch GW0402b - Beet-Batch	Canopy DCG, nutrient/water uptake and balance, yields
Beet	Batch, NFT	HD	GW0204-Beet-Batch GW0404-Beet-Batch GW0504-Beet-Batch	Canopy DCG, nutrient/water uptake and balance, leaf light and CO_2 response – excluding GW0204 series, canopy light response, harvest and yield, tissue mineral analysis and composition, crop response to enriched CO_2
Lettuce	Batch, DW	LD	GW0502a - Lettuce-Batch GW0502b - Lettuce-Batch	Canopy DCG, nutrient/water uptake and balance, yields
Lettuce	Batch, NFT	HD	GW0204-Lettuce-Batch GW0604-Lettuce-Batch GW0704-Lettuce-Batch	Canopy DCG, nutrient/water uptake and balance, leaf light and CO_2 response – excluding GW0204 series, canopy light response, harvest and yield, tissue mineral analysis and composition, crop response to enriched CO_2

Table 2.1.2. Experiment summary sheet for beet batch cultures at Low Density (LD) and High Density (HD) and under Deep Water (DW) or Nutrient Film (NFT) hydroponics. The most recent data are those designated as GWXX04, where XX represents the month of experiment start.

Parameter	Experiment DW-LD		Experiment NFT-HD		
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 3
Identification	GW0402a - Beet-Batch	GW0402b - Beet-Batch	GW0204 - Beet-Batch	GW0404 - Beet-Batch	GW0504 - Beet-Batch
Chamber used	SEC-1	SEC-2	SEC-1	SEC-1	SEC-1
Date of seeding	10/03/02	10/03/02	05/01/04	10/03/04	19/04/04
Experiment start in chamber	02/04/02	02/04/02	04/02/04	2/04/04	19/05/04
Experiment end date	06/05/02	06/05/02	17/03/04	07/05/04	24/06/04
Photoperiod (day-hours)	14	14	14	14	14
Demand temperature (ºC day/night)	25/20	25/20	25/20	25/20	25/20
Demand CO_2 (ppm)	1000	1000	1000	1000	1000
Hydroponics system	DW	DW	NFT	NFT	NFT
Number of plants in chamber	44	44	120	120	120
Production area (m^2)	2.5	2.5	5	5	5
Planting density (plants m^{-2})	17.6	17.6	24	24	24

Table 2.1.3. Experiment summary sheet for lettuce batch cultures at Low Density (LD) and High Density (HD) and under Deep Water (DW) or Nutrient Film (NFT) hydroponics. The most recent data are those designated as GWXX04, where XX represents the month of experiment start.

Parameter	Experiment DW-LD		Experiment NFT-HD		
	Rep 1	Rep 2	Rep 1	Rep 2	Rep 3
Identification	GW0502a - Lettuce-Batch-	GW0502b - Lettuce-Batch	GW0204 - Lettuce-Batch-	GW0604 - Lettuce-Batch-	GW0704 - Lettuce-Batch-
Chamber used	SEC-1	SEC-2	SEC-2	SEC-2	SEC-1
Date of seeding	28/04/02	28/04/02	06/02/04	25/05/04	9/04/04
Experiment start in chamber	21/05/02	21/05/02	25/02/04	14/06/04	8/07/04
Experiment end date	14/06/02	14/06/02	29/03/04	21/07/04	12/08/04
Photoperiod (day-hours)	14	14	14	14	14
Demand temperature (ºC day/night)	25/20	25/20	25/20	25/20	25/20
Demand CO_2 (ppm)	1000	1000	1000	1000	1000
Hydroponics system	DW	DW	NFT	NFT	NFT
Number of plants in chamber	44	44	120	120	120
Production area (m^2)	2.5	2.5	5	5	5
Planting density (plants m^{-2})	17.6	17.6	24	24	24

For each of the 2004 studies conducted using NFT, beet or lettuce were germinated in a research greenhouse at the UoG, using Rockwool© (1.5 "sq, 9.4 cm^2) cubes. The plants remained in the greenhouse until there was sufficient root exposure to facilitate planting into an NFT hydroponics system (approximately 20 days after seeding) and the SEC-2 chambers. During the germination period, seedlings were watered regularly with distilled water and once weekly with a fertilizer solution (20-8-20 N-P-K commercial mix having an EC 2.5 $dS \cdot m^{-1}$).

A total of 120 seedlings were transferred to each chamber (12 plants per stainless steel trough). The Rockwool© cubes containing seedlings were positioned in larger cubes (4" x 4" x 2.5", 625 cm^3) to improve water distribution in the hydroponics channels. Trays were covered once the blocks were in position so as to minimize the growth of algae on the surface of the Rockwool©. For most experiments, leaf area was destructively determined on the remaining (un-planted) seedlings using a Li-Cor 3100 Leaf Area Meter (Li-Cor, Lincoln, NE, USA). These initial leaf area estimates were used as input variables into the NCER models described in the sections below.

Plants were grown under conditions of between 400-450 µmol m^{-2} s^{-1} PAR lighting at stand height as supplied by the High Pressure Sodium (HPS) and Metal Halide (MH) lamps mounted externally to the chambers. A 14/10 hr light/dark (06:00 - 20:00) photoperiod was used and coupled to a 26/20 ^oC day/night temperature. Atmospheric CO_2 concentrations were fixed in these full canopy studies at 1000 µL $CO_2 \cdot L^{-1}$ air as supplied through an external tank and computer regulated compensatory system using bottled CO_2. Average relative humidity in the chambers over all replications was 73% ± 5% with no addition of external water from humidification lines.

The nutrient solution used in this study had the following composition: 1.5 mM PO_4^{3-}, 3.62 mM Ca^{2+}, 4 mM NH_4^+-N, 11.75 mM NO_3^--N, 5 mM K^+, 2 mM SO_4^{2-}, 1 mM Mg^{2+}, 0.005 mM Mn^{2+}, 0.025 mM Fe^{3+} as Fe-DTPA, 0.0035 mM Zn^{2+}, 0.02 mM B^{3+}, 0.008 mM Na^+,0.0008 mM Cu^{2+}, 0.0005 mM Mo^{6+}. This solution had an average EC of 1.9 $dS \cdot m^{-1}$. The pH of the solution was adjusted to approximately 5.5 with the addition of 1 M $NaHCO_3$ solution. At the initial transplant of the seedlings, 220 L of nutrient solution was added to the pool prior to the chamber doors being sealed. Every five days after, the solution was pumped out of the internal reservoir (without breaking the atmospheric seal) to replace it with a fresh 220 L volume having the same composition as noted above.

At the start of each solution changeover period, the total solution volume to be added was measured with a large graduated tank and three 25 mL samples were taken of the fresh solution for off-line HPLC analysis. The old solution was pumped out of the reservoir and its volume measured. Samples were also taken for HPLC analysis in triplicate. Solution volumes were measured at the start and end of the change-over periods to allow for the correction of elemental analysis results due to evapo-transpiration. During each period no amendments were made to the solution composition in any way. All solution samples were analyzed using the Dionex HPLC Model DX-120 (Sunnyvale, CA, USA) for the ions of interest which included Cl^-, PO_4^{3-}, Ca^{2+}, NH_4^+-N, NO_3^--N, K^+, SO_4^{2-}, Mg^{2+}, and Na^+.

All plant material was harvested at the end of the study. Plant parts, with the exception of roots, were sampled at the individual plant scale. Harvested root material was pooled by each trough in the chamber. Tissue water content was measured as the difference between fresh and dry weights, obtained after at least four days in a drying oven at 60 ºC. Chamber water balance was also determined from evapo-transpiration estimates and plant water content estimates derived from dry and fresh plant weights.

Harvested tissue was also pooled for mineral content analysis. Edible and inedible fractions of each crop were analyzed independently.

Leaf area was measured on a sub-sample of the plants harvested using a Li-Cor 3100 Leaf Area Meter (Li-Cor, Lincoln, NE, USA).

The Net Carbon Exchange Rate (NCER) of the developing stands was determined non-destructively using a gas compensation technique. The computer controller maintained internal chamber CO_2 concentrations during the day-light hours so that any net carbon gain by the stand through photosynthetic activity was compensated for by injections into the chamber volume from an external tank. The metered flow of CO_2 injections was used to calculate day time carbon gain by the crop. 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 was used to determine stand respiration rates (expressed as negative NCER). The sum of these signed NCER estimates over a 24 hour period (in moles C) yielded daily carbon gain (DCG).

2.2 Empirical Productivity data

The following tables provide a summary of harvest and yield data collected for both the beet and lettuce batch experiments using NFT. These productivity measures may be compared to those obtained from experimental trials with these crops in 2002 as reported upon in TN 65.5.

Table 2.2.1. Harvest data for beet grown using the NFT technique. Bracketed values represent the standard error of the mean

Dry weights and growth	Beet-Batch-GW0204	Beet-Batch-GW0404	Beet-Batch-GW0504	Means Over Experiments
Total Plant Measures				
Total plant dw at planting in chamber (g dwb plant^{-1})	0.10	0.11	0.09	0.10
Total plant dw at harvest (g dwb plant^{-1})	25.34	18.59	22.47	22.16
Total plant dw growth rate over days in chamber (g dwb plant^{-1} DIC^{-1})	0.60	0.53	0.62	0.58
Total plant yield (g m^{-2})	554.16	446.08	539.28	531.84
Equivalent carbon gain (g dwb plant^{-1} DIC^{-1})	0.23	0.20	0.24	0.22
Leaf Measures				
Leaves dw at harvest from chamber (g dwb plant^{-1})	12.23 (0.49)	10.02 (0.33)	9.49 (0.34)	10.60 (0.29)
Leaf Yield (g m^{-2})	239.52	240.48	227.76	254.4
Initial Leaf Area (cm^2 plant^{-1})	NA	25.5 (2.1)	17.28 (1.25)	21.41 (1.65)
Leaf Area at Harvest (cm^2 plant^{-1})	1375.56 (174.44)	754.58 (36.05)	1139.97 (79.67)	1046.81 (62.21)
Hypocotyl Measures				
Hypocotyl dw at harvest (g dwb plant^{-1})	12.1(0.5)	7.53 (0.35)	11.84(0.51)	10.48 (0.24)
Hypocotyl yield (g m^{-2})	289.44	180.72	284.16	251.52
Root Measures				
Roots dw at harvest (estimated by trough) (g dwb plant^{-1})	1.05 (0.08)	1.04 (0.15)	1.14 (0.09)	1.08 (0.06)
Root Yield (g m^{-2})	25.2	24.96	27.36	25.92
Harvest Index	0.95	0.94	0.95	0.95

Table 2.2.2. Harvest data for lettuce grown using the NFT technique. Bracketed values represent the standard error of the mean.

Dry weights and growth	Lettuce-Batch-GW0204	Lettuce-Batch-GW0604	Lettuce-Batch-GW0704	Means Over Experiments
Total Plant Measures				
Total plant dw at planting in chamber (g dwb plant^{-1})	0.01	0.1	0.03	0.05
Total plant dw at harvest (g dwb plant^{-1})	17.75	24.89	23.38	21.95
Total plant dw growth rate (g dwb plant^{-1} DIC^{-1})	0.54	0.67	0.67	0.62
Total plant yield (g m^{-2})	421.68	597.36	561.12	526.8
Equivalent carbon gain (g dwb plant^{-1} DIC^{-1})	0.20	0.25	0.25	0.23
Leaf Measures				
Leaves dw at harvest from chamber (g dwb plant^{-1})	14.75 (0.21)	18.77 (0.25)	14.7 (0.23)	16.07 (0.17)
Leaf Yield (g m^{-2})	354.00	450.48	352.8	385.68
Initial Leaf Area (cm^2 plant^{-1})	7.31	58.11 (3.13)	18.86 (2.16)	NA
Leaf Area at Harvest (cm^2 plant^{-1})	3246.13 (212.20)	3762.74 (98.71)	3916.44 (88.30)	3641.77 (90.06)
Root Measures				
Roots dw at harvest (estimated by trough) (g dwb plant^{-1})	2.82 (0.13)	6.12 (0.17)	8.68 (0.38)	5.88 (0.47)
Root Yield (g m^{-2})	67.68	146.88	208.32	141.12
Harvest Index	0.84	0.75	0.63	0.73

2.3 HPC Sizing Based on Crop Productivity & Dietary Requirements

A previous study has attempted to quantify the equivalent system mass of a bioregenerative food system based on an optimized menu (Waters, 2002) (Waters G.R. *et al.* 2002). From this study it was estimated that in order to feed six crew members over a 10 day menu cycle, about 67 kg of dry edible biomass is required. This equates to 1.1 kg of dry edible biomass per person per day. Taking as an initial starting point, target productivities in the chamber meeting 20% of the daily requirement of food, it may be calculated that 222.3 g edible biomass dwb/day should be reached. Under this assumption two options are possible. One may consider an even distribution of produced edible biomass among three chambers amounting to 74 g ED/d of each crop (lettuce, beet and wheat) per chamber. The table below shows the production areas required (excluding air-lock) to meet this biomass demand as calculated from the empirical productivity data presented in Table 2.3.1and Table 2.3.2.

Table 2.3.1. HPC sizing with even distribution of edible biomass (scenario 1).

Target Yields			Empirical Data				Prescribed
Crop	Edible Yield	Inedible Yield	Crop Productivity	Harvest Index	Edible Productivity	Inedible Productivity	Production Area
	g day^{-1}	g day^{-1}	g total m^{-2} day^{-1}	g g^{-1}	g m^{-2} day^{-1}	g m^{-2} day^{-1}	m^2
Wheat	74.00	145.8	40.98	0.33	13.52	27.46	5.47
Lettuce	74.00	27.36	14.88	0.73	10.86	4.01	6.81
Beet	74.00	3.89	13.92	0.95	13.22	0.70	5.60
Total	222.00	177.05	69.78				17.76

Under a second scenario it is assumed that one chamber of 5 m^2 each is devoted to each crop. Taking into account the same productivities and harvest index as above, the following results are obtained.

Table 2.3.2. HPC sizing with even production area distributions (scenario 2).

Resulting Yields			Empirical Data				Prescribed
Crop	Edible Yield	Inedible Yield	Total Productivity	Harvest Index	Edible Productivity	Inedible Productivity	Production Area
	g day^{-1}	g day^{-1}	g total m^{-2} day^{-1}	g g^{-1}	g m^{-2} day^{-1}	g m^{-2} day^{-1}	m^2
Wheat	69.00	138.00	40.98	0.33	13.80	27.60	5
Lettuce	54.30	20.05	14.88	0.73	10.86	4.01	5
Beet	66.10	3.50	13.92	0.95	13.22	0.70	5
Total	**189.4**	**177.05**	**69.78**				**15**

2.4 HPC Sizing Based on Carbon, Oxygen and Nitrogen Balance

Recently an EXCEL based, static spreadsheet model was developed for assessing mass balance in the MELiSSA Pilot Plant including an HPC. The spreadsheet model utilized the data gathered from our empirical production trials and data collected by the MELiSSA consortium, as cited. Basic inputs of the spreadsheet model include the types of crops to be produced within the higher plant chamber, allocated production areas, crop productivities, biomass allocation to plant parts, degradation efficiencies of the liquefying compartment, number of rats (assumed crew) and the input/output characteristics of the reactors in the gas, liquid and solid (biomass) phases. The most recent productivity and nutrient composition data were used to update the static mass balance model originally described in paper for the International Conference on Environmental Systems (ICES) and SAE Technical Paper Series (Waters *et al.*, 2004).

The liquid, biomass/liquid and gas loops for the MELiSSA Pilot Plant are depicted in the figures below (Figure 2.4.1 and Figure 2.4.2). These figures represent the current conceptual design of the compartment interfaces for the Pilot Plant. The daily mass balance for CO_2, O_2 and nitrogen was quantified using empirical information on mass exchanges between the compartments. Transfer of CO_2, O_2 and nitrogen sources may occur through the liquid, biomass or gas loops.

