Diplomarbeit

ILR-RFS DA 25-05

Initial conceptualization of the gas exchange system of the Atmosphere Management System of the Lunar Agriculture Module-Ground Test Demonstrator

Tabea Kayser

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Betreuer:	Prof. Dr.-Ing. Daniel Schubert
Verantwortlicher Hochschullehrer:	Prof. Dr. techn. Martin Tajmar
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Zweiter Gutachter:	Dr.-Ing. Tino Schmiel

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Name des/der Studierenden:	**Tabea Karen Kayser**
Matrikelnummer:	4805713

Thema: Erste Konzeptualisierung des Gasaustauschsystems des Atmosphärenmanagement eines lunar agriculture module-ground test demonstrator

Subject: Initial conceptualizationof the gas exchange system of the Atmosphere Management System of the lunar agriculture module-ground test demonstrator

Motivation:

Motivation: Bio-regenerative life support systems (BLSS) are essential for long-duration missions in space to ensure the crew's nutrition. The German Aerospace Centre (DLR) is developing the Lunar Agriculture Module-Ground Test Demonstrator (LAM-GTD), a BLSS demonstrator, in which the interaction of the subsystems in regards of the greenhouse and plant health is being tested and optimized. One subsystem is the Atmosphere Management System (AMS), which is responsible for circulating and processing the air. A crucial aspect of the AMS is the air exchange between Greenhouse and the habitat. There are two possible ways for the exchange. One is to either exchange the air as it is. The second way is to extract the oxygen from the greenhouse's atmosphere and the carbon dioxide from the habitat's first and then only exchange those purified gases. The topic of this work will be to analyse the possibilities of gas exchange and to perform a trade-off between them.

Aufgaben:

- Literature research on LAM-GTD and its AMS and methods of gas exchange
- Evaluation of suited method for gas separation
- Analysis of oxygen and carbon dioxide flow in habitat and greenhouse
- Comparison of air exchange methods
- System concept development for the methods
- Development of system concept in CAD

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Betreuer: Prof. Dr.-Ing. Daniel Schubert

Gutachter: Prof. Dr.-Ing. Daniel Schubert
Dr.-Ing. Tino Schmiel, ILR, TU Dresden

Ausgabe: 02.06.2025
Abgabe: 20.10.2025

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Ich bestätige hiermit, dass ich die Aufgabenstellung sowie die rechtlichen Bestimmungen und die Studien- und Prüfungsordnung gelesen und verstanden habe.

Prof. Dr. Martin Tajmar	Betreuer	Studierende(r)
Verantw. Hochschullehrer	Professur	

Selbstständigkeitserklärung

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Initial conceptualization of the gas exchange system of the Atmosphere Management System of the lunar agriculture module-ground test demonstrator
selbstständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt sowie Zitate kenntlich gemacht habe.

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Contents

Acronyms

Abbreviation	Definition
ALM	Airlock Module
AMS	Atmosphere Management System
BET	Biomass Estimation Tool
BLSS	Bio-regenerative Life Support System
CAD	Computer-aided Design
CAHEF	Closed Animal and Human Habitation Facility
CDRA	Carbon Dioxide Removal Assembly
CDRILS	Carbon Dioxide Removal by Ionic Liquid Sorbent
CEA	Controlled Environment Agriculture
CEEF	Closed Ecology Experiment Facilities
CHX	Condensation Heat Exchanger
CP	Cold Porch
CO_2	Carbon Dioxide
CPEF	Closed Plant Experiment Facility
C.R.O.P.	Combined Regenerative Organic food Production
CSA	Canadian Space Agency
DC	Direct Current
DLR	German Aerospace Center
eCCC	Electrochemical Carbon Capture
EDEN	Evolution & Design of Environmentally-closed Nutrition-Sources
EPS	Electrical Power System
EVA	Extravehicular Activity
FBCO2	Four Bed Carbon Dioxide Scrubber
FEG	Future Exploration Greenhouse
GTD	Ground Test Demonstrator
HabSim	Habitat Simulator
HEPA	High Efficiency Particulate Air
H_2O	Water
IL	Ionic Liquid
ISECG	International Space Exploration Coordination Group
ISRU	In-Situ Resource Utilization
ISS	International Space Station
LAM	Lunar Agriculture Module
LCS	Lighting Control System
LED	Light-emitting Diode
LP1	Lunar Palace 1
LSS	Life Support System
LTOT	Long-term Oxygen Therapy
MCC	Mission Control Center
MTF	Mobile Test Facility
NASA	National Aeronautics and Space Administration
NDS	Nutrient Delivery System

NM III	Neumayer Station III
O_2	Oxygen
PHM	Plant Health Monitoring System
ppm	Parts per Million
PSA	Pressure Swing Adsorption
rH	Relative Humidity
SA9T	Solid Amine Adsorbent
SES	Service Section
TAS	Thermal Amine Scrubber
TCA	Thermal Control Assembly
TCS	Temperature Control System
UV-C	Ultraviolet C Radiation
Veggie	Vegetable Production System
2BMS	Two-bed Molecular Sieve System
4BMS	Four-bed Molecular Sieve System

Symbols

Symbol	**Unit**	**Definition**
p	kPa	Pressure
$\dot{V}$	m^3/s, m^3/h	Volumetric flow rate

1 Introduction

Interest in exploring our solar system is growing steadily, as is the expansion of human presence within it. The International Space Exploration Coordination Group (ISECG), an association of many national space agencies, expects human exploration of the Martian surface for the year of 2040 [1]. The roadmap for that goal is depicted in Figure 1.

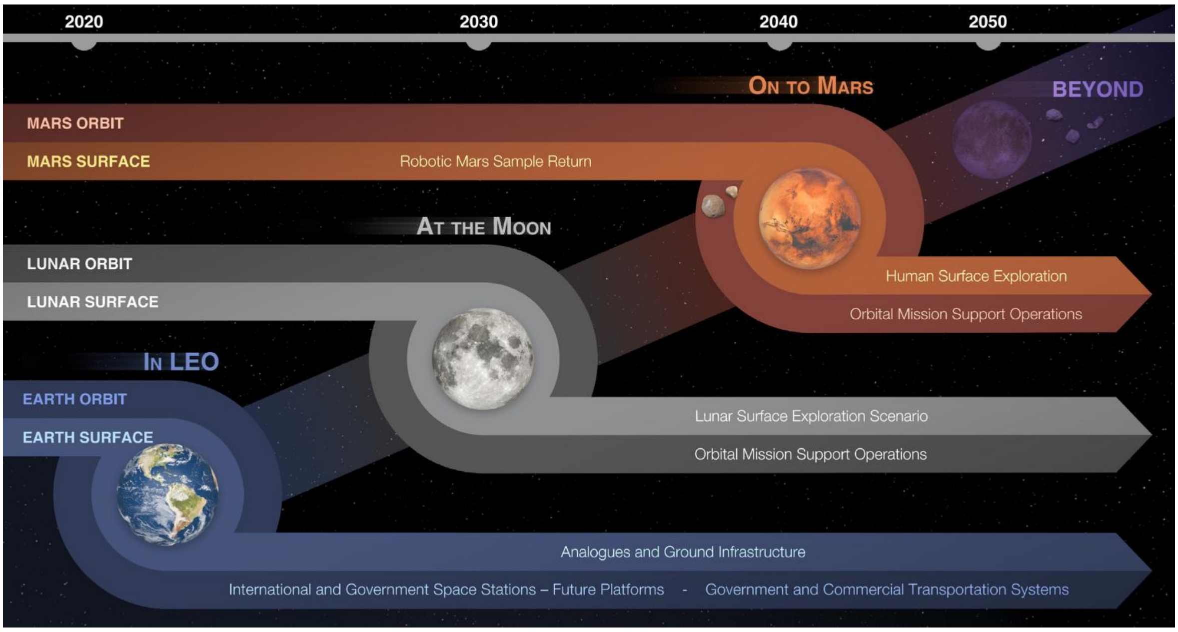

Figure 1: Exploration Roadmap by the International Space Exploration Coordination Group. It is divided into orbit and surface activities for Earth, Moon, and Mars. A timeline indicated the decade in which those activities are expected to happen. [1]

The ISECG lists eight areas of necessary critical technologies, which show the need for improvement when compared to the state-of-the-art technology [1]. One of them is the area of life support and habitability. Research must be conducted on how future crews can achieve survival in space. To this end, the ISECG specifies, among other things, loop closure and reuse of air and water as mandatory achievements to ensure the survival of a human crew. [1]
One possibility to achieve this is through the integration of a bio-regenerative life support system for each mission so that the crew can grow some of their own food and the plants can break down carbon dioxide and produce oxygen. The more space available for edible crops, the less dependent the crew will be on supply transports from Earth and the more sustainable the mission will remain. [2]
To be prepared for this, many research projects are already underway that focus on enabling the crew to live independently of Earth. One such project is being conducted by the German Aerospace Centre (DLR), which aims to develop a Ground Test Demonstrator (GTD) for a subsequent Lunar Agriculture Module (LAM). The first phase of the project involves a terrestrial application for testing purposes, in which a habitat

with a greenhouse is to be built, and the life and daily routine of a crew are simulated. For further verification, it is planned to then convert the Ground Test Demonstrator into an actual habitat on the moon's surface. The project is currently in its initial phase, and the individual subsystems are still under development. [3]
The aim of this thesis is the conceptual development of a gas exchange system for the LAM-GTD's Atmosphere Management System. This system is intended to promote the exchange of oxygen and carbon dioxide between the crew and the crops. Through it, the sustainable use of resources shall be ensured, and it contributes to the closure of the air loop. First, the theoretical principles of Life Support Systems, plant physiology, atmosphere, and the gas exchange strategies are explained. From the four gas exchange strategies that are presented, two will be examined further in the course of this thesis. Afterwards, different case studies regarding atmosphere management or plant cultivation for future off-terrestrial implementation are examined. To implement one of the strategies for exchanging gas, oxygen, and carbon dioxide must be separated from the air flow. To this end, various technical implementation options will be evaluated and compared with one another. One implementation option for the gas separation of oxygen and one to separate carbon dioxide will be selected. Based on this, a CAD model will be created for a system for the gas exchange between the modules of the LAM-GTD. For comparison purposes, another CAD model will be created to show how a gas exchange system can be implemented in a less complex manner. The thesis concludes with a comparison of the two approaches, highlighting technical feasibility and system integration. A recommendation will be issued as to which of the two gas exchange systems can be better implemented within the framework of the LAM-GTD.

2 Theoretical Background

2.1 Life Support Systems

To explain Life Support Systems, the sources 'Spaceflight Life Support and Biospherics' by Eckart and 'Space Stations: Systems and Utilization' by Messerschmidt and Bertrand were consulted and studied. The knowledge required for this thesis is summarised and explained below based on those sources. The sole purpose of a Life Support System (LSS) on board a spacecraft is to ensure the survival of the crew. This includes basic requirements such as a safe atmospheric composition and the provision of water and food. To maintain the atmospheric composition, oxygen (O_2) is supplied, carbon dioxide (CO_2) is removed, and the cabin temperature is kept at a comfortable level. Additionally, some aspects are not directly related to the crew's survival but contribute to their overall well-being. These include waste management. [4]
Furthermore, the crew must be protected from space influences such as radiation, noise, and electromagnetic exposure. Thus, LSS can be divided into five areas of responsibility, as shown Table 3. Each area is usually impacted by the others. [4]

Table 3: Five life support subsystems and their benefits for the crew. [4]

Life support subsystem	**Benefit**
Atmosphere Management	Control, balance and regeneration of atmosphere and composition; control of temperature, humidity, and pressure; ventilation; and contamination regulation
Water Management	Waste water recovery and processing; provision of hygiene and potable water
Food Management	Production, provision and storage of food
Waste Management	Storage and processing of trash and waste (human and biological)
Crew Safety	Fire detection and suppression; radiation shielding

If these requirements are met, the LSS can be further developed. This is necessary for missions that require independence from resupply from Earth. In this case, the crew must be able to provide themselves with sufficient food. To this end, additional biological processes, such as plants, animals, or algae, are added to the LSS. In addition, this should also ensure the (partial) recovery of vital resources. Plants, algae, or microorganisms are used to convert carbon dioxide into oxygen, to do water purification, and to produce food. An LSS like that is called a bio-regenerative Life Support System (BLSS). But adding extra biological compounds increases the complexity of the system significantly, while increasing independence and sustainability in habitats. [5]
The longer a space mission continues, the more difficult it becomes to provide supplies from Earth. In the past, the missions have been short in time and distance, which made it advantageous to either launch the necessary consumables at the mission's start or send the resupply during the mission. If that is not feasible any longer, materials have to be recycled and produced during the mission, or in-situ materials must be resorted to. In the past, water, air, and food were carried on board or resupplied from Earth,

and waste was returned to Earth after the mission. This type of life support is known as an open-loop LSS. [4]

Life Support System operations can generally be categorized into non-regenerative and regenerative types. Operations that do not involve any form of recycling, for example, system monitoring, are classified as non-regenerative functions. In contrast, regenerative functions deal with essential life support resources like water (H_2O), O_2, and food, which have the potential to be reused. Within regenerative systems, a distinction is made between open-loop and closed-loop configurations. Open-loop systems provide regenerative capabilities but do not recover the consumed resources. In these systems, matter continuously enters and exits, with all necessary supplies, such as oxygen, water, and food, being drawn from stored reserves. The amount of resources that need to be resupplied must match the amount used over the course of the mission. Open-loop systems are generally simpler, more reliable, and are already in use in manned spaceflight. But it is important to keep in mind that the resource consumption increases with increasing mission duration and crew size. [4]

In contrast, closed-loop systems strive to recycle the resources that are brought from Earth. To do so, the processing of waste products to recover usable materials is the aim. As the degree of closure increases, the amount of resupplied goods reduces. The advantage of such systems is the transport of equipment and the initial supply of resources only once. This means minimal follow-up shipments are needed to replace non-recoverable materials and consumables. Nevertheless, closed systems have challenges as well, such as lower technological maturity and higher energy and heat management demands. In Figure 2 can be seen how the resupply is influenced if each of the material loops were closed. [4]

Closed-loop regenerative systems can be based either on physicochemical, biological, or hybrid concepts. Hybrid Life Support Systems combine both physicochemical and biological processes. Physicochemical methods include devices like fans or filters. These systems are usually well-understood and tested, compact, and low-maintenance. However, they tend to use a lot of energy and cannot produce food, so they need an outside supply. Plus, solid waste needs to be collected, treated, and stored. Biological or bioregenerative systems rely on living organisms such as plants to produce or break down organic compounds. Although these systems are less mature and more complex, and typically require larger volumes and more maintenance, they hold the long-term potential for sustainable food production in space environments. [4]

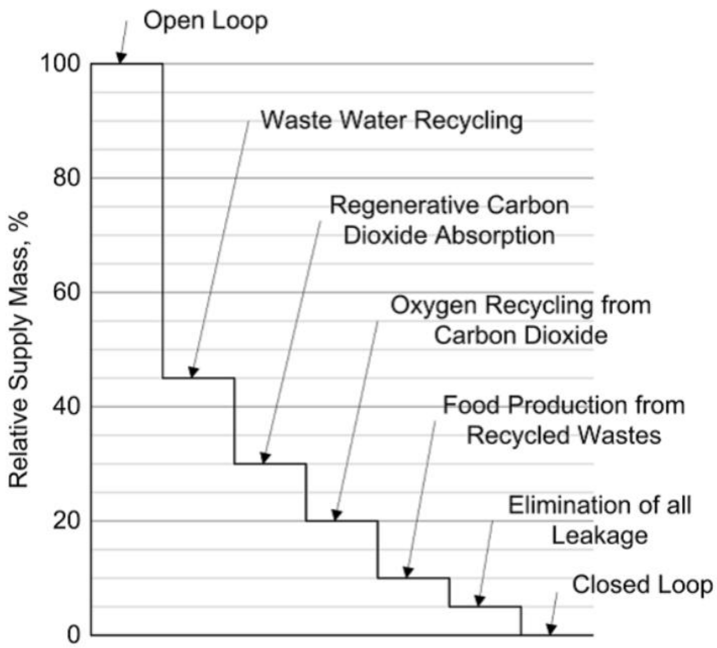

Figure 2: Influence on the resupply, if each of the material loops were closed. [2, 4]

The EDEN initiative researches BLSS. One aspect of the project is the design of greenhouse modules for habitats and planetary outposts, in which the greenhouse modules work in close connection with the physical and chemical Life Support Systems. The aim is to develop plant cultivation systems with a reliably high biomass production that are cultivated in a resource-efficient manner regarding power, water, and nutrients. The interplay between human-plant relationships and isolation was studied in the EDEN ISS project. [6]

2.2 Plant Physiology

Plants carry out several complex physiological and biochemical processes. However, for this work, it is only important to understand the basic principles of two fundamental processes. They are known as photosynthesis and transpiration. This will provide a clear understanding of the plant's role, especially in relation to greenhouses in space.
Through the photosynthesis process, plants convert radiant energy into chemical energy. The process of photosynthesis can be roughly divided into three main steps. The first step is photochemical reactions, in which photosynthetic pigments absorb light, leading to excitation. In the second phase, electrons are transferred through a series of molecules. The final step is the binding of carbon dioxide into carbohydrates. One product of the process is oxygen, which is released into the atmosphere by plants and is necessary for human respiration. Photosynthesis is only conducted when a light source is available. As soon as it gets dark, plants stop doing photosynthesis and the roots begin to produce carbon dioxide, which is released into the atmosphere. [7, 8]
Plants also undergo transpiration. This is a process in which plants lose water vapor through stomata in their leaves. This water loss is caused by the CO_2 that is absorbed during photosynthesis. The roots absorb nutrients and water from the soil. These are

transported upwards through the xylem in the plant's stem. Water diffuses from the cell walls in the leaves through air spaces and through the stomata into the atmosphere. Water vapor diffuses outward from the leaf surface due to the high negative water potential of water vapor in the air. Even minor changes in humidity lead to shifts in this potential. Water in cell walls is subject to negative pressure due to surface tension, which further reduces the water potential locally. [7, 8]
Photosynthesis and transpiration are fundamental processes that sustain plant life. This also preserves the entire ecosystem. Through photosynthesis, plants convert light energy into chemical energy. This process produces oxygen and organic compounds. By producing oxygen and absorbing carbon dioxide, plants are the perfect partners for long-term missions. The symbiosis of respiratory processes by plants and humans can create a balanced air composition. Plants produce the oxygen needed by the crew. They, in return, produce the carbon dioxide that is needed by the plants. Transpiration transports water and nutrients from the roots to the leaves, regulates leaf temperature, and maintains the water balance of plants, which is responsible for metabolic functions. Together, these processes play an important role not only in plant growth and survival but also in the composition of the atmosphere. [7, 8]

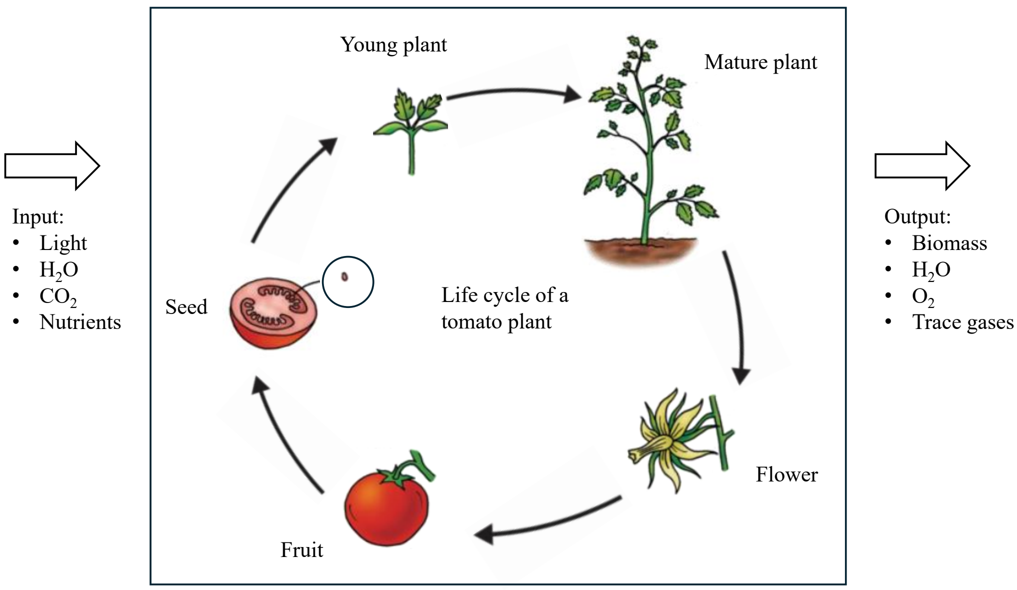

Figure 3: Life cycle system of a tomato plant with the steps of growth. The input for a plant is light, water, carbon dioxide, and nutrients. The output is biomass, water, oxygen, and additional gases. Adapted from [2, 9].

Figure 3 captures the life cycle of a tomato plant to show the importance of the photosynthesis and transpiration process for a human crew.
However, it is important to note that plants and humans have different optimal comfort ranges [2]. Those are given in Figure 4.

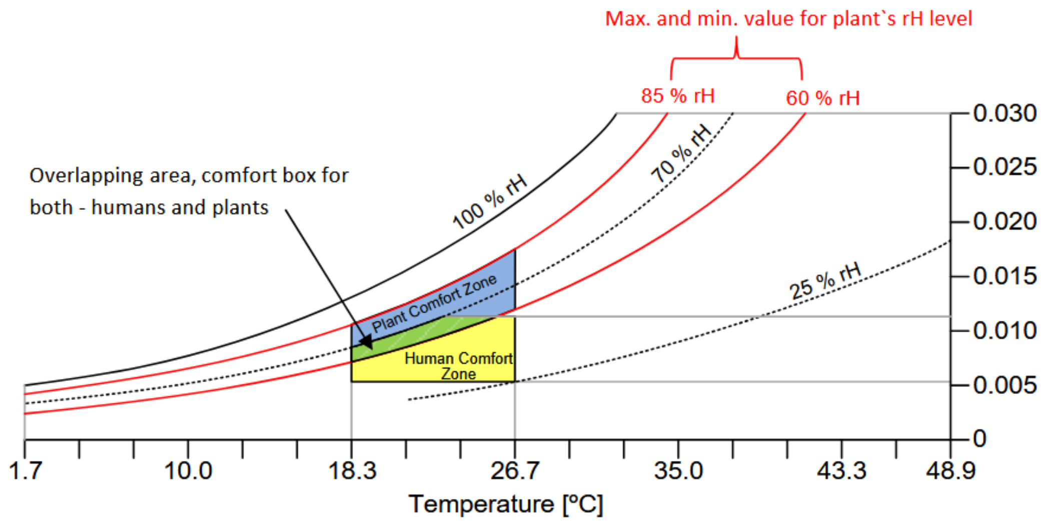

Figure 4: Comfort zones of humans and plants. The green area is the box of shared comfort zones. The values of the humidity ratio can be taken from the y-axis. [2]

Figure 4 shows the parameters for comfort for both plants and humans. Influential are the temperature and the humidity. Plants and humans share the ideal temperatures, but their accepted humidity levels differ. Humans feel comfortable in a relative humidity range from 25 % to 70 % [2, 10, 11], while plants prefer humidities between 60 % and 85 % [2]. Depending on the plant's growth stage, the ideal range lies between 70 % to 80 % [2]. That leads to a very narrow box of shared atmospheric options. [2]
But if possible, both the plants and the crew should be provided with ideal conditions. This helps the crew to perform their tasks optimally and the plants to grow as well as possible. In systems where a greenhouse exists separately from the crew's habitat, this can be achieved with a suitable gas exchange system. The goal here is to limit the exchange of the atmosphere and only allow the exchange of selected gases. In this selective gas exchange, only CO_2 and O_2 are exchanged, i.e., the gases that are necessary for the biological processes in the other room. This work aims to see what gas exchange form is possible within the scope of DLR's Lunar Agriculture Model-Ground Test Demonstrator project. [2]

2.3 Atmosphere Management in Closed Habitats

2.3.1 Atmospheric Requirements

Earth's atmosphere is composed of four layers. The bottom layer, the troposphere, is the layer in which life takes place. This is why the important values that provide information about the atmosphere are utilised from this layer, close to the ground. [4, 5]

At sea level, the atmosphere has a total pressure of p=101.36 kPa [4]. The composition is 78.08 % nitrogen [4], 20.95 % oxygen [4], 0.93 % argon [4] and 0.03 % carbon dioxide [4] with minimum quantities of additional gases . The relative humidity depends on temperature and pressure. [4, 5]
On a space mission, the crew should be able to control the temperature inside the cabin locally, since it influences the physiological and psychological health [5].
Atmospheric pressure in human-rated spacecraft can vary considerably, typically between 20.7 kPa and over 117.2 kPa [11]. Despite the feasibility of high oxygen concentrations, it should generally be avoided due to increased fire risk and concerns about potential long-term lung damage associated with continuous exposure to pure oxygen. Depending on the mission plan and the number of extravehicular activities (EVAs), the atmospheric properties might vary. On the International Space Station (ISS), EVAs are conducted from an environment with 21 % oxygen at 101.3 kPa [11], requiring a prebreathe phase at reduced pressure (70.3 kPa, [11]) to mitigate decompression sickness. This process helps eliminate nitrogen from the body tissues, preventing the formation of nitrogen bubbles that can lead to joint pain, neurological symptoms, or, in extreme cases, death. [11]
However, this method is time-consuming and not ideal for missions involving frequent EVAs. To save time, it helps to prepare the crew for the reduced pressure in the space suit in their everyday environment. This reduces breathing time and risks. Nevertheless, the O_2 partial pressure must correspond to the value at sea level; otherwise, there will not be enough oxygen. This means that the percentage of oxygen in the air must be increased. However, this increases the risk of fire as well. It is therefore necessary to monitor more carefully whether and how many combustible materials are present in the cabin. Current recommendations advocate an oxygen content of 34 % oxygen in the atmosphere at 57 kPa for more EVAs [11]. If no EVAs are planned and the cabin pressure is 101 kPa, an oxygen content of 21 % is sufficient [11], as on the ISS. Some mission segments or vehicles that support occasional or contingency EVA may operate at intermediate conditions around 70.3 kPa with 26.5 % oxygen [11]. As a result, many spacecraft now have to be designed for multiple pressure conditions. This means that all subsystems must be designed to function reliably under the various pressure conditions. However, the carbon dioxide content is also a critical factor in the composition of the cabin atmosphere. Elevated CO_2 levels can endanger the health of the crew. Symptoms such as fatigue and headaches can also turn into cognitive impairment as CO_2 concentrations increase. To improve crew performance and health, the maximum permitted CO_2 concentration was reduced to 0.40 kPa [11] (at a total cabin pressure of 101 kPa) a few years ago. This decision was based on studies that showed that levels between 0.307 and 0.360 kPa [11] already lead to fatigue and mental sluggishness. At levels above this, the crew reported a drop in performance and incorrect execution of procedures. [11]

2.3.2 Gas Exchange Strategies

When looking at greenhouse modules integrated into habitats, the question arises of how to deal with CO_2 and O_2, and how to create a cultivating environment for both the crew and the plants.
The different ideal conditions for plants and humans are shown in Figure 4 and ex-

plained afterwards. Since a certain amount of gas exchange must occur between plants and humans to ensure the survival of both, there are three strategies to facilitate it. These are called the Direct Cabin Air Strategy, the batch breathing strategy, and the Hermetically Sealed-off Strategy. [2]

These strategies are designed to ensure the exchange of CO_2 and O_2 between the crew and cultivated plants. The CO_2 from the crew's respiration enables the plants to photosynthesise, and the resulting O_2 enables human respiration. The plant processes are explained in Chapter 2.2. The exchange is intended to prevent CO_2 from accumulating in the crew quarters and an excess of O_2 from building up in the greenhouse. [2]

The air exchange in these three strategy scenarios is ultimately carried out by the Atmosphere Management System (AMS). The task of the AMS is to continuously treat and condition the air and deal with excess gases. It also ensures the crew's oxygen supply. Since the AMS operates in both the greenhouse and the habitat, two air cycles are created. One is the circulation in the greenhouse, and the other is in the habitat. The cycles are connected to each other via the AMS. This allows the air to be exchanged, controlled, and regulated throughout the entire system. [2]

