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BLiSS

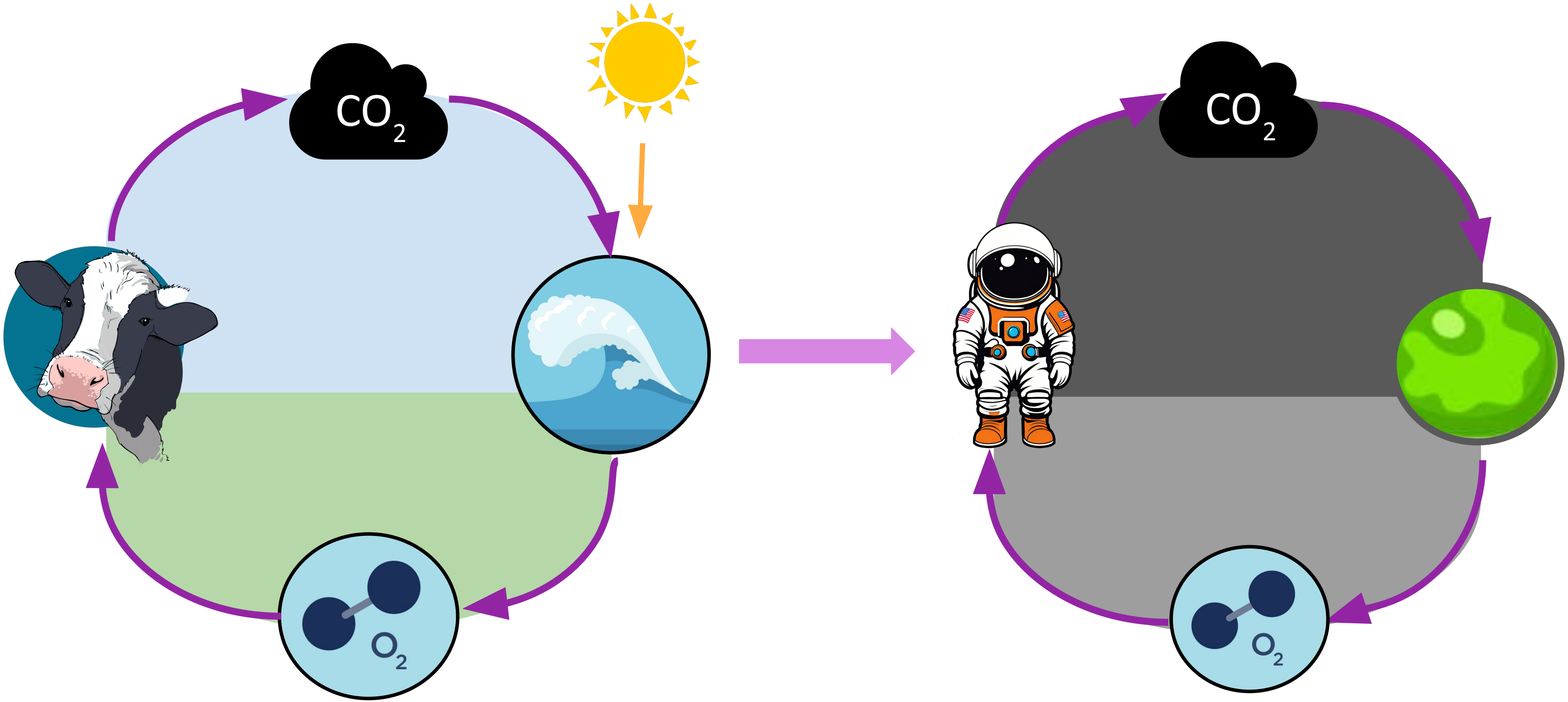
Collins Aerospace

Bloom Box Symposium Review

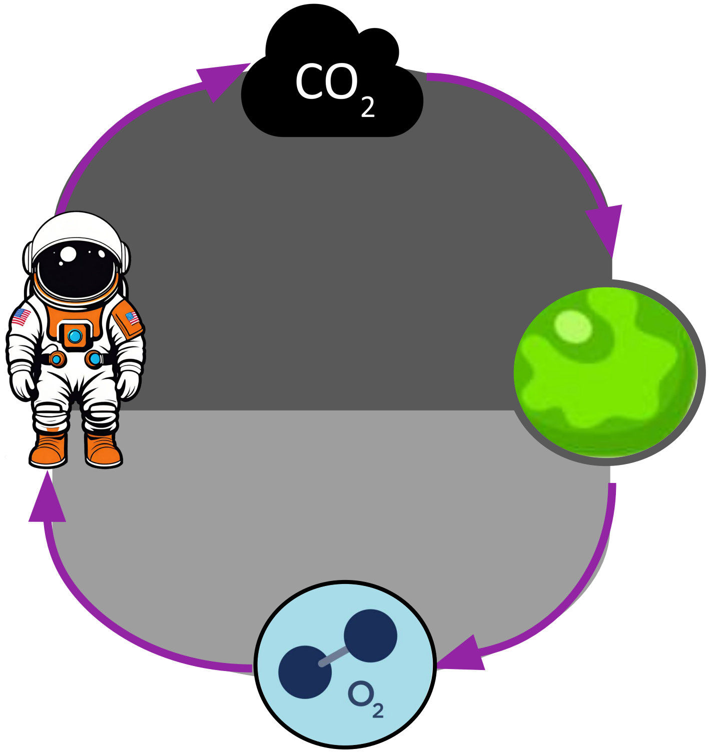
Project Overview and Scoping

What is Bloom Box?

Algae is responsible for 50-70% of the oxygen in our atmosphere.



What is Bloom Box?

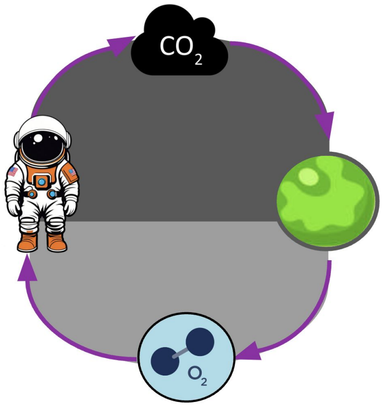


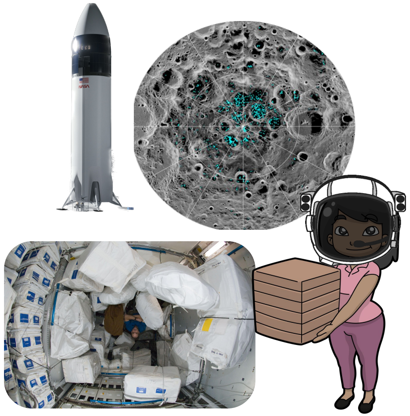
The carbon cycle on Earth is closed loop.

Replicating natural processes, while difficult, can be valuable for long-term, sustainable ECLSS systems.

How can we leverage algae's photosynthesizing abilities to create an operational closed loop algae-based CO_2 scrubber?

Creating Our End Deliverable





STEP 1

Generate the Concept

How can we leverage algae's photosynthesizing abilities to create a closed loop algae-based CO2 scrubber?

STEP 2

Bound The Application

Hypothetical Artemis mission to establish a lunar habitat. Launched on Starship. System assembled by crew on-site.

STEP 3

Limit The Scope

Ignore launch loads, vibrations, transients, specific user ergonomics: CO_2 Scrubbing for a 4 person lunar habitat for a given service lifetime.

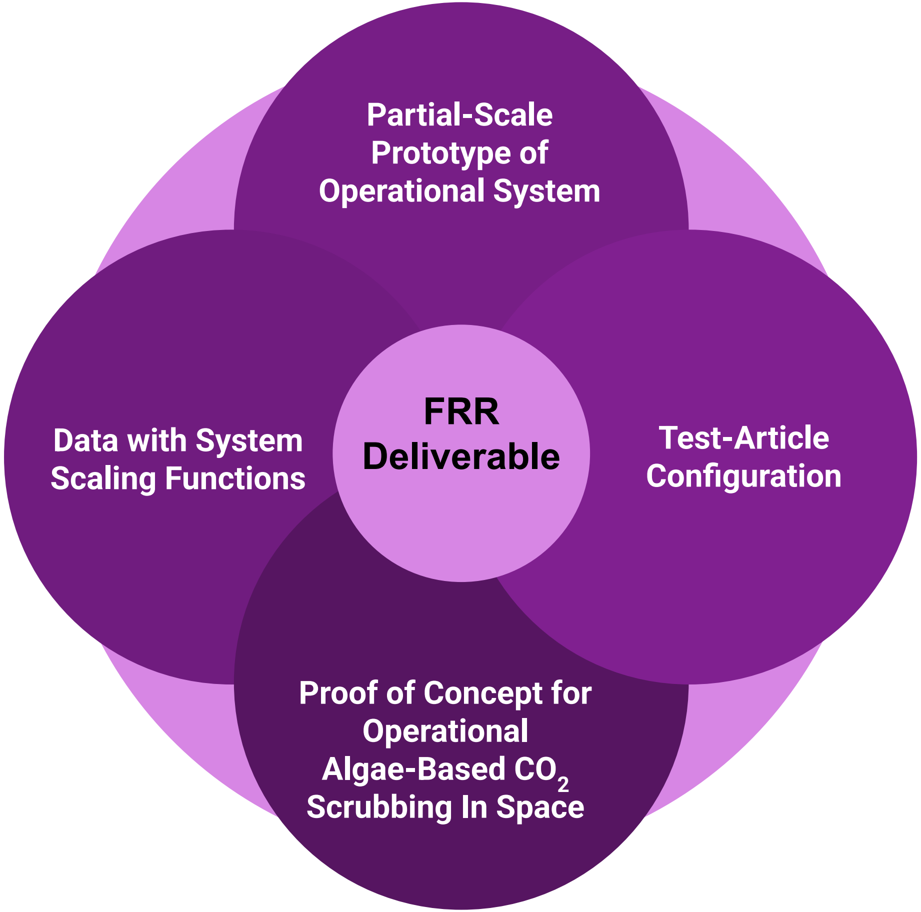
STEP 4

Create a Scale

A bioreactor that can show a verifiable reduction in CO_2 (depending on the sensor selection) can be scaled for a given scope and adapted for a given mission.