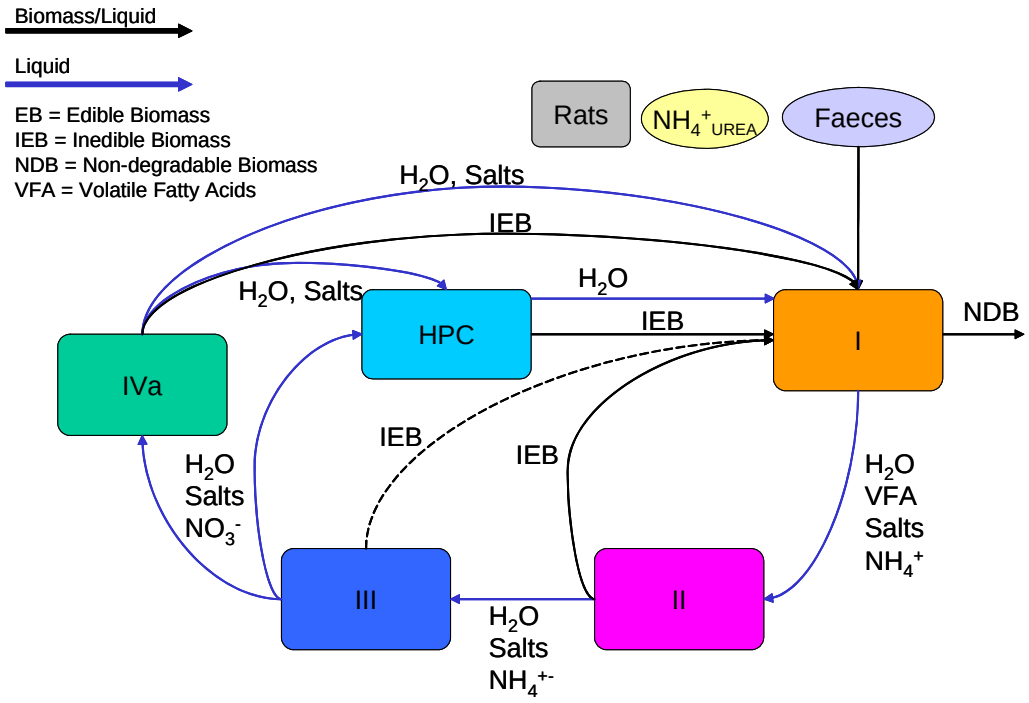


Figure 2.4.1. MELiSSA liquid loop for the Pilot Plant

The above figure (Figure 2.4.1) represents the liquid and biomass/liquid loop of the Pilot Plant. Of particular interest is the transfer of inedible biomass to Compartment I, and the flow of NO_3^- and NH_4^+ in the liquid phase. It should also be noted that there is assumed to be no biomass/liquid connection between the rats of the crew compartment and the rest of the loop.

The figure below (Figure 2.4.2) represents the gas loop of the Pilot Plant. Of particular importance are the daily rates of CO_2 sequestration and O_2 evolution from each compartment. Gas flows are described as being clean (ambient/loop demand concentrations of CO_2) or CO_2 enriched air (greater than ambient concentrations of CO_2). Assumptions made about each compartment and its exchange rates are discussed below.

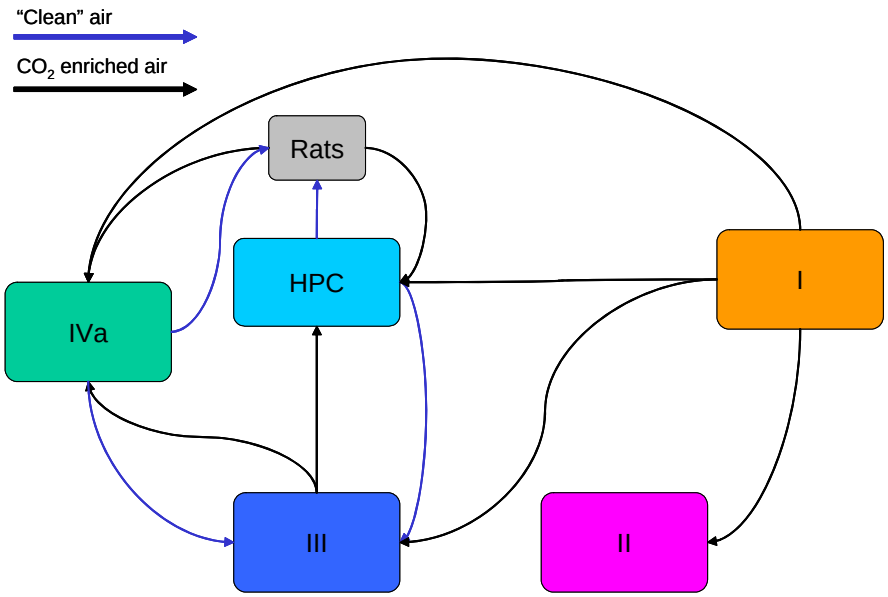


Figure 2.4.2. MELiSSA gas loop for the Pilot Plant

As is depicted in the figure above, inedible biomass (IEB) is sent from HPC, Compartment IVa and Compartment II to Compartment I for degradation. The transfer of biomass from Compartment III depicted reflects the excess of biomass recovered when a backflow cleaning procedure is applied. However, due to the slow growth of this immobilized biomass its contribution to the daily biomass generation in the MPP is considered negligible and was therefore not included in these mass balance calculations. Edible biomass from the HPC was assumed to be fed to humans living outside the MPP (note faeces input scaling as described below). In all simulations 100% of the inedible biomass produced by the HPC was assumed to be transferred to Compartment I. Faeces is assumed to enter the MPP loop via Compartment I. The quality and quantity of the faeces are assumed to be of human proportions expressed on a daily basis. Urine may be added to the loop as a nitrogen and carbon source according to its stoichiometric decomposition into NH_4^+ and CO_2. Non-degradable biomass emanating from Compartment I was assumed to be treated externally to the MPP.

The degradation efficiency of bacterial biomass and proteins in compartment I was set to 60% based on previous empirical tests and the ammonium nitrogen obtained was stoichiometrically calculated from its elemental composition. Volatile Fatty Acid (VFA) composition obtained from the degraded biomass is considered to be produced in the same molar ratios as those obtained experimentally (Hermans, 1999).

In Compartment II, the VFA from the first compartment are degraded and transformed to biomass. The stoichiometric conversions defined previously (Favier-Teodorescu L. et al. 1999) are used to calculate the biomass production, CO_2 compartment balance and net NH_4^+ production.

The small NH_4^+ consumption for biomass generation in Compartment III was determined from empirical estimates of biomass gain per mole of NH_4^+ entering the compartment. Values for conversion of NH_4^+ input into NO_3^- output and the rate of CO_2 evolution and O_2 consumption in Compartment III was determined from stoichiometric calculations (Perez, 2001).

The productivity of *Spirulina* in compartment IVa has up to now, reached values of 36 g/day for a 77 L reactor (Vernerey A. 2000). The stoichiometry of CO_2 and O_2 exchange in relation to *Spirulina* productivity is presented in the table below. The nitrate requirement from Compartment III was determined from the molecular weight of *Spirulina* (26.71 $g \cdot mole^{-1}$), the molar content of nitrogen in biomass and the rate of biomass production (36 $g \cdot d^{-1}$). The fraction of *Spirulina* biomass going to Compartment I for degradation was calculated from the total amount produced after subtraction of the fraction reserved for human consumption.

Basic assumptions about the HPC included in the Pilot Plant are derived from empirical studies with MELISSA candidate crops in controlled environment chambers. These studies were conducted with beet (*Beta vulgaris* cv. Detroit Medium Red) and lettuce (*Lactuca sativa* cv. Grand Rapids) in 2004. The average values of CO_2 consumption, O_2 production and nitrogen requirement data gathered from these 2004 empirical trials are presented in Table 2.4.2. Uptake rates were calculated from the daily plant growth rate and carbon and nitrogen fractions in harvested tissue.

The total production area available for the growth of beet and lettuce in the Pilot Plant was allowed to vary in these simulation studies but within the range of 0 to 15 m^2. The proportion of the total area occupied by beet is user defined while the occupation by lettuce is determined by difference from 100%. The calculated gas exchange rates for the HPC were derived from the user defined areas in production for each crop and the values are presented in the table below. Parameter values for the crew compartment are based on the assumption that 3 rats will occupy the compartment and that the faeces and urine entering the loop would be human in origin, when used. The rates of human urea and faeces daily production were determined from (Ganong W.F.). For a total of three 400 g rats the rates of CO_2 evolution and O_2 consumption were determined to be 2.86 mol CO_2 d^{-1} and 3.28 mol O_2 d^{-1} (De Chambure D. 1992).

An iterative calculation of *R.rubrum* biomass production rate was used to provide starting values for the contribution of biomass made by Compartment II to Compartment I.

Using the information noted above it was possible to determine the net balance, among compartments, for the daily exchange of CO_2, O_2 and nitrogen. An example of the compartment level accounting of these exchanges is presented in the table below. Net exchange rates presented in that table were determined assuming, a 50% occupation of beet by area and a production area of 3.5 $m^{2.}$ All other inputs were fixed to those of the table below.

Table 2.4.1. Basic static model input assumptions for simulation results presented below (Var: variable. Comp: compartment)

COMP.	PARAMETER	VALUE
CREW	Number of rats	3
	Faeces per person day (g dw·d^{-1})	23.5
	Fraction of human faeces into loop (%)	1
	Urine per person day (L/d)	1.5
	Fraction of human urine put into loop (%)	0.40
CI	Protein degradation Efficiency (%)	0.6
CII	Fraction of *R.rubrum* recirculated to CI (%)	1
CIII	CO_2 consumption (mol CO_2 ·mol N^{-1})	0.32
	O_2 consumption (mol O_2 · mol N^{-1})	2
CIVa	*S.platensis* productivity (g · d^{-1})	36
	Fraction of *S.platensis* into CI (%)	0
	CO_2 consumption (g CO_2 · g $biomass^{-1}$)	1.74
	O_2 production (g O_2 ·g $biomass^{-1}$)	1.6
CIVb (HPC)	Culture area (m^2)	Var.
	Fraction of edible biomass into CI (%)	0
	Fraction of inedible biomass into CI. (%)	1
	Beet area occupation	Var.
	Lettuce area occupation	Var.

Table 2.4.2. Empirical higher plant chamber gas and nitrogen exchange data collected in higher density, NFT culture for beet and lettuce. Values represent averages over each of the three replicates.

PARAMETER	UNITS	LETTUCE	BEET
Total Plant Carbon Gain	g C · m^{-2} · d^{-1}	5.69	5.37
Average CO_2 consumption	mol CO_2 · m^{-2} · d^{-1}	0.47	0.45
Average O_2 production	mol O_2 · m^{-2} · d^{-1}	0.47	0.45
Average N consumption	mol N m^{-2} · d^{-1}	0.046	0.042

Table 2.4.3. Example of compartment level accounting for gas and nitrogen balance in the Pilot Plant including an HPC with a production area of 3.5 m^2 and 50% occupation by each of beet and lettuce. All other input values are as in Table 2.12.

Compartment	Balances (moles day^{-1})		
	CO_2	O_2	N
CI	0.051	N/A	N/A
CII	-0.036	N/A	N/A
CIII	-0.012	-0.077	0.038
CIVa	-1.42	1.80	-0.229
CIVb	-1.61	1.61	-0.044
Urine Input	0.117	N/A	0.227
Crew (3 rats)	2.86	-3.28	N/A
Total	**-0.053**	**0.057**	**-0.01**

Overall balance for the Pilot Plant for various compartments is presented for different sizing scenarios in the tables below. Results are from an iterative goal seek function in EXCEL targeting CO_2, O_2 and nitrogen balance respectively. With balance as a target, the HPC production area was allowed to vary to achieve a solution. In the case of Table 2.4.6, nitrogen balance was targeted by allowing the proportion of human urine production entering the Pilot Plant loop to change.

Assuming a fixed urine input of 40%, carbon and oxygen balance was achieved at production areas near 3.3 m^2 (assuming 50% beet occupation). Nitrogen closure was achieved at production areas in excess of 5 m^2. The results of these calculations indicate that it was not possible to balance gases and nitrogen concurrently in the MPP. For a fixed production area of 3.5 m^2, it was calculated that nitrogen closure could be obtained when nearly 41% of the daily production of human urine enters the loop.

Table 2.4.4. Targeted production area for CO_2 balance assuming 50% stocking each of lettuce and beet

PARAMETER	UNITS	VALUE
Production Area	m^2	3.39
CO_2 Balance	mol $CO_2 \cdot d^{-1}$	0
O_2 Balance	mol $O_2 \cdot d^{-1}$	0.006
N Balance	mol $N \cdot d^{-1}$	-0.0055

Table 2.4.5. Targeted production area for O_2 balance assuming 50% stocking each of lettuce and beet

PARAMETER	UNITS	VALUE
Production Area	m^2	3.37
CO_2 Balance	mol $CO_2 \cdot d^{-1}$	0.006
O_2 Balance	mol $O_2 \cdot d^{-1}$	0.00
N Balance	mol $N \cdot d^{-1}$	-0.0055

Table 2.4.6. Targeted production area for N balance assuming 50% stocking each of lettuce and beet

PARAMETER	UNITS	VALUE
Production Area	m^2	5.37
CO_2 Balance	mol $CO_2 \cdot d^{-1}$	-0.91
O_2 Balance	mol $O_2 \cdot d^{-1}$	0.91
N Balance	mol $N \cdot d^{-1}$	0.00

Table 2.4.7. Targeted urine fraction entering loop required to obtain N balance for a fixed production area of 3.5 m^2 and assuming 50% stocking each of lettuce and beet .

PARAMETER	UNITS	VALUE
Production Area	m^2	3.5
Urine Fraction into Loop	Fraction	0.41
CO_2 Balance	mol $CO_2 \cdot d^{-1}$	-0.05
O_2 Balance	mol $O_2 \cdot d^{-1}$	0.057
N Balance	mol $N \cdot d^{-1}$	0.00

The CO_2 , O_2 and nitrogen balance of the Pilot Plant with respect to the production area of the higher plant chamber and the percentage of that area occupied by beet is presented in Figure 2.4.3, Figure 2.4.4 and Figure 2.4.5. Results indicate that the production area of the HPC should be near 3.5 m^2 in order to achieve a high degree of mass closure when the HPC is operating in an integrated fashion within the Pilot Plant loop.

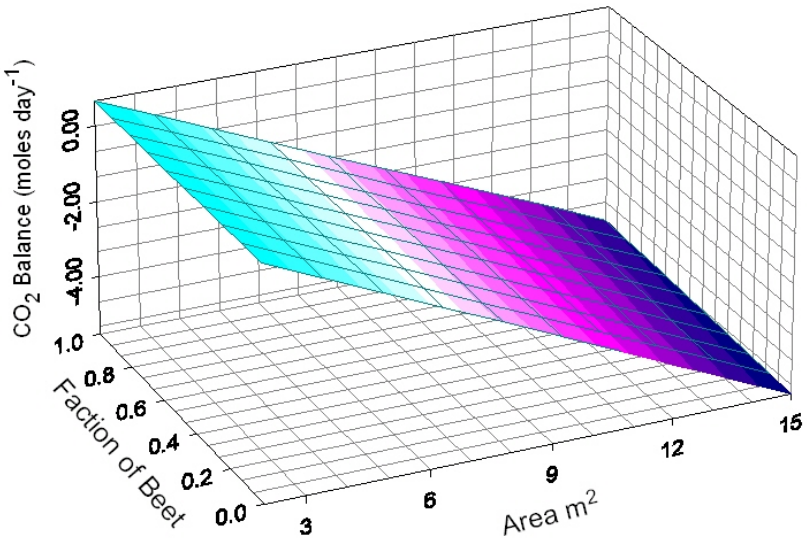


Figure 2.4.3. Carbon dioxide balance in the Pilot Plant as a function of production area and fraction of area occupied by beet, the balance being occupied by lettuce.

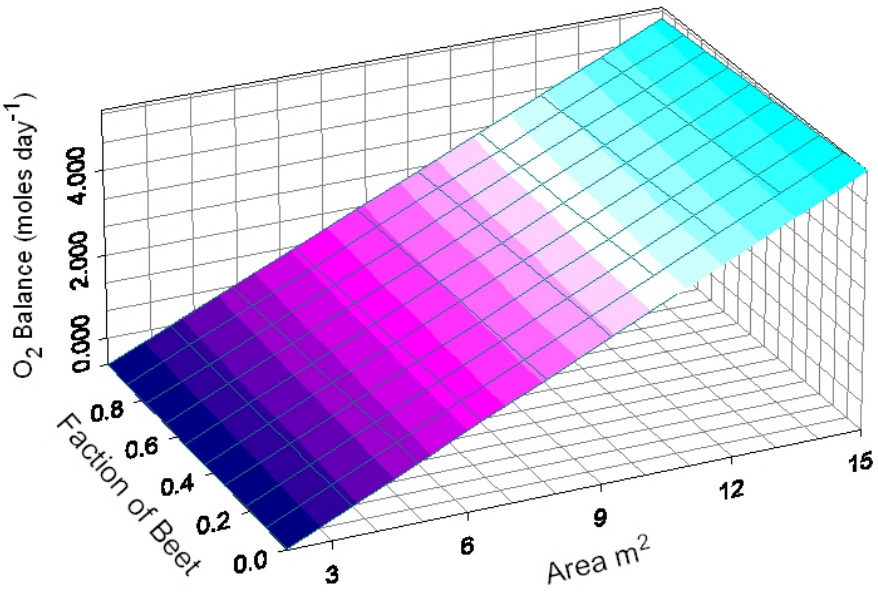


Figure 2.4.4. Oxygen balance in the Pilot Plant as a function of production area and fraction of area occupied by beet, the balance being occupied by lettuce.

