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# D3.5 – NDS Final Design Document

prepared for

**WP 3.2 – Nutrient Delivery System**

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# Executive summary

The EDEN ISS nutrient delivery system (NDS) is based on proven horticultural management technology. While some system aspects are relatively new, they will not impact the overall reliability of operation. Similarly, the control system that will operate the NDS and other subsystems is based on Argus Controls (Surrey, BC, Canada) hardware, which has been a greenhouse control and environment management standard since 1984.

The bulk of the NDS hardware is contained within the FEG, a 6 meter insulated shipping container equipped with eight growing racks holding a total of forty-two plant growth trays covering 11.9 square metres of growing space.  The system was designed to grow lettuce, herbs, pepper, tomato and cucumber and will supply the Neumayer Station III crew with fresh produce during operation. Plants will be grown in recirculating nutrient solution that has both pH and electrical conductivity (EC) control. Water will be delivered to the modular growing trays using a hybrid aeroponic/nutrient film technique (NFT) from two nutrient tanks located in the service section. While the NDS in itself uses reliable and proven hardware and growing techniques, the challenges of remote deployment in the Antarctic will provide the needed operational and productivity data required for future missions to the Moon or Mars.

# Table of contents

# Acronyms

| Acronym | Explanation | Acronym | Explanation |
|---|---|---|---|
| CESRF | Controlled Environment Systems Research Facility | MOE | Mobil optrode engine |
| DAQ | Data acquisition system | NDS | Nutrient delivery system |
| DO | Dissolved oxygen | NFT | Nutrient film technique |
| EC | Electrical conductivity | PVC | Polyvinylcholoride |
| FEG | Future Exploration Greenhouse | SS | Service Section |
| GPH | Gallons per hour | TDS | Total dissolved solids |
| INO | l'Institut National d'Optique | | |

# 1 Top-level design overview

The Future Exploration Greenhouse (FEG) section houses eight multi-level growth racks which are scaled to cultivate the selected candidate crops (see EDEN ISS plant selection report). Growth racks will hold two, four, six or eight growing trays (Figure 1), depending on the plant species, architecture and rack position within the FEG. A total of 42 growing units (positions) providing approximately 11.9 $m^2$ of growing area are accommodated within the FEG (Figure 2).

**Figure 1: FEG left side layout showing rack and tray positioning for two and four level units.**

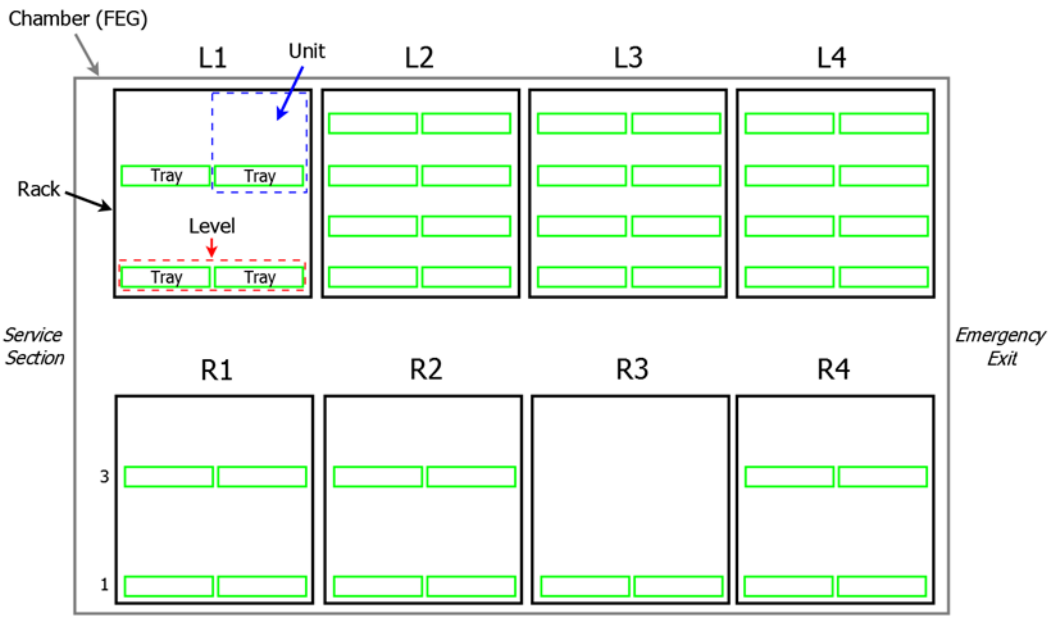



**Figure 2: Future Exploration Greenhouse – Plant tray configuration including illustration of the relevant definitions of chamber, rack, unit, level and tray.**

The overall NDS design was based on an existing hydroponic concept developed by DLR Institute of Space Systems that is a hybridization of classic NFT and aeroponics. The system utilizes standardized 400 x 600 x 120 mm food grade polypropylene shipping containers (growing trays), adapted covers and high pressure misting to achieve an appropriate degree of plant water delivery and root zone oxygenation.

The main component rack (Figure 3) located within the Service Section contains two stainless steel 250 litre nutrient solution tanks and internal primary variable speed mixing pumps. Sensors include pH, EC, temperature, water level and water flow, while manual/semi-automated system disinfection can be achieved with an integrated ozonation system. In order to make maintenance and calibration simpler, pH and EC probes are suspended directly in the nutrient tanks. Stock nutrient reservoirs, acid/base control solutions and dosing pumps are contained below the main tanks, and the high pressure self-priming delivery pumps are controlled by the Argus Control System. Both tanks have redundant sensors to ensure system reliability. Each nutrient tank is operated independently and can have different nutrient solution compositions that depend on experiment and plant requirements. Each nutrient tank has two separate stock supply tanks (traditionally known as A and B, but in this case the second tank has additional solutions C and D available). Both are supplied from the same acid and base reservoirs for pH control. All components in the NDS Service Section rack are placed to allow easy access and simplified maintenance.

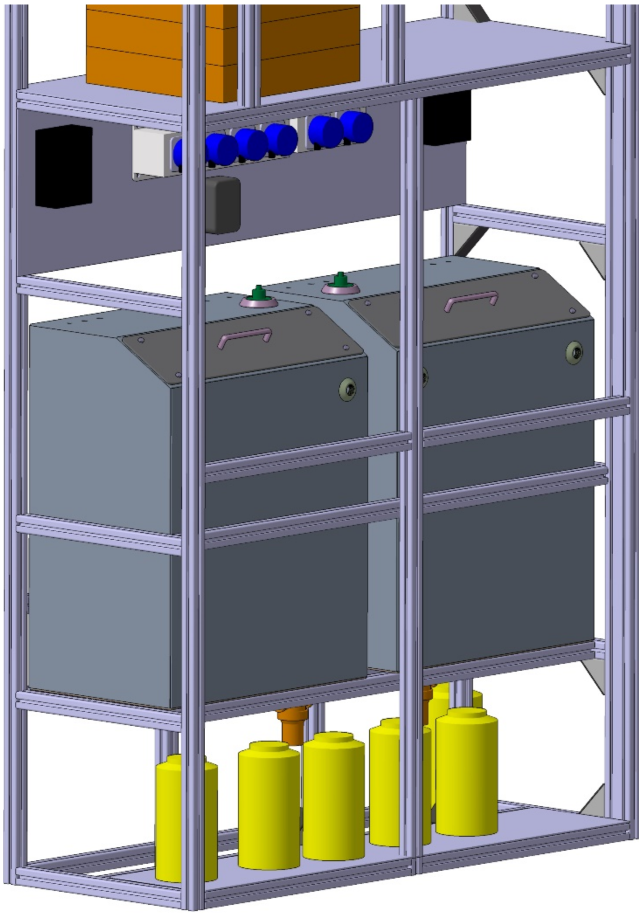


**Figure 3: Front view of the main NDS rack components within the Service Section.**

The main NDS rack feeds the growing systems located in the FEG (Figure 4) which contains four growing rack systems on each side of the central corridor. Each rack can be operated/isolated separately as each has its own high pressure primary pump for delivery to the growing tray's misting nozzles. Growing racks consist of either 8 grow trays (short plants e.g. lettuce, basil, etc.), four grow trays (medium plants, e.g. tomato) or two grow trays (tall plants e.g. cucumber). An additional 8 tray short plant rack is also available for seedling establishment or additional planting space for short-stature plants. Each stack can be fed by either nutrient tank through manually operated 3-way valves on both delivery and nutrient return. The 3-way valves are located in the floor of the FEG and are accessible via removable floor panels. Solution compositional changes should not take place very often, so access through flooring panels is appropriate and helps alleviate space constraints.