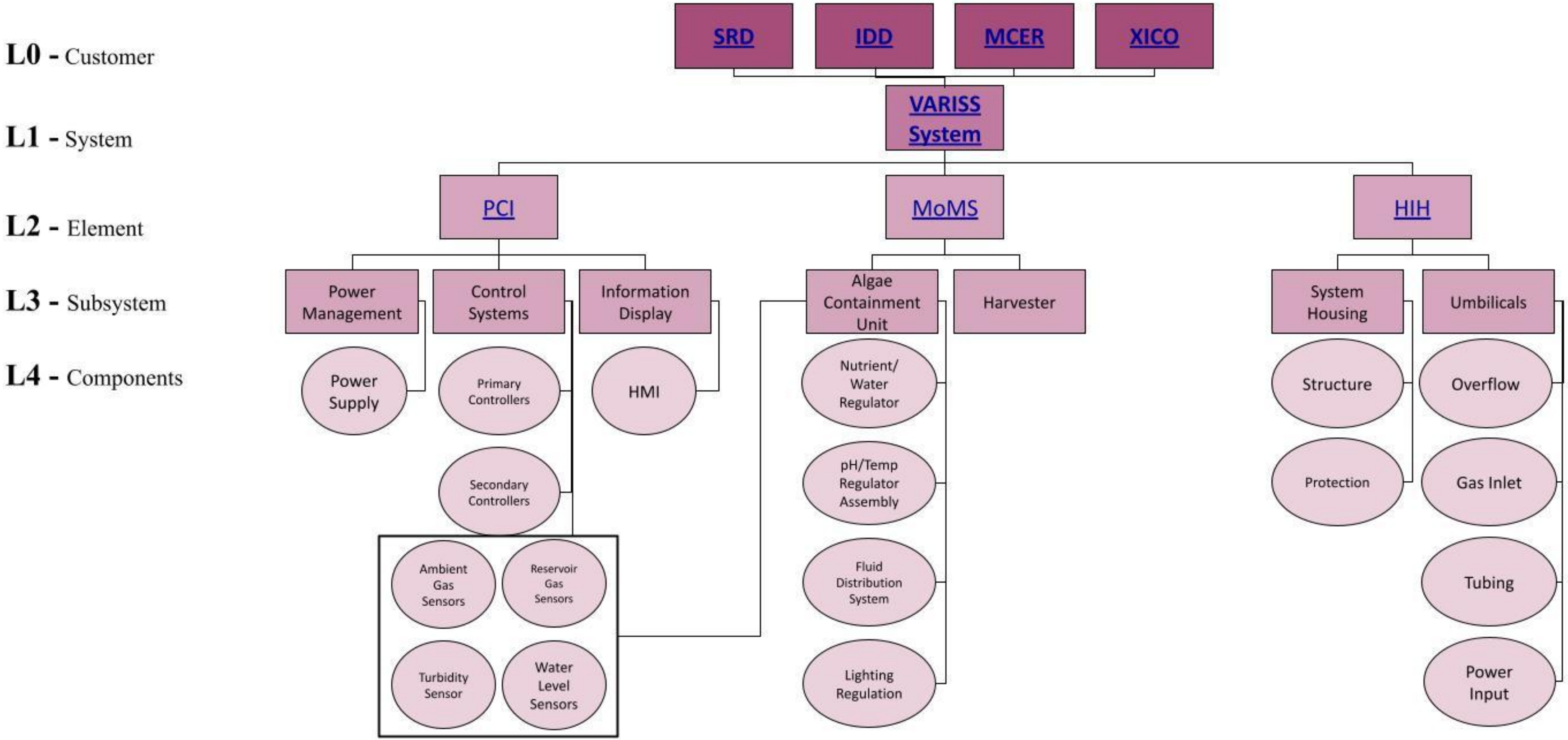
Scoping The Project

- **Scope:**
  - Test article of a fractional-scale prototype of the operational system
    - Ample sensors, mounts to 80/20, access panels, power converter, etc.
  - "Verifiable Reduction" of CO_2
  - Creating a scale factor and model function for full system equivalence.



System Requirements

VARISS System Specification Tree



SRD = System Requirement Document; IDD = Interface Definition Document; MCER = Mission Concept and Environment Requirements; XICO = XR Investigation Customer Objectives
PCI = Power, Controls and, Information; MoMS = Microorganism Management System HIH = Habitat Interfaces and Housing

System-Level Requirements

R01: The system shall reduce the partial pressure of CO_2 in its output flow by a quantity verifiable by the system during operation.

R02: The system shall apply in-situ resource utilization (ISRU) or the use of regenerative reactants in ECLS operations.

R03: The system shall support the harvest of operational byproducts that would otherwise become waste.

R04: The system shall provide an information system with the information of interest listed in Table 3.6.2-1.

R05: The system shall indicate to crewmembers the information of interest per Table 3.6.2-1 in real time collection. (prev.)

R06: The system shall have multiple operational modes that are adjustable by the crew for harvest, cleaning, and nominal operation.

R07: The system shall isolate and allow the disposal of biological and chemical waste produced in operation.

R08: The system shall allow for preventative and corrective maintenance and byproduct harvest time per Table 3.1.3-1 Crew Time Allotment.

R09: The system shall support carbon dioxide scrubbing capabilities after loading with exponential phase algae culture volume.

R10: The system shall support operations for at least one byproduct harvest and system exponential phase recovery cycle.

R11: The system shall meet all requirements during and after exposure to BLiSS Laboratory environments.

R12: The system shall operate with an input voltage of 24V DC to mimic space habitat power interfaces.

Top Level Requirements to Validating Elements

SYS-01 Verifiable CO2 Partial Pressure Reduction

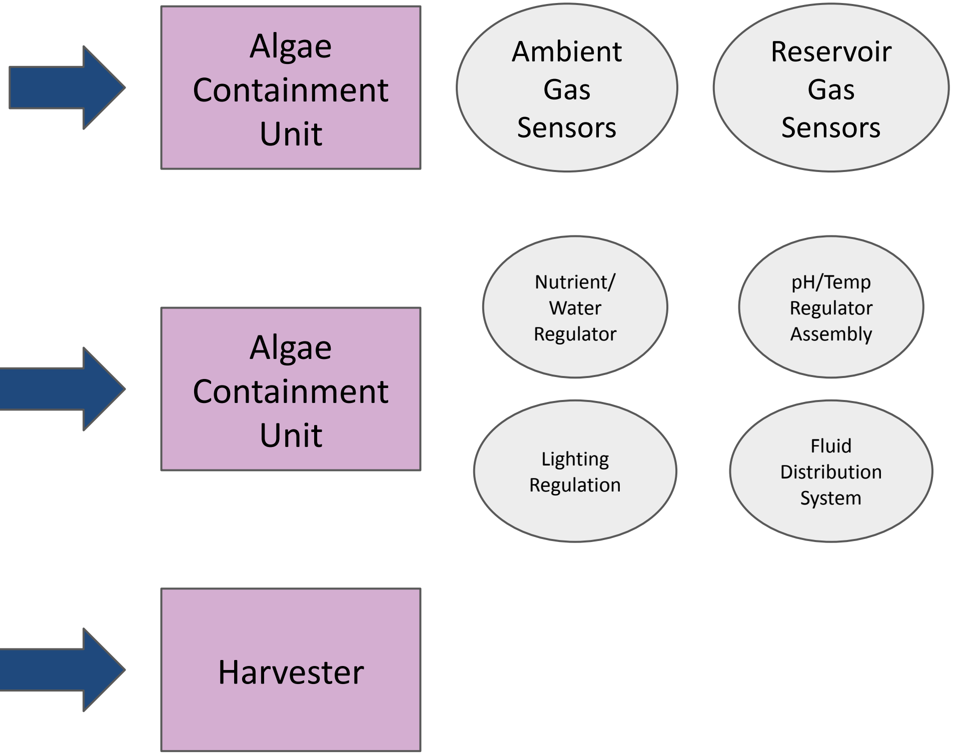
The system shall reduce the partial pressure of CO2 in its output flow by a quantity verifiable by the system during operation.

SYS-02 Regenerable Reactants

The system shall apply in-situ resource utilization (ISRU) or the use of regenerative reactants in ECLS operations.

SYS-03 Byproduct Harvest

The system shall support the harvest of operational byproducts that would otherwise become waste.

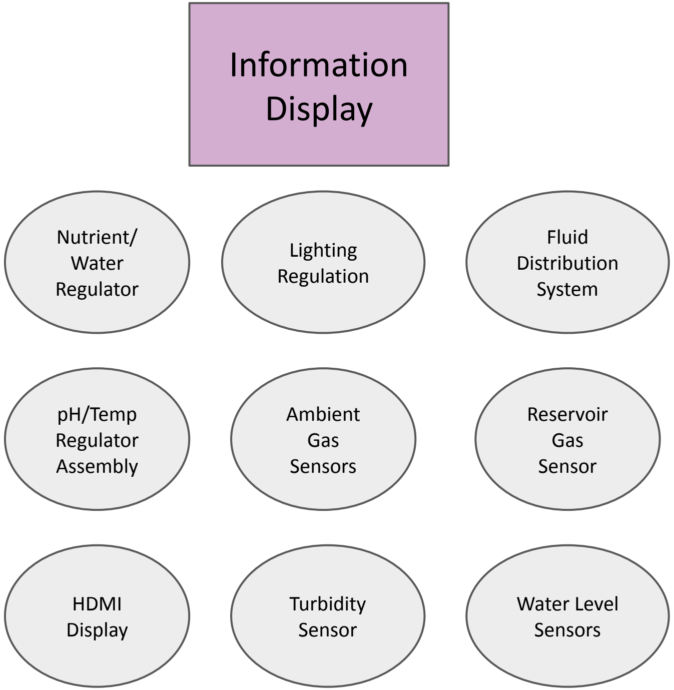


Top Level Requirements to Validating Elements

SYS-04 Information of Interest

The system shall provide an information system with the information of interest listed in Table 3.6.2-1. *(below)*

Information Description	Notes
CO_2 Scrubber Carbon Dioxide	Quantity of CO_2 downstream of the Algae Containment Unit percent volume
CO_2 Scrubber Oxygen	Quantity of O_2 downstream of the Algae Containment Unit in percent volume
Ambient Carbon Dioxide	Quantity of ambient CO_2 in percent volume
Ambient Oxygen Partial Pressure	Quantity of ambient O_2 in percent volume
Ambient Total Pressure	Total pressure of ambient conditions in Pascals
CO_2 Scrubber Temperature	Internal temperature of the Algae Containment Unit in Celsius and Fahrenheit
CO_2 Scrubber Biomass	Biomass level of the CO_2 scrubber in g/m^2 and lb/ft^2
CO_2 Scrubber pH Level	pH level inside the Algae Containment Unit
Consumables Replacement Alert	Auditory/visual alert for replacement of consumables



Top Level Requirements to Validating Elements

SYS-04 Information of Interest

The system shall provide an information system with the information of interest listed in Table 3.6.2-1. *(prev.)*

- Ambient Gas Sensors
- Reservoir Gas Sensor
- Nutrient/ Water Regulator
- pH/Temp Regulator Assembly
- Turbidity Sensor
- Water Level Sensors
- Lighting Regulation
- Fluid Distribution System

SYS-05 Status Indication

The system shall indicate to crewmembers the information of interest per Table 3.6.2-1 in real time collection. *(prev.)*

- Information Display
- HMI Display
- Primary Controller
- Secondary Controller

SYS-06 Multiple Modes

The system shall have multiple operational modes that are adjustable by the crew for harvest, maintenance, and nominal operation.

- Control Systems
- HMI Display

Top Level Requirements to Validating Elements

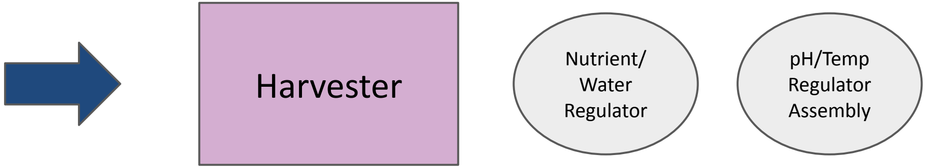
SYS-07 Biological and Chemical Waste Management

The system shall isolate and allow the disposal of biological and chemical waste produced in operation.

SYS-08 Crew Time Allocation

The system shall allow for preventative and corrective maintenance and byproduct harvest time per Table 3.1.3-1 Crew Time Allotment.

Parameter	Allocation
Byproduct Harvest	0.5 hrs/week
Preventative and Corrective Maintenance	0.5 hrs/week



Top Level Requirements to Validating Elements

SYS-09 ECLS Availability

The system shall support carbon dioxide scrubbing capabilities after loading with exponential phase algae culture volume.

→ Algae Containment Unit; Gas Inlet

SYS-10 ECLS Operational Life

The system shall support operations for at least one byproduct harvest and system exponential phase recovery cycle.

→ Algae Containment Unit; Harvester; Control Systems

SYS-11 Mission Environments

The system shall meet all requirements during and after exposure to BLiSS Laboratory environments.

→ System Housing; Ambient Gas Sensors; pH/Temp Regulator Assembly

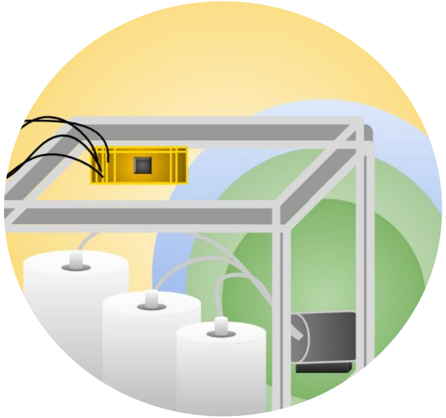
SYS-12 Space Habitat Representative Voltage Limitations

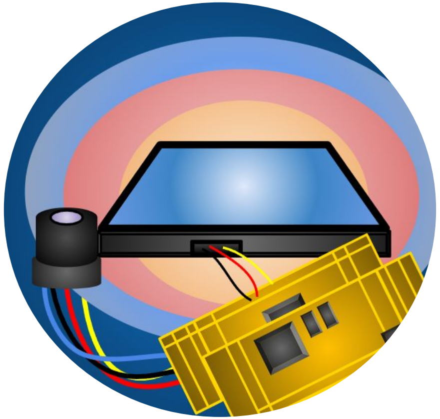
The system shall operate with an input voltage of 24V DC to mimic space habitat power interfaces.