Direct Cabin Air Strategy In the Direct Cabin Air Strategy, air exchange between the habitat and the greenhouse takes place directly. This means that all the air simply circulates between the rooms without any additional steps, except for purification. The crew's exhaled CO_2 is mixed with the air and fed into the greenhouse, where the air flows through the plants and takes up the O_2 produced by photosynthesis. It is then returned to the crew. However, this means that the atmosphere cannot be regulated independently. Any change in the atmosphere in one module immediately affects the composition in the other module. The humidity levels are therefore the same throughout the entire system. Since the levels in such a scenario must be ideal for the crew, the plants suffer from suboptimal levels. The CO_2 content for the plants cannot be regulated independently of the consequences for the crew, either. To optimise gas exchange, plants can be adapted to the crew's day and night rhythm. This means that the times when the crew's CO_2 emissions are highest overlap with the times when the plants convert CO_2. [2]

Pre-filters and HEPA filters can be used to reduce contamination. The air must pass through these filters before it is exchanged between the modules. This prevents the transmission of bacteria, for example. On the return side, the airstream should either pass through a dedicated trace gas filtration system or rely on the habitat's main air filtration to remove any plant-emitted volatiles. [2]

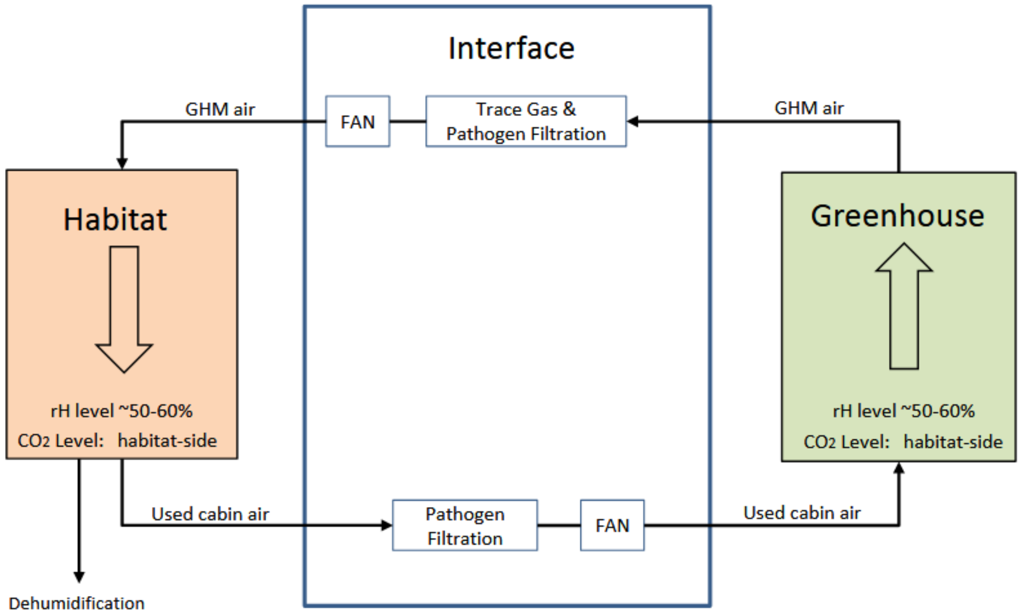

Figure 5: Schematic overview of the Direct Cabin Air Strategy. [2]

Figure 5 shows a schematic overview of this concept. Overall, this interface method is quite simple, involving a continuous air exchange loop between the greenhouse and the habitat. This strategy is not complex and can be simply implemented with a few components. However, its primary limitations are that the humidity and CO_2 levels cannot be controlled independently, both of which are critical parameters for optimal plant and human health. The lack of atmospheric separation might result in conditions that are not ideal for either biological system, especially when humidity or trace gas accumulation is not managed effectively. [2]

Batch Breathing Strategy The batch breathing strategy is a modified form of the Direct Cabin Air Strategy. It allows for elevated CO_2 levels within the greenhouse. Different from the continuous exchange in the direct approach, this strategy has its foundation in periodic gas exchanges between the greenhouse and the habitat. [2]
For this strategy, the air cycles of the habitat and the greenhouse are separate for most of the time. Both function as closed cycles. In the greenhouse, either the plants themselves provide the necessary humidity through transpiration or a humidifier is used. Extra CO_2 is supplied to the plants to optimise photosynthesis. O_2 accumulates in the greenhouse and CO_2 in the habitat. Once certain gas levels are reached, the system switches to breathing mode. Gas exchange takes place in this mode. It is designed like a controlled inhalation and exhalation cycle. The highly oxygenated air from the greenhouse is fed into the habitat. Meanwhile, air rich in CO_2 flows from the habitat into the greenhouse. Once the gas levels in the habitat and greenhouse have been reduced again, the cycles are closed. This exchange should only take a short time. The air now circulates independently again. Once the gas limits are reached again, the next breathing cycle begins. [2]

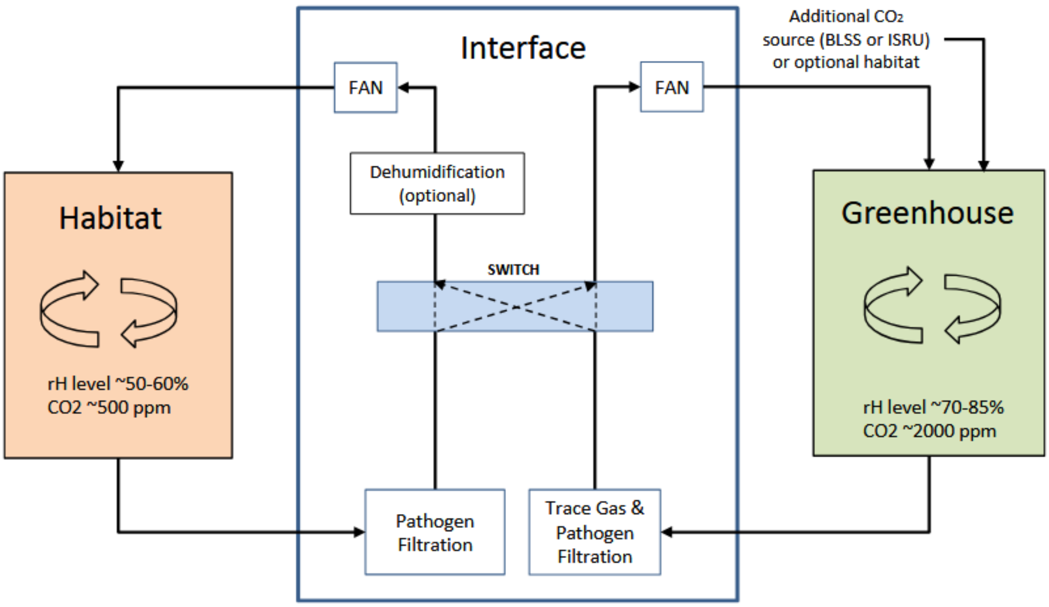

Figure 6: Schematic overview of the batch breathing strategy. [2]

Figure 6 shows a schematic overview of this concept.[2]

Hermetically Sealed-off Strategy The dilemma of the different comfort levels of plants and crew can be resolved by the Hermetically Sealed-off Strategy. This approach aims to implement all comfort parameters. This is to be achieved by ensuring that air flows in the habitat and greenhouse do not come into contact with each other and are completely decoupled. Both air flows function and operate as separate, closed air circulation systems. The gas exchange that takes place is selective and targeted. CO_2 is removed from the air in the habitat and directed into the greenhouse. Meanwhile, excess O_2 is filtered from the air in the greenhouse and directed into the habitat. This does not alter the different conditions that prevail in the greenhouse and habitat. This means that parameters can be selected for the greenhouse that are optimally adjusted to the plants and result in the highest yield in the shortest time. No compromises are necessary for the crew's living quarters either. [2]

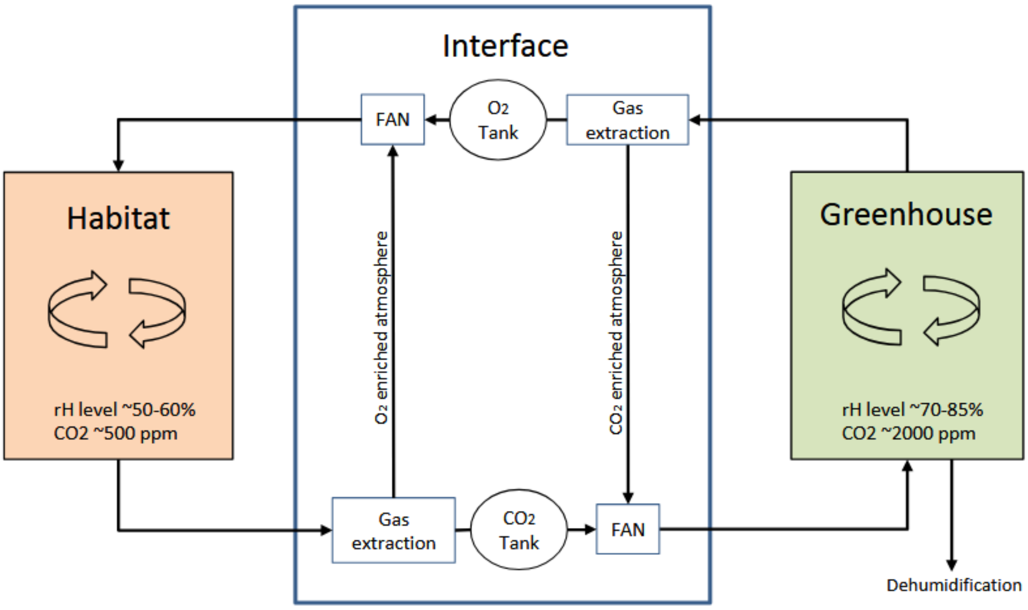

Figure 7: Schematic overview of the Hermetically Sealed-off Strategy. [2]

Figure 7 shows a schematic overview of this concept. The main drawback of this approach is its technical complexity and additional system mass. For the gas separation from the two atmospheres, gas exchange technologies can be employed, which will be explained further in Chapter 4. However, the benefits of independently managed and therefore optimal atmospheres come at the cost of significantly higher infrastructure demands in terms of mass, energy consumption, and operational complexity. [2]

Decentralised Strategy There is another, fourth method of combining plants with habitats. In this strategy, known as the Decentralised Strategy, the plants are cultivated directly in the habitat. Figure 8 gives a schematic overview of the strategy layout. [2]

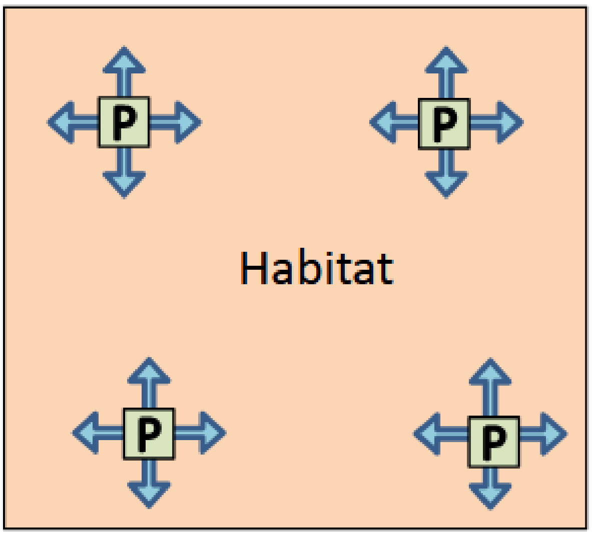

Figure 8: Schematic overview of the decentralized strategy. [2]

This method leads to a constant but uncontrolled exchange of gases. It is only suitable to a limited extent when it comes to large cultivation volumes. The strategy is being used in the Veggie project on the ISS as described in section 3.1.1. This thesis will not examine the strategy in further detail, as the LAM-GTD project framework provides for a greenhouse module that is spatially separated from the crew. [2, 3, 12]

This thesis will focus on the comparison between the implementation of a system that performs the gas exchange using either the Direct Cabin Air Strategy or the Hermetically Sealed-off Strategy. The technical implementation is the same for the gas exchange through the Direct Cabin Air Strategy and the Batch Breathing Strategy, but the regulation and control system is implemented differently. This means that the Batch Breathing Strategy is a bonus option if the gas exchange is ultimately implemented using the Direct Cabin Air Strategy. The choice between the Direct Cabin Air Strategy and the Batch Breathing Strategy can be made relatively spontaneously and at short notice. In comparison, the choice between the Direct Cabin Air Strategy and or the Hermetically Sealed-off Strategy must be made at an early stage, as the requirements for the components, design, and space requirements are very different.
Some form of gas exchange has to occur between the modules. If the gas exchange through the Hermetically Sealed-off Strategy proves to be too complicated for implementation, the gas exchange will be implemented through the Direct Cabin Air Strategy.

2.4 Conclusion

The theoretical principles for understanding Life Support Systems are summarised in Chapter 2. The advantage of biologically regenerative Life Support Systems is that additional biological components are carried along. These can be useful plants, algae or microorganisms. This should enable the crew to live independently of supply missions from Earth. Plants contribute to the material cycle through photosynthesis and transpiration. This enables the regeneration of carbon dioxide and the production of oxygen. In addition, they provide the crew with food that can be produced in situ. The problems arising from the coexistence of humans and crops in a closed Life Support System were also discussed. The central issue is that the environmental requirements of humans and plants only partially coincide. Several gas exchange strategies attempt to address this dilemma. The Direct Cabin Air Strategy and the Hermetically Sealed-off Strategy differ significantly in their approach to ensuring a stable and life-friendly atmosphere. Based on these fundamentals, the following chapters present the research in which the technical feasibility and comparison of these strategies are analysed in detail within the framework of the DLR project Lunar Agriculture Model-Ground Test Demonstrator. The aim is to find out which strategy represents a sustainable, efficient, and technically feasible solution for future lunar habitats.

3 Case Studies

3.1 ISS

One plant-related payload on the ISS is the Vegetable Production System (Veggie). It was launched in 2014 and is still in use. The goal is to add nutritious food to the diet of the astronauts while studying the influence of microgravity on plant growth. [13]
Veggie consumes little energy, has a low transport weight, and can be stored compactly. Thanks to a foldable bellows structure as a wall, it can be packed very small and also raised flexibly. This means that tall-growing crops can also be used. The bellows structure also supports moisture formation and can be seen in Figure 9. The lighting system consists of red, blue, and green LEDs. This covers the spectrum required for photosynthesis. There is also a water reservoir included. The total area for plant growth is small but efficient, making optimal use of the space within the confines of the ISS. [14, 15, 16]

Figure 9: Veggie system with tomato crop from above. Visible are the plant tray and the bellows structure as well. [17]

Because Veggie's gas exchange was designed according to a Decentralised Strategy, the atmospheric composition within the bellows structure is mainly determined by the atmosphere in the rest of the ISS. The temperature and humidity within Veggie can only be controlled to a minimal extent. The implementation of the Decentralised Strategy enables real-time interaction between crops and the ISS atmosphere, making it a good way to study the effect of zero gravity on plant growth. [2, 14, 15, 16]
A wide variety of plants can be grown in Veggie. The focus is on pick-and-eat crops such as lettuce, spinach, Swiss chard, herbs, tomatoes, and strawberries.
Due to the gas exchange approach chosen, Veggie is suitable for researching plant behaviour on a small scale, but it is not suitable for (partially) ensuring the nutrition

of an entire crew. [14, 15, 16]

3.2 Closed Ecology Experiment Facilities

A large test site has been set up in Japan where BLSSs are being developed and tested. It is called the Closed Ecology Experiment Facilities (CEEF). There, in a completely enclosed environment, the requirements for supplying humans, plants, and animals were investigated over longer periods of time. These experiments were carried out on site from 2005 to 2007. The Closed Animal and Human Habitation Facility (CAHEF) and Closed Plant Experiment Facility (CPEF) were used for this purpose, and a crew, plants, and two goats moved into the habitat. The combination of facilities enabled the recycling of air, waste, and water. At the same time, food and feed could be produced. [18, 19]

The CPEF comprised four cultivation chambers. In three of these, the crops were illuminated exclusively by artificial light, while in one chamber, a combination of artificial and natural light was used. A total of 150 m^2 [19] of cultivation area was available. Rice, soybeans, peanuts, sugar beets, vegetables, and herbs were grown there using hydroponics. This combination ensured a balanced diet for the crew and animals. The CAHEF comprised a living area for the crew (123 m^3, [19]) and an animal room (54 m^3, [19]), which was inhabited by two Shiba goats. Environmental parameters such as temperature, humidity, day-night cycles, and the composition of the atmosphere were precisely regulated in both areas. Figure 10 shows a plant chamber with rice cultivation. [18, 19, 20, 21, 22]

An important aspect of the project was the air exchange within the system between CPEF and CAHEF. The oxygen produced by the plants in the CPEF was separated by molecular sieves and then transported to the CAHEF. The CO_2 from human and animal respiration was removed from the air by solid amines. The CO_2 was then fed into the greenhouse. [18, 19, 20, 21]

The water from plant transpiration was sterilised and reused for plant irrigation. Later in the course of the experiments, it was also used as drinking water. The nutrient solution for the plants could be partially regenerated and reused. [18]

Waste processing was further developed during the course of the project. Initially, human excrement and goat manure were dried. From 2007 onwards, an incinerator was integrated, and the CO_2 from the exhaust gases was recovered and used. [18]

The human participants lived in pairs at the facility during the trials. In 2005, two male volunteers aged between 36 and 41 took part in three separate one-week trials. These were later extended, with three two-week stays in 2006 and a series of one-, two-, and four-week stays in 2007. The crew followed a structured daily routine that included plant cultivation, goat care, system checks, data collection, and routine household tasks. Their diet consisted mainly of vegetarian meals prepared from the harvested plants, with the menus changing weekly. Alongside them, both Shiba goats were fed on inedible plant residues such as straw, husks, and leaves. [18]

Figure 10: Rice cultivation in one plant chamber of the CEEF. [19]

In terms of atmospheric regulation, the CPEF successfully supplied the CAHEF with oxygen, while carbon dioxide from respiration and waste decomposition was returned to the plants. Early experiments in 2005 revealed imbalances with an excess of oxygen and a deficit of carbon dioxide. This was due to incomplete waste processing. By 2007, however, improved processes had enabled about 90 % [19] of the carbon dioxide required by the plants to be recovered internally. [18, 19]
Food and feed production also made significant progress during the course of the programme. In 2005, approximately 82 % [19] of the crew's diet (fresh weight) came from cultivated plants; this figure rose to 92-95 % [19] in 2006 and remained at 90 % [19] during the four-week experiment in 2007. The goats were fed entirely on internally produced feed during the second and third experiments in 2005, with self-sufficiency rates of 79 % [19] in 2006 and 98 % [19] in 2007. [19]
The significance of the CEEF experiments lies in demonstrating a step-by-step closure. Starting with food and atmospheric cycles in 2005, expanding to water recycling in 2006 and waste recycling in 2007, the project provided a unique data set on the step-by-step closure of Life Support Systems. It also demonstrates the technical feasibility of maintaining stable carbon, oxygen, and water flows in complex artificial ecosystems. [18, 19, 20, 21, 22, 23]

3.3 Lunar Palace

The Chinese Lunar Palace 365 experiment was a study to test the feasibility of sustaining a closed BLSS over an extended time of operation. The aim was to evaluate system stability. The condition was that the challenges of a long-term stay outside Earth should be simulated. This was achieved through crew changes and unexpected system malfunctions. The experiment was conducted at Beihang University in the Lunar Palace 1 (LP1) facility. LP1 is a fully enclosed ecological research station. The facility consists of two greenhouses and a cabin for the crew to live and work in. The crew cabin was also used as a storage room and waste treatment area. An overview of the facility can be found in Figure 11. The entire facility has a size of 160 m^2 [24]

and a volume of 500 m^3 [24]. An ecosystem with humans, plants, microorganisms, and animals was simulated. The biological components were all interconnected to recycle resources and ensure the stability of the environment. The facility could be sealed almost completely hermetically, with a daily gas leak rate of 0.043 % [25] during the 370-day experiment. [24, 25]
The study also focused on biological processes. Plants produce oxygen through photosynthesis and absorb the carbon dioxide produced by humans, mealworms, and microbial fermentation processes. LP1 covered a cultivation area of 120 m^2 [24], on which 35 plant species were grown. These contributed to the food supply and to regulating the atmosphere. Various cultivation techniques were tested for the plants. Earth-like substrates were used in one plant cabin. These were recycled from solid waste. The plants in the other plant cabin were supplied by hydroponics. In addition, various lighting concepts were tested. Continuous lighting was installed in Plant Cabin I, without night-like conditions. In Plant Cabin II, a varying day-night cycle was set up, changing every 12 hours. [24, 25, 26]
Water treatment in LP1 was carried out using a combination of biological treatment systems. Domestic wastewater was treated with a membrane biological activated carbon reactor. The crew's urine was subjected to rotational evaporation to extract nitrogen and water. The nitrogen was then returned to the purification system. To the water, the transpiration water from the plants was added. It was then reused for drinking water, sanitation, and irrigation. Solid waste, inedible plant biomass, and insect residues underwent microbial fermentation. This process produced CO_2, which was fed into the plant cabins. Yellow mealworms were also bred to provide animal protein and thus contribute to nutritional diversity. [24, 25]

Figure 11: View into a Plant Cabin of the Lunar Palace 1 with a crew member at work. [26]

The Lunar Palace 365 experiment lasted 370 days. It consisted of three phases with two planned crew changes. This meant that the system was pushed to its maximum limits, as eight people were in the cabin at the same time for several hours. This simulated an overload malfunction. In addition, three planned power failures of increasing duration were simulated to test the resilience of the system. The system's material closure rate reached 98.2 % [24]. Oxygen and water could be reused more completely. The urine recovery rate was 99.7 % [24]. The simulated system stress tests show that the BLSS can recover from elevated CO_2 concentrations and other imbalances within 12 to 24 hours. Nevertheless, it should be noted that little to no detailed information about the exact technological mechanisms of atmospheric control has been made publicly available, which limits the possibility of a complete evaluation of the technical approaches used. [24, 25]

Eight volunteers of good health served as crew members during the 370 days in two sets of four. Group I inhabited the facility for the first 60 days and the final 105 days, while Group II stayed for the 200-day middle phase, setting a record for continuous habitation within a BLSS.

The results of Lunar Palace 365 showed that a BLSS can support humans over extended periods and adapt to critical events such as crew changes and temporary system failures. [24, 26]

Food production was successful, while water was fully recycled without external inputs. An analysis predicted an average operational lifetime of over 50 years for the LP1 system. That provided essential insights into system resilience, human factors, and microbial dynamics in closed habitats. [24, 25, 26]

3.4 SpaceX Dragon Capsule

The LSS of SpaceX's Crew Dragon spacecraft provides a habitable environment for astronauts during transport missions to and from the ISS. The development of the Crew Dragon LSS was based on previous experience with the simpler Environmental Control System of the Cargo Dragon (Dragon 1). However, since Dragon 1 is an unmanned transport spacecraft, the Crew Dragon LSS required improved air management, redundancy, and safety. [27, 28]

To ensure a stable environment for the crew, the LSS regulates oxygen levels, removes carbon dioxide, and controls humidity. In addition, contaminants are filtered out, and the set temperature and pressure ranges are maintained. Oxygen is supplied from the gas reserves on board. These are also intended as an emergency resource for space suits in the event of a pressure drop in the cabin. CO_2 is removed from the cabin via lithium hydroxide cartridges housed in the air purification system. Each cartridge contains several absorbent cubes that chemically bind CO_2. Figure 12 shows an exemplary cartridge. [27, 28]

Figure 12: Lithium hydroxide cartridge for CO_2 removal in the Crew Dragon cabin. The cartridge contains multiple cubes absorbing and chemically binding CO_2. [27]

Air regeneration also includes the removal of trace gases and particles. Activated carbon filters absorb chemical contaminants, and a HEPA filter traps fine dust particles. To ensure even distribution of clean air, the cabin has a network of ducts powered by three fans. Only one of them is in operation at any given time to ensure fail-safe operation in the event of two failures. Due to the choice of CO_2 removal method, the system is limited to short-term missions. This is because lithium hydroxide cartridges are used, which are consumables and cannot be regenerated. For longer missions, a regular supply of new cartridges would have to be ensured, making this method impractical to impossible. [27, 28]

3.5 EDEN ISS

EDEN ISS was a project run by the German Aerospace Centre (DLR). The aim was to research plant cultivation technologies for human spaceflight. The methods for producing fresh food under extreme conditions were tested for reliability and validated. Antarctica was therefore chosen as the location for the experiment. This location offers remoteness, isolation, extreme weather and temperatures, small crew sizes, and limited supply options. Antarctica thus has characteristics similar to those of future extraterrestrial missions. A container structure with an integrated greenhouse was brought there. [29, 30, 31]
By operating a greenhouse under Arctic conditions, the project gained valuable insights into resource requirements, system performance, and daily operations. [30, 31, 32, 33, 34, 35]
The greenhouse was built in the Mobile Test Facility (MTF), which consisted of two converted 20-foot shipping containers. Inside was the Future Exploration Greenhouse (FEG), which offered approximately 12.5 m^2 of cultivation area. The MTF was stationed about 400 meters from Neumayer Station III (NM III). Figure 13 shows the MTF on its platform and the interior of the FEG. [29, 30, 31, 33, 35, 36]

Figure 13: Left: The Mobile Test Facility in Antarctica. Right: Future Exploration Greenhouse, with the cultivation area and crops in growing trays. [36]

The crops cultivated ranged from leafy vegetables such as lettuce and spinach to fruit plants such as tomatoes and cucumbers. The focus in selecting the plants was on so-called pick-and-eat plants. These are characterized by the fact that no post-processing is required. LED lamps illuminated the plant trays. The AMS regulated the air composition in the FEG, and air was directed to each tray via air ducts. The health of the plants was continuously monitored and documented via cameras. [30, 35, 37]
Figure 14 shows the subdivisions of the MTF.

