Title
Environmental Control and Life Support Systems: Review, Concept, Design, Build, Test of a Carbon Dioxide Removal Testbed to Investigate Degradation and Maintenance in Space Habitats

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Environmental Control and Life Support Systems: Review, Concept, Design, Build, Test of a Carbon Dioxide Removal Testbed to Investigate Degradation and Maintenance in Space Habitats

By

DANIELA BARAJAS IVEY

THESIS

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

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in the

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of the

UNIVERSITY OF CALIFORNIA

DAVIS

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2024

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Abstract

Environmental Control and Life Support Systems: Review, Concept, Design, Build, Test of a Carbon Dioxide Removal Testbed to Investigate Degradation and Maintenance in Space Habitats

by

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Master of Science in Mechanical and Aerospace Engineering

University of California, Davis

Dr. Stephen K. Robinson, Chair

A vital element of any human-rated mission is the Environmental Control and Life Support System (ECLSS), composed of multiple subsystems, including an Air Revitalization subsystem that maintains a breathable atmosphere. Tracking performance, identifying performance degradation, predicting remaining useful life of components, and performing maintenance on such a critical system are paramount to creating a safe, habitable environment and are thus key research areas at the UC Davis Center for Spaceflight Research. This thesis outlines the design, build, and test of the ZeoDe (Zeolite Capacity Degradation) testbed at the UC Davis Center for Spaceflight research, as well as the background research that went into its conception. This testbed is a chemically functional CO_2 removal system that generates degradation data for prognostics through the introduction of humidity into the system. The introduction of humidity can occur in a space habitat due to leaks or other faults. Humidity build-up within the system leads to CO_2 removal capacity degradation of the sorbent. Thus, the study of sorbent degradation is of paramount importance to any zeolite-based CO_2 removal system deployed on future spacecraft. The maintenance of such a system is equally important. The base requirements of the ZeoDe system take both human and robotic maintainability into account, along with the development of a twin robotically manipulable mockup that was also built up at the UCD Center for Spaceflight Research. The ZeoDe testbed will allow UC Davis, NASA, and any visiting researcher to investigate sensor criticality, degradation physics, detection sequences, and maintenance plans for a degraded ECLSS CO_2 removal unit in both autonomous robotic tasks and integrated robot/human teaming scenarios. The modular build will also allow for future research and visiting research to take place at the center to further ECLSS research for future space habitation.

To my friends and peers, especially the two incredible women who became not only the best ECLSS colleagues but also cherished friends. You are the absolute best. To my incredible family: Mom, Dad, Godfather, and sisters. You've listened to every space/ECLSS idea with endless patience and happiness; your support means the world. To my partner - you inspire me every day to be my best self and to tackle engineering challenges with rigor and imagination. I am so lucky to have you in my life. To my PI and mentor, who opened the door to the amazing world of human spaceflight and continues to guide me. You've shown me what kind of leader I hope to one day become. And to HRVIP, HOME, NASA, and the entire ECLSS community, you've all welcomed me so generously. Thank you all for making learning such a joyous process.

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Acknowledgments

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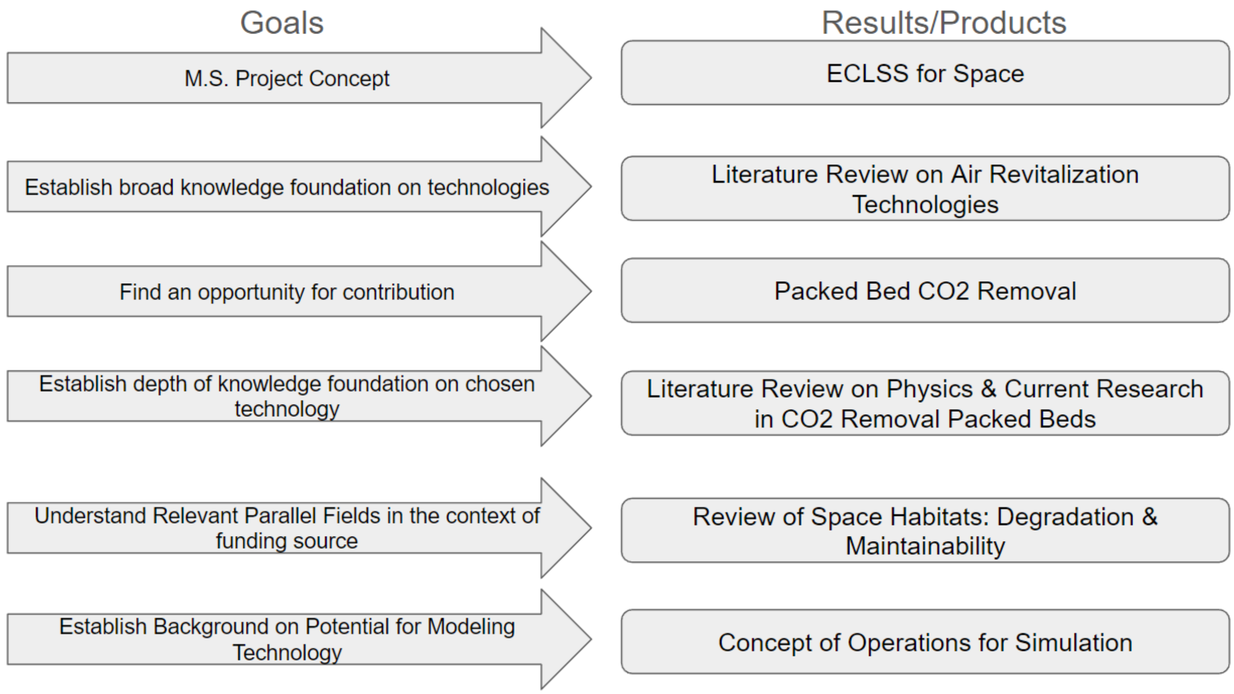
Chapter 1

Background

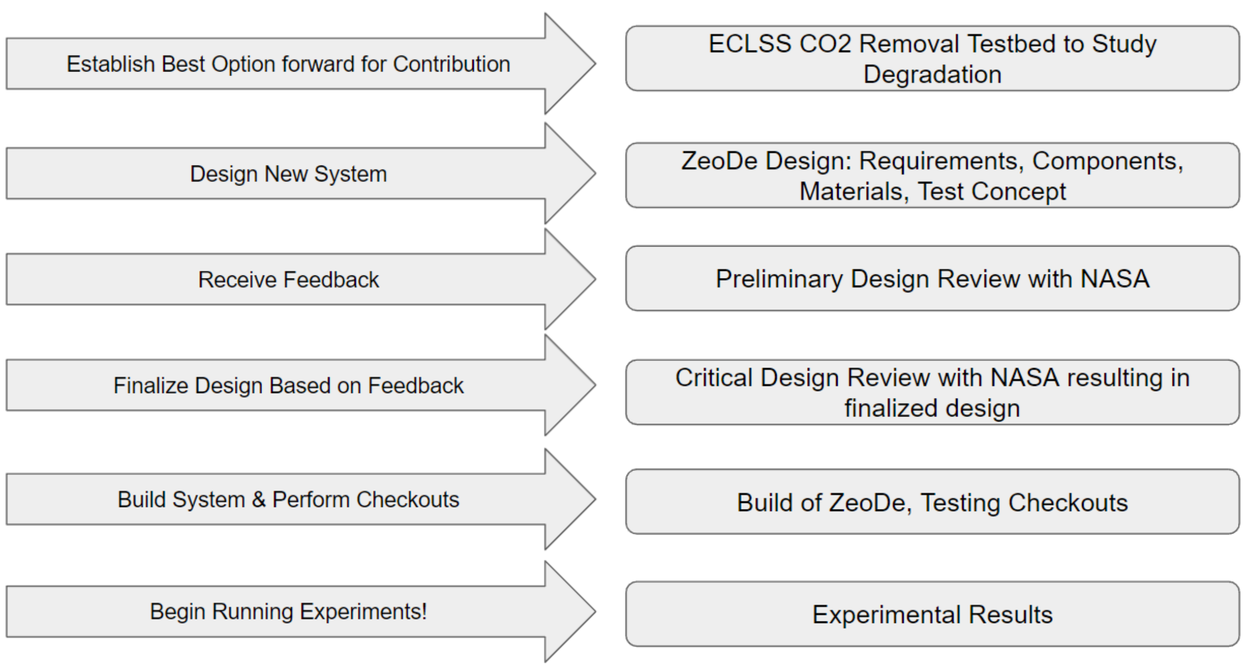
This section provides background on the context for this thesis, as well as the physics and mathematics background that were explored to choose, refine, and understand the project

1.1 About this Thesis

Below is a top-level chronological list of GOALS $\rightarrow$ RESULTS/PRODUCTS that resulted in the contents of this thesis. While you are welcome to read the entire thesis from cover to cover, my hope is that as a fellow researcher, you might be able to jump to a particular section that may align with your current research project and that it might help bring your testbed/project/goal to fruition.



[Break between theoretical work and hands-on work]



1.2 HOME STRI Background

This section gives background for the funding source, which provides context for the environment in which the ZeoDe testbed was built

The NASA Habitats Optimized for Missions of Exploration Space Technology Research Institute (HOME STRI) is focused on advancing the technologies needed for a new generation of space habitats, where distance from Earth communications and aid will necessitate a habitat with significant autonomy that can learn over time, detect faults and degradation, predict maintenance and repair requirements, and perform corresponding repairs with human-machine teaming (HMT). All technologies under development assume a human in the loop (whether as an onboard astronaut crew or in an Earth or Lunar-based Mission Control).

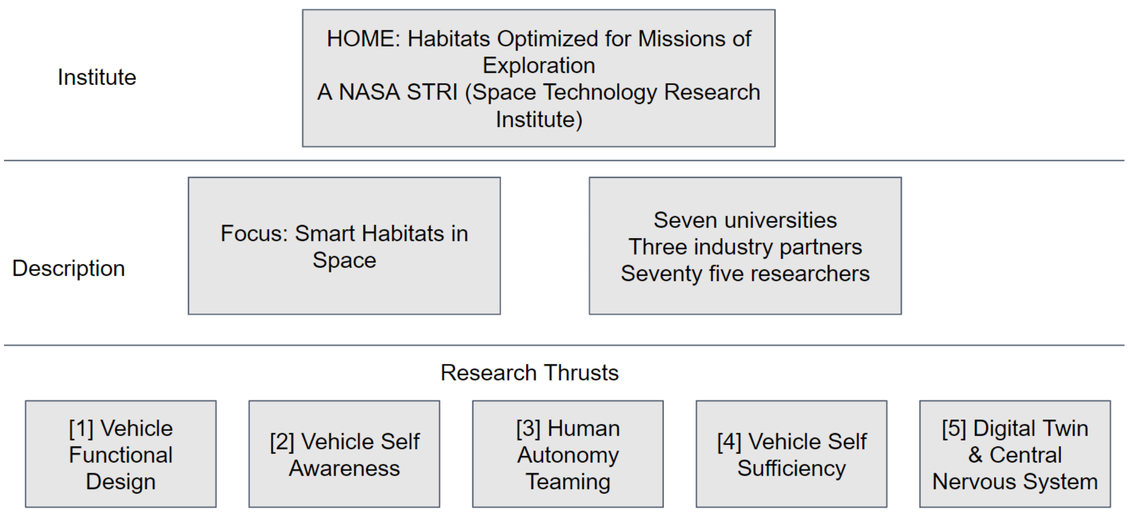


Figure 1.1: HOME description and list of the five research thrusts within the institute

The HOME STRI is a collaboration of seven U.S. universities, anchored by its headquarters at the University of California, Davis, at the UCD Center for Spaceflight Research. Joining UC Davis are the University of Colorado at Boulder, Carnegie Mellon, Georgia Tech, University of Southern California, Howard University, and Texas A&M, each bringing their expertise to advance the state-of-the-art in deep space habitation. HOME STRI's mission is further strengthened by its partnerships with three industry leaders: Sierra Space, Blue Origin, and Collins Aerospace. These partnerships combine cutting-edge technology and real-world experience to create the next generation of deep-space habitats.

HOME is currently beginning its fifth year of research. Its five-year structure allows Research Thrusts (RTs) to start by working in focused technology development teams and transition towards integration between all RTs as their technologies reach the validation stage.

HOME Research Thrusts

The following includes definitions developed by Research Thrust PIs and reported to NASA in HOME quarterly deliverables.

Research Thrust 1 (RT1) focuses on developing the foundational deep space habitat framework that enables self-sufficiency through four main approaches, as reported by PI's to NASA in the HOME Y5Q1 report

- "Defining relevant operational context and developing methodologies to assess smart/ autonomous and other emergent technology applications intended to increase self-sufficiency in a deep space habitat by identifying functional needs and establishing success metrics relative to State-of-the-Art solutions."
- "Serving in liaison roles for assimilating results from RT2, 3 and 4 aimed at evaluating autonomous technology performance for nominal operations and anomaly response, and providing input for modeling system interactions with the Digital Twin (RT5)."
- "Defining trade study criteria to assess return on investment (ROI) contributions of emergent technologies toward an overall degree of habitat self-sufficiency as a function of reliably enabling required onboard capabilities, reducing Earth communication requirements, and reducing logistical provisioning needs."
- "Incorporating terrestrial architectural best practices into the space habitat domain through application of autonomous, adaptive techniques to reconfigure the layout and other attributes such as lighting and texture that support unique needs in different operational scenarios (e.g., work vs. leisure activities, crewed vs. unoccupied phases, etc.)."

Research Thrust 2 (RT2) "builds self-awareness methodology for utilizing onboard telemetry data to provide situational awareness of SmartHab systems including optimization and decision support for maintenance and repair activities as well as spare parts provisioning" RT2's focus includes the following approaches

- "Implementing autonomy in the context of self-awareness."
- "Treating the habitat as a cyber-physical system comprised of Intranet-of-Things enabled subsystems that respect independence and interconnectedness."
- "Adopting a distributed and hierarchical approach to define how subsystems interact with each other."

Research Thrust 3 (RT3) “advances human-autonomy teaming by modeling, measuring, and incorporating information derived from humans into future highly autonomous spacecraft.”
RT3’s focus includes the following approaches

- “Integrating research from both humans and autonomy into enabling a collaborative team.”
- “Integrating a human focus which includes remotely operating crewmembers (including mission control), onboard crewmembers collaborating with embodied and embedded robots, and those individuals transitioning between these states (e.g., upon crew arrival to the unoccupied spacecraft). ”
- “Integrating an autonomy focus that incorporates an understanding of human behavior, states, and desires into autonomous systems, including decision-making guidance (connecting to RT2 and RT5) and working with autonomous agents (connecting to RT4).”

Research Thrust 4 (RT4) “develops, integrates and demonstrates planning, scheduling, execution, and learning technologies that collectively enable autonomous (or semi-autonomous) operation, maintenance and repair of spacecraft subsystems.”
RT4’s focus includes the following approaches

- “Autonomous management of spacecraft activities and resources (human and robotic) via onboard real-time planning and scheduling.”
- “Representation and composition of known autonomous (and semi-autonomous) capabilities, and methods for learning new capabilities over time.”
- “Robotic systems for onboard maintenance and repair, including robotic manipulation of flexible objects (fabrics, wires, hoses).”
- “Onboard manufacturing and process integration with robotic systems.”

