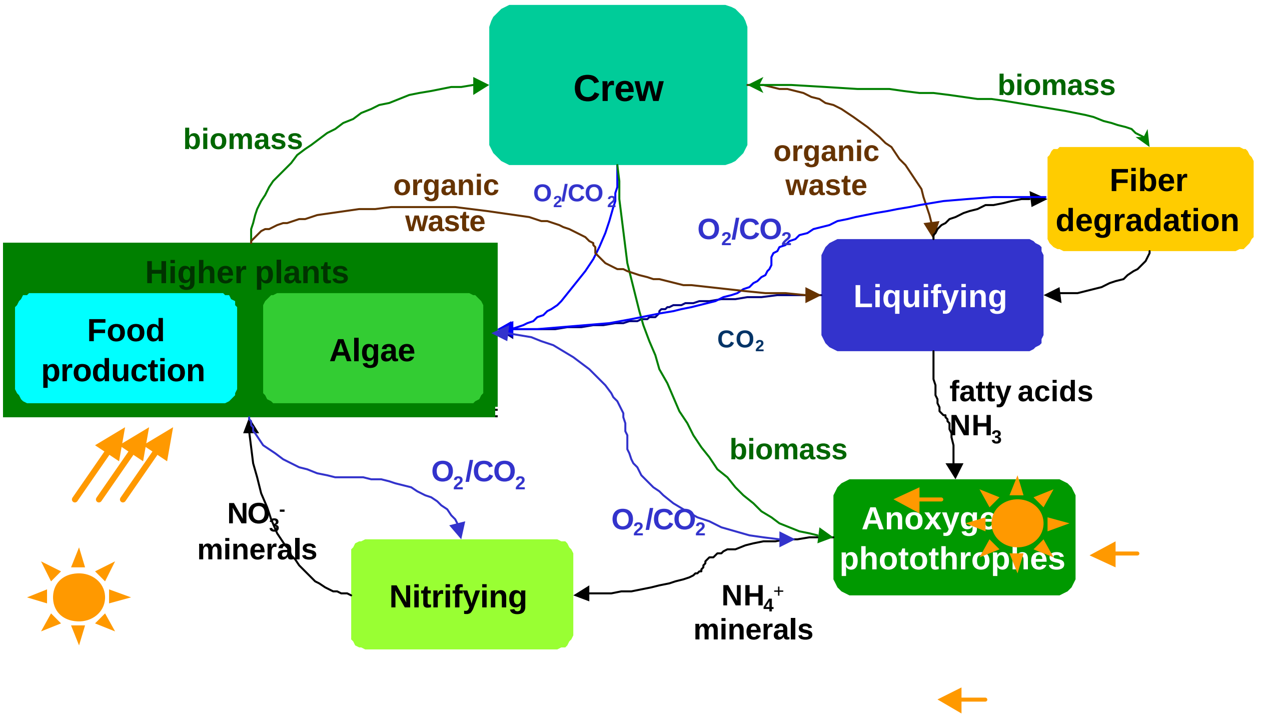
Phases Management for Advanced Life Support Processes

Final Summary Report



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Phases Management for Advanced Life Support Processes
Summary report

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Introduction

There is no doubt that man will explore other bodies in our solar system. In this exploration, Mars is one of the most likely candidates for a manned mission. Outside the Earth-Moon system, Mars is one of the most hospitable bodies for humans and is commonly seen as the only real candidate for future human exploration and colonization. The planet offers the opportunity for in-situ resource utilization, especially as it is clear now that water is available. This provides the appropriate resource materials: air to breathe for the astronauts and fuel for the rovers and the return vehicle.
To enable these missions, a reliable and safe life support system is a necessity. Due to the minimal mission duration, which varies from about 550 up to more than 900 days, physical-chemical life support systems will probably not be sufficient; these will have to be replaced (in part) or complemented by biological or biotechnological systems that mimic parts of the Earth ecosystem by recycling (organic) waste materials and producing food. MELISSA is a good example of such an advanced life support system. MELISSA, which stands for Micro-Ecological Life Support Alternative, is an on-going project, in which ESA cooperates with a number of European and Canadian partners, to develop such closed life cycle. The project started in the second half of the nineteen eighties and it is seen as a potential candidate for the life support system of future manned Mars or Moon settlements.