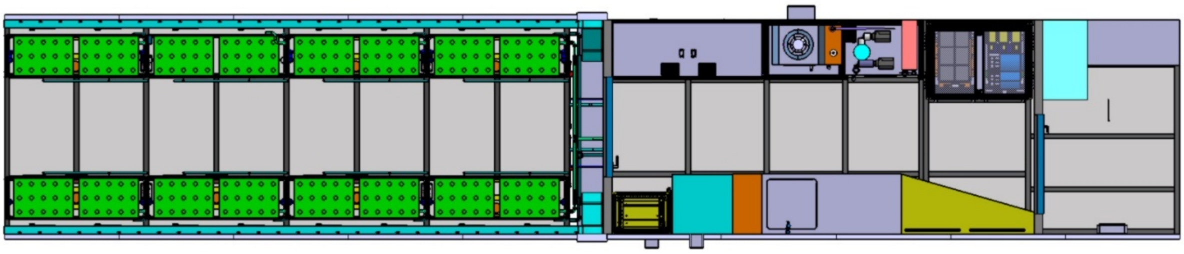


**Figure 4: EDEN ISS top view showing the FEG section on the left and the main service section on the right.**

Return of the nutrient feed stream from the growing tray is by a combination of gravity return to a central lower reservoir (Figure 5) and active pumping with submersible pumps which engage in response to water level sensors located within the sump reservoir (Figure 5 – sump pump). The entire NDS solution loop is closed (recirculating). Water lost to evaporation and transpiration is recovered by the condenser located in the Atmosphere Management System rack in the Service Section. Recovered water is directed to the fresh water tank located in the floor of the airlock. Additional water from the fresh water tank is injected into the nutrient tanks in response to the predetermined tank water level, or as required for nutrient composition control (i.e. lower EC). A cooling loop is included in the nutrient tank design, but will only be implemented if excessive temperatures are encountered in the nutrient feed during pre-deployment testing.

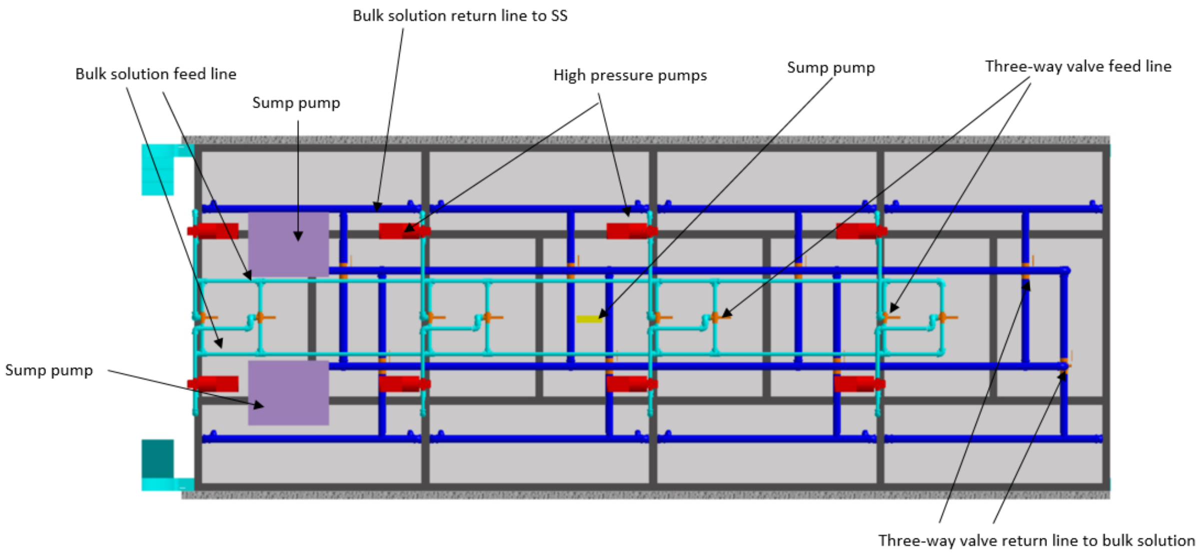



**Figure 5: Under-floor layout of the NDS supply and return piping.**

The overall NDS system design is shown in the block diagram (Figure 6).

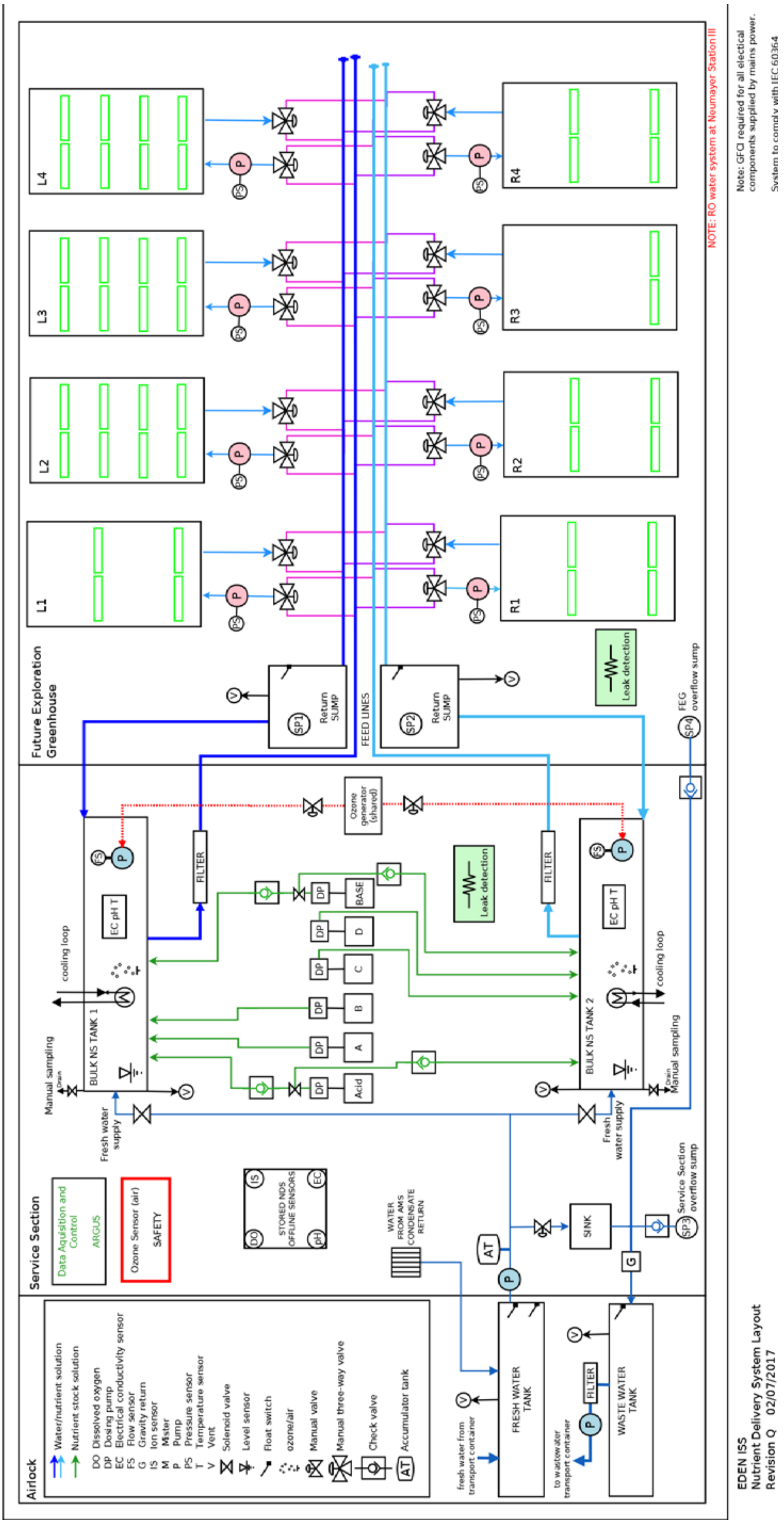



**Figure 6: Block diagram showing system flow and components of the NDS.**

# 2 Detailed design

## *2.1 NDS Service Section rack components*

### 2.1.1 Bulk nutrient tanks

Due to space constraints, the bulk nutrient tanks were custom fabricated (Figure 8) to maximize volumetric efficiency. The final design saw the relocation of the circulation pumps (needed for mixing within the tank) from below and external, to internal within each tank. This layout was found to be ergonomically more desirable as the initial design had awkward ground level access to the pumps and sensors, making maintenance and repair tasks difficult. The front/top access port allows for internal tank inspection and cleaning, and includes ports for suspending sensors in the bulk water. Each tank holds a maximum of 250 litres. A schematic diagram showing the system layout and components within the service section is shown in Figure 7.