Research Thrust 5 (RT5) “provides a unified interface for human/autonomous agents to interact with the digital representations of the SmartHab systems and components; plus a modeling framework with which to orchestrate these digital assets”
RT5’s focus includes the following approaches

- “Standardize software interfaces to models of the physical systems and components in the SmartHab.”
- “Design and implement semantic models and data exchange processes (e.g., semantic interoperability).”

- “Develop federated information models for integrating existing but siloed models of the SmartHab and its components.”
- “Design mechanisms for maintaining consistency across models and propagating uncertainty.”
- “Develop a semantically-aware unified software interface, reasoning and analysis mechanisms for translating the user queries into retrieval and modification of the underlying models, as well as modeling innovations to allow multiple information and simulation models to co-exist and maintain consistency.”

HOME Products

Over five years, the HOME community, pictured below, has delivered the following products to NASA and, as a result, to the entire space community.

- Finished software products from all RTs
- Two data producing ECLSS testbeds for CO2 removal, one focusing on fault introduction at CU Boulder and the other focusing on degradation introduction at UC Davis
- Robotics testbeds UC Davis, Georgia Tech, and Carnegie Mellon
- Publications from both HOME members, including students and faculty
- Year-end demonstrations of the technologies developed by the five RTs in realistic space scenarios, which iteratively build on each other until reaching the end of Year 5 when the demonstrations culminate into three capstone demonstrations to NASA showing technology demonstrations in an uncrewed state, a crewed state, and in a state when a habitat is in transition from an uncrewed state to a crewed state.
- A body of knowledge alongside a team to distribute that knowledge, which includes the framework for future deep space habitats for humanity

Below is a photo taken at the Year 4 Annual Review at CU Boulder, which included members of HOME from academia and industry and the NASA reviewers.

Figure 1.2: Team photo of HOME members and NASA Reviewers at the Year 4 Annual Review at CU Boulder (June 2023)

1.3 Environmental Control and Life Support Systems

This section gives a general sense of what is included in ECLSS and why it is needed in space. The included literature review was used to establish a broad knowledge foundation on ECLSS technologies, which was then used to find the best opportunity for contribution to the field

Environmental Control and Life Support Systems (ECLSS) are critical to any crewed space habitat. As a subsystem, it ensures a livable environment, including the hardware and processes to maintain a healthy, breathable atmosphere, adequate temperature, pressure, and humidity, and potable water, as well as water for hygiene. In general, crew needs require different hardware depending on the mission.

The complexity and amount of hardware required for ECLSS depends on the mission's duration. Missions lasting less than 30 days could rely on single-use components and raw materials, launching sufficient canisters of water and oxygen alongside the crew and using non-regenerable CO_2 and trace contaminant scrubbing units through which cabin air is circulated. More extended missions require more cyclic, regenerable operations as the initial up mass for larger regenerative systems yields a more significant return on investment the more extended the mission.

Mission Duration	ECLSS Characterization
0-30 days	- Non-Regenerable - No Resupply Characterized by water tank storage for drinking and hydrating food, a non-regenerable CO2 scrubbing system (like a LiOH bed through which circulating cabin air flows), and a non-regenerable trace contaminant system (like an activated charcoal bed through which circulating cabin air flows)
30+ days	- Limited Resupply - Regenerable system needed Characterized by decreased water shipments in favor of a water recycling system, and a regenerable CO2 scrubbing and trace contaminant system (that can, for example, be baked out and used again with contaminants vented to space). This system becomes more complex and requires greater maintenance.
90+ days	- Regenerable system - Little to no resupply - Closed-loop (or as close as possible) Requires more closed-loop recycling of air and water, and has the potential for greater complexity and greater maintenance needs.

Table 1.1: Mission Duration and corresponding ECLSS

To give a feel for non-regenerable vs regenerable technologies, the following is a basic example:

Non-regenerable

- LiOH (Lithium Hydroxide) block + a blower to pass cabin air over its surface area
  - Binds CO_2 to the Lithium Hydroxide groups with a high capacity
  - CO_2 chemically binds to the LiOH, the energy required to separate them is high
  - Once saturated, the block is waste mass, and a fresh LiOH block is needed
- Assume a short mission would require one LiOH block totaling a normalized mass of 1

Regenerable

- CO_2 scrubber using zeolite pellets in a packed bed + a blower to push cabin air through the bed with a medium capacity.

- CO_2 experiences weak force attraction (induced-dipole) to the pellets, so the energy required to overcome that attraction < that for chemical bonds.
- This is a cyclic operation where the ECLSS unit constantly goes back and forth between performing its air cleaning process and being regenerated.
- Air cleaning = cabin air flows until the bed is almost saturated, and then the flow stops
- Regenerating = energy is added to the system via heat; the CO_2 molecules are now moving sufficiently to overcome their attraction to the zeolites. They are pulled out of the bed by a pressure differential induced by a vacuum pump.
- After heating and pulling the vacuum, the bed is now regenerated, and cabin air can flow through again.

• Assume a long mission would require 6 LiOH blocks (this an example arbitrary number, and in actuality depends linearly on mission duration for a given crew) totaling a normalized mass of 6.

• Our regenerable CO_2 scrubber has a normalized mass of 4, so the return on investment for up-mass favors the regenerable unit over the single-use LiOH blocks.

To understand how individual ECLSS technologies could fit into an overall system, Figure 1.3 shows an example ECLSS that incorporates regenerable features. While there is no single correct design for an ECLSS, the International Space Station (ISS) is a state-of-the-art example of current life support technologies and a testbed for new life support equipment. For this reason, the below ECLSS is organized similarly to the existing ISS design. Note that this is simplified and does not provide a complete picture of the ISS ECLSS. In general, as shown below, it is desired to control levels of trace contaminants (1), control humidity and temperature (2), control levels of CO_2 by capture (3), either vent captured CO_2 into space or potentially perform recycling operations to recapture O_2 in the form of $H_2O(4)$, and recovery of O_2 (5). No fans or other forms of air circulation are depicted but are a part of the standard ECLSS system. The urine processing assembly is typically represented by its own unit block but is grouped into the water processing assembly here as a simplification. For reasons explained in the following section, Figure 1.3 shows more detail on the air processing side than the water processing side.

On the air processing side, while far more regenerable than single-use canisters of water and oxygen, one can see that in Figure 1.3, the mass balance still tilts towards the outlet. Hydrocarbons are still vented to space, and though not shown, the theoretical/idealized maximum chemical efficiency of each unit is not 100%.

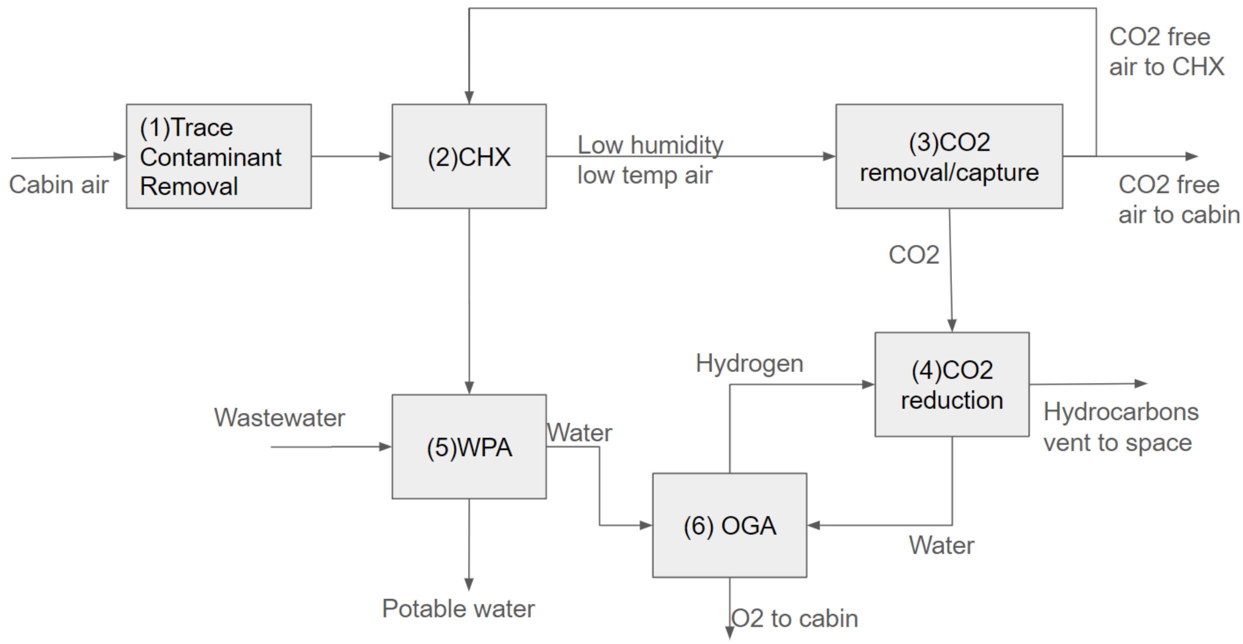


Figure 1.3: Diagram of a simplified potential ECLSS with focus on air string, with some similarities to ISS ECLSS

Air Revitalization

This section outlines the reasons for initially homing in on the air side of ECLSS rather than the water side. Subsequently, we dive into the breadth of knowledge acquired on the air side of ECLSS to understand what kind of technologies are out there and what kinds of engineering challenges might be suited to be addressed by academia here at UC Davis in the timeline of a M.S. thesis.

The Air Revitalization system predominantly consists of the unit blocks (1)-(6) in Figure 1.3. The primary purpose of air revitalization onboard a spacecraft is to maintain cabin air in the desired composition for both astronaut and station component health. NASA has identified closing the loop on Air Revitalization systems as a research focus for deep space [42]; as such, it was the first side of ECLSS that was investigated. The Air Revitalization primary subsystems can consist of a trace contaminant removal system, humidity and temperature conditioning, particulate filtration, CO_2 removal, and oxygen recovery. Depending on the configuration, the system may stop at the outlet of the CO_2 removal system, cyclically venting removed CO_2 into space. In a more closed-loop system, as shown in the above figure, the CO_2 may travel downstream to an oxygen recovery process, recovering oxygen and returning it to the cabin, venting excess gas, or storing excess carbon particulates. It is also possible to have different configurations and types of units so that the CO_2 removal/capture and the CO_2 reduction occur within the same chemical reactor. Examples such as these are given in the technology review ahead. Compared to the water processing systems currently in space, which can recycle 90% or more of its water input, the air revitalization recycling efficiency is closer to 50%. The lower efficiency is due to the nature of the chemical stoichiometry of the O_2 recovery unit on the ISS (currently down for maintenance).

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{1.1}$$

The above stoichiometry represents the Sabatier process, and the unit containing it is named accordingly. CO_2 is run through a platinum catalyst bed, along with hydrogen input from a downstream electrolysis unit. This catalytic process produces methane and water. The Sabatier process is just one type of technology that can reduce CO_2; others are discussed in the following review.

The ongoing efforts onboard the ISS and on the ground in NASA, industry, and academia have allowed us to iterate on current units and investigate upgrades and alternatives that can better serve future missions in space. The following section presents a representative list of types of air-side ECLSS technologies and their descriptions. This list was assembled to gain a top-level understanding of the ECLSS Air Revitalization field efforts and to understand specific technologies and any types of failures or difficulties reported that could be addressed in an academic research setting at UC Davis. Technology readiness levels are listed to help UC Davis understand and convey at what level the technologies reside. A key for TRL levels is listed in the appendix. The units reviewed have been published predominantly in the International Conference on Environmental Systems (ICES) in the field of air revitalization. Because of this, there is an emphasis on U.S.-developed technologies due to information access, with functionally similar technologies from other countries mentioned in each corresponding section.

Carbon Dioxide Removal

Units that remove CO_2 from a spacecraft's cabin air

1. Four-Bed Molecular Sieve (4BMS)/ Four-Bed CO_2 (4BCO_2): Carbon Dioxide Adsorption, TRL 9

The four-bed molecular sieve carbon-capture flight demonstration system[25][23]is currently onboard the ISS within the EXPRESS rack and has been chosen to perform as the prime CO_2 removal system on station. Built by NASA MSFC and Jacobs, 4BMS is a redesign of the Carbon Dioxide Removal Assembly (CDRA), a unit prepping for eventual retirement and stowage aboard the ISS. Like CDRA, the 4BMS/4BCO2 system consists of two desiccating packed beds using silica and zeolite and two carbon dioxide sorption packed beds using zeolite. The system is cross-strapped, as shown in Figure 1.4, so that while one desiccant bed and one sorbent bed are adsorbing, the other two are desorbing, switching cyclically. Sorbent beds cool down during their corresponding adsorption, after which outlet air is passed through the desiccant beds for re-humidification before returning to the cabin. The desorption cycle releases the CO_2 from the zeolite using a temperature-pressure swing via electrical heaters and vacuum, and air moves through the system with a blower. The 4BCO_2 design minimizes zeolite dust by decreasing operational temperature by switching from zeolite 5A to 13x for the desiccant bed and switching from rectangular sheet metal beds to cylindrical beds to minimize sorbent movement and increase compaction. The change in zeolite also increases CO_2 selectivity during adsorption. The heater core was upgraded to allow visibility to verify sorbent packing and the absence of voids, which contribute to dusting. Valve redesign was also implemented to decrease the need for valve repair due to dusting. A key metric that has been investigated is the effect of the presence of humidity on the zeolite within the system [22] [23] [24], predominantly for system design. This literature review identified this topic of interest since a humid cabin always presents the possibility of a leak into an ECLSS system where humidity could be introduced. NASA identified the 4BCO2 system as a key technology moving forward for the ISS and next-generation missions, and thus, it was flagged for our technology investigation purposes.