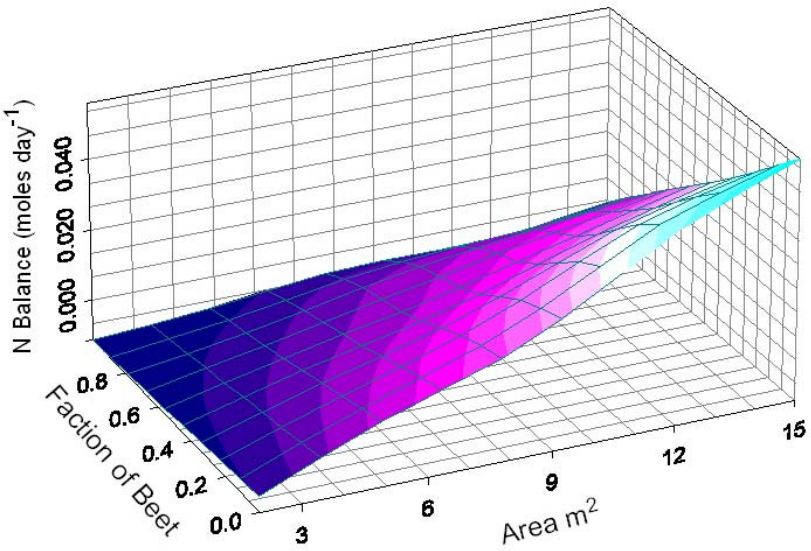


Figure 2.4.5. Nitrogen balance in the Pilot Plant as a function of production area and fraction of area occupied by beet, the balance being occupied by lettuce.

3 HPC Prototype Design Drivers and Constraints

3.1 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 and a semicontinuous steam line.
- Gas lines: Compressed air, CO_2, N_2, O_2

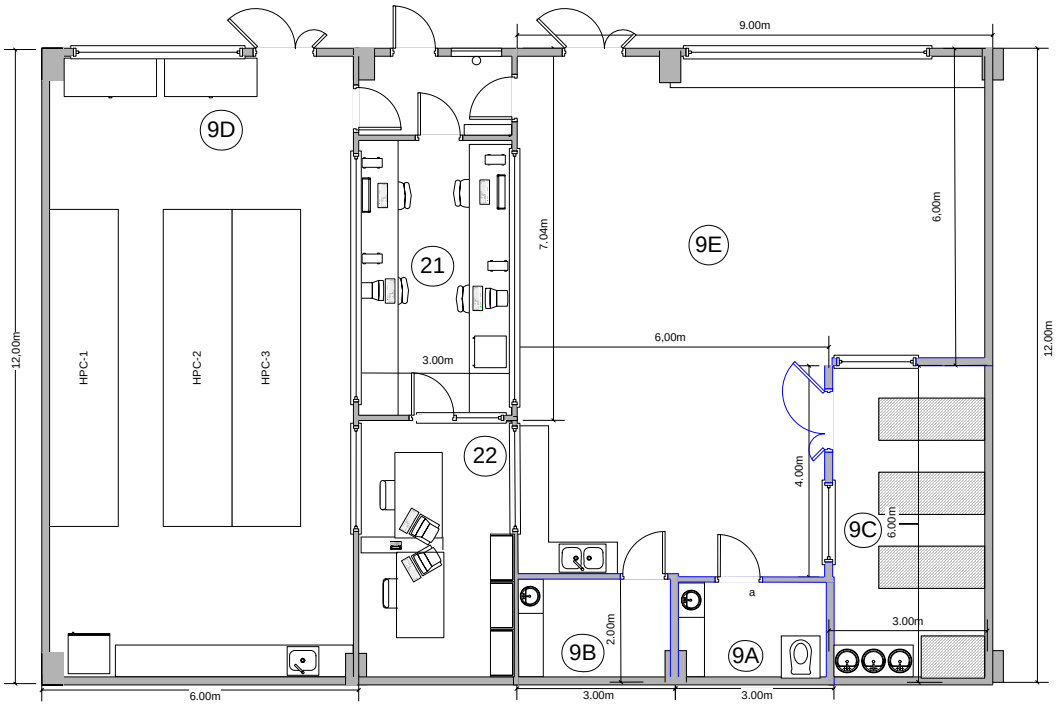


Figure 3.1.1. Higher Plant Compartment distribution in the UAB laboratory. The Higher Plants will be housed in Section 9D with a bay for analytical equipment housed at the bottom end of the room.

3.2 Prototype Dimensions

From the empirical productivity data and sizing calculations presented in Section 2.0 above, it is proposed that an HPC prototype be sized so that 5m^2 of production space is available. This will allow for some variability in predicted crop productivity and will allow for some flexibility in planting density and spacing, given that the estimated CO_2 balance sizing (presented in Section 2.0 above) was calculated to be 3.4 m^2 (Table 2.4.4 and Table 2.4.5). The dimensions of the chamber are therefore determined as follows:

Table 3.2.1. 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	1.3 m
Width of air handling envelope (each chamber side)	0.10 m
Chamber insulation width with aesthetic covering (each chamber side)	0.05 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 3.1.1.

It is proposed that this configuration will be suitable if the following conditions are met:

- The analytical systems bay houses the IRGA and control system interface panel for the prototype,
- Sensors and other hardware are positioned in the base of the chamber with the volume under the air locks used for partial placement of the feed solution reservoir. An equipment rack may be installed under the air lock to house the hydroponics system concentrate (stock) reservoirs,
- Electrical connections are made to MPP in the ceiling above the HPC rather than the sides

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.

3.3 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 3.3.1. 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	OSRAM 12V, 20W BAB 38˚
Port	Ingold
Tubing connections	Swagelok
pH-probe	Mettler-Toledo
O_2-probe	Mettler-Toledo
Electrical fuses, circuit breakers	Hager

3.4 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 3.4.1. 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 (5 cum / minute)	50W
Lamp loft circulation fan (2.5 cum / min)	50W
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	**8530 W**
Overhead (15% of total)	**1280 W**
Total Maximum Power Consumption of Prototype	**9810 W**

3.5 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 3.5.1. HPC materials, (1) Pure phenolic thermosetting resinous coating, (2) Fluoroelastomer heat resistant.

Chamber Part	Materials
Walls, floors, valves, air and liquid plumbing, tubing	Stainless steel 316
Roof, windows	Tempered glass
Liquid reservoirs	Stainless steel
Heat exchanger, motor parts, oxidation barriers	"Heresite"(1)
O-rings, solenoid seats	"Viton"(2)
Sealant	Silicone sealant (Dow-Corning RTV 732)

3.6 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).

3.7 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).

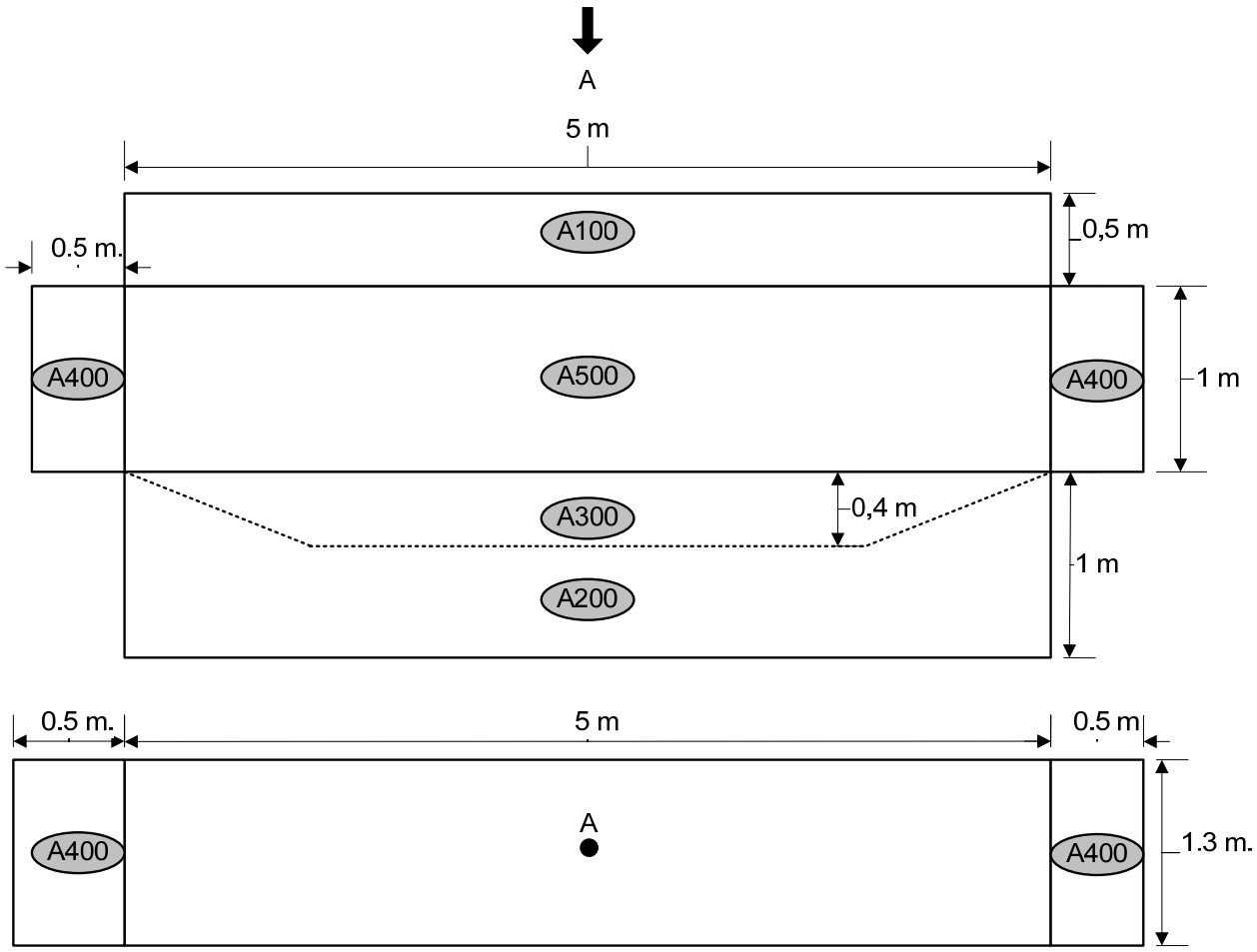


Figure 3.7.1. Schematic exterior view of the HPC prototype.

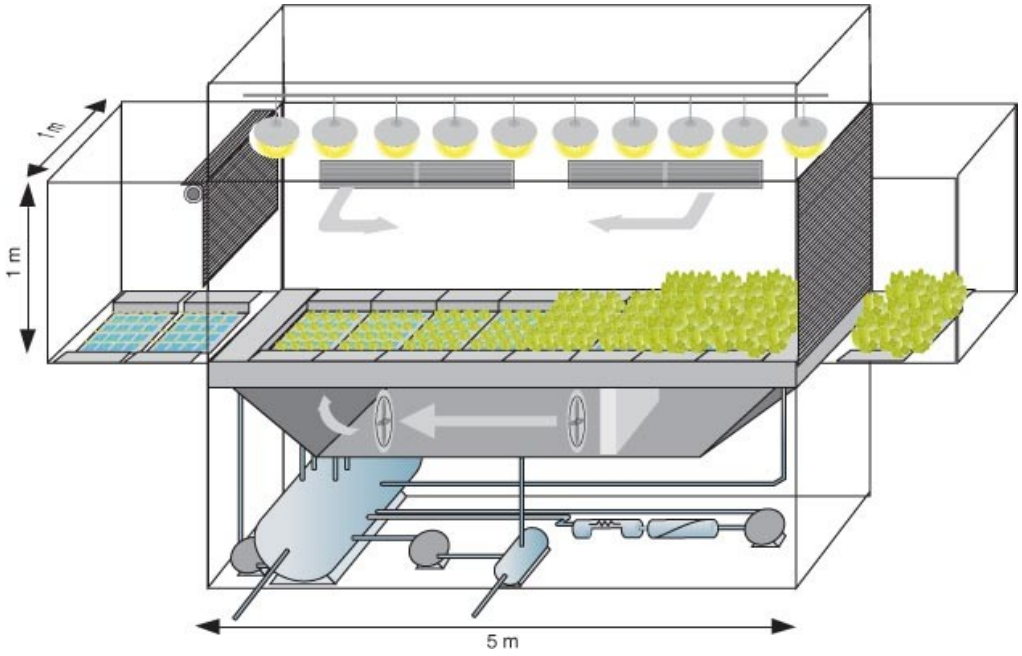


Figure 3.7.2. Diagrammatic representation of the higher plant chamber for integration into the Pilot Plant.

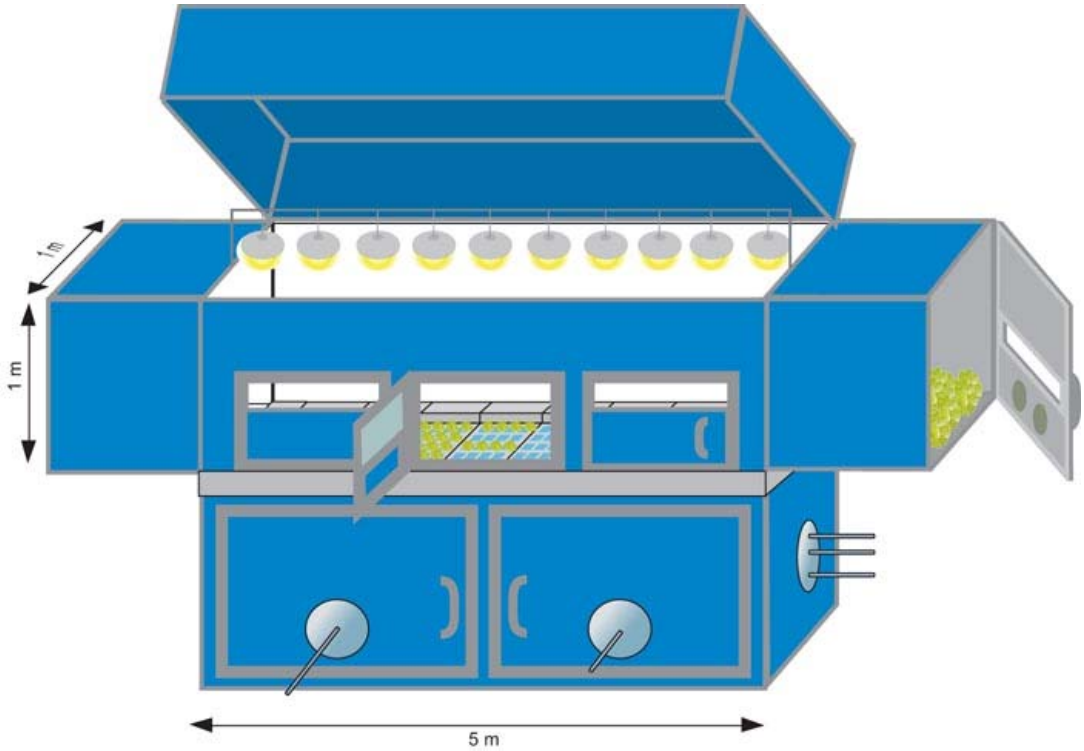


Figure 3.7.3. Diagrammatic representation - Exterior of the exterior of the higher plant chamber designed for integration into the MELiSSA Pilot Plant.

4 HPC Prototype Design – Functional Description

4.1 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 steam 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 steam and chilled water valves effect temperature and dehumidification control of the aerial environment. Steam 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%. It is therefore in the early phases of staged culture establishment, when the photosynthetic leaf area is small, that humidification using the fogging system will most likely be required.

The chamber will be fitted with two 200 litres 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.

