

SCAMPI Project: Design of an Aquatic Closed Ecological System for Microgravity

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Long-duration crewed space missions require bioregenerative life support solutions to improve mission sustainability and resiliency in the harsh environment of space. Understanding the impact of the space environment on Earth ecosystems is a critical next step in developing such solutions. This manuscript presents the experimental design of the SCAMPI Project (Saltwater Crustacean, Algae, and Microbe Population Investigation), a student mission to investigate the effect of microgravity and increased radiation on a multitrophic aquatic closed ecological system. The team is developing a custom payload, consisting of a sealed aquarium and instrumentation suite, to be integrated into the ICE Cubes facility onboard the International Space Station. Remote monitoring will collect data and imagery on the biotic and abiotic factors within the closed environment, informing a digital twin simulation that is being developed concurrently. This experiment will be the latest in a short list of ecosystem-scale experiments to fly in space, and address fundamental knowledge gaps including microbial community dynamics in microgravity. Ultimately, SCAMPI will provide data to inform the design of future closed ecological life support technologies by validating the hypothesis that Earth's ecosystems can function nominally in the space environment. The experiment is currently being built as a part of ESA's PETRI program and anticipates launching in early 2025.

Nomenclature

ABS	=	Autonomous Biological Systems
ACES	=	Aquatic Closed Ecological Systems
BLSS	=	Bio-Regenerative Life Support Systems
CEAS	=	Closed Aquatic EcoSystem
CEBAS	=	Closed Equilibrated Biological Aquatic System
CERAS	=	Closed Ecological Recirculating Aquaculture Systems
CES	=	Closed Ecological Systems
eDNA	=	environmental DNA
H	=	height of the cylindrical vessel in mm
PETRI	=	Practical Education in Technology, Research, and Innovation program by ESA
SCAMPI	=	Space Crustaceans, Algae and Microbial Population Investigation
R	=	radius of the cylindrical vessel in mm
pCO_2	=	carbon dioxide partial pressure in the gas phase in Pa
pO_2	=	oxygen partial pressure in the gas phase in Pa
T	=	temperature in the vessel in C
PISCES-v2	=	Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2
$\mathbf{u}$	=	fluid velocity field in the vessel in m/s
$\tilde{p}$	=	normalized pressure
ν	=	kinematic viscosity of the fluid

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$\boldsymbol{F}$ = external force due to the motion of the vessel in N
H = mean curvature of the free surface in m^{-1}
n_i = i-th component of the normal vector to the liquid surface
$\bar{\sigma}$ = kinematic surface tension tensor

I. Introduction

A major obstacle impeding the advancement of crewed space exploration is the need for frequent resupplies of consumables and reliance on physicochemical life support systems. Successful habitation of regions beyond cis-lunar space will require bio-regenerative life support systems (BLSS) to sustain longer-duration missions. Closed ecological systems (CES) are a promising tool to study, and eventually implement, BLSS that can sustain life in space by harnessing ecological services to provide air and water revitalization, waste processing, food/fiber/pharmaceuticals, and psychological benefits. Among the various types of CES, aquatic closed ecological systems (ACES) have several advantages over terrestrial systems.

Aquatic organisms are generally more efficient in terms of energy use, feed conversion ratios, and bioavailability of waste products. Moreover, the logistics of resource distribution are simplified in aquatic systems since all compounds (notably nutrients and waste) diffuse evenly throughout the medium, although this process is inhibited by the absence of convection and overall slower diffusion in microgravity. Identifying and characterizing the microbial community is easier in aquatic systems because collecting environmental DNA (eDNA) can provide a more representative sample of the entire community due to the largely homogenous nature of an aquatic environment.

It is essential to note that ecology is a relatively young science, barely more than a hundred years old, and it is only in recent years that the scientific method has been applied to ecological studies. Early microcosm experiments were rarely closed to gas exchange with the atmosphere, resulting in limited reproducibility and reliability. Nevertheless, they did illustrate important ecosystem dynamics concepts such as elemental cycles, energetic flows, and the effect of community composition on function.