→ Power Management

System Design

Subteam Divisions





Microorganism Management Subsystem (MoMS)

Algae life support functions including: Lighting/Heat, Mixing, Nutrients, pH

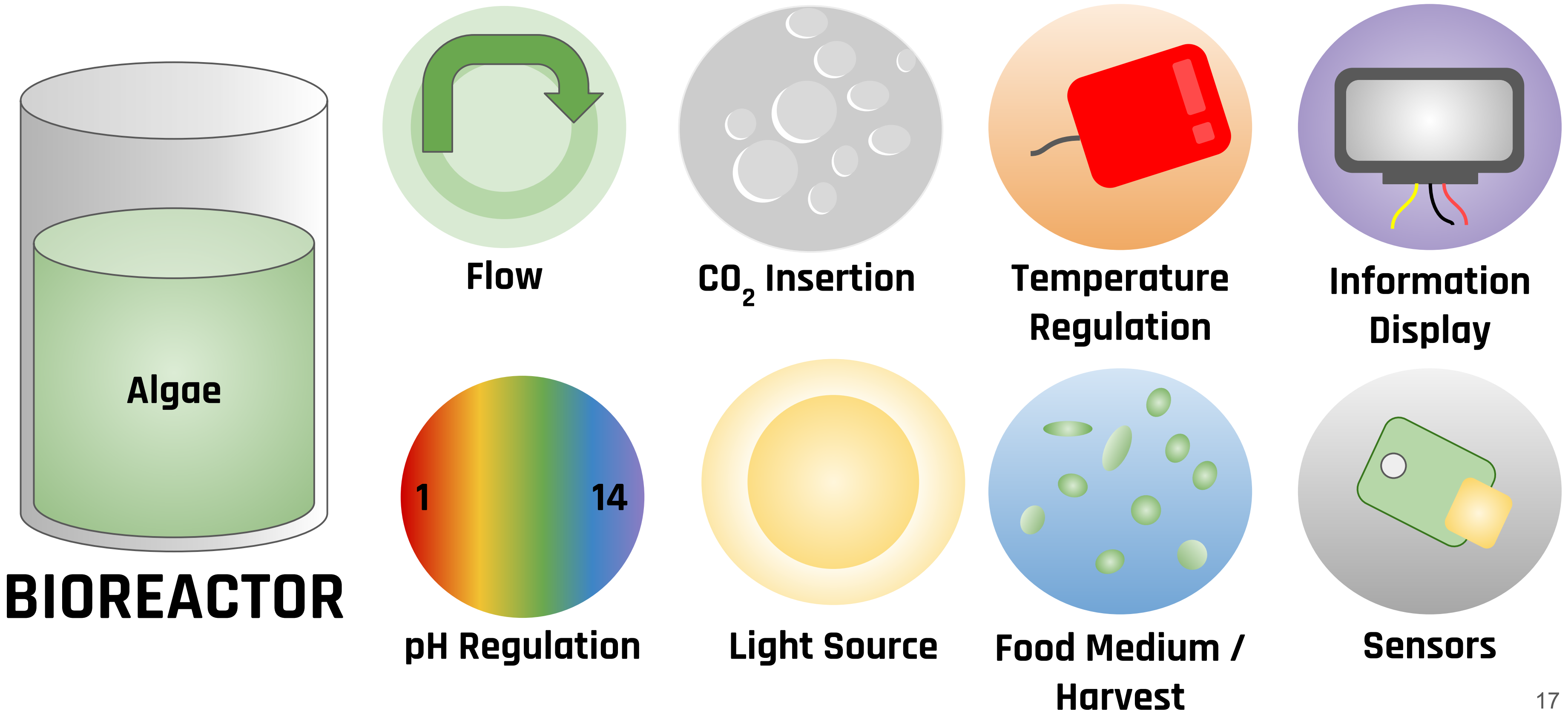
Habitat Interfaces and Housing (HIH)

Overall structural support and piping for fluids, including gas inlet mechanism

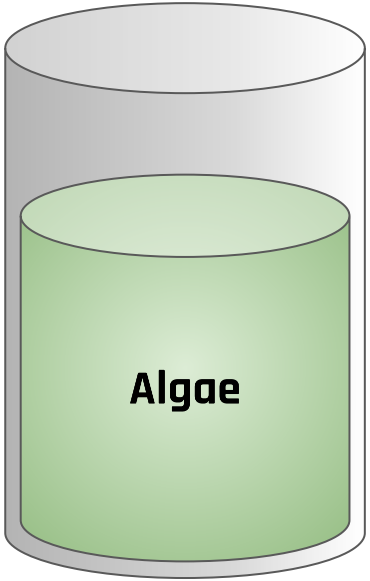
Power, Controls, and Information (PCI)

Controls systems for autonomous action, sensing, and data reports

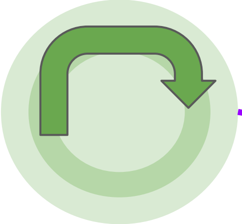
Algae-Based CO_2: Operational Elements



Operational Elements : Selected Architectures



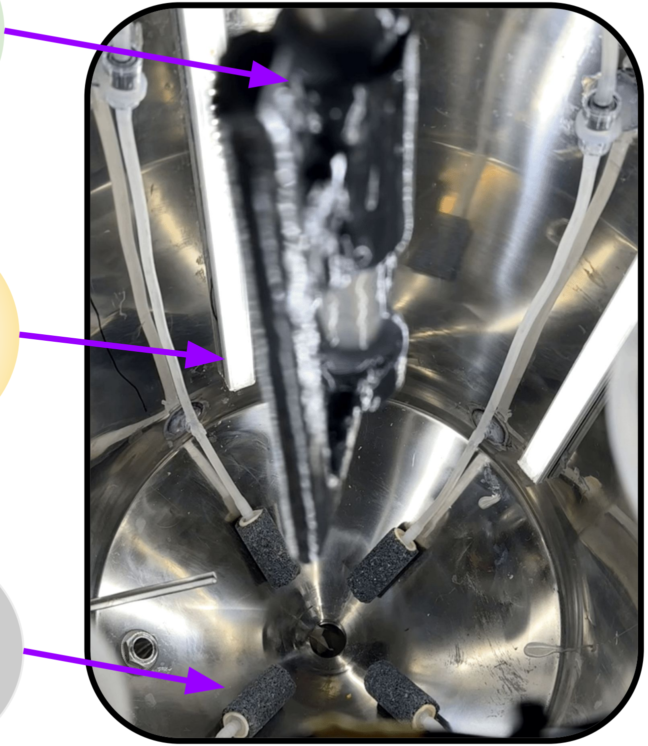
BIOREACTOR



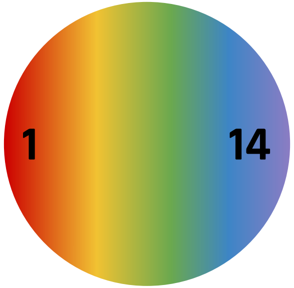
Flow

Light Source

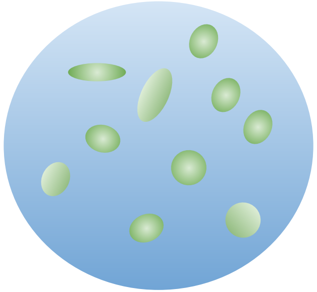
CO_2 Insertion



Operational Elements : Selected Architectures

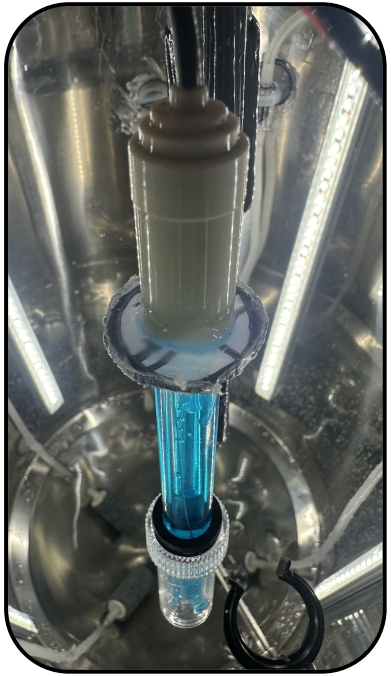


pH Regulation

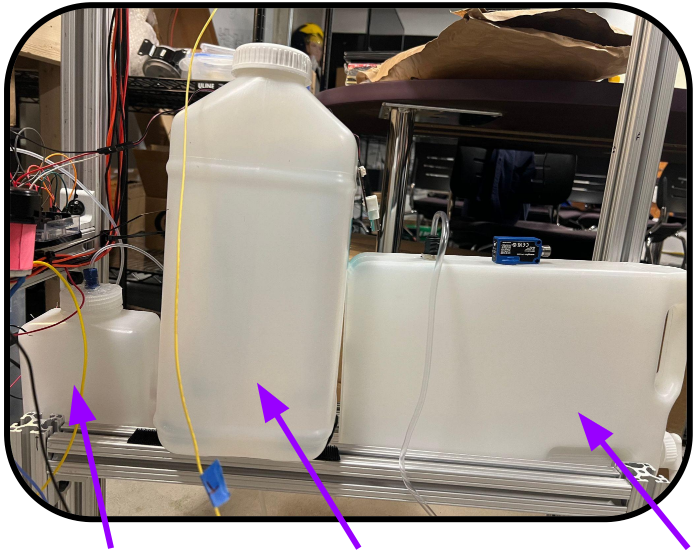


Food Medium / Harvest

pH Probe



Food/Algae/Waste Cups

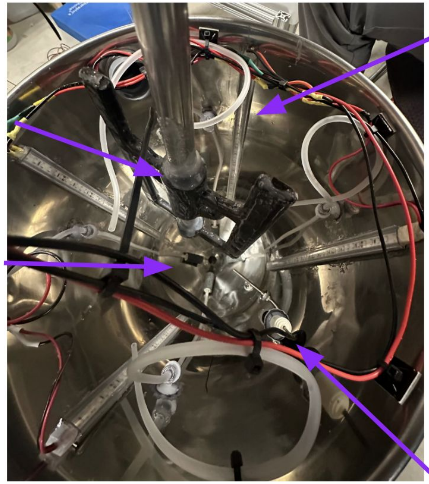


White Vinegar

Bristol-Water Solution

Waste (Excess Algae)