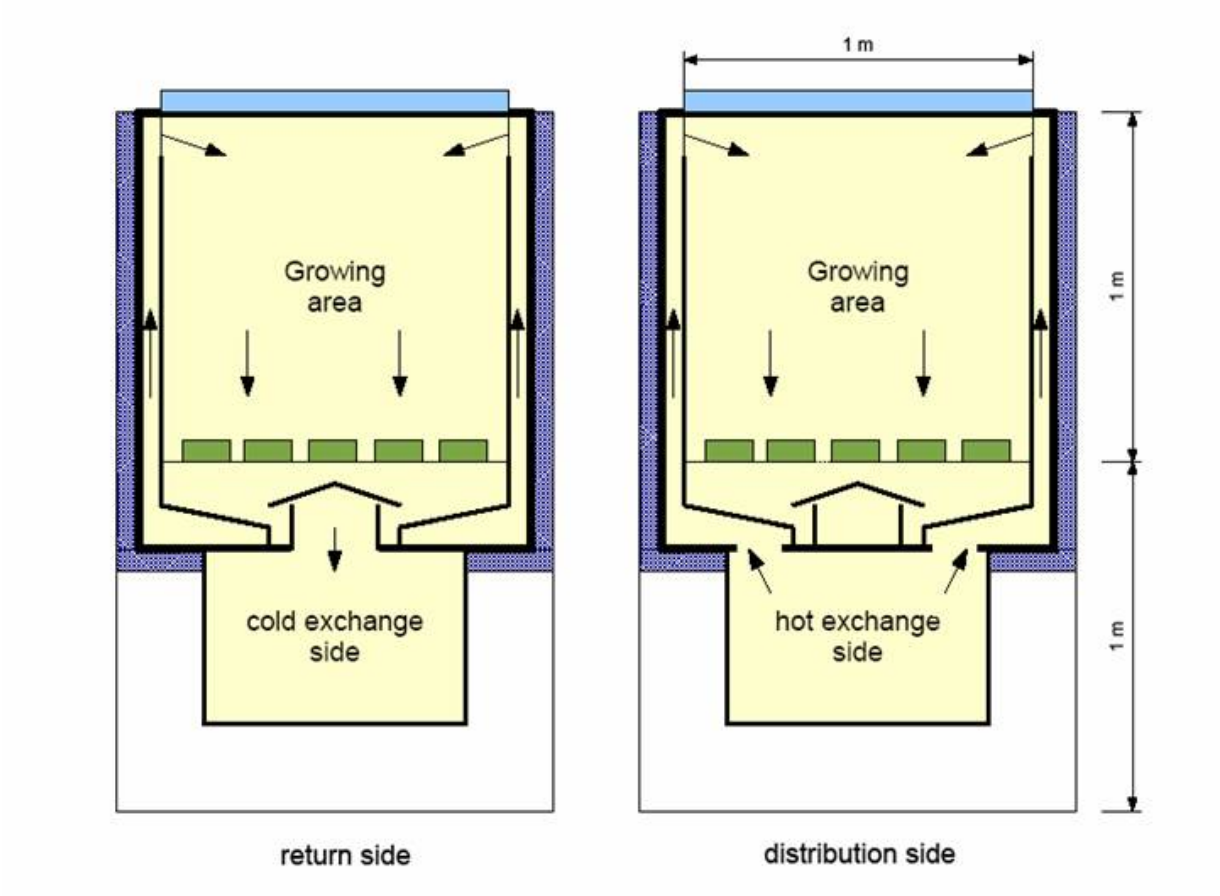


Figure 4.1.1. Representation of the air flow patterns within the prototype. Air moves through a plenum positioned on the side walls of the chamber and through vents (louvers) positioned on the upper side of the growing volume. Return is through vents positioned below the hydroponics tray support.

4.2 Hydroponics System Operation

The nutrient requirements for the plants are supplied in a hydroponic medium stored in a steel 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 hydroponic 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.

4.3 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.

5 HPC Prototype Design – Technical

5.1 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.

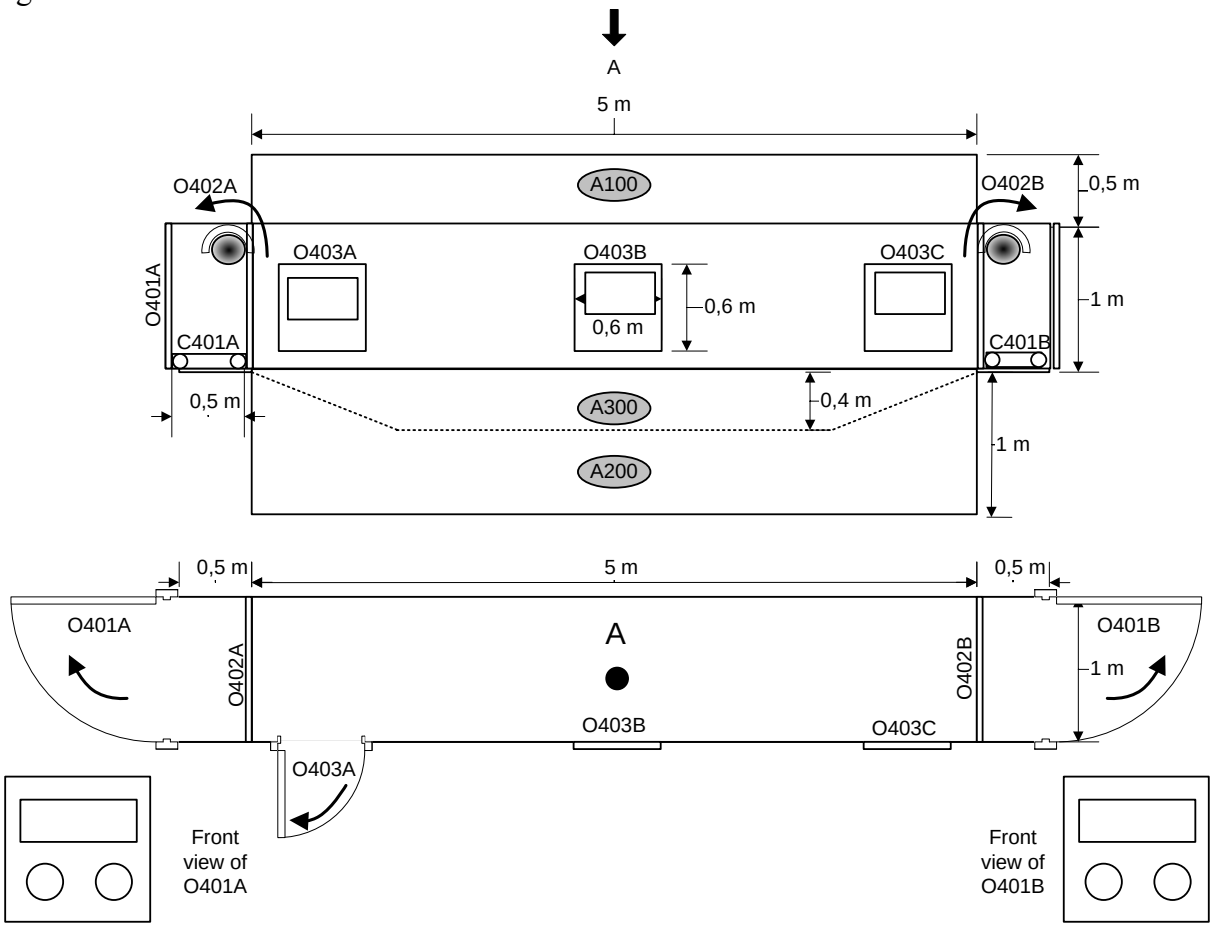


Figure 5.1.1. Schematic of the HPC access air locks (Masot, 2004).

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.

5.1.1 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.

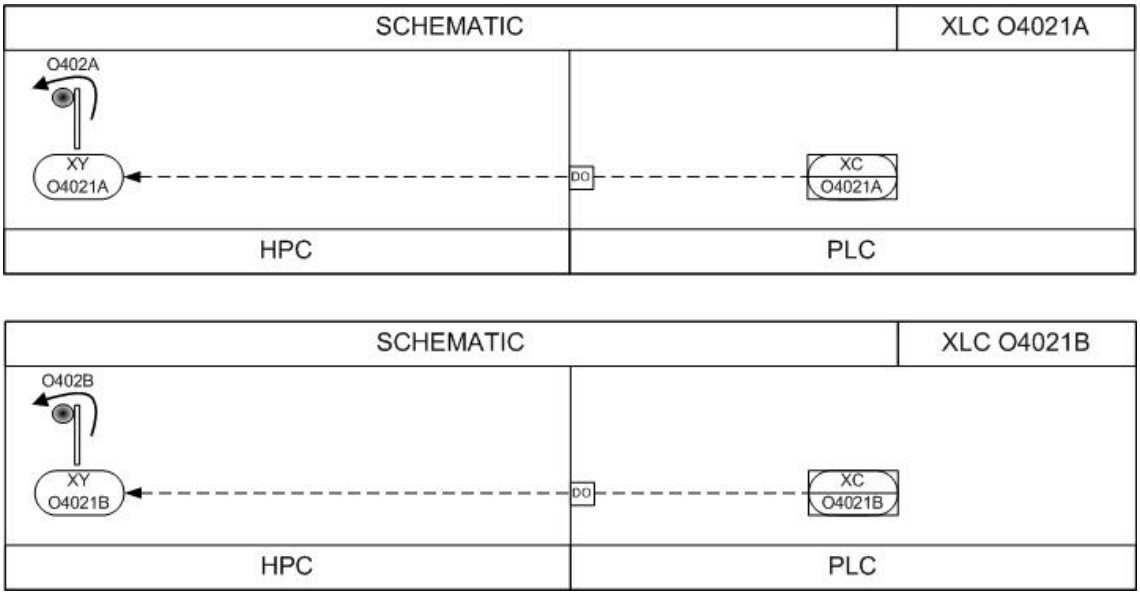


Figure 5.1.2. Control loop schematic for operation of the internal air lock doors (Masot, 2004).

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

5.1.2 N_2 Purge Air Lock Control

Below is a diagrammatic representation of the control loop for N_2 purge of the interior air-lock area.

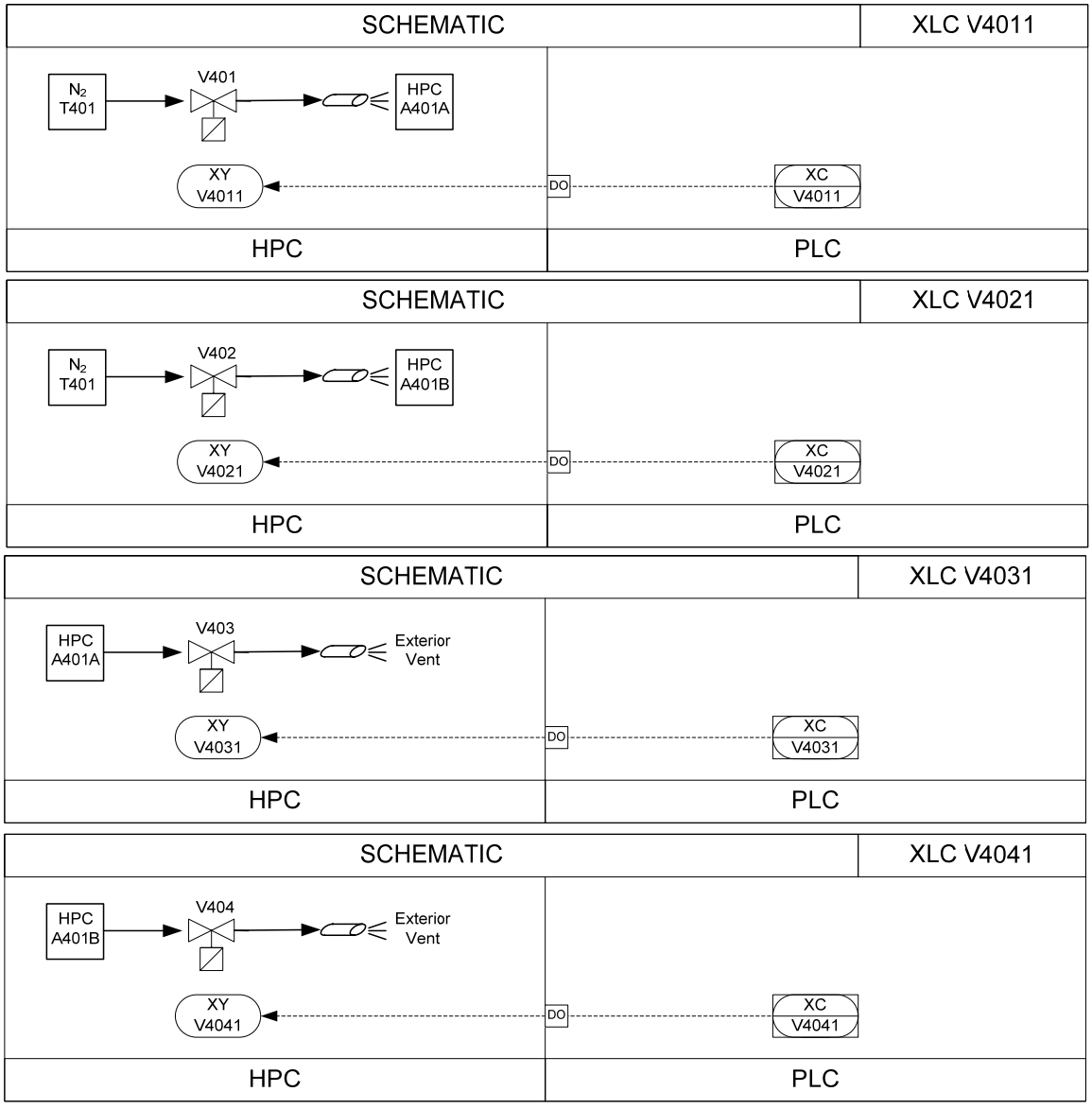


Figure 5.1.3. Control loop schematic for operation of the internal air lock doors (Masot, 2004).

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 or nitrogen gas (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

5.2 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.

5.2.1 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 5.2.1. 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:

$$60\% \times 0.0122 + 40\% \times 0.0141 = 0.01296$$

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

5.2.2 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.

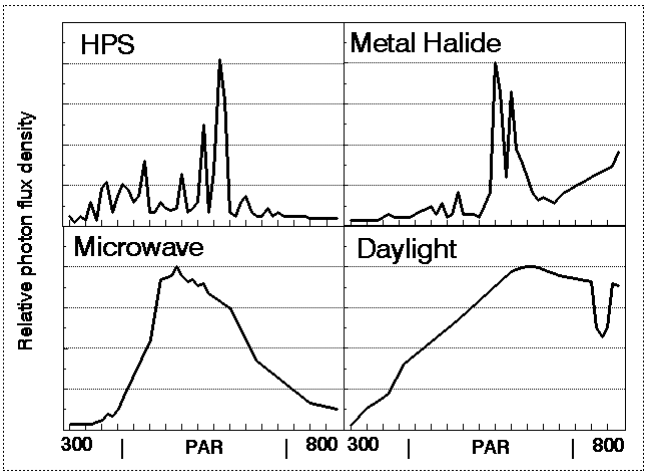


Figure 5.2.1. Relative spectral output of various lamp types in the PAR range.

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.

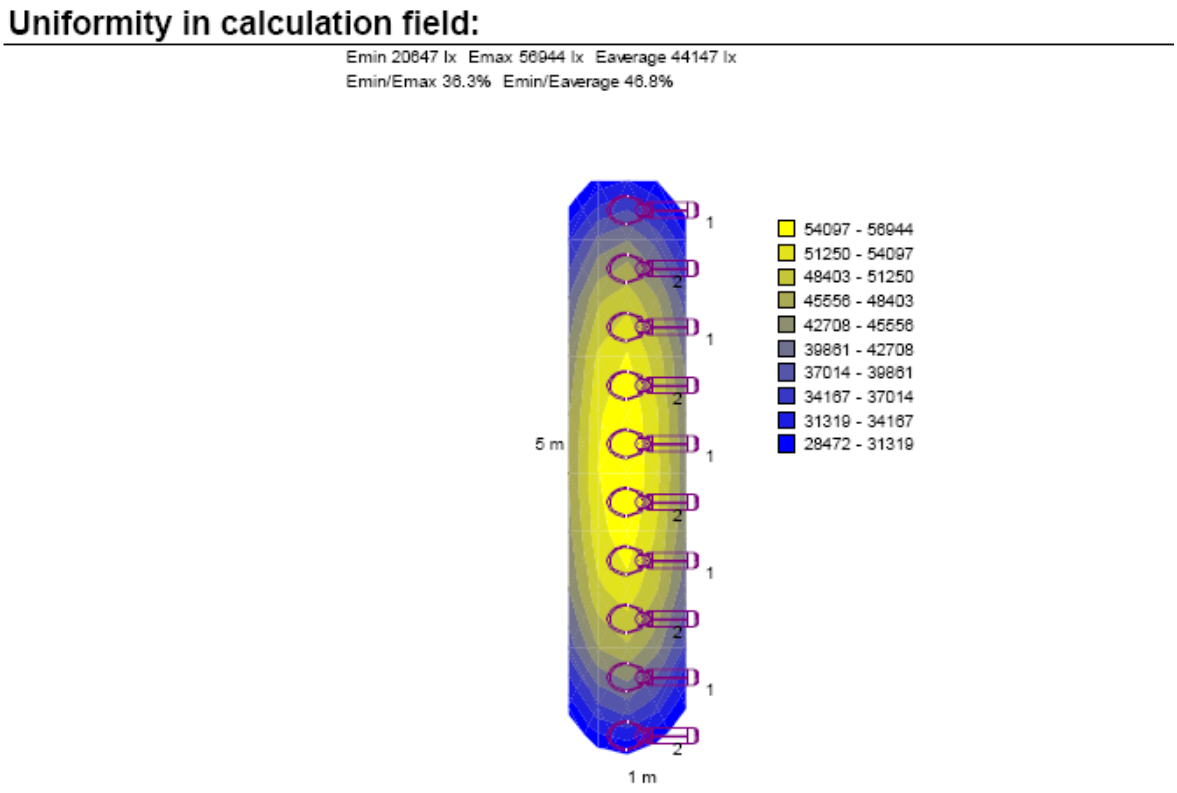
Recommended System: Remote Fixture HPS and MH

It is recommend 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.