Many of these early experiments[1] were conducted by entities such as NASA with an eye on space applications - the idea of bioregenerative life support systems is not new. It was determined, probably correctly, that our understanding of life sciences was insufficient to produce safe and reliable life support systems, so a conscious decision was made to deprioritize BLSS research in favor of physicochemical solutions.

The advancement of sensing and measurement technologies and material science (enabling more complete closure of systems) has enabled a new generation of ecologists to take a scientifically-traditional, reductionist approach to ecological studies and improve the reproducibility and accuracy of replications. However, despite these advances, research in closed ecological systems is still in its infancy.

II. Historical ACES Experiments

The last 30 years have seen a resurgence of interest in CES, with the iconic Biosphere 2 as the poster child of the movement. Despite this, ACES experiments, whether on the ground or in space, are still relatively rare. The Closed Ecological Recirculating Aquaculture Systems (CERAS)[2] experiments conducted on the ground in Japan were a series of comprehensive investigations into a variety of ACES designs. The broad-ranging experiments trialled different species of freshwater and marine fish in combination with single feed treatments (Spirulina) and multiple feeds, measured O_2/CO_2 fluxes, and even developed a transgenic Tilapia with vastly improved metabolic efficiency.

Paragon Space Development Corporation, co-founded by Biospherians Jayne Poynter and Taber McCallum among others, carried forward the legacy of Biosphere 2 with their own ACES experiments - coined Autonomous Biological Systems[3]. These small 900ml cylinders housed a very diverse array of aquatic plants, algae, micro invertebrates, and microbes to emulate a freshwater pond environment. Paragon was fortunate to fly ABS on several flights and even secure space on Mir station for observation periods of up to 4 months. They found this naturalistic aquatic ecosystem to be highly successful, with many of the micro invertebrates completing one or more lifecycles during the study. However, after these successful experiments, Paragon largely stopped pursuing CES research.

The German-led Closed Equilibrated Biological Aquatic System (CEBAS) research program[4] was a prime example of microgravity ACES research, which also took place over a series of trials establishing the robustness of various subsystems of CEBAS. The multi-chambered system included higher plant producers, snail decomposers, a biological filter with nitrifying bacteria, and medaka fish as the primary consumers. CEBAS is also notable for being one of the largest ACES flown in space with a total volume of 10L, a design which contributed to the superb stability of the system even in “crash tests” with ammonia spikes caused by dead animals. As is a recurring theme in CES

experiments, the authors stated that a typical mission duration of several weeks is simply too short to investigate ecological-scale phenomena such as equilibrium states or population dynamics.

As one of the most recent ACES experiments, the Chinese Closed Aquatic EcoSystem[5] (CAES) experiments in 2004 was a step towards more strictly controlled experimental design. Its scientists placed an emphasis on understanding the effects of the space environment on the abiotic parameters of the ecosystem, and included a more complete sensor suite than its predecessors. While the flora and fauna complements were not as varied as other ACES, CAES included centrifuge trials in space and on the ground to isolate the impact of microgravity on an ecosystem.

Utilizing lessons learned from these previous studies, the Saltwater Crustacean, Algae, and Microbe Population Investigation (SCAMPI) seeks to design a rigorously controlled experiment that investigates the impact of the space environment on an ACES. The SCAMPI payload will be modeled after the commercial Ecosphere® product, a simple yet resilient brackish ecosystem composed of *Halocaridina rubra* shrimp and uncharacterized algae and microbial communities enclosed in a baseball-sized sphere. These materially closed ecosystems have been known to regularly persist for 10+ years with no input or maintenance beyond indirect light. A robust and self-sustaining ecosystem like this is a strong candidate for a fully-integrated ACES with no supplementary life support capabilities, such as SCAMPI.

III. SCAMPI Experimental Design

The SCAMPI payload consists of a sealed, cylindrical aquarium containing a minimalistic aquatic ecosystem. It represents three trophic levels:

- Three *Halocaridina rubra* shrimp.
- The macroalgae species *Chaetomorphae capillary* characterized by its macroscopic filaments of cylindrical cells, and unidentified microalgae.
- A currently unknown microbial community, to be characterized before and after the experiment.