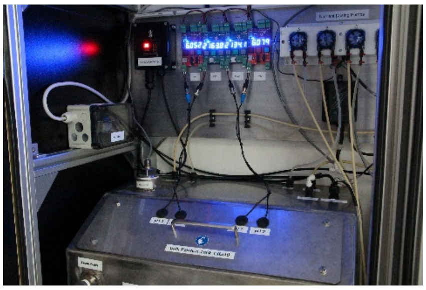


**Figure 8: NDS bulk nutrient tank design shown in the service section NDS rack.**

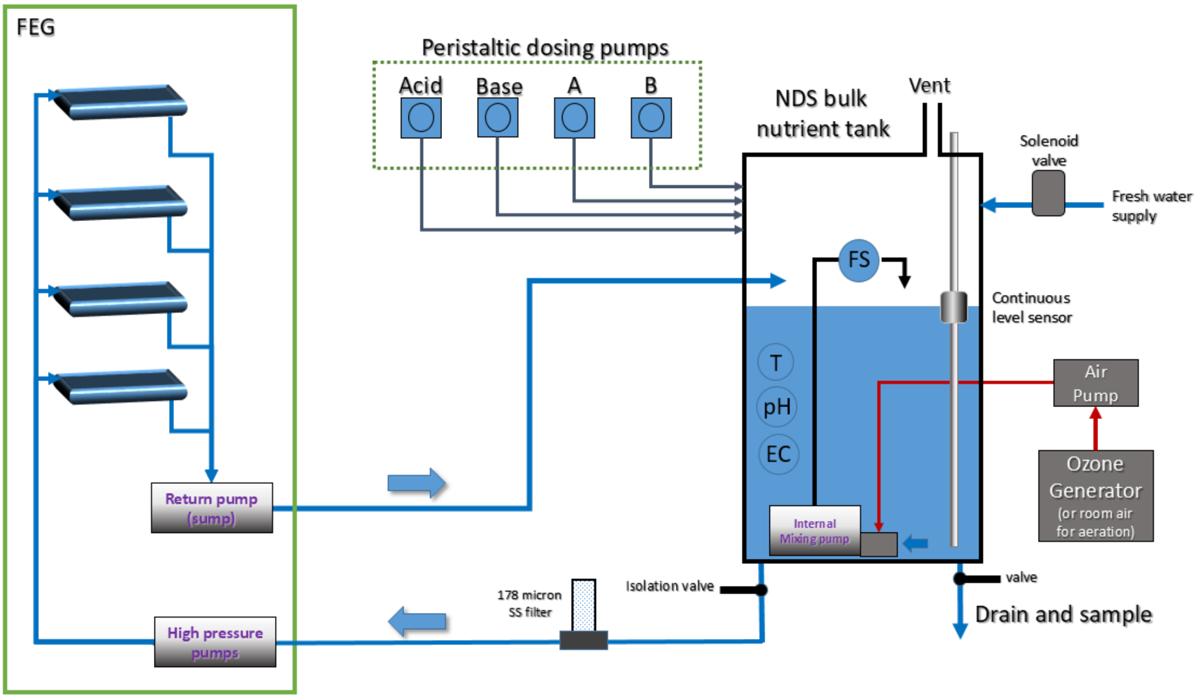



**Figure 7: Simplified schematic diagram of the NDS bulk nutrient tank and associated sensors and pumps. T = temperature sensor, pH = pH sensor, FS = flow sensor, EC = electrical conductivity sensor, A and B are nutrient stock solution mixes. In the second tank, mixes A and B are replaced by C and D.**

### 2.1.2 Sensors

The NDS utilizes submersible pH and EC sensors for nutrient solution composition control. Solution flow, temperature and fluid level sensors are also included in the system design, and monitor water quality, pump operation and tank capacities. Each NDS bulk nutrient tank is equipped with two pH

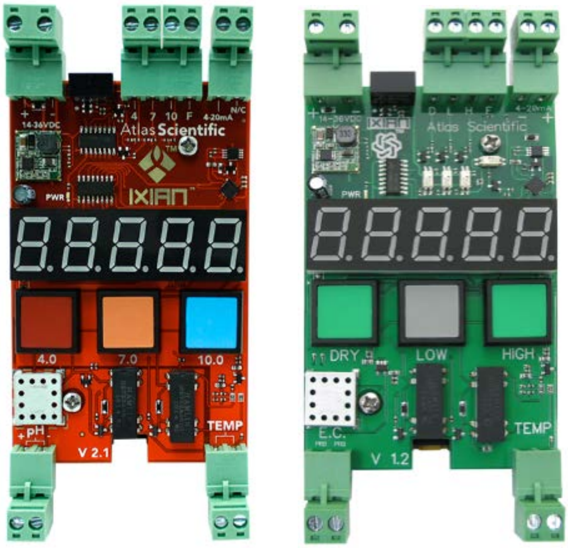



**Figure 9: Atlas Scientific industrial pH and EC.**

and two EC probes – one primary and one secondary for backup. The EC/pH components are industrial class transmitters and probes made by Atlas Scientific (New York) (Figure 9), and they integrate directly with the Argus Control System. Tertiary backup pH and EC measurements will be manually

**Figure 10: Dosatron Pro portable pH (left) and Dosatron Pro portable EC meters (right).**

taken using a hand-held pH/EC meter on a daily basis (Figure 10).

A final housing design for the prototype optrode field instrument was produced using 3D printing technology (Figure 11). The housing is printed in a durable plastic with sensitive areas covered with a metallic coating to prevent interaction with optrode materials (plasticizers). Each housing unit holds 1 fibre and is re-usable if a fresh optrode fibre is re-threaded through the housing after the expired fibre is removed.

The housing provides complete light isolation for the optrode sensor, operates using very small sample volumes (1.9 mL) and provides rigid support for delicate optical connections. This type of housing supports flow-through measurements, however it can also accommodate batch-style measurements with manual sample injection/clearing.

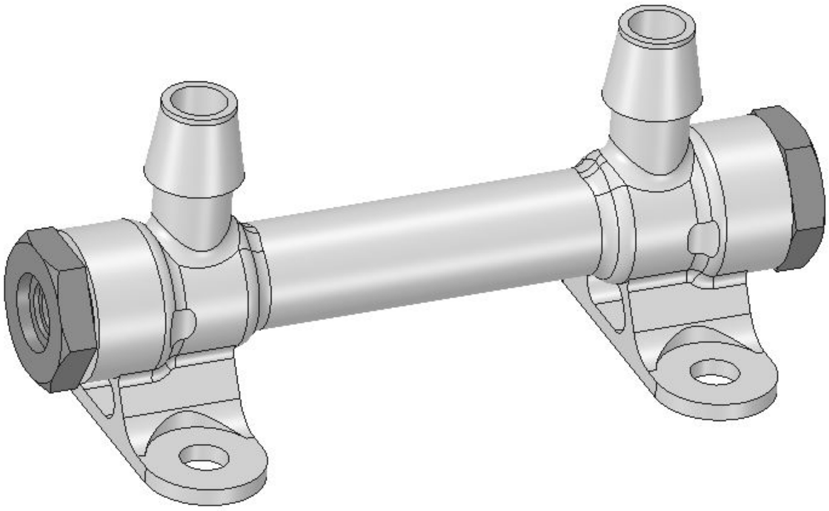


**Figure 11. Optrode housing.**

The Mobile Optrode Engine (MOE) enables optrode sensor measurements at field sites, with or without permanent power availability (can operate in battery mode if necessary). The MOE consists of all the necessary hardware to perform spectral acquisitions and is housed in a compact package: spectrometer (Ocean Optics STS); LED light source; 24VDC power supply; Raspberry Pi micro-computer; powered USB hub; 24-6 V transformer; cooling fan; 5” HDMI touch screen (FIG 2, 3, 4). The system is operated using the touch-screen and the user is provided with graphic prompts that illustrate setup