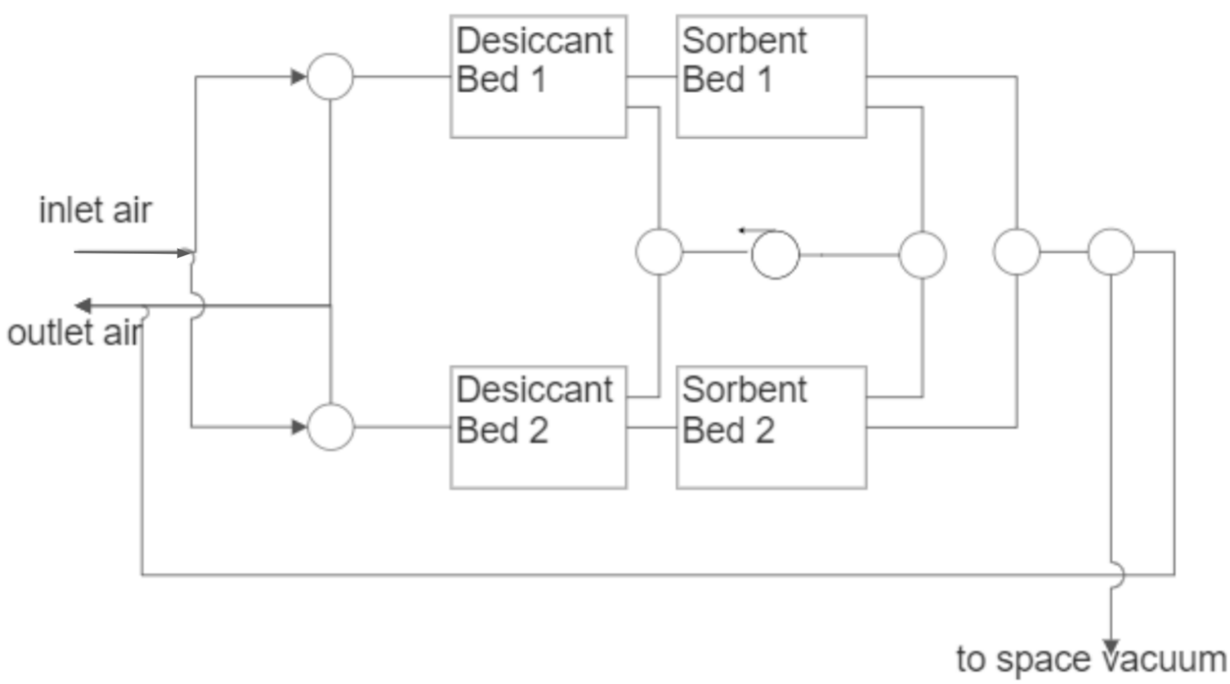


Figure 1.4: Simplified 4BMS/4BCO2 flow based on literature[25]

2. Metal-Organic Frameworks (MOFs): an alternative to zeolites within a packed bed CO_2 capture unit, TRL 3

MOFs are porous materials of crystalline structures with metal clusters and ions.

Unlike zeolites, which have inorganic linkers, these have organic frameworks, allowing for more choices in structural design [6], leading to increased selectivity for specific molecules. However, organic linkers are more susceptible to degradation than inorganic linkers. This is especially true at increased temperatures. Development of proof of concept testbeds [88] [83] as potential substitutes for zeolites in systems similar to CDRA [40] are ongoing, as bench-level tests show the possibility of higher CO_2 capacity than the currently used 13x zeolite. Additional fault modes exist in their enhanced degradation in the presence of high temperature and water; a sub-category of MOF research involves water-stable [30] MOFs, which use a polymer coating intended to reduce degradation.

3. TDA Research Inc. CO_2 Capture System: use of Sr-SAPO-34 Zeolite, TRL 3

The TDA Research Inc. has developed the Carbon Capture System [52][53], which is in bench-level tests and uses a strontium exchange silico alumino phosphate (Sr-SAPO-34) zeolite that they synthesized with the help of the University of Puerto Rico to adsorb CO_2 from cabin air selectively. In addition to a new zeolite, the TDA system claims to use a valveless design in its packed bed system. The TDA Carbon Capture System is proposed as a potential future alternative to the current 4BMS carbon capture system. The zeolite exhibits a CO_2 capacity similar to Zeolite 13x and regenerates at a lower temperature (150 degrees C). When the relative humidity of the gas stream entering the bed increased during testing, efficiency significantly decreased.

4. CO2 and Moisture Removal Amine Swing-Bed (CAMRAS), TRL 7

CAMRAS [13], in development by Collins Aerospace, is an amine-based, vacuum-regenerated CO_2 and moisture adsorption system that vents isolated CO_2 to space via a vacuum. CAMRAS is planned for use in the Orion vehicle for a maximum of 6 crew. The system contains two beds packed with a porous plastic sorbent coated with an amine. Upstream of the packed beds is a water-save function consisting of a rotating desiccant cylinder that adsorbs and heats the passing air. Once the air passes through the adsorption beds, driven by a blower, the now CO_2-free heated air is passed through the wheel again. Due to the increased temperature and connection to the ISS vacuum exhaust system, the desiccant releases adsorbed water vapor at this point. This release cools and humidifies the air stream and regenerates the desiccant. The amine beds are regenerated by exposure to space vacuum using the ISS Vacuum Exhaust System. Faults reported in literature include the following: when integrated aboard the ISS, a valve within CAMRAS failed due to the valve motor drawing too much current and blowing a fuse. This was caused by incorrect specifications used to build the motor for CAMRAS. These issues were resolved by replacing the motor.

5. Thermal Amine Scrubber, TRL 7

The Thermal Amine Scrubber (TAS)[74][72][75], in development by Collins Aerospace and which shares design origins with CAMRAS, uses a 4-bed solid amine packed system to remove CO_2 from cabin air which can travel downstream to separate units for processing; it is currently serving as a technology demonstration within the EXPRESS Rack on the

ISS. The cabin air stream is desiccated, then amine beds adsorb CO_2 from the stream while they are cooled with a propylene glycol/water loop. Dry air exiting the bed is re-humidified before returning to the cabin. Desorption within the amine beds occurs at elevated temperatures and vacuum. Figure 1.5 shows a simplified schematic based on a more comprehensive schematic from literature[75]. The TAS uses a blower to move air throughout the system, not pictured in the simplified diagram in Figure 1.5. During on-orbit start-up and installation in the ISS, the blower motor experienced overcurrent events caused by an operational speed higher than the ball-bearing lubricant allowed. This was corrected by replacement with a refurbished blower with the appropriate ball-bearing lubrication for the operational RPM. Due to this failure, adding a spare fan is under consideration for additional flow and redundancy. In addition, TAS has experienced power supply imbalances caused by high power loads switching at low frequencies; this was corrected by inverter replacement and a processor software update for heater duty cycle operations.

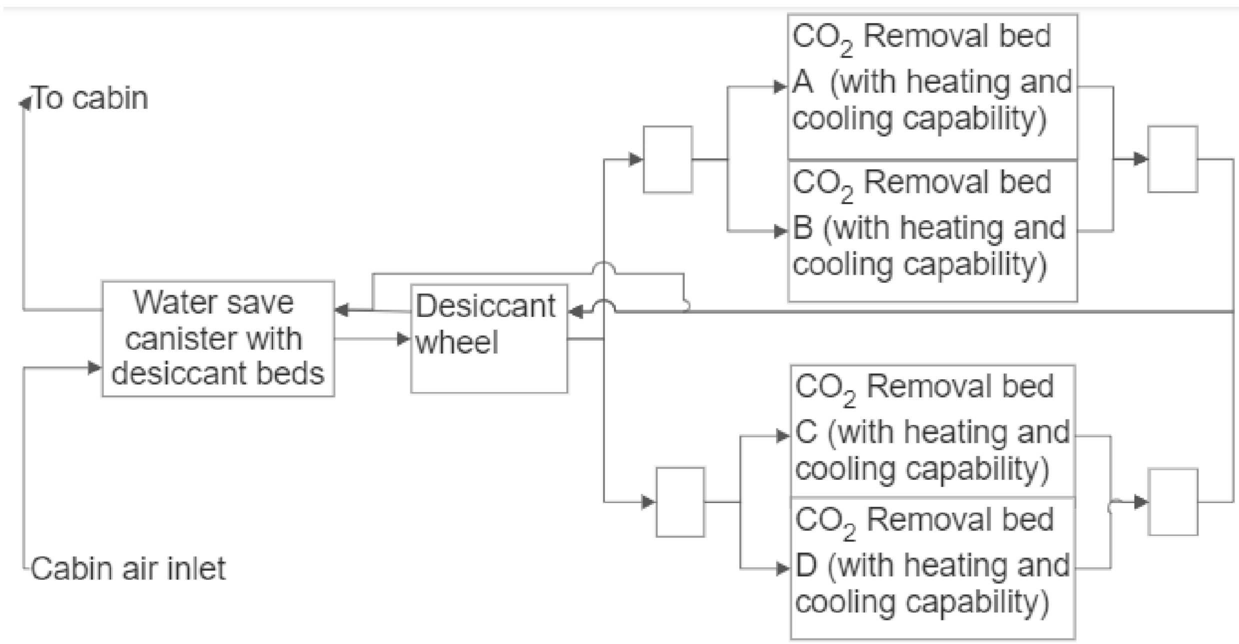


Figure 1.5: Simplified schematic of the Thermal Amine Scrubber, based on a more comprehensive diagram from literature [75]

6. Carbon Capture Assembly (CCA) within ESA Life Support Rack, TRL 9

The Carbon Capture Assembly (CCA)[7][97] of the ESA life support rack, developed by ESA and Airbus and installed in the Destiny Module onboard the ISS, adsorbs CO_2 using three amine-packed beds. The CO_2 stream then enters two water recovery units that dry the stream before either venting to space or routing downstream to an oxygen recovery unit. Desorption occurs using condensate from the wastewater bus, which passes through steam generators, increasing temperature and thus desorbing the CO_2 from the CCA beds. The CCA also includes a water management subsystem with a UV-LED unit to control microbes, a gas trap, a filter, a buffer tank, and pumps for water transportation. Post-installation faults were encountered at the interface with the wastewater bus, including a water pump not producing a pressure head. One root cause was high levels of gas bubbles in the wastewater bus; this was mitigated by flushing operations and management of fill levels to avoid large ratios of gas to liquid. This fix showed improved performance and resolution of the fault. Additionally, ESA is currently searching for the root cause of a trip to the rack power control module connected to the system, with a source deemed likely outside the ACLS (Advanced Closed Loop System).

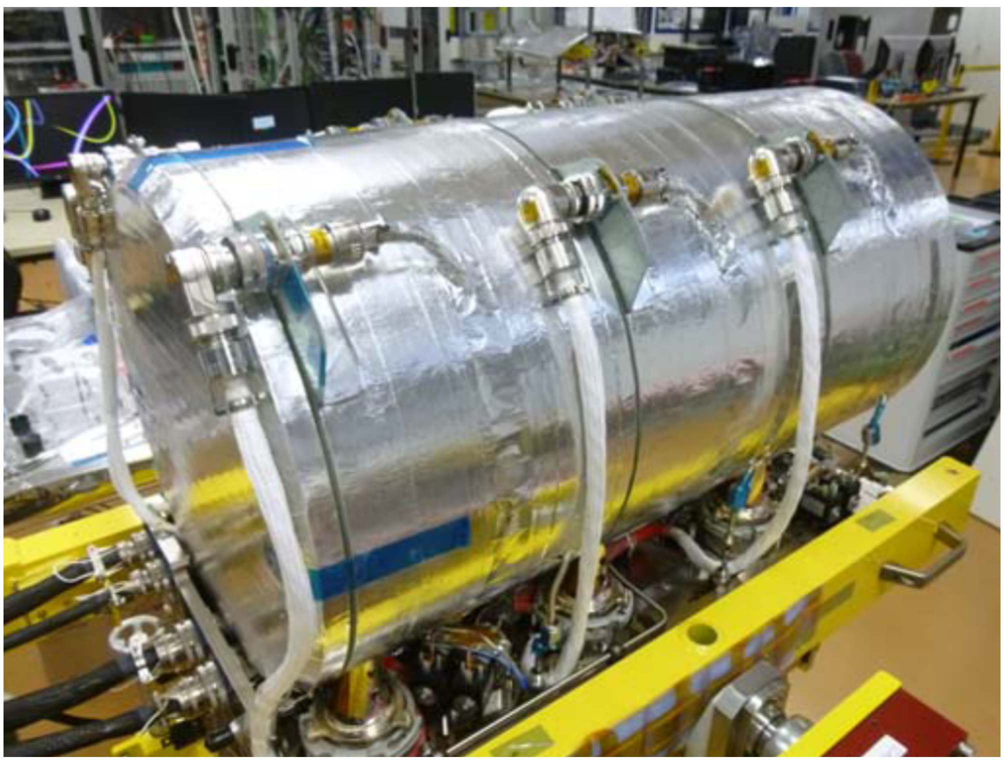


Figure 1.6: Carbon Capture Assembly (CCA) adsorber bed, as shown in literature [7]

7. Carbon Dioxide Deposition System (CDEP): Carbon dioxide removal and storage, TRL 4

The Carbon Dioxide Deposition System (CDEP)[4] is in development by NASA Ames to achieve CO_2 removal via an icing mechanism. CDEP consists of two sets of precooling units and deposition chambers alternating between cyclical deposition and subliming operations. Air is first dehumidified as it passes through hollow fiber membranes in contact with an ionic liquid. After flowing through a heat exchanger, the air passes through a precooler and enters a deposition chamber where CO_2 is deposited. The resulting cooled air returns through the heat exchangers, then through the opposite precooler, heat exchanger, and ionic liquid contactor for re-humidification. Meanwhile, the opposite set of units performs subliming operations. Failure tests showed that while humidity control upstream of CDEP affects the purity of CO_2 at the outlet, it does not affect the overall CDEP CO_2 removal capability. This makes the unit less susceptible to the humidity-induced potential failure/degradation mode experienced by the prime CO_2 removal unit on station which uses zeolite.

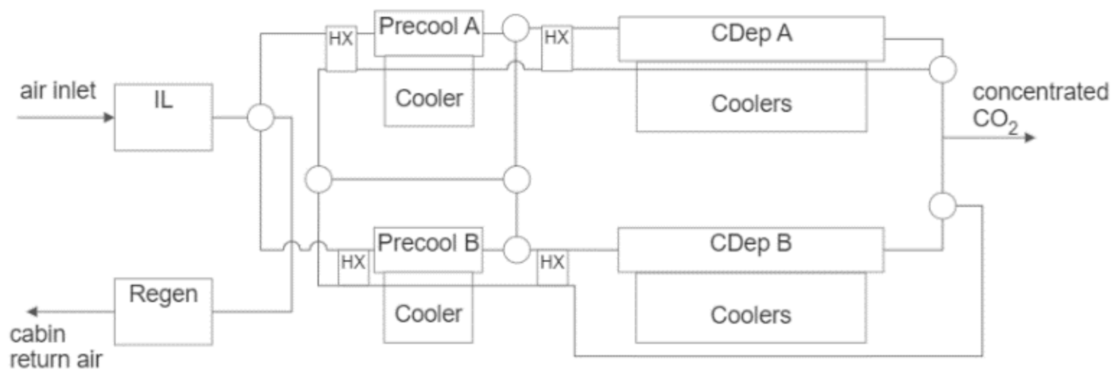


Figure 1.7: Simplified CDEP schematic based on literature depiction[4];one side performs deposition and the other sublimes

8. Carbon Dioxide Removal by Ionic Liquid System (CDRILS), TRL 5

CDRILS[46][45] under development by Honeywell Aerospace, removes CO_2 from an air stream using an ionic liquid. The system consists of two ionic liquid hollow fiber contactors: one performs scrubbing operations, and the other performs stripping operations. With the help of a blower, air passes through the first contactor, where CO_2 and water are adsorbed, and the resulting air is returned to the cabin. The CO_2-rich ionic liquid then flows through a heat exchanger, heated before entering the second contactor where the stripping operation occurs, and CO_2 and water are removed from the ionic liquid under vacuum. CO_2 and water are then separated into two isolated streams via condensation. A simplified schematic of the system is shown in Figure 1.8, based on a more comprehensive schematic in the literature[46]. Long-term stability tests investigated potential fault modes, finding that elevated temperatures contributed to the sweating of the ionic liquid through the membranes; a change in operating temperature mitigated this fault.