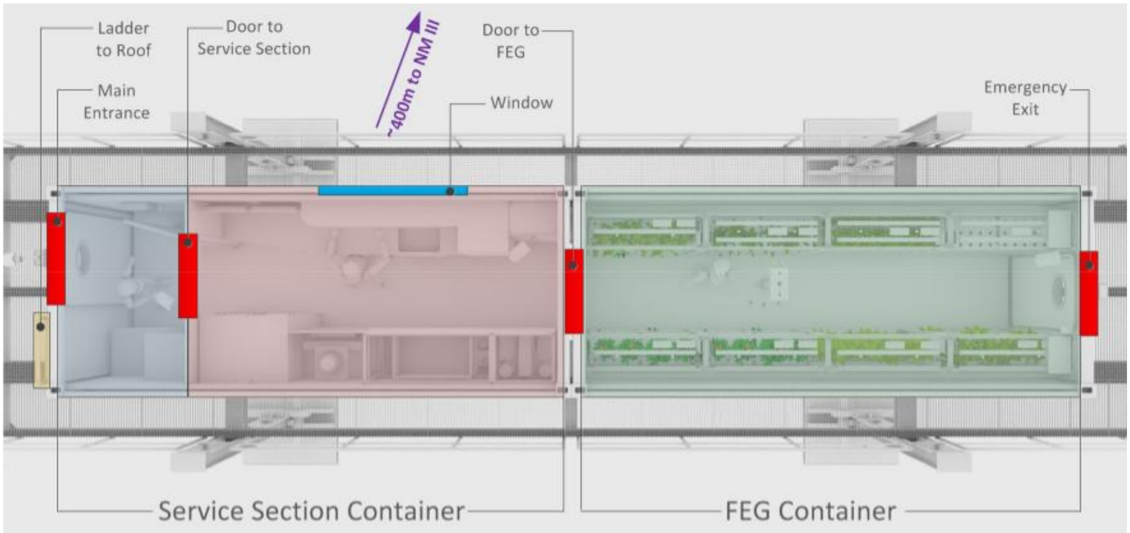

Figure 14: EDEN ISS Mobile Test Facility subdivision. Left: Cold Porch in light blue, middle: Service Section in red, right: Future Exploration Greenhouse in green. [36]

The service section (SES) housed most of the technical subsystems. It also provided workspace for the operators. For this reason, it was equipped with a desk, a sink, and storage space. [30, 31, 33, 35, 37]
The cold porch (CP) served as the entrance area. The crew could change their clothes there and had a storage room. The CP also served to prevent cold air from entering the

SES. The CP was not connected to the AMS, but had emergency heating to maintain safe temperatures. [29, 30, 35]
Several specialized subsystems were used for the project. The temperature, humidity, and CO_2 concentration were regulated by the AMS. This was intended to maintain constant environmental conditions. The AMS could be divided into two subsystems. One regulated the air distribution and treatment in the FEG, the other in the SES. This kept the temperature and humidity within predefined limits. [30, 38, 33, 32, 39]
Eight circulation fans promoted air flow within the FEG itself. Air distribution was achieved via a network of ducts. This allowed the conditioned air from the AMS unit to be directed to specific points in the FEG. The system had eight ducts supplying air to the plants. All were equipped with constant flow valves and distribution louvers to ensure air flow. [35, 39]
The dehumidification system collected the moisture released through transpiration. The air containing moisture flowed through the air-liquid heat exchanger, which is cooled by a thermal system. This reduced the air temperature below the dew point and reduced the water vapour. The condensate obtained was treated with UV-C lamps, a pump, and carbon filtration and returned to the main freshwater tank. The air was then reheated to the desired temperature. The filter system was designed to remove contaminants from the recirculated air. In particular, the UV-C lamp, which was positioned in front of the heat exchanger, served to inhibit the growth of microorganisms in the dehumidifier. [30, 31, 38, 39, 40]
A CO_2 subsystem was used to maintain a carbon dioxide content suitable for plant growth by injecting additional CO_2. This consisted of CO_2 storage cylinders, distribution pipes, and control valves. [30, 31, 38, 39]
The entire AMS was monitored by sensors that transmitted data to a central control system. The target environmental conditions were a daytime temperature of around 21 °C [40] and a nighttime temperature of 18 °C [40]. [40]
Over the years, the EDEN ISS project achieved biomass yields of 268 kg [33] of fresh produce in 2018 and 315 kg [41] in 2021, with cucumbers and tomatoes being the most commonly harvested crops. All plants were grown using hydroponics. [33, 35, 41]
Analyses of the crew's working hours showed that maintenance work took significantly more time than the direct care of the plants. This highlights the importance of reducing the workload for operators on future missions. [31]
What makes EDEN ISS special is the functional tests of the system under conditions that are as close as possible to conditions far away from Earth. This provides proof of technical feasibility. The design is intended to enable a closed cycle, and possibilities for water recycling, conversion of CO_2 into O_2, and waste disposal have been investigated. [30, 31, 32, 33, 42]
The findings from EDEN ISS are already being applied in follow-up projects. The EDEN LUNA team will integrate an updated and improved version of the MTF into the DLR-ESA LUNA facility in Cologne. Important innovations for EDEN LUNA include a robotic system for automated facility monitoring, the C.R.O.P. biofilter for nutrient recycling, and more advanced environmental control strategies. [32]
With regard to the AMS, several improvements identified during the operation of EDEN ISS need to be implemented. As this thesis involves designs and CAD modelling affecting the AMS, they will be listed here for the sake of completeness. All compo-

nents must be easily accessible to the user for inspection and cleaning purposes. In addition, during the operation of the MTF, it became clear that the CO_2 content rises to an elevated but still safe level when people are present in the FEG. In Antarctica, the air could then simply be vented to the outside, but this is not possible for EDEN LUNA. For this reason, a CO_2 scrubber filled with soda lime is used during operation. If the CO_2 content rises above the set value, the scrubber is activated to immediately reduce the CO_2 content in the air. The advantages and disadvantages of this approach will be highlighted in Chapter 4.1.1. [32, 40]
The EDEN LUNA project will also introduce humidity control based on vapour pressure deficit, which is standard practice in terrestrial horticulture. [32]
Looking to the future, the Lunar Agriculture Module Ground Test Demonstrator project aims to develop a demonstrator that already has the structure of a future lunar base. Various subsystems will also be tested, and further plant experiments will be carried out at this base. [32, 33, 38]

3.6 Lunar Agriculture Model-Ground Test Demonstrator

The Lunar Agriculture Module-Ground Test Demonstrator (LAM-GTD) project aims to design and build a ground demonstrator of a habitat for the Moon in order to test technologies for Controlled Environment Agriculture (CEA). This will ensure the food supply for a crew on the Moon. Currently, the project is in an early stage, with the next goal being to fully define the requirements. It is being carried out as part of an international collaboration led by the Canadian Space Agency (CSA) and the German Aerospace Centre (DLR). The LAM-GTD is intended to reduce dependence on supply deliveries from Earth. To achieve this, it must be possible to produce fresh food locally on the lunar surface. This capability is essential for long-term manned missions. For such missions, conventional physical-chemical systems and pre-packaged food alone no longer offer a viable supply strategy. [3, 43]
Beyond the overall objective, the demonstrator pursues a number of specific goals. It aims to increase the technological maturity of greenhouse subsystems, simulate realistic crew operations, define technical requirements for a potential lunar agriculture module, and refine system architectures and operating protocols. In this way, it contributes to the validation of BLSS concepts and ensures that food production can be reliably integrated into a closed habitat model. [3, 43]

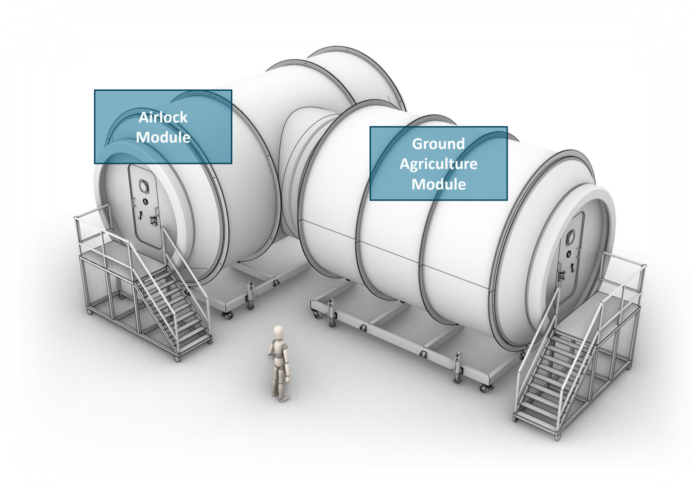

Figure 15: Schematic overview of Lunar Agriculture Module-Ground Test Demonstrator. Highlighted are the Ground Agriculture Model and the Airlock Module. [44]

The Ground Agriculture Module (GAM) on the right-hand side in Figure 15 serves as the primary plant cultivation environment. It offers a cultivation area of 23.5 m^2 and space for 48 individual trays for plant growth. The cultivation process is going to be supported by several subsystems. The Nutrient Delivery System (NDS) supplies the plants with the exactly dosed nutrient solution. The Lighting Control System (LCS) provides light ranges and intensities optimised for different plant species. The Plant Health Monitoring System (PHM) uses cameras and sensors to continuously monitor the growth of the crops and to detect early signs of stress. In addition, a Versatile Assistant robotic arm helps the crew with tasks such as planting, harvesting, and maintenance. That will reduce the workload for the crew and increase the autonomy of the system. To simulate lunar habitats, [3, 36, 43]
The Airlock Module (ALM) on the left side in Figure 15 allows the crew to enter and exit the station. The composition of the atmosphere should not be affected in the process. This module ensures the integration of the greenhouse and habitat by regulating atmospheric transfer. [3, 43, 44]
A Habitat Simulator (HabSim) is located in Figure 15 between the GAM and the ALM. This is only intended for the Ground Test Demonstrator, not for the habitat on the Moon. It simulates the exchange of matter and energy between the ALM and the GAM, which occurs on the Moon as a result of permanent habitation by the crew. Here, the transfer of gases, liquids, heat, electrical energy, and data is controlled and monitored. This enables a realistic simulation of the input and output flows. To simulate lunar habitats, the pressure inside the modules can be reduced to the low-pressure range. As already described in Chapter 2.3.1, this reduces the time required to prepare the crew for extravehicular activities. Table 5 provides a more detailed overview. [3, 11, 43, 12]
The most important subsystems that maintain the function of the LAM-GTD are explained below. The demonstrator's electrical power system (EPS) distributes power from the habitat's main supply to the subsystems. Voltage can be converted from

120 VDC to 28 VDC as required. Critical components supplied with power include sensors, valves, pumps, and relays. [3, 43]
The temperature in the LAM-GTD is maintained by a Temperature Control System (TCS). This dissipates the heat generated during operation. [3, 43]
The AMS monitors and regulates the composition and quality of the air within the LAM-GTD. It encompasses air treatment, circulation, and exchange. The AMS has different requirements from the EDEN ISS AMS, so that new ideas will be incorporated there. [3, 43]
All of the subsystems play important roles in ensuring the health of the plants. To meet one of the project's requirements, to cover 10 % [12] of the crew's caloric needs with crops from the greenhouse, the subsystems have to be precisely coordinated and work together reliably. [3, 43, 12]
The Mission Control Center (MCC) coordinates the monitoring and control of all elements. This allows the demonstrator to be operated with minimal crew effort. [3, 43]
A secondary payload, the C.R.O.P. system (Combined Regenerative Organic food Production), investigates the recovery of nutrients from human waste streams. Urine, in particular, is to be converted into usable fertilizer. [3, 43]

3.7 Conclusion

Chapter 3 discusses various case studies of experiments that focus either on LSSs or on BLSSs specifically. To this end, the various approaches to the development, testing, and optimisation of Life Support Systems are presented. The examples show that BLSSs offer a wide range of technical and organisational implementation options. All the examples discussed show that closing material cycles is of great importance. Water, nutrient, and gas exchange systems are constantly being further developed to guarantee the self-sufficient survival of the crew. The larger test facilities, such as CEEF, Lunar Palace 365, and EDEN ISS, aim to create closed-loop systems in which biological, chemical, and physical processes are combined. The LSS of the Crew Dragon capsule was examined to demonstrate the situation regarding gases in an LSS that has no additional biological components other than the crew.
The key findings from the case studies regarding BLSSs are presented in Table 4.

Table 4: Overview of the information on the case studies on the implementation of BLSSs

	Veggie	CEEF	Lunar Palace 365	EDEN ISS
Goal	Research on plant growth in microgravity	Long-term experiments on closed ecosystems with humans, animals, and plants	Long-term experiment (370 days) on the stability of a closed BLSS	Testing plant cultivation under extreme terrestrial conditions
Type of System	Decentralised Strategy, open coupling to cabin air	Gradual closure of material cycles	Almost hermetically sealed system	Partially closed system
Size of Cultivation Area	0.17 m^2	150 m^2	120 m^2	12,5 m^2
Special Technical Features	Foldable bellows structure, compact and low energy consumption	Gas separation through molecular sieve and solid amines	Different light cycles for plants, insect breeding	Remote implementation under extreme conditions
Relevance for the LAM-GTD	Not scalable for self-sufficient supply	Provides important data on complete cycle closure and human-animal-plant interaction	Proven long-term stability of closed systems	Demonstrates real operation under conditions far from Earth

The LAM-GTD ties in with these developments. It is planned to first develop a modular demonstrator for terrestrial validation, followed by a system for the lunar surface. The findings from previous research projects and experiments will be incorporated into this project. The goal is to enable a stable, self-regulating atmospheric composition within the modules. At the same time, a part of the crews nutrition is to be provided by the BLSS. The case studies provide practical experience that is incorporated into the design and optimisation of the LAM-GTD's Atmosphere Management System and contributes to the assessment of its feasibility. This helps to evaluate the gas exchange strategies introduced in Chapter 2 in the following chapters.

4 Trade-Off Analysis: Gas Separation Technologies

This chapter introduces various gas separation technologies that are used to separate either CO_2 or O_2 from the air stream. These technologies are required to implement a system for the gas exchange through the Hermetically Sealed-off Strategy. The technologies are analysed, evaluated, and compared with each other. Subsequently, the most suitable technology for the CO_2 separation and the most suitable technology for O_2 separation for a potential implementation in the LAM-GTD are determined.

4.1 Carbon Dioxide Separation

The introduction of living organisms into a closed system leads to a change in the atmosphere within that system. For example, the respiration of the human crew leads to the consumption of oxygen and the production of carbon dioxide. If this process is not actively counteracted, there is an increased risk that the O_2 content of the air will fall below the permissible level. This, in turn, can cause the CO_2 content to reach dangerous levels. To prevent an increase in CO_2 content, there are various carbon dioxide removal technologies, some of which have already been used in submarines or on the ISS and previous space missions. Beyond reducing CO_2, gas separation techniques can also be used to extract oxygen, facilitating the development of increasingly closed Life Support Systems. The integration of plants into a closed environment illustrates this approach. Plants use the CO_2 exhaled by the crew during photosynthesis to produce oxygen, which in turn supports the crew's respiration. [2, 5, 11]
To ensure optimal growing conditions for the crop, it may be advantageous to separate the atmosphere in the crew quarters from the air in the greenhouse. Targeted gas exchange can be used to transport only the gases that are beneficial for the respective area. That means that, for example, CO_2 is sent into the greenhouse and O_2 into the crew's living quarters. This exchange can be achieved and optimized using various gas separation processes. Theoretically, it can also be used for the general reduction in gas volumes, as is done on the ISS. The separated CO_2 is then vented aboard. That is not the goal for LAM-GTD, since there are biological processes that need those gases. The gas separation solutions include the use of chemical sorbents such as calcium hydroxide (soda lime) and lithium hydroxide, as well as molecular sieves, solid amine sorbents, membrane-based technologies, and electrochemical processes. These techniques enable efficient control of atmospheric gases. This improves the sustainability and safety of closed ecological systems. [2, 5, 12]

4.1.1 Calcium Hydroxide and Lithium Hydroxide

One way to separate CO_2 from the air is to use calcium hydroxide (soda lime) or lithium hydroxide. To do this, the air stream is passed through a container containing the filter substrate. The substrate can be either soda lime or lithium hydroxide. The substrate can be used in two forms: either in pellets or as a powder. The CO_2 present in the air stream reacts with the substrate and is thus chemically converted. One of the end products of the chemical reaction of CO_2 with calcium hydroxide and the chemical reaction of CO_2 with lithium hydroxide is water, which can be reused. Another advantage is the simple configuration and effortless operation. The disadvantage of this method of reducing the CO_2 content is that the CO_2 is chemically bound by the reaction, and there is currently no way to reuse the materials. This leads to increased disposal and replenishment costs. Thus, dependence on replenishment from the earth is maintained. [5, 45, 46, 47]

Figure 16: Top: CO_2 Scrubber by Atlas Scientific. Bottom: soda lime pellets used for Atlas Scientific CO_2 Scrubber. This Scrubber will be used in the EDEN LUNA project. [47]

It should be noted that two previous American missions that used lithium hydroxide for air regeneration were Mercury and Space Lab. The EDEN LUNA project will rely on the soda lime-filled CO_2 Scrubber by Atlas Scientific, shown in Figure 16, to reduce the CO_2 content in the air. As mentioned previously, the method is also used in the Crew Dragon capsule by SpaceX (Chapter 3.4). [5, 28, 45, 46, 48]

4.1.2 Molecular Sieves

The use of molecular sieves in combination with solid adsorbent zeolites as sieving material is another process that facilitates the removal of carbon dioxide from the ambient atmosphere. The material used for molecular sieves is zeolite. Its adsorbent properties make it possible to remove CO_2. The zeolite material is filled into adsorption beds through which the air stream is pumped. The CO_2 molecules remain in the adsorption bed, while the air stream at the outlet of the bed contains a negligible amount of CO_2 molecules. However, the proportion of CO_2 molecules increases steadily with increasing exposure. After a certain amount of air has flowed through the bed, the zeolite material is saturated and can no longer absorb any more CO_2. The air supply must then be interrupted and the adsorption bed desorbed. To do this, the temperature is increased and the bed is placed under vacuum. The air flow that then leaves the bed mainly contains CO_2. Due to the desorption method, this process is also known as pressure and temperature swing adsorption. The CO_2 released from the zeolite beds

during the desorption process can either be vented into space or stored for reuse. [5, 49, 50]
To ensure continuous carbon dioxide removal, two beds must be used. These alternate between adsorption and desorption modes. This concept is known as a two-bed molecular sieve system (2BMS). [5]

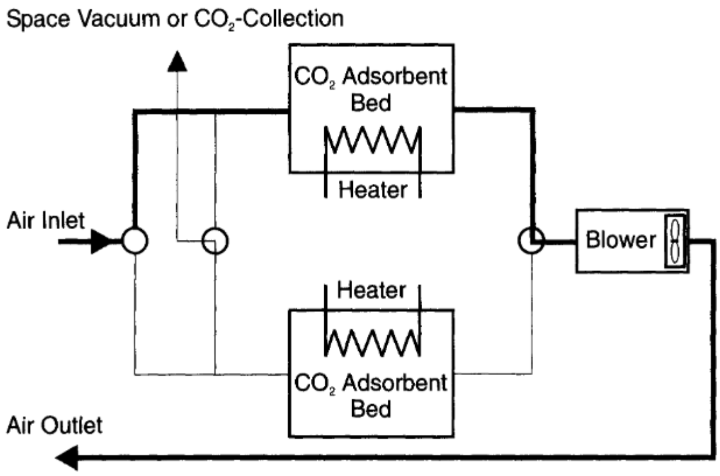

Figure 17: Schematic representation of a two-bed molecular sieve for removing carbon dioxide from the cabin air in a closed system. [5]

Figure 17 illustrates the structure of a 2BMS. The configuration consists of two beds filled with zeolite (the upper one in the adsorption phase and the lower one in the desorption phase), heating devices for desorption, and a fan that maintains the air flow and returns the air purified of CO_2 back into the cabin. [5, 49]
Zeolite tends to bind water. If air humidity were to enter the bed, the adsorption capacity of zeolite with CO_2 would be inhibited. To counteract this, desiccant beds can be installed in front of each zeolite bed. This removes water vapor from the air before it is pumped through the adsorption beds. This concept, which includes desiccant beds in addition to the two zeolite beds, is known as a four-bed molecular sieve system (4BMS). [5, 49, 50]

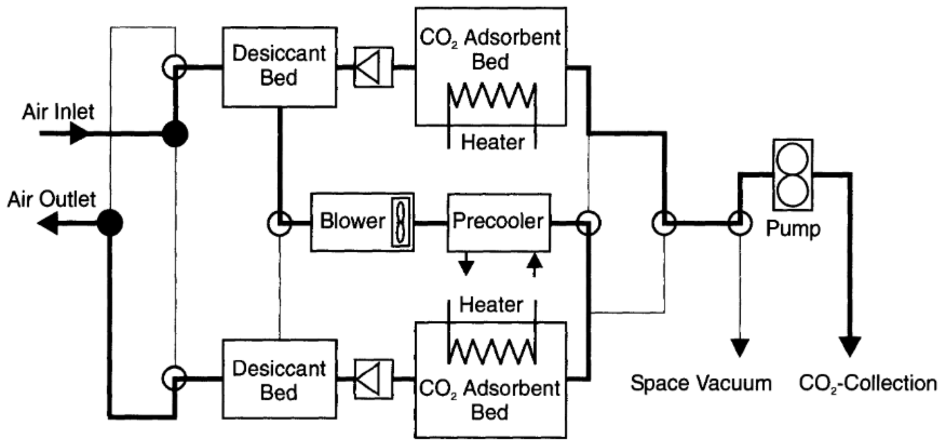

Figure 18: Schematic representation of a four-bed molecular sieve for removing carbon dioxide and humidity from the cabin air in a closed system. [5]

Figure 18 shows an example of the schematic structure of a 4BMS. After entering, the cabin air first flows through a desiccant bed, where the water vapor is removed (the upper one in Figure 18). The dried air then enters a pre-cooler and then an adsorption bed (the lower one in Figure 18). A fan drives the air flow through the beds, while the pre-cooler and heaters regulate the thermal conditions during the various operating phases. The desorbed gases are extracted by a vacuum pump and either discharged into space or to a designated storage location. [5, 49, 50]
The main advantage of CO_2 separation using molecular sieves is its reliability and continuous abrasion process. The main disadvantage, however, is the high energy requirement for heating the beds in desorption mode. [5, 49, 50]
The removal of carbon dioxide using molecular sieves was already used in the American Skylab mission. It is still used today on board the ISS in a system called the Carbon Dioxide Removal Assembly (CDRA). During the operation of the CDRA system, it was discovered that the zeolite pellets produced fine dust. This dust caused problems with the valve seals and increased pressure losses through the adsorption beds. This led to research into more modern technological solutions. For this reason, another molecular sieve system called the Four Bed Carbon Dioxide Scrubber (FBCO2) was installed on board in 2021. It is intended to support the CDRA and eventually replace it. It incorporates several innovations, such as improved materials. These are to be tested and validated. [5, 48, 50, 51, 52]

4.1.3 Solid Amine Sorbents

The separation of CO_2 molecules from the air also occurs passively using solid amine sorbents, similar to molecular sieve technology. However, in this technology, the beds through which the air is passed are filled with solid amines. The CO_2 present reacts with the amines. The moisture present in the air stream acts as a catalyst. This promotes and enhances the reactivity of the amines with the CO_2. With this technology, too, the beds have a CO_2 absorption limit. After this limit is reached, the beds must

be desorbed. This also requires a vacuum and elevated temperatures. Multiple adsorption beds can ensure uninterrupted CO_2 separation. After the desorption process, the removed carbon dioxide can either be reused or released into space. One advantage of this method is that the amine can be reused. This means that using this technology makes for reduced dependence on subsequent deliveries. A specific advantage over molecular sieves is the lower temperature required to desorb the beds and the reduced energy consumption resulting from the fact that the water content does not first have to be removed from the air flow. One disadvantage is that energy is required to heat the beds and create a vacuum, and the system with the beds is more space-consuming and complex than, for example, a solution with soda lime. [5, 53, 54, 55, 56]
Currently, a system called Thermal Amine Scrubber (TAS) is used on the ISS to adsorb carbon dioxide from the cabin air. That is shown in Figure 19. [57]

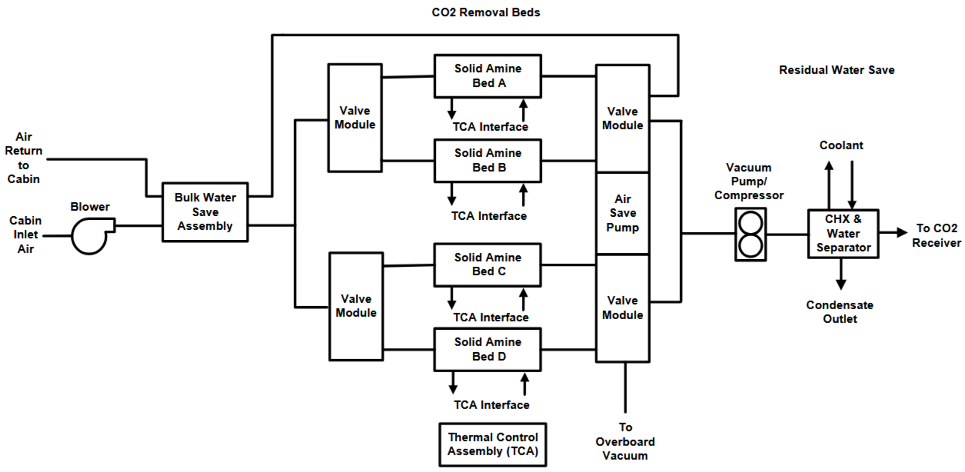

Figure 19: Block diagram of ISS's Thermal Amine Scrubber, a system to remove the carbon dioxide from the cabin air by solid amines. [57]

As can be seen in Figure 19, the cabin air enriched with CO_2 is drawn into the system by a fan. The air first enters the Bulk Water Save Assembly, where excess water vapor is removed from the air. This step is useful for saving as much water as possible, because carbon dioxide is treated as a waste product on the ISS and released into space. The water can be recycled after being saved by the Bulk Water Save Assembly. [53, 55, 57]
The next step is to direct the air to the CO_2 removal beds. These can be seen in the center of Figure 19. The TAS consists of four beds with solid amines. These are labelled with the letters A to D.
These beds operate in a cycle so that three beds actively remove CO_2 from the incoming air (adsorption phase) while one is in the regeneration phase (desorption phase). Another bed is regenerated alternately. Regeneration begins when the bed is saturated with CO_2. [53, 55, 57]
The Thermal Control Assembly (TCA) supports this regeneration process. It supplies the amine beds with heat. At the same time, a vacuum is created with the help of the

vacuum pump/compressor. The combination of heat and vacuum drives the CO_2 from the amine surface and effectively resets the bed for reuse. [53, 55, 57]
The air, which no longer contains CO_2, is fed back into the cabin via the air return line shown at the top left. During regeneration, the gases released from the beds, including water vapor and CO_2, are fed through the Air Save Pump, which recovers the residual air from the cabin. This is to prevent losses. The gas stream is then directed to a condensation heat exchanger (CHX) and a water separator, where the water condenses and is separated. The remaining dry CO_2 is either directed to a CO_2 container for storage or discharged to the outside. Throughout this process, the valve modules coordinate the flow direction and bed switching, ensuring that CO_2 is continuously removed from the cabin atmosphere. At the same time, high operating efficiency is maintained. Switching between adsorption and desorption enables continuous operation. [53, 55, 57]
The advantages of using amines include their high CO_2 adsorption capacity and reusability. In addition, many amine-based sorbents, such as the SA9T sorbent used for the TAS on the ISS, have excellent moisture tolerance. This makes them suitable for environments with fluctuating humidity levels. Furthermore, a lower temperature is required for regeneration. [53, 55, 57, 58]
However, there are some complexities to consider. The sorbent regeneration process involves controlling a variety of variables, such as pressure, temperature, air flow rate, vapor flow rate, and cycle duration, as is the case with molecular sieves. It should also be noted that the TAS is still in an earlier stage of development, with efforts to demonstrate that the TAS has a Technology Readiness Level 5 by testing a prototype onboard the ISS. But this leads to uncertainties regarding long-term reliability and effectiveness. [53, 55, 57]

4.1.4 Membranes

Different membranes use different physical and chemical mechanisms for CO_2 separation. These are designed for specific material properties of the membranes and application requirements. [59, 60, 61, 62, 63]
In polymer membranes, solution diffusion is responsible for gas transport. This phenomenon causes the CO_2 molecules to first dissolve on the feed side in the membrane material. They then diffuse through the polymer matrix due to the concentration gradient. Finally, they desorb on the low-pressure side into the permeate stream. The separation performance depends on both the solubility of CO_2 in the membrane material and its diffusivity. [59, 60, 61]
In contrast, microporous membranes operate according to a pore flow mechanism, in which separation is based on molecular size exclusion. Gases with smaller diameters can pass through nanopores more easily than those with larger diameters. This results in size-dependent transport through the pores. These typically have diameters of 0.5 to 1 nm. [59, 60, 61]
The use of liquid water membranes can also be considered. This involves using a membrane with a very thin layer of water. The water layer is stabilized by capillary forces. The fact that CO_2 is highly soluble in water is advantageous for the use of these membranes. In addition, there is a pressure difference across the membrane, which results in gas transport through solution diffusion. The process not only separates CO_2, but also captures moisture from the air stream. [62]

Electrochemical membranes use carrier molecules that reversibly bind CO_2. CO_2 reacts with a carrier molecule on the feed side. This compound diffuses through the membrane. On the permeate side, the carrier is electrochemically oxidized, releasing the CO_2. The carrier is regenerated for another cycle. Transport is electric. This is a highly selective process for CO_2 that does not require external pumps or pressure gradients. These membranes are therefore ideal for applications with low energy consumption. [63]
The widespread use of membranes remains limited due to technical challenges. In theory, membranes are an interesting option to test as a separation method in BLSS due to their ability to reduce volume, weight, energy consumption, and complexity. One of the most fundamental limitations in membrane use is the trade-off between permeability and selectivity. This means that high gas flow reduces separation performance. This trade-off limits the use of membranes for CO_2 separation. Operational problems include membrane fouling, clogging, and wetting. This can become a problem in microgravity. In addition, some membrane materials can be prone to thermal decomposition and chemical instability. That compromises their long-term reliability and robustness. Furthermore, the complexity of manufacturing and high costs make the use difficult. The production of flawless membranes for more than laboratory use remains a challenge. Therefore, the extreme reliability required for long-term missions cannot be guaranteed. [59, 60, 61, 63]
In summary, it can be said that membrane technologies are promising for CO_2 capture, but are not yet mature enough for large-scale use.