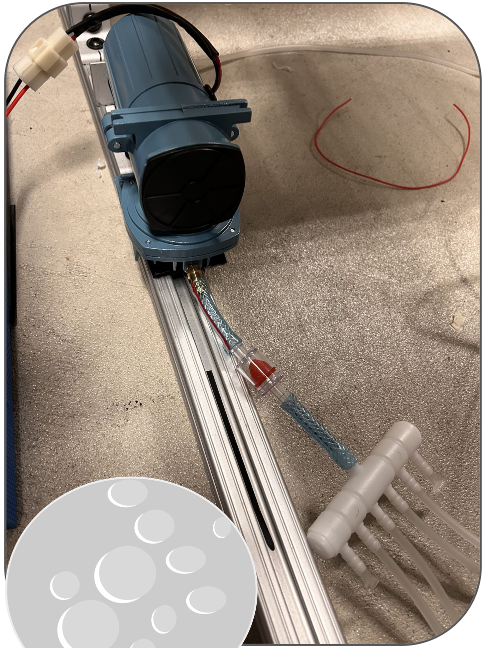
MoMS Components - General Locations



Algae Containment Unit

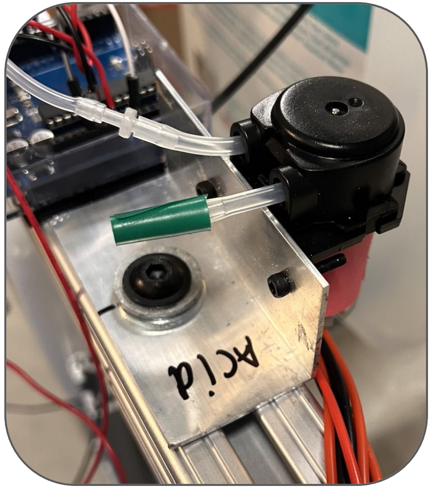
HIH Key Components

CO_2 Inlet System

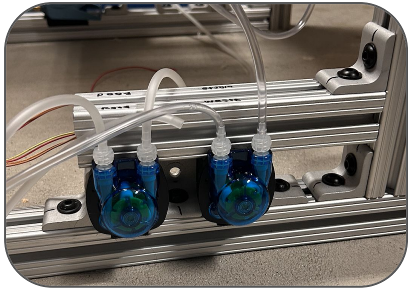


CO_2 Insertion

Acid Pump Mount



Peristaltic Pumps Mount



Structural Support
(L brackets, 80/20 bars and Velcro support harvest, food, and waste)