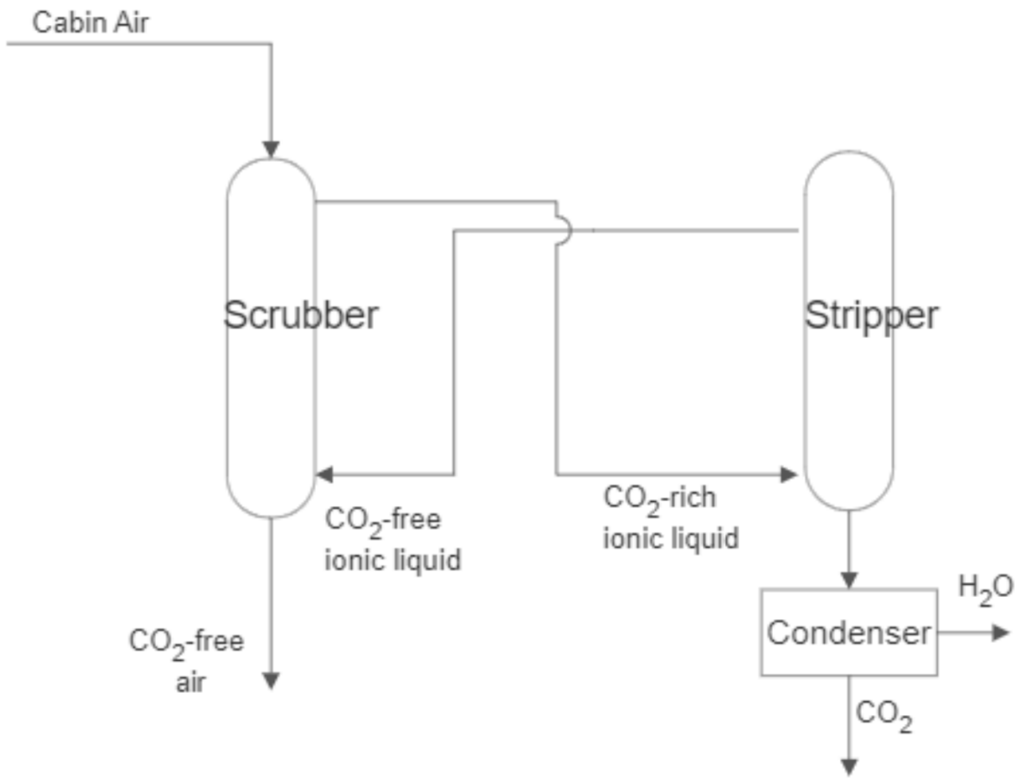


Figure 1.8: Simplified CDRILS testbed schematic based on literature depiction [46], blower not pictured

9. Liquid Amine Contactor, TRL 3

The Liquid Amine Contactor CO_2 Removal system[20], in development by NASA Ames, uses gas-liquid interaction in a 3D printed contactor reactor for adsorption and desorption, based on the V-Tube contactor design and previous sorbent studies[76]. A capillary channel with an inside corner angle holds liquid in place via surface tension. The contactors sit in trays within a housing, which allows for modularity in testing different surface areas and is designed to provide a short diffusion path with respect to airflow. CO_2-rich air flows horizontally across the amine-filled contactors, which adsorb the CO_2. The current fault mitigation design includes visibility into the trays' amine filling to diagnose potential issues and implement a central drainage location in case of a leak.

Carbon Dioxide Reduction Technologies

The technologies described here are predominantly from the published ICES repository. TRL levels are estimated to give the reader an idea of technology maturity.

10. Sabatier Reactor, TRL 9

The Sabatier[81] is a CO_2 reduction system designed by Collins Aerospace to partially close the life support loop on the ISS. A similar additional Sabatier system built by ESA and Airbus resides on the ISS [8]. Within the US system, CO_2 from a CO_2 capture unit and H_2 from the Oxygen Generation Assembly react at elevated temperature and pressure in the presence of a metal catalyst in a packed bed to produce water and methane, CH_4. This reactor was aboard the ISS from June 2011 through October 2017. In 2016, the Sabatier stopped producing water[15]. Contamination from zeolites, silica, and nickel coating from an upstream compressor and sulfur, silicon, fluorine, and chlorine all contributed to 70% deactivation of the catalyst. The unit is currently undergoing ground maintenance, including installing additional filters and cyclic flushing of the OGA loop to decrease humidity in the CO_2 feed.

11. Plasma Pyrolysis Unit: Recovering H_2 from Sabatier Methane output, TRL 6

The Plasma Pyrolysis unit [93][94] developed by Umpqua Research Company, uses microwave-generated plasma within a waveguide to convert methane to acetylene and hydrogen by oligomerization reactions within the plasma under excess hydrogen conditions. The methane mixes and reacts with a hydrogen plasma via gas jets – hydrogen shifts the reaction towards products and inhibits the generation of compounds other than acetylene. When added downstream of the Sabatier reactor, this unit recovers a maximum of 75% of the hydrogen from methane to then be recycled back into the Sabatier reactor. The system's output is a mixed hydrogen-acetylene stream; future designs may separate these streams. While the components predominantly remain in the gaseous phase, some sooting remains. Thus far, this unit has undergone a zero-g parabolic flight experiment.

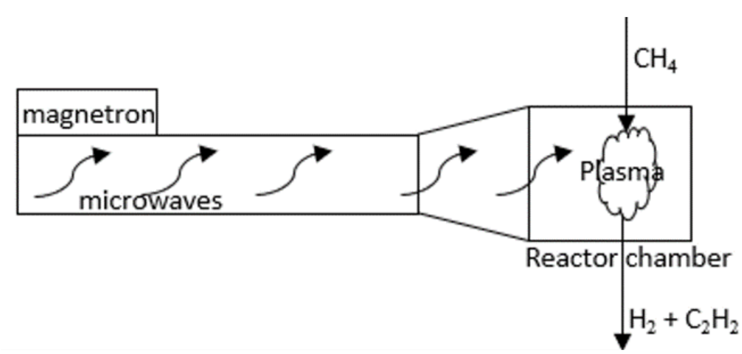


Figure 1.9: Simplified Plasma Pyrolysis unit diagram, based on literature depiction [93]

12. Laser Pyrolysis Unit: Recovering Hydrogen from Sabatier Methane Output, TRL 3

The Laser Pyrolysis unit[27], developed by Dynetics Inc., uses a laser to thermally decompose methane outputs from the Sabatier unit into solid carbon and gaseous hydrogen. The process is based on laser chemical vapor deposition, where a laser shines through a focusing lens and the decomposed carbon product deposits on a substrate. While using the laser, the substrate is pulled backward, resulting in robust, dense fibers sitting on the substrate that can then be cut off and collected. In microgravity, these collected fibers are more manageable than powder as discrete parts can be grouped more efficiently, and the risk of small particles infiltrating sensitive systems is mitigated.

$$CH_4 \rightarrow 2H_2 + C(s) \tag{1.2}$$

If added downstream of the current Sabatier reactor, this unit will recover a maximum theoretical value of 100% of the hydrogen from methane. Compared to the higher TRL plasma pyrolysis unit, it is estimated to have comparable power usage. Carbon dust is a byproduct and leads to decreased laser functionality when suspended in the chamber; when removed, carbon dust is accumulated by a downstream filter. The flow rate of the precursor gas was found to impact this fault mode significantly, so mitigation operations included an increased flow rate.

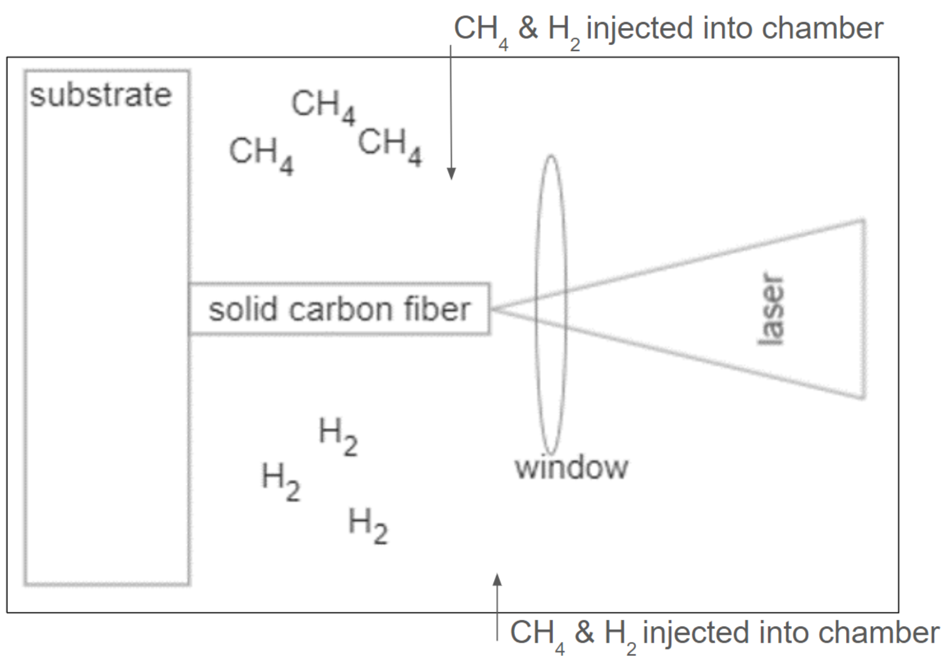


Figure 1.10: Simplified Laser Pyrolysis unit diagram, based on literature depiction [27]

13. Series Bosch Reactor: Carbon Dioxide Reduction, TRL 6

NASA MSFC and Jacobs are developing the Series Bosch Reactor[85]. The system converts a CO_2 and H_2 stream into water and elemental carbon using a Reverse Water Gas Shift reactor (RWGS), a Carbon Formation Reactor (CFR), a Carbon Dioxide Extraction Assembly membrane, and a Hydrogen Extraction Assembly membrane. The reverse water gas shift reactor consists of a packed bed with a catalyst converting CO_2 as seen in Equation 1.3. The carbon formation reactor is a radial flow reactor that also consists of a packed bed with a catalyst, in which the CO Hydrogenation and Boudouard reactions take place, as seen in Equation 1.4 and Equation 1.5, respectively. Equation 1.6 shows the overall Bosch process. The production of elemental carbon results in fouling within the reactor, which requires continual replacement of the Fe/Ni catalyst. Mitigation via additional research and technology is outlined in the following sections.

$$CO_2 + H_2 \rightarrow H_2O + CO \tag{1.3}$$

$$CO + H_2 \rightarrow H_2O + C(s) \tag{1.4}$$

$$2CO \rightarrow CO_2 + C(s) \tag{1.5}$$

$$CO_2 + 2H_2 \rightarrow 2H_2O + C(s) \tag{1.6}$$

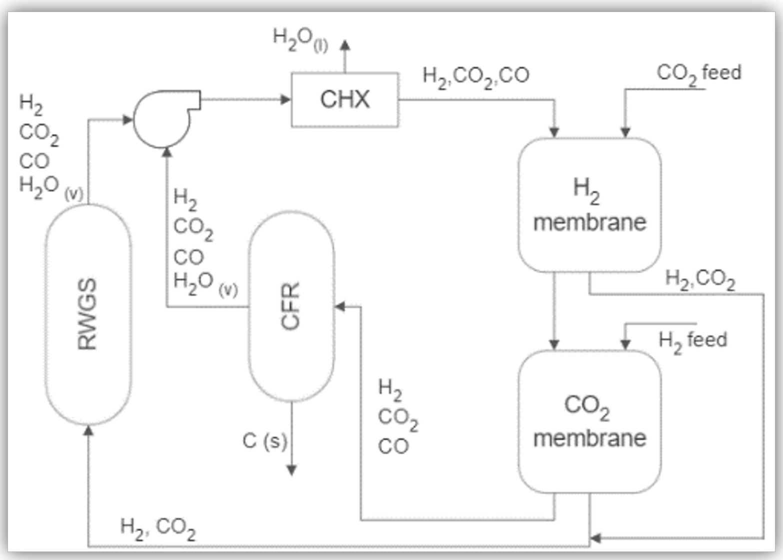


Figure 1.11: Simplified diagram of the Series Bosch Reactor, based on literature depiction [85]

14. Ionic Liquid Bosch Reactor, TRL 3

Ionic liquid-Series Bosch[84][9], in development by NASA MSFC, Qualis Corp, AZ Technology, and Auburn University, aims to address the carbon fouling in the Series-Bosch system. The system replaces the Carbon Formation Reactor (CFR) from Series-Bosch with a reactor that incorporates electroplating a catalyst onto a substrate, carbon formation via the Bosch Process, and the regeneration of the carbon-coated catalyst substrate. The ionic liquid series Bosch essentially regenerates the catalyst by separating the Fe/Ni from the pure carbon by carrying it out in an ionic liquid. The cathode chamber, made of a ceramic anion exchange membrane, is encased by the anode chamber, which is covered by a heating element. The cathode chamber houses two square copper mesh plates that can rotate 90° to be electroplated. During regeneration, agitation of the copper mesh and contact streams from a liquid diffuser release carbon dust from the system. During carbon formation, the feed gases enter the system. Regeneration consists of pumping the cathode chamber with ionic liquid. Carbon dust suspended in the ionic liquid runs through a filter, with potential fault modes depending on filter replacement or flushing.

15. Self-Cleaning Boudouard Reactor, TRL 3

A mechanical rotating brush is in development by NASA KSC as a self-cleaning mechanism for the Boudouard reactor within the Series Bosch system[47]. The brush, made of catalytic carbon steel, becomes coated with carbon; contact with non-catalytic rods located along the sides of the Boudouard reactor then removes the carbon, which is carried downstream in a gas flow and deposited into a HEPA filter bag. Bench-level tests exhibited a maximum of 73% carbon removal. Faults included jamming and subsequent damage to the brush mechanism when opening the reactor, a clog in the reactor, and entangling brush bristles, causing bent rods. Mitigation of this fault mode is being developed in a system with more durable materials and without brushes.

16. Continuous Bosch Reactor (CBOS), TRL 3

The CBOS, in development by Umpqua, is functionally similar to the series Bosch reactor system but uses a single packed bed catalytic reactor to convert CO_2 and H_2 into H_2O and C(s) [84][1][85]. The system would continuously intake fresh catalyst and expel carbon-coated catalyst, assuming that new catalyst is readily available. The fault mitigation for carbon dust accumulation within the reactor is a motorized shaft that breaks up and forces the carbon and the catalyst out of the reactor and into a collection site where a vacuum removes accumulated carbon. This continuous process would not require downtime for carbon removal or catalyst addition. During testing[84], the reactor experienced heater and shaft faults, the latter of which impeded contact of the flow with the catalyst.