As MELISSA is evolving, also the necessary hardware has to be studied and mapped. Up to now, the emphasis has been on the treatment of solid and liquid waste streams. In the project on Phases Management for Advanced Life Support Processes, the development of a gas phases management system has been explored. The main goal of a life support gas management system is to provide the crew members with breathing air. For long duration missions, the breathing air should be as close as possible to the earth atmosphere. The levels of the most important components oxygen, carbon dioxide and water need to be in a given range to provide a healthy environment. Furthermore, levels of toxic components or substances with unpleasant smells should be low. For advanced life support systems where living organisms are part of the loop, the gas control system also needs to supply air streams with appropriate composition for each of the organisms or compartments, and deal with gaseous substances produced by the organisms. The control requirements depend on the way the different gas streams from different compartments are tied together in a gas loop. It is clear that the design of such a gas phase management system is a complex task, with many critical points to be solved on the way.

In this project, different gas loops are studied; critical points are identified and candidate technologies are identified for a selection of the critical points. Two critical points where selected based on how critical they are and the technology readiness of the candidate technology. A breadboard is designed, built and tested for the candidate technology of the identified most critical point.

Gas Loop Concepts and Simulation

A typical life support system consists of a crew compartment, a waste compartment where waste and excrements are recycled, a nitrification bioreactor where ammonia from urine is oxidised to nitrates for plant fertilizer, a photosynthetic bioreactor where carbon dioxide is fixated by micro-organisms (e.g. algae) and higher plant compartments for the production of food. For this study, two different crops were considered: rice, which has a relatively long harvest cycle (about 95 days), and lettuce that has a relatively short harvest cycle of about 30 days.

The base case for the PMALS project was a transit flight to Mars. It is assumed that 80% of the food required (about 1 mole C per day) is taken from stock and that 20% is grown on board. Also, half of the waste stream carbon is recycled as CO_2 and half is stored as undegradable fibres (see Figure 1)

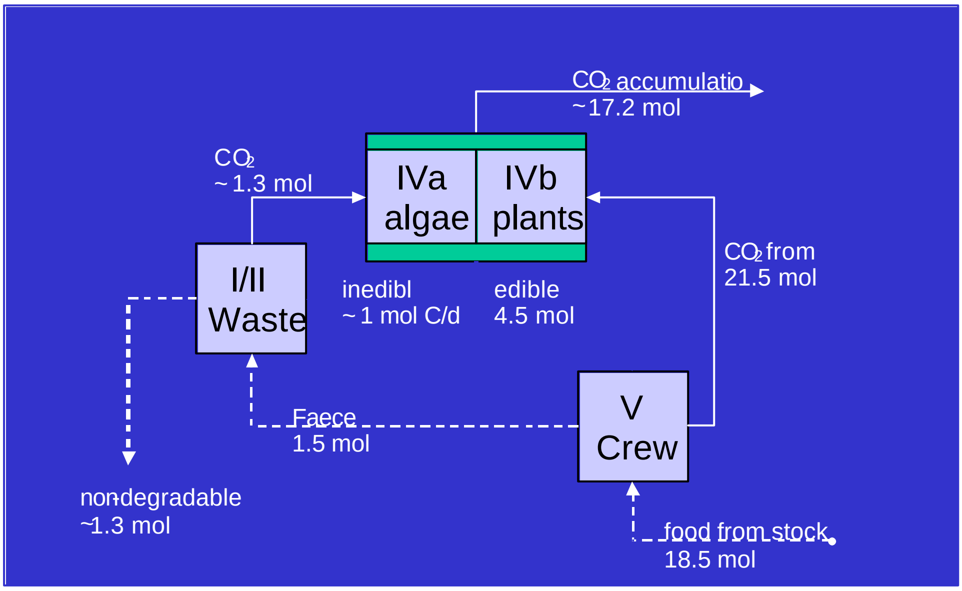

Figure 1. Steady state carbon balance for the base case system. Solid lines represent carbon in the gas phase (as CO_2); dashed lines represent carbon in the solid or liquid phase.

The basic gas loop concepts considered are shown in Figure 2.

