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PRELIMINARY DESIGN OF A PLANT CHARACTERIZATION UNIT

prepared by/*préparé par*	Michael Stasiak, Martin Weihreter
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List of Abbreviations

AC:	Air Conditioning
ALS:	Advanced Life Support
CFD:	Computational Fluid Dynamics
CS:	Control System
DIN:	Deutsches Institut für Normung (German Institute for Standardization)
DO:	Dissolved Oxygen
EMI:	Electromagnetic Interference
FC:	Food Characterization (project)
GUI:	Graphical User Interface
HPS:	High Pressure Sodium
HVAC:	Heating, Ventilation and Air Conditioning
IRGA:	Infrared Gas Analyzer
I/O:	Analog and digital inputs, analog and digital outputs
IP:	Internet Protocol
MH:	Metal Halide
NCER:	Net Carbon Exchange Rate
NFT:	Nutrient Film Technique
PAR:	Photosynthetically Active Radiation
PCU:	Plant Characterization Unit
P&ID:	Piping and Instrumentation Diagram
PLC:	Programmable Logic Controller
PPFD:	Photosynthetic Photon Flux Density
PPU:	Plant Production Unit
RH:	Relative Humidity
RIO:	Remote Input/Output
UPS:	Uninterruptible Power Supply
VOC:	Volatile Organic Compound
VPD:	Vapor Pressure Deficit

Glossary

Gully:	Also known as trough or gutter. Inclined channel used in hydroponic systems to hold the roots, and where the nutrient solution flows through.
PCU:	An array of three independent chambers used to grow plants in separate environments. The three separate subunits are used to achieve statistical reliability through independent parallel repeats by keeping a maximum of flexibility. Several PCUs (composed of three subunits each) will be installed in different laboratories.
PCU subunit:	A single independent plant growth chamber. Three PCU subunits outline one complete PCU as it is installed in a laboratory.

1. Introduction

The purpose of this technical note is to present the preliminary design of the Plant Characterization Unit (PCU) which is based on previous technical notes within this contract, as well as on consultation with FC1 partners and external consultants. A preliminary component listing is included in Appendix 1 and includes all components referenced within this document. Critical areas that require further investigation will be noted and will be discussed in a subsequent technical note (TN 98.8.3 'Study Of Critical Subsystems And Selection Of Most Suitable Technologies').

The PCU preliminary design consists of three identical subunits, each capable of autonomous operation (Fig. 1 and Fig. 2). Each subunit consists of five primary subsystems:

- Hydroponic subsystem (nutrient delivery)
- Illumination subsystem (lighting)
- HVAC subsystem (environment control)
- Chamber shell
- Control subsystem (only EPIC cabinets, see chapter 3.9)

In order to reduce complexity, some components are shared between the three subunits. This allows for more efficient operation and the ability to add additional subunits with relative ease in the future without limiting the independent work of each subunit. Shared components include:

- Control system PLC (centralized control, see chapter 3.9)
- Hot water supply for heating in HVAC heat exchangers
- Chilled water supply for cooling in HVAC heat exchangers
- Carbon dioxide supply (gas bottles and distribution hardware)
- 4 Stock solution tanks (2x EC and 2x pH, visible on the right side of Fig. 2)
- HMI (schematically represented left next to the stock solution tanks in Fig. 2)
- Gully/plant manipulation hardware (tray for insertion of gullies)

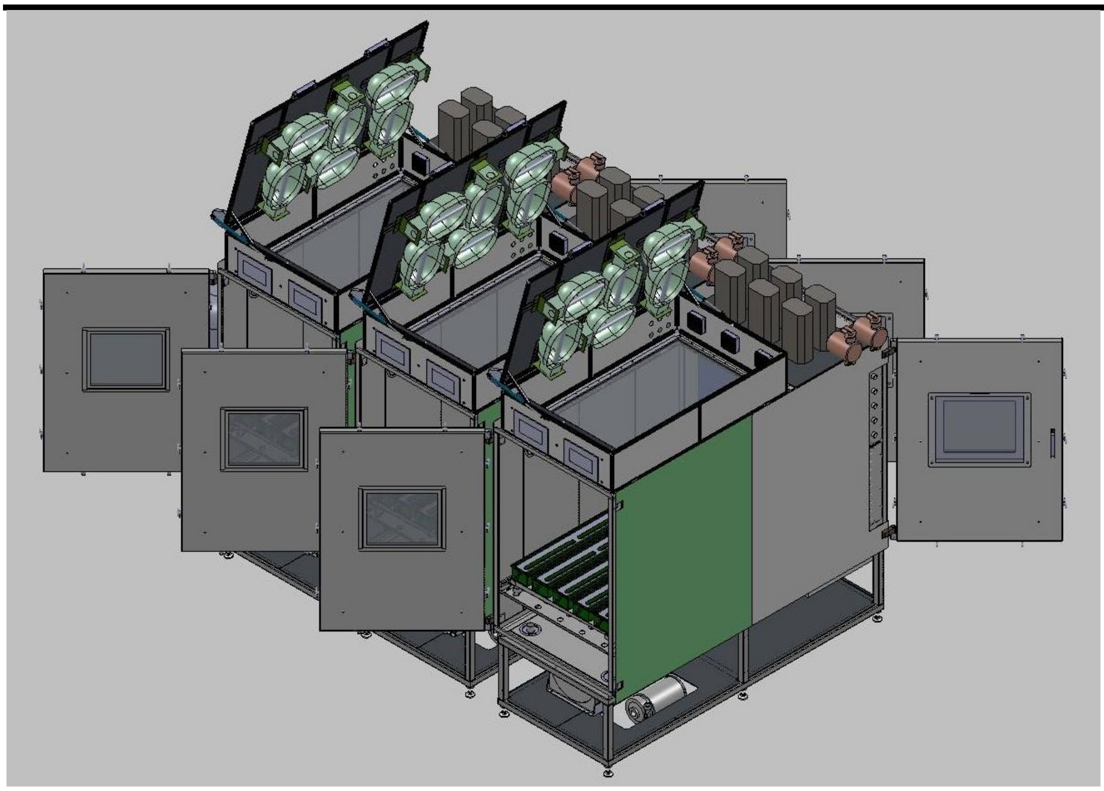

Fig. 1 PCU preliminary design showing all three subunits, front view

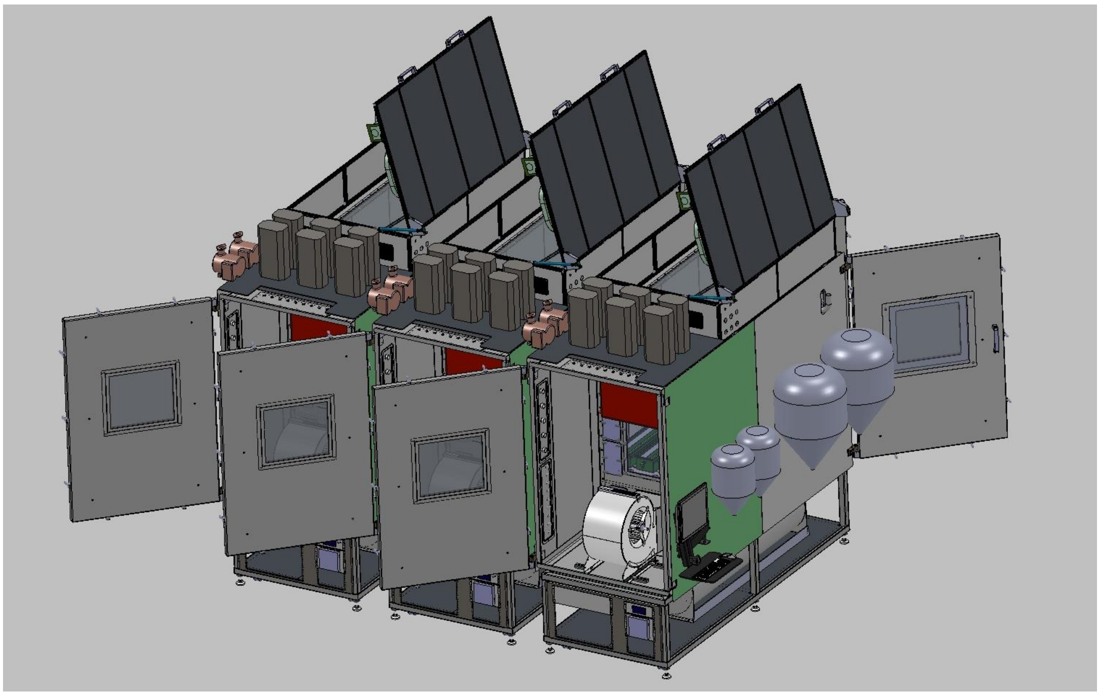

Fig. 2 PCU preliminary design showing all three subunits, rear view

Each subunit consists of a central growing compartment with 1.66 m^2 of growing area (1.66 x 1.0 m) in a volume of 1.826 m^3 (Fig. 3). The growing area contains five gullies designed for nutrient film technique (NFT) hydroponic plant growth. Nutrient solution is stored in a 200 liter main reservoir located beneath the growing area. Nutrient solution is both delivered to the gullies through a low pressure metered feed system, and continuously circulated within the nutrient tank and through pH, electrical conductivity (EC), temperature and dissolved oxygen sensors (DO) located in a bypass loop. The bypass loop can be separated from the main system for routine calibration and servicing. The gullies are designed to be adaptable to a closed nutrient system that will allow separation of the root zone from the growing area air space. Nutrient solution composition will be monitored and controlled by the Schneider PLC. Solution pH will be adjusted by gravity fed injection of centralized acid or base solutions, and EC will be adjusted (upwards only) by gravity fed injections of stock nutrient solutions. Solution temperature will be able to be cooled through the use of an internal cooling loop located within the main nutrient tank and centralized chilled water. The control system will monitor flow and alarms and/or lighting system shut downs will ensue in the event of low or no flow events. Alarms will be available for out of tolerance EC and/or pH with similar links to system shutdown functions.

Lighting will be provided by six high pressure sodium lamps (HPS) located above the growing area in a separately air cooled lighting compartment (Fig. 3). Laminated glass will be the interface between the lamps and the growing area. Lamp ballasts will be user-switchable to operate either HPS or metal halide (MH) lamps so that different lighting combinations can be tested. Lamp ballasts will be located on top of the chamber behind the lamp loft. The lamp loft is of sufficient size that different lighting systems (LED, induction, Radio Frequency) can be accommodated with minimal difficulty. Lamp activation will be under the control of the Schneider PLC and temperature in the lamp loft will be monitored for high temperature events with alarm and lamp deactivation at user defined setpoints.

The chamber temperature and humidity will be under the control of the Schneider PLC. A single commercial direct drive blower will circulate air through the chamber in a bottom up direction through the developing plant canopy and returning through chilled and hot water heat exchangers. Condensed water from humidity control is collected on the chilled heat exchanger, routed through a tipping bucket for measuring the amount of condensate, and then returned to the main nutrient reservoir. The control system will have accommodation for over and under temperature and humidity/VPD alarm states, with user definable courses of action (notification, alarm delay time, system shutdown, etc).

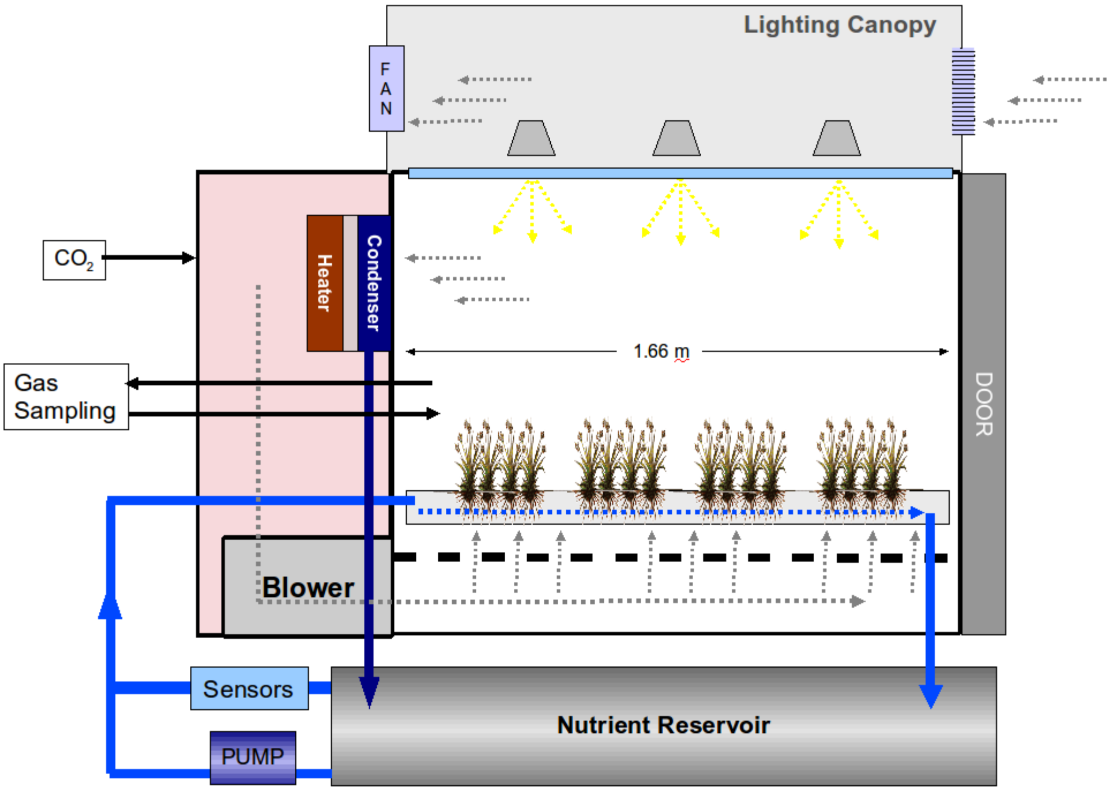

Fig. 3 Generalized schematic representation of chamber configuration

The chamber itself will be constructed of, for the most part, inert and/or food grade materials within the interior of the chamber. Exterior materials will be selected for ease of machining and cost optimization. Some small amounts of different materials may be required due to product designs and availability, but these will be minimal and minimized. For the most part, the components will adhere to the MELiSSA Harmonized Hardware Specifications (Issue 1, Revision 0), however some components are not available from these manufacturers or the parts that are available are not suitable for this application. For example, Swagelok products are generally designed for high pressure system applications. Where applicable, harmonized hardware components are specified.

As mentioned previously, the control system will consist of a Schneider PLC, which will be physically separate from the PCU subunits. PLC configuration options are described in detail in this document. Specific design specifications for all subsystems are presented below.

1.1. Functional overview

The PCU and its three subunits are designed to provide the statistical reliability required by plant modeling researchers. Designed as an expandable system, additional chambers can be added and internal components can be adapted to accommodate future research objectives.

In generalized operation in response to an approved experimental protocol, seeds or established seedlings would be planted in each gully in rockwool blocks spaced at intervals appropriate for the species studied or placed directly in the gullies without a specific substrate. Irrigation would then be started and flow to each gully would be verified visually (flow calibration would be performed prior to experiment startup). At this point, the door would be closed and the Schneider PLC engaged to begin control of T, VPD, EC, pH, [CO_2] and lighting. During the course of plant growth and development, the following parameters would be monitored and recorded at a user selectable interval of up to 1 second.

- [CO_2]
- [O_2]
- Subunit T
- Lamp loft T
- Laboratory T
- Subunit RH
- Laboratory RH
- Subunit pressure
- Laboratory pressure
- VPD
- Air velocity
- PAR
- pH
- EC
- DO
- Nutrient flow
- Acid level
- Base level
- Nutrient stock 1 level
- Nutrient stock 2 level
- Main tank high level
- Main tank low level
- Condensed H_2O amnt
- Chilled water supply T
- Chilled water loop in T
- Chilled water loop out T
- Chilled heat exchanger T
- Hot water supply T
- Hot water loop in T
- Hot water loop out T
- Hot heat exchanger T
- Status of ALL solenoid valves
- Lamp loft fan status (on/off)
- CO_2 mass flow

Alarm states would be issued for all user specified, predetermined out of specification parameters including but not limited to:

- Temperature high/low (all locations)
- VPD high/low
- pH high/low
- EC high/low
- pH high/low
- Air velocity high/low
- Nutrient flow high/low
- Nutrient main tank level high/low
- Acid/base/A/B level low
- [CO_2] high/low
- [O_2] high/low

The control system would allow for user implementation of new alarm points for any recorded data element.

It will be possible to manually subsample whole gullies during the course of an experiment. This gives the option to harvest up to 15 times at different time intervals if the three subunits are harvested subsequently or 5 points if subunits are harvested together (with three times the amount of harvest compared to 15 harvest points). Online measurements such as NCER would have to be recalibrated according to the amount of biomass remaining in the chamber after each harvest.