To this lighting plan (drawing + computer calculation the "Explanation to the Lightingplan", the supplementary guarantee provisions PL light systems Inc. apply.

Figure 5.2.2. 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.

5.2.3 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.

5.2.4 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).

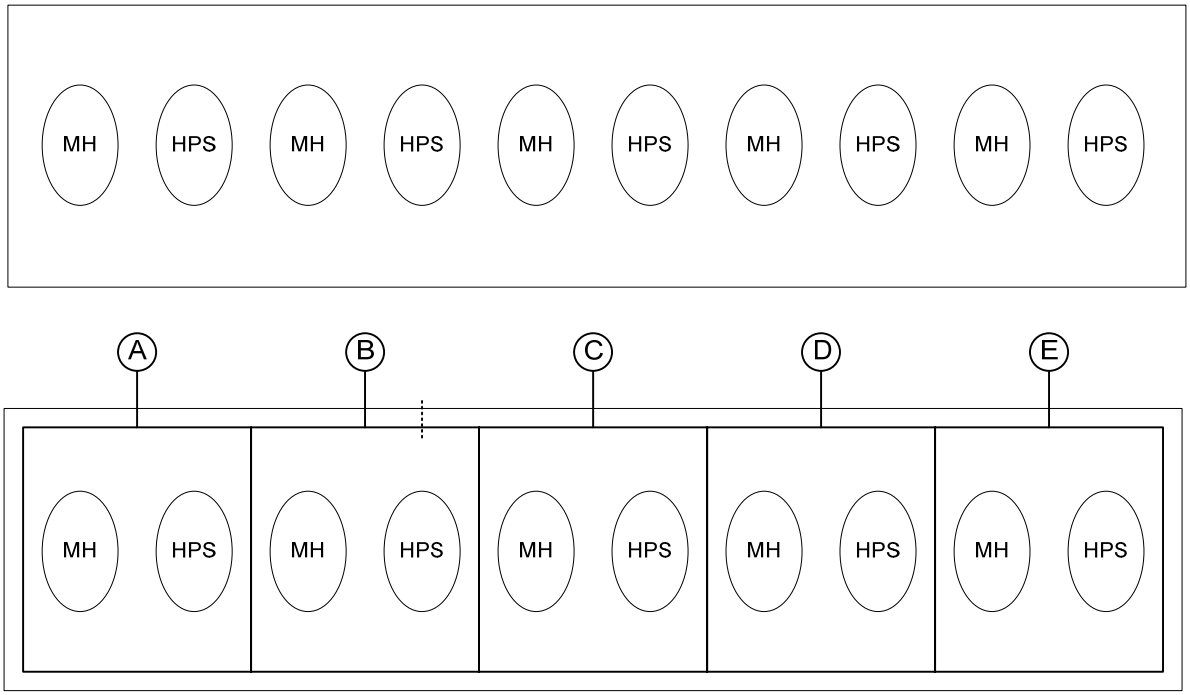


Figure 5.2.3. Lamp distribution in the lighting loft and binary control scenario (Masot, 2004)

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.

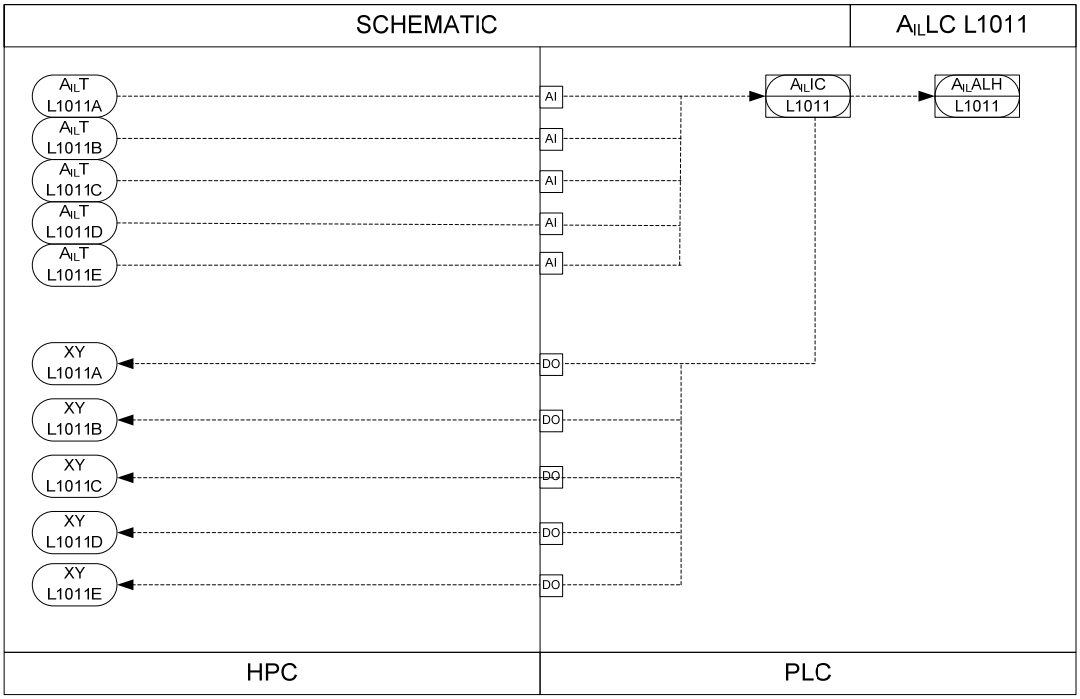


Figure 5.2.4. Light intensity control schematic (Masot, 2004)

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

5.2.5 Lighting Loft Temperature Control

Four copper-constantan thermocouple 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 one exchange of the air loft volume per minute (0.5 m^3 / minute). 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 the cooling of the lamp loft to a maximum of 25° C may be challenging in the summer months at the MPP. If the proposed cooling system based on the chilled air supply to the MPP proves inadequate dedicated air conditioning units may have to be employed in the lamp loft.

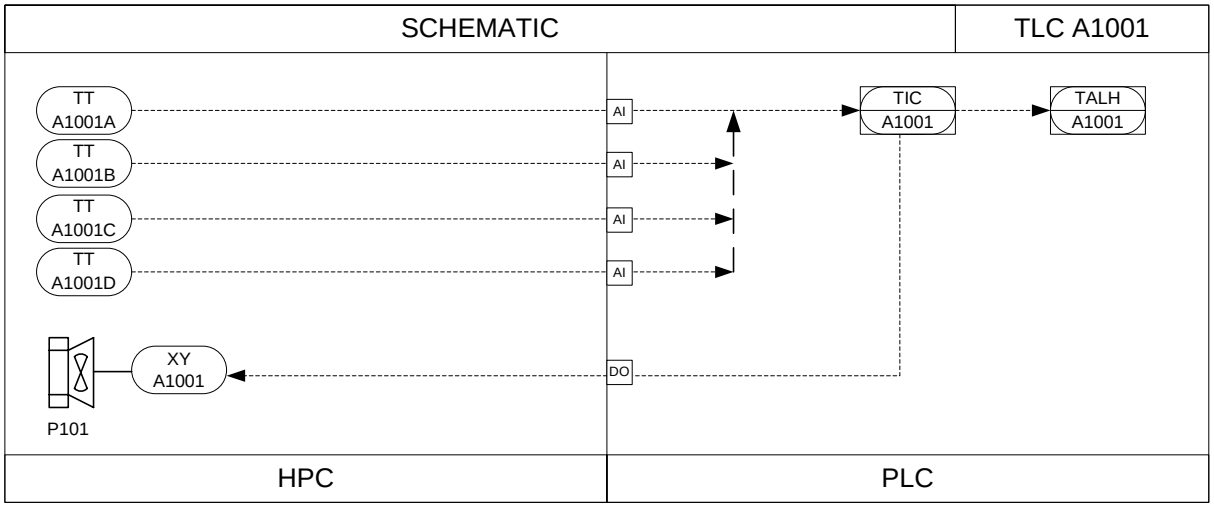


Figure 5.2.5. Control loop schematic for lighting loft temperature (Masot, 2004)

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 a fan (P101). 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:

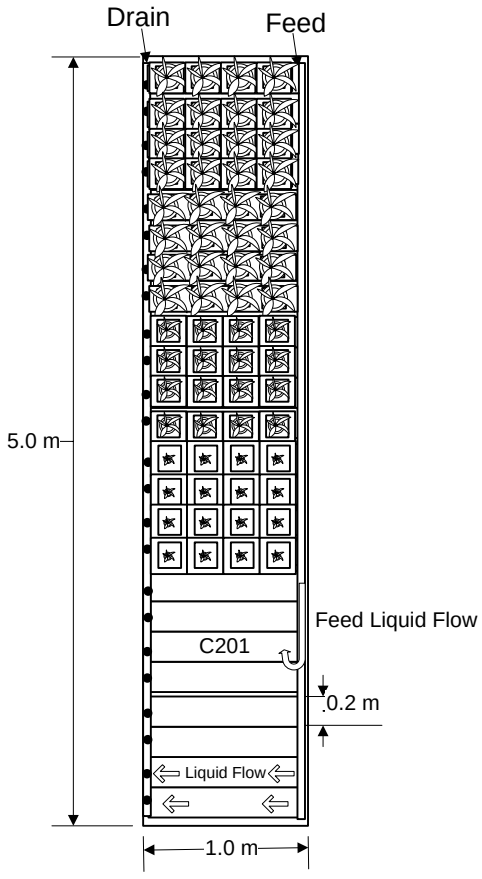
Hardware	Reference
Lighting Loft	A100
Fan and vent with ducting	P101

Instrumentation and Signals:

Instrument	Reference	Signal
Temperature thermocouple	TT A1001A-D	4xAI
Fan Relay	XY A1001	DO

5.3 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.



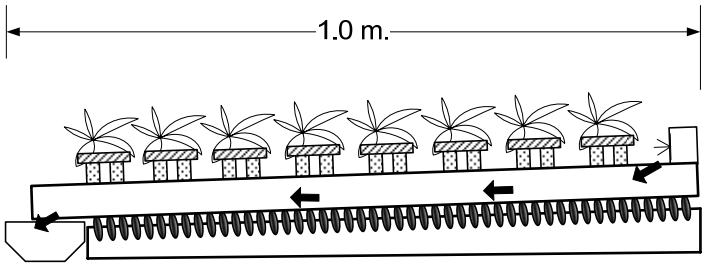


Figure 5.3.1. Representation of the growing trough distribution and in side profile.

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 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 vapor 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)

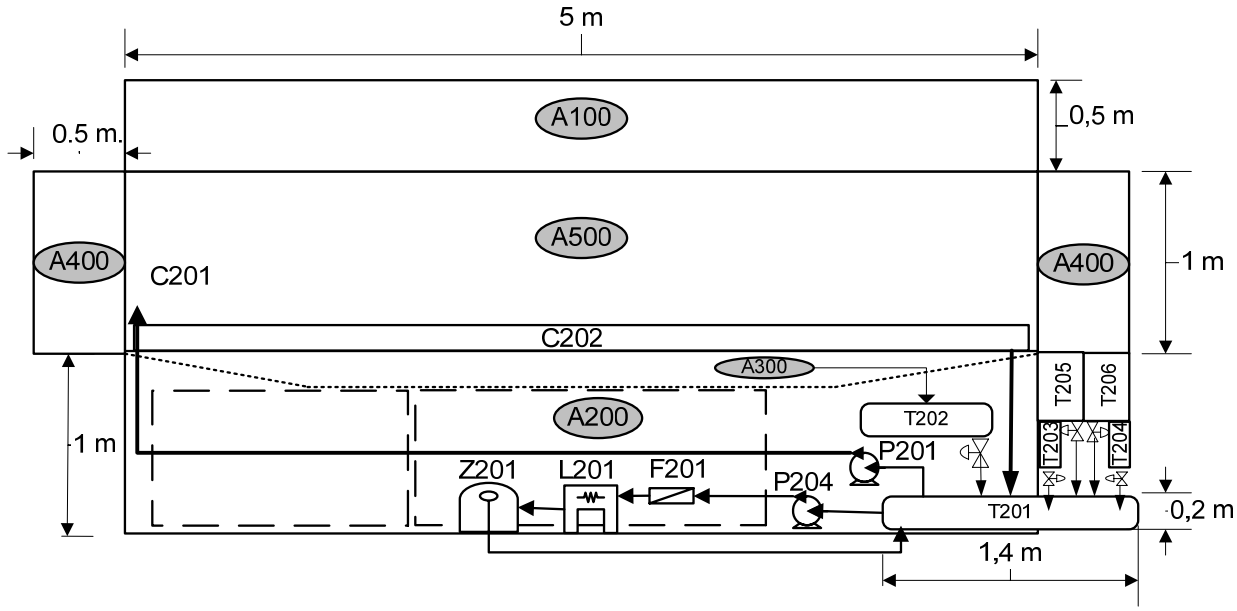


Figure 5.3.2. Representation of the HPC liquid sub-system. The growing troughs, C201, is behind C202 in this profile view. Dotted lines indicate the position of the access panels in the chamber belly.

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.

5.3.1 Hydroponics Reservoir Pump

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

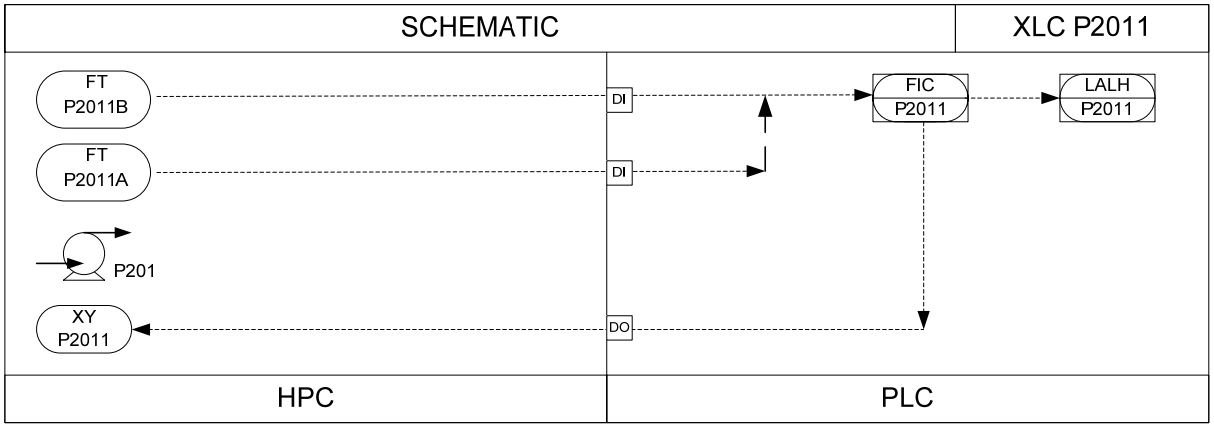


Figure 5.3.3. Control loop schematic for hydroponics plumbing and pumps (Masot, 2004)

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

5.3.2 Control of pH in the Solution

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

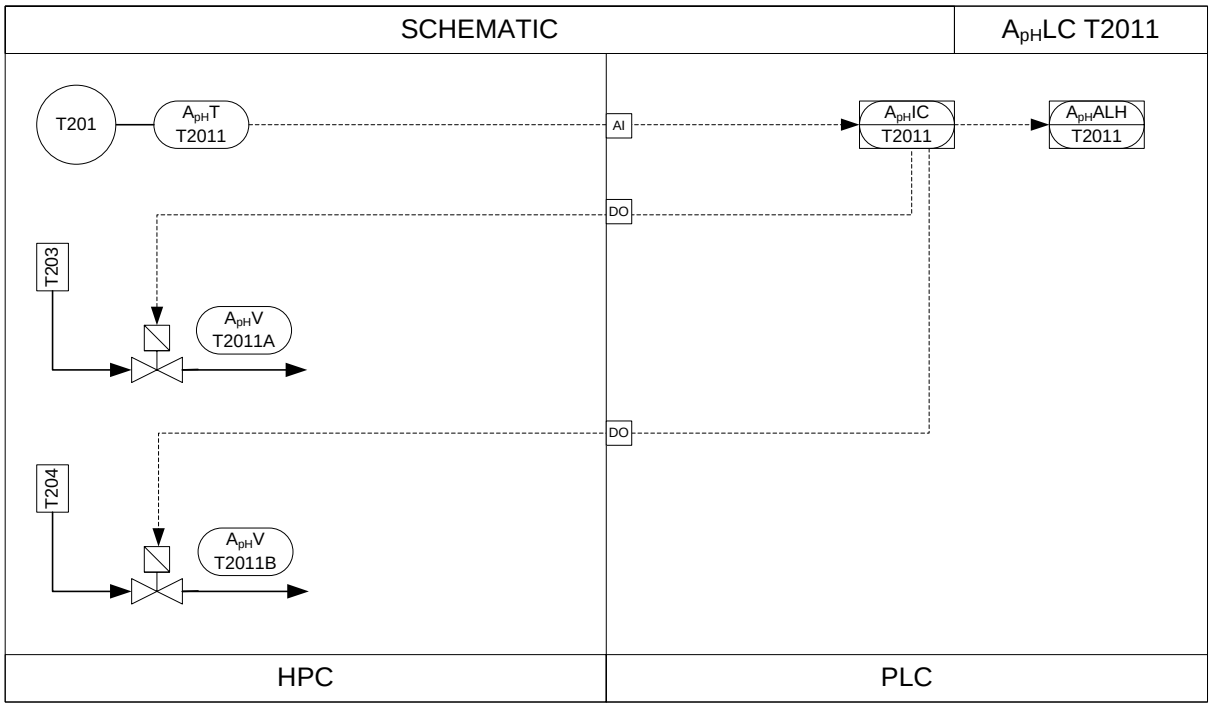


Figure 5.3.4. Control loop schematic for control of pH in the hydroponics solution (Masot, 2004)

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

5.3.3 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 $\mu S^{-1}{}_{m}{}^{-1}$.