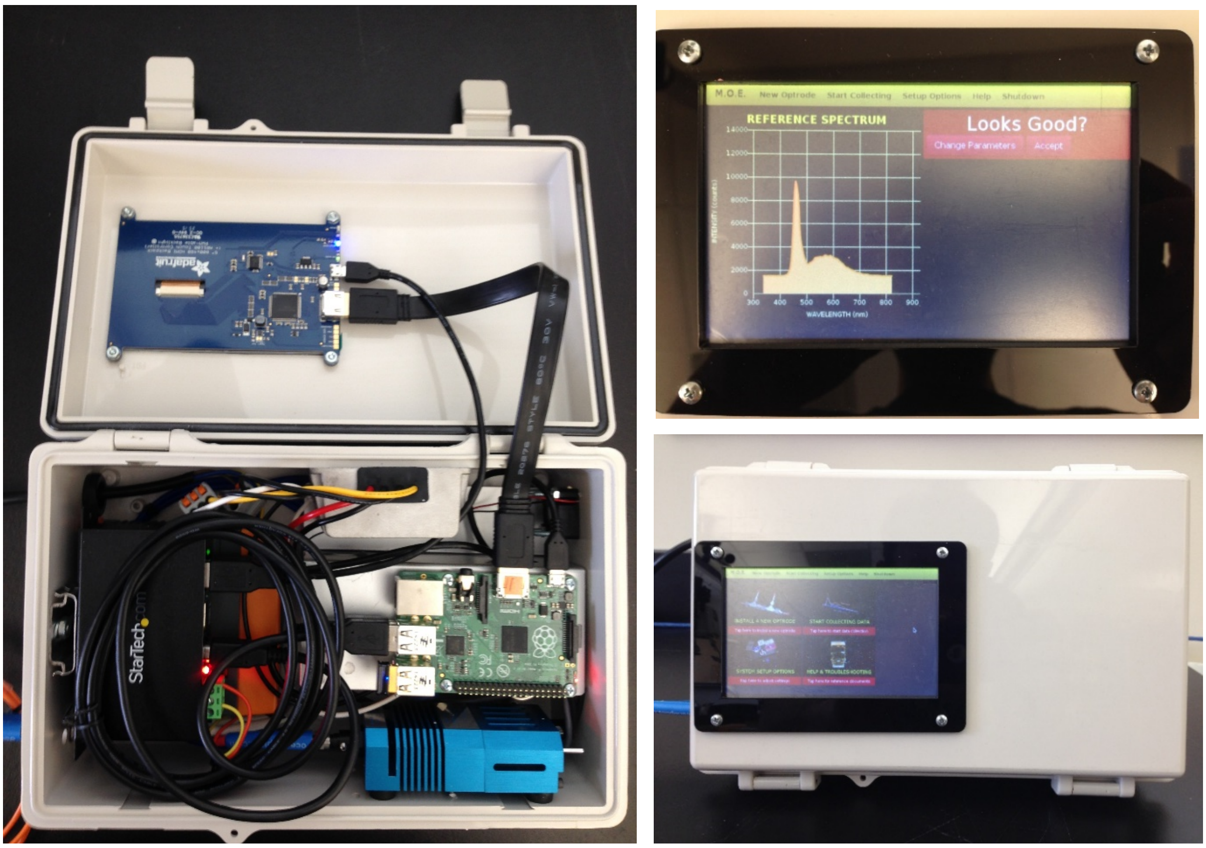



**Figure 12. Mobile Optrode Engine package design and example output.**

and sample methods.

Data are stored on the Raspberry Pi and organized into individual folders by sample date/time. After the completion of a data collection sequence, data can be transferred to a USB memory stick or connected to a PC using a "Data Dump", which will upload all stored data to the connected device. Regular data-dumps will be required due to the limited memory capacity of the microcomputer. Sample data is processed using a post-processing app.

A software application built in the Node environment using Javascript provides control functionality for acquisitions. Using the touch-screen, users can adjust/save acquisition parameters, perform new-fibre installations, execute data acquisition sequences, consult help/troubleshooting information, and initiate "data-dumps". Menus provide visual references and acts as a "real-time" user manual, helping users execute acquisitions.

Post-processing of data is executed using an offline app that accesses the individual data folders generated during sample sequences and performs analysis of the collected spectra. This app can run on an offline PC and data can be transferred via USB (using the Data-Dump feature of the MOE software). Separation of the post-processing step from the hardware application was required due to the limited processing capacity of the Raspberry Pi.

Project collaborators INO (l'Institut National d'Optique, Quebec, Canada) will provide fresh optrode fibres for the Antarctic mission in exchange for results. The sensor chemistry, as developed by INO, has developed since the onset of this project and they can provide a reliable calcium sensor for the project. INO also has a sodium sensor which could be interesting to include.

Further information on theory and operation of the MOE can be found in the MOE operation manual.

### 2.1.3 Main circulation pumps

Figure 13: Red Dragon 3 pump with speed controller.

Within the service section NDS rack, each NDS bulk nutrient tank has a single circulation pump which will continuously mix the bulk tank solution. The selected pump (Red Dragon 3 Mini Speedy 50 Watt / 5,0m³) is both variable speed and capable of either external or submerged operation, and is designed as a reef pump for salt water aquariums so will easily withstand the less salty nutrient solution.

### 2.1.4 Dosing pumps

The acid, base and nutrient dosing pumps are controlled by the Argus Control System in response to sensor feedback from the pH and EC sensors. The pumps are basic peristaltic pumps (Agrowtek, Gurnee, IL, USA) with easily serviceable components and are operated at 24 VDC with contact inputs for operation by Argus (Figure 14).

**Figure 14: Agrowtek nutrient dosing pumps in 2 and 4 unit configurations.**

Dosing pumps take their stock solutions from individual screw-top polypropylene containers located below the bulk nutrient tanks (Figure 3).

### 2.1.5 Ozonation

The intake of each NDS bulk tank pump is equipped with a ¼" air inlet connection which serves as the injection point (Figure 7) for ozone gas (for static system sterilization) or room air when the power to the ozonator is not engaged (nutrient solution oxygenation). Ozone gas is pumped directly into the water stream to provide a supply of aqueous ozone. The ozonation hardware consists of an ozone generator (Aquatic 2 Spa Ozone Generator, A2Z Ozone, USA), a KNF mini air pump (Model NMP 830 KVE 230 V / 50 Hz) and associated tubing and backflow prevention valves. The ozone generator itself is shared between the two NDS bulk nutrient tanks, while separate air pumps supply each tank. Ozone production from this generator is 50 mg $hr^{-1}$, and will easily supply the batch generation requirements for system sterilization. System ozonation will be performed manually when disinfection is required. Although the use of ozone during plant production has been shown to be effective in tomato (Graham et al, 2011; Veronico et al, 2017), automation in a tightly closed indoor system should be approached with caution as off-gassing of ozone during water distribution could reach levels detrimental to plants and/or human occupants. Research is required to determine safety limits and effects on plant growth and productivity in this type of system.


**Figure 15: Ozone sensor.**

An ozone sensor (EZ-1X, Gas-Sensing Inc., Hull, IA, USA) located within the service section will alarm in the event ozone concentrations in the air exceed limits. The sensor measures 0.02 – 0.14 ppm atmospheric ozone.

## *2.2 NDS FEG components*

### 2.2.1 High pressure pumps

Nutrient solution from the NDS bulk nutrient tanks leads through a water filter (Figure 23) and on to eight high pressure Flojet self-priming 24 VDC diaphragm pumps (Figure 17, TF Pumps Supplies & Services Ltd, Derbyshire, England). Pumps are powered on demand by the Argus Control System in response to plant nutrient delivery scheduling. Each pump has a pressure transducer (MSP 300, TE Connectivity, Figure 16) monitored by Argus in order to verify pump activation and pressure stability (an indicator of pump health). Pumps feed the high pressure nozzles described below.

**Figure 17: Pressure transducer.**

**Figure 17: Flojet high pressure self-priming diaphragm pump.**

### 2.2.2 Growing trays

The growing trays, an integral part of the hybrid aeroponic/NFT growing system, are constructed of food-grade polypropylene (Figure 19) and are repurposed Euro shipping containers (Auer Packaging, Germany). Trays measure 400 x 600 x 120 mm and have a total volume of 20 litres. Integrated tops

**Figure 18: Polypropylene growing trays.**

are customizable to all required plant spacing requirements. This growing system concept was in development for three years at DLR (and tested at the University of Guelph) and has proven very successful for plant cultivation. Water from the high pressure pumps is directed into the growing trays with 6.35 mm polypropylene tubing leading to a series of 0.5 mm aperture misters within the tray (Figure 19). Misting is performed intermittantly, and the frequency is dependent on plant size, number and stage of development. Frequency was determined during the system test phase and can be adjusted as needed depending on plant growth. Three nozzle configurations were used in the final planting configurations (Figure 20).

Drainage is through a bulkhead drain fitting with a 12.5 mm hole in the bottom of each tray. Because of the low nutrient flow rate inheirant an aeroponics system, potential for overflowing the system is minimal. During growth and development, the status of root growth will be inspected on a weekly basis to ensure root growth does not block the drain. This protocol will be included in future operational procedure documents.