2. Preliminary operation and procedures protocol

2.1. Safety

There are a number of chemicals and products required during the operation of a controlled environment plant growth chamber, some of which may require protective equipment. All operators of these systems MUST consult local laboratory MSDS records and adhere to all laboratory safety protocols. Proper training in the operation and maintenance of the PCU will be required prior to use.

Minimally, approved safety shoes, safety glasses and approved laboratory protective garments (lab coat) should be worn while working on or within the PCU subunits.

2.2. Cleaning

To ensure a minimized level of contamination with algae, biofilms, and other microorganisms, thorough cleaning should be performed at the end of each experimental period. The material choices for each PCU element are based on compatibility issues with the following cleaning procedures as well as durability and reliability requirements.

2.2.1. Exterior

The exterior surfaces can be cleaned with warm water with a dilute, mild dish washing soap (~200 uL soap per litre of water).

2.2.2. Nutrient delivery system

Cleaning of the nutrient delivery system is crucial for effective operation and plant development. After each experiment the main nutrient tank should be drained and refilled with 180 litres of a 10 ppm ozone solution. With the gullies installed in the PCU subunit, the ozonated water would be circulated through the system for a period of 24 hours. If possible, the ozone solution concentration should be maintained at 5 ppm for the duration of the cleaning process. After this procedure, the system is drained and ready for use.

2.2.3. Interior

The interior stainless steel surfaces should first be cleaned with a mild dish washing soap in warm water, followed by disinfection, if required by the experimental protocol, with a high-concentration alcohol mixture (i.e. 80% ethanol + 5% isopropanol). Alcohol disinfection is only required where microbial community investigations are an integral part of the experiment protocol.

2.2.4. Gullies

Gullies should be removed from the chamber and cleaned with warm water containing mild dish washing soap. Surface disinfection can be performed with a 5 ppm ozone solution or 85% alcohol if required by experimental protocol.

2.2.5. Lighting Canopy Glass Panel

The glass panel in the lighting canopy should be cleaned with warm water and mild dish washing soap and then rinsed with clean water and dried with a clean cloth.

2.2.6. Sealing Surfaces

Door gaskets should be cleaned with warm water and mild dish washing soap on a quarterly basis. During experiments, seals should be wiped with a damp cotton cloth prior to each closure.

2.3. Gully harvesting

In some cases it might be necessary to provide samples for further analysis of the produced biomass (e.g. nutritional analysis or biomass composition). Further details and calculations on this issue are given in TN 98.7. The PCU will provide sufficient surface area to provide 5 intermediate harvests to assess the nutritional quality development over time. This is done by removing one gully from every subunit for each subsample (5 times 3 gullies in total). Alternatively up to 15 intermediate samples are possible by harvesting only one gully of one subunit at once. In this case the amount of biomass is not sufficient for a full nutritional analysis but other less demanding analyses (e.g. elemental composition) are possible. Thus the evolution over time can be assessed without having to run several cultivations.
A preliminary procedure is given below showing that the preliminary design is compatible with the required harvesting strategies:

1. Turning off of nutrient solution delivery: The nutrient solution flow can be stopped for 30 minutes up to several hours depending on the root quantity without damaging the plants.

2. Turning off of HVAC system: This will avoid losing too much CO_2 by automatic addition and too abrupt temperature/RH changes due to a running blower with an opened door.

3. Opening the door.

4. Pulling out the whole gully tray.

5. Disconnecting the required amount of gullies from the feed and outflow.

6. Removing the required gullies: To ease the removal of single gullies it is recommended to use fences (resp. foils) between the gullies to avoid entanglement of neighboring plants during the growth. Interfaces for such a system will be provided on the gully tray. The fences themselves will not be delivered with the PCU as it is not needed for every experiment and crop. These will be customized as required onsite in the respective laboratories.

7. Insertion of empty gullies in the free slots: It is recommended to have one or more spare gullies available to avoid too long interventions with an open door. Removing a full gully and inserting an empty one should not take more than a few minutes. Empty gullies in the free slots are necessary to ensure a homogeneous airflow through the chamber.

8. Connection of feed and outflow to the newly inserted gullies: To avoid recalibration of the flow distribution, the newly inserted gullies shall be fed with nutrient solution even without plants.

9. Insertion of the gully tray into the PCU subunit.

10. Door closure: preferably by cleaning and verifying the gaskets before closing.

11. Reinitiating of HVAC and CO_2 control and nutrient solution delivery.

2.4. Gully flow calibration

Previous experience has shown that a minimum flow and relatively even distribution among the gullies is necessary to ensure homogeneous growth. The overall flow rate is regulated with a flow controller at subunit level. Thus atmospheric pressure fluctuations in the chamber will be compensated by the controller. But as the five gullies of each PCU subunit are fed by a common line, pressure drop and (constantly) different flow resistances in the delivery system might lead to uneven flow. To overcome this problem the flow distribution can be calibrated. This is preferably done prior to an experiment run. The preliminary procedure is as follows:

1. Starting of nutrient delivery without plants with an open door.
2. Wait a few minutes until a constant flow is achieved.
3. Disconnect the outflow of the gullies from the sealed collection gutter. Route the outflow of each gully into volumetric flasks.
4. Let run for a pre-determined duration timed with a stopwatch.
5. Route the outflow back to the nutrient tank.
6. Compare the volume collected from each gully per unit of time.
7. Recalibrate the individual feed lines. This is accomplished by raising or lowering the outflow of the feed line in each gully depending on whether it is delivering too much (raise the outflow) or too little (lower the outflow). The outflows in each gully are held in their respective locations with a set screw.
8. Repeat step 2-7 until an evenly distributed flow has been measured.

As each feed-line is calibrated by imposing a more or less strong flow resistance (and the initial variation of flow is also due to slightly different flow resistances in each feed line) the calibration should stay the same for different overall flow rates.

If a flow rate change is envisaged during a cultivation, a calibration should nevertheless be done for the different flow rate settings to make sure no major variations are present. If necessary the different setpoints for the different flow rates must be noted prior to the experiment and applied when the flow rate is changed.

This procedure will ensure that the flow of each gully achieves an adequate level of consistency during a whole experiment even if atmospheric pressures vary.

2.5. Nutrient solution sampling

A manually operated sampling valve will be located at the positive pressure side of the circulation pump for samples of nutrient solution. If required by experimental protocol, the valve outlet can be covered between sampling periods to reduce contamination. Generally the first few seconds of flow are discarded to ensure a clean sample.

3. Design Specifications

3.1. Dimensions

The volumetric dimensions of the growing area in each PCU subunit were derived from cultivar and food processing evaluations and plant modeling requirements. The total external volume of the chamber was limited by the delivery and placement options at UGent. Detailed information on sizing criteria was presented in TN 98.7 ‘Definition of the requirements for a plant characterization unit’ and is summarized in Tab. 1. Generalized schematic dimensional diagrams are shown in Fig. 4 and Fig. 5. The dimensions of the preliminary design are given in Fig. 6 and Fig. 7. The lamp loft design will allow opening of the system within the height restrictions of the UGent laboratories (315 cm).

Tab. 1 Dimensional requirements/limitations for PCU design.

Parameter	**Requirement**
Growing area height	110 cm
Growing area width	100 cm
Growing area depth	166 cm
Maximum total height	240 cm
Maximum total width	120 cm
Maximum total depth	260 cm

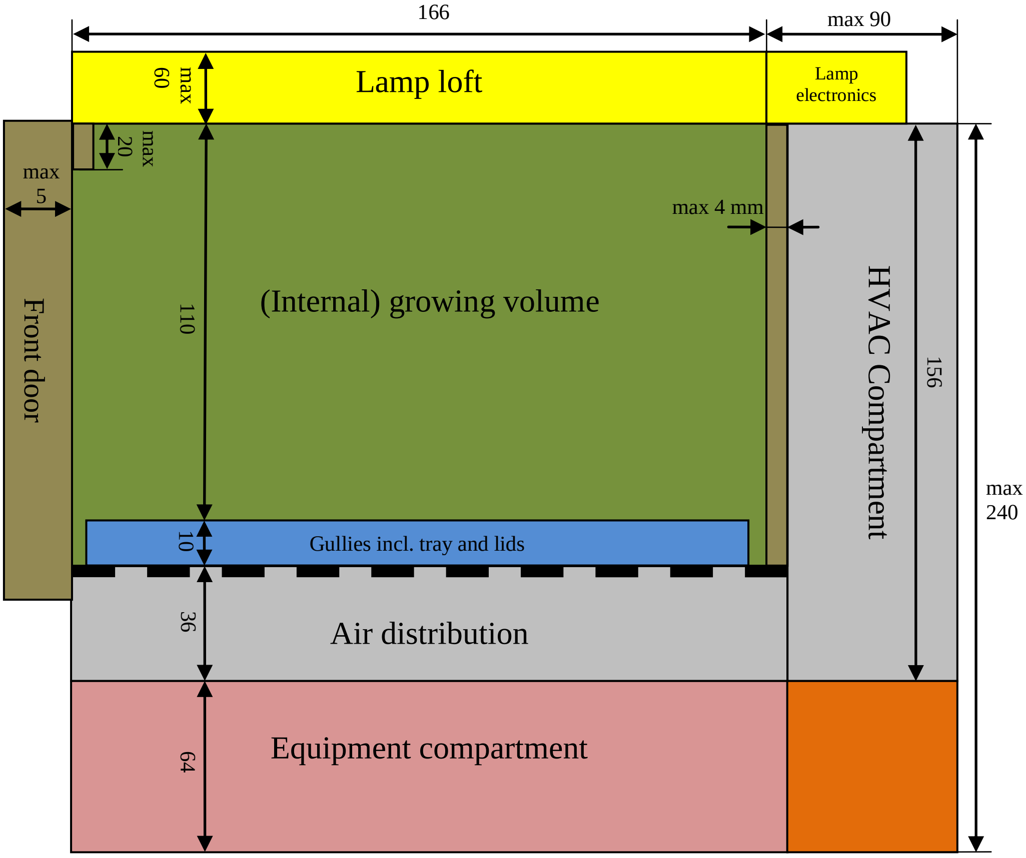

Fig. 4 Schematic of a PCU subunit; dimensions in cm; side view

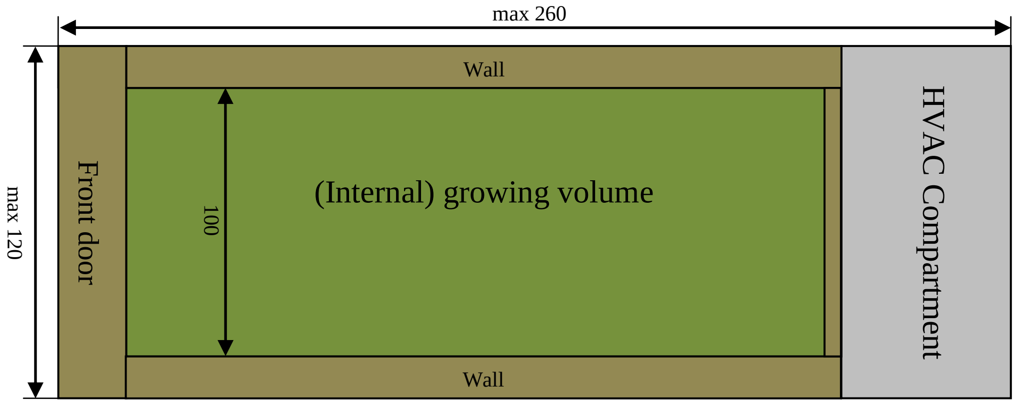

Fig. 5 Schematic of a PCU subunit; dimensions in cm; top view

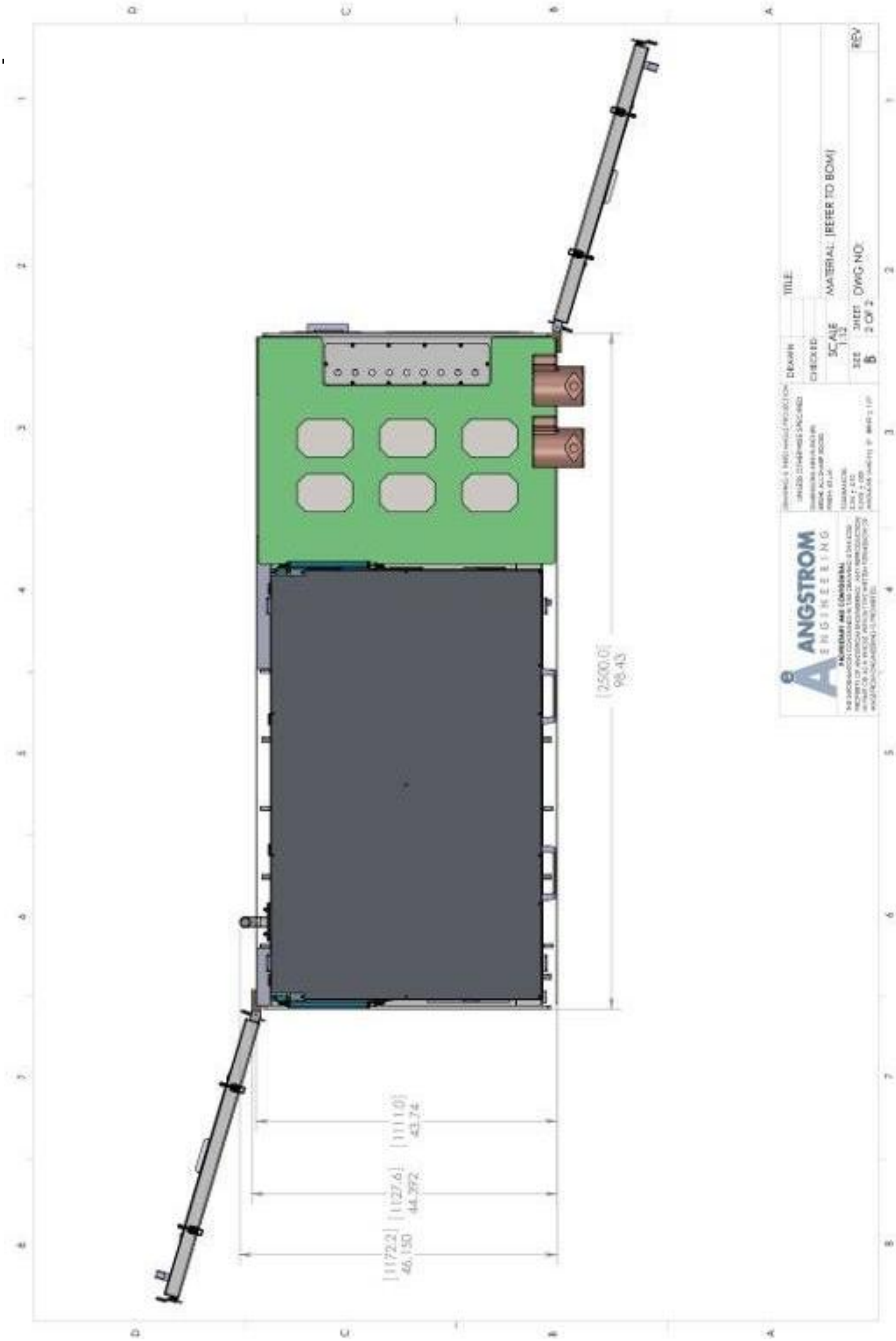

Fig. 6 Overall dimensions of the preliminary design (top view)

Fig. 7 Overall dimensions of the preliminary design (side view)

3.2. Preliminary mass budget

The total mass of one PCU subunit is estimated to:

Tab. 2 Preliminary mass budget

Full main tank	200 kg
Hydroponic system	200 kg
HVAC system	100 kg
Chamber shell	550 kg
lamps + ballasts	150 kg
Electronics	50 kg
Rest	100 kg
Total	**1350 kg**

In this preliminary mass budget the stock solution tanks and the control system are not included as they are positioned separately from the PCU.
This preliminary mass budget shows that the requirements for delivery (1425 kg for elevator) are met. There is sufficient margin as the PCU is not delivered in one piece. Weight restrictions of the building floors (500 kg/m^2) will also not be exceeded:
1,350 kg (subunit + nutrient tank) / 2.8 m^2 (total surface area of one subunit) = **482 kg/m^2**.

3.3. Environment control requirements

Detailed information/discussion on the environment control requirements have been presented previously (TN 98.7, TN 98.8.1) and are summarized in its main features in Tab. 3.