Ecological experiments with a microbial component typically treat them as a "blackbox". The microbes themselves remain undefined, but their role in the system is measurable and understood. This approach introduces uncertainty in experimental replicability, so the SCAMPI project seeks to clarify the identity and role of this important trophic level. Genetic analyses will be conducted before and after the experiment to define the baseline microbial community and to understand the impact of the space environment on community composition and gene expression.

Figure 1 illustrates the configuration of the aquarium, adapted to accommodate the unusual bubble physics anticipated in microgravity. Note that the shrimp in question are known to have occasional excursions outside of water, so are expected to be unaffected by brief bubble interactions. In addition to the organic inhabitants, it also consists of three non-organic layers:

- An aragonite (orthorhombic $CaCO_3$) and lava rock substrate which hosts the microbial community and also serves as a calcium carbonate buffer. This layer corresponds to ⅕ of the volume.
- Brackish water at 13 ppt salinity with pH ranging between 7.5 and 8.5. This layer corresponds to ⅗ of the volume.
- Air/head gas volume that acts as an active reservoir for the excess oxygen and carbon dioxide. This layer corresponds to ⅕ of the volume.

The substrate and the algae are placed in horizontal layers and are secured using separation nets to prevent them from floating freely in the aquarium and interfering with optical measurements. The sensors will be affixed within these restrained layers so that, with the help of adhesion, they should be always submersed for accurate measurements.

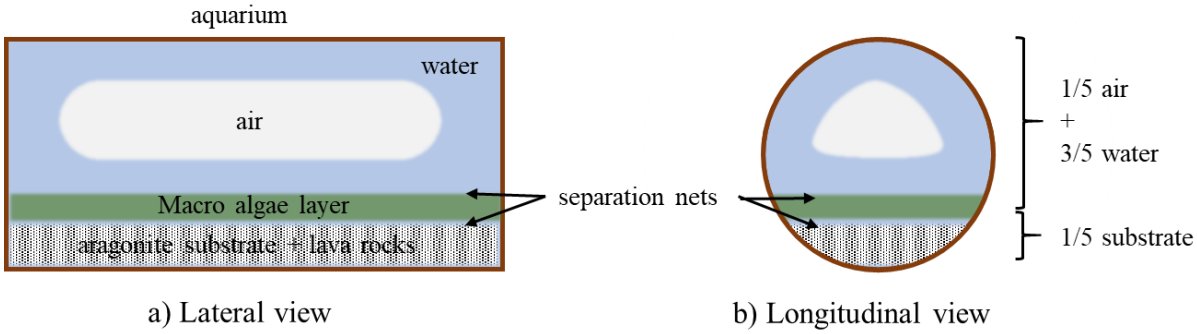

Figure 1 Overview of the experiment layout as it is expected to appear in microgravity.

The payload will be sent onboard the International Space Station for 90 days as part of the ESA's educational PETRI program, once all safety requirements are validated.

The experimental timeline for the SCAMPI project is divided into four steps: pre-launch, launch, ISS phase and return. Table 1 gives a quick overview of the projected tasks and diagnostics planned for each phase which are presented in more detail in the following subsections.

A. Pre-launch Phase: Concept validation

A "mother colony" aquarium has been built containing 100 shrimp and the algae and microbial components. Sand and lava rocks will be added to provide a suitable substrate to support bacterial growth. The mother colony will be divided into many samples, some of which will be subjected to thermal and vibration testing to validate the system's resilience before launch. Once the feasibility of the experiment - in terms of ecosystem persistence - is assessed, one experimental trial, along with 10 Earth trials, are extracted from the mother colony. Of the 10 Earth controls, five are submitted to launch stresses to specifically investigate the impact of stress from the launch on the inhabitants.