4.1.5 Electrochemical Methods

Electrochemical carbon capture (eCCC) is a technology that uses electrical energy to drive redox reactions. This allows CO_2 to be selectively captured and concentrated from gas mixtures. This process usually takes place in two main phases. First, the CO_2 is absorbed either into a liquid electrolyte or by direct binding to redox-active molecules. It is then released electrochemically. During desorption, the absorption molecule is regenerated by applied electrical potentials. [64, 65, 66]
Different electrochemical principles can be considered to implement the eCCC. Electrochemically induced pH fluctuations in aqueous media are important to promote the adsorption and desorption of CO_2. Although CO_2 is not very soluble in water, it reacts with hydroxide ions, and bicarbonate or carbonate compounds are formed. A release can happen again later during acidification. [64, 65, 66]
Another possibility is separation through redox-active molecules, so-called redox carriers. Here, certain molecules bind CO_2 during reduction and release the gas again during oxidation. Quinones are mostly studied for this method, but transition metal complexes, bipyridines, and thiols can also be used. [65]
Historically, the concept of the eCCC can be traced back to the 1960s and 1970s. At that time, NASA first attempted to develop lightweight and reliable carbon dioxide removal systems for LSS. Early designs were characterised by long service life and high carbon dioxide purity, but were not particularly energy efficient. Still, eCCC is not yet widely used due to a few limitations. The most important of these is energy intensity. Although the theoretical energy requirement is low, practical systems often fall short of expectations due to kinetic and mass transport losses as well as ohmic resistances.

Slow CO_2 absorption kinetics, particularly in aqueous systems with low solubility and thick diffusion layers, limit reaction rates and result in limited current densities. [65, 66, 67, 68]
The stability of materials and systems also poses a challenge. Membrane degradation, catalyst instability, and salt precipitation (which reduce the active surface area for gas transport) are common problems. In addition, cell design and scaling present technical difficulties. Cost-effective scaling requires the development of high-performance catalysts that do not rely on expensive platinum group metals, as well as the achievement of significantly higher current densities. [65, 66, 67, 68]
In theory, eCCCs are promising for carbon dioxide removal. However, extensive research and development work are needed to overcome current limitations in terms of efficiency, durability, scalability, and cost. Continuous advancement in materials, system design, and process integration will be critical to transferring eCCC from laboratory research to practical applications. Electrochemical carbon capture is not yet a method that is ready for use on board a mission. [64, 65, 66, 67, 68]

4.1.6 Ionic liquids

Ionic liquids (ILs) are salts with special properties. They are liquid at room temperature. This means that their vapour pressure remains negligible. Therefore, ILs cannot evaporate. They have non-volatile and odourless properties. This is an advantage for enclosed environments where the formation of vapours with toxic properties is a problem. [69, 70, 71]
Many ILs have high oxidation stability. However, ILs can decompose at higher temperatures, especially if they are exposed to the temperature for long periods of time. Another important property of ILs is their ability to bind CO_2. Furthermore, their non-flammability and non-toxicity are essential safety features.[69, 72]
Various types of ILs have been investigated for CO_2 capture, either imidazolium-based or phosphonium-based. An imidazolium-based IL is used in Honeywell's Carbon Dioxide Removal System using Ionic Liquid Sorbents (CDRILS). All ILs are chemisorbing substances, which means that they undergo a chemical reaction with CO_2. At reduced partial pressures, phosphonium-based ILs have shown excellent CO_2 absorption properties. [69, 70, 71, 72, 73]
To use ILs for CO_2 capture has several advantages. One of them is their energy efficiency. For example, some ILs require about 1-2 $MJ/(kg\mathrm{CO_2})$ [69] less for carbon dioxide desorption than solid sorbents such as zeolites or solid amines. Another advantage is the continuous operation that IL systems provide. This simplifies system design and volume. Furthermore, IL systems have increased tolerance to water and contaminants compared to zeolite-based systems, which require dry air. [69, 70, 71, 72, 73]
However, there are also some challenges associated with the use of ILs for carbon dioxide capture. One serious problem is their thermal decomposition. ILs begin to decompose at temperatures above 60 °C [69, 73], especially after prolonged periods of time. [69, 73]

4.2 Oxygen Separation

In order to extract the oxygen produced by the plants from the greenhouse module and deliver it to the crew, the necessary technical implementation options are needed. Four possibilities are examined below: molecular sieves, electrochemical oxygen concentration, cryogenic distillation, and membrane-based technologies. [74, 75, 76, 77]
On Earth, there are two main areas of application for oxygen separation technologies: industrial air separation and medical oxygen therapy.
In industrial air separation, the goal is to separate oxygen and nitrogen (N_2) from the atmosphere. The separated gases are widely used in industries such as petrochemicals, food preservation and power generation. The goal of industrial application is the cost-effective production of these gases on a large scale. [74, 75, 76, 77]
Medical oxygen therapy, on the other hand, aims to treat chronic hypoxaemia (low oxygen levels in the blood) in patients with conditions such as interstitial lung disease or chronic heart failure. Long-term oxygen therapy (LTOT) can significantly improve outcomes for patients by increasing survival rates and improving both physical performance and quality of life. [74, 75, 76, 77]

4.2.1 Molecular Sieves

The molecular sieves used to separate oxygen from the air are similar to those used to remove carbon dioxide. The air flows through beds filled with an adsorbent. Nitrogen and other gases are adsorbed. Once the bed is saturated with nitrogen, the air is diverted to another bed. The first bed is regenerated by vacuum and heat. Here, too, a continuous air flow is possible by using several beds. This technology can achieve oxygen purity of 90 % [74] and above. However, it should be noted that the air must flow more slowly through the beds to achieve higher purities. A prototype of this NASA system for space applications was able to produce oxygen concentrations of about 90 % at 1 litre per minute (*lpm*) [74] and 45 % at 6 *lpm* [74].
Molecular sieve systems are relatively easy to operate and maintain, especially when compared to some of the other methods presented later, making them suitable for small to medium-sized applications. They also meet various requirements of space missions, such as reduced power consumption and operation under various atmospheric conditions. However, the performance of molecular sieves can be limited at low ambient pressures and high humidity. [74, 76]
Various types of concentrators can be used for medical oxygen supply. Stationary oxygen concentrators for LTOT provide a constant oxygen flow of up to 6 *lpm* and produce oxygen purity of over 90 % [74]. Portable devices are battery-powered and offer different usage times depending on the model. These are smaller and lighter, but still offer the same oxygen purity. [74, 76]

4.2.2 Electrochemical Oxygen Concentration

This process uses an electrochemical stack. A voltage is applied to this stack to separate oxygen from other gases. A NASA prototype tested using this method employed a cathode air vapour supply and required deionised water to prevent the system from drying out. Although this enabled oxygen concentrations of over 90 % [74] to be generated, the system had several disadvantages. It consumed an excessive amount of power (over 600 W), whereas the target was 360 W, and generated large amounts of waste heat. In addition, the prototype weighed over 30 kg and was not transportable. The system also had a long start-up time and required a constant supply of deionised water. Although it offered the advantage of external monitoring and software control, which is useful for remote operation, its power requirements and complex operation ultimately made it unsuitable for space missions or portable applications.[74]

4.2.3 Cryogenic Distillation

In cryogenic distillation, gases are separated by fractional distillation at extremely low temperatures. To do this, the air is filtered and compressed. It is then cooled and passed into the distillation chambers. Nitrogen has a lower boiling point than oxygen, so it evaporates first, and the oxygen condenses at the bottom. This process is efficient for large-scale production and can achieve oxygen purity of over 94 % [75]. However, the costs and energy requirements for this method are very high due to the need for cooling below the boiling point. This makes this solution unsuitable for small and mobile applications. [75, 76]

4.2.4 Membranes

This technology uses a polymer membrane with selective properties. Certain gases pass easily through the membrane, while others are retained. Separation can be driven by a pressure gradient or a concentration gradient and is based on the principle of solution diffusion. Gases are separated based on their different permeability. However, oxygen and nitrogen have a low kinetic diameter, which makes it difficult to achieve high selectivity. Oxygen purity is therefore typically only between 25 % and 40 % [75]. Although membrane systems are energy-efficient, cost-effective, and environmentally friendly, they are more suitable for smaller applications that do not require high purity. In addition, conventional polymer membranes can be chemically and thermally unstable, which limits their long-term effectiveness. [75]

4.3 Comparative Analysis and Ranking

In the following subchapter, the most suitable method for both CO_2 and O_2 separation will be selected, while keeping the project requirements in mind. For this purpose, the information from Chapters 4.1 and 4.2 is used and supplemented with further information and technical specifications from the sources. As many of the already established requirements as possible should be met. First, the requirements relating to gas exchange between the greenhouse and the habitat will be presented. Next, the crew's and the plant's gas behaviours are calculated. Then, the evaluation criteria will be explained. After that, the advantages and disadvantages of each scrubbing method will be presented for comparison. The methods will then be evaluated, and a trade-off analysis will be conducted, after which a separation method will be selected for each gas. This method will be compared with the gas exchange using the Direct Cabin Air Strategy in the further course of the work.

4.3.1 Project Requirements and Evaluation Criteria

During the CE study for the LAM-GTD project, conducted in 2024, the system design was developed. In the process of this, the preliminary parameters that the LAM-GTD must meet were also determined. The general requirements apply to the system with all its subsystems, and there are additional, more specific requirements for each subsystem. There are some requirements regarding the AMS, but not all of them are important for the gas exchange between ALM and GAM. Table 5 lists all requirements that must be considered for gas exchange. These include both general requirements and AMS-specific requirements. Table 5 is followed by a brief, individual explanation of each requirement and a classification of how broad this requirement is, i.e., whether it applies to the entire system or only to the AMS subsystem. The requirements must be taken into account and fulfilled as far as possible by the gas exchange system, regardless of whether the gas is exchanged using the Direct Cabin Air Strategy or the Hermetically Sealed-off Strategy. [12, 78]

Table 5: LAM-GTD project requirements, which are of importance for the gas exchange system. [12]

Number	Requirement
R01	The system shall be operational for 2 years without resupply (aside from the material flows between habitat and lunar agriculture module based in the closed loop). [12]
R02	The system shall support a closed-loop and self-sustainable operation of the habitat in providing 10 % amount of caloric intake for 4 crew members. [12]
R03	Piping and harness diameters shall be similar among parts. [12]
R04	The oxygen concentration of the air within the system shall be controllable and be maintained between 16 and 24 % at standard atmosphere. [12]
R05	The system shall be compatible with local voltage. GAM and LAM shall use the same power interface of external supply with 120 $V\ DC$. [12]
R06	The LAM shall be nominally operable at between 57 kPa (TBD +/-) and 34 % of oxygen over 70.3 kPa (TBD +/-) at 26 % oxygen to 101.33 kPa (TBD +/-) at 21 % oxygen and testable for tightness with a margin of 10 %. [12]
R07	The carbon dioxide concentration of the air within the LAM shall be controllable and be maintained between 350 and 5000 ppm. [12]
R08	The AMS life-time shall be designed for a minimum of 3 to a maximum 10 years. [12]
R09	Commercial Off-The-Shelf (COTS) components shall be used for the AMS if the specified environmental parameters (thermal range, vibration loads, and vacuum) are compatible with the AMS requirements and the performance is sufficient. [12]
R10	The AMS shall be designed so that the LAM is redeployable for tests at another location than its original construction point. [12]

R01 - R07 are requirements that regard the system as a whole and therefore the gas exchange as well. R01 determines how long the crew and the LAM-GTD should manage without resupply and thus how long the installed technologies and systems have to function reliably. R02 makes a statement about how much the plants should contribute to the crew's nutrition and how large the crew is. Originally, the requirement and project planning envisioned a crew of three, but that specific aspect of the requirement has changed. The crew is now to consist of four people instead of three. The caloric intake has not changed. R03 states that the piping between the parts should have similar diameters. This must be considered when designing the gas exchange system. R04 specifies the limits of the permissible oxygen concentration in the system. R05 indicates the power supply of 120 VDC for the system, which means that components should be operated with direct current. R06 shows the different pressure conditions under which the LAM is to be operated and which oxygen concentration is to prevail in each condition. The LAM might be operated under different pressure conditions

so that the crew can be better prepared for Extravehicular Activities (EVA), and less crew time is spent adapting to an EVA pressure level. The low-pressure condition is to be used for phases in which many EVAs are planned. The reasoning for this has been explained in more detail in Chapter 2.3.1. R07 describes the limits of carbon dioxide concentration in the LAM. [12]
R08 - R10 are specific AMS requirements. R08 specifies the service life periods for the AMS components. R09 states that commercial off-the-shelf products should be used, provided they meet the environmental parameters. R10 reminds us that the test location for the LAM has not yet been determined, so the AMS must be able to withstand transport without damage. [12]
Further criteria for the evaluation of the gas separation technologies are shown in Table 6. Those will be used to conduct the trade-off of the technologies. Once this trade-off has been made and gas separation methods for the Hermetically Sealed-off Strategy have been selected, the gas exchange methods (Direct Cabin Air Strategy and Hermetically Sealed-off Strategy) can be compared.

Table 6: Evaluation criteria to conduct the trade-off between the gas separation technologies and clarification of meaning.

Evaluation criterion	Clarification
Advantages	What makes the method special?
Disadvantages	What could cause problems?
Gas concentration	What is the output concentration?
Regenerative capabilities	Does the method have regenerative capabilities?
Power consumption	What amount of the mission's power budget will be spent?
Weight	What amount of the mission's weight budget will be spent?
Volume	Is there still enough space in the LAM-GTD modules?
Technology Readiness Level	What is the current state of the art?
Max. temperature	To what extent does the method place an additional burden on the thermal control system?
Capacity	Does the method match the volume flows generated in the LAM-GTD?

In order to make a statement about the last criterion, capacity, it must first be calculated how much gas is actually involved in relation to crew and crops.

4.3.2 Crop Parameter

Another student thesis within the LAM-GTD project focused on creating a Biomass Estimation Tool (BET). The tool recommends plants for cultivation that have already been tested by the EDEN ISS project and other comparable projects. The technology can be utilised to calculate the biomass yield for a mission, whether in the ground test demonstrator or on the Moon. To execute this process, it is first necessary to select the number of trays to be utilised, a figure that can range up to 48. That is the number of trays currently planned for in the GAM. In addition, the duration of the mission can be specified. The stored data encompasses the spatial requirements of each plant within the tray, thereby determining the maximum number of plants that can be accommodated, the average cultivation cycle duration per plant, and the mean edible fresh weight. [79, 80]
With minor modifications, the tool has also been used to determine the CO_2 uptake and O_2 output of the plant selection. To achieve this objective, the uptake and output values for all crops were obtained from the extant literature. For certain crops, data was only available for the general, overarching crop type, which was then assumed to apply to all crops of that type. The literature exclusively provided static values, regardless of the individual growth phases of crops. Due to the scope of this work, these values had to be used, even though the use of a static value to describe a living and changing system must be considered critical.

Table 7: CO_2 uptake and O_2 output values of crop selection for LAM-GTD.

Crop name	CO_2 uptake $[kg/m^2/d]$	O_2 output $[kg/m^2/d]$
Batavia	0.011 [11]	0.008 [11]
Chives	0.013 [2]	0.009 [2]
Radish Lennox	0.016 [11]	0.012 [11]
Cucumber Picowell	0.023 [2]	0.017 [2]
Tomato F1 1202	0.036 [11]	0.026 [11]
Bell Pepper	0.034 [11]	0.025 [11]

Table 7 displays a selection of crops, accompanied by their respective CO_2 uptake and O_2 output values. These values are utilised for calculation within the BET. It should be noted that not all crops suggested to be used in LAM-GTD are included in Table 7, as many crops from the same crop type have been found to share the values. In addition to Batavia, there are five other varieties of lettuce, two other herbs than chives, two additional brassicas to Radish Lennox, and one other fruiting crop than Cucumber Picowell, Tomato F1 1202, and Bell Pepper, namely Tomato F1 3496B. As previously stated, these crops have already been tested, which is why they are being considered for use in a mission once more. [79]
In Table 7, the information about the maximum and minimum uptake and output of crops can be found. A correlation can be detected between uptake and output, with plants of the crop type lettuce (Batavia) exhibiting the capacity to absorb the smallest amount of CO_2 and produce the smallest amount of O_2. Tomato F1 1201 has been identified as a key species in terms of CO_2 uptake and O_2 output.

These two plants were used to simulate the largest and smallest amounts of gases that can be processed and emitted by the plants in the BET. Firstly, the BET was configured to plant all 48 trays with Batavia exclusively. This allowed for an estimation of the lowest amounts of CO_2 uptake and O_2 output. The outcome is shown in Table 8.

Table 8: Lowest amount of CO_2 uptake and O_2 output possible.

Minimum total system CO_2 uptake $[kg/d]$	**0.252**
Minimum total system CO_2 uptake $[kg/m^2/d]$	0.011
Minimum total system O_2 output $[kg/d]$	**0.183**
Minimum total system O_2 output $[kg/m^2/d]$	0.008

The process was then repeated, with the modification that only Tomato F1 1202 plants were cultivated in all 48 trays, to ascertain the maximum values. Those are presented in Table 9.
This process establishes a framework for the gas exchange system. The values determined by the BET make it possible to now be used to design a system for the gas exchange through the Hermetically Sealed-off Strategy and dimension it to the correct size.

Table 9: Highest amount of CO_2 uptake and O_2 output possible.

Maximum total system CO_2 uptake $[kg/d]$	**0.852**
Maximum total system CO_2 uptake $[kg/m^2/d]$	0.040
Maximum total system O_2 output $[kg/d]$	**0.620**
Maximum total system O_2 output $[kg/m^2/d]$	0.030

In comparison, Table 10 shows the amount of O_2 the crew needs and the CO_2 produced by the crew. For a crew of four that adds up to 3.36 kg of O_2 per day to take in and 4.04 kg of CO_2 per day added to the cabin air.

Table 10: Crew member(s) CO_2 output and O_2 input.

CO_2 output of single crew member $[kg/d]$	1.01 [11]
CO_2 output of four-member crew $[kg/d]$	4.04
O_2 need of single crew member $[kg/d]$	0.84 [11]
O_2 need of four-member crew $[kg/d]$	3.36

The key information provided by the calculations done with the Biomass Estimation Tool is that the processes of the plants in the greenhouse can absorb and process a quantity of CO_2 that falls between the minimum and maximum values of 0.252 kd/d and 0.852 kd/d. Photosynthesis then produces an amount of oxygen between the minimum and maximum values of 0.183 kd/d and 0.620 kd/d. The capacity of these plants to absorb CO_2 is significantly lower than the amount produced by a four-person crew, resulting in a comparatively lower level of O_2 being produced. Consequently, a daily surplus of CO_2 in the habitat and a deficit of O_2 will be generated. This must be taken into account for further planning and may impact the design of the solution for the gas exchange.

4.3.3 Carbon Dioxide Separation

To design a system that utilises the Hermetically Sealed-off Strategy for gas exchange, a trade-off must be made between the methods for gas separation presented in Chapter 4.1. First, the technologies for CO_2 separation are examined closely to select the most suitable technology. Table 11 shows the advantages and disadvantages of the individual CO_2 separation technologies. It should not be forgotten that none of these methods is fully mature and developed yet. Intensive research is being conducted on each method to identify opportunities for improvement.

Table 11: Advantages and disadvantages of CO_2 separation methods.

CO_2 separation method	Advantages	Disadvantages
Calcium hydroxide & lithium hydroxide	Effortless operation, easy system	CO_2 bound preventing reuse, single-use material, disposal system
Molecular sieves	Reliability, flight approved	Dry airflow necessary, high energy demand
Solid amine sorbents	Adsorption capacity, moisture tolerance	Less knowledge about behaviour during long-term use
Membranes	Lightweight, small in volume	Selectivity and permeability trade-off; operational issues (e.g. clogging)
Electrochemical methods	Long operational lifetime, high purities	Not ready for onboard missions
Ionic liquids	Energy efficient, moisture tolerance	Degradation at elevated temperatures

Already, this comparison shows that not all technologies are equally suited for long-term missions. A reduced selection of technologies will be considered from this point onwards. Lithium hydroxide and calcium hydroxide will not be examined further as an option to separate the carbon dioxide from the air in the cabin of the crew, as they both cannot be used regeneratively and would require a constant resupply of material from Earth. Additionally, membranes, electrochemical methods, and ionic liquids will not be examined further, as their Technology Readiness Level is not sufficient for consideration in mission planning. Furthermore, the focus is placed on explicit, tested systems, rather than just the overarching technology, so that decisions can be made as realistically as possible. If the molecular sieving technology were to be chosen for the gas separation, a system similar to ISS's FBCO2 would be suggested. It is flight-approved and reliable. The novel sorbent that is used in the FBCO2 system, compared to the CRDA system, is 13X zeolite [81]. For a scenario where solid amine sorbents are used to separate CO_2 from the air, the Thermal Amine Scrubber (also used on ISS) is highlighted. That system uses SA9T solid amines [57].
To now accomplish the trade-off between the FBCO2 and the TAS, additional evaluation criteria are being used for comparison.

Table 12: Comparison of the relevant CO_2 separation technologies in terms of technical criteria.

Evaluation criterion	Four Bed Carbon Dioxide Scrubber	Thermal Amine Scrubber
Gas concentration	85 % [82]	No data
Performance	4.6 kg/d [82]	4.0 kg/d [55]
Power consumption	975 W [82]	914 W [53]
Energy consumption	20 $MJ/kgCO_2$ [69]	21 $MJ/kgCO_2$ [69]
Weight	233.6 kg + 45.8 kg [82]	129.3 kg [53]
Volume	No data	880.88 x 506.48 x 770.13 mm [53, 83]
Max. temperature	140 °C [84]	40-60 °C [57]
Capacity	Yes	0.04 kg/d too few

Unfortunately, not all the values required for the trade-off could be obtained from the literature. The gas concentration of the CO_2 removed by the TAS system and the FBCO2 system volume are missing.
All values for FBCO2 taken from [82] are estimates from the design phase, and no information could be found about the actual values. The estimated weight includes the weight of the core system plus the additional materials launched; both are listed in Table 12.
The TAS system consists of an H_2O locker and a CO_2 locker. When used on the ISS, the CO_2 removed from the cabin air by the TAS system is treated as a waste product and released into space. For this reason, the air is first passed through an H_2O locker to store and reuse the water. This is unnecessary with LAM-GTD, which is why the TAS system weight is reduced by the H_2O locker weight. While the weight without the H_2O locker can be found in the literature, the energy consumption cannot, which is why the value in the table is higher than that of the FBCO2. However, this value would be lower if the TAS system were used in LAM-GTD without the H_2O locker. [53, 55, 85]
Table 12 shows that the TAS is superior in terms of power consumption, weight, and maximum temperature during the process compared to the FBCO2. It can also be assumed that it prevails in terms of energy consumption as soon as the H_2O locker is omitted. Unfortunately, no information is available on gas concentration. However, since both systems are used on the ISS in an environment with a human crew, it can be assumed that the requirements are similar and that the TAS's gas concentration is not significantly lower than that of the FBCO2. The only area in which the TAS falls short is capacity. However, not all the crew's CO_2 is exhaled exclusively in the habitat, as some plant care tasks and the harvesting are carried out directly in the GAM. So this amount would not fall within the remit of the CO_2 removing system. Additionally, the TAS is not an off-the-shelf product; instead, it must be custom-made for the project. So there is a chance that this quite small amount can be filtered out by, for example, enlarging the beds.
All of this led to the Thermal Amine Scrubber being chosen as the CO_2 removal system.

4.3.4 Oxygen Separation

The same procedure utilised in Chapter 4.3.3 for selecting a technology to separate CO_2 from the air will be used now to select a O_2 separation technology. First, the advantages and disadvantages are highlighted in Table 13; then the technical parameters are compared, as far as they are available in the literature.

Table 13: Advantages and disadvantages of O_2 separation methods.

	Advantages	Disadvantages
Molecular sieves	Reliability, medical use approved	Dry airflow necessary, high energy demand
Electrochemical oxygen concentration	Remote operations	High energy demand, waste heat produced, high weight
Cryogenic distillation	Very high purity of O_2	Very high costs and extreme temperatures below 0 °C
Membranes	Energy- and Cost-effective	Low purity of O_2; chemically and thermally unstable

Although the cryogenic distillation technology can achieve an O_2 purity level of 94 %, there are several arguments against its use. As it is used for industrial-scale separation processes, it is too large to separate the relatively small amount of a maximum 0.62 kg of O_2 per day. Additionally, the process requires a significant amount of energy to cool the gases. For long-term use, the gases would also need to be heated before being supplied to the cabin to maintain a comfortable temperature for the crew, representing an additional energy requirement.

Membranes only achieve a purity of 25-40 %, which is not effective enough for use in the LAM-GTD.

That is why the focus will be on the other two technologies, comparing a medical-use oxygen concentrator that utilize molecular sieves and NASA's electrochemical oxygen concentrator prototype.

Table 14: Comparison of the relevant O_2 separation technologies in terms of technical criteria.

Evaluation criterion	Medical oxygen concentrator	NASA's Electrochemical Oxygen Concentrator Prototype
Gas concentration	87-96 % [86]	>90 % [74]
Performance	840-1260 ml/min [86]	No data
Power consumption	No data	>600 W [74]
Energy consumption	No data	No data
Weight	2.2-2.7 kg [86]	30 kg [74]
Volume	$\tilde{2}$00 x 200 x 100 mm [86]	406.4 x 406.4 x 406.4 mm [74]
Max. temperature	No data	No data
Capacity	Yes	No data

For Table 14, the same evaluation criteria are used as those for the carbon dioxide separation technologies in Table 12. Less information was available in the literature, which is why there are some gaps in Table 14. At this point, it is necessary to draw attention to a particular paper from which the information on the Electrochemical Oxygen Concentrator Prototype was taken.
This document, a NASA Technical Memorandum, presents an evaluation of two distinct prototypes of oxygen concentrators intended for potential use in future human space missions. Both prototypes are tests as potential devices designed to supply crew members with enriched oxygen in medical emergencies. The aim is to avoid having to resort to the limited supplies of pure oxygen. The prototypes will therefore be used to test how well oxygen can be extracted from the cabin air. This approach would also have the advantage of preventing excessive oxygen accumulation in spacecraft. Otherwise, the oxygen content could rise above the vehicle's fire safety limit. [74]
The source evaluates both prototypes based on requirements that correspond to real mission requirements. These include requirements for oxygen concentration, flow rate, energy consumption, operating time, and portability. The two technologies evaluated are a prototype using pressure swing adsorption (PSA), which uses molecular sieves that regenerate through pressure fluctuations, and a prototype of an electrochemical oxygen concentrator. [74]
Both prototypes were tested in a controlled climate chamber at NASA's Glenn Research Center. During these tests, various atmospheric parameters such as pressure, temperature, humidity, and oxygen concentration were varied. This allowed the performance of the individual systems to be evaluated. [74]
The PSA prototype performed well under various environmental conditions. It thus met most of the defined requirements, for example, in terms of oxygen concentration, power consumption, and behavior at different temperatures and humidity levels. Based on the results, the authors recommend further development, as the PSA technology met 14 of the 23 requirements. [74]
The Electrochemical Oxygen Concentrator Prototype lacked in performance, oxygen concentration flow, and power consumption, as can be seen in Table 14. Additionally, the system showed a high complexity. For the 23 requirements, the Electrochemical

Oxygen Concentrator Prototype only fulfilled 8.
In summary, the prototype using the molecular sieving technology demonstrates superior performance across a range of critical criteria. An off-the-shelf product thats widely tested and used is the oxygen concentrators used by lots of patients with a need for purified oxygen daily.
As the source draws such a precise comparison between the variants and PSA performs significantly better, the source was used as a guide, and molecular sieving was established as the method for separating oxygen from ambient air for the further steps of this thesis.