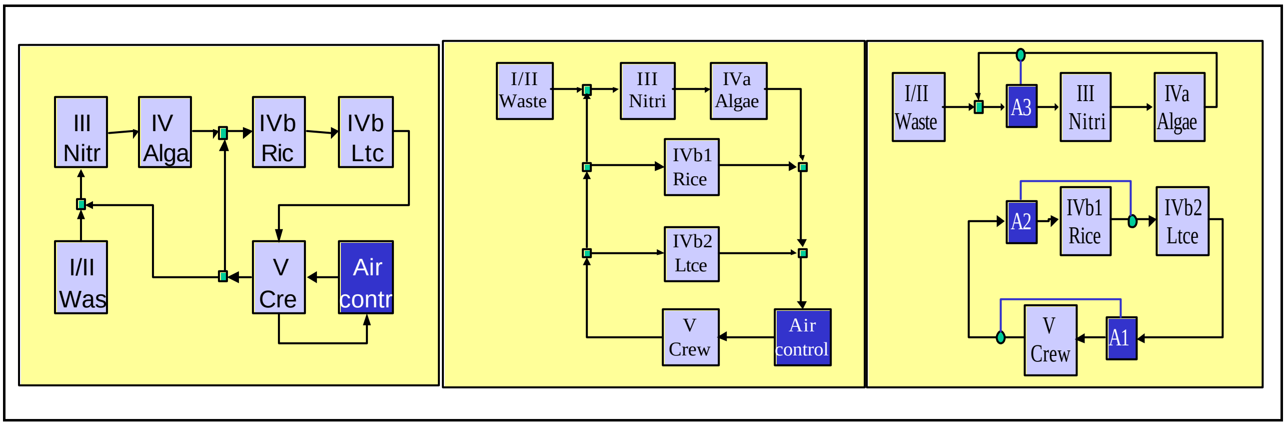

Figure 2 Gas loop concepts considered: (1) in series with bypass to reduce bioreactor air flow, (2) in parallel and (3) separate bioreactor loop. Ltce = lettuce.

Dynamic simulations of the gas loops were performed using EcosimPro software. Figure 3 shows the accumulation of biomass (in the form of two types of nitrifying bacteria, algae, rice and lettuce) in time. The gas composition of the different streams varies with the harvest cycli of the plants and with the daily rhythm of crew activities and light/dark periods in the plant compartments. This is shown for gas loop concept 3 in Figure 4.

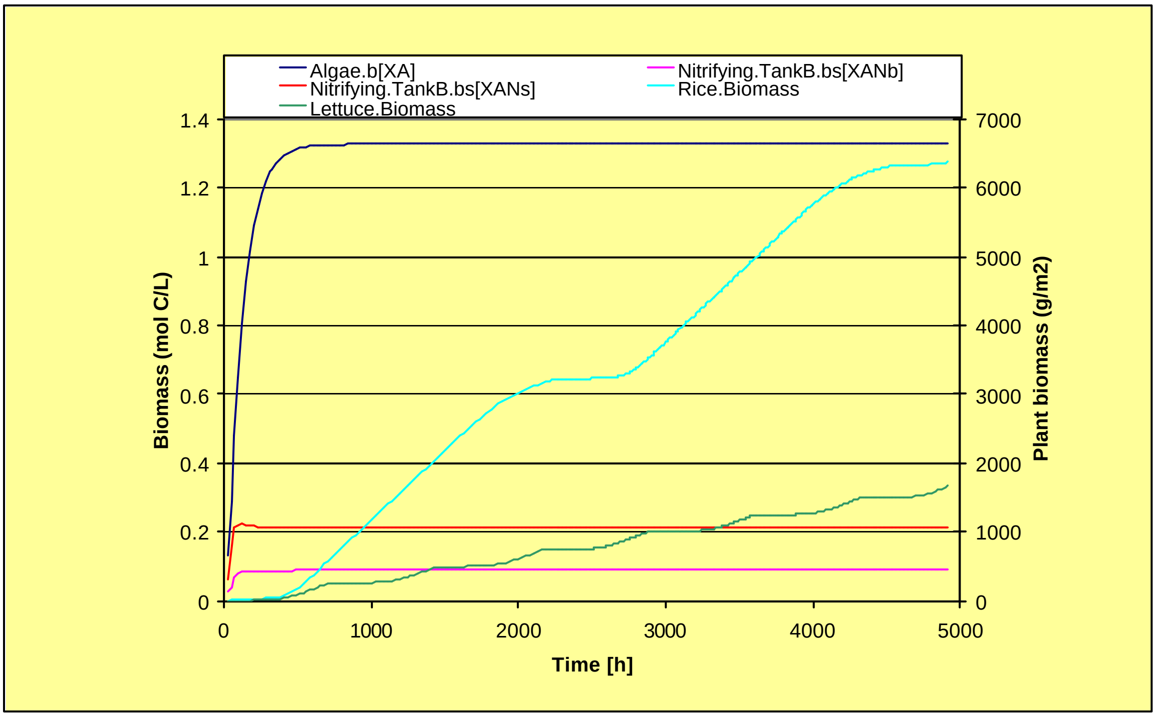

Figure 3. Accumulation in time of biomass in gas loop 3. Results of dynamic simulation of gas loop concept 3 (separate bioreactor loop).