Ex. Acid Cup Support

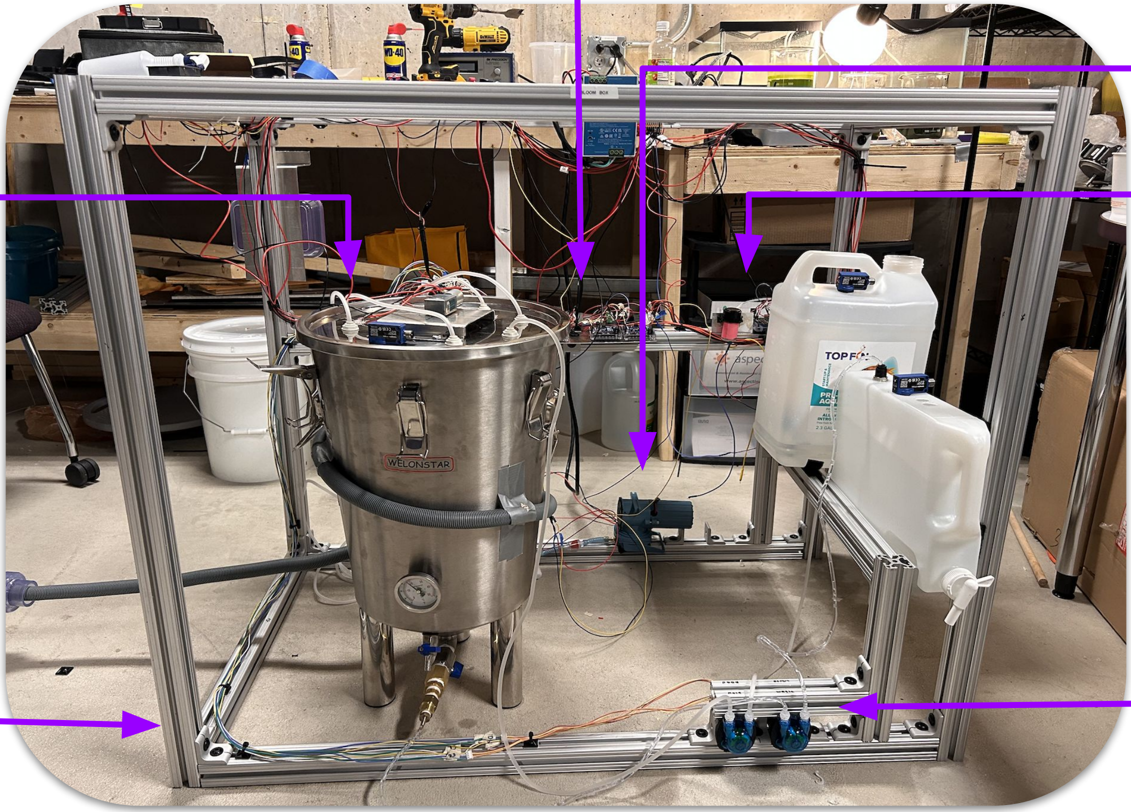
HIH Components - General Location

Electronics Mount

CO_2 Pump

Acid Pump Mount

CO_2 Inlets

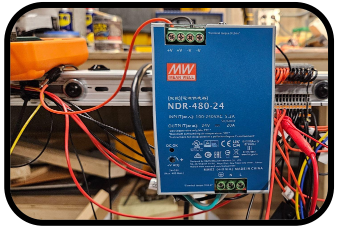


80/20 Structure

Food and Waste Pump Mounts

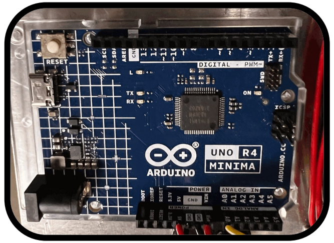
PCI Key Components

Power Supply



Human Interface

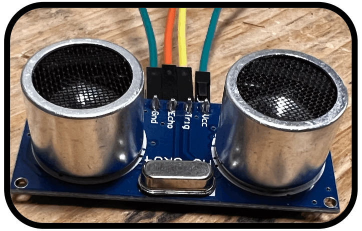
Arduino Board



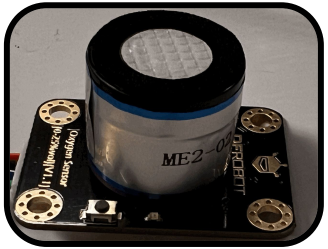
Raspberry Pi Board

Turbidity Sensor

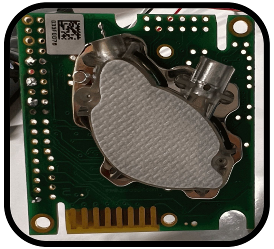
Water Level Sensor



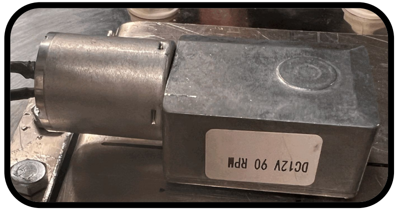
Ambient Oxygen Sensor



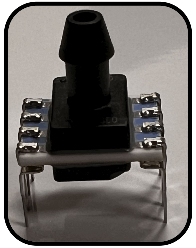
Ambient CO_2 Sensor



Mixing Motor



Ambient Air Pressure Sensor



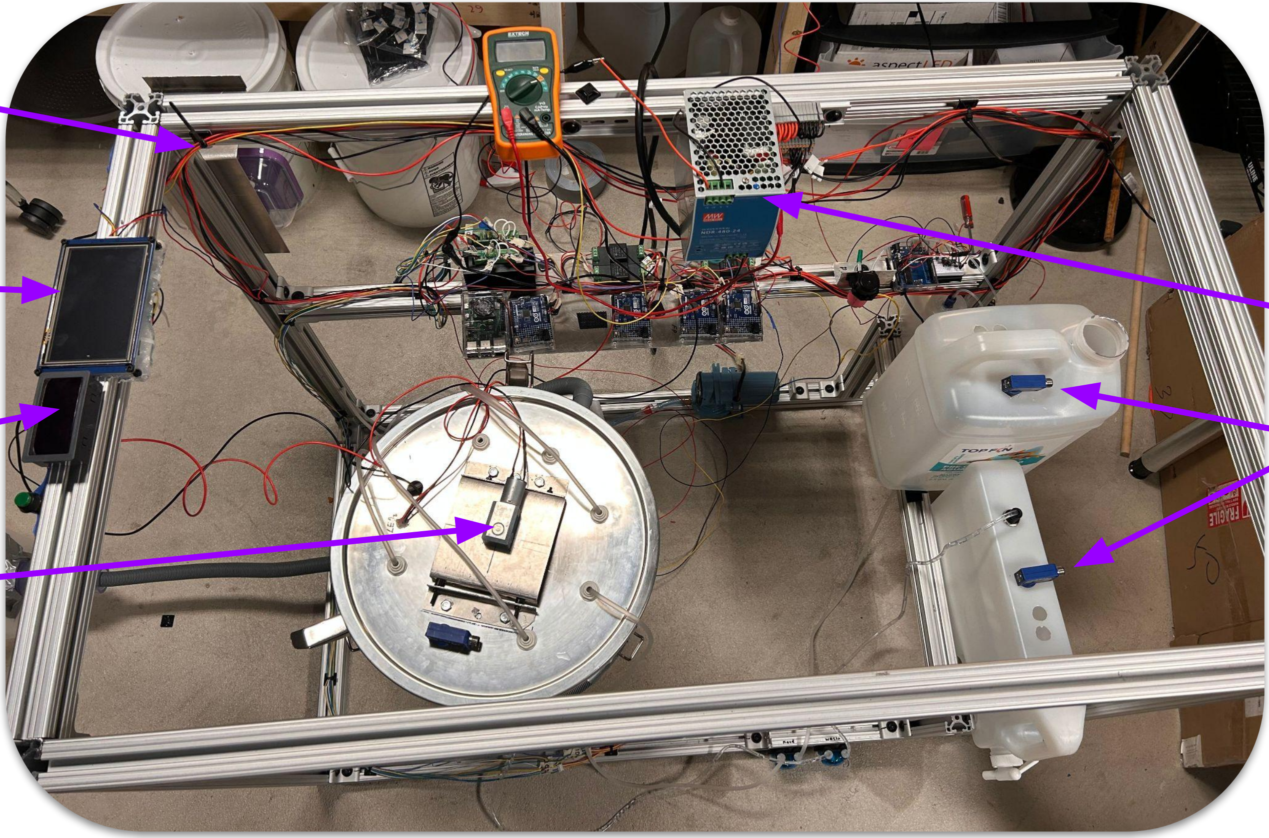
PCI Full System

Ambient gas sensors

HMI

RPM Monitor

Mixer Motor

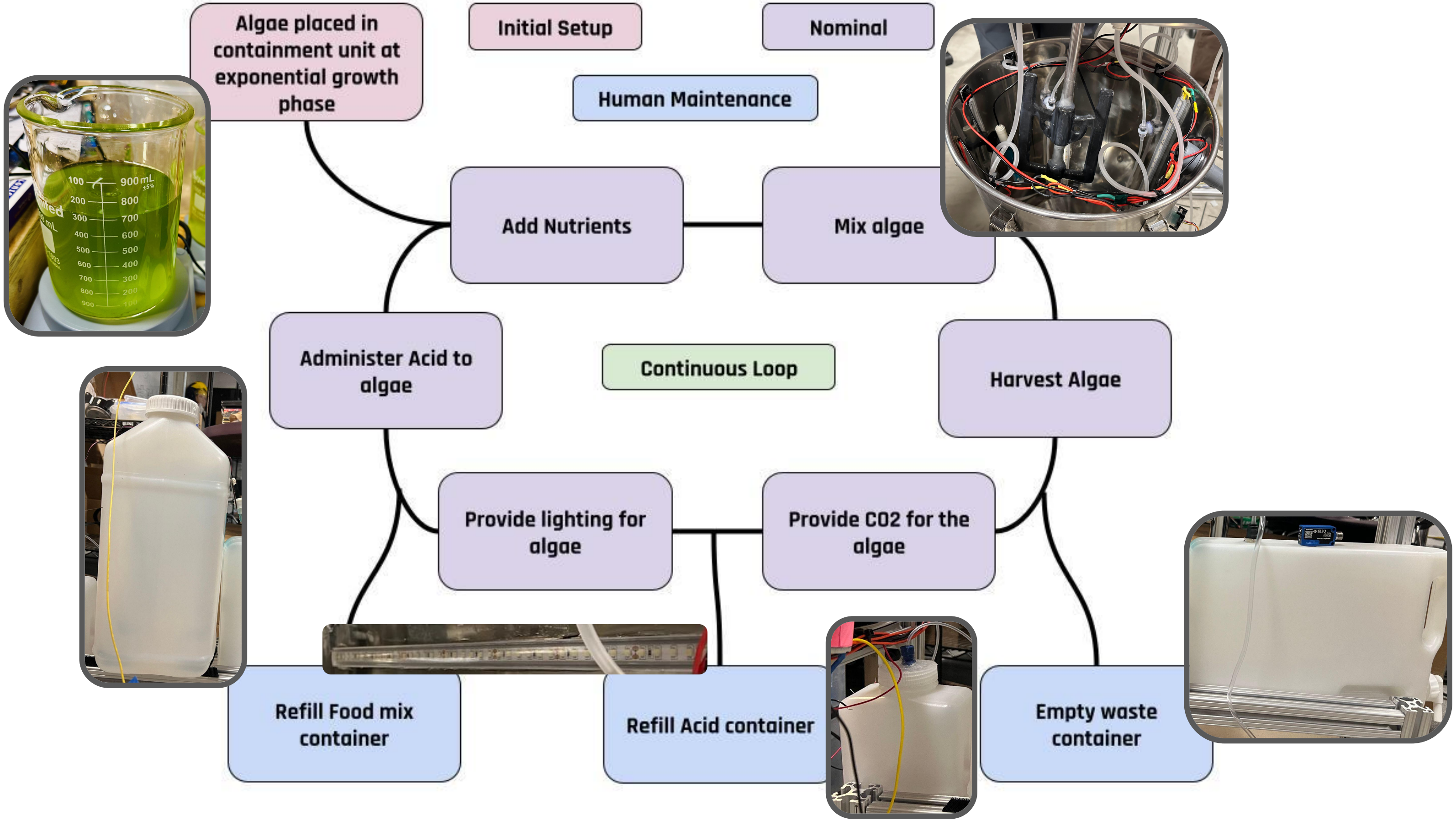


Power Supply

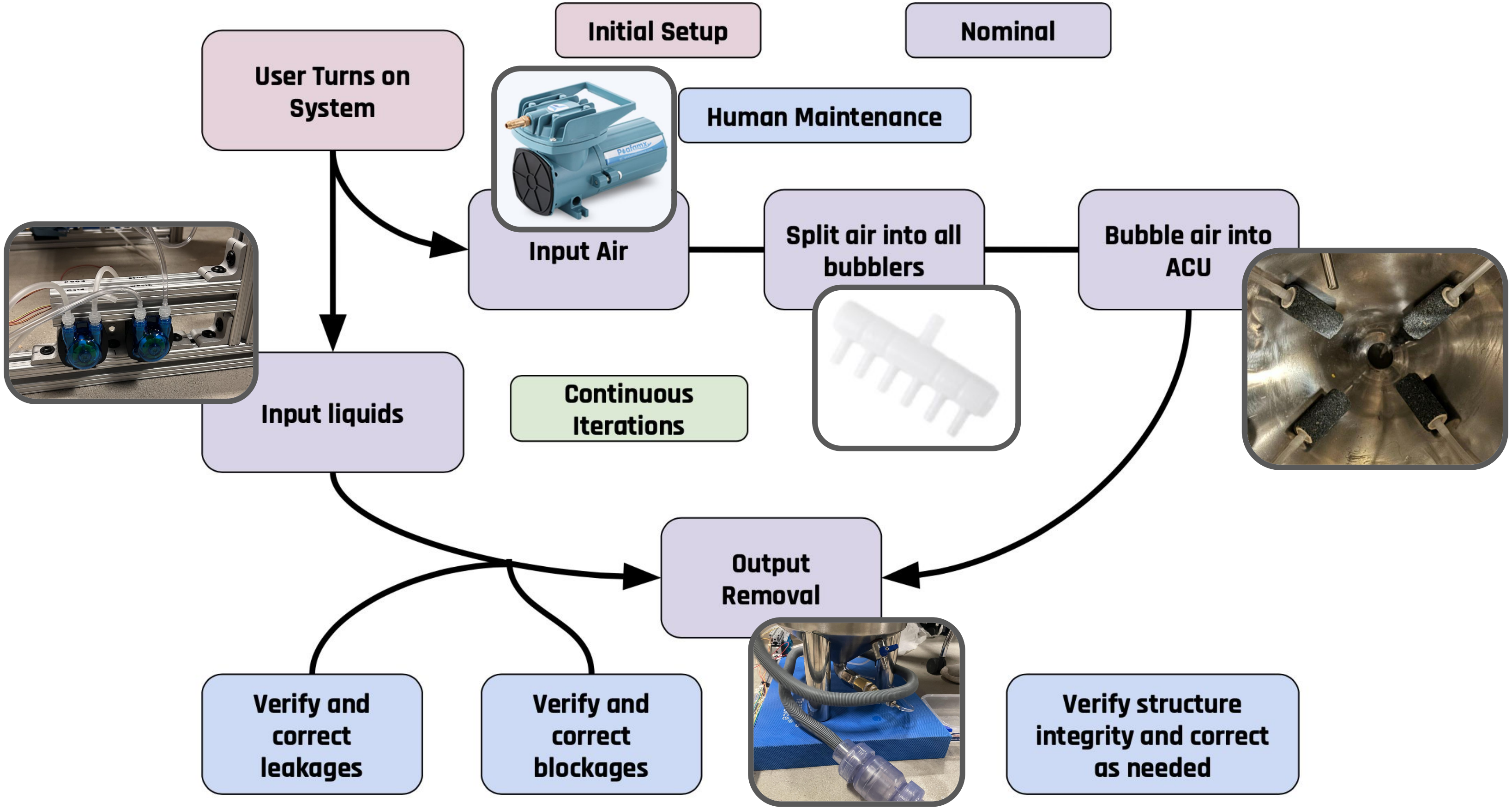
Ultrasonic Sensor

System Concept of Operations

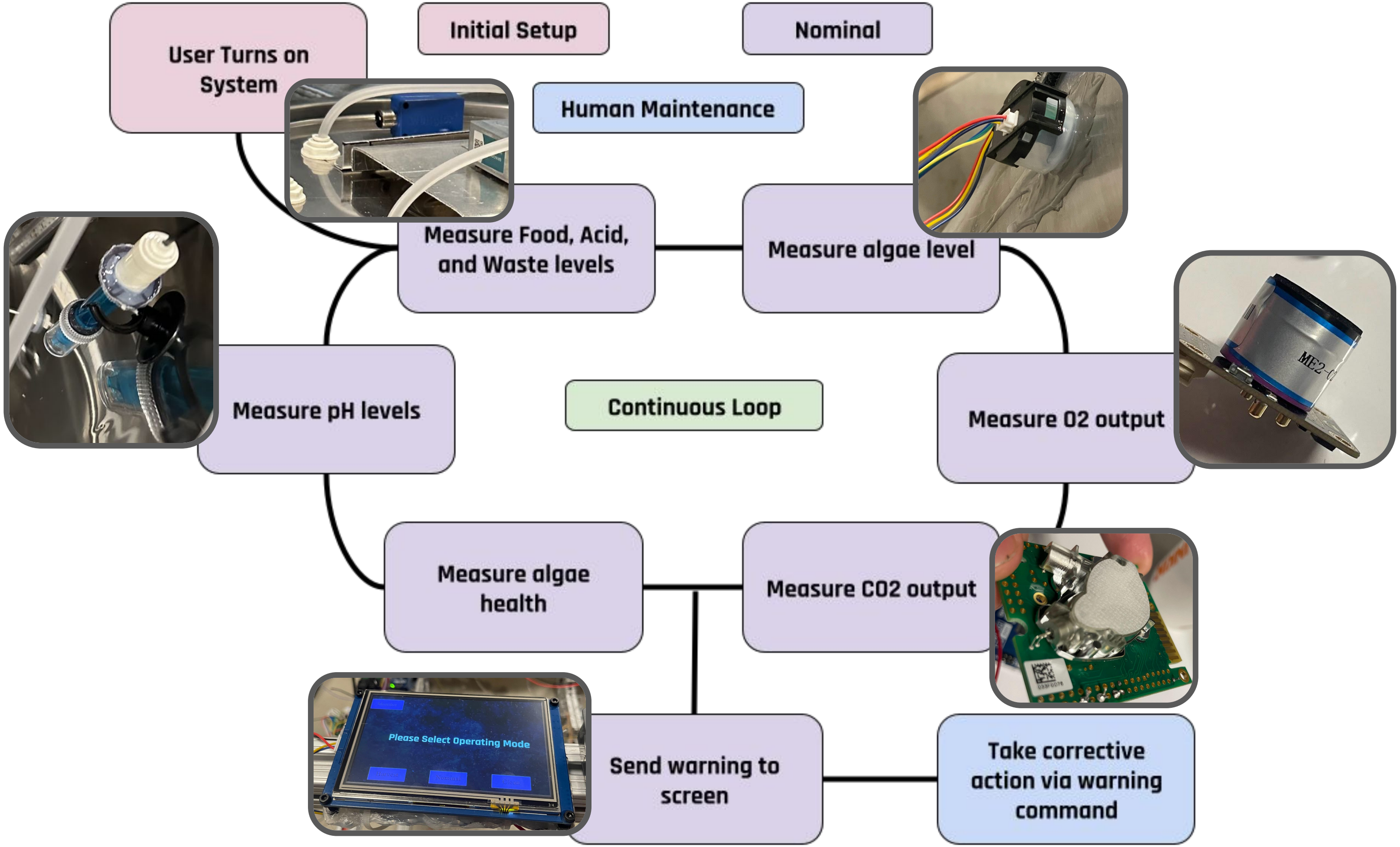
MoMs Subsystem Concept of Operations



HIH System Concept of Operations



PCI System Concept of Operations



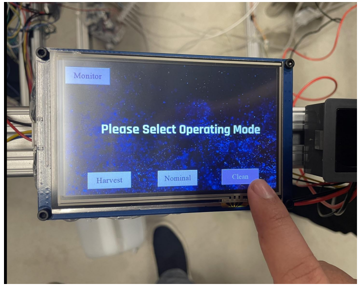
Human Concept of Operations

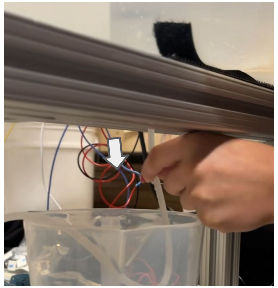
Acid and Nutrient Replacement

Low Acid/Food Alert

Switch System to Maintenance Mode

Unplug Tubing From ACU Bulkheads



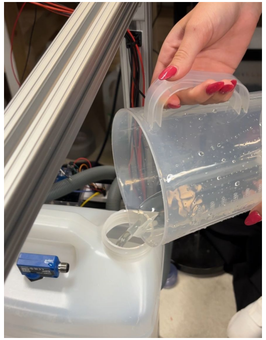


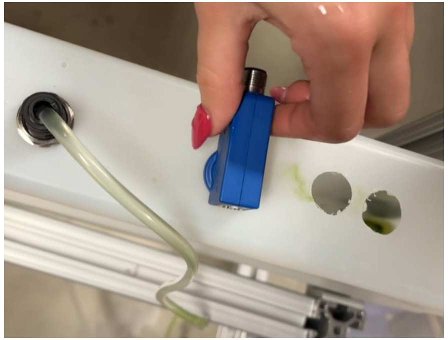
Remove Water Level Sensors from Tanks

Refill Tanks to Maximum Level

Replace Tank Tubing and Sensors

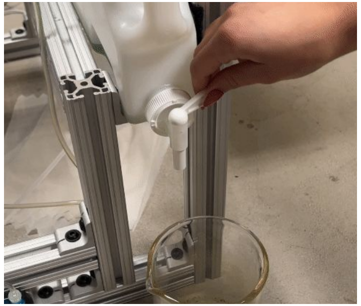
Switch System to Nominal Mode



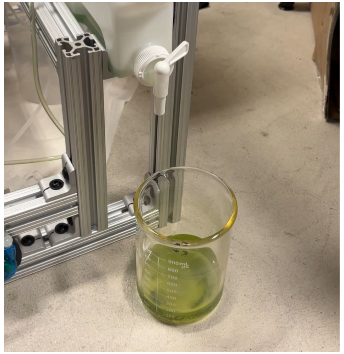


Harvesting

Full Harvester Alert → Switch System to Harvest Mode → Obtain Post- Harvest Container → Manually Open Harvester Spigot