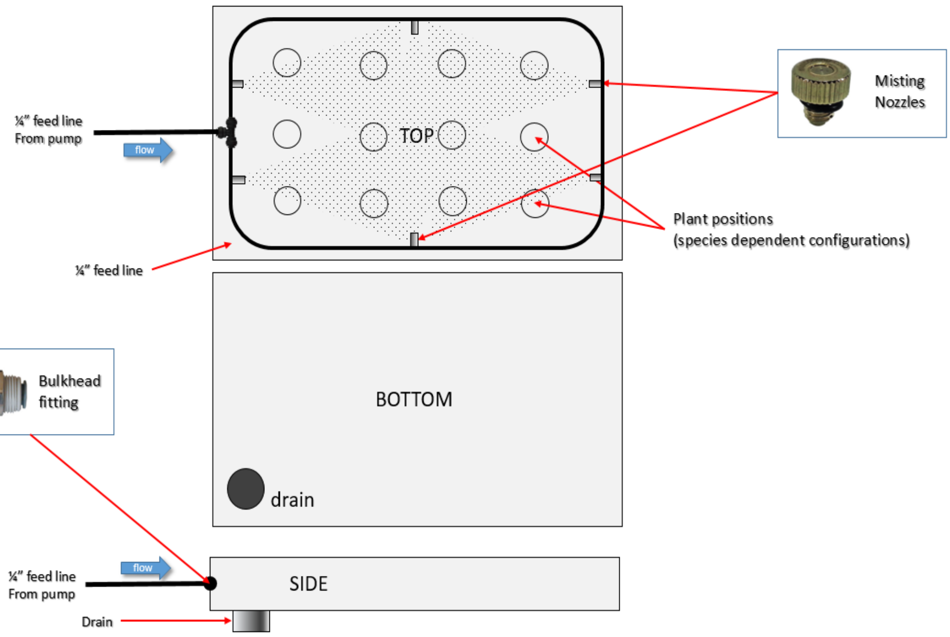



**Figure 19: Generalized mister nozzle and tray configuration.**

The configuration of the growing tray covers are illustrated in Table 1. Tray configurations are based on plant species and growth habit. Note, the trays in L4 that have no misters are the trays of the nursery in which nutrient solution is pumped into the trays via tubing with no mister adapters and

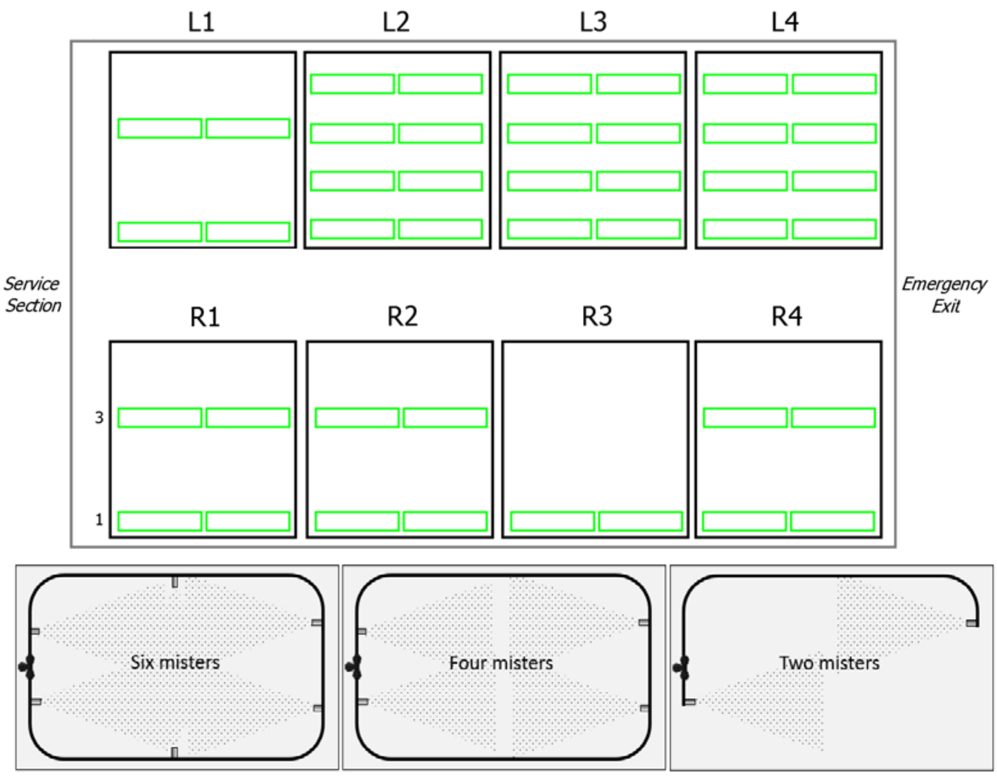
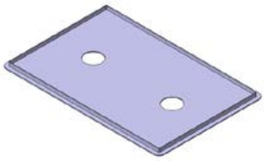
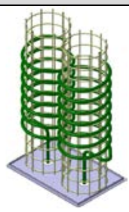
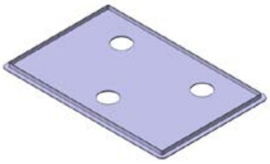
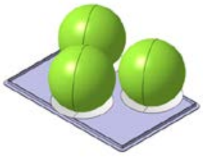
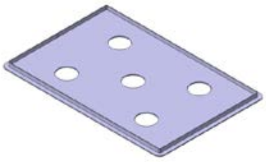
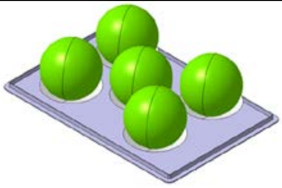
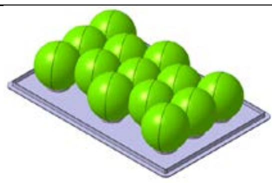
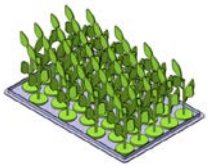
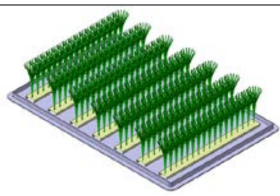



**Figure 20. Rack and internal mister orientation within the growing trays.**

left flooded to a pre-defined level. To accommodate this, the top-level trays of L4 are connected to the high pressure pump of rack L3.

Table 1. Plant tray top configurations for the various crop types.

| Tray layout | | Description |
|---|---|---|
|  |  | 2-hole tray, allowing enough space for tall plants. Certain training and pruning procedures are necessary (e.g. cucumber, tomato) |
|  |  | 3-hole tray layout. Bushy small growing plants can be integrated on this tray. (e.g. pepper, dwarf tomato) |
|  |  | 5-hole tray; Small bushy crops. (e.g. dwarf tomato, cabbage) |
|  |  | 13-hole tray, suitable for leafy greens with a relative small growth diameter as well as the for overlapping canopy conditions (e.g. lettuce, different herbs) |
|  |  | High-dense 36-hole tray for small and compact growing plants with lower space requirements (e.g. radish, green onion, spinach) |
|  |  | Seven-line tray layout for high density cultivation. (e.g. carrot, microgreens) |

### 2.2.3 Sump pumps (nutrient return from FEG)

Given the reduced space available in a shipping container system, return of nutrient solution from the plant trays could not be completed using gravity. The vertical distance between the bottom tray in the racks and the NDS bulk nutrient tank is approximately 2 metres, and required an active pump tank return. To achieve this, a marine based shower return system (Whale Marine, Northern Ireland, (Figure 21) was used to return nutrient solution to the main tanks. An additional float sensor (monitored by Argus) near the top of the sump tank is installed to respond to an over filled condition (indicating a possible pump failure). Overfill/pump failure will result in an alarm and cessation of water delivery to the plant trays. An extended failure will require the shutdown of the lighting systems to avoid plant loss through desiccation. Initial testing of the sump system found the pump (500 GPH) was insufficient at moving water the vertical distance requires, so a larger pump (950 GPH) with higher capacity was installed.

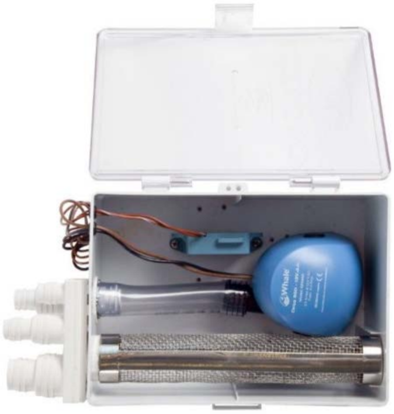


**Figure 21: Shower return sump system.**

### 2.2.4 Valves and piping

Nutrient solution pipes leading to the high pressure pumps are 19 mm PVC, while return pipes are 40 mm PVC. Each of the eight growing racks can be fed from either of the two NDS tanks, and a series of manual 3-way valves will switch inlet (6.35 mm) and drain (40 mm) flows to and from the appropriate tanks (Figure 22).

**Figure 22: Supply and return 3-way valves for switching between NDS bulk nutrient tanks.**

**Figure 23. Filter**

### 2.2.5 Filters

In order to protect the pumps and misting nozzles from possible debris, a 178 micron (0.18 mm) stainless steel filter (Figure 23) is fitted in-line before the high pressure pumps. The misting nozzles have an aperture of 0.5 mm, far larger than the filter screen.