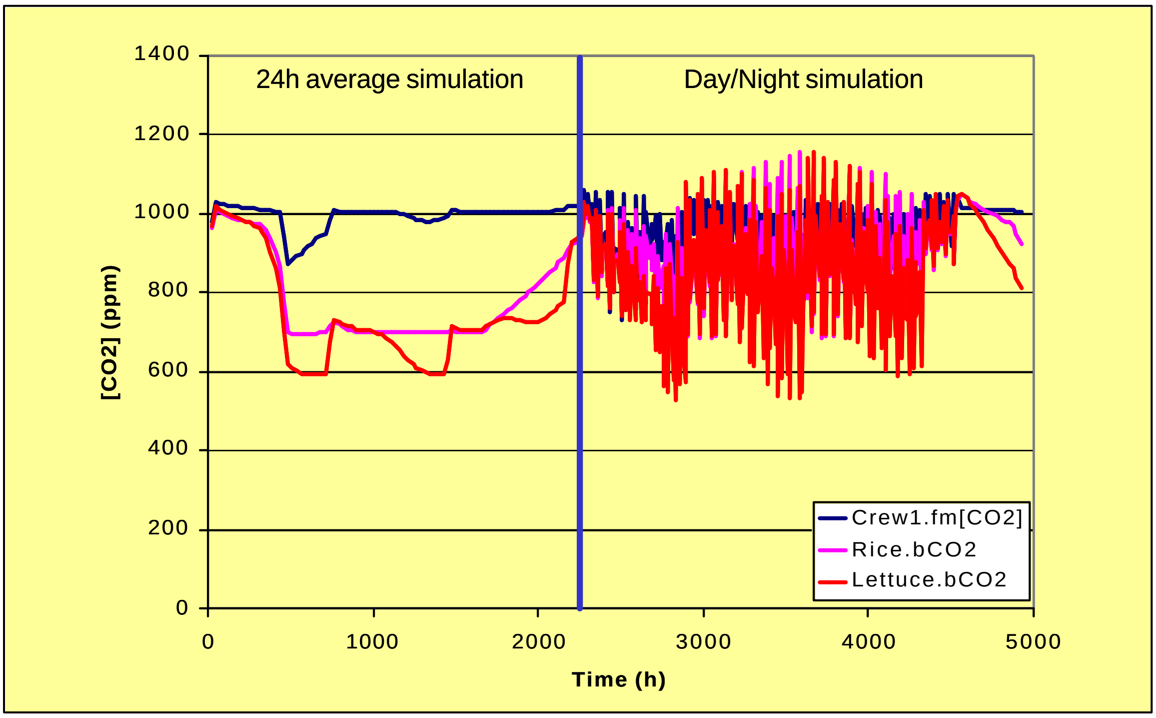

Figure 4. CO_2 concentration in crew and higher plant compartment in time. Results of dynamic simulation of gas loop concept 3 (separate bioreactor). The crew compartment CO_2 concentration was controlled to be <1000 ppm.

The following critical points were identified:

- Reversible removal (recovery) of CO2 from a gas stream to collect CO_2 in the crew compartment and add the CO_2 to a green plant or algae compartment, or to pump CO_2 from a dark plant compartment to a light plant compartment.
- Reversible removal (recovery) of O2 from a gas stream, e.g., remove oxygen produced by the algae from the bioreactor loop and supply it to the crew compartment.
- Removal of NH3 from a gas stream with oxidation to nitrate as a back-up for failing nitrifying compartment.
- Removal of trace components / unpleasant odours
- Removal of ethylene which acts as a plant hormone
- Recovery of water from gas streams.

The first two points were selected for further investigation.

Candidate Technologies and Breadboard Design

For oxygen recovery, Pressure Swing Adsorption is a well-known and established technology, used e.g. in personal medical oxygen supply systems. For the recovery of CO_2 at low concentrations (<1000 ppm) no established technology exists. Several candidate technologies have been identified, among which

- Solid amine adsorption (ARES)
- Membrane gas adsorption (MGA)
- Electrical Swing active carbon adsorption (ELSA)

Of these technologies, the last one, the ELSA technique, promises to be low in energy consumption and efficient, although only few literature data are available. Therefore the ELSA technology was selected for breadboard development. In this technology, CO_2 is adsorbed in a special type of active carbon. Desorption is aided by running an electrical current through the active carbon bed. The advantage of active carbon adsorption is that the adsorption energy is relatively low (much lower than for amine-based adsorbents), so that regeneration of the adsorbent (and recovery of the CO_2) could also be a relatively low energy process. Lab scale experiments have shown that the electrical current increases both the rate and the depth of desorption.