→ Fill Post- Harvest Container → Manually Close Harvester Spigot → Switch System to Nominal Mode



Human Machine Interface (HMI) Status Indication

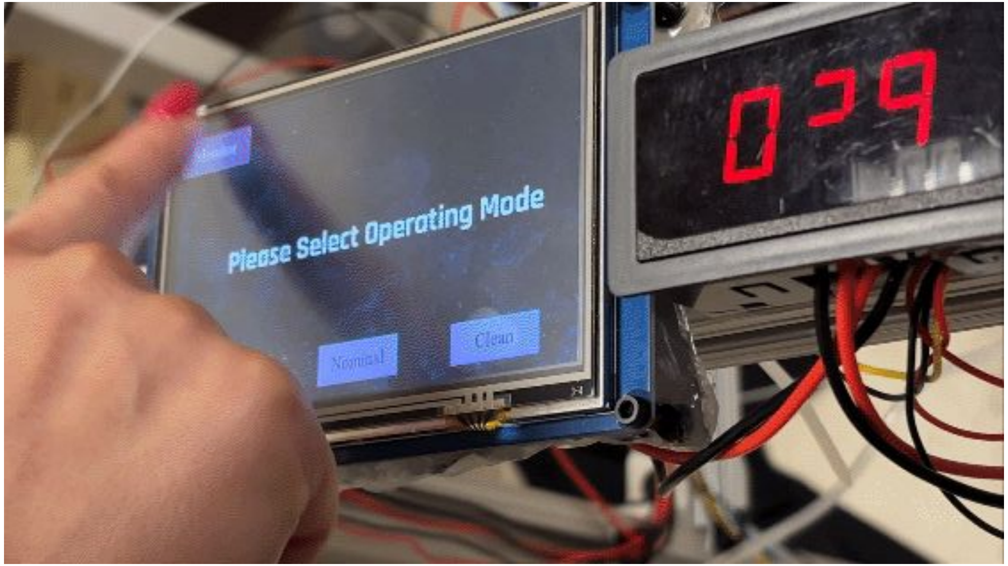
Activate HMI Display

or

Deactivate Alert

→ Select Status Indication → Observe System Performance Metrics → Return to Home Page

→ Select Desired Mode → Observe Mode Change → Return to Home Page

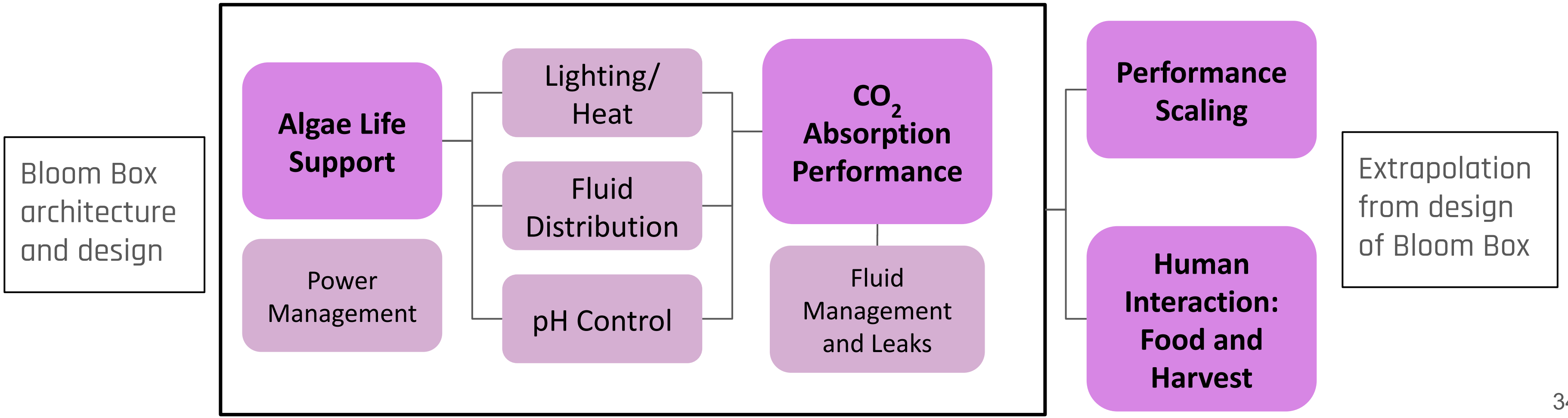


Discussion of Findings

Discussion of Findings Section Outline

Basic findings were collected to support the further development of a bioregenerative CO_2 scrubber of a similar architecture to the *Bloom Box*

These findings largely comment on the design choices for the *Bloom Box* yet also speak to lessons learned for future iterations



Algae Life Support

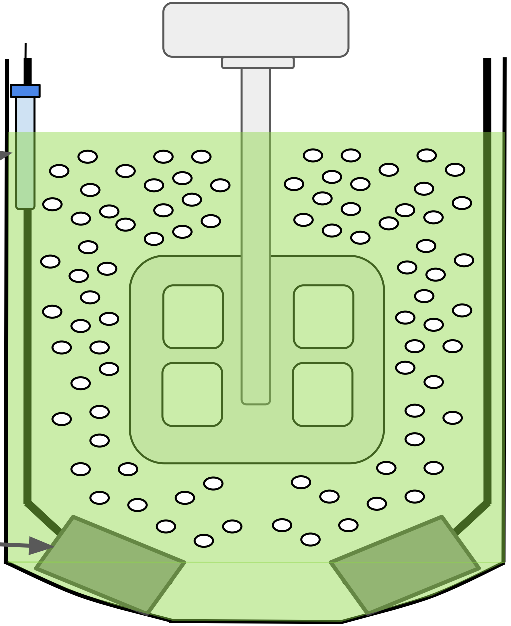
SYS-02 Regenerable Reactants

The system shall apply in-situ resource utilization (ISRU) or the use of regenerative reactants in ECLS operations.

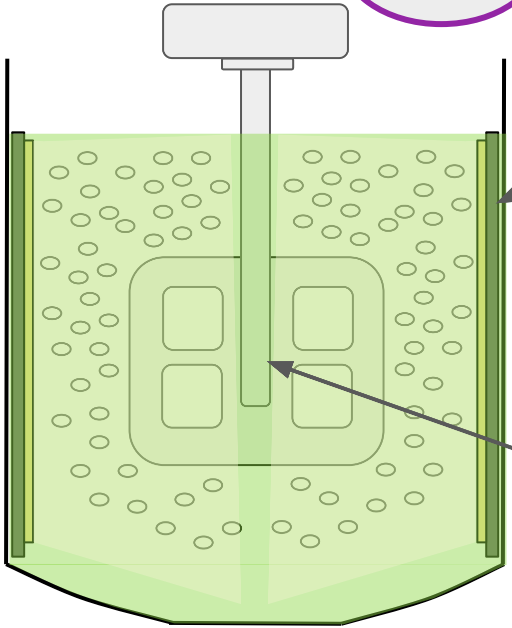
→ Algae Containment Unit

- Nutrient/ Water Regulator
- pH/Temp Regulator Assembly
- Lighting Regulation
- Fluid Distribution System

pH Probe



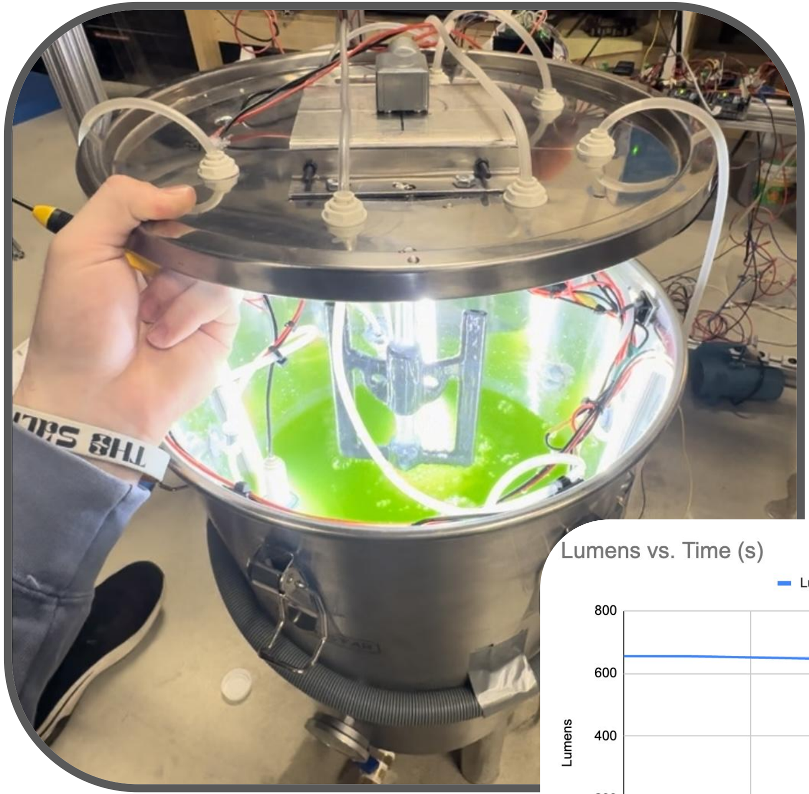
CO2 Bubblers



Lighting

Fluid Distribution

Lighting



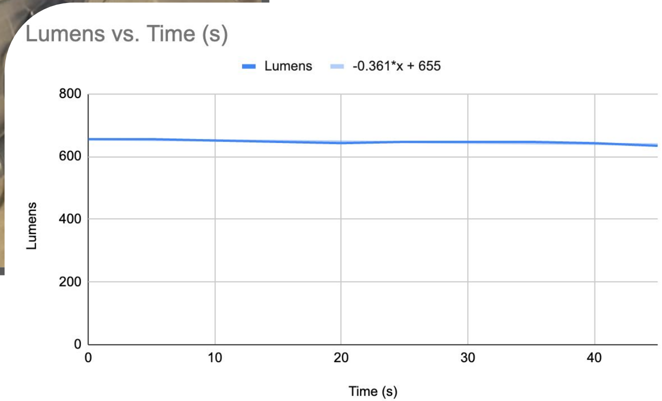
Algae Containment Unit

Nutrient/ Water Regulator

pH/Temp Regulator Assembly

Lighting Regulation

Fluid Distribution System

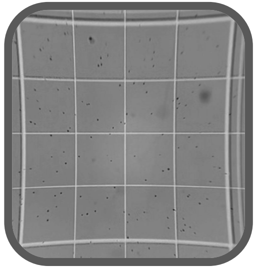


Results

- Blackbody temperature ~4000K worked to maintain algae health
- Average Luminosity between 630-660 Lumens maintained algae health

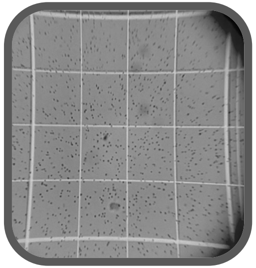
Fluid Distribution

Cell Count 1



+

Cell Count 2



Cell Count 3

=

Algae Containment Unit

Nutrient/ Water Regulator

pH/Temp Regulator Assembly

Lighting Regulation

Fluid Distribution System

Results

- Fluid Distribution System worked!
- Motor failed while we were testing
- Determined that CO2 bubblers provided enough mixing