Tab. 3 Summary of main environment control requirements

Parameter	**Requirement**
Irradiation day	SUB-ILLU-INT-1: The illumination system shall be capable of providing a photon flux density of at least 500 µmol/m²s PAR at mid canopy level. SUB-ILLU-HOM-1: The irradiation during light phases shall be homogeneous in its PAR photon flux density at leaf level over the plant growing area with a max. 25% variation. SUB-ILLU-HOM-2: The illumination shall be homogeneous in its spectral photon flux density (within the three above mentioned bands (380-510-650-780 nm)) at leaf level over the plant growing area to within ±25% of the maximal value of each band.

Irradiation night	SUB-ILLU-INT-3: During dark periods the photon flux density shall always be below 0.5 µmol/m²s PAR in the volume occupied by plants.
Temperature (air)	SUB-CATM-TMP-1: The chamber atmosphere temperature shall be settable between 15°C and 35°C with 1°C increments for light and dark phases. SUB-CATM-TMP-2: Up to 30 min after a switch from dark to light phases and vice versa (with a constant temperature setpoint for light and dark phases), the temperature stability shall be ±5°C until a stable state is reached. SUB-CATM-TMP-3: The temperature stability after the transition phases from dark to light and vice versa shall be ±0.5°C. SUB-CATM-HOM-1: The temperature in the volume occupied by the plants shall be homogeneous to ±2°C.
Air velocity	SUB-CATM-FLO-1: The blower of the HVAC system shall be capable of providing sufficient air velocity (respectively recirculation) to counterbalance the lamps heat load and to provide sufficient mass exchange in the foliage. SUB-CATM-FLO-2: The average air velocity in the growth compartment shall be below 1 m/s to avoid stress effects on plants. SUB-CATM-FLO-3: The flow pattern shall be bottom up. SUB-CATM-HOM-3: The flow speed in the volume occupied by the plants shall be homogeneous in its magnitude to ±0.1m/s.
Humidity	SUB-CATM-RH-1: The chamber atmosphere VPD shall be settable between 0.2 and 1.5 kPa with 0.1 kPa increments during dark and light phases. SUB-CATM-RH-2: The RH stability shall be ±5%RH during continuous working. SUB-CATM-RH-3: During the first 30 minutes after the switching from light to dark phases (and vice versa) the RH stability shall be ±20%RH.
Pressure	SUB-CATM-PRS-1: The static pressure inside the main growing volume shall be equal to ±2 kPa to the lab atmospheric pressure at all times.
Gas composition control	SUB-CATM-CMP-2: The PCU shall be capable of setting CO_2 concentrations between 350 (approximately atmospheric CO_2 content) and 5000 ppm in the chamber atmosphere with increments of 10 ppm. SUB-CATM-CMP-3: The PCU shall be capable of keeping O_2 level in each subunit permanently below 25%. SUB-CATM-CMP-4: The PCU shall be capable of keeping ethylene level in the each subunit permanently below 10 ppb.

Nutrient supply	SUB-HYDR-LIQ-9: The pH setpoint shall be definable from 4 to 8 with increments of 0.1. SUB-HYDR-LIQ-11: The EC setpoint shall be definable from 0 to 3000µS/cm with increments of 1µS/cm.
Leakage	SUB-SHEL-LEK-1: The PCU shall have an atmosphere leak rate at or below 5% of the internal volume within 24 hours as measured by passive CO_2 leak testing with a 1000 ppm starting concentration.

3.4. Auxiliary equipment

This section describes external equipment to be provided by the laboratory infrastructure for a proper functioning of the PCU. All common elements of the PCU (elements used by all subunits together) have been mentioned in chapter 1. Some of these elements will be delivered with the PCU (i.e. control system PLC, stock solution tanks, HMI, gully manipulation trolley). This section specifies in more detail the auxiliary equipment not delivered with the PCU in terms of it compatibility and its interfaces.

3.4.1. Hot and cold water supply

Tab. 4 Interface requirements for the hot water supply

Parameter	**Requirement**	**Design specification**
Pressure	SYS-INTF-LIQ-1: The pressure of the supplied heating and cooling water shall be between 2 and 10 bars.	UoGuelph: 4.1 bar source pressure at heater 8.3 bar source pressure at chiller UGent: TBD
Hot water temperature	SYS-INTF-LIQ-2: The temperature of the heating water shall be user selectable between 40 and 80°C with 1°C increments.	UoGuelph: adaptable, currently set to 50°C UGent: TBD
Cold water temperature	SYS-INTF-LIQ-3: The temperature of the cooling water shall be between 5 and 8°C.	UoGuelph: 5-8°C UGent: TBD
Temperature stability	SYS-INTF-LIQ-4: The temperature of the heating and cooling water supply shall not drift or oscillate by more than 0.2°C per hour.	UoGuelph: TBD UGent: TBD

Heat exchanger outlet temperature	SYS-INTF-LIQ-5: The heating and cooling water inlet and outlet temperature at the heat exchanger shall be logged for possible failure analysis and to increase the performance of the controlling system.	Inlet and outlet temperatures will be measured and logged for both (hot and cold) heat exchangers

At UGent no dedicated cooling and heating equipment is currently available. Appropriate hardware will be selected and installed prior to the PCU delivery.

3.4.2. Carbon dioxide supply

Tab. 5 Interface requirements for the CO_2 supply

Parameter	**Requirement**	**Design specification**
CO2 pressure	SYS-INTF-GAS-2: The laboratory CO_2 supply shall be pressure regulated.	Appropriate CO_2 bottles and pressure regulators will be provided.

3.4.3. Retrofitting hardware

Several elements will be required to perform all planned retrofits. This includes (but is not limited to) the sealed hydroponic system elements, gully monitoring, gully fences, alternative illumination systems, oxygen and ethylene removers. Due to the nature of these retrofitting plans these elements will not be delivered with the PCU and cannot be specified in more detail at this stage. Further research is needed to assess these elements.

3.5. Hydroponic subsystem

3.5.1. Gullies

Each PCU subunit will have five gullies that will be adaptable to a sealed system (Fig. 8) in future iterations of chamber experimentation. The initial gullies will be supplied with simple gully covers, similar to those employed and used extensively at UoGuelph (Fig. 9), that will prevent light transmission to the nutrient film. Each cover will have three longitudinal slots and spaces between plants will be covered with adaptable stainless steel cover plates. Adequate slot sizing will be in place to accommodate all currently identified crops to be tested (durum wheat, bread wheat, soybean and potato). In the case of wheat growth, the cover will be left off and replaced with black/white plastic with slits that are more suited to wheat growth. The sealed gully system will require extensive testing before implementation across all systems can be performed.

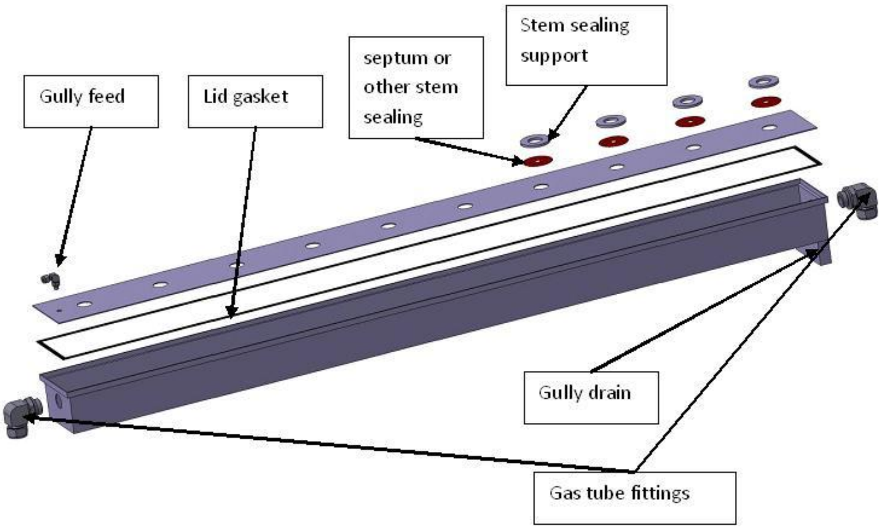

Fig. 8 Sealed gully design concept to be accommodated in the current design

Fig. 9 Simplified gully slotted cover as used in current UoGuelph chambers

In Fig. 9 cover plates to reduce light transmission are shown in the first photo. Also shown are optional covers designed specifically for radish growth.

3.5.2. Nutrient solution delivery

The irrigation system will be of a recirculating closed Nutrient Film Technique (NFT) design as this is the most common system in Advanced Life Support (ALS) research. The main nutrient tank (200 L) will be gravity fed from two common stainless steel nutrient stock tanks (referred to as EC stock solution tanks above, with ability to expand to multiple component injection), as well as common acid and base storage tanks (Fig. 10). Stock solution tanks will be separate from each PCU subunit and attached at one end of the PCU subunit array. Nutrient solution (EC) and acid/base stock containers will have level monitoring.

Nutrient solution temperature, DO, EC and pH will be monitored continuously with redundant sensors (2 per PCU subunit). A bypass circulation system will maintain solution homogeneity and ensure adequate solution aeration. A subsampling valve off the main bypass line will be available for manual solution sampling during sealed crop growth trials. A nutrient solution flow sensor located on the chamber (PCU subunit) in flow line will control the flow at PCU subunit level and will be coupled to the lighting system in case of failure. As mentioned in chapter 2.4, the flow is controlled at chamber level. Equal distribution between gullies is ensured by a calibration prior to the experiment. The control system will turn off the lighting in response to ‘no flow’ or a user specified ‘low flow’ set point.

As with the chamber general requirements, the primary construction materials for the nutrient delivery system will consist of polypropylene, 316 stainless steel, Teflon, or Viton. IR video camera with IR lighting for root/tuber visualization within the growing trough can be adapted at a later time by simple remanufacturing of the gully cover.

Although adequate aeration is seldom an issue with NFT systems, the option to allow chamber air (or bottled O_2 if operated as an open system) injection through the low pressure side (intake) of the circulation pump is included. The amount of air injected in this manner is minimal and will not affect pump or sensor operation. Additional ports to connect aeration devices are provided as mentioned in chapter 3.5.9. These ports will however not be used for normal chamber functioning. They are given to allow additional flexibility on closed hydroponic system functioning. Improved mixing of the air/water is provided by the impeller of the pump which is upstream of the injection. A needle valve will be employed to allow precise low flow injection of chamber air.

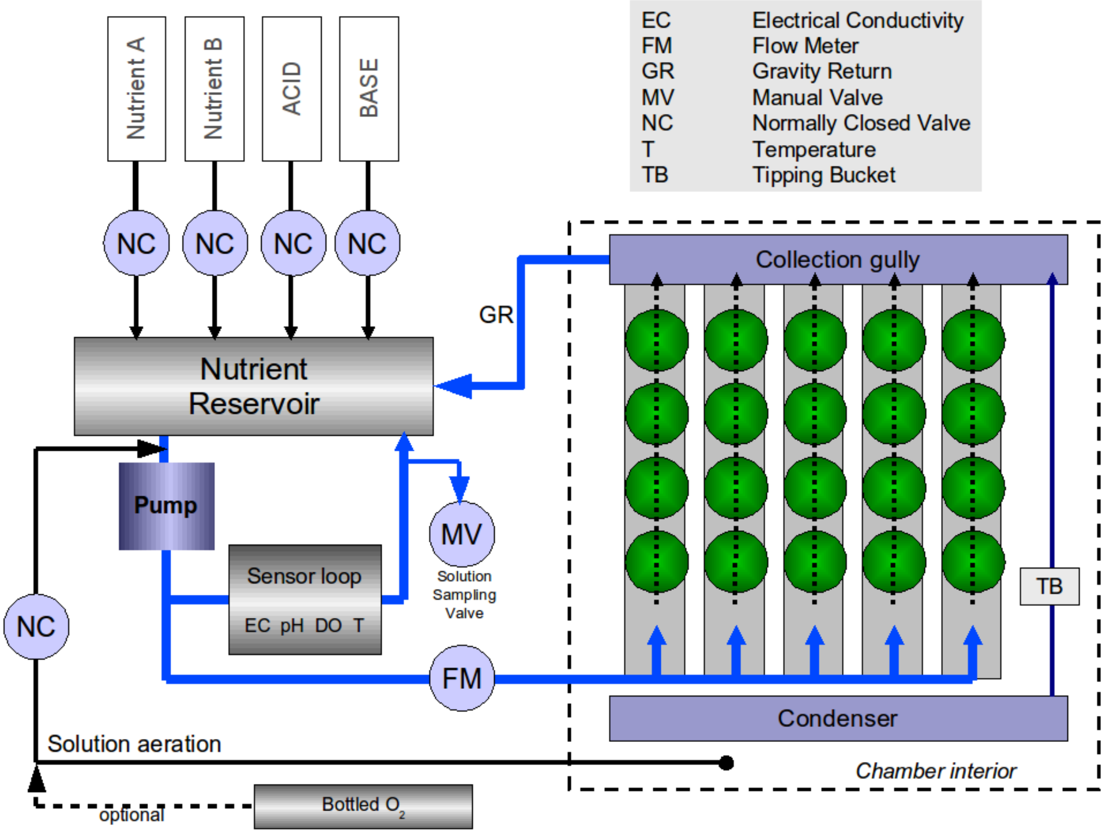

Fig. 10 Schematic representation of the nutrient delivery system

3.5.3. *Nutrient solution recovery*

Nutrient solution will exit the gullies and enter a collection gully at the front of the chamber. Solution will flow directly to the nutrient tank situated below the chamber growing volume.

3.5.4. *Pumps*

Each subunit will have a single stainless steel variable speed impeller pump capable of providing up to 379 liters per minute. This will provide adequate flow for gully and bypass lines.

3.5.5. *Tanks*

All nutrient solution and stock tanks will be constructed of polypropylene or stainless steel and will be sized to meet the operational requirements outlined in TN 98.8.1.

3.5.6. *Stock solution level monitoring*

All nutrient solution and stock tanks will have level sensors to determine the state of fluid levels. The main reservoir will have two sensors, one for low level indication and one for high level indication. Both sensors will be alarmed in the CS and will require user intervention/remediation when activated. Sensors in the main nutrient tank will be simple float level sensors made of food grade materials (see image).

Level sensors for stock tanks will show full solution levels with a 6.4 mm graduation to enable use calculations and prediction of refill intervals. Sensors are stainless steel and acid/base tolerant.

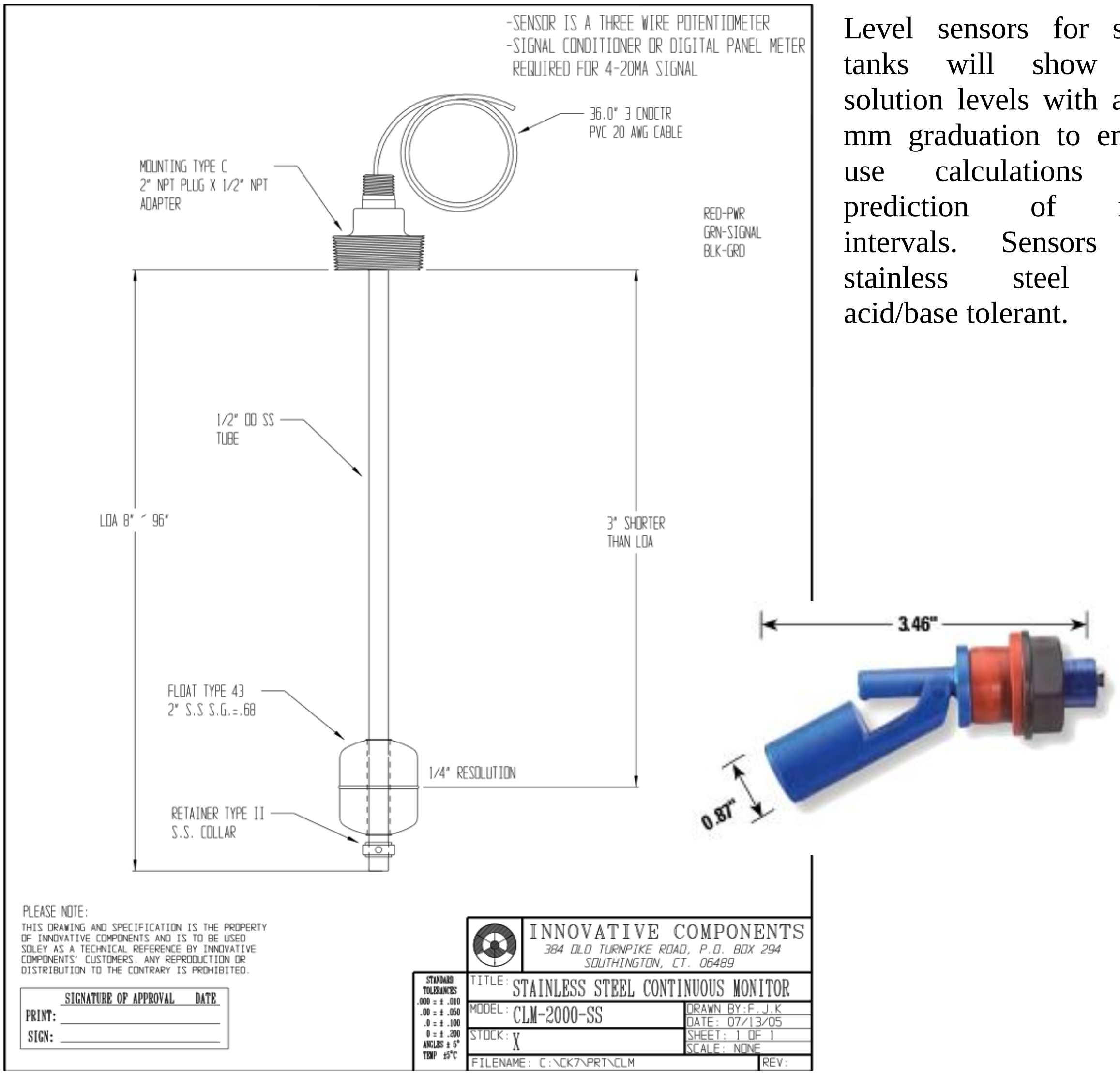

Fig. 11 Nutrient system stock tank level sensors

3.5.7. *Stock solution dosage principle*

Besides the level monitoring which is used for purely technical resp. alarm functionalities, the exact amount and interval of each EC and pH stock solution addition to the nutrient solution is logged. The dosage and measuring principle is based on integration of the time opening of the different valves. A reset of the counters can be done by the user when desired.