17. Carbon Dioxide Electrolysis in Ionic Liquid, TRL 4

CO_2 Electrolysis in Ionic Liquid[80] is under development by JAXA as an alternative to the Sabatier reactor. The system converts CO_2 at low temperatures by using carbon formation by electrolysis of CO_2 in an ionic liquid with a nickel cathode and a platinum anode within an enclosed electrolytic cell. Multiple ionic mixtures were tested, and favorable results were exhibited when using [DEME][TFSI] and [BMIM][BF4] (25:75 mol%).

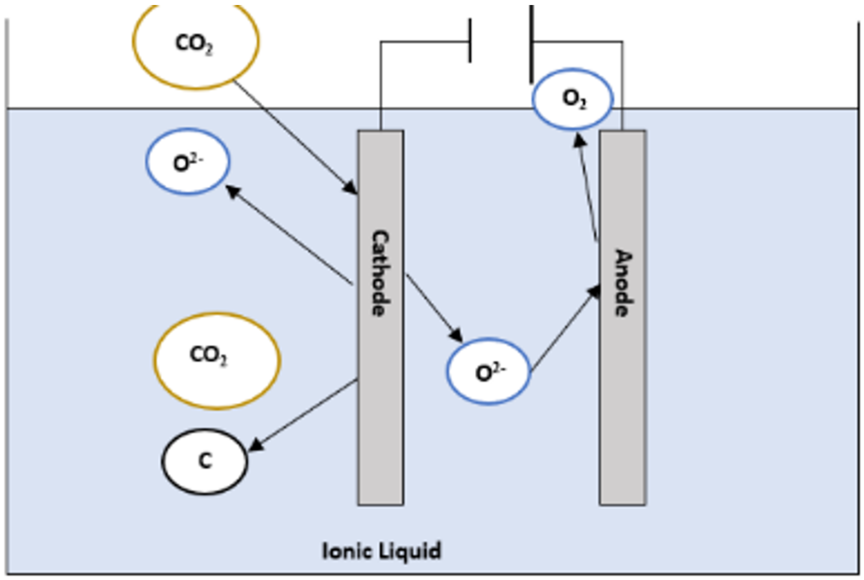


Figure 1.12: Concept of CO_2 electrolysis in ionic liquid based on literature depiction [80]

18. Solid Oxide Electrolysis, TRL 2

The solid oxide electrolysis stack for the MOXIE Mars rover system was developed and built by Ceramatec, Inc. [43]. The system operates at high temperatures, using stacked electrolyte-supported cells with electrodes and catalytic cathode coating on one side and anode coating on the other. CO_2 flows over the cathode with electric potential and is electrolyzed to form CO and O_2. CO can then be exhausted, and O_2, released from the anode cavity, can be reused. Ceramatec, Inc. proposes a variation: the electrochemical recovery of oxygen for use on a spacecraft. A solid oxide electrolyzer and a hydrocarbon synthesis reactor reduce CO_2 and water vapor to CO and H_2 at the cathode. The O_2 is transferred to the anode, where it exits the system. The cathode-generated CO and H_2 can feed into a Fischer Tropsch synthesis reactor, predominantly producing n-alkanes and water.

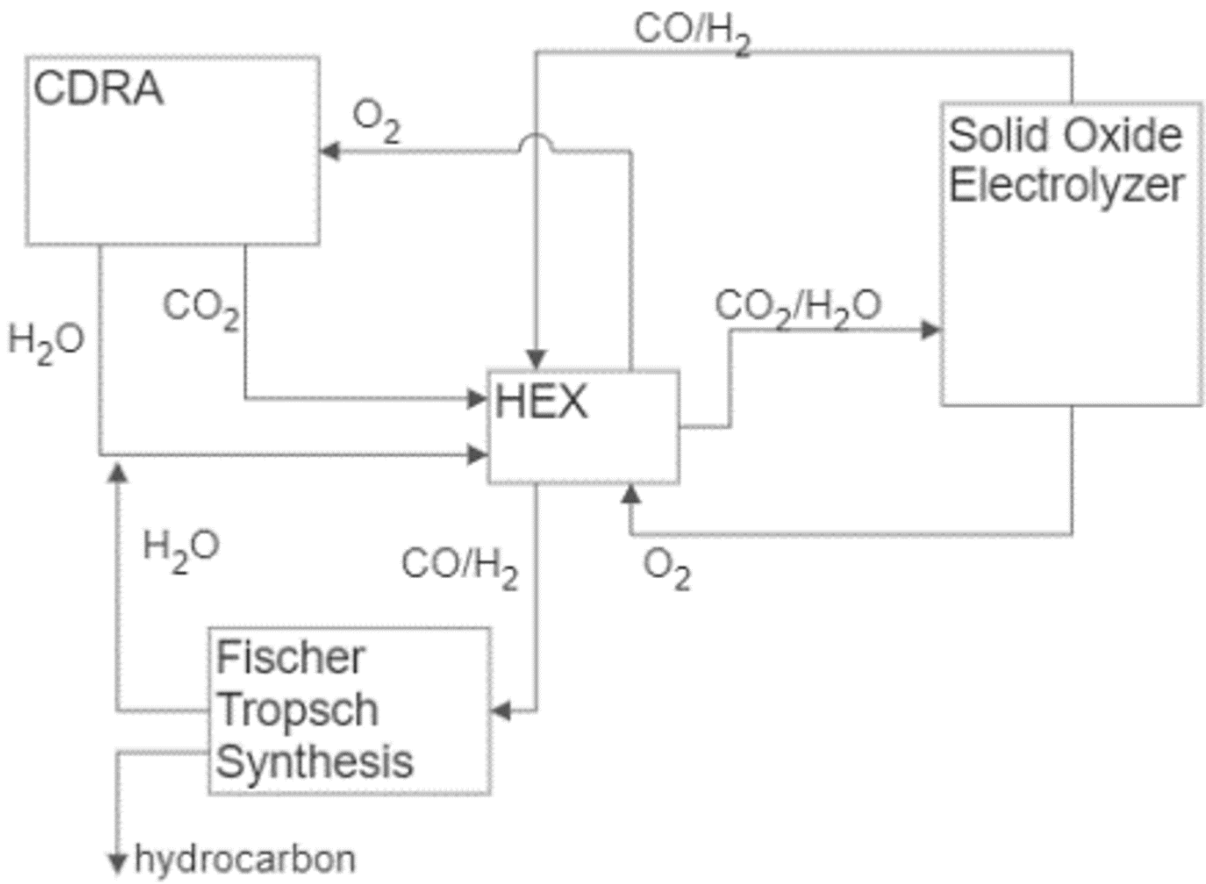


Figure 1.13: Simplified concept of co-electrolysis with Fischer Tropsch for spaceflight, based on literature depiction [43]

19. Hydrogen Recovery by Carbon Vapor Deposition, TRL 3

The hydrogen recovery by carbon vapor deposition, in development by Honeywell, aims to deliver a methane pyrolysis assembly downstream of a Sabatier reactor that minimizes power and generates carbon in an easily handled form[18]. The system uses heterogeneous nucleation on a surface at increased temperatures, resulting in chemical vapor deposition onto a high surface area substrate. This substrate is a consumable. A recycle stream feeds back into a Sabatier reactor. Uneven deposition onto the substrate can result in soot formation, resulting in shorter maintenance intervals and the possibility of soot entering neighboring units. Mitigation plans published by Honeywell include further research into substrate design to avoid soot generation.

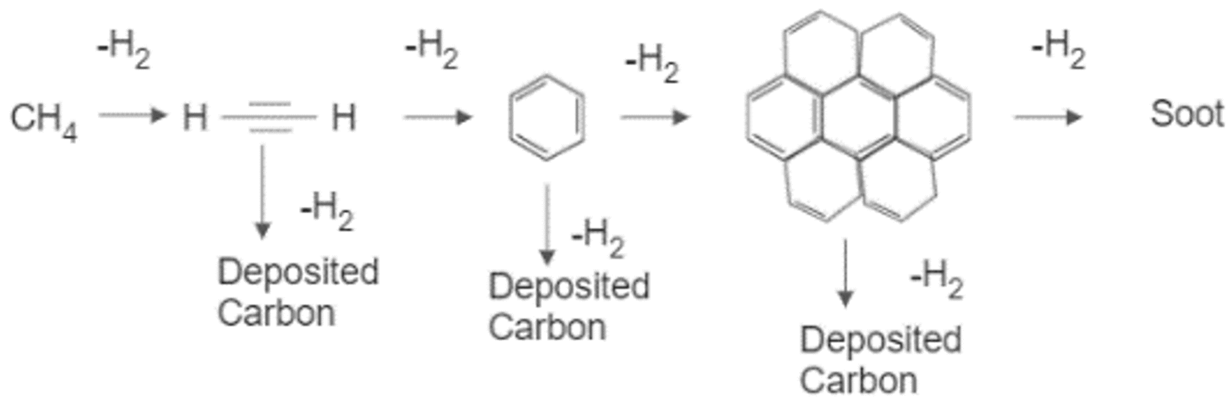


Figure 1.14: Simplified mechanism for carbon vapor deposition, based on diagram in literature [18]

20. Algae Photo-BioReactor: Biological Carbon Dioxide Reduction, TRL 5

The Algae Photo-BioReactor[44][28], built by the Institute of Space Systems at the University of Stuttgart, cultivates microalgae C. Vulgaris in a microgravity-packed bed reactor. Meant to contribute to a hybrid physiochemical and biotechnical life support system, it would supplement a physiochemical carbon dioxide reduction process by taking part of the CO_2 stream along with a water input and would produce biomass and oxygen. The current input to the Sabatier reactor would be split in two, and part of the CO_2 stream would then go to the photobioreactor. A simplified design for the unit is shown in Figure 1.15, based on a more comprehensive diagram from literature[44], where the algae medium is continuously pumped in a meandering path through a pipe reactor, preventing stagnation and adhesion to the inner walls. The reactors are continuously lit using LED lighting and are covered by a fluoroethylene propylene gas exchange membrane to exchange CO_2 and O_2. These gases reside in the enclosure, with O_2 and relative humidity (rH) regulated via absorbers. Feeding and harvesting take place from the liquid exchange device. The resulting biomass could potentially be used as a high-protein food supplement source. The build-up of biomass within the tube and the potential growth of biofilms are potential faults mitigated by the tuning of light wavelengths.

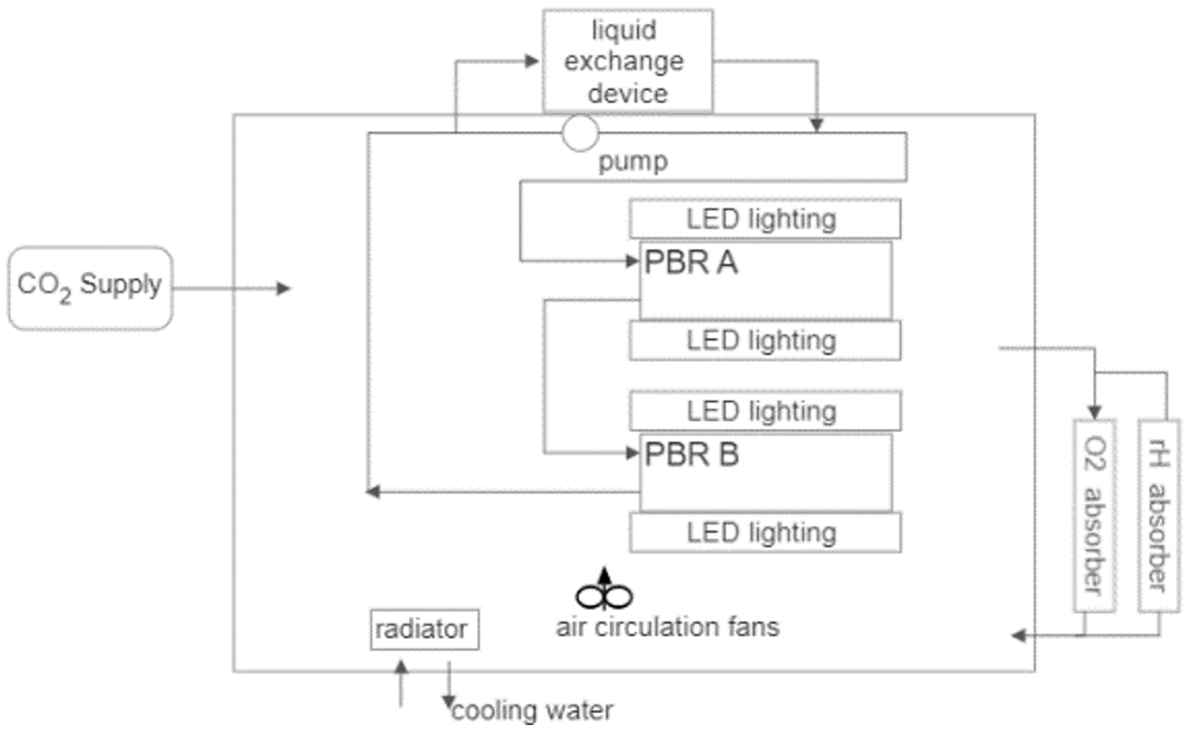


Figure 1.15: Simplified Algae Photo-BioReactor diagram based on literature depiction [44]

21. Water Walls: Air Revitalization combined with Radiation Protection, TRL 3

Water Walls[36][41][26] is a concept developed by NASA Ames for a largely passive (only using valves and small pumps) life support system that applies disposable forward osmosis membranes within bags to replace the current mechanical reactors. Water walls double as radiation protection. Each bag's capacity is consumed gradually throughout the mission, acting as a single-use part. Because of this, there is a large margin on the number of bags within the system to accommodate the mission duration. Water walls could perform the following tasks: control humidity and VOCs, remove CO_2, produce O_2 using cyanobacteria and algae, process urine and grey water, treat solids and black water, and generate energy. Bags are launched dry and hydrated in space. Excess biomass buildup would eventually retire a unit.