Table 1. Phases of SCAMPI mission

Mission Phase	Expected tasks and diagnostics
Pre-Launch	• Build a "mother colony". • Divide mother colony into 0.7L trials. • Vibration and thermal testing on the trials, to assess feasibility of the experiment. • Conduct meta-barcoding and meta-transcriptomics analyses on the microbial community of the mother colony. • Conduct epigenomics and transcriptomics on macroalgae and shrimps of the experimental trial.
Launch	• Launch of the experimental trial. • Submit 5 out of 10 Earth controls to simulated launch conditions. • No experimental data will be generated in this phase.
ISS	• Capture video of shrimp behavior and adaptation to microgravity. • Monitor environmental factors of the experimental trial to compare to Earth controls. • Capture video of container sloshing to compare against simulations.
Return	• Disassemble experimental trial. • Run meta-transcriptomics and meta-barcoding analyses on the microbial community of the experimental trial and Earth controls. • Run epigenomics and transcriptomic analyses on shrimps and macroalgae

B. ISS Phase: Ecosystem Monitoring and Sloshing Modes Observations

The payload will be equipped with a camera to examine the behavioral adaptations of the shrimps to microgravity. It is expected that shrimps will initially display a "looping" behavior before acclimatizing, previously described in aquatic animals in microgravity conditions[7].

Several sensors (described in section IV) will also provide information on multiple biotic and abiotic factors, such as dissolved O_2 and CO_2 in the liquid and gas phase, pH, temperature, NH_4^+, and chlorophyll. The instrumentation suite will thus be crucial to define carbon and nitrogen cycles, microalgae population, partial pressure, and shrimp metabolism as well as for linking environmental factors to biological changes. Collectively, the information gathered via camera and sensors on the ISS phase will be used to validate the mathematical model of the ecosystem dynamics of the experiment and also compare them to the ground-based controls.

A second camera is included in the design in order to observe the free surface between the gas phase and the liquid phase. This is of paramount importance in liquid tanks and fluid management systems in space[8,9] since it highly impacts spacecraft operations. The data will allow us to observe and compare it with simulations which will be detailed in section V. During the launch and return phase, the payload won't have electrical power, therefore no data will be retrieved during these phases.

C. Expected Genomic Analysis

Water samples will be analyzed before and after the mission, and metagenomics and transcriptomics analysis will be performed to characterize the microbial population and its changes in terms of viable species and gene expression. Considering every trial in our experiment will be generated from the same "mother colony", we assume the microbial community to be the same among treatments. Metabarcoding and transcriptomics analysis will be performed on the mother colony in the pre-launch phase to identify the microbial taxa present and how their gene expression changes as a result of exposure to radiation and microgravity[6]. Once the payload is retrieved, the same analysis will be performed on the experimental trial and the earth controls, to compare the difference in terms of viability and functionality of the microbial community. Epigenomics and transcriptomics analysis will also be performed on the macroalgae of the experimental trial, pre-launch, and after retrieval of the payload. As for the shrimps, we are exploring ways of performing the same analysis on the same individuals of the experimental trial, pre-launch and after retrieval. Epigenomics and transcriptomics analysis will provide important information on the mutagenic potential of the space environment, but they need to be performed on the same individual, to prevent biases due to random individual mutations. Finding a way to collect sufficient biological material from the shrimps before launch, without harming them, will be a challenge for this project.

IV. Payload Mechanical Structure and Sensors Suite

A. System Requirements

First, the primary constraint for the design of the payload is the volume allowed by Space Application Services (SAS) for any educational mission within the PETRI program. The payload should be a multiple of $10cm \times 10cm \times 10cm$ cubes containing both the experiment, the sensors required, and the onboard computer for storage and data handling. A trade-off is paramount given the small space between the needed hardware and the space required by the experiment itself.

On one hand, the biological payload should be large enough to host the macroalgae, the bacterial culture, and the shrimps, and provide a favorable environment in terms of nutrients for the development of the ecosystem. On the other hand, it needs to accommodate various hardware to answer the science questions of interest. Moreover, the containment vessel should be leakage free first to ensure the validity of the experiment and second to prevent any harm to the astronauts on board. This also means that it needs to survive the launch and return phases without breaking.