3.5.8. *Nutrient solution aeration strategy*

One of the major advantages of the NFT strategy is that adequate aeration of the nutrient solution is inherently achieved through the large liquid/gas surface area of the thin liquid film flowing inside the gullies as long as the gas in the gullies is constantly refreshed. Therefore no additional equipment such as bubblers or dispersers is needed to inject oxygen into the solution for an unsealed system. In case of a sealed gully system, gas exchange is however limited. Here a separate solution aeration might become necessary depending on the sealing strategy.
The design of the PCU will provide two possibilities of oxygenation to give a maximum of flexibility for the future sealed gully implementation:

- A tube connection in the nutrient solution loop will be available at the low pressure side of the pump. Due to the underpressure air can be sucked in and dispersed in the stream without additional equipment. As most likely only very small amounts of air are needed, the sensors upstream the air injection site are not affected by passing bubbles and the flow measurement/control is still accurate enough.
  Air can be drawn from two different sources: The chamber atmosphere in case of a semi closed hydroponic system (see further explanations in chapter 3.5.9) or an external source in case of a fully isolated hydroponics loop.
  If high aeration rates are required (the exact amount of oxygenation is not yet known) this option could turn out to be impossible. High air fluxes will have a negative impact on the in-line sensors and flow control. Therefore a second (more complex) option is provided as well:
- Tubing ports (or possibilities to ad ports) will be given in the nutrient solution tank to integrate a bubbler and a vent line. This option will be used in case an aeration with the above mentioned solution is not sufficient.

3.5.9. *Sealed gully retrofitting strategy*

Following several discussions and scientific requirements (see TN 98.7), the PCU hydroponic system should be sealed off from the chamber atmosphere to allow more precise mass balances and to avoid interactions between the root zone and the aerial zone. A sealed off system however implies several complex problems to be solved from a technical point of view. Further research and development is needed to address these problems. In the near future, experiments will be performed with opened gullies as it has been done in FC1 bench tests. But the system is designed with a retrofitting in mind and will keep sufficient flexibility to perform tests and research on this issue and to implement a sealed hydroponic system at later stages.

The following critical design issues have been identified:

Baseline evaporation: At the beginning of a cultivation, when the plant transpiration is insignificant, problems with chamber humidity could occur (once plants have reached a certain size, transpiration will be sufficient to keep the chamber RH balanced).

With an open gully system (as used in all FC1 bench tests) a dedicated humidification system is not needed to keep the chamber atmosphere humidity at the required levels. Sufficient water evaporates from the gullies themselves (baseline evaporation). Adequate humidity control is possible by condensation (water removal) on the HVAC cold heat exchanger only.

Sealing off the gully completely from the chamber atmosphere might lead to too dry air at the beginning of a cultivation cycle. Thus a humidifier might have to be added to the HVAC system if the hydroponic system is completely sealed. The water management system of the hydroponic system might also require revision as the condensate is recovered to the nutrient solution tank. Addition of an external water source (humidifier) could jeopardize nutrient solution levels and control depending on the quantities added. The real necessity of an external humidifier will depend on the control system performance and the performance of the cold and hot heat exchangers.

A semi sealed hydroponic system as proposed in chapter 4.1.6 of TN 98.7 would mitigate the problem of low humidity at the beginning of a cultivation by flushing the gullies and thereby providing a constant baseline evaporation. The mass transfer of water, O_2 (and CO_2) can be quantified by measuring the difference between the in and outflow of the gas phase. Thus mass transfer is quantifiable but not blocked (the parameters of the root and shoot zone remain interdependent). This reliability of this solution in terms of measurement precision is still unknown as the measurable differences will certainly be very low.

Air tight interface with plant stems: Sealing off growing plants at the stem level is very difficult. First of all, the plant must not be damaged. Secondly, the seal must be flexible enough to allow growth while keeping the interface tight at all times.

Ventilation of the nutrient solution: The nutrient solution must be oxygenized and ventilated to ensure proper root growth and functioning. The advantage of a NFT system is constant solution aeration due to the thin liquid film in the gully and the thereby inherent large contact area between liquid and gas. Sealing off the gullies from the atmosphere will however create a stagnation zone in the gullies gas phase. Therefore a certain level of mass exchange with either the chamber atmosphere or an external source is necessary.

The aeration strategy will largely depend on the overall sealing design. A completely sealed-off design will require an external oxygen source and a pressure/volume management system to avoid overpressure due to addition of oxygen (e.g. vent or expansion bag). A semi sealed hydroponic system as proposed in chapter 4.1.6 of TN 98.7 will use chamber air for gully flushing. Here interdependence between the gas and liquid phase would still be present but quantifiable (TBC).

Pressure gradients: in case of a completely separated hydroponic system, pressure differences between the gullies interior and the chamber atmosphere could lead to leaks or influences on plant growth. Therefore equal pressure must be ensured at all times.

Based on these critical aspects the following list of required interfaces and design aspects has been determined to ensure a full retrofitability and design flexibility:

- Air input and output port at gullies.
- Air input and output port at nutrient solution tank.
- Accessibility at chamber level to rout additional (gas) tubing between the gullies and the equipment compartment respectively the nutrient solution tank.
- Sufficient space to implement a gas expansion compensation system in the hydroponic gas loop. If an expansion bag will be used, it will be installed externally. The equipment compartment does not necessarily need to provide spare volume for this purpose as the volume cannot be determined at this stage.
- Sealed nutrient solution input and output ports at gully level.
- Interface for addition of an external humidifier to the HVAC system.
- Data interface to implement the humidifier into the control system strategy.
- Routing options for recovered condensate to nutrient tank and to (external) humidifier or other.
- Sealed gully covers or gully design which will allow usage of sealed covers.

3.6. Illumination subsystem

The following figure shows a view of the lamping loft concept.

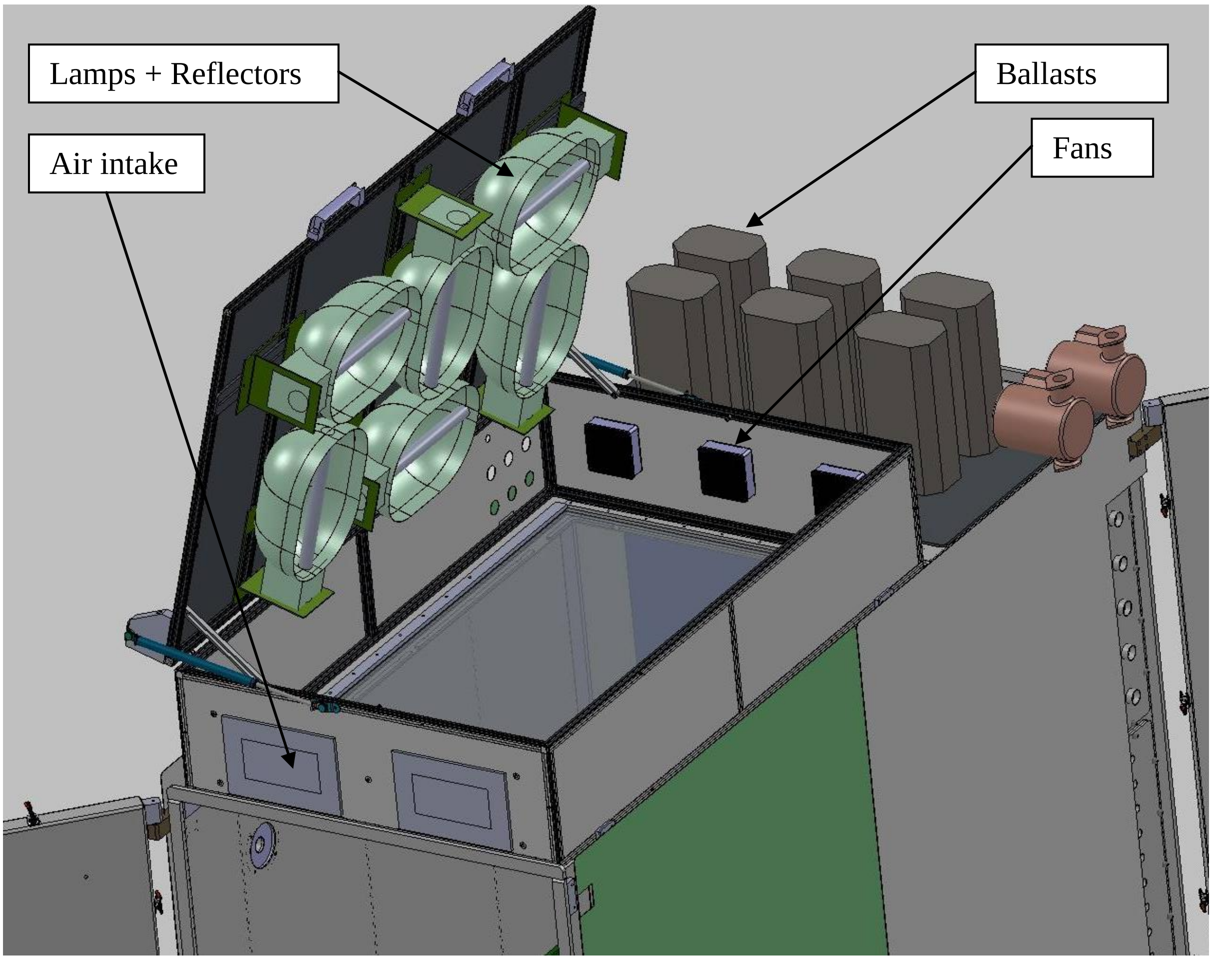

Fig. 12 View on opened lamping loft

3.6.1. *Lamps*

For this 1.67 m^2 growing area, 6 x 1000 Watt HPS lamps will be used (Fig. 13). The ballasts selected will be capable of running MH lamps as well, through a user-selectable toggle switch located on the side of the ballast. As spectral homogeneity is a problem when HPS and MH are combined in a multi-lamp configuration, it is recommended that only HPS or MH be used at any one time. The lamp loft will be designed to accommodate a complete change in the lighting system, so that future efficient LED, induction, or radio frequency lighting systems can be tested.

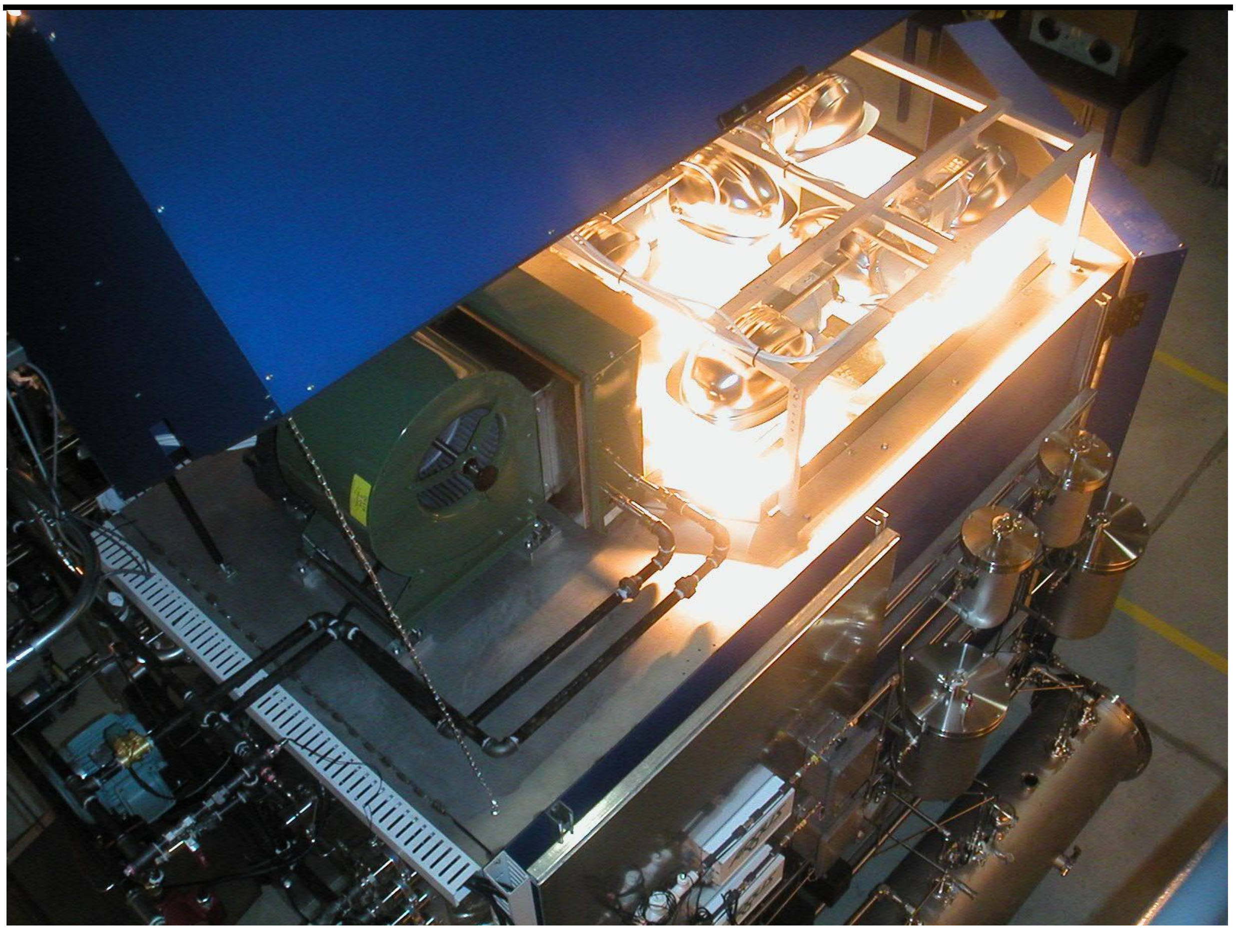

Fig. 13 Example of a six lamp HPS lighting system (UoGuelph hypobaric systems)

3.6.2. Ballasts

A user configurable combination ballast that can accommodate either HPS or MH lamps will be employed. This will allow a degree of versatility in lighting spectra with reasonable power input requirements.

3.6.3. Cooling

Lamp cooling will be achieved through active circulation of room air across the lamps (through the lamp loft) using three 2888 L min^{-1} box fans. Note that this method requires the provision of temperature control infrastructure in the building that is able to handle the heat load from this lighting system.