A flow scheme of the breadboard is shown in Figure 5. Air from the crew compartment is compressed to moderate pressures (2-3 bar), dried, filtered and stored in a buffer tank. A mass flow controller controls the flow from the buffer tank; from there it flows through one of the two adsorption columns where CO_2 is adsorbed, and then back to the crew compartment. When one column is adsorbing CO_2, the other is desorbing due to reduced pressure and aided by an electrical current going through the bed (electrical swing).

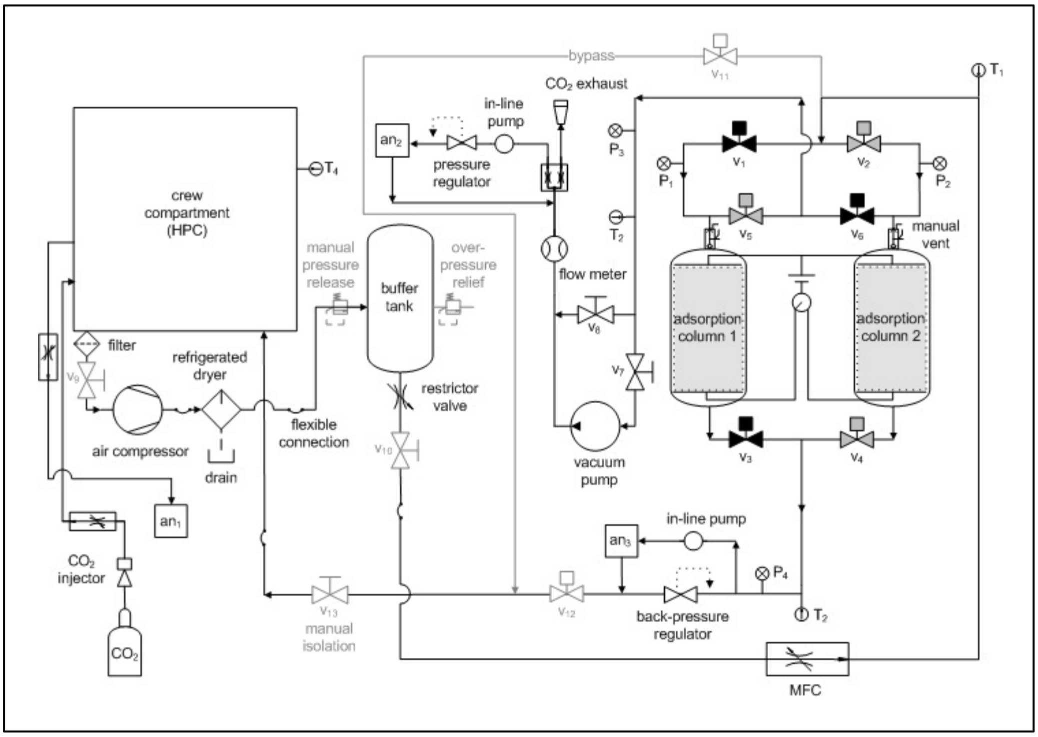

Figure 5. Flow scheme of the ELSA CO_2 recovery breadboard.

The breadboard was designed to recover the CO_2 produced by a single crew member. The layout of the breadboard is shown in Figure 6 and a picture of the overall set-up is presented in Figure 7.