Second, in terms of thermal requirements, there aren't any since the payload is inside the ISS where the temperature is already controlled. Yet it is critical to ensure that heat generated by the electrical hardware is easily transferred to the outside of the experiment module without unduly raising the temperature and harming the biological payload. Initial thermal simulations indicate that this should be accomplished passively with the conductive bridge between our payload and ICE Cubes, which has its own cooling capacities.

Finally, as explained before in terms of instrumentation, the main requirement is to be able to robustly characterize the health of the ecosystem non-invasively.

B. Payload Design

The payload design is based on the work of Christian Haughwout's dissertation[8]. Figure 2 provides the exploded view of the biological payload of SCAMPI. Given the previous requirements, the payload has the following dimensions $22.52\ cm \times 10\ cm \times 10\ cm$ and weighs $2.1 kg$. The payload vessel is placed horizontally and consists of a 0.7L sealed cylinder shown at the left in Figure 2. On the other hand, the instrumentation suite and all the supporting hardware are placed to the right. On the lateral side, 4 LED pylons are placed in the corners of the cube around the payload to provide sufficient energy flux to maintain the ecosystem. In the next sections, each sub-module will be presented separately.

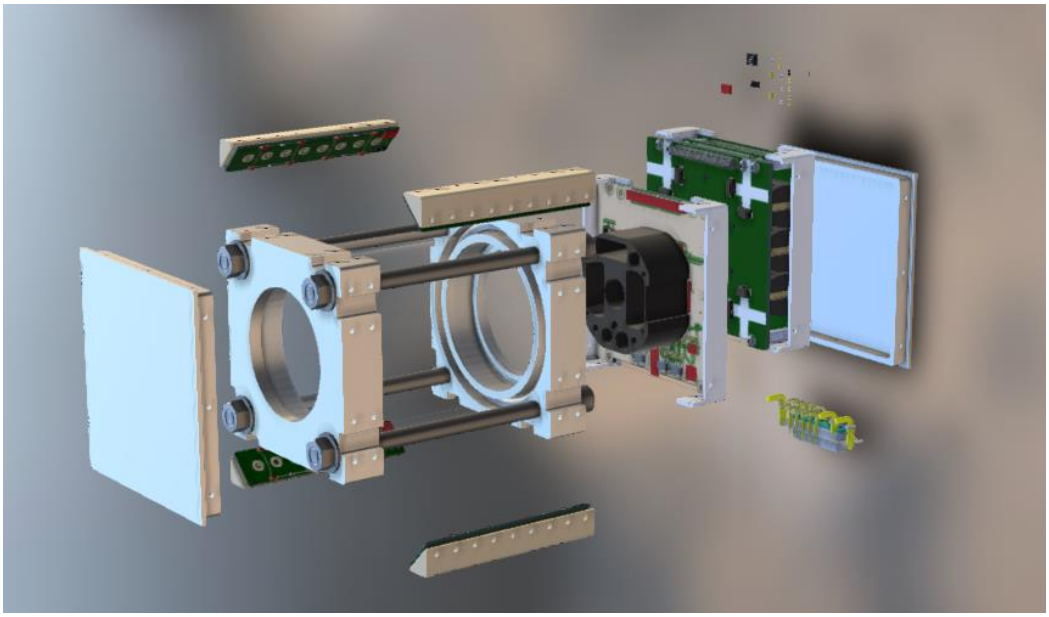

Figure 2. View of the experimental module.

1. *Payload Vessel:*

The payload vessel, shown in Figure 3, is constructed around a polycarbonate cylinder ($R = 88mm$ and $H = 140mm$) that will contain the ecosystem and all the wireless sensors. The choice of material will allow for correct trans-vitro observation whilst enhancing the mechanical resistance and resilience of the container, reducing the risk of shattering or leakage. The container is then kept together by two square blocks of aluminum machined to securely hold the container. The two blocks are then secured together with 4 bars of aluminum that give the payload high mechanical resistance to torque tension and compression. There is some extra space between the container's walls and the aluminum pieces to prevent the plastic from impacting anything in the case of an accidental drop.