3.7. HVAC subsystem

The HVAC subsystem includes a volume behind the growth compartment in which the heat exchangers and the blower are positioned. This is referred to as the HVAC compartment. It also comprises the air distribution compartment underneath the growing tray where the ducting and air distribution pipes are located. Further information and hardware specifications are found in TN 98.7. The ducting mounted in the PCU is limited to a volute in front of the blower with baffles guaranteeing an equal flow distribution over the lateral axis and a perforated plate. In the rear part of the PCU subunit (the HVAC compartment) no specific ducting is installed. The whole compartment serves as “ducting”.
The following pictures shows the general air flow configuration:

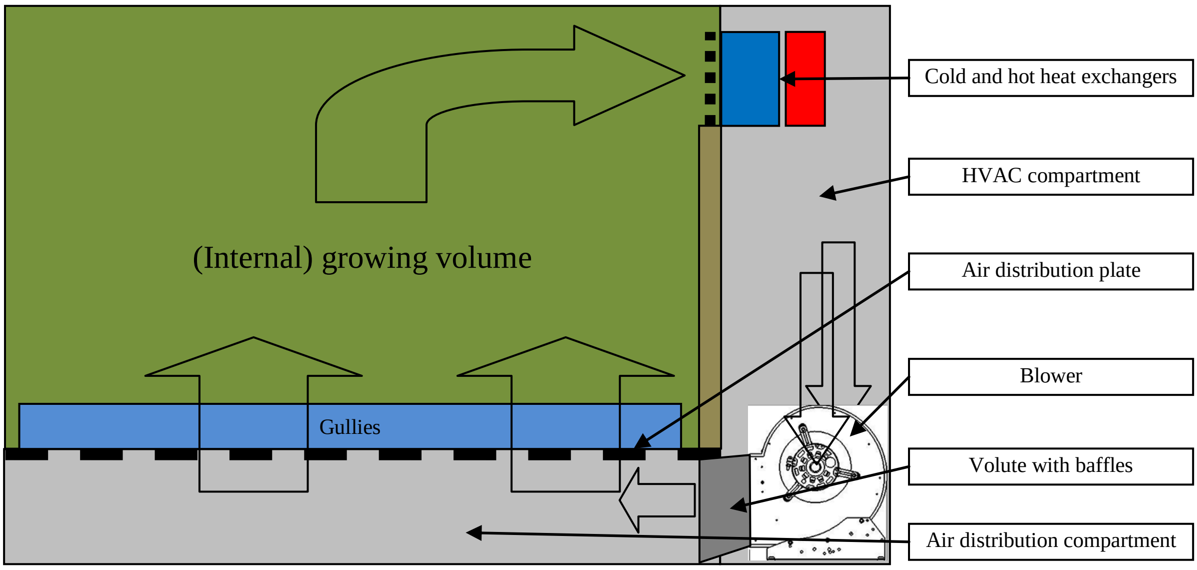

Fig. 14 Air flow configuration

To achieve homogenous air flow to the plants, a perforated distribution plate will distribute air from the plenum to the plant canopy (Fig. 15). To achieve this, smaller perforations are placed in areas of highest pressure to ensure even flow distribution. As the exact pressure gradient is not known and the HVAC system is deemed a critical point of operation, a detailed simulation will be performed to optimize the design and will be detailed in TN 98.8.3 and TN 98.8.4.

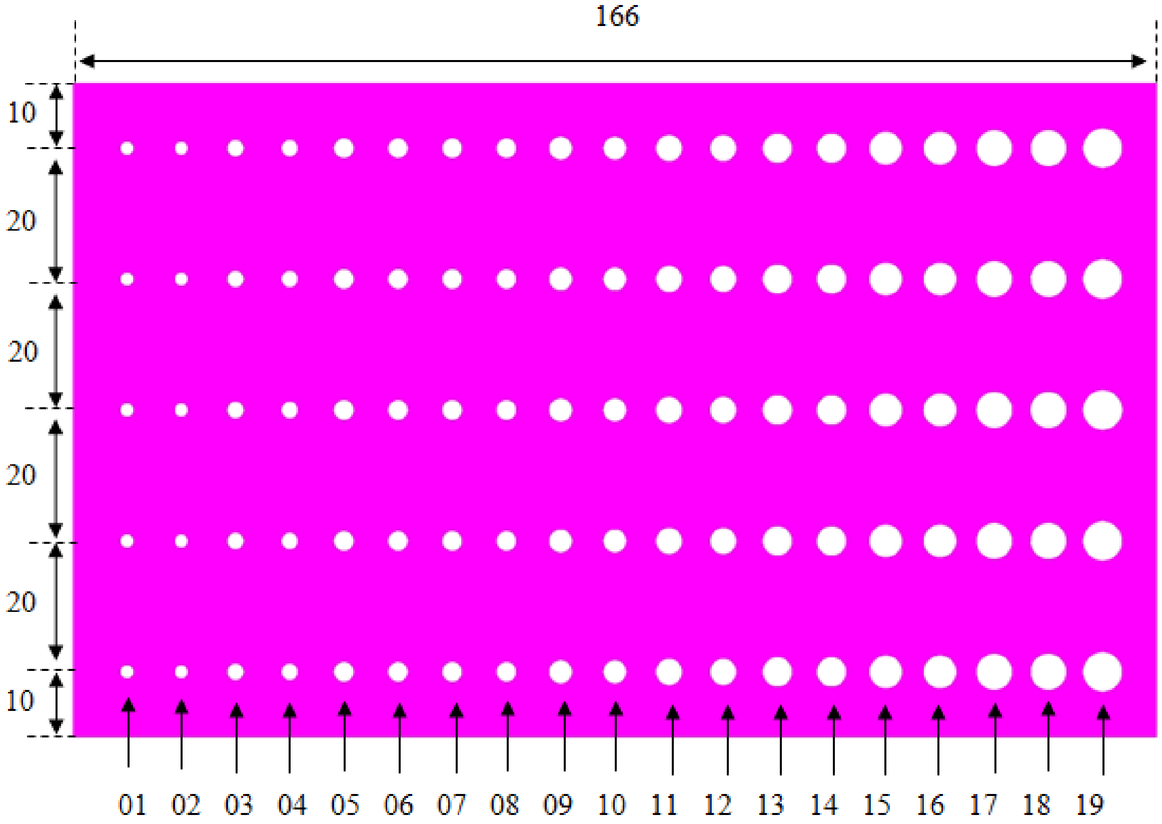

Fig. 15 Hole pattern in the distribution plate for air flow homogeneity

3.7.1. HVAC blower

Each PCU subunit will have a single variable speed centrifugal blower that is designed to deliver up to 45 m^3 min^{-1}. The blower will be the Delhi Industries G12-9-DD.
The speed variability will be achieved with a variable frequency drive (VFD). The speed of the blower will be either manually configurable or can be feedback controlled with an air velocity probe (hot wire anemometer) placed in the air distribution compartment. Exact placement of the probe will be determined based on CFD simulations to obtain optimal results.

3.7.2. HVAC cooler

For the cold heat exchanger the Delhi Industries CW-12 heat exchanger will be used. This cooling coil has an integrated condensate recovery system which will be routed to a tipping bucket water measuring device.

3.7.3. *HVAC heater*

For the hot heat exchanger, the corresponding Delhi Industries HC-12 heat exchanger will be used. Both the hot and cold heat exchangers were engineered to function with the Delhi G12-9-DD blower.

3.7.4. *CO_2 control*

The amount of CO_2 in the PCU will be under the control of the CS in response to a user defined set point with feedback control from CO_2/O_2 gas analyzer (California Analytical Model 600) and mass flow controller feeding pure CO_2 to the growing volume. In this application, CO_2 control is upwards only. No accommodation, other than through photosynthesis, has been made for CO_2 removal. During PCU operation, air is drawn from the PCU subunit by the pump located within the CO_2/O_2 analyzer where it is analyzed by internal IRGA and paramagnetic sensors. Sampled air is then returned to the PCU subunit. In response to CO_2 levels below the user specified setpoint, the CS will inject pure CO_2 from a laboratory source, utilizing a mass flow controller and solenoid valve to ensure accurately metered and recorded injections. Fig. 16 shows the functional principle of the CO_2 analysis loop.

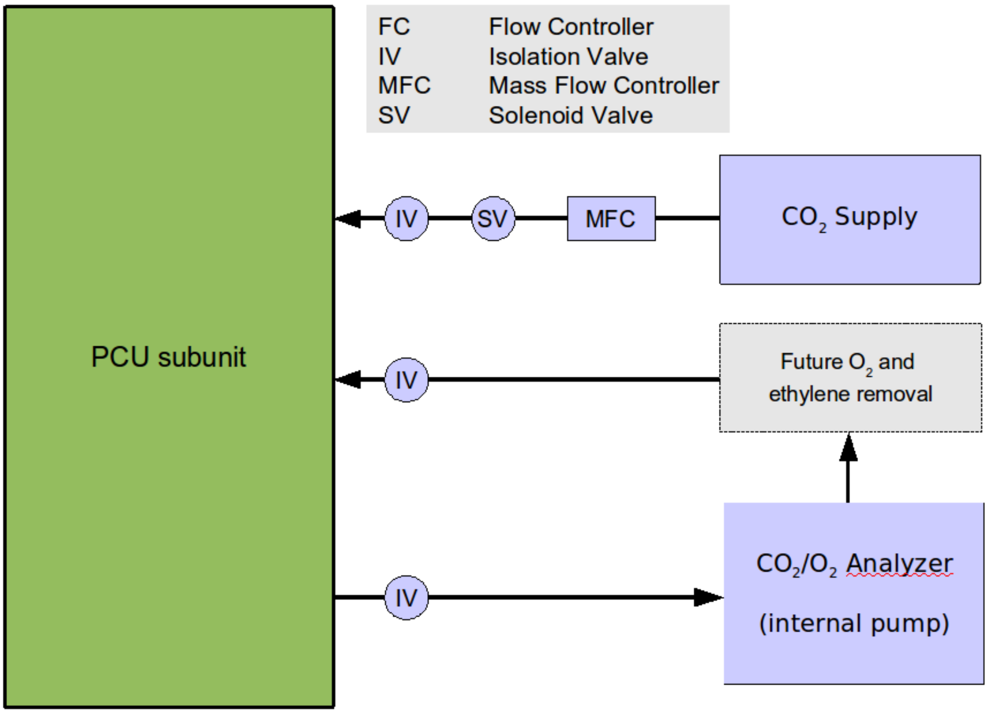

Fig. 16 Schematic representation of the CO_2 sampling system

3.7.5. Gas analysis loop

Currently the gas sampling loop is only composed of the above mentioned CO_2 analysis system. Future expansion of this sampling loop may include O_2 and/or ethylene removal systems for increased control of the chamber environment. Addition of a separate pump and/or bypass might be necessary if the flow rate and pressure capacity of the IRGA internal pump are not sufficient to feed the oxygen and ethylene removal devices.

3.7.6. Oxygen removal

Oxygen removal is not currently available for incorporation in this design. Further research is required to find an ideal method of selective control. TN 98.8.3 ‘Study of critical subsystems’ will describe control options.

3.7.7. Ethylene removal

As with oxygen, no method is currently defined. TN 98.8.3 will outline various options for control.

3.7.8. Condensate recovery

Condensate from the cold heat exchanger will be measured by a tipping bucket and then returned directly to the nutrient tank.

3.7.9. Pressure compensation

An externally mounted pressure compensation bag will allow for air volume changes associated with a +/- 10C range of temperature control. This means that volume fluctuations induced by temperature changes of up to 10C in either direction (at constant external pressure) will be compensated when starting with a half full compensation bag. Internal and external pressure will be monitored with pressure transducers. A passive vent will account for over pressure events.

3.8. Chamber shell subsystem

The primary design criteria for the chamber shell revolve around component material selection. All internal surfaces will be made of inert materials to minimize potential off gassing of VOCs that could influence plant productivity. Suitable materials include passivated 316 stainless steel, polypropylene, Teflon, glass, and Viton. Internal stainless steel surfaces (walls) will have a beaded finish to avoid hot spots and aid in light diffusivity.

The chamber will be insulated, where possible, with up to 2” of extruded polystyrene to mitigate thermal fluctuations induced by the external environment. The building HVAC should be sized appropriately to minimize external influences.

In addition to the PCU, a separate common rack is required to house the common materials including nutrient and acid/base stock tanks, gas tanks, and computer systems space (if not provided with building infrastructure). External racks (cabinets) will also be required for the control system as specified below. The rack will be either attached directly to the side of one PCU as depicted in the accompanying diagrams, or can be attached to a wall close to the PCU subunits.

3.9. Control subsystem

The control system will be provided by Sherpa Engineering utilizing Schneider PLC hardware. A SCADA system is also connected to the architecture. The SCADA is in charge of the HMI and data acquisition system.

3.9.1. I/O port specifications

Each PCU subunit will have a separate electrical cabinet (EPIC cabinet in fig 7), and there will be a physically separate main controller (PCU control cabinet in fig 7) capable of communicating with the 3 growth chambers and to handle centrally supplied resources (nutrient supply, ambient sensors). All digital outputs will have a manual Auto/Off/On switch and all 4-20mA outputs will have a manual override. Preliminary I/O control and input points are shown in Tables 3 and 4.

Tab. 6 Common control points

INPUTS:	
4 stock level	0-5 VDC Digital
1 ambient T	4-20 mA
1 ambient RH	4-20 mA
1 ambient pressure	4-20 mA
1 hot water source T	Thermister
1 cold water source T	Thermister
1 hot water flow	4-20 mA
1 cold water flow	4-20 mA

Tab. 7 Control points for *each* PCU subunit

INPUTS:	
2 Air T	4-20 mA
2 Air RH	4-20 mA
2 PAR quantum sensor Li-Cor	0-10 mV
1 pressure	4-20 mA
1 air flow	4-20 mA
1 nutrient tank level	0-5 VDC Digital
1 nutrient flow	pulse
1 nutrient tank T	thermister
2 lamp on detect	0-5 VDC
2 lamp loft T	thermister
2 lamp loft fan detect	0-5 VDC
1 O_2 level	4-20 mA
1 CO_2 level	4-20 mA
1 CO_2 flow	4-20 mA
1 condensate tipping bucket	pulse
2 EC	4-20 mA
2 pH	4-20 mA
2 EC/ pH associated T	thermister
2 hot rad T	thermister
2 cold rad T	thermister
2 heat supply T (inlet/outlet)	thermister
2 cold supply T (inlet/outlet)	thermister
2 hot/cold valve position	4-20 mA

OUTPUTS:	
6 lamp contactors	110/220 VAC
1 irrigation pump	digital
1 irrigation pump speed	4-20 mA
1 irrigation valve	digital
4 nutrient stock valve	digital
1 blower	digital
1 blower speed	4-20 mA
1 lamp loft fan	digital
1 CO_2 inject	4-20 mA
1 hot water valve	4-20 mA
1 cold water valve	4-20 mA
2 recirculation pump	digital

3.9.2. PLC

For the PLC, there is a single controller option. Initially two PLC units were considered, but the less expensive Schneider Modicom Momentum PLC has been discontinued as it would require one separate unit for each PCU subunit. The controller selected by Sherpa Engineering for the PCU is the Schneider Modicom Quantum PLC as one unit can handle all PCU subunits.

3.9.3. PCU System Overview

PCU system can be represented by two main hardware blocks: the chambers and the control cabinet. All these hardware is needed to maintain the proper conditions in the chambers. PCU system overview is shown in Fig. 17.

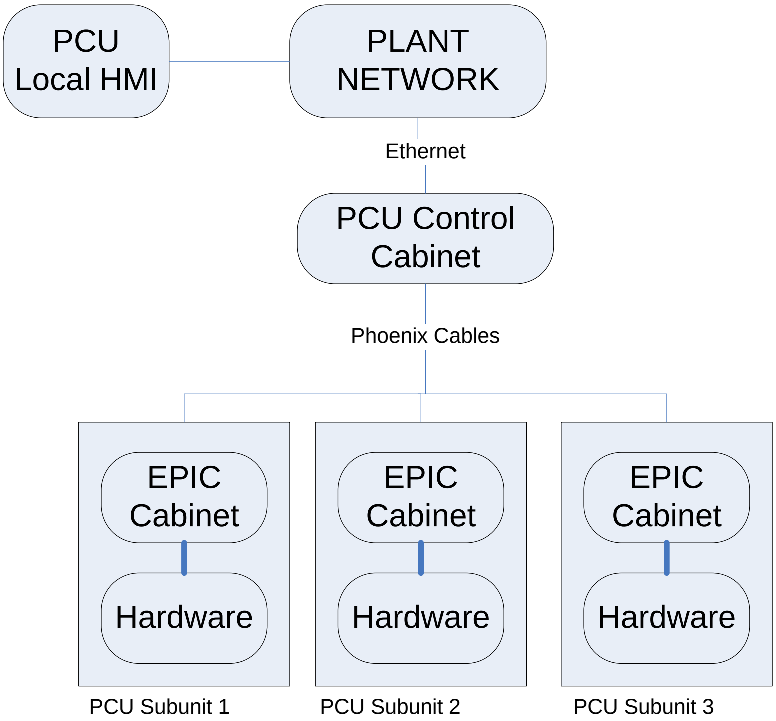

Fig. 17 PCU system overview

PCU

From the control point of view the PCU can be seen as a set of sensors and actuators. There are about 175 sensors and actuators in total. All these signals are wired to EPICs, placed closed to the PCU chambers. The EPIC have: electrical protection, power interfaces and the electrical interfaces necessary to connect directly to the control cabinet. This means that all the power circuits are in the EPIC, which is placed closed to the chambers, while the PCU Control Cabinet only manages information signals.