4.4 Conclusion

This chapter examined various technologies for separating carbon dioxide and oxygen from ambient air. Their suitability has been evaluated for use in the LAM-GTD. The selected technologies are necessary to develop a system for the gas exchange through the Hermetically Sealed-off Strategy. This gas exchange strategy allows the different requirements of the atmospheric composition of crops and crew to be considered by enabling targeted gas exchange between the ALM and the GAM. The analysis of the separation technologies for carbon dioxide showed that chemical sorbents such as lithium or calcium hydroxide are easy to handle but cannot be regenerated and therefore do not represent a sustainable solution for long-term missions. Technologies such as membranes, electrochemical methods, and ionic liquids either have too many technical shortcomings or are not technically mature enough to be considered for such a demanding application as the use in the LAM-GTD at this moment in time. In comparison, molecular sieves and solid amine sorbents are more technically advanced and show regenerative properties. Considering the advantages and disadvantages, the performance parameters, and the energy efficiency of the separation technologies, the Thermal Amine Scrubber proved to be the most suitable technology for CO_2 separation in the LAM-GTD. As possible technologies for the oxygen separation, molecular sieves, electrochemical concentration, cryogenic distillation, and membrane separation were analysed. Due to its low energy consumption, reliability, and high technological maturity, the molecular sieve-based medical oxygen concentrator was selected as the preferred option. The Biomass Estimation Tool was used to verify whether the gas separation technologies were suitable for the separation of carbon dioxide and oxygen. This tool was used to calculate how much carbon dioxide uptake and how much oxygen output would be guaranteed by the crops. It became apparent that the crew and the crops would not create a closed air cycle. The crew produces too much carbon dioxide, and the plants produce too little oxygen for the gas quantities to balance out and remain in equilibrium. Without additional systems to reduce carbon dioxide, the concentration of the gas would eventually rise to life-threatening levels. In addition, oxygen must be supplied to the system; otherwise, the crew would also be unable to survive. Together, the Thermal Amine Scrubber and the medical oxygen concentrator form the basis for implementing the Hermetically Sealed-off Strategy as the basis of the system for the gas exchange in the LAM-GTD. Chapter 4 lays the technical foundation for the subsequent comparison between the implementation of the Hermetically Sealed-off Strategy and the implementation of the Direct Cabin Air Strategy, which is carried out in the following two chapters.

5 System Concept and Technical Design

The following section will focus on creating an initial draft for the implementation of the Direct Cabin Air Strategy and the Hermetically Sealed-off Strategy. To this end, block diagrams will first be created that include all the important components that would be needed to realize the gas exchange through these strategies. The block diagrams will be used to select commercially available components that could be suitable for the system. This will allow the size, weight, and energy consumption to be estimated. Subsequently, rudimentary CAD models of both strategies will be designed to assess whether and how well they fit into the existing design of the GTD. Finally, a system for implementation will be proposed after careful consideration and comparison of the two possible implementations.

5.1 Block Diagram of Gas Exchange through Direct Cabin Air Strategy

The block diagram is divided similarly to the spatial layout of the LAM-GTD in Figure 15. On the left-hand side is the ALM, and on the right-hand side is the GAM. Between them is the Connecting Ring, which contains the HabSim Measuring Tool. The striped lines indicate which parts come from other students' theses. These components are the Air Treatment Unit and the HabSim Measuring Tool.

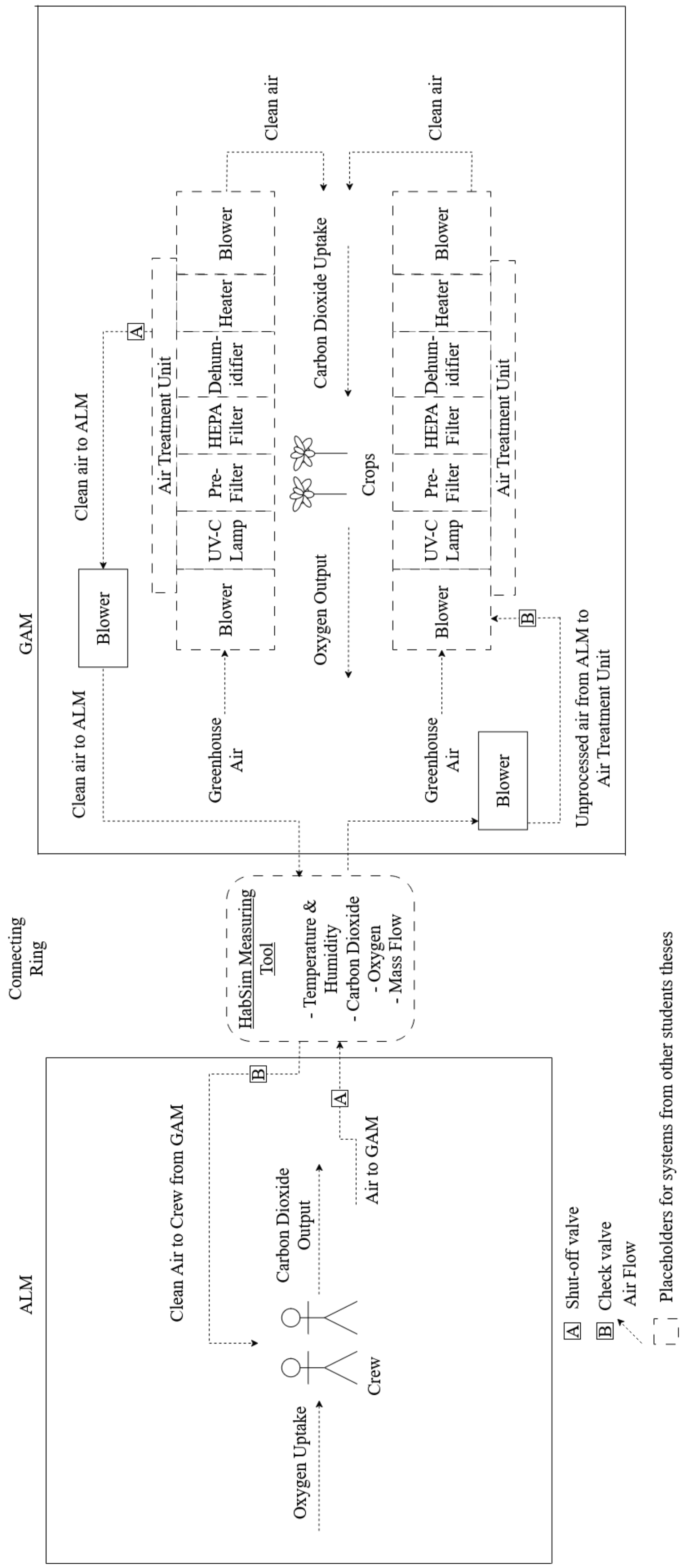

Figure 20: Block diagram of the system for the gas exchange through the Direct Cabin Air Strategy.

The crew is depicted in the ALM. The dotted arrows represent the gas flow. The crew contributes to it by breathing in O_2 and breathing out CO_2. The air flows through the HabSim Measuring Tool, driven by a fan in the GAM. This measures the temperature, humidity, CO_2 content, and O_2 content [87]. In addition, the mass flow is controlled [87].
The air is then fed into the GAM and passes through the Air Treatment Unit.
This unit also regularly cleans the air that is already in the greenhouse. According to current conceptual ideas, the Air Treatment Unit consists of a blower, a UV-C lamp, a pre-filter, a HEPA filter, a dehumidifier, a heater, and a final blower. The air from the ALM is also treated here and cleaned of any germs before it is released into the GAM. This is to prevent the spread of mould or spores that could potentially be hazardous to the health of the crew or crops. [88]
After the air has been purified, it is fed to the plants so that they can benefit from the increased CO_2 content. To save space and weight, the air should only be treated in the GAM, not additionally in the ALM. For this reason, the Air Treatment Unit in the GAM consists of two air treatment strands, both of which can provide sufficient air purification should one strand fail or require maintenance [88]. To prevent air from flowing back, a check valve is installed at the outlet, allowing flow only in one direction. In an emergency, it must be possible to shut off the air supply from the ALM. A shut-off valve is provided for this purpose.
In the GAM, plants contribute to the gas balance through photosynthesis. They absorb CO_2 and convert it into O_2, among other things. The air in the GAM is regularly purified by the Air Treatment Unit. It consists of two strands. At the beginning, air from the ALM is fed into one strand. To prevent the air from being fed directly back into the ALM, the air that goes into the ALM is extracted from the other strand. This is diverted after the dehumidifier. It has thus passed through all the filters and should no longer contain any harmful germs or bacteria. Theoretically, connections should be made at both ends of both strands of the Air Treatment Unit to ensure air exchange even if one strand fails. Driven by a blower, the air then flows through the HabSim Measuring Tool and into the ALM to supply the crew with the O_2 produced by the plants. A shut-off valve and a check valve are also integrated in this direction.
The design of the Air Treatment Unit was the topic of another student's thesis [88] and may be modified in the future. The design from August 2025 will be used for this thesis regardless of any ideas and discussions for change among the LAM-GTD team.

5.2 Block Diagram of Gas Exchange through Hermetically Sealed-off Strategy

The block diagram for gas exchange via the Hermetically Sealed-off Strategy (Figure 21) is also divided so that the ALM is shown on the left, the GAM on the right, and the Connecting Ring, which contains the HabSim Measuring Tool, in the middle. The airflow is indicated by the dotted lines. Again, the striped lines indicate which parts come from other students' theses. These components are, again, the Air Treatment Unit and the HabSim Measuring Tool.

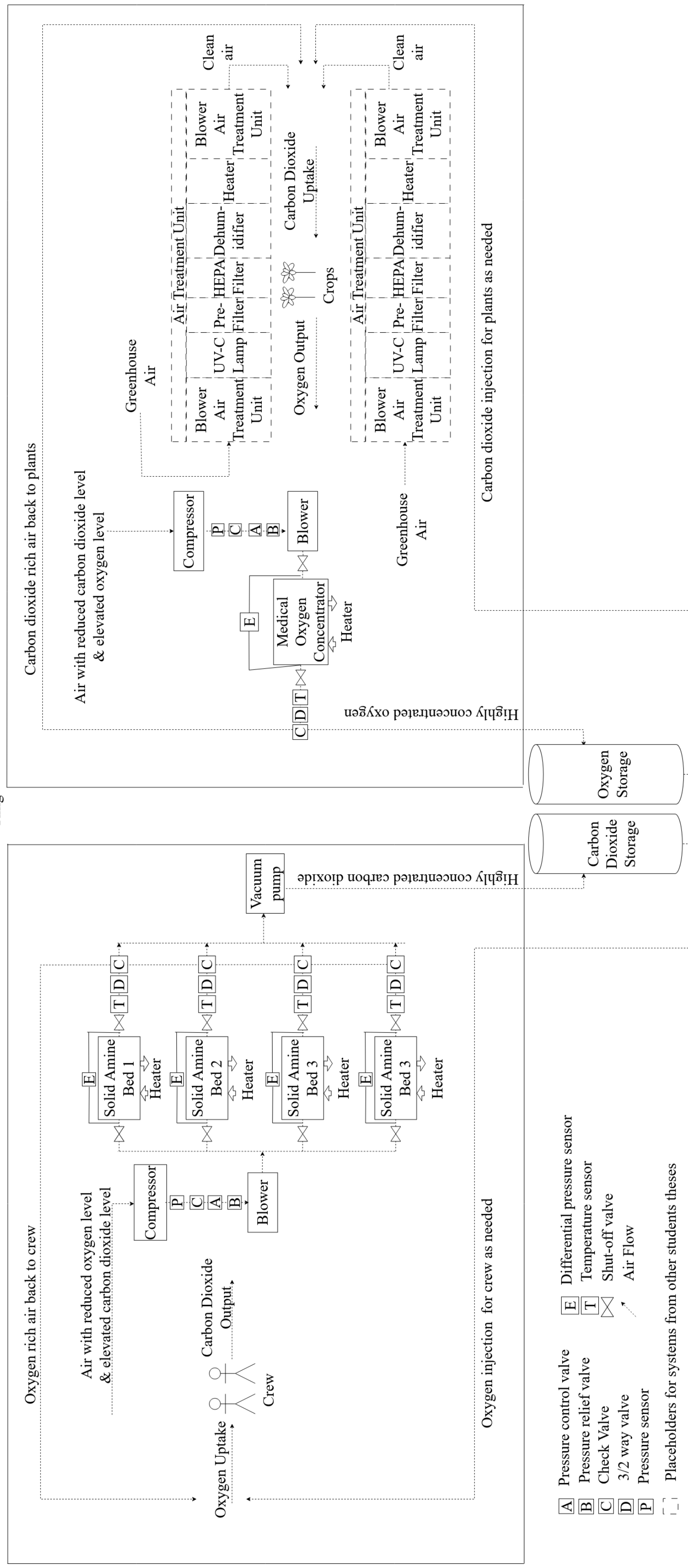

Figure 21: Block diagram of the system for the gas exchange through the Hermetically Sealed-off Strategy.

Here, too, the CO_2 content in the ALM is increased by the crew. The CO_2 removal process is started by first passing the air through a compressor. In this gas exchange scenario, the pressure at which the gas is treated plays an important role. One requirement of the project is that all components must be able to operate at three different pressure levels. At reduced pressure, the total number of molecules is reduced. This would require the size of the beds to be increased to remove the same amount of CO_2. Since the system for gas exchange through the Hermetically Sealed-off Strategy is already significantly larger than the one for the gas exchange through the Direct Cabin Air Strategy, a compressor is intended to keep the air constantly at a pressure of 101 kPa. This means that the pressure condition in the cabin is irrelevant. The air is then distributed via the blower to the four beds filled with solid amines. During the TAS operation on the ISS, three beds are always in the adsorption module, while one is in the desorption phase. Once the air is flown through the adsorbing beds, the CO_2-poor air is returned to the cabin. The CO_2 remains in the beds until desorption. Desorption is achieved by heat and vacuum, which is why a vacuum pump is part of the block diagram. After desorption, the highly concentrated CO_2 is stored in a tank until it is needed in the GAM for the plants.

The separated CO_2 cannot be exchanged directly for the separated O_2, as the quantities are not the same. In Table 8, Table 9, and Table 10, the quantities produced by the crew's respiration were compared with the amount of O_2 produced by photosynthesis. To avoid creating a pressure imbalance in the system, both the separated CO_2 and the separated O_2 must be stored in tanks and returned to the system in equal parts as needed.

In the GAM, the crops produce O_2 from CO_2. This increases the O_2 content. In the ALM, a compressor is also used to bring the air to the correct pressure; this is not used. With the help of a blower, the air now flows through the bed of the molecular sieve. The air flow that leaves the bed in the adsorption module is the concentrated oxygen. This is fed into the tank and stored until it is needed in the ALM. The bed is heated for desorption. The air flow that this creates is fed back to the GAM.

Various valves and sensors are used on the way from the ALM to the GAM. A pressure sensor between the compressor and the blower measures whether the air has been brought to the correct pressure and is within the permissible safety values. This is followed by a check valve to prevent backflow into the compressor. Next, a pressure control valve regulates the pressure. By opening or closing, it can maintain the pressure at a desired value. If the pressure is too high, a pressure relief valve is provided to protect the system from damage due to overpressure.

The pressure drop upstream and downstream of each bed is to be determined by a differential pressure sensor in order to detect possible leaks. In addition, each bed must have a shut-off valve upstream of the inlet and downstream of the outlet in order to cut it off from the air flow in case of emergencies and during desorption and adsorption changes.

The temperature of the air flows leaving the bed is controlled by a temperature sensor. A 3/2-way valve returns the CO_2-low air flow to the cabin or returns the concentrated CO_2 to the storage tank.

The same sensors and valves are used on the way from the GAM to the ALM. A pressure sensor, a check valve, a pressure control valve, and a pressure relief valve should

be used between the compressor and the blower. The pressure difference across the bed is measured by a differential pressure sensor. Shut valves are located before and after the bed. The temperature is measured after the air leaves the molecular sieve bed. The 3/2-way valve directs the air flow into the tank after adsorption and back into the cabin after desorption.
The concentrated gases are added from the tanks as required via an air distribution system. This has not yet been designed and is not part of this work. Therefore, it cannot be discussed further at this point.

5.3 Additional Approaches

Another method of exchanging CO_2 and O_2 between the GAM and the ALM was also considered. This would involve installing the system that removes CO_2, i.e., the TAS, twice. CO_2 would be removed from both the ALM and the GAM. The concentrated CO_2 would then always be fed into the GAM, and the air containing less CO_2 would always be fed into the ALM. No storage tanks would be required. However, this approach has some problems.
Firstly, plants do not need constantly elevated CO_2 concentrations. CO_2 is a plant fertiliser that increases plant yield [89]. But not if it is added continuously [89]. Especially during the first one to two hours after the start of light irradiation and the last one to two hours before the end of light irradiation, CO_2 should not be used as a fertilizer [89]. This is because at night, the roots emit CO_2, which is why the CO_2 content in the air also rises, just as it does in the ALM [89]. This means that if CO_2 is separated in both rooms and all CO_2 is fed into the GAM, the CO_2 content there will rise above the safety limits, and the crew may no longer be able to enter the GAM without protective measures. In addition, the yield of the crops would be jeopardised [89].
Another problem is that CO_2 does not make up half of the air composition in the ALM or GAM, but only a small part. This means that different quantities would be fed into the modules, and that more air would constantly be fed into the ALM than into the GAM. This can lead to pressure differences.
Due to these problems, this approach was not pursued further.

5.4 CAD Models

To determine whether it is more advantageous for the LAM-GTD project to achieve gas exchange through the Direct Cabin Air Strategy or the Hermetically Sealed-off Strategy, the systems are created as CAD models. The block diagrams are used as a guideline. The CAD models are then inserted into the existing CAD model of the LAM-GTD to check whether there would even be enough space left to implement the system for the gas exchange through the Hermetically Sealed-off Strategy. Implementing the gas exchange system through the Direct Cabin Air Strategy is the safety option, in case the other system is too bulky for the design of the LAM-GTD.
It is not part of this thesis to make a final component selection. Nevertheless, preliminary components that meet the requirements and technical specifications are proposed.

These are intended to help create a suitable volume estimation for each element provided in the CAD model's block diagram.

5.4.1 Gas Exchange through Direct Cabin Air Strategy

Figure 22 and Figure 23 show the CAD model for the system for the gas exchange through the Direct Cabin Air Strategy, one from the side and one from above. SolidWorks was used to create them. Figure 22 and Figure 23 are both divided into three sections. The left side shows the components that would be added in the ALM, the right side shows the GAM components, and the Connecting Ring is in between. The only part of the housing shown is the half of the Connecting Ring that connects to the GAM.

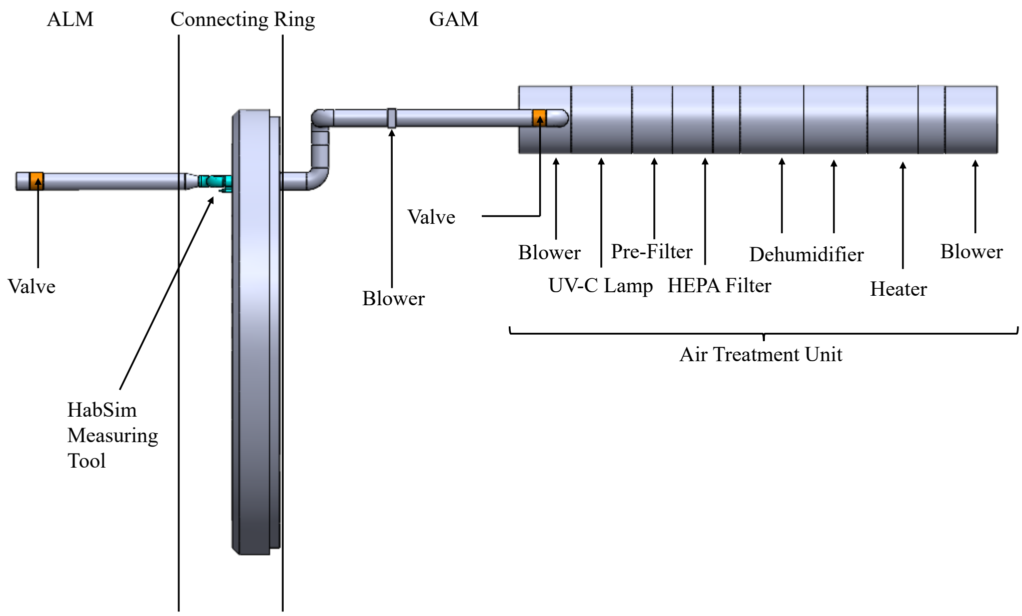

Figure 22: CAD model of the system for the gas exchange through the Direct Cabin Air Strategy, from the side.

From the side view, only the elements that ensure the air supply in the direction from the ALM to the GAM can be seen. The view from above allows both air ducts to be seen.

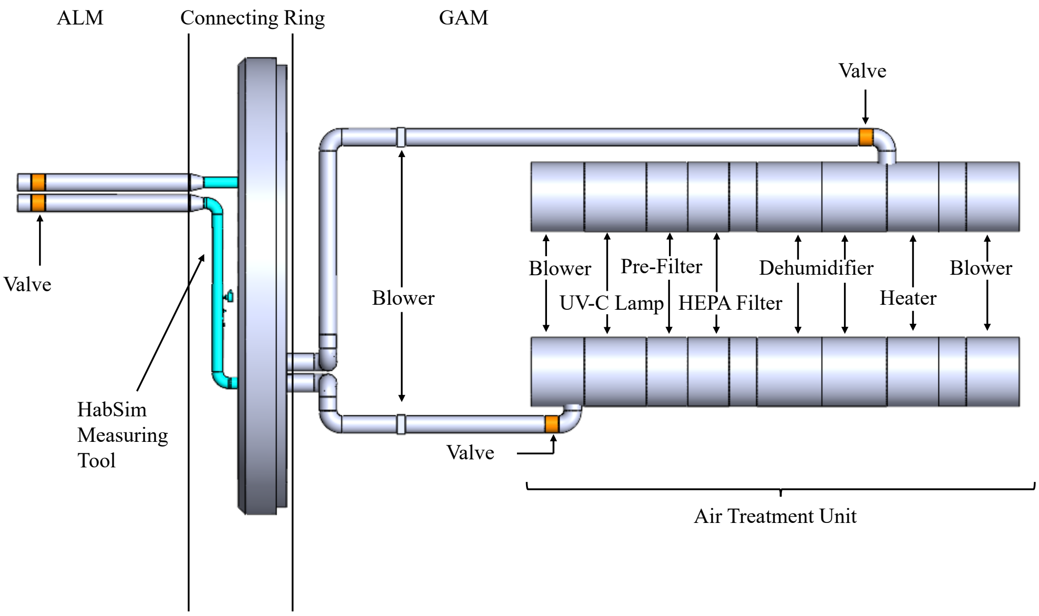

Figure 23: CAD model of the system for the gas exchange through the Direct Cabin Air Strategy, from the top.

In Figure 22 in the ALM, the air duct inlet can be seen with a placeholder for the valves. This is colored orange. This is the lower air duct in Figure 23. The upper air duct is part of the air duct system from the GAM and ALM. Here, too, the placeholder for the valves is shown in orange. The outlet is not shown because an air distribution system is to be connected there, but this has not yet been designed.
The HabSim Measuring Tool is located in the Connecting Ring [87]. This is shown in turquoise. This design was taken from another student's thesis that deals with designing this specific HabSim Measuring Tool in the LAM-GTD. A pipe diameter of 80 mm was determined for the HabSim Measuring Tool [87]. However, R03 specifies that the pipe diameters should be similar for all parts (listed in Table 5). Therefore, a larger diameter was chosen for the air ducts of the gas exchange system that do not belong to the HabSim Measuring Tool, because most piping is estimated to have a larger diameter in the LAM-GTD.
The GAM's overhead compartment is dominated by the Air Treatment Unit. The two strands are represented by placeholders in Figure 22 and Figure 23. For simplicity and clarity, the CAD model of the actual Air Treatment Unit was not included; instead, placeholders were used. Their volumes were taken from [88], the thesis of another student with the scope of designing the Air Treatment Unit. One placeholder was inserted per component. The air is pulled in on the left side of the Air Treatment Unit and cleaned by the UV-C lamp, the pre-filter, and the HEPA filter. The air then flows through the two dehumidifiers and the heater. There is another blower on the right side of the Air Treatment Unit. Since the Air Treatment Unit has already been designed and adapted to the space available in the LAM-GTD, the placeholders also serve to ensure the correct positioning of the gas exchange system.
The gas exchange is driven by the two blowers located on both air ducts in the GAM. Figure 23 displays the layout of the air duct from ALM to GAM at the bottom. In the

GAM, the air flow passes through the blower. Behind it, the placeholder for the valve can be seen again in orange. Then the air duct at the end of the blower merges into a strand of the Air Treatment Unit (visible in Figure 23 as the lower strand). In the CAD model of the Air Treatment Unit, no adapters between the individual components have been considered so far, which is why this point was chosen for display purposes. The air from the GAM can be fed after the blower or before it; it does not matter. The air duct through which the air from the ALM enters the GAM mustn't cover the blower inlet. However, for hygiene reasons, the air from the ALM should be treated by the UV-C lamps.

The air fed into the ALM should be taken from behind the dehumidifier. A valve placeholder is also shown at the beginning of the air duct. Driven by a blower, the air flows through the HabSim Measuring Tool in the Connecting Ring and is then blown into the ALM. Space for a valve is also provided before the outlet. A strategy for distributing the air in the ALM still needs to be designed.

The blowers for gas exchange were designed for the air flow from the GAM to the ALM. This is the upper air duct in Figure 23. These considerations were made because all parameters at the air duct inlet in the GAM are defined by the Air Treatment Unit. Since the Air Distribution Unit is missing in the ALM, information is not available at the inlet of the air pipe that carries the air from the ALM to the GAM. To this end, the pressure at the inlet after the dehumidifier was first determined.

A static pressure of 500 Pa [88] was specified for the blower at the start of the Air Treatment Unit. The following information can be found in the thesis on the design of the Air Treatment Unit. [88]

Table 15: Air Treatment Unit components and their pressure drops. [88]

Component	Pressure drop (Pa)
Blower	0
Sensors	0
Fans	0
UV-C Lamp	10
Pre-Filter	40
HEPA Filter	50
Dehumidifier	70
Heater	5
Blower	0

Table 15 implies that there is a pressure loss of 170 Pa between the inlet of the Air Treatment Unit and the end of the dehumidifier [88]. This leads to a reduction of the initial 500 Pa [88] to 330 Pa after the dehumidifier. The pressure drop is caused by the UV-C lamp, the pre- and HEPA filter, and the dehumidifier[88]. To determine the pressure that the blower must overcome for gas exchange through the air duct and the test section, a flow simulation was performed using SolidWorks. Special focus was paid to the air flow in the HabSim Measuring Tool.

Two flow analyses were performed. For the second one, a finer mesh was used in the rectifier, so that more cells were available and the result was more accurate.

Figure 24 shows the simulation with the less refined mesh. The flow is indicated by arrows. These change colour along the length of the air duct. At the start, they are yellow; after the cross-section narrows in front of the HabSim Measuring Tool, they turn green; behind the rectifier, they are blue. After the cross-section widens again, they become slightly lighter in colour. Figure 24, Figure 25, Figure 26, and Figure 27 also show the colour-pressure-scale, indicating which colour corresponds to which pressure. For each Figure showing the entire flow in the air duct (Figure 24 and Figure 26), there is also an image that shows an enlarged view of the HabSim Measuring Tool (Figure 25 and Figure 27).

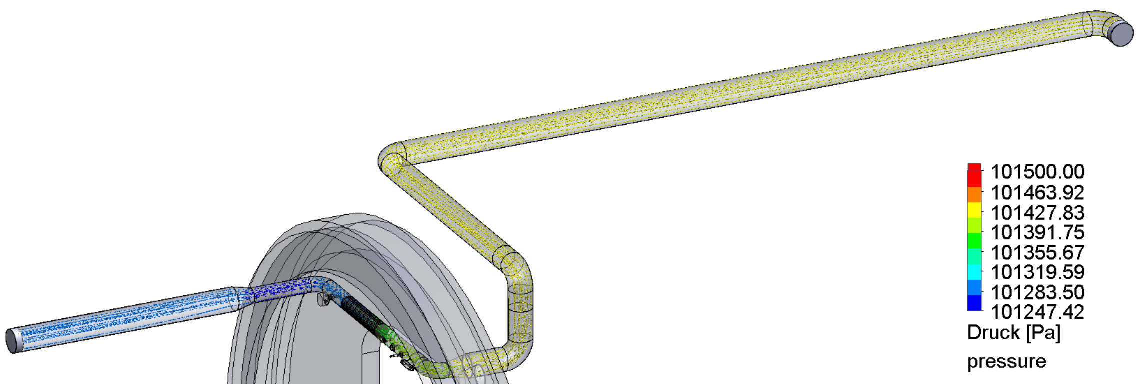

Figure 24: Flow analysis of the system for the gas exchange through the Direct Cabin Air Strategy from GAM to ALM with the scale indicating the colour to pressure correspondence.

Figure 25 is the enlarged view in the HabSim Measuring Tool in Figure 24. The more detailed view is necessary to show the pressure curves at the decisive points more accurately.