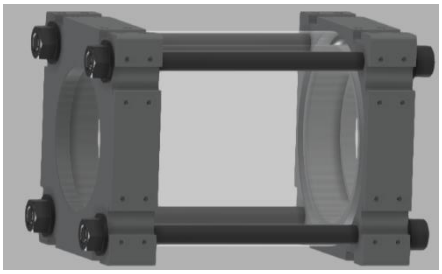

Figure 3. Payload vessel.

2. *Support Structure:*

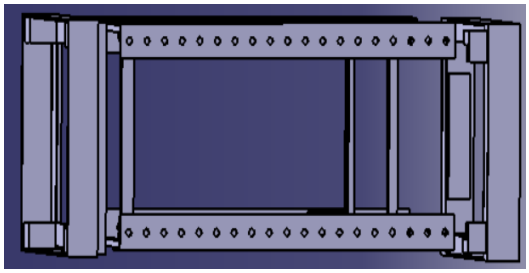

Figure 4. View of the support structure. LEDs are to be embedded in the corner pylons, illuminating the interior.

To hold the payload and provide it with light, a support structure is designed and a CAD rendering is given in Figure 4. The structure will also support the sensors and electronics boards. The support structure is built around four bent aluminum strips with perforations. These strips are to be placed over the corresponding corners of the payload. four plates are then placed between each of the strips and bolted into place. These plates contain the LEDs at a color temperature between 5500K-6000K needed to provide energy to the ecosystem. Cables can also be run over these plates, connecting both sides of the payload. The LEDs are sized to provide a photosynthetically active radiation (PAR) on the order of 60 µmols/m^2/s to the payload measured at the LED surface and are laid out in such a way as to provide isometric lighting conditions to the payload. An aluminum adaptor is then created to provide a floor to the support structure. A similar structure is designed to hold the electronic board over the payload, and all the components are bolted to the metallic strips.

3. *Sensor and electronics board:*

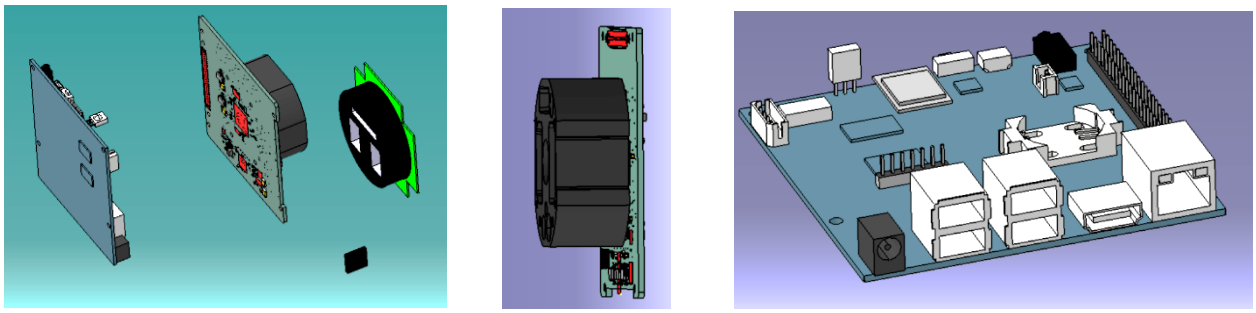

Figure 5. View of the electronics components and boards. Left is exploded view of the custom sensor suite. Center is the sensor suite. Right is the Raspberry Pi.

To observe the different parameters of interest to be measured throughout the experiment, the following sensor suite in Figure 5 is implemented. Table 2 summarizes the parameters measured during this ISS phase and how they will be measured:

Table 2. List of parameters measured during the ISS phase.