Algae Containment Unit

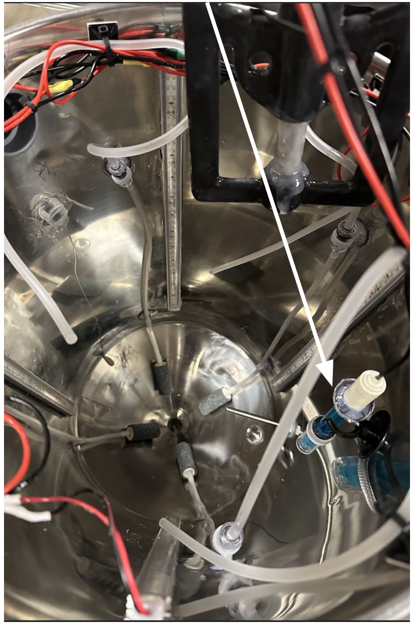
Nutrient/ Water Regulator

pH/Temp Regulator Assembly

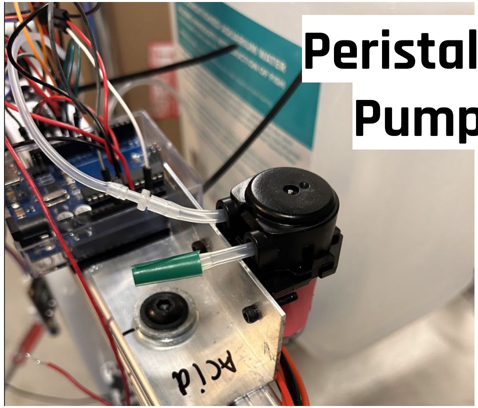
Lighting Regulation

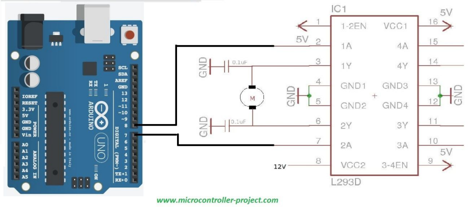
Fluid Distribution System

pH Probe



Peristaltic Pump





Results

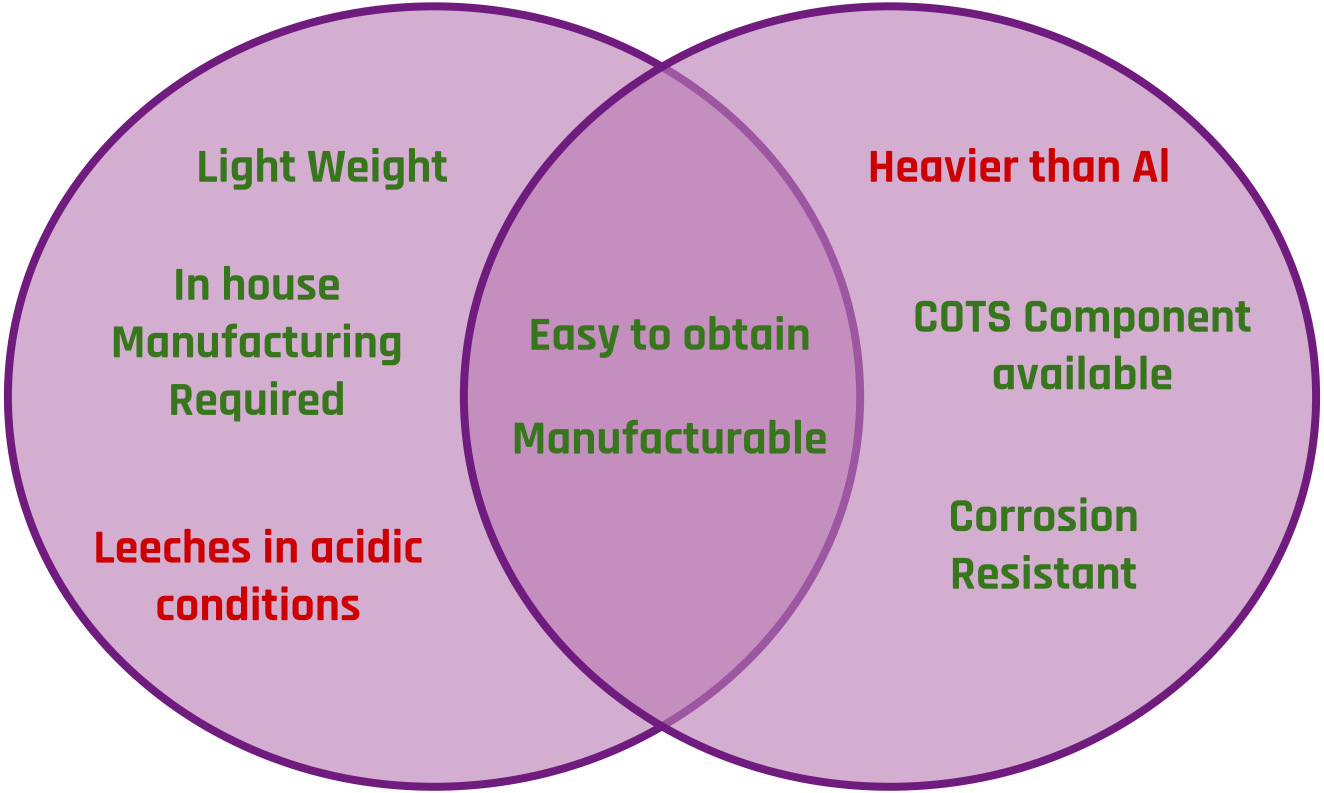
- PH probe attached to a standalone arduino and peristaltic pump
- Calibration issues due to constant power cycling during testing

- **Yet to determine if necessary**

Materials Choices

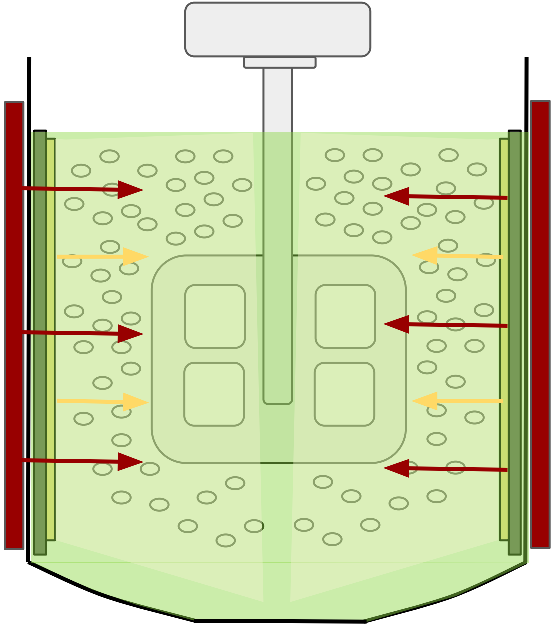
Initial Option: **6061 Aluminum**

Final Option: **Stainless Steel**



Heating [Lessons Learned]

Initial Design:
Heat from pads + Lights



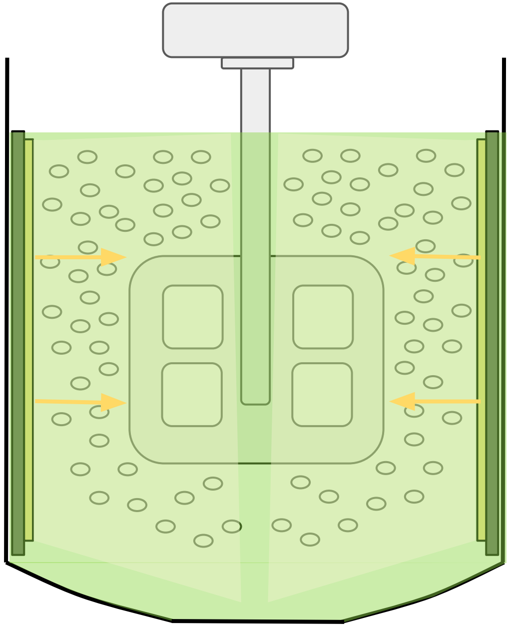
Justification: Algae optimal growth temperature is **~80 deg F**

However, in a closed system, **lighting** will **provide** additional **heat**

Additionally, algae can **grow** in **room temperature**

Therefore **temperature control** is **not needed**

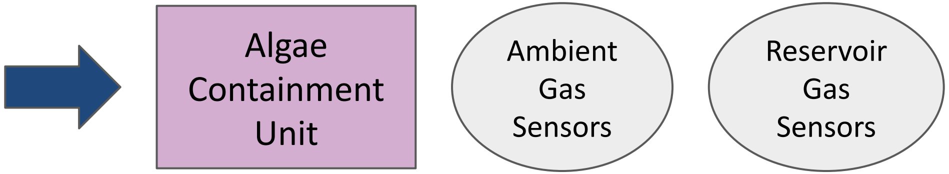
Final Design:
Heat from Lights

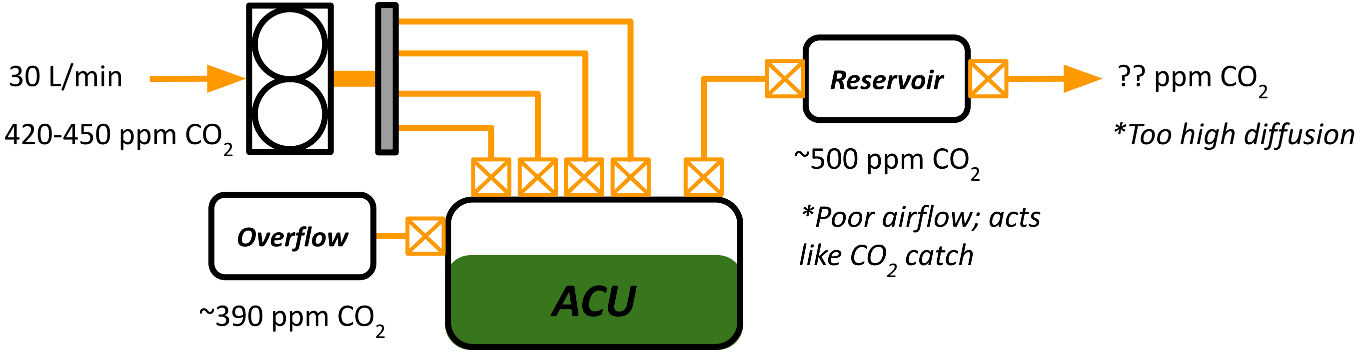


Carbon Dioxide Absorption Performance

SYS-01 Verifiable CO2 Partial Pressure Reduction

The system shall reduce the partial pressure of CO2 in its output flow by a quantity verifiable by the system during operation.





CO_2 In	420 - 450 ppm
CO_2 Out	390 - ? ppm

*Upper range of exiting CO_2 is unclear at all locations
*Drop describes vol. fraction absorption at inlet flow rate

Carbon Dioxide Absorption Performance

Use mass fraction and mass flow with measurements to find range of CO_2 absorption rate

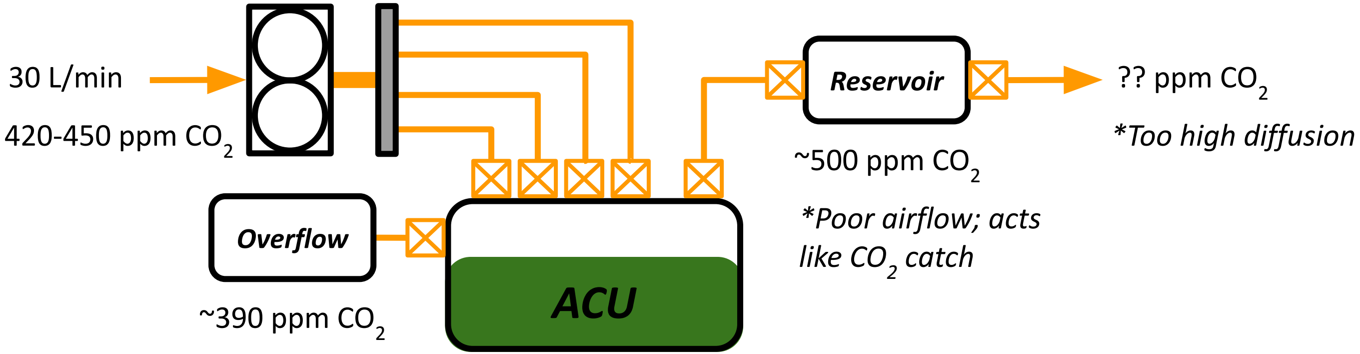
1) $M_f(\mathrm{CO_2}) = \dfrac{44.02}{28.96} = 1.5203$