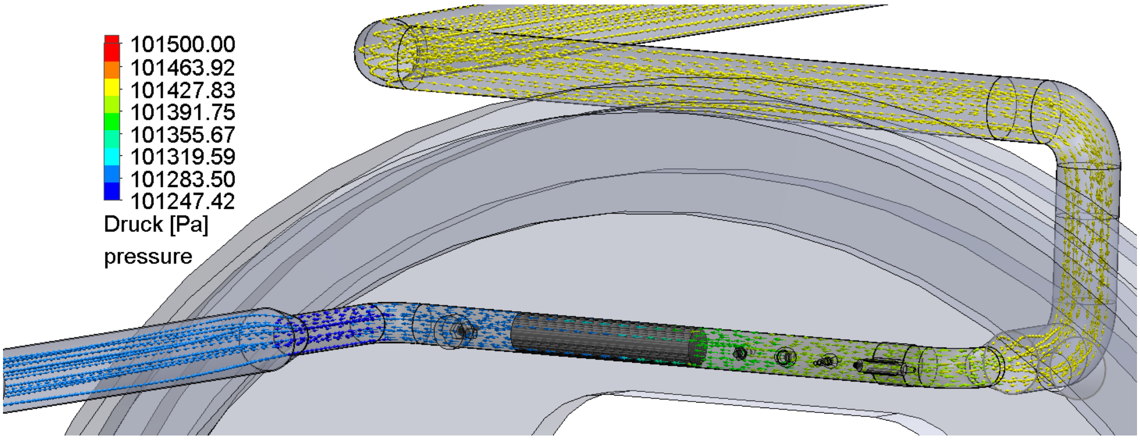

Figure 25: HabSim Measuring Tool of first flow analysis of the system for the gas exchange through the Direct Cabin Air Strategy from GAM to ALM with the scale indicating the colour to pressure correspondence.

Figure 26 shows the flow analysis with a finer mesh. The colour gradient is slightly altered compared to Figure 24 and Figure 25.

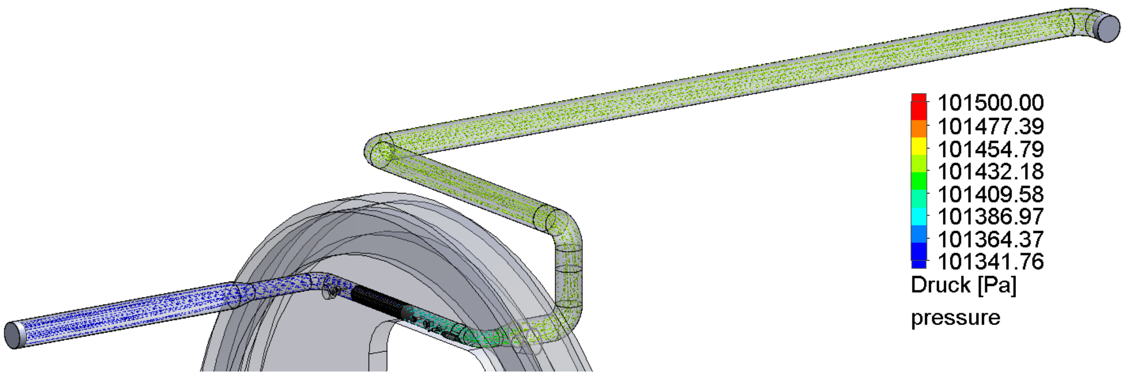

Figure 26: Flow analysis with refined mesh of the system for the gas exchange through the Direct Cabin Air Strategy from GAM to ALM with the scale indicating the colour to pressure correspondence.

The slightly altered colour gradient is particularly evident in Figure 27 at the HabSim

Measuring Tool.

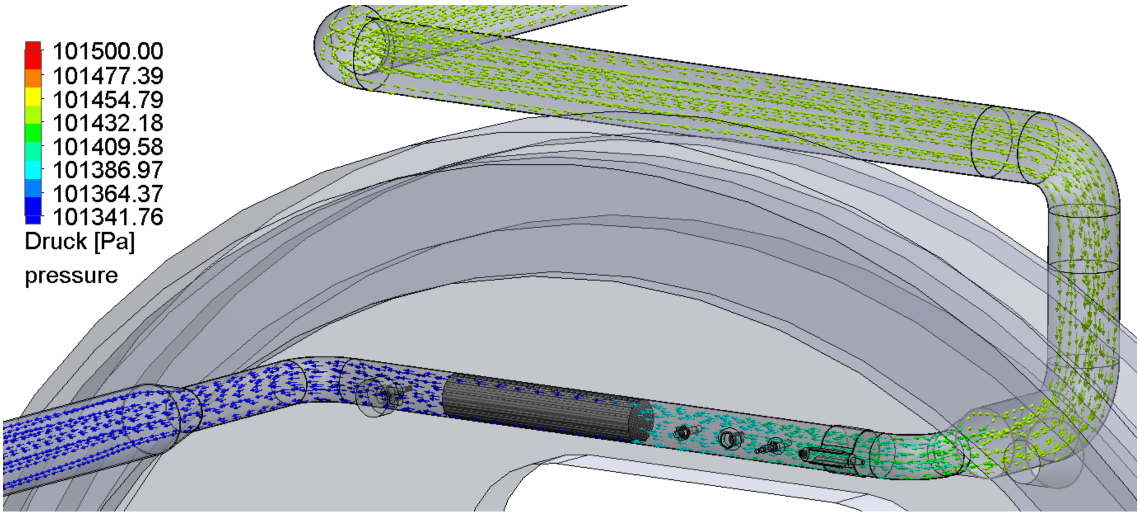

Figure 27: HabSim Measuring Tool of second flow analysis of the system for the gas exchange through the Direct Cabin Air Strategy from GAM to ALM with the scale indicating the colour to pressure correspondence.

To compare the flow analyses, Table 16 has been created. It lists the number of cells for both analyses. It also shows the inlet and outlet pressure for both analyses in Pa.

Table 16: Results of the flow analyses.

	Flow analysis 1	Flow analysis 2
Number of cells	approx. 160 000	approx. 770 000
Inlet pressure $[Pa]$	101 437.42	101 439.62
Outlet press $[Pa]$	101 281.69	101 281.69

If the outlet pressure is subtracted from the inlet pressure for the first analysis, the result is 155.73 Pa. In the analysis with the refined mesh, that is 157.93 Pa. After two analyses were performed, which produced nearly identical results, even though significantly more cells were inserted in the second analysis, these values appear to be realistic. For safety purposes, a margin of 25 % is added to the higher value of 157.93 Pa. This leads to 197.42 Pa, which will be rounded up to 200 Pa. This is the pressure that the blower must overcome for the gas transfer from the GAM to the ALM.
The student thesis, which deals with the design of the Hab Sim and measuring system, shows that the maximum air flow achieved between GAM and ALM is 105 m^3/h [87]. This already includes a safety margin of 25 % [87]. The exact parameters for the simulation are detailed in the thesis.
This leads, in conclusion, to the certainty that the blower has to be able to accelerate

the air to a velocity of 105 m^3/h and overcome a pressure loss of 200 Pa.
A blower fulfilling these requirements was selected from a German manufacturer of electric motors and fans called EBM-Papst. It belongs to the VUCG140A series and can be found in the company's catalogue for DC axial fans. A VDC blower was chosen because, to comply with requirement R05, components that operate on direct current had to be selected.

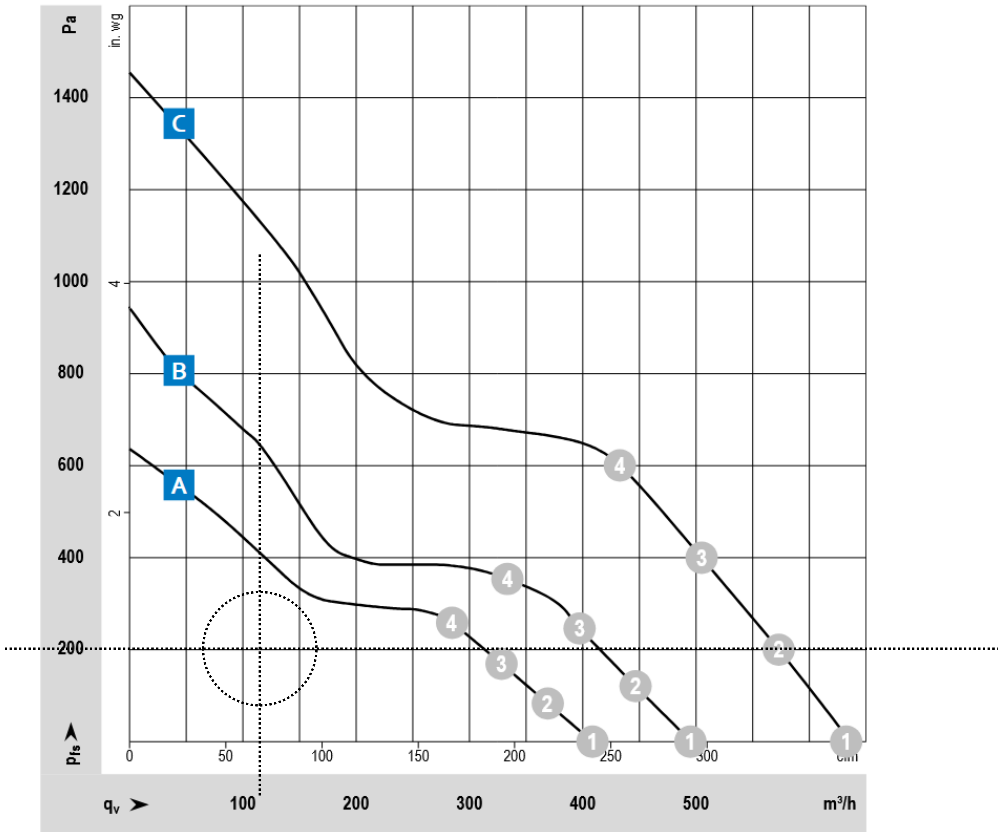

Figure 28: Performance curves of EBM-Papst's VUCG140A series blowers. Required pressure and velocity are indicated by dashed lines. The intersection of the lines is marked by a circle. Adapted from [90].

Figure 28 shows three performance curves of the blowers of the VUCG140A series. The curves have letters from A to C on them. Three blowers belong to curve A, two blowers to curve B, and one to curve C. All of them share the same measures. The X-axis shows the volumetric flow rate in m^3/h, while the Y-axis shows the pressure in Pa. In addition, the required parameters are marked by dotted lines, and the intersection point is marked with a dotted circle. It can be seen that the intersection point lies below all lines. All blowers can implement the required specifications. For the CAD model, the size specification, which is the same for all three blowers, as can be seen in the catalogue, is sufficient. If the assumptions for the design calculations change in the course of the project, there is a chance that one of the other blowers in the series will still meet the changed specifications. Since they all share the measures, it would not change anything in the CAD model and therefore in the volume and spatial need of the system for the gas exchange. In addition to size and performance curves,

the catalogue also provides information on voltage ranges and service life. The service life for blowers that share curve A is 70,000 hours, which is just under eight years. The voltage ranges for blowers with performance corresponding to curve A are 8-16, 16-36, and 36-72 VDC. For the LAM-GTD project, all components for which 120 VDC is converted to lower voltages should require a voltage of 28 VDC [90]. This range includes a blower that corresponds to the performance curve A, namely blower VUCG140AJLQS 5314/2 TDHP. [90]
The size of the blower is 140 x 140x 51 mm and the weight is 900 g [90]. The power consumption depends on the volume flow and can be up to 60 W [90]. An inlet grille is recommended to be used to protect the blower. This might add a further 10 mm to the length of the body, while the cross-section would also be 140 x 140 mm.
The blower is used both for air flow from GAM to ALM and vice versa. Using the same blower twice is intended to reduce the complexity of the system, for example, for repairs. The Air Distribution Unit is missing, which is why the air duct from GAM to ALM ends abruptly. Since it is also unclear how the air is distributed further, it may be that the blowers need to have a higher capacity. This must be taken into account as necessary in the further course of the project.

5.4.2 Gas Exchange through Hermetically Sealed-off Strategy

The gas exchange through the Hermetically Sealed-off Strategy is significantly more complex and involves more components than the gas exchange through the Direct Cabin Air Strategy. Figure 29 and Figure 30 show the gas exchange system that uses the Hermetically Sealed-off Strategy with the gas separation technologies. The right-hand side of Figure 29 and Figure 30 shows the part of the system located in the ALM, while the left-hand side shows the part located in the GAM. The Connecting Ring is located between them. The actual LAM-GTD housing is not visible in Figure 29 and Figure 30.

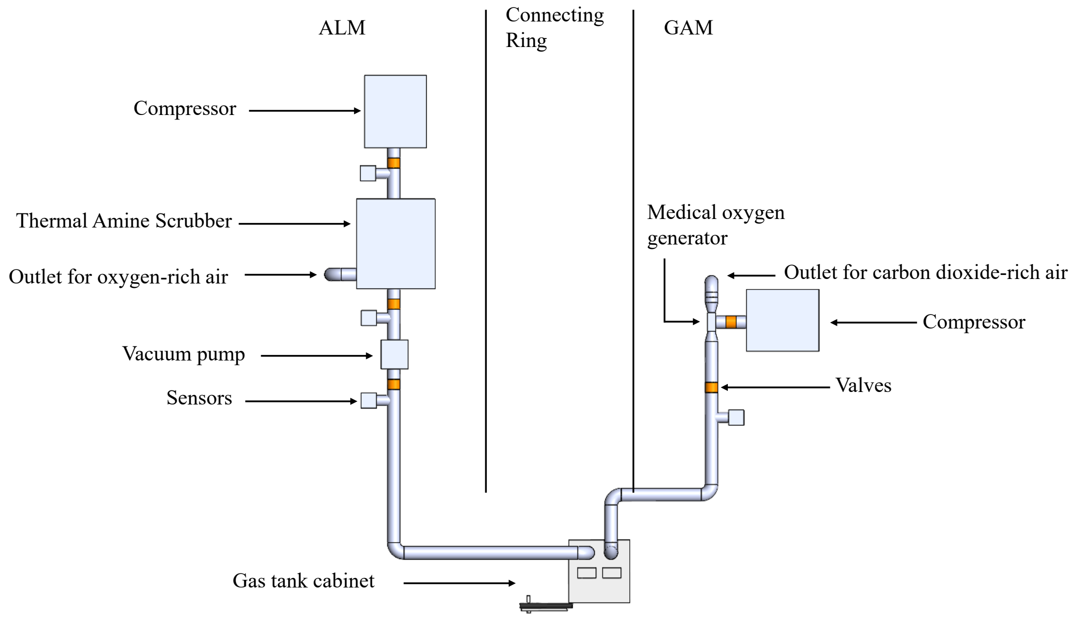

Figure 29: CAD model of the system for the gas exchange through the Hermetically Sealed-off Strategy, from the top.

Figure 29 shows the system from above, and Figure 30 shows it tilted back slightly, also from above.

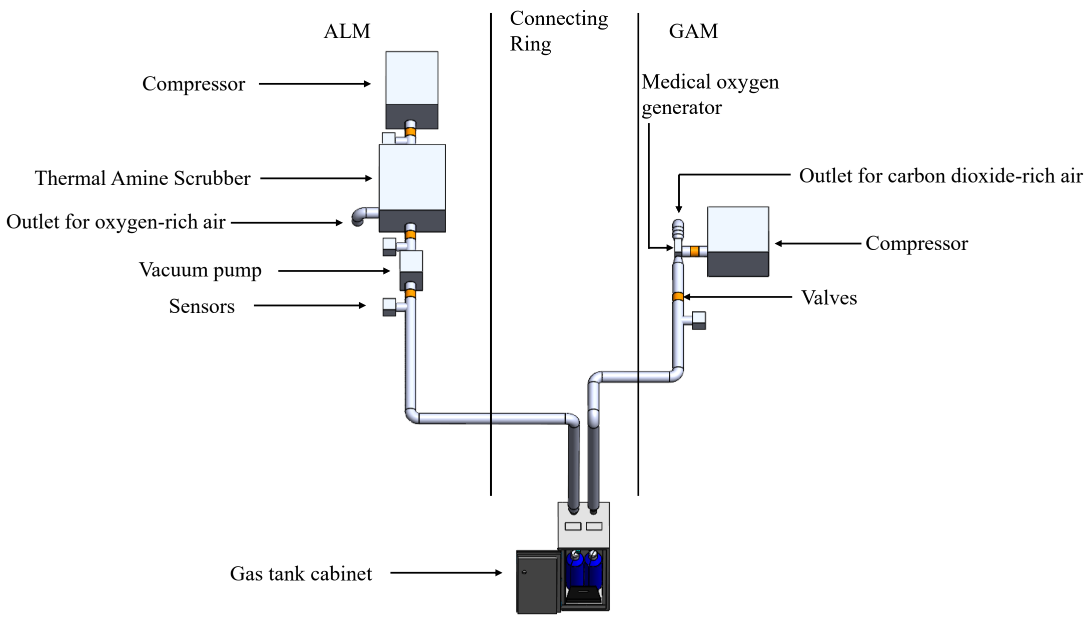

Figure 30: CAD model of the system for the gas exchange through the Hermetically Sealed-off Strategy, tilted from the top.

Since the gas cannot be exchanged directly, it must be stored in storage tanks until it is used. These are represented by the gas tank cabinet.

The CO_2 is to be filtered out of the air in the ALM, which is why the TAS with the other necessary components is to be installed there. The part for filtering CO_2 is significantly larger than the part for filtering O_2, as there is much more CO_2 emitted, which needs to be removed. Furthermore, the composition of air generally consists of a larger percentage of O_2 than CO_2. This means that more air must be treated to separate the same amount of CO_2 as when O_2 is separated.
As shown in Figure 21, the components needed for the CO_2 removal consist of a compressor, the Thermal Amine Scrubber, and a vacuum pump. Various valves and sensors are required as smaller components. The valves are indicated by orange markings on the air ducts. Placeholder boxes connected to the air duct were created as the sensors. These are intentionally larger than most sensors to test the space capacity in the ALM. The placeholder for the Thermal Amine Scrubber represents the four beds filled with solid amines and the Air Safe Pump. An outlet is shown on the TAS through which the oxygen-enriched air is returned to the air stream in the ALM after passing through the beds.
To release the CO_2 from the amines, the bed to be desorbed is heated to 40 to 60 $°C$ [57]. In addition, a vacuum is generated. The temperature of the bed is reduced again when the larger part of the CO_2 has been desorbed. Meanwhile, the vacuum is maintained. Then the bed that is currently being desorbed is connected to the bed that is to be desorbed next. This equalizes the pressure between the two beds. An Air Save Pump is used to remove the residual air from the bed that is next to enter the desorption phase. The fully desorbed bed is then reconnected to the air flow coming from the cabin and starts absorbing CO_2 again. Desorption continues with the next bed. The vacuum pump and heater operate synchronously. This ensures that the correct pressure conditions are achieved to convey the concentrated CO_2 to the tank. Four beds are used to ensure constant CO_2 removal. [57]

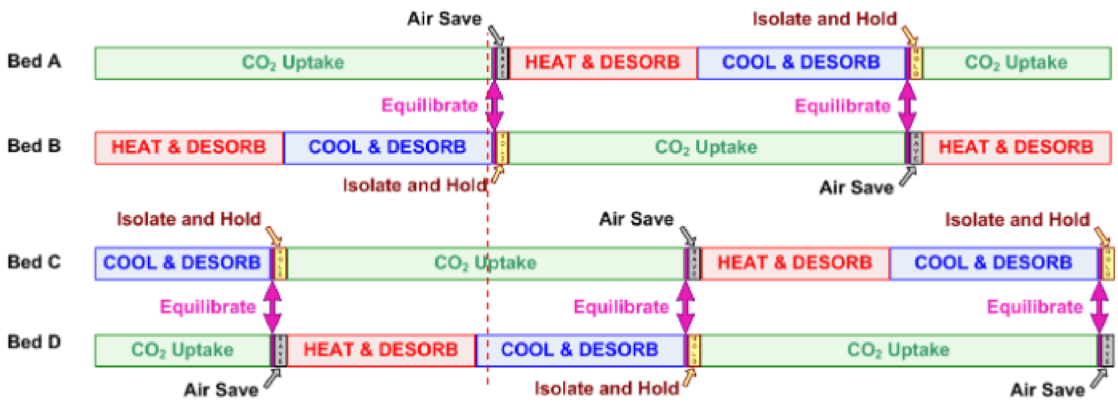

Figure 31: Temporal coordination of the beds of the Thermal Amine Scrubber to switch between adsorption and desorption. [57]

One bed is always in desorption mode. Figure 31 shows the process across all four beds. The beds are divided into two groups. Beds A and B are in one group, and beds C and D are in the other. Within the groups, the beds are connected when executing the pressure equalisation. The process between the groups is delayed so that at least one bed is always adsorbing CO_2. While one group has a saturated bed and an almost completely desorbed bed, the other has a half-saturated bed and a half-desorbed bed. A red dotted line is shown in the diagram. At this point, CO_2 is being removed by beds A and C. The other two beds are in the desorption phase. [57]
Because the beds are subject to temperature fluctuations that must be compensated for, the Thermal Amine Scrubber must be connected to the LAM-GTD subsystem that handles the thermal loads.
In Table 12, the volume, weight, power consumption, and energy consumption are already listed for the TAS. Those values are estimations made by the information given in the literature.

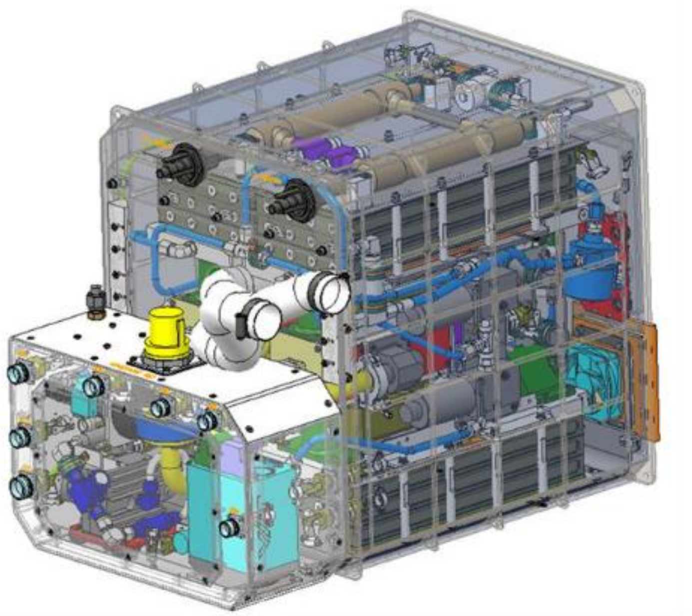

Figure 32: CAD model of the CO_2 locker of the Thermal Amine Scrubber. [53]

Figure 32 shows the carbon dioxide locker of the TAS on the ISS as a CAD model. On the ISS, the TAS consists of an additional H_2O locker, which would be unnecessary for the LAM-GTD. Not adding the H_2O locker to the LAM-GTD's CO_2 removing system reduces the weight, volume, power consumption, energy consumption, and cost.
For the Thermal Amine Scrubber to operate at ambient pressure in the LAM-GTD, a compressor is required to compress the air when the pressure in the demonstrator is reduced.
According to the literature, a blower is used for the TAS on the ISS, which operates well but is mainly operated at maximum speed with a crew of four, rather than at the optimum speed [85]. An improved blower is being sought that will generate an air flow of 0.014-0.017 m^3/s [55] at the optimum speed [55, 85]. Therefore, a speed of 0.017 m^3/s is assumed for the initial volume flow into the TAS and, therefore, the outlet

flow of the compressor, as the compressor is positioned in front of the TAS. To select a compressor fitting for this, the pressure difference before and after the compressor is required. This reaches the maximum value when the operating pressure of the LAM-GTD is 57 kPa. The difference the compressor has to overcome is then 44.3 kPa, which is equivalent to 443 $mbar$. Those parameters are also listed in Table 17.

Table 17: Overview of necessary parameters to decide on a compressor. Inlet volumetric flow rate and pressure difference need to be calculated.

Outlet flow [$\dot{V}2$]	0.017 m^3/s = 61.2 m^3/h
Pressure after outlet [$p1$]	101.33 kPa
Pressure before inlet [$p2$]	57 kPa/70.3 kPa/ 101.33 kPa
Inlet volumetric flow rate [$\dot{V}1$]	
Pressure difference Δp	

Missing values are the inlet flow and the pressure difference before and after the compressor. The pressure difference Δp is calculated by subtracting the pressure before the compressor from the pressure after the compressor. The inlet volumetric flow rate can be calculated using the equation for ideal gases, using the inlet pressure, the outlet pressure, and the outlet volumetric flow rate, as can be seen in Equation 1.

$$\dot{V}1 = \frac{p2}{p1} \times \dot{V}2 \qquad (1)$$

To get the maximum $\dot{V}1$, the lowest $p1$ (57 kPa) is used. That leads to 108.8 m^3/h as an inlet volumetric flow rate.

Table 18: Complete overview of necessary parameters to decide on a compressor. Inlet flow and pressure difference have been calculated.

Outlet flow [$\dot{V}2$]	0.017 m^3/s = 61.2 m^3/h
Pressure after outlet [$p1$]	101.33 kPa
Pressure before inlet [$p2$]	57 kPa/70.3 kPa/ 101.33 kPa
Inlet flow [$\dot{V}1$]	108.8 m^3/h
Pressure difference Δp	44.33 kPa = 443.3 $mbar$

Table 18 provides a complete overview of all the necessary values to decide on a compressor.

An Elmo Rietschle side channel compressor from the G-BH1 series was selected as the appropriate compressor. Upon request, the company provided access to the data sheet for the 2BH1 810 side channel compressor.

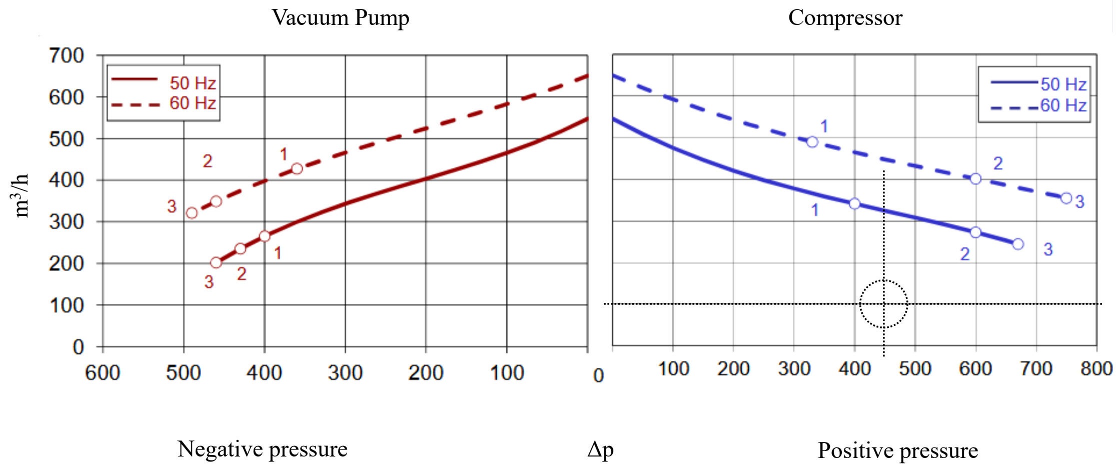

Figure 33: Characteristic curve of Elmo Rietschle's 2BH1 810 side channel compressor. [91]

The inlet volumetric flow rate and the pressure difference across the compressor are plotted on the compressor characteristic curve diagram. It can be seen in Figure 33 by the dotted lines. The dotted circle marks the intersection point. This point lies well below the curve, meaning the compressor is suited for the purpose.
Additionally, this is confirmed by looking at the selection and ordering data in Figure 34. Here, three options are given for specific compressors. The first one can generate a maximum pressure difference of 400 $mbar$ at 50 Hz [91], the second one 600 $mbar$ [91], and the third one can generate 670 $mbar$ [91]. The second compressor on the list is the needed one, since it can handle the 443.3 $mbar$ [91] pressure difference calculated earlier. This is indicated by the yellow marking Figure 34.