The technologies are summarized in the tables below:

#	Technology	Technology Type	TRL estimate	Fault Modes	Source
0	CDRA	4-Bed desiccant and CO_2 adsorbent using zeolite packed beds	9	Dust generation leads to part failures & humidity introduction causes degradation.	NASA Honeywell
1	4BMS/4BCO$_2$	4-Bed desiccant and CO_2 adsorbent using zeolite packed beds	9	Humidity introduction could potentially cause degradation	NASA MSFC Jacobs
2	Metal-Organic Frameworks	CO_2 Adsorbent using metal nodes and organic linkages	3	Degradation of physical framework at elevated temperatures	Iowa State University
3	TDA Carbon Capture	CO_2 Adsorbent using Sr-SAPO-34 Zeolite packed bed	3	Degradation due to humidity	TDA Research Inc.
4	CAMRAS	Amine-based vacuum regenerated CO_2 and moisture adsorption	7	not reported	Collins Aerospace
5	Thermal Solid Amine Scrubber	4-Bed solid amine packed bed system	7	Blower fan failures	Collins Aerospace
6	CCA in ESA Life Support Rack	Amine packed beds regenerated by steam from the wastewater system	9	Intake failures from wastewater system	ESA Airbus
7	CDEP	Separation by icing using two deposition chambers and three sterling coolers	4	Upstream humidity could affect CO_2 purity but does not a[illegible] performan[illegible] system.	NASA Ames
8	CDRILS	Separation via ionic liquid and hollow fiber membranes	5	Degradation at high temperatures	Honeywell
9	Liquid Amine Contactor	Flow over 3D-printed grooved trays, enhancing surface tension with a liquid amine for direct contact with air	3	not reported	NASA Ames

Table 1.2: CO_2 Removal Technologies, numbers corresponding to order in which they are discussed in this review

All tabulated technologies were reviewed after homing in on NASA's need for work on the air side of space habitats. This review provided ample areas for consideration where academic research work could contribute to the field. The technology that stood out for us in the context of the NASA HOME STRI was the 4BCO2 type system, which has now been chosen as a prime on station and was developed from a previous unit that has published and logged fault modes. This allows for a perfect case study of faults, degradation, and maintainability - all of which are key research focuses within HOME.

#	Technology	Technology Type	TRL estimate	Fault Modes	Source
10	Sabatier	CO_2 and H_2 catalytic conversion to H_2O and CH_4	9	Degradation due to the contamination from upstream units	Collins
11	Plasma Pyrolysis	Microwave plasma conversion of CH_2 into C_2H_2 and H_2	6	Sooting within the system, which fouls the system	Umpqua Research Company
12	Laser Pyrolysis	Laser conversion of CH_4 to elemental carbon "strings" and H_2	3	Sooting within the system, which clogs the system and fogs the laser	Dynetics
13	Series Bosch	Catalyst packed bed and membrane system to convert CH_4 and H_2 into H_2O and Carbon	6	Sooting within the system, which fouls the reactor	NASA MSFC Jacobs
14	Ionic Liquid-Series Bosch	Replacement for the CFR in Series Bosch - regenerates catalyst using an ionic liquid to separate carbon	3	Replacement of filter for carbon catchment	NASA MSFC Qualis Corp AZ Technology Auburn university
15	Self-Cleaning Boudouard Reactor	Mechanical rotating brush for self-cleaning of sooting	3	Damage to brush when handling reactor, entangling of brush with the system	NASA KSC
16	Continuous Bosch Reactor	Single packed bed catalytic reactor with continuous input of single-use batches of catalyst	3	Shaft failures impeding the flow of catalyst	Umpqua
17	CO_2 Electrolysis in Ionic Liquid	It uses electrolysis to bubble out O_2, leaving carbon in the solution	4	not reported	JAXA
18	Solid Oxide Electrolysis	Production of H_2O, O_2, and n-alkanes with solid oxide electrolyzer and the Fischer Tropsch process	2	not reported	Ceramatec Inc.
19	Hydrogen Recovery by Carbon Vapor Deposition	Methane pyrolysis produces carbon on a substrate	3	Uneven deposition onto the substrate causes soot	Honeywell
20	Algae Photo-Bioreactor	It uses algae to convert CO_2 and water into O_2 and edible biomass	5	Formation of biomass and growth of biofilms, which is mitigated by light sensitivity analysis	Institute of Space Systems at the University of Stuttgart DLR Airbus
21	Water Wall	Integrates single-use ECLSS in water-heavy bag form with radiation shielding, covering walls of	3	Single-use, with end-of-life of individual bags due to biomass buildup,	NASA Ames

Table 1.3: Oxygen Recovery Technologies, numbers corresponding to order in which they are discussed in this review

1.4 Mass & Energy Transfer in Packed Beds on and off Earth

The previous section guided the choice of technology for our research: CO_2 removal packed beds. This section establishes the depth of knowledge of the chosen technology. If we want to investigate, model, or build our own packed bed in the lab, we should understand the current state of research and the basic physics behind the technology. This section includes many derivations and reviews of processes that have not been employed in the project but provide a deep understanding of the technology.

Packed Bed Reactors Background

Packed bed reactors describe any vessel filled with solid material through which fluid flows, inducing some **chemical** or **physical** process. They are ubiquitous in Earth systems – accounting for approximately 80% of all the reactors used in the chemical process industry – and in space systems, playing a pivotal role in life support systems for air and water processing. **Typical physical processes selectively remove a compound from the inlet stream, such as carbon dioxide. In an adsorbent bed, the compound is trapped by a sorbate, such as porous pellets, by its crystal lattice structure: cage-like geometries sized to the compound and by weak induced dipole forces from cations placed at nodes within the structure; this entire process is referred to as adsorption. Due to the implementation of weak forces, adsorption tends to take place at or below room temperature.** Some sorbents are used only once, but most are regenerated through temperature and/or pressure swing. An example of this occurs on the International Space Station, where CO_2 is selectively adsorbed from a cabin air stream at around 25 degrees C. The bed is then heated to around 250 degrees C, adding enough energy to the system for the components to break free of the cages and weak attractive forces. A separate flow path is opened to a vacuum to allow the CO_2 to flow downstream to a system that recovers O_2 from the CO_2.

Typical chemical systems consist of catalytic beds where a chemical reaction induced by the catalyst remains unchanged from the process. An example of this is the catalytic converter in one's car, as shown in Figure 1.16 [29], which takes in harmful chemicals from the car's engine, such as NO_2, CO, and HC. A palladium catalyst converts these to the less harmful N_2, H_2O, and CO_2. Instead of the most common pelletized form, a catalytic converter uses a monolith: an extruded or 3D-printed material onto which the catalyst can adhere. These monolith systems can also be used for adsorption systems, where the extruded material has the same crystal lattice internal structure as a pellet. Monolith systems have a higher design and manufacturing cost than the standard pelletized bed. They are not expected to be as prevalent for the foreseeable future. Still, they can grant increased mass transfer capabilities [98] and decrease shear stress that leads to the sorbent's or catalyst's degradation.

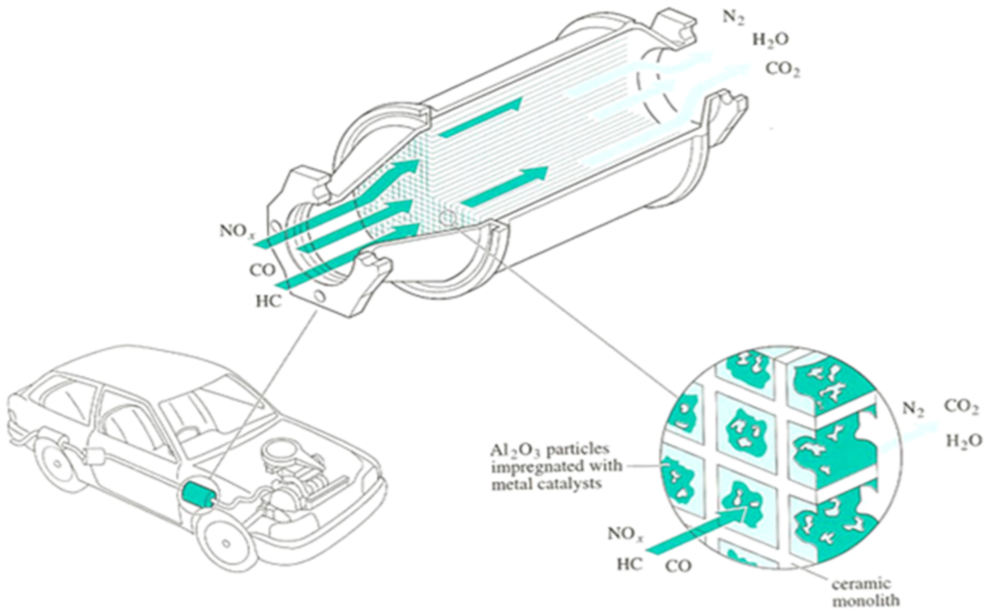


Figure 1.16: Catalytic converter diagram, which uses a monolith [16]

While packed bed systems are highly prevalent on Earth, the field of life support systems for space habitats has created new needs for their mathematical descriptions and corresponding models. One area that now requires development is a need for greater lifetime accuracy, more prognostics, and reduced time to criticality — the time between identifying there is something wrong with the system and responding to that fault without creating a mission-critical scenario [2] — through increased knowledge of the system. This is especially relevant in the case of intermittently uncrewed habitats. While earth-based systems are open-loop, long-term space habitation depends on the ability to create a closed-loop system that recycles all components onboard. This is especially true for a HOME-like system that is only visited by crew for one to three months out of a year. Figure 1.3 describes a standard interconnected overall system within the Air Revitalization section. This system needs to maintain itself for varying lengths of time in the case of partially uncrewed habitats.

The time to criticality for a catalytic converter in the car is on the order of months, as shown by the yearly inspection requirement; the time to criticality for an open-loop earth-based refinery is on the order of hours to days; **the current time to criticality for a space-based system is on the order of hours** [2] due to the interconnectivity and the finite number of resources. Lifetime accuracy in Earth-based refineries and nuclear reactors [103] are already subjects of predictive modeling research based on Earth-based physics models [49]. The modeling requires precision for human safety and cost-effectiveness for expensive parts with long lead times. **Lifetime accuracy for space systems will require**

even greater precision as the logistics planning needs increase with increasing target habitat distance from Earth. The high cost of all mass launched for resupply further incentivizes increased accuracy. Due to the possible lack of crew to provide immediate investigation in a habitat that is only crewed for part of the year, predictive models, along with models of mass and heat transfer and catalyst models, may have to be more comprehensive to predict potential issues best.

The second reason contributing to a need for more refined mathematical descriptions and models is a difference in environment – microgravity could significantly impact the current models. Here, fluidization comes into play.

On Earth, a fluidized packed bed is one where the upward force of buoyancy outweighs the downward force of gravity from a large flow rate.

Fluidized beds are typically avoided in earth systems as they lead to greater rubbing between sorbent or catalyst pellets.

Beds in space are always fluidized, and it is predominantly the flow rate that determines the amount of degradation in the system, which is one reason why the flow rates in space are set at a fraction of those on Earth.

The lack of published computational fluid mechanics research around fluidized packed beds in microgravity lends itself to many open opportunities in that field. Having a model that can incorporate complex, low Re flow with mass and heat transfer in this environment, especially when the system performs temperature swings between 200 degrees C and 10 degrees C, could prove helpful.

Both physical and chemical packed beds are most commonly modeled using first principles 1D approaches for mass and heat transfer with varying assumptions for earth systems and space systems [61]. These make use of empirical correlations and simplified flow descriptions[62]. CFD modeling, using Navier-Stokes for flow characterizations [33], and sometimes Newton's laws for particle dynamics, is also employed, though less so for packed beds in space-like environments.

The following review aims to create in-depth knowledge of packed beds and investigate the current state of packed bed characterization. Current assumptions and their effects on the fidelity of models are highlighted, and applications for these models are discussed. For applicability to the 4BCO2 and CDRA-like systems that have been chosen, packed bed reaction systems will not be addressed as heavily, and the focus will instead be on pelletized sorbent systems in disturbed laminar flow, which are mainly used in the gas-solid state. There are strong similarities between the math of the two, but sorbent systems are slightly simplified and do not require a discussion of kinetics or generation of heat from inside the bed. Turbulent systems, found in some earth-based reactors, are discussed briefly.

Driving Physical Phenomena

The first principles-based equations are discussed to understand current models and descriptions of packed bed phenomena.

Fluid Mechanics

The flow through a packed bed, which follows a torturous three-dimensional path, has been likened to a flow in a closed conduit with an irregular cross-section during laminar flow and similar to the passage through an extremely rough pipe during turbulent flow [70]. This is shown in Figure 1.17, where at low Re, the Poiseuille number is constant, and at high Re, the friction factor becomes constant. Equations used to define the shown friction factor and Re numbers are shown below, where ϵ is the void fraction, or empty space, in the bed represented by a percentage of the whole bed of volume 1, L is the length of the bed, V is the volume of the bed, Δp is the delta pressure across the bed, and ν_0 is the inlet flow rate to the bed.

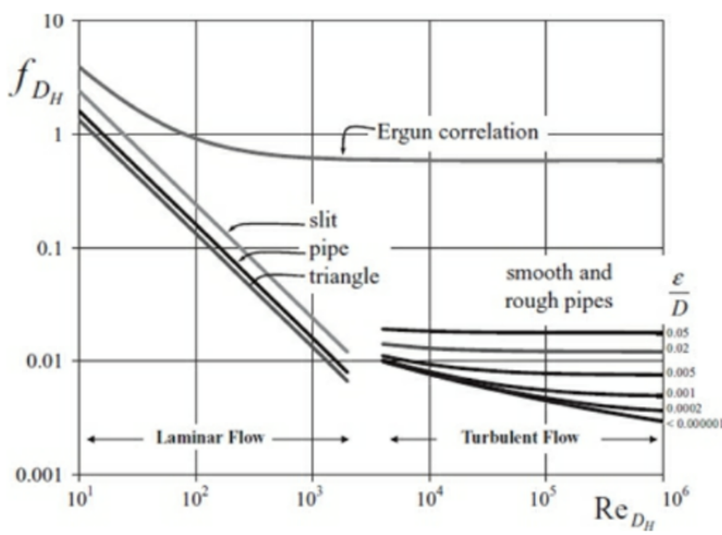


Figure 1.17: Ergun correlation, with Reynolds number on the x-axis and friction factor on the y-axis

$$A_{xs} = \frac{empty\,bed\,volume}{L} = \frac{\epsilon V}{L} \tag{1.7}$$

$$a_v \equiv \frac{total\,particle\,surface\,area}{particle\,volume} \tag{1.8}$$

$$D_H = \frac{4\epsilon}{(1-\epsilon)a_v};\ f_{DH} = \frac{\frac{\Delta p}{L} D_H \epsilon^2}{2\rho\nu_0^2}\ ; Re_{DH} = \frac{\rho\frac{\nu_0}{\epsilon} D_H}{\mu} \tag{1.9}$$

The Ergun equation (common form shown in Equation 1.10) has been shown to generally match data fits, with data showing that $f_{DH}\ Re_{DH}$ is a known constant 33.33 for slow flow through packed beds and that above $Re_{DH} = 10$, the friction factor instead is a known constant $f_D H = 1.75/3$ as is seen in Figure 1.18[70].