PCU Control Cabinet

The PCU Control Cabinet houses the PCU Control System equipment. It will contain the PLC (Programmable Logic Controller) with the required processor, I/O cards and power supply modules, interface connectors, network elements and power safety devices. The Control Cabinet will be installed closed to the PCU subunits.

Plant Network

The plant network interconnects the PLC of the PCU, the SCADA server and SCADA client. The following picture (Fig. 18) shows the PCU system structure.

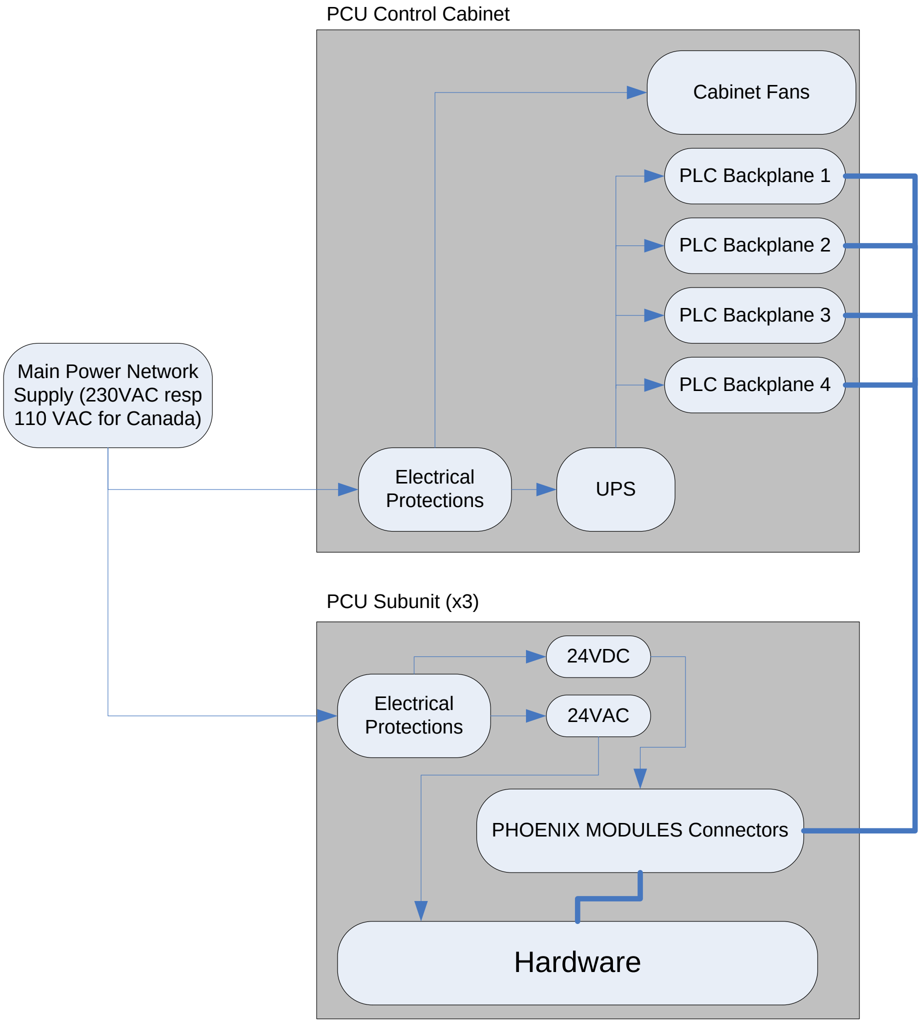

Fig. 18 PCU System

Only one PCU subunit is represented in Fig. 18 but PCU Control Cabinet is connected with 3 PCU subunits using PHOENIX cables.

3.9.4. PCU Control Hardware Description

The PCU Control Cabinet acquires data from the PCU subunits (respectively from the EPIC cabinets) and supplies control commands accordingly. Fig. 18 describes the control concept and the main elements involved.

Two proposals of the control cabinet design are represented in this section. One represents a reduced version minimizing the number of PLC cards used for the whole PCU, sharing signals from different PCU subunits in the same PLC card. Another proposal is the extended version, where each PLC card will receive or send signals from only one PCU subunit. It is possible to wire signals from different PCU subunits in one PLC card but this is not recommended. The extended version proposal uses more PLC cards than the reduced version but allows for more spare input/output signals and a better arrangement of the signals.

3.9.4.1. PCU Control Cabinet Description (Reduced version)

PCU Control Cabinet Overview

The reduced version of the control cabinet is a simple 600x600x2000mm (width x depth x height) Rittal electrical cabinet with one mounting plate and one front door cabinet. The following figure represents the control cabinet with its components.

Mount plate layout component description of the reduced version as seen in Fig. 19:

1. Fans
2. 30mm. width cable guide
3. PLC Backplane
4. 50mm width cable guide
5. 4 free slots in PLC backplane
6. T RIO system
7. Magnetothermic circuit breaker
8. Differential circuit breaker.
9. EMI Filter
10. DIN rail
11. UPS
12. Mounting plate

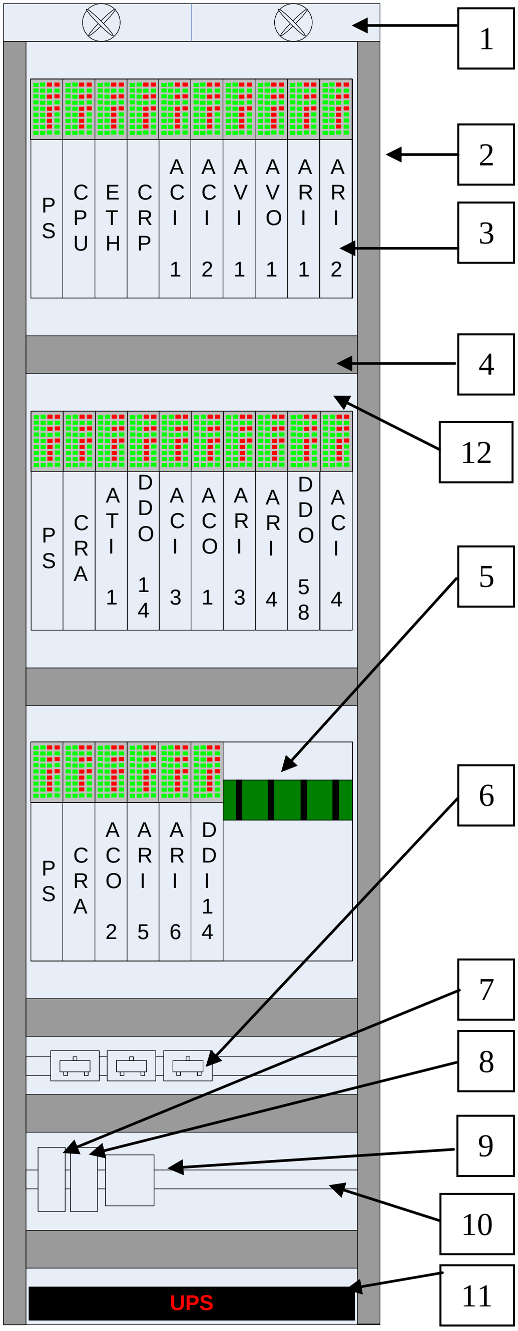

Fig. 19 Control Cabinet Mounted plate (reduced version)

The reduced version of the control cabinet allows updating the backplane 3 by adding 4 more PLC cards in the free slots.

The following figures represent the EPICs of the PCU reduced version. Signals from/to EPIC subunits are divided in the three EPICs. Each EPIC houses the electrical protections, 24VDC power supply, 24VAC power supply and Phoenix terminals blocks to wire the signals from/to each chamber. EPIC is 800x300x1000mm (width x depth x height) Rittal electrical cabinet and there is enough room to place the magnetothermics, fuses and contactors for pumps or blower connection but these devices are not considered in this document.

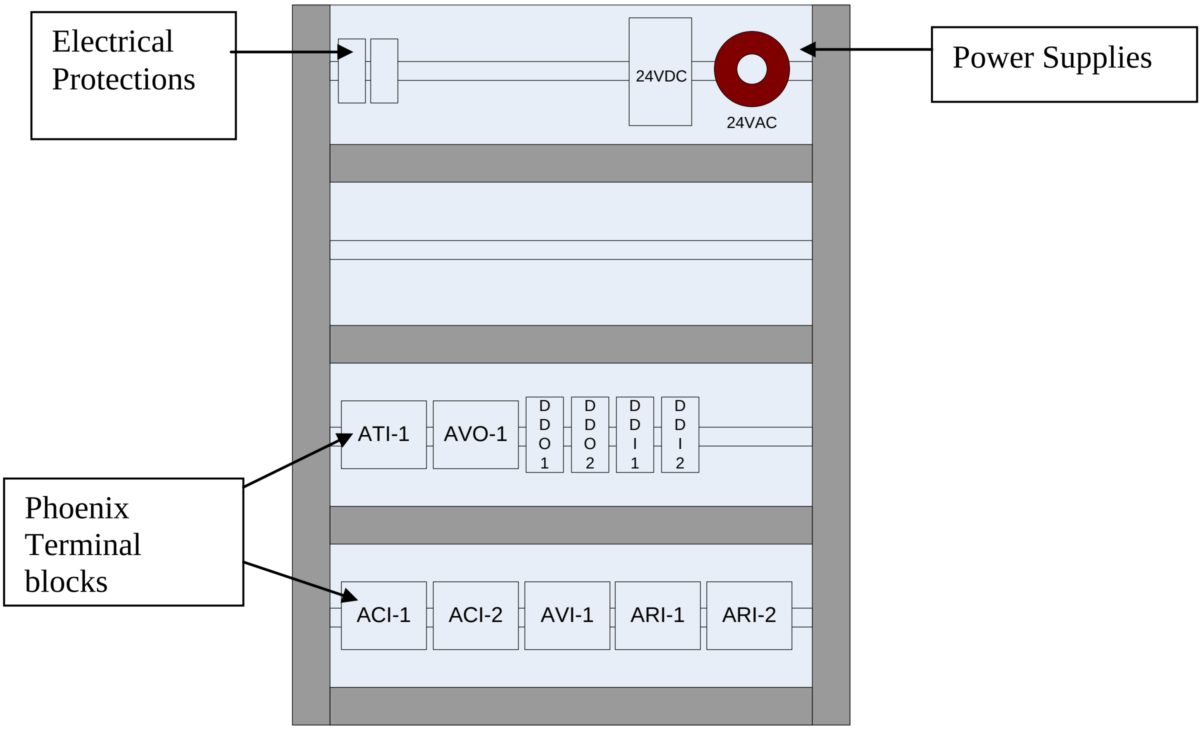

Fig. 20 EPIC PCU subunit 1 (reduced version)

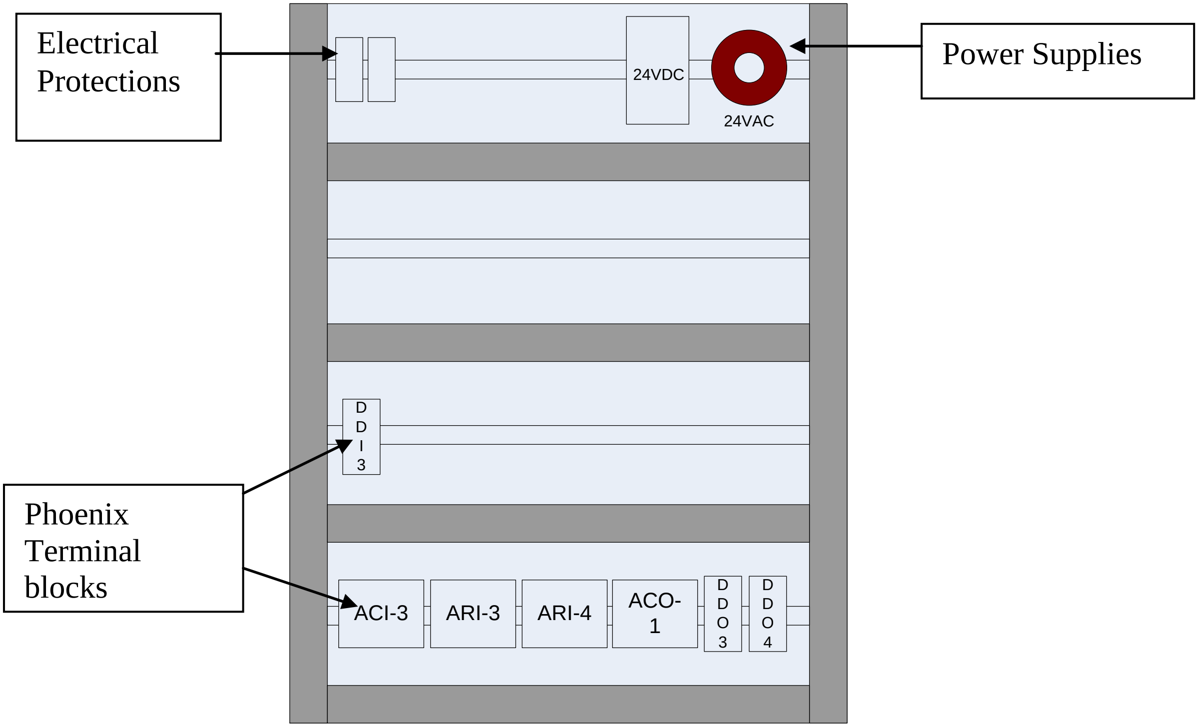

Fig. 21 EPIC PCU subunit 2 (reduced version)

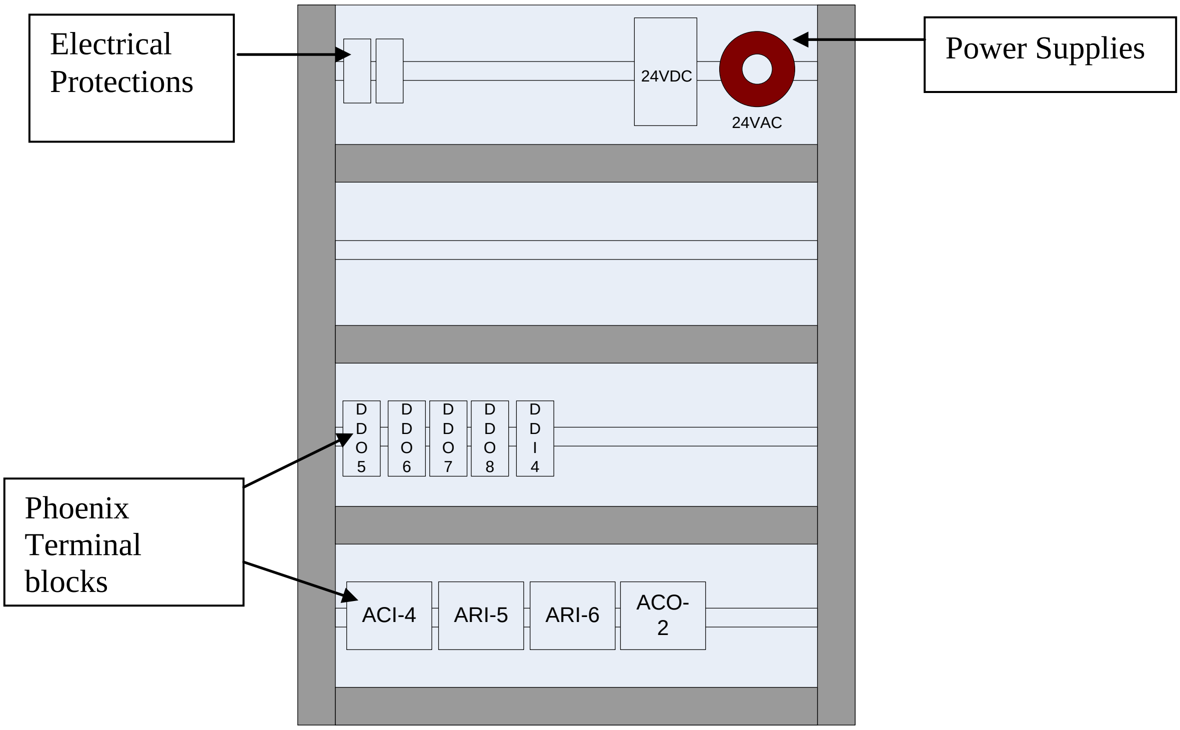

Fig. 22 EPIC PCU subunit 3 (reduced version)

PLC configuration

The Schneider PLC I/O cards installed are the following:

- Digital Input, DI cards → model ***140DDI35300***, with 32 ports. One unit.
- Digital Output, DO cards → model ***140DDO35300***, with 32 ports. Two units.
- Analogue Voltage Input, AVI card → model ***140AVI03000***, with 8 ports. One unit.
        - Voltage: (0 – 10 VDC) or (0 – 5 VDC) or Current (4 – 20 mA)
        - Resolution 16/15/14 bits and bipolar option is available.
- Analogue Current Input, ACI cards:
    - Model ***140ACI04000***, with 16 ports, four units.
        - Current: (0-20mA, 0-25000counts) or (0-20mA, 0-20000counts) or (4-20mA, 0-16000counts) or (4-20mA, 4095 counts).
- Analogue Voltage input ATI cards for thermocouples and low voltage values → model ***140ATI03010***, with 8 ports. One unit.
- Analogue Input cards for thermisters. → model ***140ARI03000***, with 8 inputs. Six units.
- Analogue Current Output (current sink), ACO cards → model ***140ACO13000***, with 8 ports, two units.
        - Current: (0-25mA, 0-25000counts) or (0-20mA, 0-20000counts) or (4-20mA, 0-16000counts) or (4-20mA, 4095 counts).
- Analogue Voltage Output, AVO cards → model ***140AVO02000*** with 4 ports, one unit.
        - Voltage: (-/+ 10VDC), (-/+ 5VDC), (0-10VDC) or (0-5VDC).