## *2.3NDS Airlock components*

### 2.3.1 Fresh and waste water tanks

Both the fresh and waste water tanks were custom made to fill the space in the sub-floor in the air lock. Each tank holds approximately 300 litres and has integrated float sensors that are monitored by the Argus Control System to indicate a full condition (waste tank) or full and near empty conditions (fresh water tank) (Figure 24, Figure 25). Due to the location of the tanks in the subfloor and the nature of the thick floor panels, flexible-resistive heaters have been installed with an adhesive directly onto the external surfaces of the tanks. The fresh water tank includes a 6” x 24” heating blanket (Omega, SSHB-624-360-240-P) while the waste water tank includes a 6” x 12” heating blanket (Omega, SSHB-612-180-240-P).

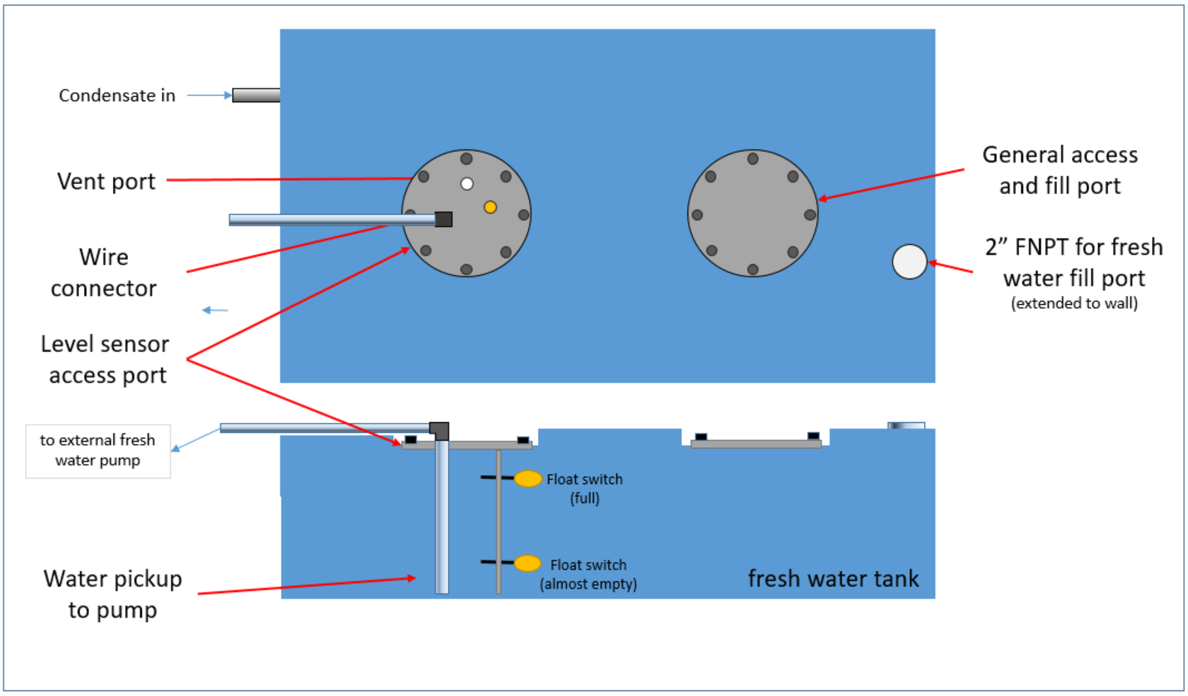



**Figure 24: Fresh water tank schematic.**

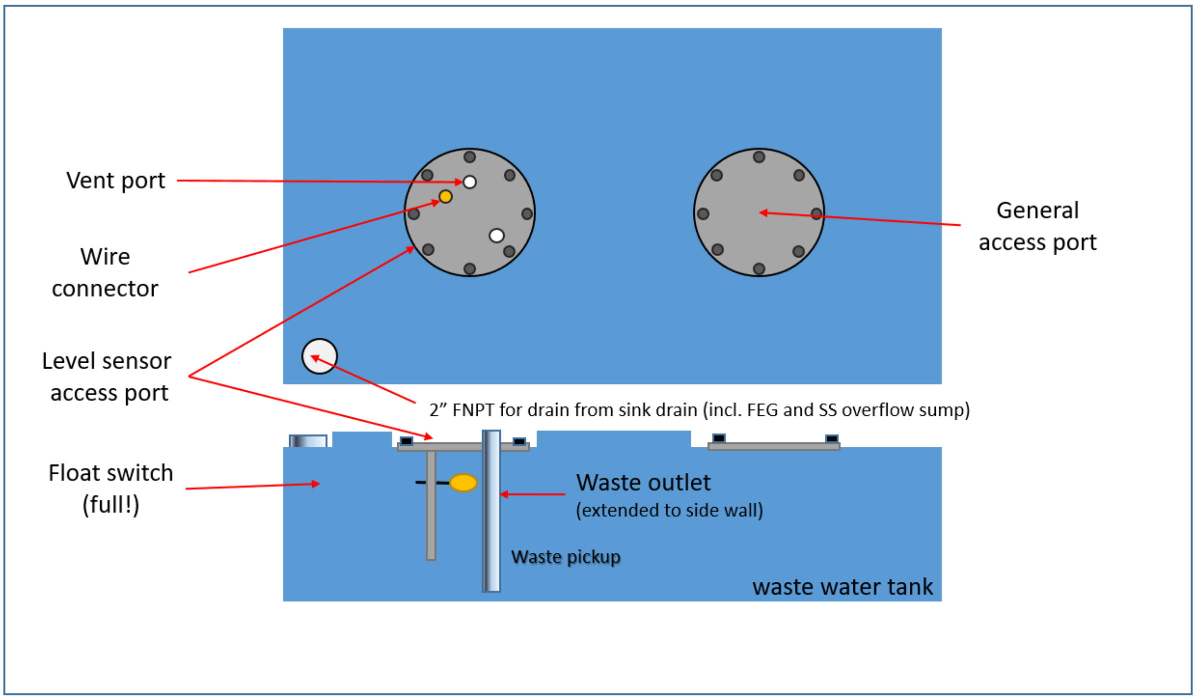



**Figure 25: Waste water tank schematic.**

The fresh water tank pump consists of a self-priming pump (SHURFLO AQUA KING II marine fresh water pump) and accumulator tank (SHURFLO 0.7 l accumulator tank) to reduce pump demand and to increase pump lifespan. The fresh water tank feeds water to the sink and to the NDS bulk nutrient tanks. Water is dispensed either through a tap at the sink, or via feedback response though Argus from the internal water level sensor in the NDS bulk nutrient tanks. Control of water flow in this case is by Argus controlled solenoid valves. When water levels fall below the desired set-point in the NDS tanks, fresh water will fill the tank until the desired level set-point is reached.


**Figure 26: Fresh water pump (left) and accumulator (right).**

The waste water tank is pumped out using an external pump (SHURFLO AQUA KING II marine fresh water pump) that is manually activated when required. Waste water is to be transferred to external tanks and taken by sled to the Neumayer Station III for processing at the sewage treatment plant.

## *2.4 Lab supplies*

The NDS as a system has few laboratory supply requirements. The main requirements are:

- pH calibration standards
- EC calibration standards
- Optrode calibration standards

- Beakers to contain calibration standards (4 x 250 mL, 1 x 500 mL)
- Rinse bottle (clean water)
- Acid, base and stock nutrient solutions according to cultivation requirements

Proper safety equipment including a lab coat, nitrile gloves and safety glasses will be required for maintenance of acid, base and stock nutrient reservoirs and their associated dosing pumps and tubing. An eye-wash station should be available in case of emergency.

## *2.5 Subsystem key values*

Table 2 presents the key subsystem values for the NDS.

**Table 2: Key values of the NDS subsystem.**

| | Mass | Peak power | Power day - nominal mode | Power night - nominal mode |
|---|---|---|---|---|
| **Mobile Test Facility** | 561.1 kg | 256.0 W | 165.9 W | 165.4 W |
| **Neumayer Station III** | TBD | N/A | N/A | N/A |
| **Spares, consumables, tools** | 287.2 kg | N/A | N/A | N/A |
| **TOTAL** | **848.3 kg** | **256.0 W** | **165.9 W** | **165.4 W** |

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# 3 Operations

## *3.1 Nominal operations*

The NDS subsystem operation will follow standard hydroponics plant production control algorithms and maintenance procedures. Generalize procedures follow, however more specific information will be contained with system operation manuals that will be written according to actual requirements ascertained during system testing at DLR in Bremen.

There are two main NDS bulk nutrient tanks, and each can have a different nutrient recipe (see detailed plant management criteria in another document). Solution composition is dependent on feedback control from EC and pH sensors and user supplied set-points. Set-point level targets are maintained by the Argus Control System according to the following control algorithms.