$$f_p = \frac{150}{Gr_p} + 1.75 \tag{1.10}$$

Where f_p and Gr_p are defined as:

$$f_p = \frac{\Delta p}{L}\frac{D_p}{\rho\nu_s^2}\left(\frac{\epsilon^3}{1-\epsilon}\right) \tag{1.11}$$

$$Gr_p = \frac{Re}{(1-\epsilon)} \tag{1.12}$$

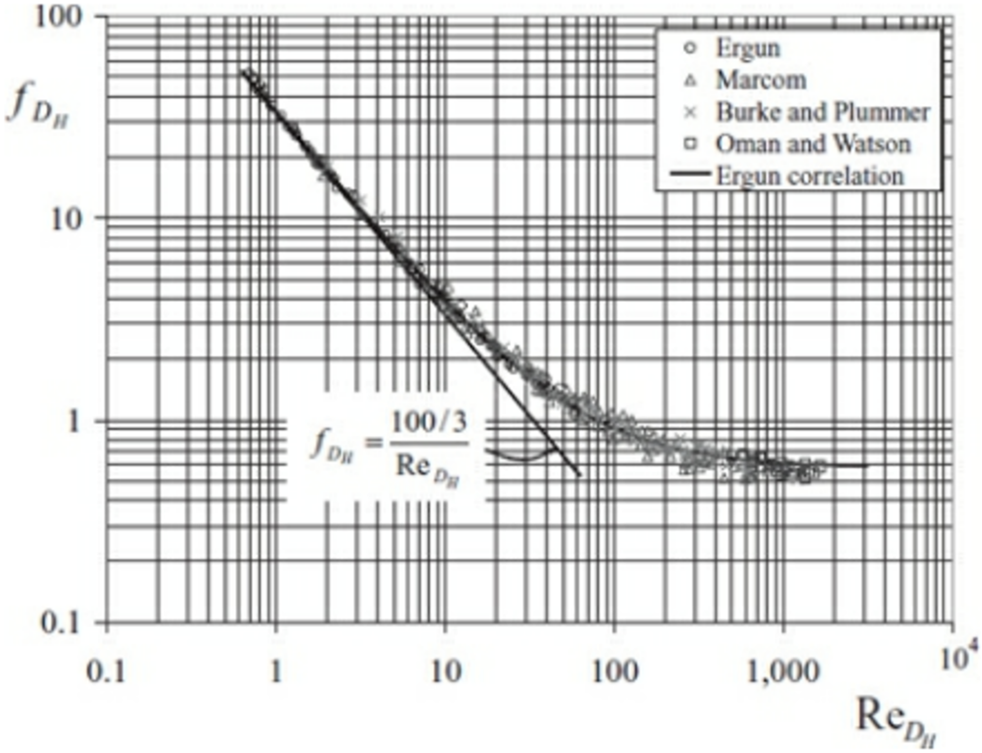


Figure 1.18: Data fit with Ergun correlation, with Reynolds number on the x-axis and friction factor on the y-axis

The Ergun correlation is why Chemical Engineering texts refer to flow in packed beds as turbulent when the Re **is greater than 10, when this is not the case, as discussed later.**

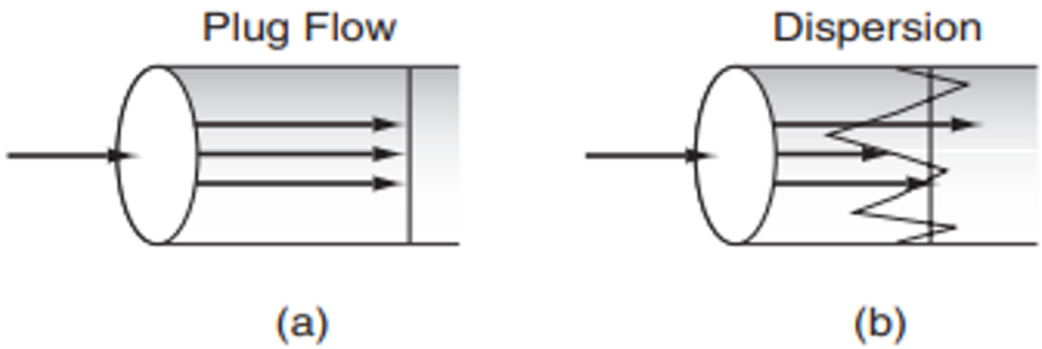


Figure 1.19: Diagram of plug Flow (a) and plug flow with dispersion (b)

Correlations like the Ergun correlation have been used to describe basic relationships, like the relationship between the initial velocity and the pressure drop needed to reach a final velocity at the outlet of the bed. The first models used for describing flow through a packed bed made a plug flow assumption, as shown in Figure 1.19 [37], and almost always referred to the beds as turbulent. Plug flow ignores the no-slip condition, assuming a uniform velocity throughout the bed due to the unknown complex nature of the bed flow. With this assumption, a momentum equation is not employed. Instead, a constant velocity is plugged into the mass transfer and heat transfer equations, as shown in the following derivation. Subsequent models used a term known as dispersion, which was used to account for the discrepancy between expected and actual mass transfer in packed beds. This, too, uses a constant velocity in the streamwise direction but with a dispersion coefficient, shown in 1.14, that works as an empirically derived coefficient to account for the complex interaction between the inlet stream and the tortuous path. This coefficient is typically obtained from a correlation like that from Wakao and Funazkri [92] in (1.13), with definitions of the Reynolds number, Schmidt number, and Peclet number provided in Equation 1.13 and Equation 1.14.

$$\frac{1}{P_e} = \frac{20}{\epsilon}\left(\frac{D}{2\nu R_p}\right) + \frac{1}{2} = \frac{20}{R_e S_c} + \frac{1}{2} \tag{1.13}$$

$$R_e = \frac{2\rho f \epsilon \nu_i R_p}{\mu}\,; Sc = \frac{\mu}{\rho_f D}\,; De = \frac{2\nu_i R_p}{P_e} \tag{1.14}$$

Here, ϵ is the void fraction within the bed, which is around 0.40 for perfectly spherical pellets [5], R_p is the pellet radius, D is the fluid diffusion coefficient, which is a property of the fluid itself and independent of the flow, ν is the inlet velocity in the streamwise direction, ν_i is the interstitial velocity accounting for the void fraction, D_e is the dispersion coefficient, and μ is the viscosity.

When looking at mass transfer through the bed, these typically employed assumptions and correlations can give a decent approximation [61] but provide no insight into the actual flow phenomena following this tortuous path.

Mass Transfer

As noted in the section above, the chemical engineering processes driving research into packed beds are primarily concerned with mass transfer from the free stream entering the bed to the sorbent or catalyst within the bed or vice versa. Because of this, insight into the assumptions made for most packed bed models can be found within the commonly used mass transfer equations. The mass balance in Equation 1.15 describes both sorption systems, where a compound is pulled out of the free stream, and catalytic systems, where a reaction occurs between the free stream's components and the catalyst itself. This states that the change in concentration C of a species i in the bed corresponds to the net flux N and a reaction term. For packed beds, this can be extended to Equation 1.16 in cylindrical coordinates. The reaction term is a generation/consumption term, so it can either describe a rate equation for a catalyst or a mass transfer equation for a specific sorbent.

$$\frac{\partial C_i}{\partial t} + \Delta N_i = R_i \tag{1.15}$$

$$\frac{\partial C_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(rN_{ir}\right) + \frac{1}{r}\frac{\partial}{\partial \theta}\left(N_{i\theta}\right) + \frac{\partial}{\partial z}\left(N_{iz}\right) = R_i \tag{1.16}$$

Most models assume axial symmetry, dropping out the θ term to turn this 3D system into a 2D system.

Assumption 1 *Assume axial symmetry, where* $\frac{\partial N_{i\theta}}{\partial \theta} = 0$

This results in Equation 1.17

$$\frac{\partial C_i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(rN_{ir}\right) + \frac{\partial}{\partial z}\left(N_{iz}\right) = R_i \tag{1.17}$$

The net flux comprises both diffusive flux J and convective flux.

$$N_{ir} = J_{ir} + C_i \nu_r \tag{1.18}$$

$$N_{iz} = J_{iz} + C_i \nu_z \tag{1.19}$$

Assumption 2 *Assume plug flow, so* $\nu_r = 0$

This is where the plug flow assumption typically enters, so $v_r = 0$. Chemical engineering texts usually assert that this assumption holds as long as no significant mass transfer comes from the walls in the form of a coating being released or a permeable wall. Due to this assumption, information on the flow is lost, and the need for the Navier Stokes momentum equations to describe flow is dismissed.

Assumption 3 *Fick's first law of diffusion applies, so* $J = -D_m \Delta C_i$

In addition, a third assumption is typically made for the diffusion within the system, assuming it can be described by a constant effective diffusivity D_m, with an equation that can be substituted into Equation 1.20 and Equation 1.21. This is a simplification of the Maxwell-Stefan equations, which describe the momentum transfer between two molecules, where elastic collisions are assumed, and the molecules of component 2 exert a drag on component 1 and vice versa.

$$N_{ir} = -D_m \frac{\partial C_i}{\partial r} \tag{1.20}$$

$$N_{iz} = -D_m \frac{\partial C_i}{\partial z} + C_i V_z \tag{1.21}$$

The new governing equation is now Equation 1.22, with convection terms on the left and diffusion and reaction terms on the right, where C is a function of t, r, and z.

$$\frac{\partial C_i}{\partial t} + \frac{\partial}{\partial z}\left(C_i \nu_z\right) = \frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C_i}{\partial r}\right) + D\frac{\partial C_i^2}{\partial z^2} + R_i \tag{1.22}$$

The following simplification is made to reach a form where an empirically derived dispersion coefficient can be used to area average. The area average is defined in Equation 1.23, with the corresponding area average concentration in Equation 1.24. The reaction term can be treated as either a sorbent system or a catalytic system, so it is temporarily removed to be discussed later.

$$\bar{\phi} = \frac{1}{\pi R^2}\int_0^R \phi 2\pi r dr \tag{1.23}$$

$$\bar{C_i} = \frac{1}{\pi R^2}\int_0^R C_i\left(t, r, z\right) 2\pi r dr \tag{1.24}$$

Using this definition, each term in Equation 1.22 is area-averaged, applying the Leibnitz rule if any of the derivatives are functions of the integrators to pull them out of the integral.

$$\frac{\partial \bar{C_i}}{\partial t} = \frac{1}{\pi R^2}\int_0^R \frac{\partial C_i}{\partial t} 2\pi r dr = \frac{\partial}{\partial t}\left[\frac{1}{\pi R^2}\int_0^R C_i 2\pi r dr\right] \tag{1.25}$$

$$\overline{\frac{\partial}{\partial z}\left(C_i \nu_z\right)} = \frac{1}{\pi R^2}\int_0^R \frac{\partial}{\partial z}\left(C_i \nu_z\right) 2\pi r dr = \frac{\partial}{\partial z}\left[\frac{1}{\pi R^2}\int_0^R C_i \nu_z 2\pi r dr\right] = \frac{\partial}{z}\overline{\left(C_i \nu_z\right)} \tag{1.26}$$

$$\overline{\frac{D}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C_i}{\partial r}\right)} = \frac{1}{\pi R^2}\int_0^R \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C_i}{\partial r}\right)2\pi r dr = \frac{2D}{R^2}\int_0^R \partial\left(r\frac{\partial C_i}{\partial r}\right) =$$

$$\frac{2D}{R^2}\left[\left(r\frac{\partial \bar{C_i})}{\partial r}\right)_{r=R} - \left(r\frac{\partial \bar{C}_i}{\partial r}\right)_{r=0}\right] \quad (1.27)$$

The following assumptions eliminate Equation 1.27 altogether.

Assumption 4 *There is no mass transfer coming from the walls, so* $\left(\frac{\partial \bar{C_i})}{\partial r}\right)_{r=R} = 0$

Assumption 5 *Finite flux at* $r = 0$ *to mitigate discontinuity where a derivative goes to infinity, so* $\left(\frac{\partial \bar{C}_i}{\partial r}\right)_{r=0} = 0$

With these simplifying assumptions, equation 1.26 becomes:

$$D_m\overline{\frac{\partial^2 C_i}{\partial z^2}} = \frac{D}{\pi R^2}\int_0^R \frac{\partial^2 C_i}{\partial z^2}2\pi r dr = D_m\frac{\partial^2}{\partial z^2}\left[\frac{1}{\pi R^2}\int_0^R C_i 2\pi r dr\right] = D_m\frac{\partial^2 \bar{C}_i}{\partial z^2} \quad (1.28)$$

The area-averaged version of Equation 1.22 is now Equation 1.29, where the second term is the net flux, the third term represents diffusion and the radial term has been eliminated.

$$\frac{\partial \bar{C}_i}{\partial t} + \frac{\partial}{\partial z}\overline{(C_i\nu_z)} = D_m\frac{\partial^2 \bar{C}_i}{\partial z^2} \quad (1.29)$$

Steps in Equations 1.30, 1.31, and 1.32 expand the $(C_i\nu_z)$ flux term, starting with the definition of an area-averaged flux.

$$\overline{(C_i\nu_z)} = \frac{1}{A_c}\int \left[C_i\nu_z - C_i\bar{\nu_z} + C_i\bar{\nu_z}\right]dA \quad (1.30)$$

$$\bar{\nu_z} = \frac{1}{\pi R^2}\int_0^R \nu_z(r)\,2\pi r dr \quad (1.31)$$

$$\overline{C_i\nu_z} = \frac{1}{A_0}\int C_i\left(\nu_z - \bar{\nu_z}\right)dA + \frac{1}{A}\int C_i\left(\bar{\nu_z}\right)dA \quad (1.32)$$

Where ν_z is the axial velocity at a given radial position, $\bar{\nu_z}$ is the average streamwise velocity. The term $\frac{1}{A_0}\int C_i\left(\nu_z - \bar{\nu_z}\right)dA$ is the dispersion flux as it is defined with respect to a relative velocity. Therefore, Equation 1.32 becomes Equation 1.33, where W is the dispersion flux, and Equation 1.29 becomes Equation 1.34, where the third term is a convective flux.

$$\overline{C_i\nu_z} = W + \bar{\nu_z}\bar{C}_i \quad (1.33)$$

$$\frac{\partial \bar{C}_i}{\partial t} + \frac{\partial W}{\partial z} + \frac{\partial}{\partial z}\left(\bar{C}_i \bar{\nu_z}\right) = D_m \frac{\partial^2 \bar{C}_i}{\partial z^2} \tag{1.34}$$

The dispersion flux is redefined in terms of a dispersion coefficient D_e, a proportionality parameter that accounts for velocity difference within this packed bed. Dispersion flux is not a fundamental property of the stream mixture like D_m, and it is typically estimated via correlations that have been determined experimentally and adjusted iteratively. Equation 1.35 is the new governing equation with area-averaged partial derivatives and a new term describing the effect of dispersion.

$$\frac{\partial \bar{C}_i}{\partial t} + \frac{\partial \left(\bar{C}_i \bar{\nu_z}\right)}{\partial z} = \left(D_m + D_e\right) \frac{\partial^2 \bar{C}_i}{\partial z^2} \tag{1.35}$$

As the dispersion coefficient (D_e) can be orders of magnitude greater than the diffusion coefficient (D_m), the diffusion coefficient is typically dropped depending on the inlet flow rate. To further account for the effects of packed porous substrates on the velocity in the z-direction, a common approach is to take the velocity far upstream, ν_s, deemed the superficial velocity, and divide it by the void fraction in the bed, resulting in what is called in interstitial velocity, ν_i. Employing these modifications, we get Equation 1.36.

$$\frac{\partial C_i}{\partial t} + \frac{\partial \left(C_i \bar{\nu_i}\right)}{\partial z} = D_e \frac{\partial^2 C_i}{\partial z^2} \tag{1.36}$$

To integrate the reaction term for a sorption system, the linear driving force model is typically used - an equation that spans across mass, heat, momentum transfer, and even electricity as it is the same model as Ohms law. Equation 1.37 shows the change in average adsorbed concentration $\bar{q}$ with time per unit solid volume (comparable to current in Ohms law), equivalent to a mass transfer coefficient k_n (which is comparable to 1/Resistance in Ohms law, as it is the inverse of resistance to mass transfer) multiplied by a driving force made up of the difference between q^*, the equilibrium adsorption concentration, and $\bar{q}$. While mass transfer occurs between the free stream and the boundary layer surrounding the pellet, then into the macro pores, and then into the crystal lattice structure, all mass transfer is lumped into one term. This is an additional assumption typically made by most simplified models.

$$\frac{\partial \bar{q}}{\partial t} = k_n \left(q^* - \bar{q}\right) \tag{1.37}$$

Assumption 6 *All forms of mass transfer within the system can be lumped into one term, k_n, experimentally fitted with empirical formulas.*

The experimental fitting of the mass transfer equation uses breakthrough curves: running a packed bed constraining as many variables as possible until the outlet concentration of flow equals the inlet concentration of flow–fitting curves using an empirical correlation such as the Toth equation in Equation 1.38. The equilibrium adsorption concentration is a constant and can be determined based on various models derived from experimental models.

$$q^* = \frac{q_m P}{\left[b + P^n\right]^{\frac{1}{n}}} \tag{1.38}$$

$$n = \frac{aP}{\left[1 + (bp)^t\right]^{\frac{1}{t}}} \; ; b = b_0^{\frac{E}{T}} \; ; a = a_0^{\frac{E}{T}} \; ; t = t_0 + \frac{c}{T} \; ; c = \frac{mGC}{RT} \tag{1.39}$$

Equations 1.38 and 1.39 relate the sorbent loading (current concentration capacity in mol/kg), n, to the saturation capacity of the pellets a, to the partial pressure of the adsorbed gas P, to the equilibrium constant of the compound in question b, and to t, the heterogeneity parameter representing the structural heterogeneity of the crystal structure.