PCU Quantum (by Schneider) Programmable Logic Controller will be mounted on three backplanes

- PLC primary (housing CPU, Ethernet Card, RIO head and Input/Output cards)
- PLC backplane 2 (RIO drop card and Input/Output cards)
- PLC backplane 3 (RIO drop card and Input/Output cards)

with 10 slots available in each backplane.

3.9.4.2. PCU Control Cabinet Description (Extended version)

PCU Control Cabinet Overview

The extended version of the control cabinet uses two 600x600x2000 mm (width x depth x height, 1200 x 600 x 2000 mm in total) Rittal electrical cabinets mounted together with two mounting plates and two cabinet front doors. In the following figure the control cabinet with its components is represented:

Mount plate layout component description as seen in Fig. 23:

1. Fans
2. 30mm width cable guide
3. PLC Backplane
4. 50mm width cable guide
5. 4 free slots in PLC backplane
6. 100mm width cable guide
7. T RIO system
8. Magnetothermic circuit breaker
9. Differential circuit breaker
10. EMI Filter
11. DIN rail
12. UPS
13. Mounting plate

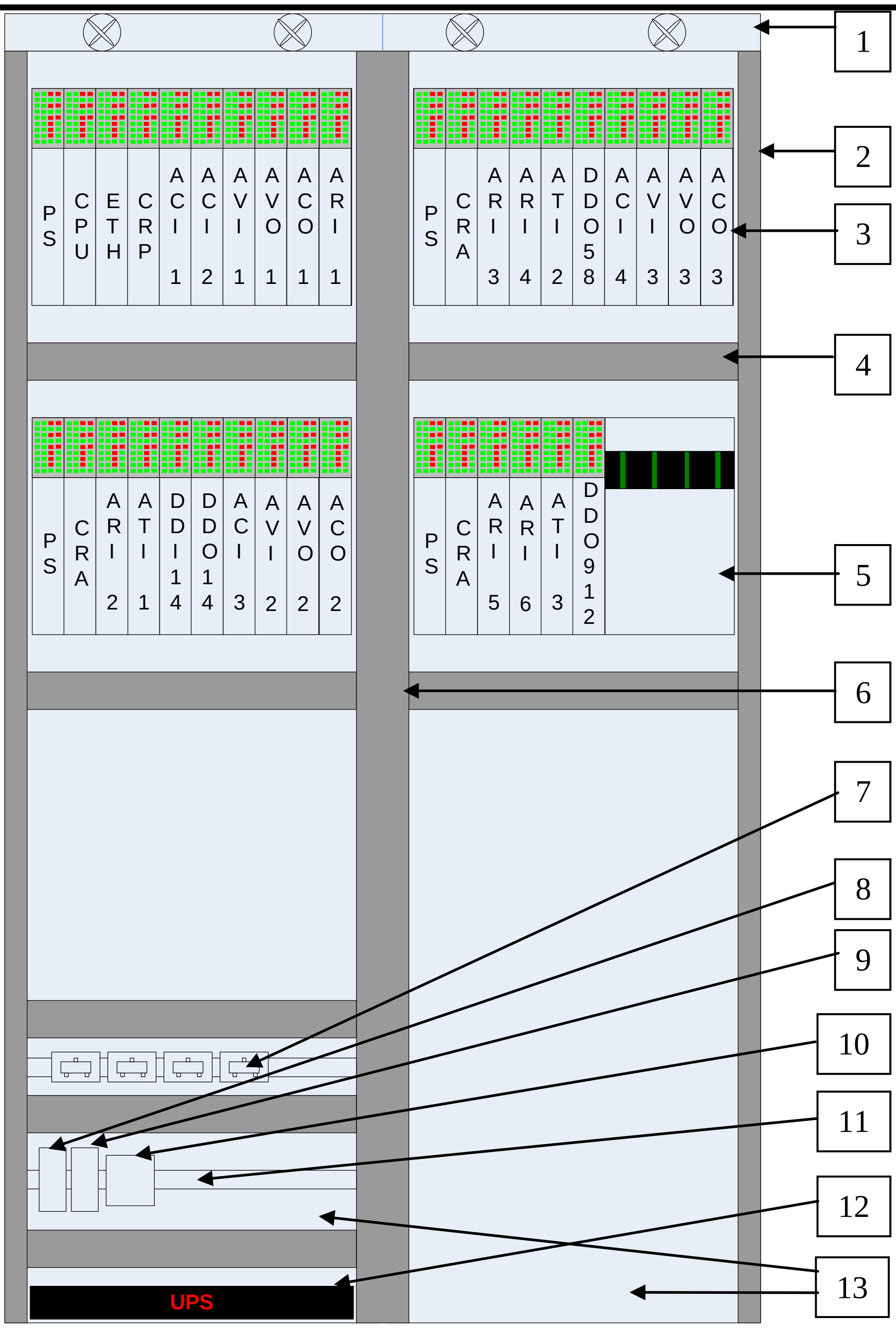

Fig. 23 Control cabinet Mounted plate (extended version)

The extended version of the control cabinet allows expansion of the PLC as free slots are available in the 4th backplane and sufficient room is left in the mounting plates to place two more PLC backplanes.

The following figures represent the EPIC of the each PCU subunit of the extended version. Each EPIC houses the electrical protections, 24VDC power supply, 24VAC power supply and Phoenix terminals blocks to wire the signals from/to each chamber. EPIC is 800x300x1000mm (width x depth x height) Rittal electrical cabinet and there is enough room to place the magnetothermic, fuse and contactors for pump or blower connection but it is not considered in this document.

Common signals and signals from/to PCU subunit 1 will be wired to EPIC PCU subunit 1.

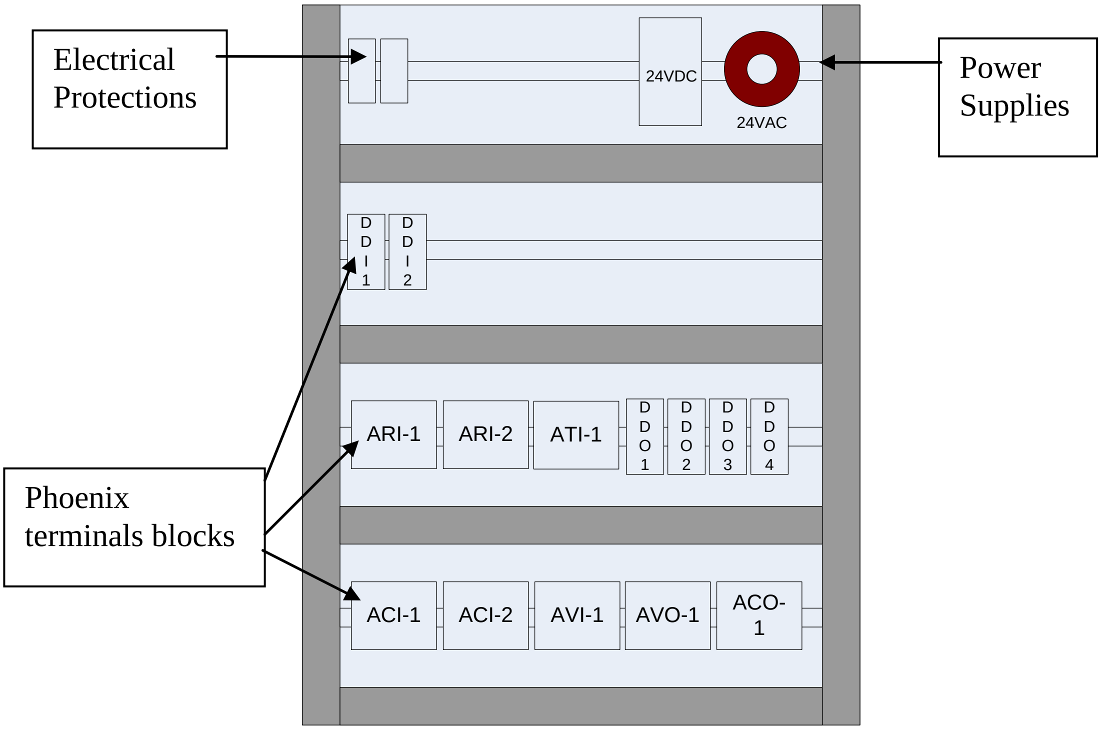

Fig. 24 EPIC PCU subunit 1 (extended version)

Signals from/to PCU subunit 2 will be wired to EPIC PCU subunit 2.

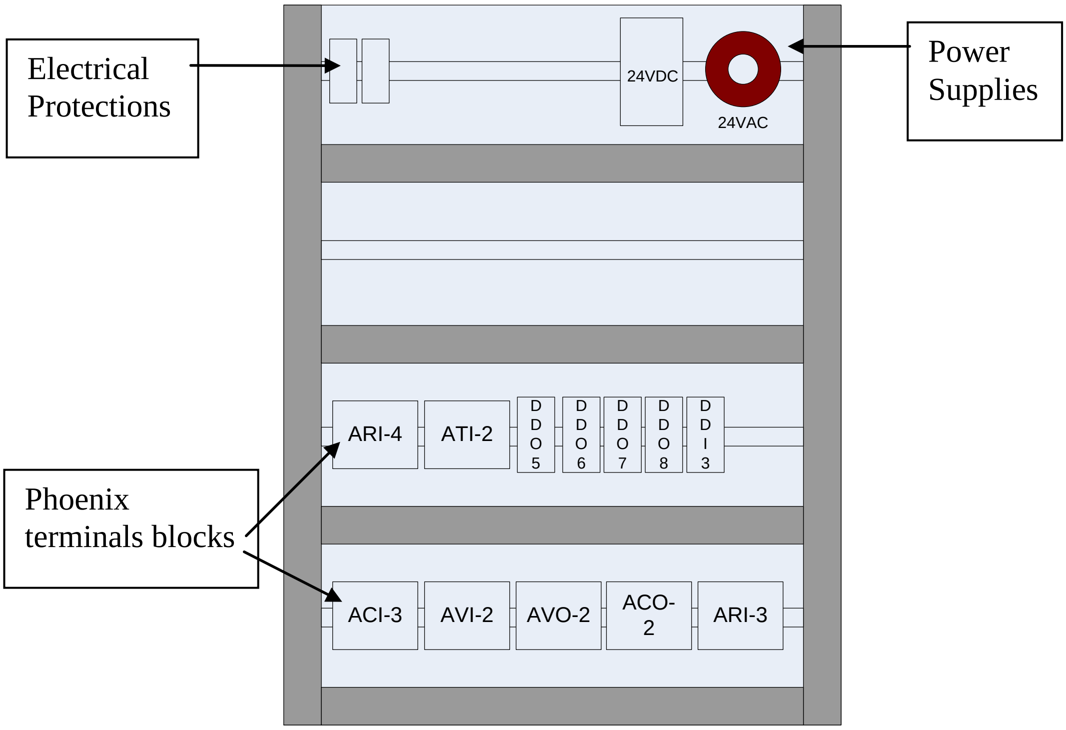

Fig. 25 EPIC PCU subunit 2 (extended version)

Signals from/to PCU subunit 3 will be wired to EPIC PCU subunit 3.

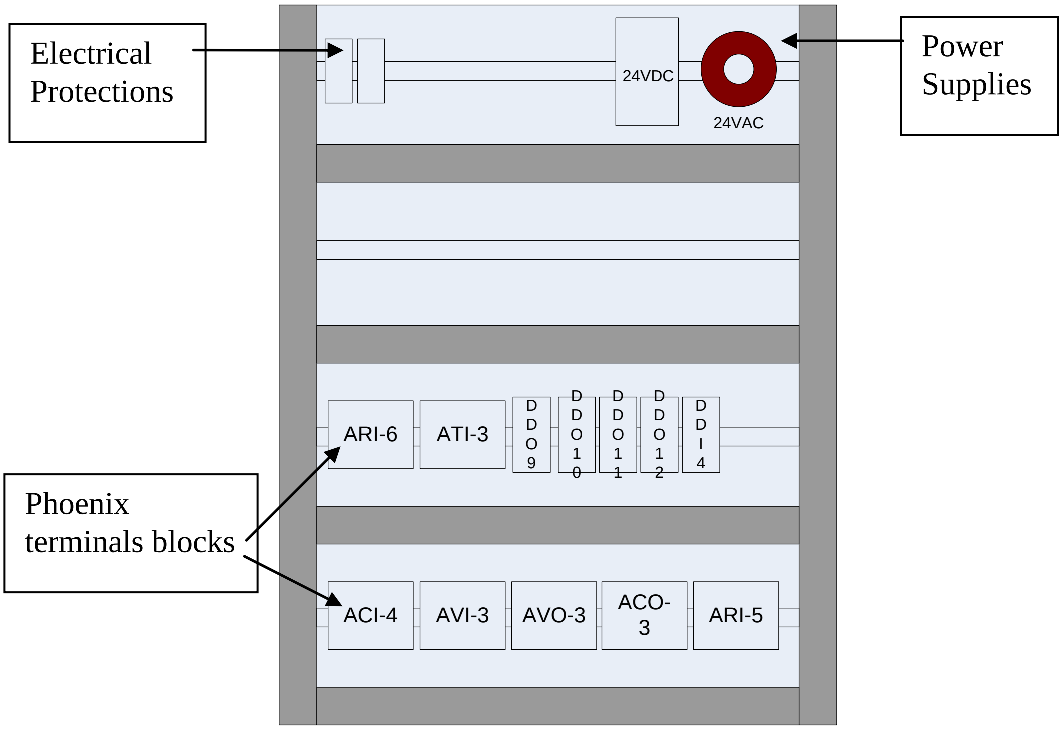

Fig. 26 EPIC PCU subunit 3 (extended version)

PLC configuration

The Schneider PLC I/O cards installed are the following:

- Digital Input, DI cards → model ***140DDI35300***, with 32 ports. One unit.
- Digital Output, DO cards → model ***140DDO35300***, with 32 ports. Three units.
- Analogue Voltage Input, AVI card → model ***140AVI03000***, with 8 ports, three units.
    - Voltage: (0 – 10 VDC) or (0 – 5 VDC) or Current (4 – 20 mA)
    - Resolution 16/15/14 bits and bipolar option is available.
- Analogue Current Input, ACI cards:
    - Model ***140ACI04000***, with 16 ports, four units.
        - Current: (0-20mA, 0-25000counts) or (0-20mA, 0-20000counts) or (4-20mA, 0-16000counts) or (4-20mA, 4095 counts).
- Analogue Voltage input ATI cards for thermocouples and low voltage values → model ***140ATI03010***, with 8 ports. Three units.
- Analogue Input cards for thermisters. → model ***140ARI03000***, with 8 inputs. Six units.
- Analogue Current Output (current sink), ACO cards → model ***140ACO13000***, with 8 ports, three units.
    - Current: (0-25mA, 0-25000counts) or (0-20mA, 0-20000counts) or (4-20mA, 0-16000counts) or (4-20mA, 4095 counts).
- Analogue Voltage Output, AVO cards → model ***140AVO02000*** with 4 ports, three units.
    - Voltage: (-/+ 10VDC), (-/+ 5VDC), (0-10VDC) or (0-5VDC).

PCU Quantum (by Schneider) Programmable Logic Controller (extended version) will be mounted on four backplanes

- PLC primary (housing CPU, Ethernet Card, RIO head and Input/Output cards)
- PLC backplane 2 (RIO drop card and Input/Output cards)
- PLC backplane 3 (RIO drop card and Input/Output cards)
- PLC backplane 4 (RIO drop card and Input/Output cards)

with 10 slots available in each backplane.