Auswahl- und Bestelldaten

Typ 2BH1 810

Nr.	Frequenz	Bemessungs- Spannung	Bemessungs- Strom	Bemessungs- Leistung	Max. Differenzdruck Vakuum	Max. Differenzdruck Verdichter	Schalldruck- pegel	Gewicht ca.	Bestell-Nr.
	Hz	V [1)]	A	kW	mbar [2)]		dB(A) [3)]	kg	
3~ 50/60 Hz, IP55, Isolierstoffklasse F, UL 1450 und CNA/CSA 22.2 No 68-09 (certificate number E225239)									
1	50	345-415 Δ / 600-720 Y	16,7 Δ / 9,6 Y	7,5	-400	400	71	157	**2BH1810-1HH27**
	60	380-480 Δ	17,3 Δ	8,6	-360	330	76		
2	50	345-415 Δ / 600-720 Y	28 Δ / 16,2 Y	11,0	-430	600	71	172	**2BH1810-1HH37**
	60	380-480 Δ	29 Δ	12,6	-460	600	76		
3	50	345-415 Δ / 600-720 Y	32,5 Δ / 18,8 Y	15,0	-460	670	71	181	**2BH1810-1HH47**
	60	380-480 Δ	34,5 Δ	17,3	-490	750	76		
3~ 50/60 Hz, IP55, Isolierstoffklasse F, UL 1450 und CNA/CSA 22.2 No 68-09 (certificate number E225239)									
1	50	500 Y	13,0 Y	7,5	-400	400	71	157	**2BH1810-1HC23**
	60	575 Y	13,6 Y	8,6	-360	330	76		
2	50	500 Y	20,3 Y	11,0	-430	600	71	172	**2BH1810-1HC33**
	60	575 Y	20,4 Y	12,6	-460	600	76		
3	50	500 Y	24,0 Y	15,0	-460	670	71	181	**2BH1810-1HC43**
	60	575 Y	24,5 Y	17,3	-490	750	76		

Figure 34: Additional data for Elmo Rietschle's 2BH1 810 side channel compressor through the selection and ordering data. [91]

Based on the characteristic curve (Figure 33) and the selection and ordering data (Figure 34), the compressor with the order number 2BH1810-1HH37 was selected. This one meets the required technical specifications and weighs approximately 172 kg [91]. A power output of 11 kW [91] is required for operation.

The drawings of the compressor were also sent on request so that the dimensions could be taken from them. Those indicates that the compressor has the dimensions 710 x 606 x 570 mm [92]. Both the data sheet and the drawing can be found on the disk with additional data enclosed with this work.

In addition, a vacuum pump is required to generate the vacuum for desorption. When selecting this pump, it is important to consider that moisture may be present in the air flow. No values could be found for the TAS on the ISS that provide information on the air flow behaviour at the outlet. Therefore, only a rough estimate could be made for the vacuum pump.

Edwards brand vacuum pumps are moisture-resistant. The nXDS scroll pump series includes various vacuum pumps with different performance levels and weights, but all of the same size. This size is 432 x 282 x 302 mm [93] and the volume is used for the placeholder. The heaviest of the pumps weighs 26.2 kg [93]. [93]

The sensors and valves have already been described in Figure 21.

By determining the capacity of the plants to absorb CO_2 and release O_2, it was shown that the plants alone cannot achieve a closed cycle with the crew in terms of atmospheric composition. The CO_2 emissions of the four-person crew are far too much for the plants and cannot be recycled. Similarly, the plants do not produce enough O_2 to supply the crew. Additional payloads should be added to the mission that can reduce CO_2 and possibly generate O_2. One possibility would be a payload with an algae photobioreactor. Another thesis focuses on the integration of an algae photobioreactor into LAM-GTD. Other possibilities would be to add physicochemical components whose sole task is to break down the CO_2. However, this would not produce food for the crew, as would be the case with an algae photobioreactor or plants. As it is not yet clear which other systems will be used to reduce CO_2, the actual amount of CO_2 that needs to be stored in the tank is also unclear. In addition, an O_2 storage facility will also be provided for the ALM, which will be needed to supply the crew with external oxygen. This has not yet been selected either. As the tanks for the separated gas will be located outside the LAM-GTD, they have not been designed in further detail. A gas tank cabinet, which is already used for other purposes in the CAD model of the LAM-GTD, was used as a placeholder.

The system in the GAM comprises significantly fewer components and is smaller, as less gas needs to be removed here because the crops cannot produce as much O_2. There is also less space available in the GAM, as many subsystems have already taken up space here. Since the oxygen concentrator is so small, no dedicated compressor was selected. Instead, the volume of the compressor in the ALM was used for a compressor placeholder in the GAM as well. The compressor designed for the ALM would be rather oversized as a compressor in the GAM. Firstly, CO_2 accumulates more slowly in the GAM because the plants produce less throughout the day. Secondly, less air has to flow through the system until the O_2 produced is separated from the air, as the proportion of oxygen in the composition of the air is significantly higher than the proportion of CO_2. The oversized volume of the compressor from the ALM should therefore be used so that this system can secure enough space in the GAM, should further changes be made. In addition, the system will certainly fit into the GAM with a smaller compressor if it already fits with the oversized compressor. Conversely, the fit is always more difficult. This choice also gives flexibility in terms of weight. Once all the masses have been added up and the total weight is determined, the estimate needs to be done, whether it falls within the weight limit. If some components have been included with too much weight, this leaves room for adjustments.
The Inogen One G5 System (IS-500) with a 16-cell battery was selected for the medical oxygen concentrator. It can reach concentrations of 96 % [94] and is small and handy. It meets all FAA requirements, making it approved for use on aeroplanes.
Its dimensions are 183 x 83 x 203 mm [94] and it weighs 2.6 kg [94]. There are six levels at which the oxygen flow is generated. At the highest level, an oxygen flow of 1260 ml/min [94] is achieved. The concentrator can be operated continuously with direct current. [94]
To compare the oxygen flow with the maximum amount of gas produced by plants, it must be converted from ml/min to kg/d. This requires the density of oxygen, which is 1.429 g/l at 0 °C and 101.3 kPa [95]. This allows the volume of the flow to be converted into mass. Over the course of a day, this concentrator can generate a flow of 2.592 kg/d. This is significantly more than the maximum 0.620 kg/d of oxygen produced by photosynthesis.

5.5 Conclusion

Chapter 5 examined two different systems for the gas exchange in the LAM-GTD. The technical design was described in detail. The two systems are possible ways of

implementing the gas exchange between the ALM and the GAM in the LAM-GTD. The two strategies used in these considerations are the Direct Cabin Air Strategy and the Hermetically Sealed-off Strategy. These were initially designed as block diagrams to identify the functional correlations and the necessary components. Based on these, both approaches were modelled in CAD, which enabled a spatial and volumetric evaluation within the existing LAM-GTD layout. The results show that the system for the gas exchange through the Direct Cabin Air Strategy involves a simple design and little space. The system for the gas exchange through the Direct Cabin Air Strategy, therefore, represents a practical solution.
The system for the gas exchange through the Hermetically Sealed-off Strategy offers more control over the gas parameters, but at the cost of more construction space, power demands, and technical complexity. The use of additional components such as compressors, vacuum pumps, and gas storage tanks increases the weight and maintenance requirements. In summary, it can be said that both concepts are technically feasible, but with differences in terms of system efficiency. The next chapter will be used to compare the two concepts in terms of mass, volume, and power consumption. Then, a proposal on which of the two concepts shall be implemented in the LAM-GTD will be made.

6 Comparative Analysis of the Systems for the Gas Exchange

To compare gas exchange through the Direct Cabin Air Strategy with that through the Hermetically Sealed-off Strategy, parameters such as size, weight, and power consumption are considered. For the size comparison, the two CAD models were individually inserted into the existing CAD model of the LAM-GTD. Then, it was checked whether any components of the CAD model of the system for the gas exchange intersected with components of the LAM-GTD model, and whether the gas exchange models could be adapted accordingly if necessary.
Figure 35 and Figure 36 are excerpts from the LAM-GTD CAD model, into which the system for the gas exchange utilising the Direct Cabin Air Strategy has been integrated.

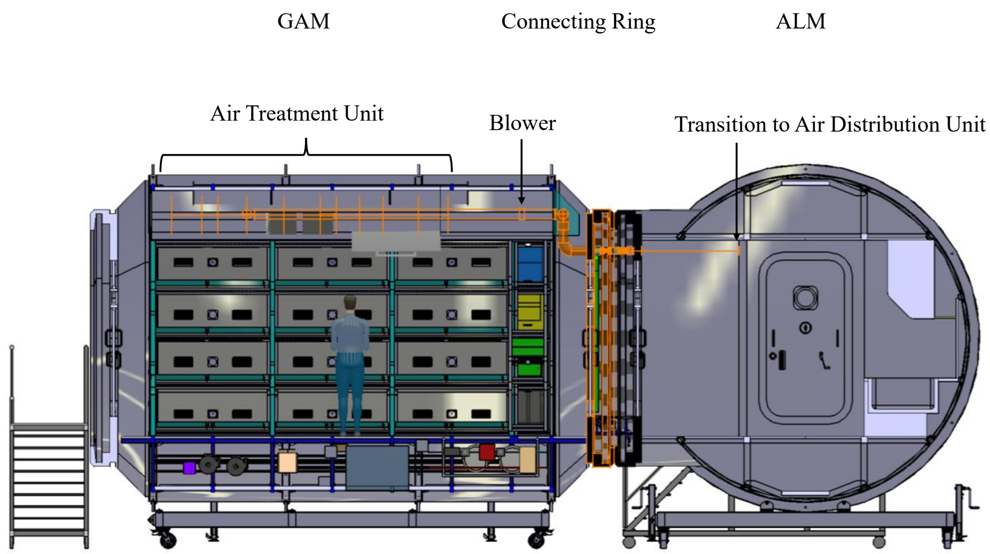

Figure 35: System for the gas exchange through the Direct Cabin Air Strategy within the CAD model of the LAM-GTD. Cross-section view into the GAM and the ALM.

In Figure 35, the viewing position on LAM-GTD is from the other side than in previous figures; the ALM is now on the right-hand side and the GAM on the left. Through the orange outlines, the CAD model of the system for the gas exchange through the Direct Cabin Air Strategy can be identified. Since the system is so small and is not easy to see in the CAD model of LAM-GTD, it had to be highlighted. In this view of the system, the air duct in the direction from the GAM to the ALM is shown. The Air Treatment Unit can be seen from the left to the centre of the GAM, followed by the gas exchange system. The blower can be seen on the right side of the GAM. The air duct then carries the air through the HabSim and into the ALM, where the duct abruptly ends because an Air Distribution Unit still needs to be designed. No component of the

CAD model of the system for the gas exchange through the Direct Cabin Air Strategy overlaps with any components that are already provided for by subsystems other than the AMS in the CAD model of the LAM-GTD.
In Figure 36, the view for the image on the left is selected so that the GAM is on the right and the ALM is on the left. The image on the right is a view from the rear of the GAM (the side not connected to the Connecting Ring) into the GAM.

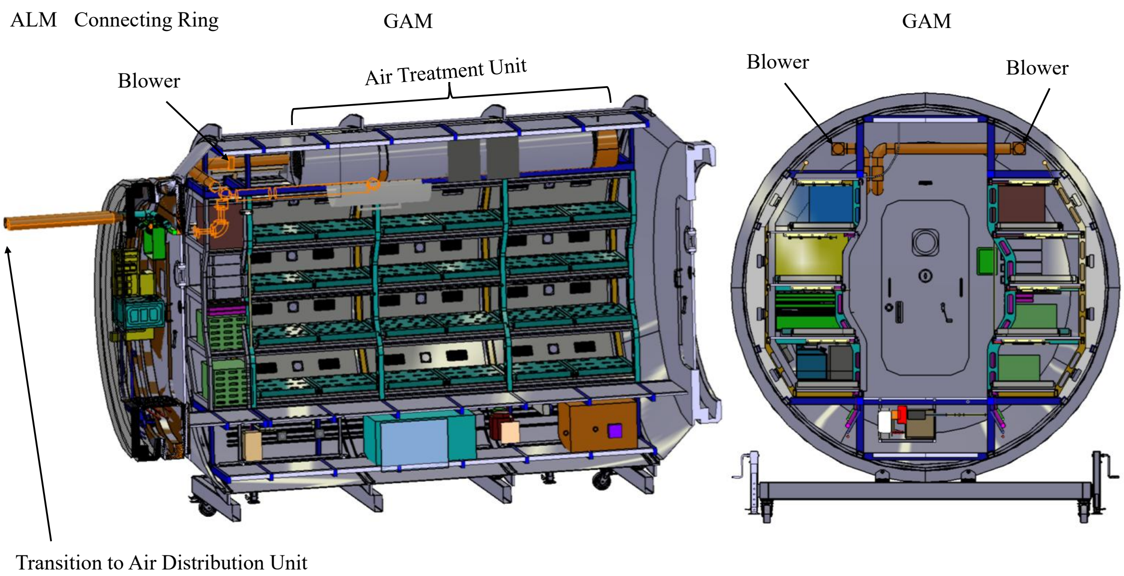

Figure 36: System for the gas exchange through the Direct Cabin Air Strategy within the CAD model of the LAM-GTD. Left: Cross-section view into the GAM. Right: View from the end of the GAM towards the door into the Connecting Ring and ALM.

On the left side of Figure 36, the position of the system for the gas exchange in the GAM above the tray rack is clearly visible. The Air Treatment Unit is also visible. The rear half of the system for the gas exchange can be seen with the air ducts, but due to the cutaway view, the front part is only visible in orange. The air ducts to the HabSim can be seen, as well as its components in the Connecting Ring. Behind the Connecting Ring, the air ducts extend into the ALM, where the Air Distribution Unit is to be connected. On the right-hand side of the image, the air ducts can be seen. The blowers are also visible. For this image, the Air Treatment Unit has been hidden so that the air ducts can be seen.
Figure 37, Figure 38, and Figure 39 show the CAD model of the system for the gas exchange through the Hermetically Sealed-off Strategy within the LAM-GTD model.

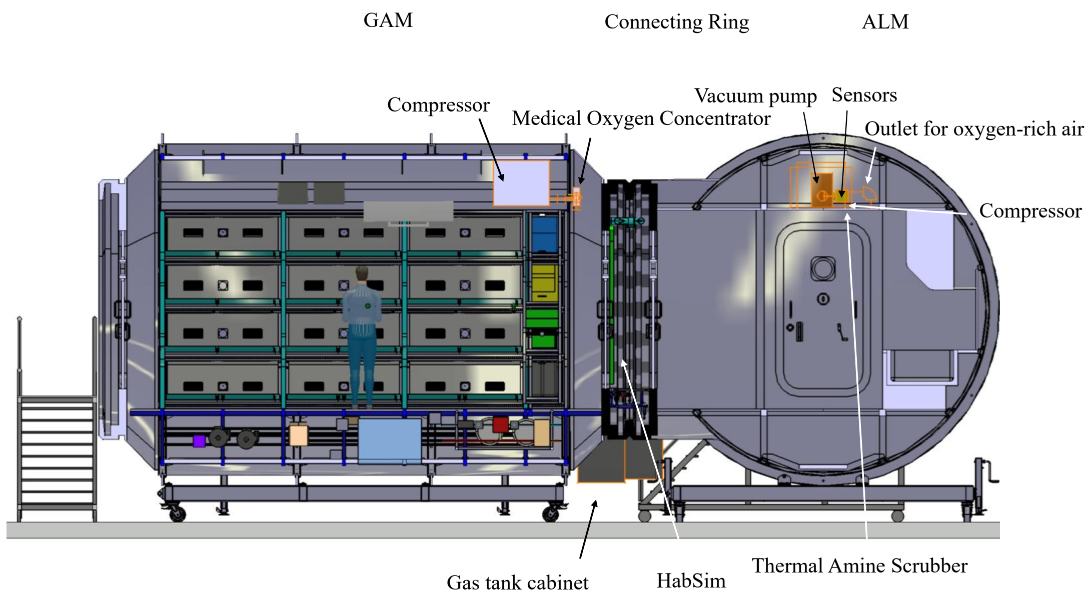

Figure 37: System for the gas exchange through the Hermetically Sealed-off Strategy within the CAD model of the LAM-GTD. Cross-section view into the GAM and the ALM.

Figure 37 shows the model in such a way that the ALM is on the right and the GAM is on the left. In the GAM, the part of the system for the gas exchange responsible for separating oxygen from the air flow can be seen in the inlet area, directly next to the Connecting Ring. It is clearly visible how small the medical oxygen concentrator is compared to other components. In order to make all components visible in the ALM, some had to be hidden so that only the outlines are visible. This is because the components were aligned along the long side of the ALM. First comes the compressor, whose position can be identified by the taller but narrower cube. This is followed by the Thermal Amine Scrubber, which is lower but wider. The vacuum pump did not need to be hidden; it can be seen in orange. Next to it, the placeholder for the sensor technology can be seen in yellow.

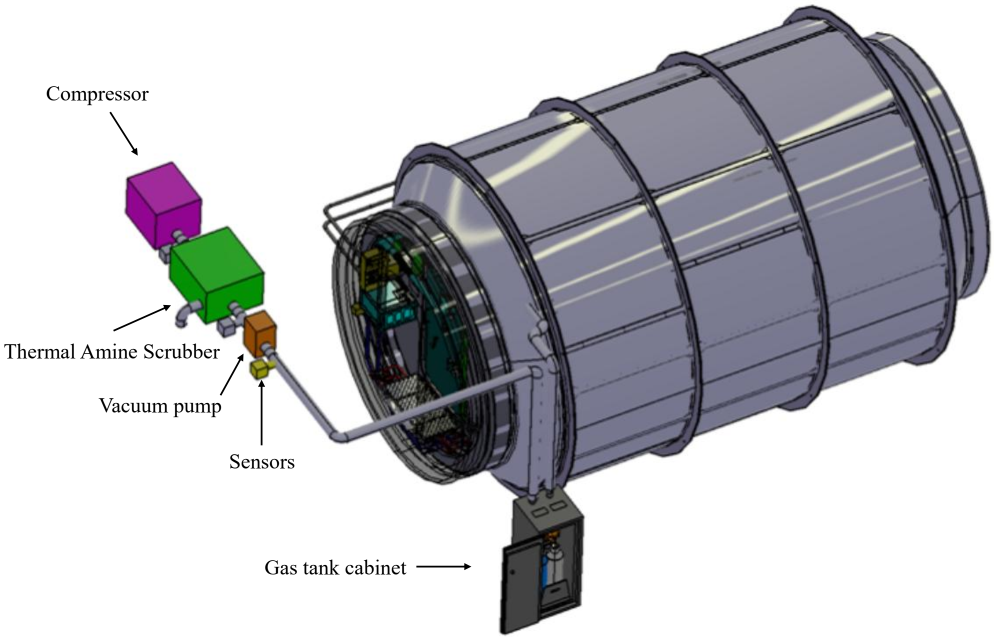

Figure 38: System for the gas exchange through the Hermetically Sealed-off Strategy within the CAD model of the LAM-GTD. The ALM is hidden and the outer shell of the GAM is visible.

Figure 38 shows the outer shell of the GAM part of the LAM-GTD on the right-hand side. To the left is the part of the gas exchange system located in the ALM. However, the outer shell of the ALM and everything within, except for the components for the gas exchange, is hidden. The important components of the part in the ALM are coloured to make them easier to recognise. The compressor is purple, the Thermal Amine Scrubber is green, the vacuum pump is orange, and one of the placeholders for the sensor technology is yellow. The gas tank cabinet is positioned so that it is outside the LAM-GTD.

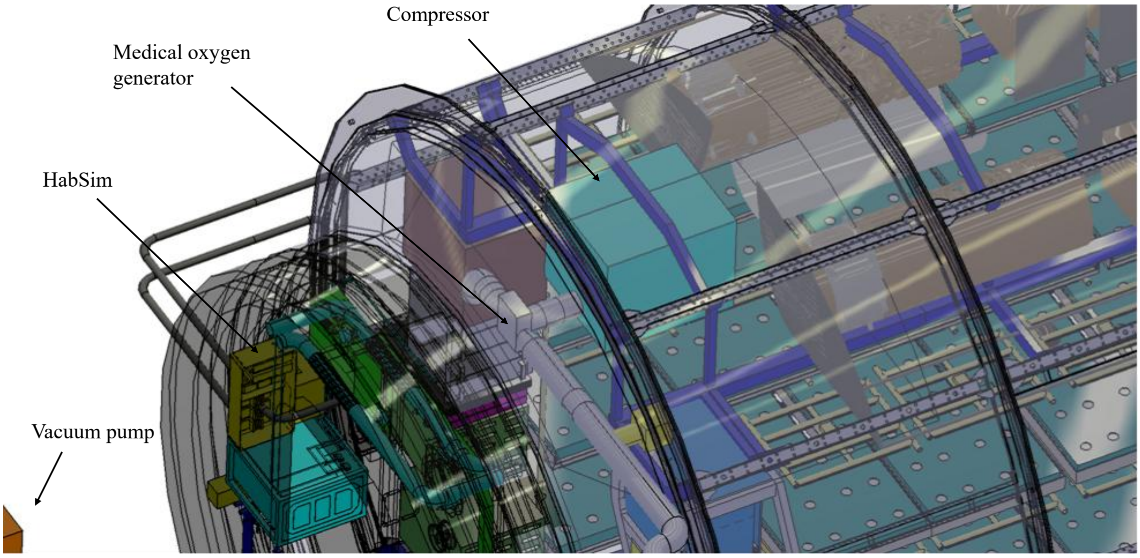

Figure 39: System for the gas exchange through the Hermetically Sealed-off Strategy within the CAD model of the LAM-GTD. Enlarged view into the GAM to show the components.

Figure 39 shows the enlarged view into the GAM. The outer shell has been made transparent for this purpose. A small section of the vacuum pump can be seen in orange at the bottom left of the image. The compressor is now visible in turquoise in the GAM, as is the medical oxygen generator. Both of the compressors, one in the ALM and one in the GAM, have been positioned so that no components are located in front of the inlet, allowing air to be drawn in without obstruction. Figure 37, Figure 38, and Figure 39 make clear that the system for the gas exchange through the Hermetically Sealed-off Strategy fits in the LAM-GTD CAD model, without intersecting any of the already planned components.
This leads to the comparison of both of the systems for the gas exchange, one utilizing the Direct Cabin Air Strategy for it and one the Hermetically Sealed-off Strategy.
Table 19 lists the volume, weight, and power consumption of all components of the system for the gas exchange through the Direct Cabin Air Strategy to conduct the comparison to the system for the gas exchange through the Hermetically Sealed-off Strategy.

Table 19: Volume, weight, and power consumption of the components of the system for the gas exchange through the Direct Cabin Air Strategy.

Component	Volume	Weight	Power Consumption
Blower GAM to ALM	140 x 140 x 51 *mm*	0,9 *kg*	60 *W*
Inlet Grille GAM to ALM	140 x 140 x 10 *mm*	No data. Assumption: 0,9 *kg*	0 *kW*
Blower ALM to GAM	140 x 140 x 51 *mm*	0,9 *kg*	60 *W*
Inlet Grille GAM to ALM	140 x 140 x 10 *mm*	No data. Assumption: 0,9 *kg*	0 *kW*
Total	CAD model compatible with LAM-GTD CAD model.	3.6 *kg*	120 *W*

No weight specifications could be found for the inlet grill. Although it must be lighter than the blower due to the reduced size, it has simply been assumed that the inlet grilles have the same weight as the blowers. The blower is already very light, and this potential overestimation allows for more leeway.
Table 20 lists the volume, weight, and power consumption of all components of the system for the gas exchange through the Hermetically Sealed-off Strategy to conduct the comparison to the system for the gas exchange through the Direct Cabin Air Strategy.

Table 20: Volume, weight, and power consumption of the components of the system for the gas exchange through the Hermetically Sealed-off Strategy.

Component	Volume	Weight	Power Consumption
Compressor ALM	710 x 606 x 570 *mm*	172 *kg*	11 *kW*
Thermal Amine Scrubber	880.88 x 506.48 x 770.13 *mm*	129.3 *kg*	914 *W*
Vacuum Pump	432 x 282 x 302 *mm*	26.2 *kg*	No data. Assumption: 520 *W*
Compressor GAM	710 x 606 x 570 *mm*	172 *kg*	11 *kW*
Medical Oxygen Concentrator	183 x 83 x 203 *mm*	2.6 *kg*	No data. Assumption: 141,71 *W*
Total	CAD model compatible with LAM-GTD CAD model.	502.1 kg	23.576 *kW*

Unfortunately, the power consumption for the medical oxygen concentrator is not apparent from the literature. Since the Thermal Amine Scrubber separates 6.45 times more gas from the air flow, the power consumption of the TAS was divided by this value, and the result was taken as the power consumption of the oxygen concentrator. For the vacuum pump, no power consumption was provided, only a motor power of 260 *W* [96]. Therefore, a power consumption of twice the motor power was assumed.

For both methods, the weight of the air ducts was not included in the calculation, as the length of the components is not final and the air duct lengths may therefore still change.
In terms of size, both methods are compatible with the existing plans for the arrangement within the GAM and ALM. It is also clear that the system for the gas exchange through the Direct Cabin Air Strategy is a lot simpler and contains fewer components. This system, therefore, results in far less weight and power consumption.
At first glance, the system for the gas exchange through the Direct Cabin Air Strategy looks more appealing due to the advantages regarding weight and power consumption. However, to implement the system for the gas exchange through the Direct Cabin Air Strategy, it must be clarified how the crew's CO_2 emissions will be reduced. One of the CO_2 separation techniques that have been described in Chapter 4.1 will most likely be used for this purpose. The EDEN LUNA project uses a soda lime-filled scrubber by Atlas Scientific. In those, the filter material cannot be reused. Such a method can theoretically be used in the GTD as well. But then, when it becomes an actual Lunar Agriculture Module on the lunar surface, it should be avoided to maintain dependence on resupply from Earth, especially since there are other options available. In addition, with a crew of four people, the amounts of CO_2 that need to be filtered out of the

cabin is quite high, which would lead to a high resupply. At this point in the project progression, the payloads to be installed in the ALM have not yet been determined. Therefore, it cannot be assumed that all CO_2 emissions from the crew can be reduced through those, like an additional algae photobioreactor.
As things stand at present, the use of the system for the gas exchange through the Hermetically Sealed-off Strategy is therefore quite attractive, provided that the project management agrees to add the additional weight and power-consuming components to the mission. Since this project offers a rather unique opportunity to test innovative and technically challenging applications over a longer period of time in a research scenario in the Ground Test Demonstrator, this chance should not be missed, and the system for the gas exchange through the Hermetically Sealed-off Strategy should be tested. If, for example, it turns out that more than one greenhouse module needs to be connected to the actual Lunar Agriculture Model on the moon's surface to increase the cultivation area and thus the crew's caloric intake from 10 % supply to a higher percentage, this would help to increasingly close the air loop within the LAM-GTD. Then, the system for the gas exchange through the Hermetically Sealed-off Strategy, with all its advantages, would become inevitable. At that point, however, the gas exchange through the Hermetically Sealed-off strategy should already have been tested.

7 Discussion of the Results

This chapter is intended to serve as a critical reflection on the approach and results of this thesis. Attention should be drawn to those values and results that should be treated with caution, for which not all important aspects were accessible and therefore need to be re-examined at a later point in the project's timeline, or which were taken from the literature without being able to be thoroughly checked.
Values that should be viewed with caution are the statements on the CO_2 absorption capacity and the O_2 production quantity of the different crops. These values were taken from the literature and are static values, even though plants are living organisms. They live through growth cycles and therefore have different uptake and output capacities on a day-to-day basis over a prolonged period of time. Additionally, through the light and darkness cycle they are exposed to, their uptake and output capacity vary a lot over the day. For calculations done in this thesis, it was assumed that the static value given by the literature is an average value over the complete growth cycle. However, it is not specified in the sources how the values were determined. In order to have reliable values that give reliable daily or hourly uptake and output information, separate experiments should be carried out on the selected crops to determine these values. This would allow the cultivation schedule in the GAM to be adjusted so that CO_2 decomposition and O_2 exchange are as uniform as possible. To achieve this, the crops would have to be grown in such a way that not all of them are at the point in the growth cycle where CO_2 uptake and O_2 production are at their maximum at the same time, but the growth cycle should be delayed to one another. Once the experiments have been carried out and more precise and reliable values are available, it must then be checked whether the medical oxygen concentrator can deliver sufficient performance. Another aspect that was not examined in detail is that plants emit CO_2 through their roots at night. No information on these values could be found in the literature. This has to be taken into account in experiments to determine the gas behaviour of plants.