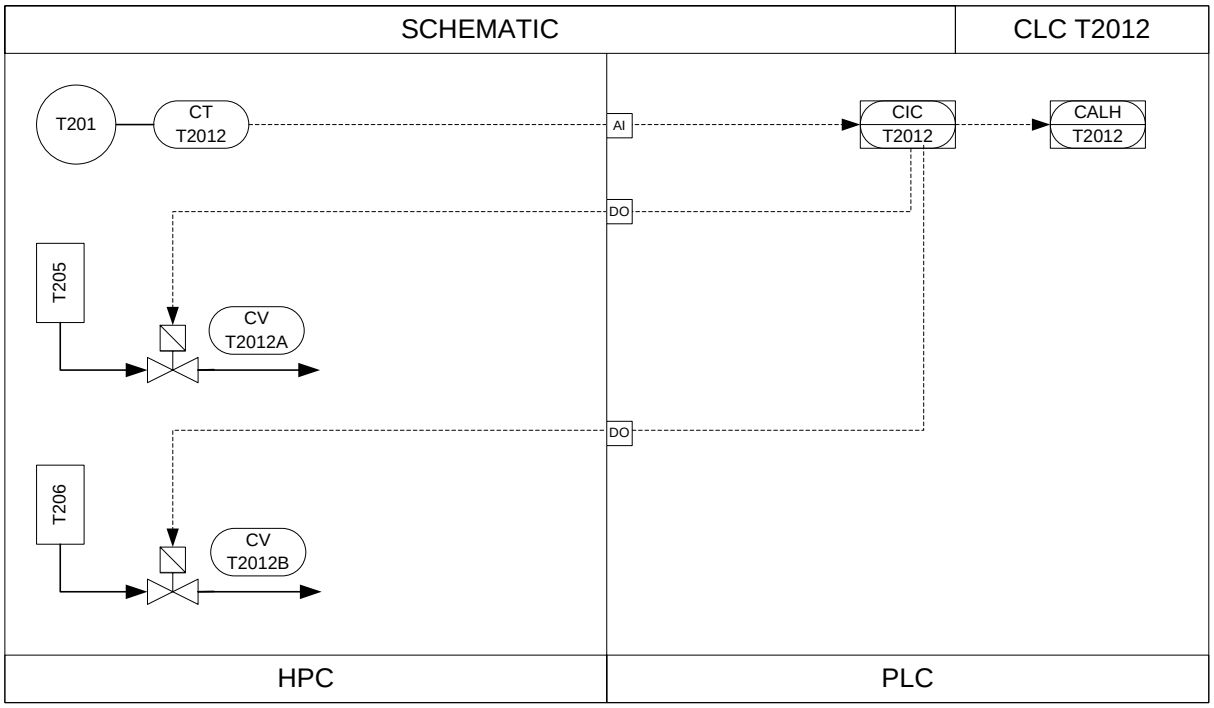


Figure 5.3.5. Control loop schematic for electrical conductivity control in the hydroponics reservoir (Masot, 2004)

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

5.3.4 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.

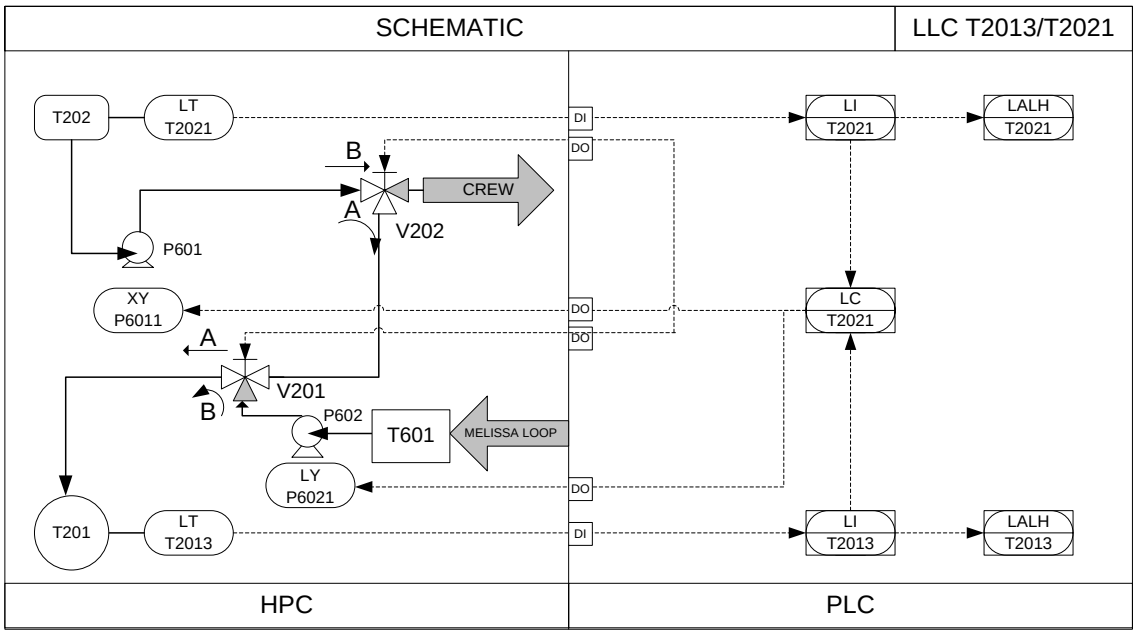


Figure 5.3.6. Control loop schematic for nutrient solution and condensate water levels (Masot, 2004).

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 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

5.3.5 Ultraviolet and Ozone System for Solution Contaminant Control

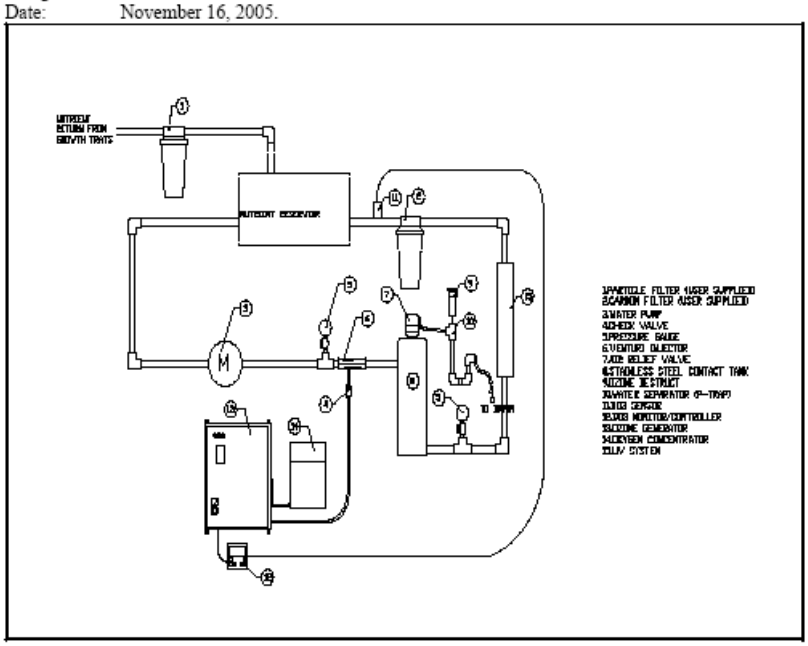
Ultraviolet radiation is to be used as a germicidal agent in the HPC prototype. The dosing of the nutrient solution with wavelengths of UV radiation between 200 – 300 nm is effective at inactivating micro-organisms by altering key metabolic enzymes and nucleic acids. Care must be taken to replace the 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 5.3.7. Preliminary design for the UV/Ozone disinfection systems to be installed on by-pass of the hydroponics system.

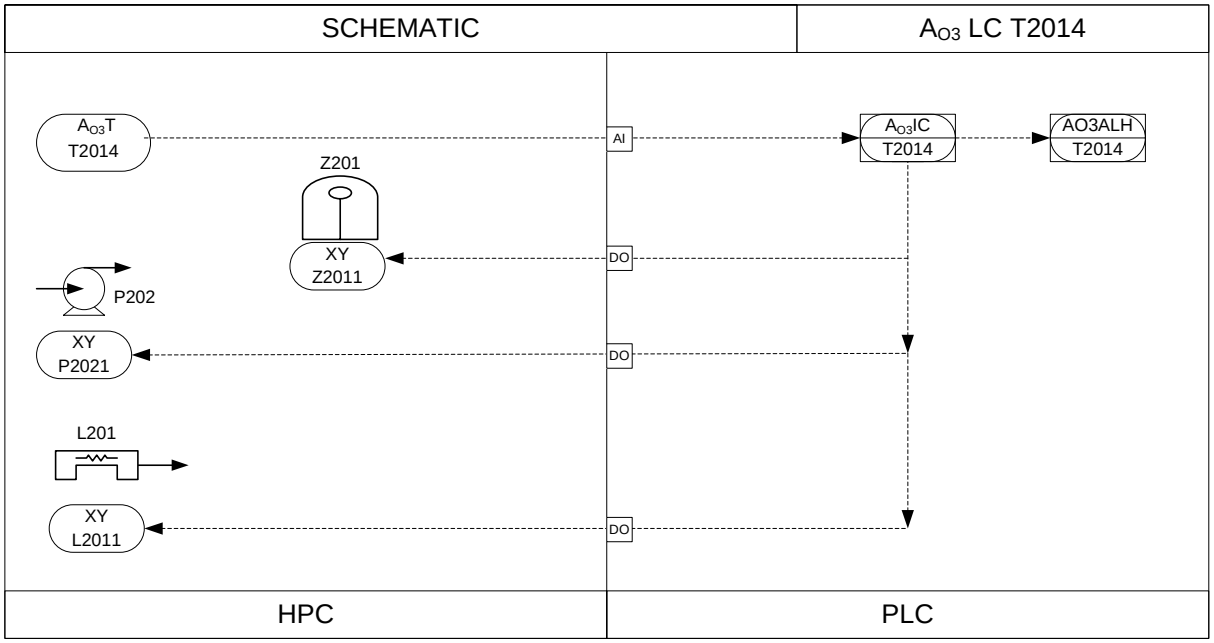


Figure 5.3.8. Control loop schematic for the ultraviolet and ozonation sterilization system.

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	AO_3T 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.

5.4 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.

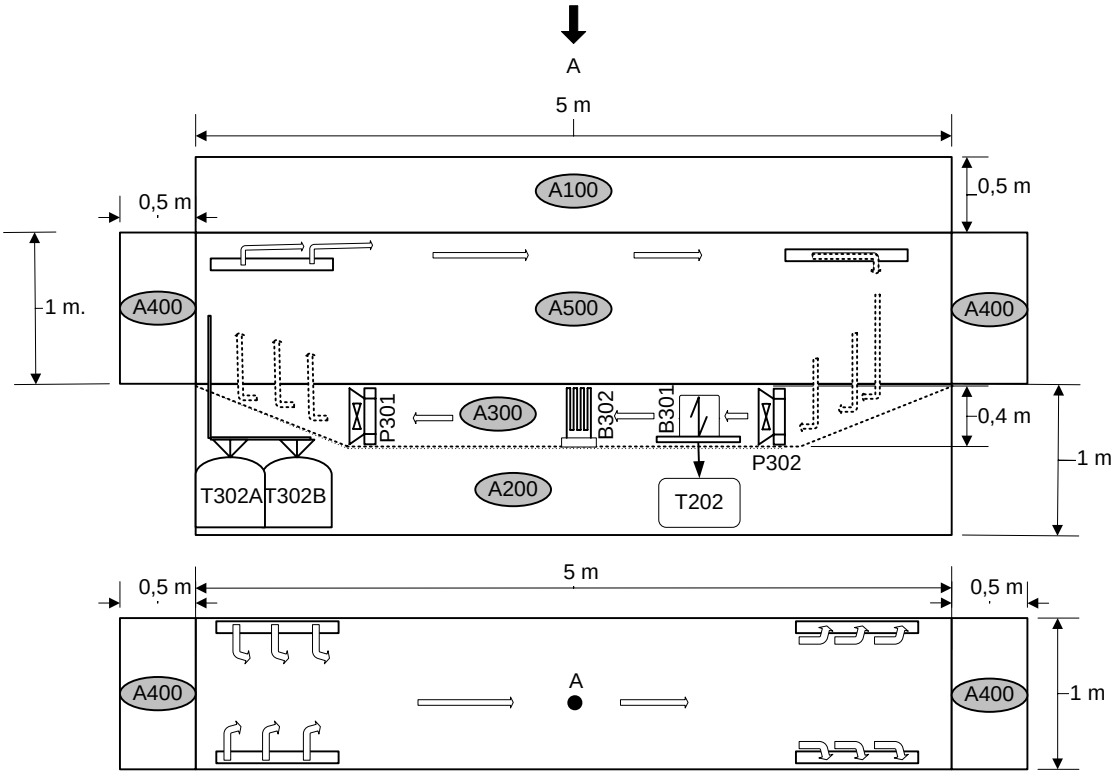


Figure 5.4.1. Air circulation patterns and handling system for the prototype chamber (Masot, 2004).

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 steam and chilled water supplies. In cooling the chamber, chilled water flows through the coil causing the condensation of atmospheric water vapor. 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 vapor into the chamber atmosphere.