**Table 3: NDS basic control system algorithms.**

| Control | Argus response |
|---|---|
| **If pH > set-point** | Activate acid dosing pump for x[1] seconds and wait 30 minutes |
| **If pH < set-point** | Activate base dosing pump for x[1] seconds and wait 30 minutes |
| **If EC > set-point** | If tank is full, do nothing<br>If tank is below full level, activate fresh water solenoid for x[1] seconds and wait 30 minutes |
| **If EC< set-point** | Activate A and B dosing pumps simultaneously for x[1] seconds and wait 30 minutes |
| **If watering required (timer)** | If sump tank level sensor detects over fill, do nothing<br>If sump tank level sensor is normal, activate pump relay for x[1] seconds |
| **If sump tank level sensor detects over fill** | Turn off lighting and pump activation in the FEG and set sump tank full alarm |
| **If the fresh water tank high level sensor is activated** | Set the stop filling the tank alarm |
| **If fresh water tank low level sensor is activated** | Set low water level alarm |
| **If waste water tank high level sensor is activated** | Set waste tank full alarm |
| **If any/all high pressure pump pressure sensors reads zero while pump is active** | Set water pressure failure alarm, turn off lighting |
| **If water flow meter reads zero or below a user set threshold** | Set water flow failure alarm |
| [1] These values will be determined an optimized during system testing and deployment. | |

The main routine operational requirement involves maintaining the fresh and waste water tanks in full and empty conditions respectively. Other tasks are covered under maintenance.

## *3.2Off-Nominal operations*

All NDS controlled subsystems have manual override capability which should only be used by qualified personnel and only while present within the container in order to verify function.

## *3.3 Maintenance and spares*

The maintenance required for the NDS system mainly involves routine systems monitoring, cleaning and sensor calibrations (Table 4). A maintenance and repair log book should be kept to record the date, operator, and activity performed.

**Table 4. Operational and maintenance requirements for the EDEN ISS nutrient delivery system.**

| Task[1] | Maintenance Interval | | | | | |
|---|---|---|---|---|---|---|
| | daily | weekly | monthly | quarterly | yearly | other |
| pH/EC sensor calibration | | | X | | | Or when verification test does not agree with sensor reading |
| pH/EC sensor validation | X | | | | | |
| NDS system cleaning | | | | | | Before each experiment or when contamination is suspected/confirmed |
| Exterior cleaning | | | X | | | |
| Stock tank cleaning | | | | | X | Also between changes in stock composition |
| NDS main filter | | X | | | | |
| Misting nozzles | | | X | | | Also during general tray maintenance after plant harvest |
| Inspect tray drains | X | | | | | |
| Tray cleaning | | | | | | Before each planting and/or according to horticultural management procedures |
| Pinch valve tubing inspection/repositioning | | X | | | | See note in design lessons learned section |
| [1]Task procedures are noted below | | | | | | |

Most of the subsystems require periodic calibration and cleaning to maintain proper functioning. All calibration requirements recommended by the manufacturer of the analytical equipment or control system supersede any procedures outlined in this document.

### 3.3.1 pH and Electrical Conductivity (EC) sensor calibration

EC and pH sensor calibration should be performed on a monthly basis during crop growth. Sensor readings are confirmed manually each day using hand-held pH and EC probes. Off-nominal readings obtained from the daily manual validation will require re-calibration of the sensors.

1. Pour known standards of pH and EC into 250 mL beakers. Use two point calibrations with solutions of 4.00 and 7.00 pH units, and 500 and 3000 uS
2. Turn off nutrient, acid and base injection in Argus software or manually at the relay panel. Change settings from ‘automatic’ to ‘manual off’
3. Remove sensors from the tanks and test one at a time
4. Place the sensor into its respective solutions and follow the calibration procedures outlined in the manufacturers’ operation manuals. Rinse with deionized water when switching between solutions
5. Rinse the sensors and return them to the nutrient system tank

6. Turn on nutrient, acid and base injection in Argus software or manually at the relay panel. Change setting from 'manual off' to 'automatic'

### 3.3.2 pH/EC sensor validation

On a daily basis, verify the main system readings of EC and pH using the manual pH and EC probes (Figure 10).

1. Calibrate manual EC and pH probes according to manufacturer instructions
2. Using the drain/sampling valve, add 500 mL of nutrient solution to a 500 mL beaker
3. Return contents to the same tank
4. Obtain a second 500 mL sample and measure the EC and pH of the solution
5. Record measurements in a log book and compare them to readings on the Argus control system
6. Return sample to the same tank
7. If system readings on either of the in-tank sensors differs from the manual measurement by more than 10%, recalibrate the tank sensors as noted above (3.3.1)

**CAUTION! Cleaning chemicals can be extremely dangerous. Be sure to read and understand your SDS and follow all laboratory safety protocols when handling chemicals.**

**CAUTION! Alcohol, and ozone can be dangerous in confined spaces. Be sure the air handling system is operational. NEVER work with cleaning chemicals in a closed environment alone.**

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.

### 3.3.3 Exterior cleaning

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

### 3.3.4 Nutrient delivery system cleaning

Cleaning of the nutrient delivery system is crucial for effective operation and plant development. Cleaning should be performed prior to each experiment or when contamination is suspected/confirmed. Procedure is for a single tank. Repeat for the second tank.

1. Turn off all pumps associated with the tank to be cleaned in Argus (includes internal circulation pump and high pressure pumps) or manually at the relay panel. Change settings from 'automatic' to 'manual off'
2. Turn off acid/base/stock nutrient injection manually at the relay panel or in the Argus controller interface. Change settings from 'automatic' to 'manual off'
3. Drain nutrient supply tank
4. Refill the nutrient tank with 150 litres of clean water (deionized or equivalent)
5. Re-activate the tank circulation pump – back to 'automatic' mode
6. Activate the ozonation system
7. Allow the ozonation system to run for 60 minutes with internal circulation (actual time to be determined during the testing phase at DLR in Bremen) in order to build up a sufficient amount of aqueous ozone within the water
8. Ensure empty trays and covers are in place in all locations within each rack of the FEG and close the FEG door to reduce ozone gas entry into the service section
9. Re-activate high pressure pumps – back to 'automatic' mode

10. Run the NDS as per normal operation for 12 hours to allow the ozonated water to circulate through the system
11. Turn off all pumps as previous
12. Drain the tank and discard the water
13. Clean the in-line filter

NOTE: Virkon may be used instead of ozone. Follow manufacturer's directions for use.

#### 3.3.5 Growing tray cleaning

The polypropylene trays that are removed during harvest procedures should be 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.

#### 3.3.6 Stock tank cleaning

1. Empty and dispose of acid, base, and nutrient stock solutions according to laboratory protocol for hazardous waste materials
2. Rinse each reservoir with clean water three times
3. Refill stock tanks with solutions as outlined in the experimental protocol

#### 3.3.7 NDS main filter cleaning

1. Turn off all pumps associated with the tank filter to be cleaned in Argus (includes internal circulation pump and high pressure pumps) or manually at the relay panel. Change settings from 'automatic' to 'manual off'
2. Close the shut-off valve above the filter
3. Unscrew the filter housing from the filter base
4. Carefully remove the inner stainless steel filter from the housing
5. Clean the filter and housing with clean water and a glassware brush until all traces of biofilm are removed
6. Sterilize both parts with alcohol
7. Spray alcohol on the inside of the filter base and wipe with a soft cloth
8. Put filter in the filter housing and screw back on to filter base
9. Open shut-off valve
10. Return to normal operation

#### 3.3.8 Misting nozzle cleaning

1. Unscrew nozzles from the tee fitting in the tray
2. Place misting nozzles in a small beaker and cover with acetic acid (vinegar)
3. Let stand for 10 minutes
4. Decant and dispose of the acetic acid
5. Triple rinse misting nozzles with clean water
6. Using a syringe cleaning wire (24-26 gauge) ensure the orifice in the nozzle is clear (as an alternative, an air compressor has also been shown to be very suitable in re-moving material from the aeroponic misters)
7. Replace nozzles on the tee fittings

#### 3.3.9 Tray drains

1. Carefully lift the tray top off of the tray base
2. Prop open using the tray propping tool
3. Inspect drain for the presence of roots around and entering the drain hole
4. Using small scissors, cut back roots around and in the drain to a distance of 3 cm
5. Close tray lid
6. Discard roots as per disposal protocol

### *3.4 Preparation for shipment*

1. Empty all tanks of liquids
2. Remove pH and EC probes and place in original shipping boxes

3. Remove polypropylene stock tanks, wrap in bubble wrap and place inside the nutrient tanks
4. Using Styrofoam, brace the float level sensor on all sides to restrict movement
5. Fill NDS nutrient tanks with a suitable packing material to further restrict movement of the float sensor and stock bottles
6. Secure any moveable objects, including the main NDS tanks using tied down ratchet straps where needed
7. Secure drain and feed lines – disassemble and wrap with cardboard and/or bubble wrap where possible
8. Secure all trays in their rack positions using tie down straps

# 4 Design lessons learned

## 4.1Pinch valves

While system testing, the tubing on one of the pinch valves for acid delivery was fused together after being 'pinched' for a long period of time while in storage. The result was an excess of pressure in the line coming from the peristaltic pump and subsequent rupture at one of the connections.