3.9.4.3. Interfaces

Both reduced and extended versions of the PCU Control Cabinets feature three interfaces:

- Interface to the UGent power supply (mains) with European characteristics (220-230 VAC, 50 Hz) or 110/220 VAC, 60 Hz in Canada.
- Interface with the PCU subunits by three EPIC cabinets.
- Interface with the Control Room using an Ethernet connection to allow the implementation of the monitoring and surveillance functions on the PCU central computer

Modicon RIO (Remote I/O) LAN architecture will be used in both versions (extended and reduced) to connect PLC primary (first backplane) with the other backplanes.

The following hardware will be required to implement RIO architecture:

1. 140CRP93100 (Quantum RIO head-end adaptor)
2. 140CRA93100 (Quantum RIO drop adaptor)
3. MA0185100 (T-connector, connects the RG-6 drop cable to the RG-11 trunk cable)
4. 520422000 (Trunk Terminator 75 ohms)
5. RG 6 quad shield coaxial cable
6. F Connector cassette

3.9.5. Functional overview

Control cabinet diagram is shown in Fig. 17. It is divided in basically 2 subsystems:

1. Energy distribution
    1.1. Electrical protections
    1.2. Power supplies
        1.2.1. PLC power supply
2. Electronics
    2.1. PLC
        2.1.1. PLC Ethernet card.
        2.1.2. PLC processor card
        2.1.3. LC I/O cards
        2.1.4. PLC RIO cards

3.9.6. Energy Distribution

This section describes the energy distribution of the control cabinet and EPIC cabinets.

3.9.6.1. PCU Control Cabinet

This subsystem supplies energy to all components of the PCU control cabinet.
Components of the energy distribution subsystem:

- Electrical protections
    - Magnetothermic AC_MGTH2: MERLIN GERIN MULTI9 C60HB C10
    - Differential: HAGER CDC748M (Imax: 40A; ΔImax: 0.03A).
- EMI Filter Yunpen YK06T1.
- Power supplies
    - PLC power supply 140CPS11420.

3.9.6.2. EPIC Cabinets

This subsystem supplies energy to all components of the EPIC cabinet. Moderate or high power consuming devices like pumps, blower and other actuators will be feed from other sources.
Components of the energy distribution subsystem:

- Electrical protections
    - Magnetothermic AC_MGTH2: MERLIN GERIN MULTI9 C60HB C6
    - Differential: HAGER CDC748M (Imax: 40A; ΔImax: 0.03A).
- Power supplies
    - 24VDC : Telemecanique ABL8REM24050 (or the same features)
    - 24Vac : NORATEL RT250/2024 (or the same features)

3.9.7. Reduced / Extended options trade-off

This section compares two proposals of the control cabinet with its advantages and disadvantages. The table below compares the total Input/Outputs of the two versions with its free inputs/outputs available.

		Reduced Version	**Extended Version**
AI	**Used**	**105**	
	Available	128	160
	Free	23	55
DI	**Used**	**13**	
	Available	32	32
	Free	19	19
AO	**Used**	**15**	
	Available	20	36
	Free	5	21
DO	**Used**	**48**	
	Available	64	96
	Free	16	48

Tab. 8 Reduced version vs. Extended version

The table below indicates the advantages and disadvantages of the two proposals:

Reduced version	Extended version
• Less expensive • Less space needed • Less possibilities of expansion (only room for 4 more cards). • Complex cabling, routing from same PLC card to several PCU subunits.	• More Expensive • More space • Better possibilities of expansion (up to 20 more cards). • Cabling simplified; one PLC IO card for each PCU subunit.

Tab. 9 Reduced version vs. Extended version advantages / disadvantages

It is recommended that the extended version be employed in PCU control as this will give far more flexible and simpler upgrade and expansion possibilities.

4. Conclusions

This document has provided a detailed outline of the preliminary FC1 PCU design and underlying principles. The PCU consists of three independently controllable subunits suitable for studies on plant growth and development in a closed system. Accommodations have been made to allow future expansion in the number of PCU subunits, as well as with internal configurations that can adapt to future experimental plans.

A number of critical areas have been outlined including air distribution, selective oxygen removal, and ethylene evolution. The HVAC system will be analyzed in detail using CFD simulations. The results of these simulations and conclusions will be discussed further in TN 98.8.3 ‘Study Of Critical Subsystems And Selection Of Most Suitable Technologies’. The design will then if necessary be optimized using the results of the CFD simulations and computer based optimization algorithms. An optimized design will be presented in TN 98.8.4 ‘PCU final design’. Oxygen and Ethylene control strategies will be further investigated and potential strategies will be explained in TN 98.8.3.

Another critical area is the sealing of the hydroponic system against the chamber atmosphere. The PCU has been designed with several levels of flexibility allowing to perform further research and development on this issue and future retrofitting to a sealed system.

5. References

Statement of Work MELiSSA Food Characterization Phase 1; ESA Directorate of Technical and Quality Management; TEC-MCT/2008/3633/In/CP.

MELiSSA Food Characterization Phase 1; TN 98.7 Definition of PCU requirements; Contract No. 22070/08/NL/JC.

MELiSSA Food Characterization Phase 1; TN 98.8.1 Consolidation of specifications for the design of a plant characterization unit; Contract No. 22070/08/NL/JC.

6. Appendix 1 – Preliminary component listing

Component	Quantity	P&ID naming	Manufacturer	Part number	Supplier
Atmosphere control					
Main Centrifugal Blower	1	HVAC-BLWR-01	Delhi	G12-9-DD	Delhi
VFD Motor Controller	1		TBD	TBD	TBD
Temperature Sensor – hot coil	1	HVAC-Tcoil-01	Argus	TN2	Argus
Temperature Sensor – hot coil	1	HVAC-Tcoil-02	Argus	TN2	Argus
Temperature Sensor – cold coil	1	HVAC-Tcoil-03	Argus	TN2	Argus
Temperature Sensor – cold coil	1	HVAC-Tcoil-04	Argus	TN2	Argus
Temperature/RH Sensor 1	1	HVAC-TRH-01	Vaisala	HMT 100	Hoskin Scientific
Temperature/RH Sensor 2	1	HVAC-TRH-02	Vaisala	HMT 100	Hoskin Scientific
Temperature sensor – hot loop	1	HVAC-Tloop-01	Argus	TN21-DW/C	Argus
Temperature sensor – cold loop	1	HVAC-Tloop-02	Argus	TN21-DW/C	Argus
Temperature sensor – hot inlet	1	HVAC-Tin-01	Argus	TN21-DW/C	Argus
Temperature sensor – cold inlet	1	HVAC-Tin-02	Argus	TN21-DW/C	Argus
Temperature sensor – hot outlet	1	HVAC-Tout-01	Argus	TN21-DW/C	Argus
Temperature sensor – cold outlet	1	HVAC-Tout-02	Argus	TN21-DW/C	Argus
Flow sensor – hot loop	1		TBD	TBD	TBD
Flow sensor – cold loop	1		TBD	TBD	TBD
Chilled water coil with condensate outlet	1	HVAC-COIL-02	Delhi	CW12	Delhi
Cold water isolation valve	1	HVAC-MVLV-03	Swagelok	TBD	TBD
Cold water isolation valve	1	HVAC-MVLV-04	Swagelok	TBD	TBD
Chilled water valve (3-way proportional)	1	HVAC-3VLV-02	Belimo	Belimo B317	TBD
Chilled water recirculation pump	1	HVAC-PUMPcold-02	Grundfos	UPS 15-42F	TBD
Hot Coil	1	HVAC-COIL-01	Delhi	HW12	Delhi
Hot water isolation valve	1	HVAC-MVLV-01	Swagelok	TBD	TBD
Hot water isolation valve	1	HVAC-MVLV-02	Swagelok	TBD	TBD
Hot water valve (3-way proportional)	1	HVAC-3VLV-01	Belimo	Belimo B311	TBD
Hot water recirculation pump	1	HVAC-PUMPhot-01	Grundfos	UPS 15-42F	TBD
Pressure relief valve (2 kPa)	1	HVAC-PRV-01	TBD	TBD	TBD
Pressure Sensor	1	HVAC-kPa-01	Microfused Technology	MSP-600	TBD
Pressure sensor isolation valve	1	HVAC-MVLV-05	TBD	TBD	TBD
Pressure compensation bag	1	HVAC-PBAG-01	Keika Ventures	Custom	Keika Ventures

Tipping bucket	1	HVAC-TIP-01	La Crosse Technology	WS-7048	TBD
Air flow sensor	1	HVAC-FLOW-01	Geneq	8455	TBD
Lighting subsystem					
Lamp Loft Cooling Fan	1	LAMP-FAN-01	Comair Rotron	MC24B3	Digi-Key
Lamp Loft Cooling Fan	1	LAMP-FAN-02	Comair Rotron	MC24B3	Digi-Key
Lamp Loft Cooling Fan	1	LAMP-FAN-03	Comair Rotron	MC24B3	Digi-Key
Lamp Loft Air Flow Sensor	1	LAMP-AIRFLW-01	UoGuelph	n/a	n/a
Lamp Loft Temperature Sensor	1	LAMP-Tloft-01	Argus	TN2	Argus
Lamp fixture/ballast	1	LAMP-BLST-01	P.L. Lighting	220581 MAXIMA PL 1000W	P.L. Lighting
Lamp fixture/ballast	1	LAMP-BLST-02	P.L. Lighting	220581 MAXIMA PL 1000W	P.L. Lighting
Lamp fixture/ballast	1	LAMP-BLST-03	P.L. Lighting	220581 MAXIMA PL 1000W	P.L. Lighting
Lamp fixture/ballast	1	LAMP-BLST-04	P.L. Lighting	220581 MAXIMA PL 1000W	P.L. Lighting
Lamp fixture/ballast	1	LAMP-BLST-05	P.L. Lighting	220581 MAXIMA PL 1000W	P.L. Lighting
Lamp fixture/ballast	1	LAMP-BLST-06	P.L. Lighting	220581 MAXIMA PL 1000W	P.L. Lighting
Lamp String Relay	1	LAMP-RLY-01	Hager	TBD	TBD
Lamp String Relay	1	LAMP-RLY-02	Hager	TBD	TBD
Lamp String Relay	1	LAMP-RLY-03	Hager	TBD	TBD
PAR Sensor	1	LAMP-PAR-01	LiCOR	LiCOR 190SZ	LiCOR
PAR sensor amplifier	1	LAMP-AMP-01	TBD	TBD	TBD
Gas Analysis Subsystem					
CO2/O2 analyzer	1	INST-NDIR-01	California Analytical	Model 600	Pacwill Environmental
Filter for analyzer flow	1	INST-FLTR-01	Cole Parmer	R-79700-60	Cole Parmer
Spare filters for above	1	n/a	Cole Parmer	R-79700-61	Cole Parmer
Mass Flow Controller for CO2 injection	1	INST-MFC-01	MKS	M100	CCR: Process Products
Power Supply/Display for MKS MFC	1	INST-PWR-01	MKS	n/a	CCR: Process Products
Cable for MKS MFC	1		MKS	n/a	CCR: Process Products
OPTIONAL REPLACEMENT FOR MKS MFC – cheaper			Cole Parmer	R-32907-67	Cole Parmer
CO2 Injection Valve	1	INST-SVLV-01	ASCO	8262G007 24DC	ASCO
Manual Shut off valve - CO2 inject	1	INST-MVLV-01	Parker	n/a	Cole Parmer

Manual Shut off valve – analyzer isolation – inlet	1	INST-MVLV-02	Parker	n/a	Cole Parmer
Manual Shut off valve – analyzer isolation – outlet	1	INST-MVLV-03	Parker	n/a	Cole Parmer
Tube connection fittings	8	n/a	John Guest Fittings	PP010822W	Cole Parmer
Tube connection plugs	5	n/a	John Guest Fittings	PP0808W	Cole Parmer
Tube unions	10	n/a	John Guest Fittings	PP0408W	Cole Parmer
Hydroponics Subsystem					
Nutrient Reservoir	1	HYDRO-NUTR-01	Custom design		
Main Irrigation Pump	1	HYDRO-PUMP-01	Emerson	Penta KB Drive	International Pump
Irrigation isolation valve – pump inlet	1	HYDRO-MVLV-01	TBD	TBD	Tubefit
Irrigation isolation valve – pump outlet	1	HYDRO-MVLV-02	TBD	TBD	Tubefit
Irrigation isolation valve – hydroponics	1	HYDRO-MVLV-03	TBD	TBD	Tubefit
Irrigation isolation valve – sensor loop in	1	HYDRO-MVLV-04	TBD	TBD	Tubefit
Irrigation isolation valve – sensor loop out	1	HYDRO-MVLV-05	TBD	TBD	Tubefit
Irrigation Flow Sensor	1	HYDRO-FLOW-01	TBD	TBD	TBD
pH Sensor	1	HYDRO-pH-01	Mettler-Toledo	InPro 4260	TBD
pH Sensor	1	HYDRO-pH-02	Mettler-Toledo	InPro 4260	TBD
pH Transmitter	1	HYDRO-XMIT-01	Mettler-Toledo	M300	TBD
EC Sensor	1	HYDRO-EC-01	Mettler-Toledo	InPro 7012	TBD
EC Sensor	1	HYDRO-EC-02	Mettler-Toledo	InPro 7012	TBD
EC Transmitter	1	HYDRO-XMIT-02	Mettler-Toledo	M300	TBD
Gully feed temperature sensor	1	HYDRO-Tfeed-01	Argus	TN21-DW/C	Argus
Main loop temperature sensor	1	HYDRO-Tloop-01	Argus	TN21-DW/C	Argus
Acid Manual isolation valve	1	HYDRO-MVLV-06	Swagelok	TBD	Swagelok
Base Manual isolation valve	1	HYDRO-MVLV-07	Swagelok	TBD	Swagelok
Stock A Manual isolation valve	1	HYDRO-MVLV-08	Swagelok	TBD	Swagelok
Stock B Manual isolation valve	1	HYDRO-MVLV-09	Swagelok	TBD	Swagelok
Acid Inject (Solenoid)	1	HYDRO-SVLV-01	Parker	SV-2-1144-2	Tubefit
Base Inject (Solenoid)	1	HYDRO-SVLV-02	Parker	SV-2-1144-2	Tubefit

Stock A Inject (Solenoid)	1	HYDRO-SVLV-03	Parker	SV-2-1144-2	Tubefit
Stock B Inject (Solenoid)	1	HYDRO-SVLV-04	Parker	SV-2-1144-2	Tubefit
Tipping bucket isolation valve	1	HYDRO-MVLV-10	Ta Chen	BALLVLVSS-12	Tubefit
Nutrient Return isolation valve	1	HYDRO-MVLV-11	Ta Chen	BALLVLVSS-32	Tubefit
Nutrient Aeration Needle Valve	1	HYDRO-NVLV-01	Swagelok	SS-4L	Swagelok Southwestern
Nutrient Aeration isolation valve	1	HYDRO-MVLV-12	Ta Chen	BALLVLVSS-4	Tubefit
Nutrient cooling solenoid valve	1	HYDRO-SVLV-05	ASCO	8262G007 24DC	Tubefit
Nutrient cooling isolation valve – inlet	1	HYDRO-MVLV-13	Ta Chen	BALLVLVSS-4	Tubefit
Nutrient cooling isolation valve – outlet	1	HYDRO-MVLV-14	Ta Chen	BALLVLVSS-4	Tubefit
NPT Connectors for above	16	n/a	Swagelok	SS-400-1-4	Swagelok Southwestern
Acid Tank	0.3	HYDRO-TANK-01	Blichmann Engineering	F3-7	TBD
Base Tank	0.3	HYDRO-TANK-02	Blichmann Engineering	F3-7	TBD
Stock A Tank	0.3	HYDRO-TANK-03	Blichmann Engineering	F3-27	TBD
Stock B Tank	0.3	HYDRO-TANK-04	Blichmann Engineering	F3-27	TBD
Acid Level Sensor	0.3	HYDRO-LVL-01	Innovative Components	CLM-2000-SS	Innovative Components
Base Level Sensor	0.3	HYDRO-LVL-02	Innovative Components	CLM-2000-SS	Innovative Components
Stock A Level Sensor	0.3	HYDRO-LVL-03	Innovative Components	CLM-2000-SS	Innovative Components
Stock B Level Sensor	0.3	HYDRO-LVL-04	Innovative Components	CLM-2000-SS	Innovative Components
Main nutrient tank Level Sensor	0.3	HYDRO-LVL-05	Innovative Components	CLM-2000-SS	Innovative Components