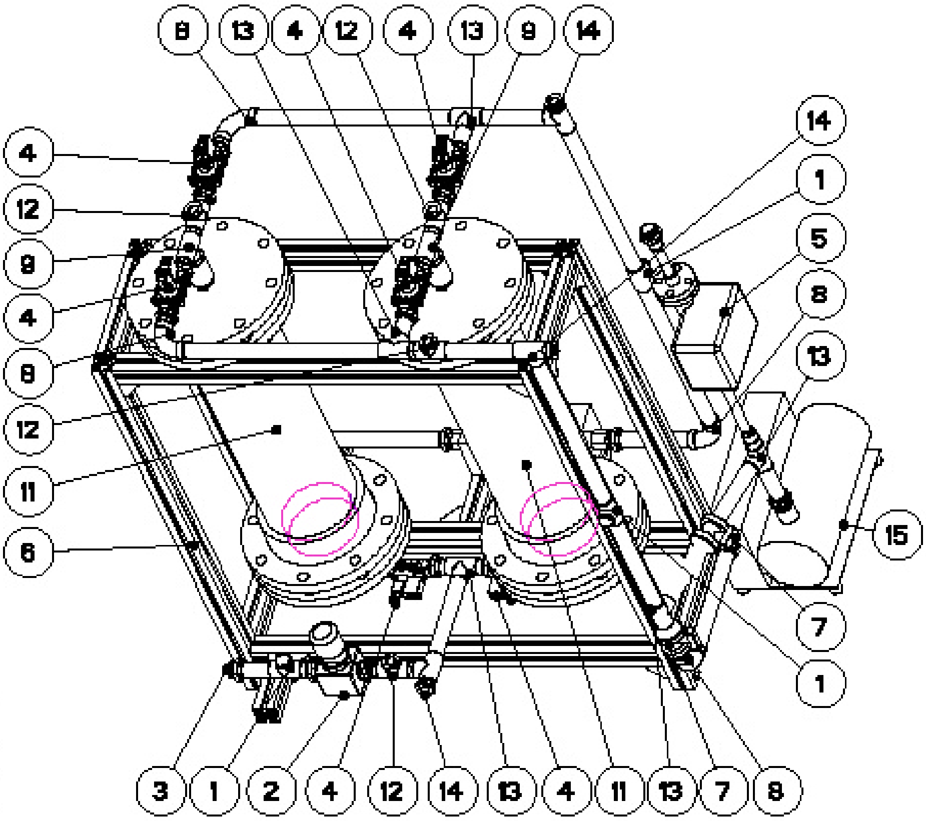

Figure 6. View of the layout of the breadboard. 1: gas analysis connection; 4: automatic valve; 5 CO_2 rich stream flow meter; 11 adsorber column; 15 vacuum pump.