Parameters	**How are they measured?**
pCO2	CO2 sensor
pO2	Optical O2 sensor
pH	pH sensor
T	Optical Temperature sensors
Algae population	Chlorophyll fluorometers
Shrimps population	Still image using a visible light camera
Free surface tracking	Videos using a visible light camera
ISS acceleration profile	Accelerometer

Since the time scales of the interactions within the ecosystem are mainly driven by diffusion of the nutrients in the liquid phase and given the geometry of the payload vessel, measurements are conducted every 30 minutes. Finally, to incorporate all the instruments that have been mentioned above, a printed circuit board (PCB) has been designed and included in the cube and a CAD rendering is given in Figure 5. Finally, a motherboard (Odroid) for the external communication and control of the experiment will be placed underneath the PCB.

4. External Case:

To conclude the design, an external casing is created as illustrated in Figure 6. This casing will protect the experiment from external harm and provide a safe-to-handle interface for the operator or astronaut during assembly, testing, and the integration into ISS. The case is built from 5 pieces. Two "doors" comprised of simple aluminum plates will be bolted to the case and two rings will hold the doors and connect with the support structure. One of the rings will also hold the DB13W3P connector needed to be able to exchange data with the ICE Cubes facility during the mission. Finally, a case made from aluminum connects tightly with both rings, completing the structure and adding redundant layers of containment for safety.

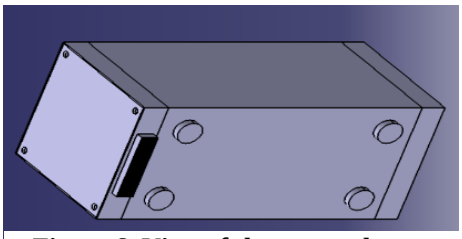

Figure 6. View of the external case.

C. The power budget for the different components/subsystems:

Table 3 gives a preliminary power budget based on the experiment requirements and literature research. This highlights the need for thermal simulations to design appropriate thermal control solutions if needed.

Table 3. Preliminary power budget

Subsystem	Typical Consumption (W)	Maximum Consumption (W)
Controller board	3.5	**4.5**
Lighting	3.5	**4**
Sensors	1.5	**3.5**
Cameras	3	**3**
Total	11.5	**15**

V. Current work and expected outcomes

We are currently developing a mock ecological model and fluid mechanics model in order to compare observations in microgravity of the abiotic factors of the ecosystem and the sloshing mode instabilities with onboard measurements.

A. Aquatic System Modeling

The experimental data will be compared with results from numerical simulations, currently under development and which are mainly inspired by the PISCES-v2[9] model.

PISCES-v2 is a widely-used biogeochemical model for studying carbon and ecosystem processes in marine ecosystems. It is usually used to simulate the interactions between ocean physics, biogeochemistry, and ecosystems. It includes a variety of biogeochemical processes, such as the cycling of carbon, nitrogen, oxygen, and the formation of biomass. It also takes into account the effects of several abiotic factors such as temperature, salinity, and other physical variables relevant to these processes.

To model the ecosystem, the full set of equations included in PISCES-v2 are not needed and the model may be simplified to the following key processes:

- Carbon cycle
  - Air-liquid gas exchange: The exchange of carbon dioxide (CO_2) between the liquid phase and the gas phase in the payload which is influenced by factors such as exchange surface area, temperature, salinity, and biological activity (Henry's Law).
  - Biological metabolism: The exchange of dissolved inorganic carbon by the microalgae and the shrimps through photosynthesis/respiration, and its conversion into organic carbon.

    - Remineralisation: The breakdown of organic matter by heterotrophic bacteria, which releases dissolved inorganic carbon and nutrients back into the liquid phase.
    - Dissolution and precipitation: The dissolution and precipitation of calcium carbonate ($CaCO_3$) onto the aragonite calcium buffer which affects the pH of the liquid phase and thus the concentration of the dissolved CO_2 in water.
- Oxygen cycle
    - Air-liquid gas exchange: The exchange of oxygen (O_2) between the liquid phase and the gas phase by differences in oxygen concentration (Henry's Law). The exchange surface area is an important factor.
    - Biological metabolism: The production/consumption of oxygen by organisms through photosynthesis/respiration.
    - Chemical reactions: The oxidation of organic matter and reduced substances in seawater, which can consume oxygen
- Nitrogen cycle
    - Nitrogen fixation: The conversion of nitrogen (N_2) into biologically useful nitrogenous compounds, such as ammonia (NH_3) or ammonium (NH_4^+), by nitrogen-fixing bacteria.
    - Nitrification: The oxidation of ammonium to nitrite (NO_2^-) and then to nitrate (NO_3^-).
    - Denitrification: The reduction of nitrate to N_2 by bacteria, which removes nitrogen from the liquid phase and returns it to the gas head volume of the aquarium.
- Biomass
    - Shrimps biomass is considered constant
    - Primary production: the growth of microalgae through photosynthesis.
    - Bacterial community growth: This is treated by model growth, grazing and predation of the bacterial community with respect to the availability of the nutrients.