2) $m(\mathrm{CO_2})\ \text{per million} \ = ([\text{ppm range}] \times 10^{-6}) \cdot M_f(\mathrm{CO_2})$

3) $M_{f,f} - M_{f,i} = \left(\dfrac{m(\mathrm{CO_2})_f}{m(\text{air})} - \dfrac{m(\mathrm{CO_2})_i}{m(\text{air})}\right) = \dfrac{1}{m(\text{air})}(\Delta m(\mathrm{CO_2}))$

4) $\dot{m}(\text{air}) = Q_v \cdot \rho = 30\ \text{L/min} \ \cdot \ 1.29\ \text{g/L} \ = 38.7\ \text{g/min}$

$$\rightarrow \Delta\dot{m}(\mathrm{CO_2})) = 1.76\ \text{to}\ 3.53\ \text{mg/min}$$



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Compare absorption rate to minimum theoretical absorption rate from literature (Matula ICES-2016-147)

1) $\frac{\dot{m}(\mathrm{CO_2}))_{theory}}{\text{Liters of Algae}} = 0.65\text{ g/L/day}$

2) $\dot{m}(\mathrm{CO_2}))_{theory} = \frac{0.65 \cdot 30}{24 \cdot 60} \cdot 1000 = 13.54\text{ mg/min}$

$\eta = 13\%\text{ to }26\%$

4) CO_2 Out theoretical target: **230 ppm**

Carbon Dioxide Absorption Performance

Use mass fraction and mass flow with measurements to find range of CO_2 absorption rate

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3) $M_{f,f} - M_{f,i} = \Big(\frac{m(}{m}$ ... $= 38.7\text{ g/min}$

...in

CO_2 absorption rate for Chlorella vulgaris is shown to reach past 5 g/L/day, putting efficiency at **1.7% to 3.4%**

It is likely that some efficiency loss is due to mis-measurements from **leaks** and **diffusion**

Compare absor... (Matula ICES-2016-147)

1) $\frac{\dot{m}(\text{CO}_2))_{theory}}{\text{Liters of Algae}}$ ... $\frac{}{24 \cdot 60}$ ...$0 = 13.54\text{ mg/min}$

$\eta = 13\%\text{ to }26\%$

4) CO_2 Out theoretical target: **230 ppm**

Performance Scaling to System Scaling

$$\Delta\dot{m}(CO_2)) = f(T, I, D_c, \dot{m}_{gas}, N_c)$$

*intrinsic (volume independent)

Temperature	Light Intensity	Gas-Algae Distribution Coefficient	Air Mass Flow	Cell Count
*Supplied by lighting or habitat ECLS *Power increases with increase in volume (linear with mixing)	*Drops off with dimension scaling (inverse square) *Increasing light power output increases local temperature	*Could scale linearly with proper mixing *Highly dependent on geometry and gas flow	*Must fit to absorption saturation rate *Can increase with more exposure or more pumping	*Ideally keep algae in exponential phase *More complicated to measure a characteristic curve for complex geometry

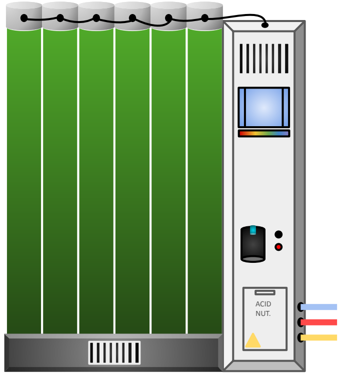
Performance Scaling to System Scaling

Linear Scaling of Full System:

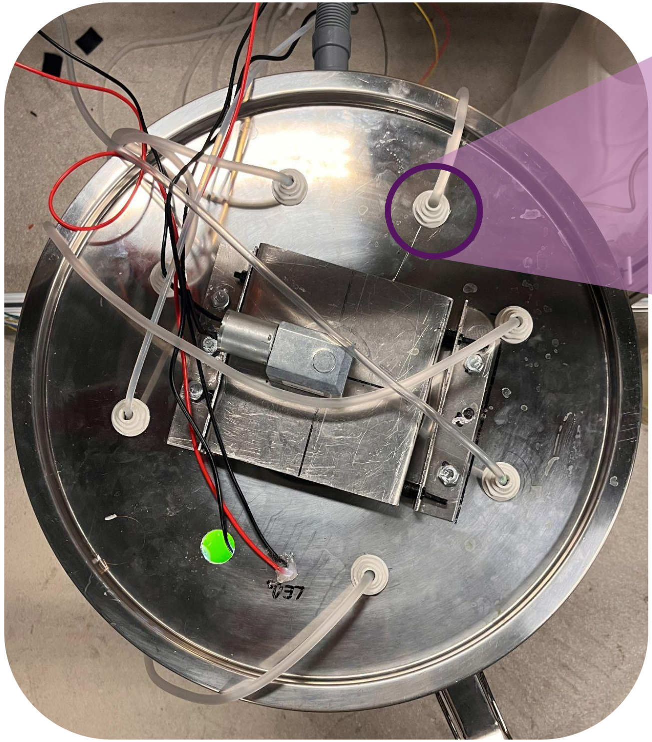
- Keeps annular geometry (volume inefficient with increase)
- Equivalent mixing and gas-algae distribution coefficient
- Linear gas flow increase
- Light intensity drops off in center of volume
- Only gas pump power and mixer power increase
- **Sub-Linear increase in CO_2 absorption with volume increase**

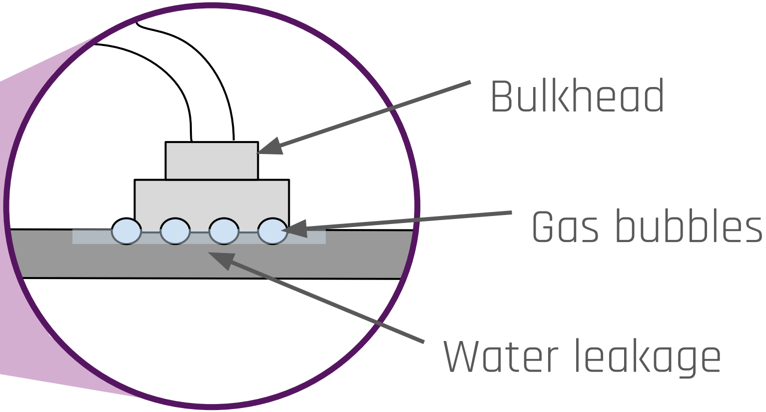
Geometry Change with Volume Increase:

- Change to cells of tubes that line walls of habitat (low envelope)
- Mixing dependent on gas flow only
- More pumps with higher flow rate and power
- Light intensity stays the same with LEDs spanning tubes
- Small cross sections mean lower heat requirement
- High complexity for harvest, nutrients, pH, and controls
- **Approx Linear increase in CO_2 absorption with volume increase**



Fluid Control: Leaks





Bulkhead leakage = error in CO2 absorption + humidity loss

Fluid Control: Pump Pressure

Current Design

Outputs const. 30 L/min

COTS Component

Less Expensive

Both

Maintains algae health

Future Design

Output custom CO_2 flow

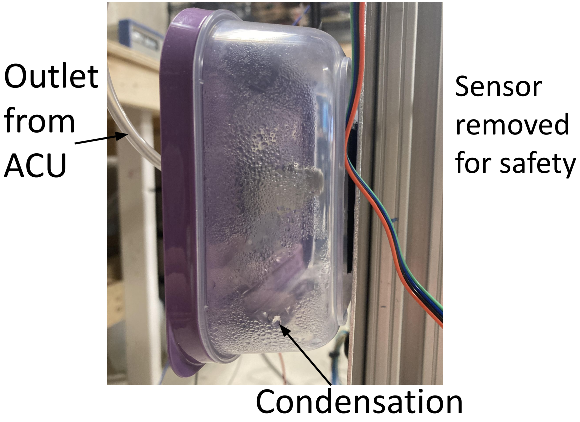
Improves CO_2 consumption

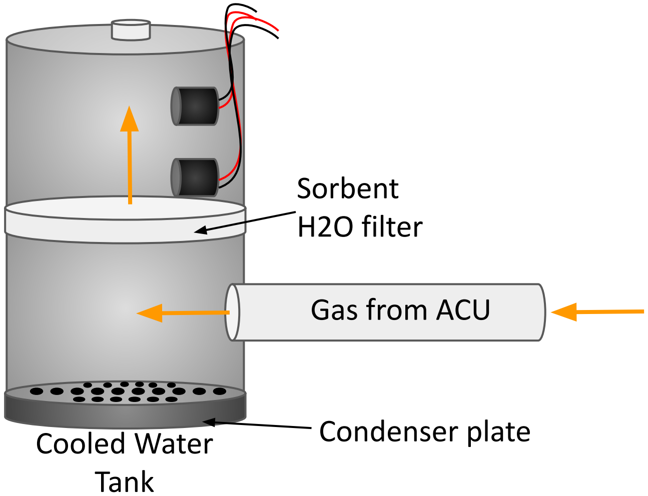
More Expensive custom component

Fluid Control: Water in Gas Reservoir

The flowing gas mixture consists of CO_2, O_2, (air etc.) and $\boldsymbol{H_2O}$

- Water exists in both gaseous and liquid phase with high humidity as it travels through outlet
- Poses danger to gas reservoir sensors if water condenses in sensors
- Opens opportunity for water reclamation with a condenser downstream of ACU





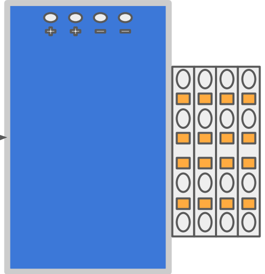
Power: Power Supply

SYS-12 Space Habitat Representative Voltage Limitations

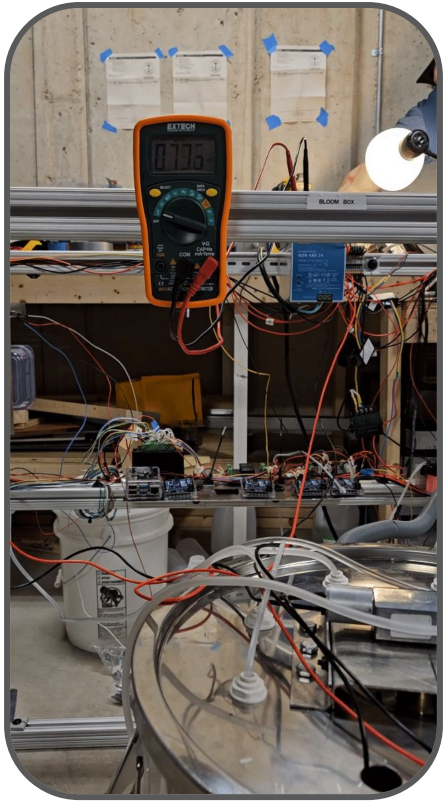
The system shall operate with an input voltage of 24V DC to mimic space habitat power interfaces.

Power Management

DDCU → Buck Converter →



- U.S. segment of ISS runs on 124V DC output from the DC-DC-Conversion-Unit (DDCU)
- Our system runs on 24V DC at 80W.

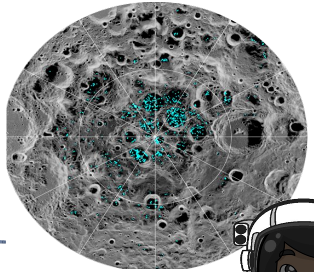


Conclusion / Summary

Path to Flight (Hypothetical)

Example Considerations / Needs For Flight:

- Implementation of excessive algae volume
    - Line the walls
    - Incorporate a dedicated location
- More extensive algae growth and transient consideration
- Mechanical changes for algae survival and cultivation in zeroG
- Structural considerations for launch and flight environment
- Advanced ergonomic studies
- Human-in-the-loop Testing



Lessons Learned and Future Work

- Focus on high impact, low difficulty components
  - Heating, Mixing, etc
- Emphasize design with not only manufacturing but testability in mind
- Start Early!! (More Testing)