Fusion is a known issue with peristaltic pump-type tubing, and although there are some types of tubing that have reduced incidence of fusion, mitigation of the problem by periodic valve cycling (weekly) or periodic tubing replacement (monthly) is the preferred option. A weekly activity has been built into the maintenance schedule in that the tubing should be gentle pulled out from the pinch valve, visually inspected and then reinstalled into the pinch valve into a slightly new position (i.e. a different section of the pipe being restricted via the pinch valve). For additional operator safety, a curtain has been installed in front of the NDS rack dosing pumps.

## 4.2Nutrient Tanks and Gravity

The system as designed has two pumping requirements, one to deliver nutrient solution to the plant boxes and the other to return nutrient solution to the main nutrient reservoirs using bulk transfer sump pumps located in two central reservoirs (one for each of the two nutrient tanks). There is an amount of risk associated with reliance on pumps for return flow. Future iterations of the DLR mobile greenhouse concept should utilize sub-floor tanks which would allow for gravity return of nutrient solution from the plant boxes.

## 4.3Maintenance considerations

The original NDS design had mixing pumps and sensor probes beneath the nutrient tanks in a relatively small space where access was difficult. Although these components fit this location, ease of pump maintenance and sensor calibration was considerably hampered in a floor level tight space. To improve access, sensors and pumps were moved to in-tank positions in order to simplify access. Maintenance, access and calibration activities should be primary considerations in systems design.

# 5 Parts list

| Element/Part | Qty | Spares | Manufacturer | Part Number |
|---|---|---|---|---|
| **SERVICE SECTION** | | | | |
| Subequipment 1 - General System | | | | |
| Bulk nutrient tank (250 L) | 2 | | Digital Haptic Lab, University of Guelph | N/A |
| Fresh water pump | 1 | 1 | SHURFLO | Aquaking II STD 3.0 24V AM |
| Fresh water pump AC-DC Converter | 1 | 1 | CUI Inc. | VDRS 100 24 |
| Fresh water accumulator tank | 1 | 1 | SHURFLO | Model 182-200 |
| Solenoid (fresh water feed ) | 2 | 1 | ASCO | 8262G7 |
| Dosing pumps (Acid/Base) | 1 | | Agrowtek | AD2 |
| Dosing pumps (solution A/B/C/D) | 1 | | Agrowtek | AD4 |
| Dosing pumps (replacement heads) | | 2 | Agrowtek | AD-PUMP |
| Check valve | 8 | 4 | A2Z Ozone Ltd | Check valve 1/4" |
| Stock bottles (A, B, acid, base) (4 L) | 6 | | Fisher Scientific | 03-313 |
| Three-way pinch valves (Acid, Base) 24 VDC, 1/8" ID x 1/4" OD tubing | 2 | 1 | Cole Parmer | 98302-54 |
| Manual valve (two-way - drain and sampling) | 4 | | RUB valves and actuators | S.131 Stainless Steel |
| Pipe union (1/2") | 4 | | N/A | N/A |
| Pipe union (3/4") | 4 | | N/A | N/A |
| Pump (tank nutrient recirculation) | 2 | 1 | Royal Exclusiv | Red Dragon 3 mini pump |
| Filter (NDS prepump, fresh water, waste tank) | 3 | 2 | Atlas Scientific | COM-203F |
| Ozone generator | 1 | 1 | A2Z Ozone Ltd | Aquatic 2 Spa Ozone Generator |
| Ozone check valve | 2 | 2 | A2Z Ozone Ltd | check valve 1/4" |
| Ozone Air Pump | | 1 | KnF | NMP 830 KNE |
| Tubing/piping type 1 - main distribution lines | 8 | | IPEX Inc | ¾" PVC |
| Tubing/piping type 1 - main return lines | 8 | | IPEX Inc | 1 ½" PVC |
| Tubing - feed lines | 40 | 10 | TubeFit | PPB-43-0500 |
| Optional NDS cooling system | 2 | | Custom | N/A |
| | | | | |
| Subequipment 2 - Sensors | | | | |
| Flow sensor | 2 | 1 | Yuanben | 1/2" high precision flow meter |
| Tank continuous level sensor | 2 | | Innovative Components | CLM-2000-SS |
| Leak Sensor | 2 | 2 | George Risk Industries | 2800 5V DC Water Sensor |
| Float switch (fresh water tank) | 1 | | Standex Meder | LS-02 1A66-PP-500W |
| pH sensor | 4 | 2 | Atlas Scientific | ENV-40-pH |
| EC sensor | 4 | 2 | Atlas Scientific | ENV-40-EC-K0.1 |
| Industrial pH transmitter | 4 | 1 | Atlas Scientific | IXIAN-pH |
| Industrial EC transmitter | 4 | 1 | Atlas Scientific | IXIAN-EC |
| Temperature sensor (thermistor) | 4 | 2 | Adafruit | EXP-R15-221 |
| Temperature sensor (thermistor) | 4 | 2 | Amphenol | MA100 |
| Ion-selective sensor and associated HW | 1 | | UofG | Custom |
| Ozone sensor - air for safety | 1 | | ECO Sensors | EZ-1X |
| pH meter – hand held | 1 | | Dosatron | PH-200 |
| pH replacement sensor | | 1 | Dosatron | SP-P2 |
| EC meter – hand held | 1 | | Dosatron | COM-100 |

| | | | | |
|---|---|---|---|---|
| EC replacement sensor | | 1 | Dosatrn | SP-C1 |
| | | | | |
| **FUTURE EXPLORATION GREENHOUSE** | | | | |
| Subequipment 1 - Solution Delivery | | | | |
| Pump (high pressure - aeroponic) | 8 | 2 | Flojet | R3811233 |
| Pump (sump - hydroponic return) | 2 | 1 | Whale Marine | ORCA 950 |
| Sump pump box | 2 | 1 | Whale Marine | GW0500 |
| Sump pump AC-DC converter | 2 | 1 | CUI Inc. | VDRS-60-12 |
| Manual valves (three-way) 1 1/2" for NDS return | 8 | | GF Piping Systems | 161543046 |
| Manual valves (three-way) 1/2" for NDS supply | 8 | | Ontario Beer Kegs | Stainless Steel 3-way ½" Female NPT Ball Valve |
| Plant trays (short) | 24 | | Auer Packaging | EG 64/12 HG |
| Plant trays (tall) | 16 | | Auer Packaging | EG 64/75 HG |
| Plant tray tops | 40 | | Auer Packaging | DE 64 |
| Misters (0.02" orifice with nickel plating) | 160 | 40 | Mistcooling Inc. | MC2010 – NP |
| Tee-junctions | 32 | | John Guest | S-34007-46 |
| Other mister hosing and mister connectors | | | AFT | Various |
| Tubing/piping type 1 - main distribution lines | 20 | | IPEX Inc | ¾" PVC |
| Tubing/piping type 1 - main return lines | 20 | | IPEX Inc | 1 ½" PVC |
| Tubing - feed lines | 200 | 20 | TubeFit | PPB-43-0500 |
| Subequipment 2 - Sensors | | | | |
| Float switch (sump tanks) | 2 | 2 | Madison | M8700 |
| Pressure sensor | 8 | 2 | TE Connectivity Measurement Specialties | MSP3251P4-ND |
| **COLD PORCH** | | | | |
| Float switch (waste water tank) | 1 | 1 | Madison | M8700 |
| Fresh water tank (ca. 250 L) | 1 | | DLR | Built in to container floor |
| Waste water tank (ca. 250 L) | 1 | | DLR | Built in to container floor |
| Cold porch tank heater (small) | 1 | | Omega | SSHB-612-180-240-P |
| Cold porch tank heater (large) | 1 | | Omega | SSHB-624-360-240-P |
| Cold porch tank heater thermostat | 1 | | Selco | OA-60 |

# 6 References

Graham, T., Zhang, P., Woyzbun, E., and Dixon, M. (2011), Response of hydroponic tomato to daily applications of aqueous ozone via drip irrigation. Scientia Horticulturae, 129: 464-471. Doi: 10.1016/j.scienta.2011.04.019

Veronico, P., Paciolla, C., Sasanelli, N., De Leonardis, S. and Melillo, M. T. (2017), Ozonated water reduces susceptibility in tomato plants to *Meloidogyne incognita* by the modulation of the antioxidant system. Molecular Plant Pathology, 18: 529–539. doi:10.1111/mpp.124