One major assumption in this model is that we assume that the concentrations of iron, silicon, and phosphorus are constant. This is done in order to keep the complexity of the model reasonable, at first.

B. Sloshing Modes Numerical Model

Another interest lies in tracking the free surface between the gas and the liquid in order to predict the formation of bubbles at certain conditions. The geometry of the experiment is involved in the sense that all desirable fluid symmetries are broken in favor of the biology experiment. An accurate treatment of the problem in fluid mechanics requires 3D CFD models which are out of the reach of our group at the moment.

For that reason, we try to adapt the model from the previous work of Veldman et al.[10] in order to test several hypotheses before going to complicated geometry. In their work, Veldman et al. study liquid dynamic in a partially filled axisymmetric cylindrical container in microgravity using a numerical simulation program based on unsteady Navier-Stokes equations.

The model is formulated in terms of pressure and velocity field for an incompressible fluid in order to facilitate tracking the free surface boundary condition. The flow is assumed laminar and all fluid properties are assumed constant (i.e. viscosity surface tension and contact angle) in the container' frame of reference, the equations are written as follows:

$$\nabla . \mathbf{u} = \mathbf{0} \qquad \text{(mass conservation)}$$

$$\frac{D\mathbf{u}}{Dt} = \nabla \bar{p} + \nu \, \boldsymbol{\nabla^2 \mathbf{u}} + \mathbf{F} \quad \text{(momentum conservation)}$$

Where $\mathbf{u}$ is the velocity in the container, $\bar{p}$ is the normalised pressure, ν is the kinematic viscosity and $\boldsymbol{F}$ is an external force that is due to the motion of the container. The set of equation is complemented with a no-slip condition on the container's wall such as:

$$\mathbf{u} = 0$$

Hence, the free surface can be described with the following equation:

$$\bar{p}\, n_i + \nu\left(\frac{\partial u_i}{\partial n_j} + \frac{\partial u_j}{\partial n_i}\right) n_j = 2\bar{\sigma} H n_i \text{ , with i} = 1, 2, 3$$

Where **n** is the normal to liquid surface, $\bar{\sigma}$ is the kinematic surface tension tensor and H is the mean curvature of the free surface between the gas phase and the liquid phase.

The numerical scheme to solve this equation is currently being developed and results of the free surface for different external force profiles will be investigated.

Conclusion

In conclusion, the SCAMPI project is an ongoing research initiative that aims to design and conduct a rigorously controlled experiment investigating the impact of the space environment on an aquatic closed ecological system. Utilizing lessons learned from previous ACES experiments, SCAMPI will control for the effects of launch stresses and investigate the behavioral and genetic consequences on several trophic levels.

The SCAMPI experiment is significant because it seeks to advance our understanding of closed ecological systems and their potential as bio-regenerative life support systems for long-duration manned space exploration. By monitoring the ecosystem with sensors, SCAMPI can help us create a model of nutrient cycling and understand ecological-scale phenomena in space. Furthermore, by studying the impact of the space environment on transcriptomics and epigenomics, SCAMPI could gather valuable information regarding the population dynamics and the mutagenic potential of the space environment.

Ultimately, the success of the SCAMPI project will provide critical information for the development of more advanced and reliable BLSS that can sustain life in space for longer durations, thereby overcoming one of the major obstacles to the advancement of human space exploration

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