When comparing the relevant CO_2 separation technologies in terms of technical aspects in Table 12, for some of the aspects sought no specific information was available. For FBCO2, this was the volume of the system, and for the TAS, it was the gas concentration achievable.
In addition, estimated values had to be used for the comparison. The current values that could be found for the FBCO2 originate from the design phase; no updated values could be found for the implementation. The weight listed in Table 12 is the sum of the weights of the core system and the other materials that had to be launched. The TAS system on the ISS consists of a water locker and a carbon dioxide locker. For the implementation of the TAS into the LAM-GTD, the water locker will not be necessary, which will result in significant savings in volume, weight, and power requirements. The weight and volume for the carbon dioxide locker without the water locker were found in the literature, but not the power demands. The power demands for the entire TAS system are not significantly higher than the estimated power demands for the FBCO2 from the design phase, which is why a reduction in the power demands by omitting the water locker tips the balance in favour of the TAS.

For the system for the gas exchange through the Direct Cabin Air Strategy, the same blower should be used for both air ducts if possible. These should then be installed once in the air duct in the direction from the ALM to the GAM and once in the other direction from the GAM to the ALM. Chapter 5.4.1 describes how the blower was selected. For that selection, only the information required for the air flow from the GAM to the ALM is available at this moment in the projects timeline, not from the ALM to the GAM. This is because the system for the gas exchange through the Direct Cabin Air Strategy will be connected to the Air Treatment Unit in the GAM. In the ALM, it will be connected to the Air Distribution Unit. The latter has not yet been designed; the Air Treatment Unit has already been designed in another students thesis [88]. Therefore, only information on the Air Treatment Unit is available. Once the Air Distribution Unit has been designed, it will be necessary to check whether the blowers meet the new requirements as well or whether they need to be selected again under the new criteria.
The status as of August 2025 was considered for all calculations and designs related to the Air Treatment Unit. Considerations and ideas for improvement regarding this subsystem of the AMS that were expressed after this date could not be taken into account in this thesis. This also includes incorrect designs or incorrect assumptions in the thesis on the Air Treatment Unit. Table 14 is to be considered here. The values have been taken from the thesis on the Air Treatment Unit and indicate that the blowers, sensors, and fans do not influence the pressure loss in the air treatment unit.
After having decided on the TAS as the reference technology for the system for the gas exchange through the Hermetically Sealed-off Strategy, all the necessary information was collected to design the system. No technically relevant information could be found on the TAS vacuum pump on board the ISS. The only reliable information is that the vacuum pump that will be used in the LAM-GTD must be able to withstand moisture in the air flow, as the moisture is not removed by the water locker. A random pump that meets this criterion was selected in the hope that it is oversized, and the appropriate pump will then have enough space to be added in. The size and mass specified in the data sheets provided by the manufacturer of the selected pump were used for the design. However, only the motor power rating could be obtained from these data sheets. To gain insight into the total power consumption for the evaluation, this value was assumed to be twice as high. A suitable vacuum pump must be selected for the implementation of the system for the gas exchange through the Hermetically Sealed-off Strategy.

To determine whether the medical oxygen concentrator has sufficient flow rate to remove the oxygen from photosynthesis from the GAM, a conversion from ml/min to kg/d had to be carried out. This required the density of oxygen, which is usually determined when oxygen is at a temperature of 0 °C. However, the temperature in the LAM-GTD is higher, which is why the result of the calculation may differ from reality. However, since the medical oxygen concentrator generates significantly more flow than the plants produce oxygen, the selection should still be sufficient.

To compare the total volume, total weight, and total power consumption of the systems for the gas exchange, one through the Direct Cabin Air Strategy and one through the Hermetically Sealed-off Strategy, several assumptions had to be made for missing values. For the system for the gas exchange through the Direct Cabin Air Strategy, an assumption had to be made regarding the weight of the inlet grills. For the system for the gas exchange through the Hermetically Sealed-off Strategy, assumptions had to be made regarding the power consumption of the vacuum pump and the medical oxygen concentrator.

Two further things that were only marginally considered in the design of the systems for the gas exchange are that the crew does not stay exclusively in the ALM, but also has to work in the GAM, so that crew-related CO_2 emission and O_2 consumption also take place directly in the GAM. Additionally, some gas exchange also occurs when the door is opened. It would be helpful to simulate the behaviour of all gases over a certain period of time to verify this. To examine the gas behaviour in these two scenarios, a simulation of the gas behaviour in the LAM-GTD would be useful. This could potentially take into account the crew's daily routine and working schedule.

8 Conclusion and Outlook

The aim of this thesis is the conceptual development and evaluation of a system for the gas exchange between the ALM and the GAM of the LAM-GTD. First, a detailed literature review was conducted. Life Support Systems, their subsystems, and the plant physiology were summarized. The theoretical analysis of the case studies has shown that BLSSs have the potential to close various material cycles. By integrating plants, for example, the carbon dioxide generated by the crew can be reduced, and the oxygen required by the crew can be produced. At the same time, part of the crew's nutrition can be provided by the plants. The discrepancy between the optimal environmental conditions for the crew and the plants requires targeted control of the gas components if high plant production and a crew-friendly indoor climate are to be achieved at the same time.

The literature review was followed by the presentation of four gas exchange strategies, as well as the detailed technical development, evaluation, and CAD modelling of the two best-suited solutions to implement into the LAM-GTD. These were the Direct Cabin Air Strategy and the Hermetically Sealed-off Strategy. The Direct Cabin Air Strategy comprises an air loop that covers the entire LAM-GTD. The air is processed in the GAM and passed back and forth between the GAM and ALM. In the ALM, the crew inhales O_2 and exhales CO_2. The carbon dioxide-enriched air is transported to the GAM, where the CO_2 is absorbed by the plants. In return, they then produce O_2, which is transported back to the crew in the ALM by the air flow. The advantage is that it is easy to implement, as few components are required. However, individual requirements of the crew and crops, as well as temperature and humidity, cannot be the main focus. Crops must cope with crew needs, which can reduce yields. The Hermetically Sealed-off Strategy, on the other hand, comprises two air loops that are separate from each other. One is in the ALM, the other in the GAM. The air circulates without exchange in the ALM and GAM. Only CO_2 and O_2 are exchanged. The gases are separated from the air flow where they are produced. This means that CO_2 is separated in the ALM and O_2 in the GAM. Additional components are required for separation, but this allows individual atmospheric conditions to be achieved in the modules, depending on the needs of crops and crew.

To implement the Hermetically Sealed-off Strategy for gas exchange, technologies must be used that separate carbon dioxide and oxygen from the air. Various technologies were analysed and evaluated for this purpose. Those technologies that can be regenerated are preferable in the mission context for separation. Solid amines, a material also found in the Thermal Amine Scrubber on board the ISS, were selected as the best option for separating carbon dioxide. A medical oxygen concentrator proved to be the most suitable option for oxygen separation. This is based on the use of molecular sieves. On this basis, the technical combination of TAS and a medical oxygen concentrator was chosen as the architecture for implementing the Hermetically Sealed-off Strategy.

A key interim result is the quantitative assessment of the contribution of the plants through photosynthesis to the crew's needs. The modelled yields and calculated oxygen production rates of the planned plant types are neither sufficient to cover the entire oxygen requirements of the four-person crew nor to process the crew's carbon dioxide emissions. Against this background, additional payloads for gas control should be in-

tegrated into the LAM-GTD.
To compare the systems for the gas exchange through the Direct Cabin Air Strategy and the Hermetically Sealed-off Strategy, the CAD models of both systems were integrated into the existing LAM-GTD model using block diagrams as the basis for the models. This resulted in the following findings. The Direct Cabin Air Strategy has low system complexity, low mass, and low space requirements; however, it does not allow independent optimisation of climate parameters in GAM and ALM. The Hermetically Sealed-off Strategy, on the other hand, enables targeted, selective gas transfer, which simultaneously creates optimal growing conditions for plants and favourable living conditions for the crew. However, this only works with higher space requirements, higher power consumption, and increased system complexity, such as compressors, vacuum pumps, and gas tanks. The integration of the CAD model confirms the basic suitability and integrability of the system for the gas exchange through the Hermetically Sealed-off Strategy into the LAM-GTD layout.
The selection of components for the systems was not the aim of this thesis. Components were selected solely for the purpose of estimating the space requirements of the two possible implementations of the gas exchange.
Against the backdrop of the mission objectives, the gas exchange through the Hermetically Sealed-off Strategy is recommended as the preferred solution. This decision was made based on several arguments. Firstly, it was clearly demonstrated that an oxygen deficiency and a carbon dioxide excess develop over a certain period. Currently, no further payloads are planned to break down carbon dioxide, but the carbon dioxide must be reduced in greater quantities than plants can through photosynthesis to protect the crew. This can only be achieved through the Hermetically Sealed-off Strategy. Secondly, this gas exchange strategy allows the growing conditions for the plants to be optimised, which in turn optimises the yield. This allows for the maximum BLSS performance to be achieved. Thirdly, this makes the processes controllable. A fourth argument is that the gases can also be used for other processes in a later habitat due to the temporary storage in the tanks.
Further work on this topic could include experimental validation of the values given by the literature regarding the CO_2 uptake and O_2 output by the individual crops. Additionally, a CFD study might be carried out to take a detailed look at the air flow within the LAM-GTD. This could also take into account the crew's daily schedule.
All in all, it can be said that, in theory, both systems are suitable for implementation as the system for the gas exchange in the LAM-GTD. The advantages and disadvantages have been explained in detail, and a recommendation for one of the two systems has been made.

Appendix

References

[1] The International Space Exploration Coordination Group. *Global Exploration Roadmap*. 2024.

[2] Daniel Schubert. "System Analysis of Plant Production in Greenhouse Modules as an Integrated Part of Planetary Habitats". PhD thesis. University of Bremen, 2018.

[3] Volker Maiwald et al. "From Antarctic prototype to ground test demonstrator for a lunar greenhouse". In: *Acta Astronautica* 212 (2023), pp. 246–260.

[4] Peter Eckart. *Spaceflight Life Support and Biospherics*. Springer Science & Business Media, 1996.

[5] Ernst Messerschmid and Reinhold Bertrand. *Space Stations: Systems and Utilization*. Springer-Verlag Berlin Heidelberg 1999, 1999.

[6] Institut für Raumfahrtsysteme. *EDEN Initiative*. 2025. URL: https://www.dlr.de/de/irs/ueber-uns/abteilungen/systemanalyse-raumsegment/planetare-infrastukturen/eden-initiative. Access at: 2025-07-08, 02:07 pm.

[7] Park S Nobel. *Physicochemical and Environmental Plant Physiology*. Elsevier Science Technology, 2005.

[8] Alan R Hemsley and Imogen Poole. *The evolution of plant physiology*. Elsevier, 2004.

[9] Life Worksheets. *Life Cycle of Tomato Plant*. 2025. URL: https://i2.wp.com/www.kindpng.com/picc/m/155-1551668_seeds-clipart-plant-life-cycle-simple-life-cycle.png. [Access at: 2025-09-05, 02:25 pm].

[10] Michael R Barratt and Sam Lee Pool. *Principles of clinical medicine for space flight*. Springer Science & Business Media, 2008.

[11] Michael K. Ewert, Thomas T. Chen, and Camilah D. Powell. *Life support baseline values and assumptions document*. Tech. rep. National Aeronautics and Space Administration, 2022.

[12] LAM-GTD Project Members. "LAM-GTD Altium Requirements Database". Unpublished.

[13] National Aeronautics and Space Administration. *Veggie*. 2025. URL: https://science.nasa.gov/mission/veggie/. Access at: 2025-11-07, 11:14 am.

[14] Gioia D Massa et al. "Growth chambers on the International Space Station for large plants". In: *VIII International Symposium on Light in Horticulture 1134*. 2016, pp. 215–222.

[15] Paul Zabel et al. "Review and analysis of over 40 years of space plant growth systems". In: *Life sciences in space research* 10 (2016), pp. 1–16.

[16] Gary Stutte et al. "Operational evaluation of VEGGIE food production system in the habitat demonstration unit". In: *41st International Conference on Environmental Systems*. 2011.

[17] NASA Jim Cawley. *NASA Teams Persevere Through Plant Challenges in Space*. 2023. URL: https://www.nasa.gov/missions/station/nasa-teams-persevere-through-plant-challenges-in-space/. Access at: 2025-10-01, 12:04 pm.

[18] Y Tako et al. "One-week habitation of two humans in an airtight facility with two goats and 23 crops-Analysis of carbon, oxygen, and water circulation". In: *Advances in Space Research* 41.5 (2008), pp. 714–724.

[19] Yasuhiro Tako et al. "CEEF: closed ecology experiment facilities". In: *Gravitational and Space Research* 23.2 (2010).

[20] Keiji Nitta. "The Mini-Earth facility and present status of habitation experiment program". In: *Advances in Space Research* 35.9 (2005), pp. 1531–1538.

[21] K Nitta, K Otsubo, and A Ashida. "Integration test project of CEEFA test bed for closed ecological life support systems". In: *Advances in Space Research* 26.2 (2000), pp. 335–338.

[22] Yasuhiro Tako et al. *Major achievements of material circulation-closed habitation experiments using Closed Ecology Experiment Facilities: JAXA*. 2017.

[23] Koichi Abe et al. "Simulation model for the closed plant experiment facility of CEEF". In: *Advances in Space Research* 35.9 (2005), pp. 1597–1608.

[24] Yuming Fu et al. "Establishment of a Closed Artificial Ecosystem to Ensure Human Long-term Survival on the Moon". In: *BioRxiv* (2021).

[25] Yuming Fu et al. "How to Establish a Bioregenerative Life Support System for Long-term Crewed Missions to the Moon or Mars". In: *Astrobiology* 16.12 (2016), pp. 925–936.

[26] Jingfei Hu et al. "Reliability and lifetime estimation of bioregenerative life support system based on 370-day closed human experiment of lunar palace 1 and Monte Carlo simulation". In: *Acta astronautica* 202 (2023), pp. 609–616.

[27] Jason Silverman, Andrew Irby, and Theodore Agerton. "Development of the crew dragon ECLSS". In: *International Conference on Environmental Systems*. International Conference on Environmental Systems. 2020.

[28] Brenda Hernandez, Mauro Prina, and Siarhei Piatrovich. "Spacex dragon air circulation system". In: *International Conference on Environmental Systems*. 2011.

[29] Paul Zabel et al. "The Preliminary design of the EDEN ISS mobile test facility-an antarctic greenhouse". In: *International Conference on Environmental Systems*. 46th International Conference on Environmental Systems. 2016.

[30] Paul Zabel et al. "Energy and power demand of food production in space based on results of the EDEN ISS Antarctic greenhouse". In: *International Conference on Environmental Systems*. 51st International Conference on Environmental Systems. 2022.

[31] Paul Zabel et al. “Crewtime in a Space Greenhouse based on the Operation of the EDEN ISS Greenhouse in Antarctica”. In: *International Conference on Environmental Systems*. 49th International Conference on Environmental Systems. 2019.

[32] Tobias Korth et al. “Environmental Control Systems for EDEN LUNA Plant Production Module”. In: *International Conference on Environmental Systems*. 54th International Conference on Environmental Systems. 2025.

[33] Vincent Vrakking et al. “Status and future of the EDEN ISS Mobile Test Facility”. In: *International Conference on Environmental Systems*. International Conference on Environmental Systems. 2020.

[34] Conrad Zeidler and Jess Bunchek. “Workload measurements in the EDEN ISS greenhouse during the 2021 Antarctic overwintering mission”. In: *International Conference on Environmental Systems*. 52nd International Conference on Environmental Systems. 2023.

[35] Paul Zabel et al. “Future exploration greenhouse design of the EDEN ISS project”. In: *International Conference on Environmental Systems*. 47th International Conference on Environmental Systems. 2017.

[36] Volker Maiwald et al. “From ice to space: a greenhouse design for Moon or Mars based on a prototype deployed in Antarctica”. In: *CEAS Space Journal* 13.1 (2021), pp. 17–37.

[37] Paul Zabel et al. “Implications of different plant cultivation techniques for food production in space based on experiments in EDEN ISS”. In: *International Conference on Environmental Systems*. International Conference on Environmental Systems. 2020.

[38] Vincent Vrakking et al. “System design of the EDEN LUNA greenhouse: Upgrading EDEN ISS for future Moon mission simulations”. In: *International Conference on Environmental Systems*. 53rd International Conference on Environmental Systems. 2024.

[39] M. Franke et al. *DLR-EL-AMS-DD-0028 AMS Design Document*. Sept. 2024.

[40] V. Vrakking and G. Bonzano. *D3.7Environmental Control Design Document*. Sept. 2017.

[41] Vincent Vrakking et al. “Summary of research and outreach activities during the 2021 season of the EDEN ISS Antarctic greenhouse”. In: *International Conference on Environmental Systems*. 51st International Conference on Environmental Systems. 2022.

[42] Daniel Schubert et al. “Status of the EDEN ISS greenhouse after on-site installation in Antarctica”. In: *International Conference on Environmental Systems*. 48th International Conference on Environmental Systems. 2018.

[43] Jared Stoochnoff et al. “Canadian Food Production Subsystem Designs for a Lunar Agriculture Module-Ground Test Demonstrator (LAM-GTD)”. In: *International Conference on Environmental Systems*. 54th International Conference on Environmental Systems. 2025.

[44] Michel F. Franke. *Lunar Agriculture Module Ground Test Demonstrator: Project Presentation for NASA*. Jan. 2025.

[45] Maria Antonietta Costagliola, Maria Vittoria Prati, and Giuseppe Perretta. "Post Combustion CO2 Capture with Calcium and Lithium Hydroxide". In: *Scientific Reports* 12.1 (2022), p. 10518.

[46] AtlasScientific Environmental Robotics. *Co2 Scrubber Spec Sheet*. 2025. URL: https://files.atlas-scientific.com/Co2-scubber-spec-sheet.pdf. [Access at: 2025-07-09, 11:17 am].

[47] AtlasScientific Environmental Robotics. *Co2 Scrubber*. 2025. URL: https://atlas-scientific.com/co2/co2-scrubber/. [Access at: 2025-10-01, 01:37 pm].

[48] P. O. Wieland. *Designing for Human Presence in Space: an Introduction to Environmental Control and Life Support Systems (ECLSS)*. Tech. rep. National Aeronautics and Space Administration, 2005.

[49] Dina El Sherif and James C Knox. *International space station carbon dioxide removal assembly (ISS CDRA) concepts and advancements*. Tech. rep. SAE Technical Paper, 2005.

[50] K. Murdock. *Integrated Evaluation of Closed Loop Air Revitalization System Components*. Tech. rep. National Aeronautics and Space Administration, 2010.

[51] Jun Isobe et al. "Carbon dioxide removal technologies for space vehicles-past, present, and future". In: *International Conference on Environmental Systems*. 46th International Conference on Environmental Systems. 2016.

[52] Gregory E Cmarik, James C Knox, and John Garr. "Progress of four bed carbon dioxide scrubber". In: *International Conference on Environmental Systems*. 51th International Conference on Environmental Systems. 2021.

[53] Holden Ranz, Steven Dionne, and John Garr. "A Thermally-regenerated Solid Amine CO2 Removal System Incorporating Water Vapor Recovery and Ullage Air Recovery". In: *International Conference on Environmental Systems*. 49th International Conference on Environmental Systems. 2019.

[54] Elif Erdal Ünveren et al. "Solid Amine Sorbents for CO2 Capture by Chemical adsorption: A Review". In: *Petroleum* 3.1 (2017), pp. 37–50.

[55] Holden T. Ranz, Steven Dionne, and John D. Garr. "Thermal Amine Scrubber-Renewed Operational Status & Planned Upgrades". In: *International Conference on Environmental Systems*. 53rd International Conference on Environmental Systems. 2024.

[56] X. Duan et al. "Chemisorption and Regeneration of Amine-based CO2 Sorbents in Direct Air Capture". In: *Materials Today Sustainability* 23 (2023), p. 100453.

[57] William Papale et al. "An Advanced CO2 Removal System Using Regenerable Solid Amines". In: *International Conference on Environmental Systems*. 46th International Conference on Environmental Systems. 2016.

[58] John R Tidwell et al. “Xplo-SA9T: Optimization of Sorbent Technology With Existing and New Amine Variants for Carbon Dioxide Removal and Humidity Control”. In: *53rd International Conference on Environmental Systems*. International Conference on Environmental Systems. 2024.

[59] Nadia Norahim et al. “Recent Membrane Developments for CO2 Separation and Capture”. In: *Chemical Engineering & Technology* 41.2 (2018), pp. 211–223.

[60] Adolfo Iulianelli and Enrico Drioli. “Membrane Engineering: Latest Advancements in Gas Separation and Pre-treatment Processes, Petrochemical Industry and Refinery, and Future Perspectives in Emerging Applications”. In: *Fuel processing technology* 206 (2020), p. 106464.

[61] NS Hassan et al. “A Comprehensive Review on Zeolite-based Mixed Matrix Membranes for CO2/CH4 Separation”. In: *Chemosphere* 314 (2023), p. 137709.

[62] Max Saffer-Meng, Anthony P Straub, and Kian P Lopez. “Liquid Water Membranes for Carbon Dioxide Removal and Humidity Condensation in Spaceflight Systems”. In: *International Conference on Environmental Systems*. 54th International Conference on Environmental Systems. 2025.

[63] P Bernardo et al. “Membrane Technologies for Space Engineering”. In: *Journal of Membrane Science* 626 (2021), p. 119177.

[64] P Sledzik et al. “Continuous Electrochemical Carbon Capture via Redox-Mediated pH Swing Experimental Performance and Process Modeling”. In: *The Journal of Physical Chemistry Letters* 16.5 (2025), pp. 1343–1351.

[65] Alessandra M Zito et al. “Electrochemical Carbon Dioxide Capture and Concentration”. In: *Chemical Reviews* 123.13 (2023), pp. 8069–8098.

[66] Alexander P Muroyama, Alexandra Ptru, and Lorenz Gubler. “CO2 Separation and Transport via Electrochemical Methods”. In: *Journal of The Electrochemical Society* 167.13 (2020), p. 133504.

[67] MS Sajna et al. “Electrochemical System Design for CO2 Conversion: A Comprehensive Review”. In: *Journal of Environmental Chemical Engineering* 11.5 (2023), p. 110467.

[68] JJ Schneider et al. *Electrochemical Carbon Dioxide Concentrator Advanced Technology Tasks*. Tech. rep. National Aeronautics and Space Administration, 1975.

[69] Joseph C. Shy and James A. Nabity. “Ionic Liquid CO2 Capture: CO2 Desorption Technology Review”. In: *International Conference on Environmental Systems*. 54th International Conference on Environmental Systems. 2025.

[70] Felix Nitschke and James Nabity. “Ionic Liquid-based CO2 Control of Plant Growth Chamber Atmospheres”. In: *International Conference on Environmental Systems*. 52nd International Conference on Environmental Systems. 2023.

[71] Stephen F Yates et al. “Scale-up of the Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) System”. In: *International Conference on Environmental Systems*. 49th International Conference on Environmental Systems. 2019.

[72] Bharath Tate, M. Lucas Chernoff, and James A. Nabity. "Humidity Effects in Supported Ionic Liquid Membranes for Spacecraft CO2 Capture". In: *International Conference on Environmental Systems*. 54th International Conference on Environmental Systems. 2025.

[73] Phoebe Henson et al. "Carbon Dioxide Removal by Ionic Liquid System (CDRILS): Continuous Operation and Full-Scale Brassboard Testing". In: *International Conference on Environmental Systems*. 50th International Conference on Environmental Systems. 2021.

[74] Kelly M Gilkey and Sandra L Olson. *Evaluation of the Oxygen Concentrator Prototypes: Pressure Swing Adsorption Prototype and Electrochemical Prototype*. Tech. rep. National Aeronautics and Space Administration, 2015.

[75] Randeep Singh, Babul Prasad, and Young-Ho Ahn. "Recent Developments in Gas Separation Membranes Enhancing the Performance of Oxygen and Nitrogen Separation: A Comprehensive Review". In: *Gas Science and Engineering* 123 (2024), p. 205256.

[76] Michell Instruments. *Process oxygen - air separation applications*. 2016.

[77] P. et al. Haidl. *Guideline for Long-Term Oxygen Therapy*. 2020.

[78] Olivia Mendelsohn. "Lunar Agriculture Module-Ground Test Demonstrator Mission and System Design Definition File". Unpublished.

[79] Olivia Mendelsohn. "Biomass Estimation Tool". Unpublished. 2025.

[80] Olivia Mendelsohn and Mark Lefsrud. "Framework for Optimizing Crop Selection for Future Space Missions". In: *International Conference on Environmental Systems*. 54th International Conference on Environmental Systems. 2025.

[81] James Knox, Gregory Cmarik, and John Garr. "Four Bed Carbon Dioxide Scrubber Engineering Development Unit Cabin Air Inlet Testing". In: *International Conference on Environmental Systems*. 53th International Conference on Environmental Systems. 2023.

[82] Gregory E. Cmarik, Warren T. Peters, and James C. Knox. "4-Bed CO2 Scrubber - From Design to Build". In: *International Conference on Environmental Systems*. International Conference on Environmental Systems. 2020.

[83] Sean W. Thompson, Lee P. Jordan, and Ginger N. Flores. *An Overview of ExPRESS, WORF, and MSG Platforms*. 2014. URL: https://ntrs.nasa.gov/api/citations/20140011706/downloads/20140011706.pdf?attachment=true. Access at: 2025-10-17, 02:12 pm.

[84] A Gutierrez-Ortega et al. "A fast methodology to rank adsorbents for CO2 capture with temperature swing adsorption". In: *Chemical Engineering Journal* 435 (2022), p. 134703.

[85] Holden Ranz, Steven Dionne, and John Garr II. "Thermal Amine Scrubber-Space Station Installation and Start-Up". In: *International Conference on Environmental Systems*. International Conference on Environmental Systems. 2020.

[86] GPG Gase Partner GmbH. *Mobile Sauerstoffkonzentratoren*. 2025. URL: https://gase-kaufen.de/blog/mobile-sauerstoffkonzentratoren-n56. Access at: 2025-09-28, 01:00 pm.

[87] Niklas Moos. "Conceptual system design of a Habitat-Simulator (HabSim) for the operation of the Lunar Agriculture Module-Ground Test Demonstrator (LAM-GTD)". Diploma Thesis, Unpublished. 2025.

[88] Paul Guastavino. "Development of the Atmosphere Management System for the Lunar Agricultural ModuleGround Test Demonstrator LAM-GTD". Master Thesis, Unpublished. 2025.

[89] Dr. Gerald Lattauschke. *Anbau von Gewächshausgemüse, Hinweise zum umweltgerechten Anbau*. 2004.

[90] ebmpapst. *Productübersicht DC-Axiallüfter*. 2022. URL: https://www.ebmpapst.com/content/dam/ebm-papst/products/compact-fans/axial-compact-fans/DC-Axiall%C3%BCfter-katalog.pdf. Access at: 2025-10-19, 01:50 pm.

[91] Elmo Rietschle. *G-BH1 Datenblatt 2BH1 810 Seitenkanalverdichter*. Tech. rep. Gardner Denver Deutschland GmbH, 2021.

[92] Bayer and Kraus. *Massblatt 2BH1810-1H.3.* Tech. rep. Gardner Denver Deutschland GmbH, 2022.

[93] Edwards. *Dry Vacuum Pump nXDS Scroll Pump Instruction Manual*. 2024. URL: https://new.marshallscientific.com/v/vspfiles/specs/Edwards%20nXDS%20Dry%20Scroll%20Pumps%20Manual%20-%20Marshall%20Scientific.pdf. Access at: 2025-10-17, 04:16 pm.

[94] GPG Gase Partner GmbH. *Mobiler Sauerstoffkonzentrator Inogen One G5 (16-cell)*. 2025. URL: https://gase-kaufen.de/sauerstoffkonzentratoren/671-mobiler-sauerstoffkonzentrator-inogen-one-g5-system-is-500-4260509847346.html. Access at: 2025-11-10, 10:32 pm.

[95] Robert C. Brasted. *oxygen*. 2025. URL: https://www.britannica.com/science/oxygen. Access at: 2025-10-19, 11:20 am.

[96] Edwards Limited. *nXDS Dry Scroll Pumps*. 2028. URL: https://www.edwardsvacuum.com/content/dam/brands/edwards-vacuum/general-vacuum/downloads/dry-scroll-pumps/3601-0088-01-nXDS-brochure.pdf. Access at: 2025-10-20, 01:35 pm.