5.4.1 Control of Air circulation fans

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

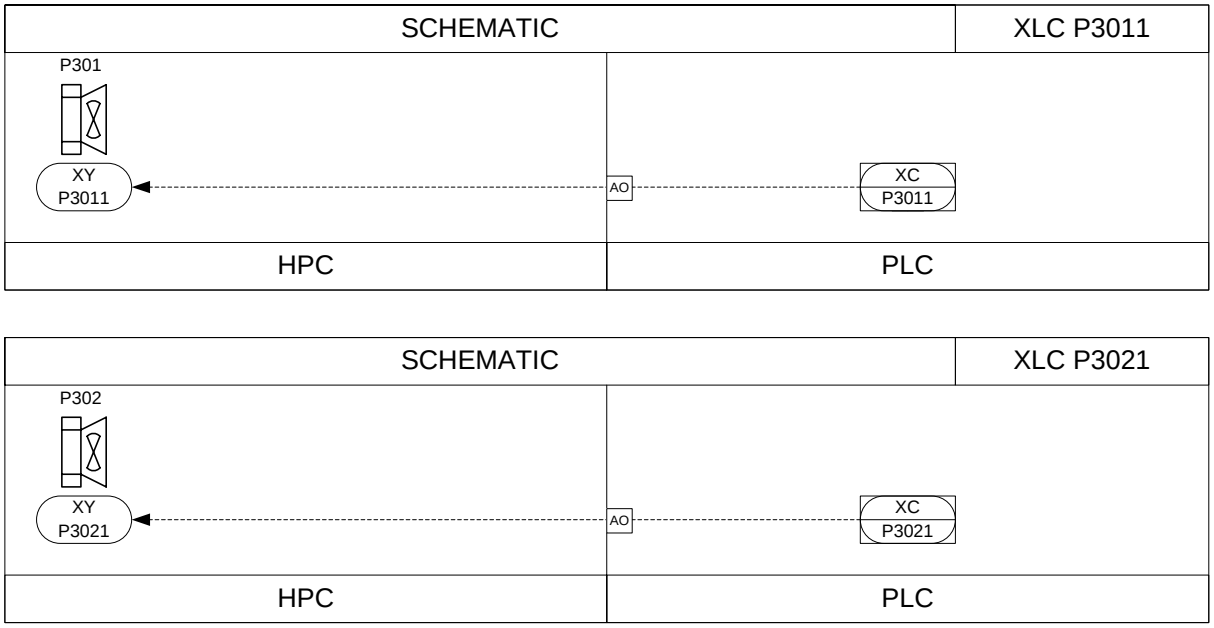


Figure 5.4.2. Control loop schematic for air circulation fans (Masot, 2004)

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

5.4.2 Temperature and Humidity Control

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

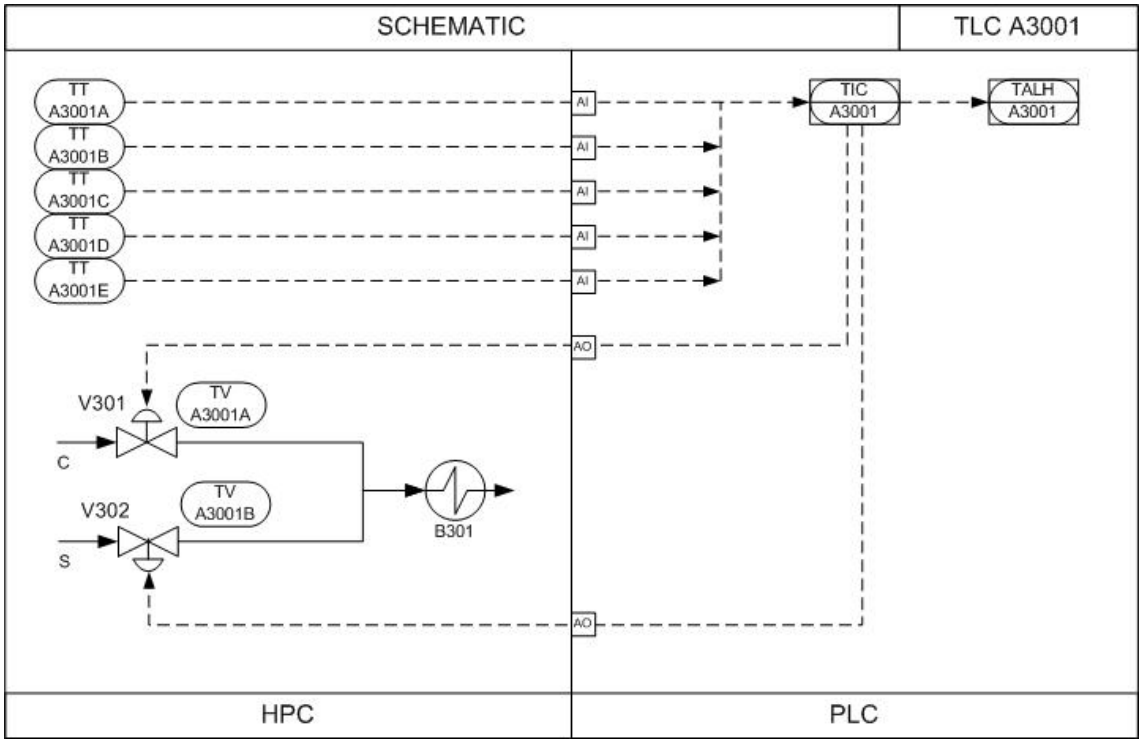


Figure 5.4.3. Control loop schematic for air temperature control (Masot, 2004)

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 vapor 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 steam 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 hydroponic 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 steam (s) is passed through the coil. The entry of steam 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/steam 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.

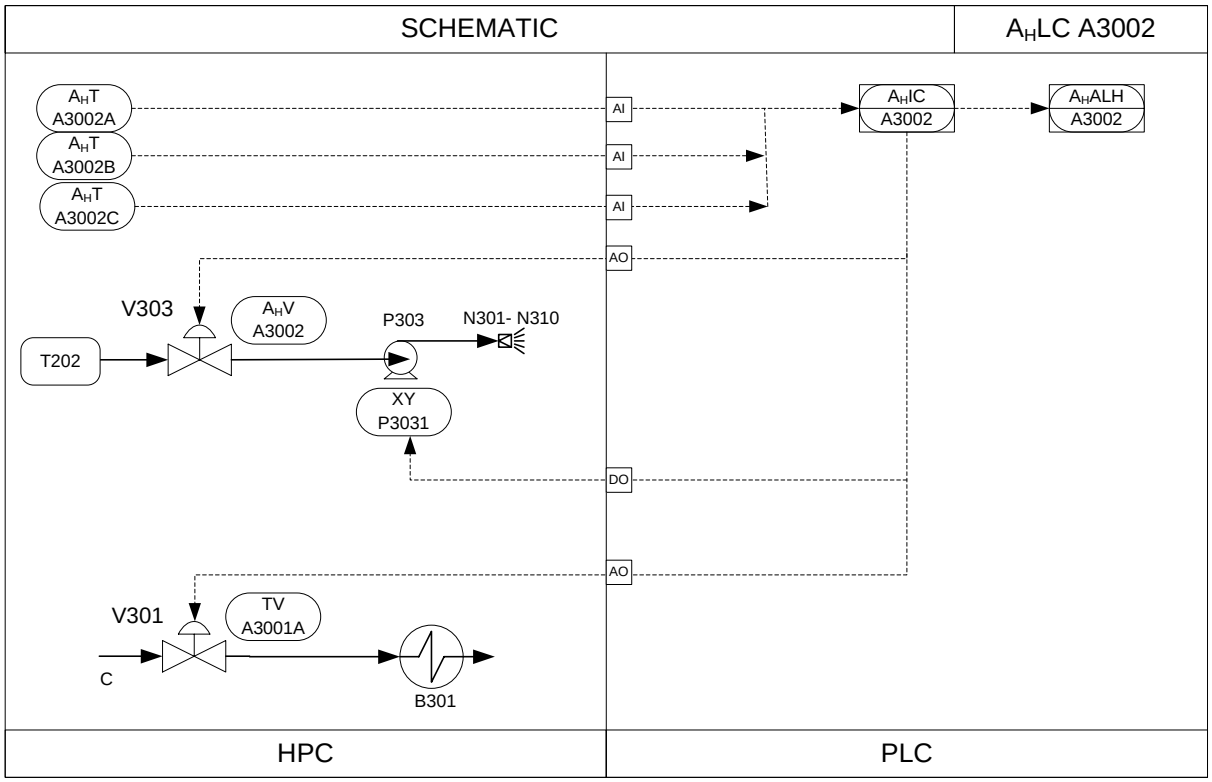


Figure 5.4.4. Representation of the control loop for chamber humidity control.

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 vapor 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 vapor is condensed at the heat exchange coil whenever chilled water is passed through the coil. Atmospheric water vapor may be injected into the chamber whenever humidity or vapor pressure deficit falls below demand levels. This may be accomplished through injection nozzles positioned in the chamber with the purified water for humidification coming from the condensate collection tank (T202) or an external supply. The external water supply may often be required when the crop canopy is not fully developed and transpiration rates affecting condensate recovery are low. If humidity is too high, the controller will regulate the opening of the chilled water valve to supply cooling to the heat exchange coil and to precipitate condensation. Care must be taken so as not to over-condense water resulting in a circulation "chasing" of the water condensation and misting system.

Equipment:

Hardware	Reference
Misting system pump	P303
Misting nozzles (10)	N301 – N310

Instrumentation and Signals:

Instrument	Reference	Signal
Humidity sensor	A_HT A3002A-C	3x AI
Mist regulator valve	A_HV A3002	AO
Relay P303	XY P3031	DO

5.4.3 CO_2 Control

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

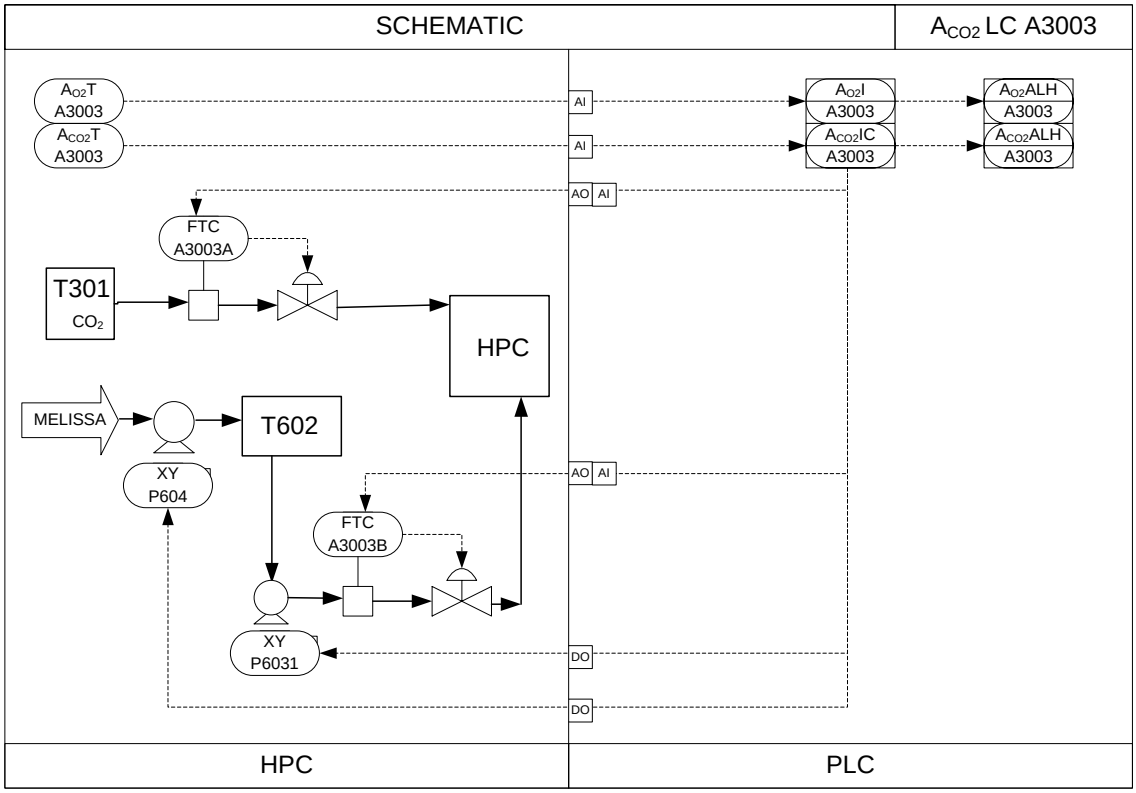


Figure 5.4.5. Control loop schematic for CO_2 levels (Masot, 2004)

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

5.4.4 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

Equipment List, Specifications and Control Requirements

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 5.4.1, Equipment list and specifications for the HPC

Equipment/Part	Quantity	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	Copper-Constantan thermocouple
Fan and vent	1	P101	2.5 m^3 / min
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		0.95 cm (3/8”) OD, steel
Hydroponics troughs, channels	30	C201	Steel, 20cm wide, 1m long
Collecting/return trough	1	C202	Steel 10cm wide, 5 m long
Nutrient solution reservoir	1	T201	Steel, 200L
Condensate collection tank	1	T202	Steel, 20L
Irrigation pump	1	P201	10 L / min (maximum) - TBD
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 centre	1	$A_{O2}T$ T201	TBD
A300 and A500			
Air circulation fans	2	P301, P302	Variable speed, 5 m^3 / min
Temperature Sensors	5	TT A3001A-E	Vaisala
Chilled water valve	1	V301	TBD
Steam valve	1	V302	TBD
Heat exchanger/radiator	1	B301	TBD
Humidity sensors	3	A_HT A3002A-C	Aspirated humidity sensors, Vaisala
Humidification line valve	1	V303	TBD
Humidification line pump	1	P303	TBD
Misting Nozzles and Line	10	N301-310	TBD
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 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 air)	1	T401	Calibrated nitrogen or air gas cylinder with regulator and two way splitter

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	0.63 cm (1/4") 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

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 Scheiner PLC as is consistent with Table 3.3.1.

Table 5.4.2. Summary of control requirements for the HPC

AREA	EQUIPMENT	AI	AO	DI	DO	TOTAL
A100	L101	5			5	10
	A100	4			1	5
	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**

6 Chamber Interface with the MPP

The conceptual points of interface between the HPC and the MPP were represented in the diagrams of Figure 2.4.1 and Figure 2.4.2. The major points for the HPC are described below for the gas, solid, liquid and utility interfaces.

6.1 Liquid Interface

The liquid interface between the HPC and the HPC 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.

6.2 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.

6.3 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).

6.4 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 steam lines are also required to feed the HPC directly from the MPP for temperature control through regulator valves (V301 and 302).

7 Control Law for 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.

7.1 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)

$$P_n = \frac{C_a - C_i}{r_{dc}} \qquad \textbf{Equation 7.1.1}$$

$$P_n = \frac{O_i - O_a}{r_{do}} \qquad \textbf{Equation 7.1.2}$$

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;

$$P_n = \frac{\alpha \cdot I \cdot \left(\frac{C_i}{r_x} - \frac{O_i}{r_p} \right)}{\alpha \cdot I + \frac{C_i}{r_x} + \frac{O_i}{r_p}} - R \qquad \textbf{Equation 7.1.3}$$

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.

$$I(l) = I_0 \cdot \frac{k}{1-m} \cdot e^{-k \cdot l} \qquad \textbf{Equation 7.1.4}$$

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)

$$k = (1 - m) \cdot \xi \cdot \zeta \qquad \textbf{Equation 7.1.5}$$

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

$$P = \int_0^l \left[\frac{\alpha \cdot I_0 \cdot e^{-k \cdot l} \cdot \left(\frac{C_{bs}}{r_x} - \frac{O_{bs}}{r_p} \right)}{\alpha \cdot I_0 \cdot e^{-k \cdot l} + \frac{C_{bs}}{r_x} + \frac{O_{bs}}{r_p}} - R \right] \cdot dl \qquad \textbf{Equation 7.1.6}$$

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,

$$R = k_p \cdot P_n + c \cdot W \qquad \textbf{Equation 7.1.7}$$

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.

$$\frac{dl}{dt} = \frac{P \cdot L_{plant} \cdot SLA}{C_{leaf}} \quad \textbf{Equation 7.1.8}$$

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.

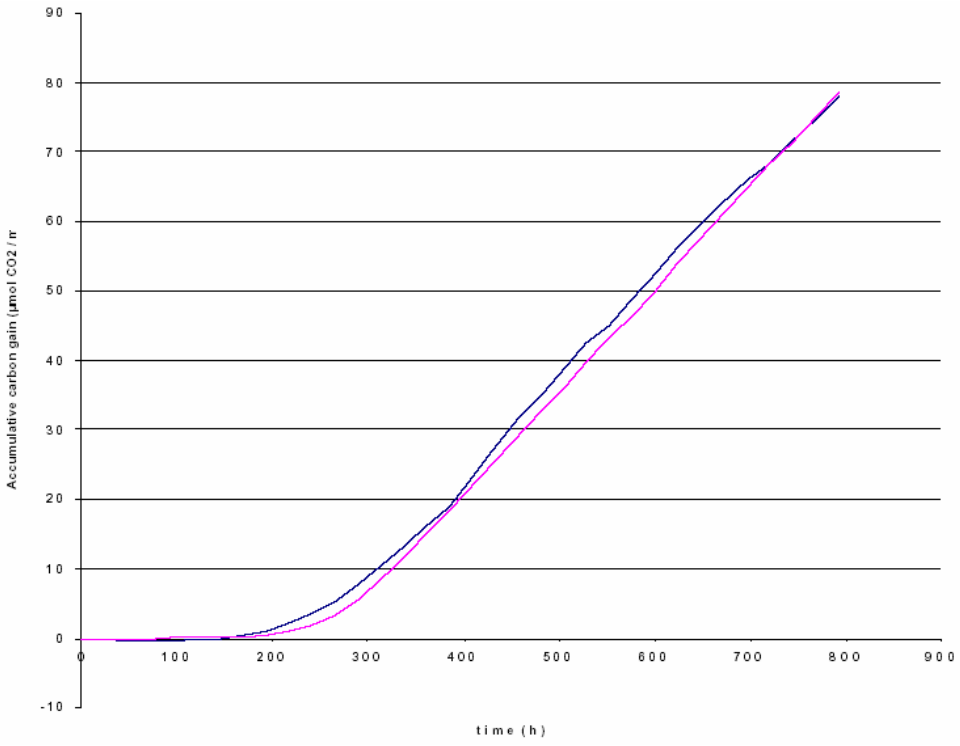


Figure 7.1.1. Comparison between lettuce experimental results (blue) and simulation results (pink) - Accumulated Carbon Gain (mol C)

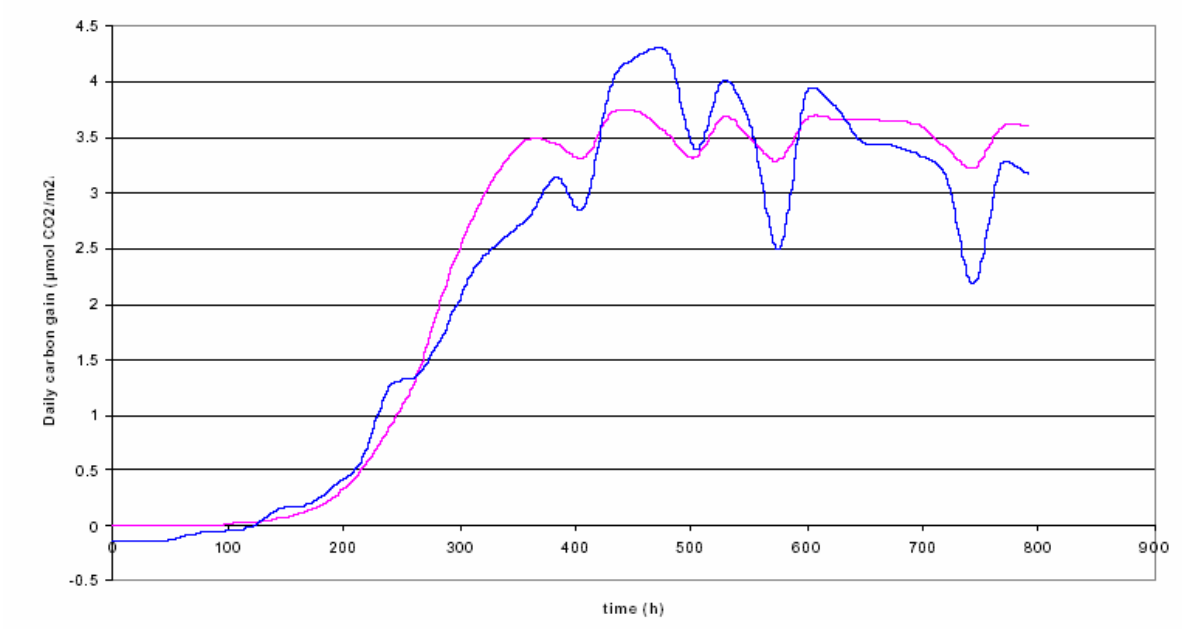


Figure 7.1.2: Comparison between lettuce experimental results (blue) and simulation results (pink) - Daily Carbon Gain (mol C / d)

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

Table 7.1.1. Lettuce model parameters

Parameter	Value	Units
C	1000	ppm
O	21	%
l_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 7.1.3 and Figure 7.1.4. shows the values of the parameters which resulted from fitting the beet model to experimental data. Table 7.1.2 presents estimations of model parameters for fits on beet experimental data.