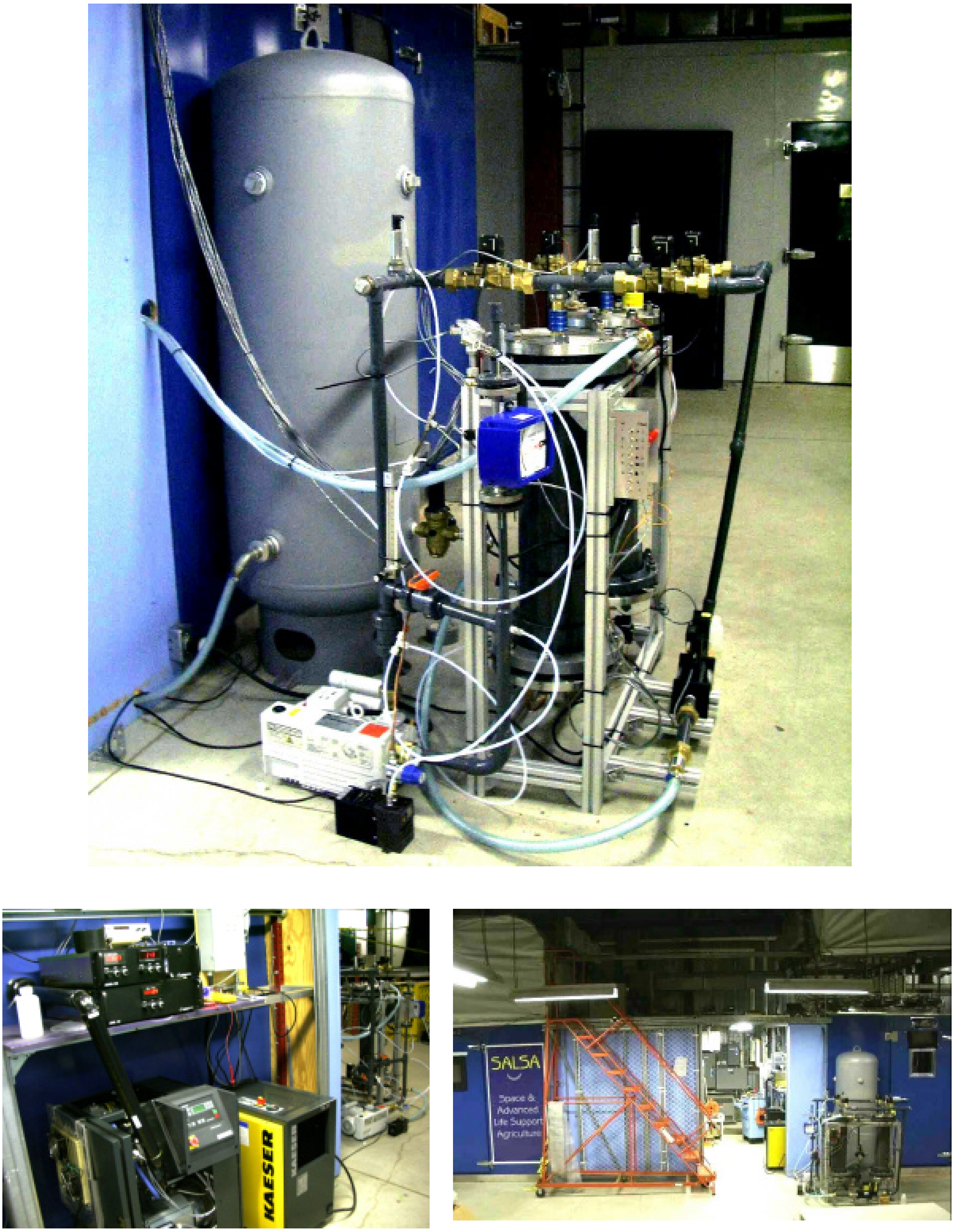

Figure 7. Pictures of the ELSA breadboard at the University of Guelph.

Breadboard testing

The breadboard was assembled and tested at the Controlled Environment Systems Research Facility of the University of Guelph.

Measurement of the breakthrough curve shows that the CO_2 content at the outlet of the adsorber begins to rise almost immediately after switching; this indicates that the performance is limited by the rate of adsorption (transport from the gas phase to the adsorption sites in the pores) (Figure 8).

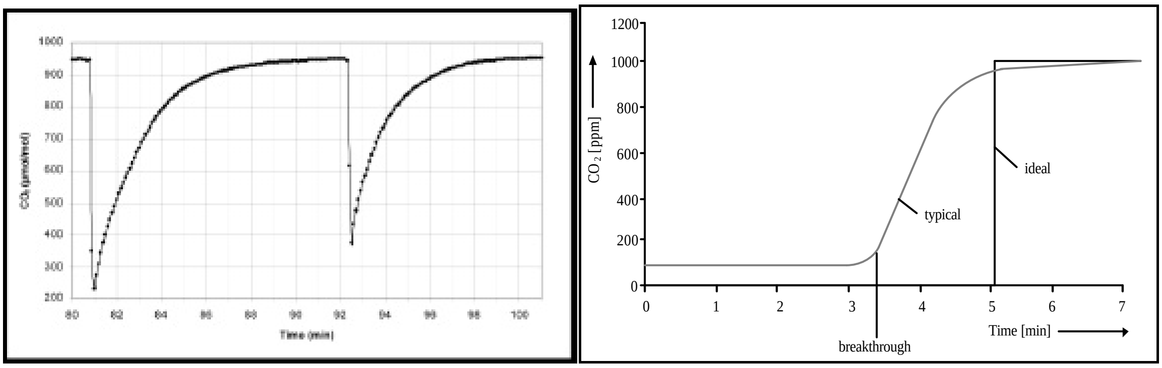

Figure 8. Measured breakthrough curve (left) compared to expected breakthrough curve (right).

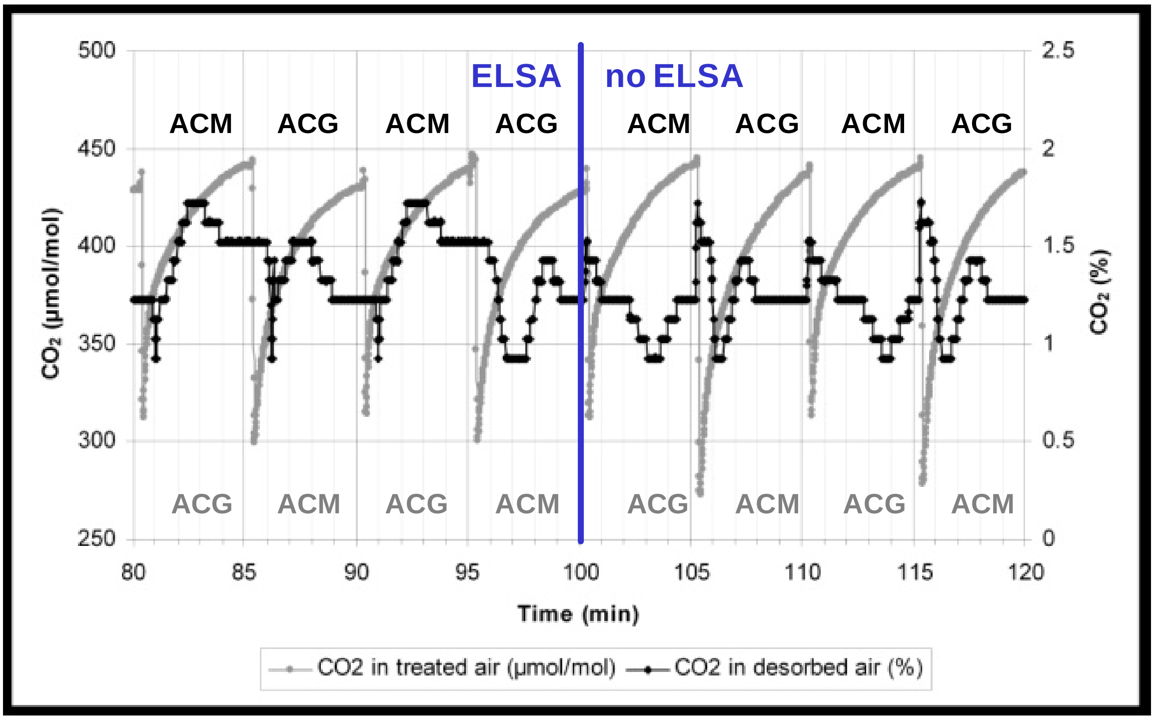

Figure 9. Adsorption and desorption curves with and without electrical current (ELSA) using alternately an active carbon monolith (ACM) absorber and an active carbon granulate (ACG) adsorber.

The curves measured during a test where the columns were switched shows that there is some effect of the electrical current on desorption: the CO_2 concentration in the rich stream (black line) is somewhat higher when electrical current is supplied (left half of graph) for the monolith adsorber (ACM). For the granulate adsorber this effect is not seen since it does not conduct electric current as good as the monolith. It is expected that the electric current supply the heat for adsorption of CO_2 more efficiently in the monolith beds compared to the beds with the unbound carbon granules.

Table 1 shows the amount of carbon dioxide removed by the breadboard from a 700 L/min stream of air for different inlet air CO_2 concentrations. The average amount of CO_2 produced by a crew member is about 850 mg/min. The breadboard removes 18 to 40% of the CO_2 from the incoming air stream, depending on the inlet concentration. However, the production of a single crewmember is only matched at higher concentrations (between 1000 and 2000 ppm).

CO_2 concentration		Adsorption at 0.7 m^3/min		
ppm	mg/min	ml/min	mg/min	ratio
500	632	58	115	0.18
1000	1265	193	382	0.30
2000	2529	516	1021	0.40

Table 1. Adsorption efficiency at different crew compartment CO_2 concentrations.

Conclusions and Recommendations

A working breadboard for low pressure CO_2 recovery has been developed and tested. From the outcome of these tests the following conclusions can be made, that with the present design:

- The electric current (ELSA mode) did not improve the desorption rate considerably although a small positive effect was observed
- It was not possible to reach the required removal capacity for the target crew compartment CO_2 concentrations (<300 ppm)
- It was possible to reach the required removal capacity for crew compartment at CO_2 concentrations of about 2000 ppm
- It was not possible to produce high concentrated (>90%) CO_2 streams
- It was possible to concentrated CO_2 from the order of 1000 ppm to the order of 1 %
- The system showed stable operation
- The system was not sensitive to humidity
- Some O_2 adsorption was observed but stays within the specs.

In conclusion it can be stated that a promising CO_2 adsorption technology has been identified, but the breadboard shows some limitations. Therefore the following recommendations for future work have been defined:

- Further development of the ALS dynamic simulation model
    - Create dynamic model for the demonstrator as a CO_2 controller
    - Review and improve EcosimPro gas loop models
    - Write documentation for EcosimPro gas loop models
    - Include the possibility to simulate minor gaseous components
- Characterisation of ELSA technology
    - Desorption tests using electrical field without current to establish whether the ELSA effect is due to heating (current) or due to electrical potential
    - Desorption tests at higher electrical power (or the same power at reduced bed volume) to determine if a higher heating effect leads to a better desorption
    - Measure effect of air/bed temperature on desorption without electrical current
    - Measurement of bed temperature at desorption with/without electrical current
- Further test and optimization active carbon absorption/desorption via e.g.
    - Small scale adsorption/desorption tests with different types of active carbon
    - Investigate multi-stage adsorption
    - Investigate alternative regeneration and/or purging technologies enabling to increase the output CO_2 concentration level
- Further test demonstrator behaviour
    - Dynamic behaviour
    - Test demonstrator as a CO_2 control system for a simulated crew member (CO_2 injection)
    - Test demonstrator in more realistic circumstances e.g. using animals, and crop.