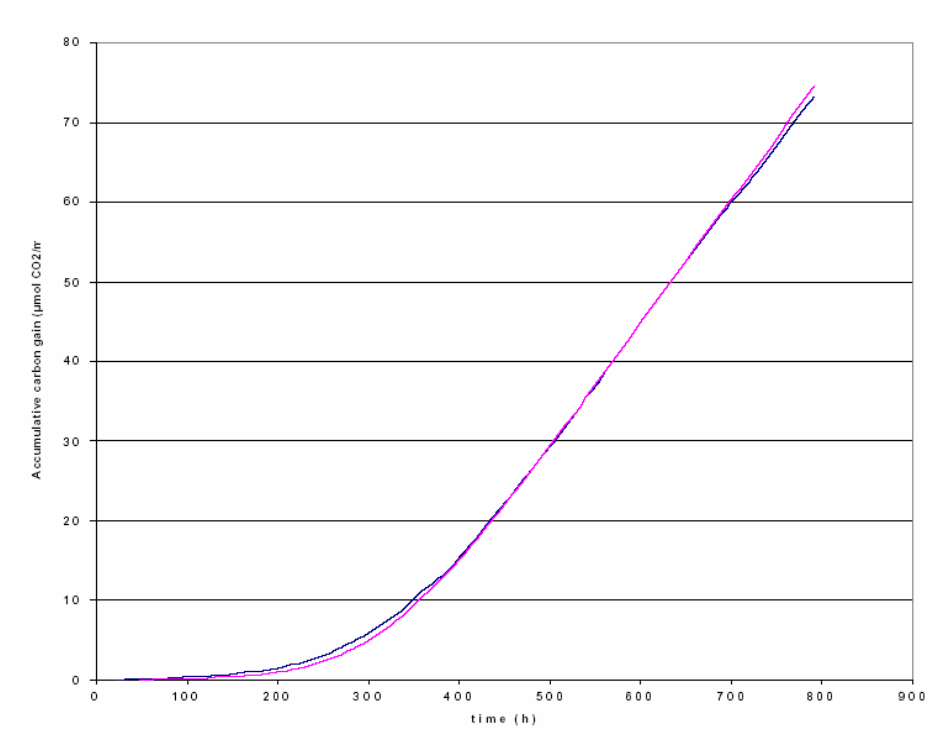


Figure 7.1.3: Comparison of beet experimental results (blue) with simulation results (pink) - Accumulated Carbon Gain (mol C)

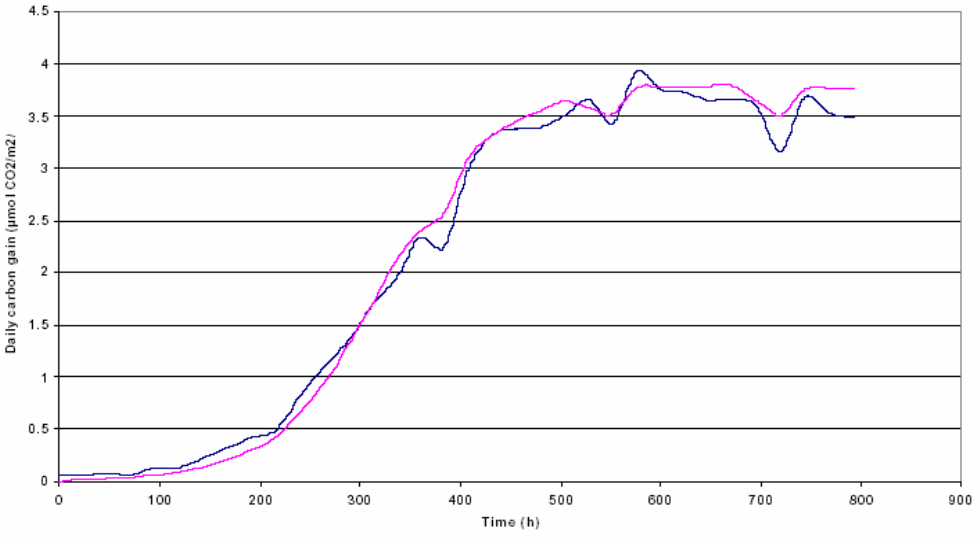


Figure 7.1.4: Comparison of beet experimental results (blue) with simulation results (pink) - Daily Carbon Gain (mol C / d)

Table 7.1.2. 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.

7.2 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:

$$RGR(t) = \frac{NCER(t)}{\int_{t=0}^{t} NCER(t) \cdot dt} \qquad \textbf{Equation 7.2.1}$$

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:

$$U\eta(t) = \frac{NCER(t)}{\int_{t=0}^{t} NCER(t) \cdot dt} \cdot \int_{t=0}^{t} U\eta(t) \cdot dt \qquad \textbf{Equation 7.2.2}$$

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

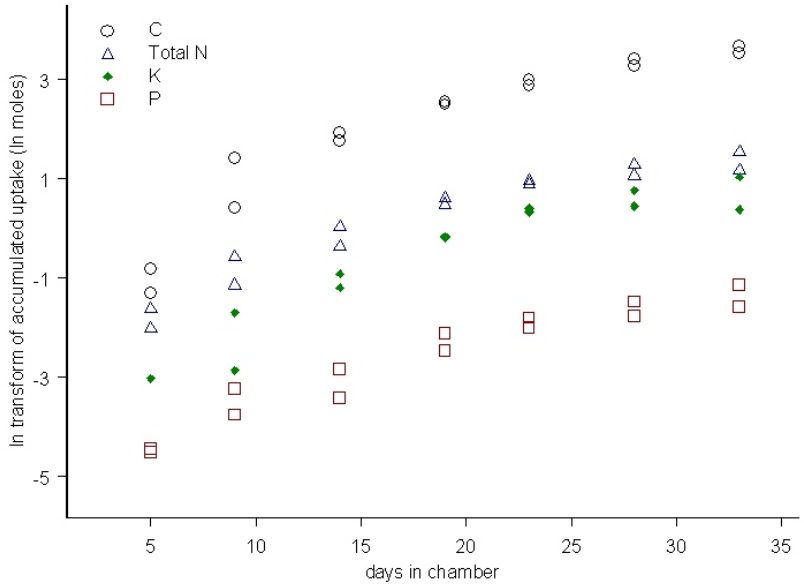


Figure 7.2.1. Patterns of the ln transform of nutrient uptake for beet canopies grown in a sealed environment chamber.

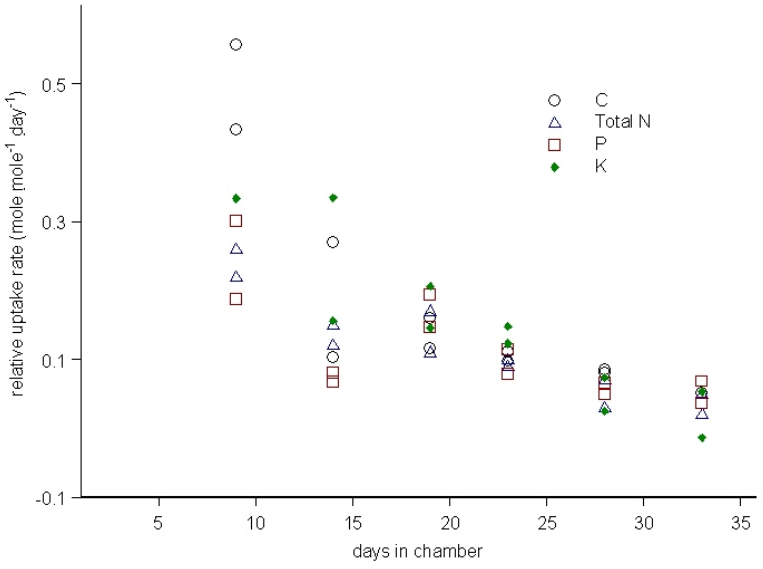


Figure 7.2.2. Relative nutrient and carbon uptake for beet canopies grown in a closed environment

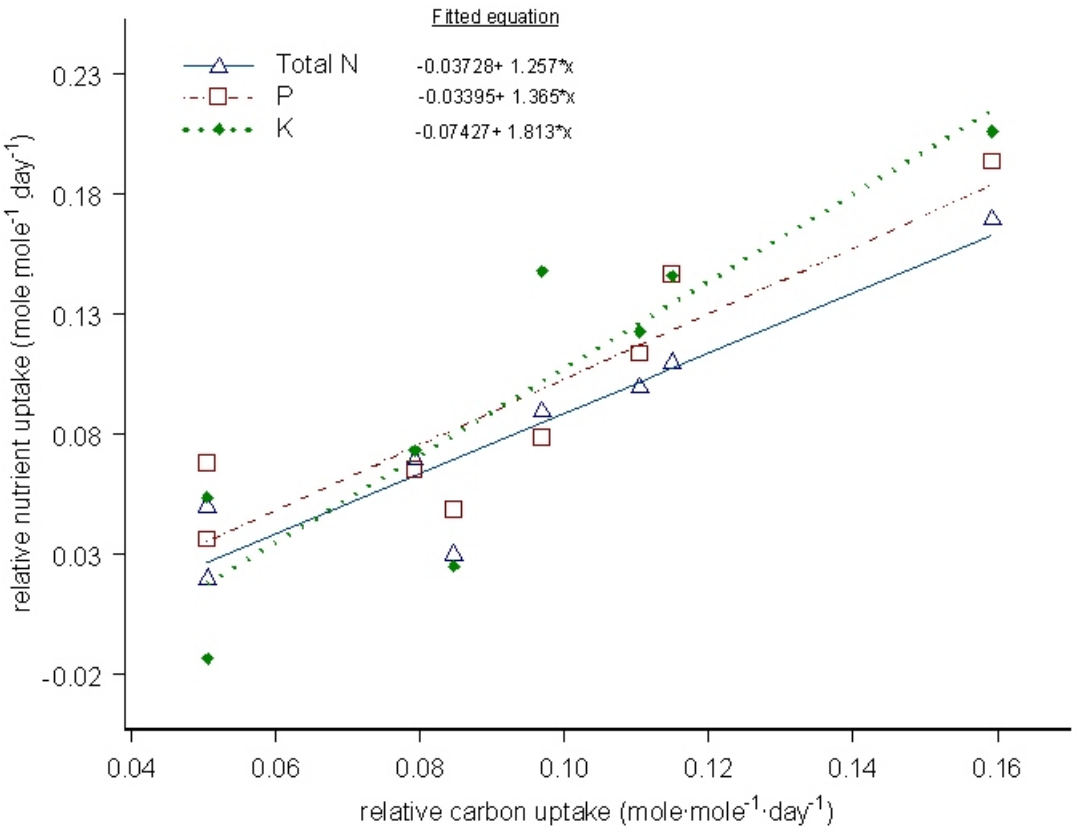


Figure 7.2.3. Relationships between relative nutrient uptake rate and relative carbon uptake rate derived from NCER analysis.

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.

8 Other Design Considerations

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

8.1 Aesthetics

The chamber should have an exterior color 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.

8.2 Transportation and HPC construction on Site

No single dimension of chamber 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.

8.3 Labour Requirement

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

8.4 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.

9 Typical Chamber Maintenance and Operational Scenarios

9.1 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.

9.2 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.

9.3 Chamber Operating Procedures

9.3.1 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 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 condensate collection and nutrient and acid/base stock reservoirs should be autoclaved prior to experiment start. The nutrient solution reservoir may be thoroughly cleaned but will likely be too large to be autoclaved.

9.3.2 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 9.3.1. Typical demand set-points for HPC operation verification tests.

Parameter	Demand Set-Point	Part Verification
Temperature	30 to 10 °C (5 °C intervals)	Chiller/steam 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.

9.3.3 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.

9.3.4 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 9.3.2. 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.

9.3.5 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)

9.3.6 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.

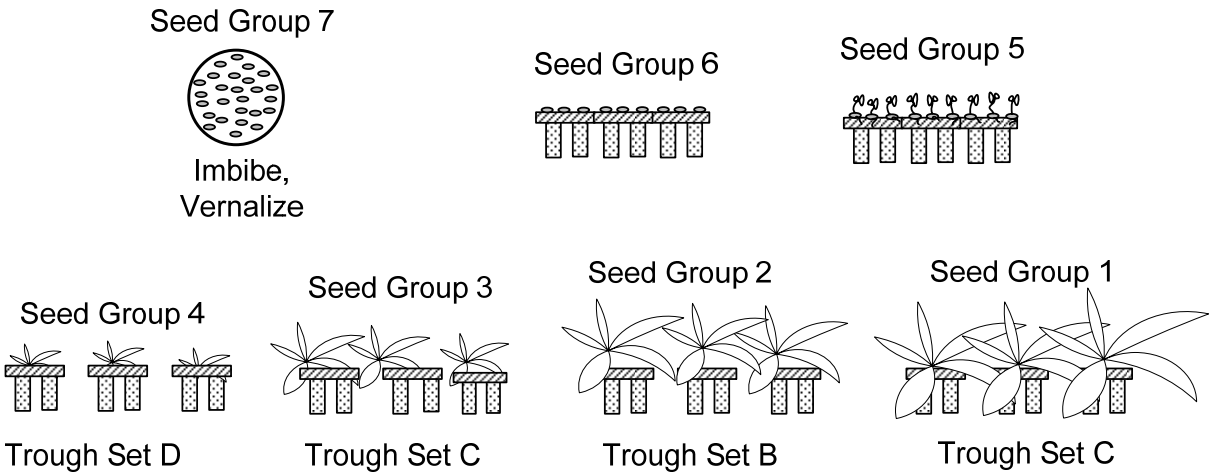


Figure 9.3.1. Profile diagram of seed groups and trough sets used in the staged planting trials as would be achieved on Day 60 of a staged culture experiment.

9.3.7 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).

9.3.8 Regular Chamber Maintenance Procedures

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. Appropriate plumbing and solenoids are dedicated to this automated calibration system and are described at the detailed design level.

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.

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.

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11 Acknowledgements

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Much of the work presented in this technical note was compiled by A. Masot while a master's student at UAB.

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	Explanation
A	HPC area
B	Condenser, Resistance
C	Chanel, Conveyor
F	Filter
H	Hydroponics Troughs
L	Lamp
O	Open, access 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	Analyzed Variable (1)	Alarm
C	Conductivity	Controller
F	Flow	
H		High (2)
I		Indicator
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 indicates analyzed 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 composed by a 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: Indicator (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/High (LW) for light intensity (AIL) in the first (1) control loop for lamps (L101).