This additional reaction type term can be integrated into the governing equation from Equation 1.36. once a unit correction is performed: $\frac{\partial C_i}{\partial t}\,[=]\,\frac{mol}{time*fluid\,vol}$ and $\frac{\partial \bar{q}}{\partial t}\,[=]\,\frac{mol}{time*solid\,vol}$. The void fraction ϵ is used to correct the volume term. The volume of the bed occupied by solid material is $(1-\epsilon)$, so multiplying the reaction term by $\left(\frac{1-\epsilon}{\epsilon}\right)$ will yield appropriate units for concentration reacted in the volume of fluid. The result is Equation 1.40, the most commonly used equation for mass transfer in a packed bed system [79].

$$\frac{\partial C_i}{\partial t} + \left(\frac{1-\epsilon}{\epsilon}\right)\frac{\partial \bar{q}}{\partial t} + \frac{\partial\left(C_i \nu_i\right)}{\partial z} = D_e \frac{\partial^2 C_i}{\partial z^2} \tag{1.40}$$

Boundary and Initial Conditions

The governing equation, Equation 1.40, now requires boundary conditions. The second term, from Equation 1.37, can be determined separately and then input in. The equation is first order with time, so it requires one initial condition, where the average adsorbed concentration is zero at time equal to zero.

$$\bar{q}\left(t = 0, z\right) = 0 \tag{1.41}$$

The rest of Equation 1.40 is first order with time and second order with space so that it will require an additional initial condition and two boundary conditions. The initial condition states that at time zero, the concentration of the compound of interest – CO_2 – is zero.

$$C_i\left(t = 0, z\right) = 0 \tag{1.42}$$

The boundary conditions are established for the entrance and exit of the packed bed. At the entrance, a constant flux boundary condition is used, where C_{i0} is the inlet concentration and ν_s is the velocity far upstream of the bed. Danckwert's boundary condition is employed at the outlet of the bed, which predicts concentration profiles in the dispersion regime that are unrealistic due to convection outweighing diffusion. The change in the overall concentration of the gas stream is zero at the outlet as adsorption will have taken place throughout the bed.

$$-D_e \frac{\partial C_i}{\partial z}_{z=0} = \frac{\nu_s}{\epsilon}\left(C_{i0} - C_i\right) \tag{1.43}$$

$$\frac{\partial C_i}{\partial z}_{z=L} = 0 \tag{1.44}$$

Heat Transfer

While heat transfer has not historically been as focused as mass transfer within packed beds, it has recently received more attention, especially as the effects of temperature on catalyst or sorbent activity and degradation are investigated. Some of the first heat transfer equations lumped heat capacities and effective thermal conductivities for one comprehensive energy balance equation in two dimensions [39], as shown in Equation 1.45, neglecting the θ direction.

$$C_p \frac{\partial T}{\partial z} = k_r \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + k_a \frac{\partial^2 T}{\partial z^2} \right) \tag{1.45}$$

Over time, however, studies showed that many packed bed systems, including sorption systems, deviated significantly from isothermal conditions [59] [67]. Standard energy balances now consider heat transfer between the fluid and the sorbent, heat transfer between the fluid and the wall, and heat transfer between the ambient environment and the wall[60]. Equation 1.46 gives the fluid phase energy balance with the sorbent.

$$\epsilon a_f \rho_f c_{pf} \frac{\partial T_f}{\partial t} - \epsilon a_f k_{eff} \frac{\partial^2 T_f}{\partial z^2} = -\epsilon a_f \rho_f \nu c_{pf} \frac{\partial T_f}{\partial z} + a_f a_s h_s \left(T_s - T_f\right) + P_i h_i \left(T_w - T_f\right) \tag{1.46}$$

Just as the diffusion and dispersion coefficients are lumped for mass transport, the mechanisms for radial transport are lumped into an effective thermal conductivity k_{eff}. Equation 1.46 uses the void fraction ϵ, the superficial free flow area a_f, the fluid density ρ_f, the fluid heat capacity $c_p f$, the effective fluid conductivity k_{eff}, the velocity of the fluid v, the pellet external surface area per unit volume a_f, the adsorbent to fluid heat transfer coefficient h_s, the sorbent temperature T_s, the inner perimeter of the column P_i, the heat transfer coefficient between the column wall and the fluid h_i, and the column wall temperature T_w.

Equation 1.47 provides the sorbent energy balance, which includes transient energy storage and heat transfer from the fluid. Here, ρ_s is the sorbent density, c_{ps} is the sorbent heat capacity, and λ is the isosteric heat of adsorption.

$$\left(1 - \epsilon\right) \rho_s c_{ps} \frac{\partial T_s}{\partial t} = a_f a_s h_s \left(T_f - T_s\right) - \left(1 - \epsilon\right) a_f \lambda \frac{\partial \bar{q}}{\partial t} \tag{1.47}$$

Equation 1.48, similar in form to Equation 1.47, shows the column wall energy balance, which includes transient energy storage, heat conduction, and heat transfer from the fluid to the ambient environment. Here, a_w is the cross-sectional area of the column, ρ_w is the column wall density, c_{pw} is the column wall heat capacity, k_w is the column wall conductivity, P_0 is the column wall outer perimeter, T_a is the ambient temperature, and h_0 is the column wall to ambient environment heat transfer coefficient, which is determined empirically.

$$a_w \rho_w c_{pw} \frac{\partial T_w}{\partial t} - a_q k_w \frac{\partial^2 T_w}{\partial z^2} = p_i h_i \left(T_f - T_w\right) + P_0 h_0 \left(T_a - T_w\right) \tag{1.48}$$

When in the gaseous phase, the heat capacity of the fluid is typically determined from an empirical polynomial equation where coefficients are determined from experimental heat capacity values. The fluid to pellet heat transfer coefficient h_s is typically calculated using a thin film correlation [92], [79] as shown below, where Sh is the Sherwood number, R_p is the pellet radius, and D is the diffusion coefficient.

$$Sh = 2 + 1.1 Sc^{\frac{1}{3}} Re^{0.6} \; h_s = \frac{ShD}{2R_p} \tag{1.49}$$

The heat transfer coefficient from the fluid to the wall, h_s, is calculated via correlations like the one below for 1D models [65] using the Nusselt number, where R_i is the bed radius and k_f is the fluid conduction.

$$Nu = 2.03 Re^{0.6} exp \left(-\frac{6R_p}{R_i}\right) \; h_i = \frac{k_f}{2R_i} Nu \tag{1.50}$$

The effective thermal conductivity is calculated from a correlation such as that in Equation 1.51 [101], [57], using a correlation previously found for effective thermal conductivity of a packed bed without flow, in Equation 1.50, where k_s and k_f are the individual thermal conductivities for the solid and the fluid.

$$k_e = k_f \left(\frac{k_s}{k_f}\right)^n \; ; \; n = 0.280 - 0.757 log_{10} \epsilon - 0.057 log_{10} \left(\frac{k_s}{k_f}\right) \; ;$$
$$k_{eff} = k_f \left(\frac{k_e}{k_f} + 0.75 Pr Re\right) \; ; Pr = \frac{c_p \mu}{\rho_f k_f} \tag{1.51}$$

It is worth noting that these coefficients will vary considerably based on the empirical formula chosen. Figure 1.20 [61] shows heat transfer coefficients vs temperature for a variety of correlations[92] [32][73][87][68].

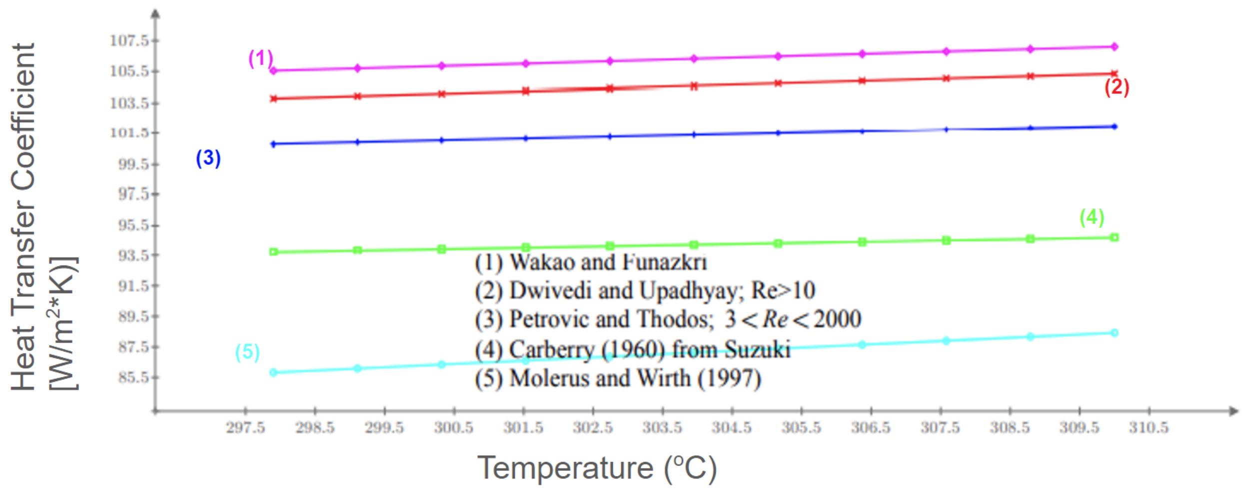


Figure 1.20: Heat transfer coefficient from particle to free stream vs temperature for five correlations, as reported in literature [61]

Fluidization Velocity

The mechanics of the flow, mass transfer, and heat transfer within a packed bed can be significantly altered by fluidization. Fluidization is typically categorized on Earth-based systems as taking place at some v_{max}, where the velocity is enough to counteract the effect of gravity, and the pellets begin to float. This is shown in a common correlation in equation 1.52. Fluidized beds are sometimes employed on earth, but only when moving catalysts or sorbents with the flow from one bed to the next. In certain applications, however, such as space systems, beds are always closer to fluidization as there is a negligible gravitational effect, g.

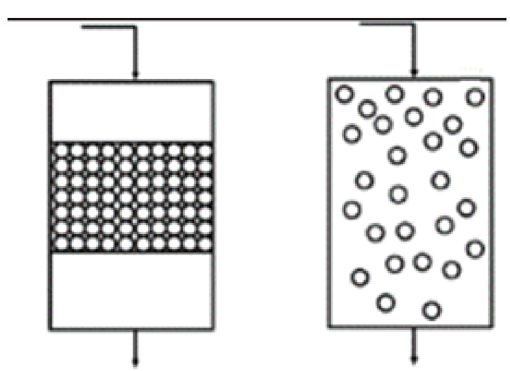


Figure 1.21: Left: non-fluidized bed, right: fluidized bed

$$\nu_{max} = 0.8\nu_{mf} \approx 6x10^{-4} g \frac{(2R_p)^2}{\mu} (\rho - \rho_f) \tag{1.52}$$

Summary of Driving Physical Phenomena

The primary restriction to understanding a packed bed's internal mechanisms is the flow description. It is common within chemical engineering applications for mass transfer of the entire bed described with commonly used correlations and without Navier-Stokes momentum equations.

Literature Review on Packed Beds

While packed beds have been around for thousands of years, the first patent filed for a sorption-packed bed was for a water filter of charcoal-laden wool stuffed into a pipe in the early 1700s. The essence of a packed bed has mostly stayed the same in three hundred years. Still, there have been considerable technological advances regarding the materials used and the modeling of the internal dynamics. By 1915, ordered pellets entered into use [82], and by 1951, ordered packing using grids of material emerged to increase contact surface area and durability [64].

The study of heat and mass transport of packed beds began increasing in the 1950s, driven mainly by the fuel industry and building off of fundamental work by Chilton and Colburn into heat exchangers [19]. There was a focus on transient temperature profiles during packed bed regeneration for the removal of coking from the breakdown of hydrocarbons, and transient temperature profiles were derived mathematically with simplifying assumptions [91] [12].

In the 1990s, literature published by Knox et al. through NASA showed that the axial dispersion coefficient estimated by empirical correlations, in this case using the Wakao correlation from Equation 1.13, was significantly incorrect for a tube-to-pellet ratio of 20 or less. To fit the experimental data provided in Figure 1.22[59], the curve had to be multiplied by a factor of 7. For some sorbates, correction factors as significant as 50x had to be applied. This was hypothesized to be because of channeling, where the flow field at the wall deviates significantly from the flow throughout the rest of the bed, a limitation of the simplified flow field assumed for most packed bed models. Further, as shown in Figure 1.23, packed beds were found to vary significantly from isothermal conditions [67], which could also be attributed to the same limitations, with convective heat transport correlating with the flow field. Literature reviews have shown significant differences between wall heat transfer coefficients [31], which is unsurprising when taking Figures 1.22 and 1.23 into account, as well as the fact that the correlations for wall heat transfer coefficients depend on flow velocity.

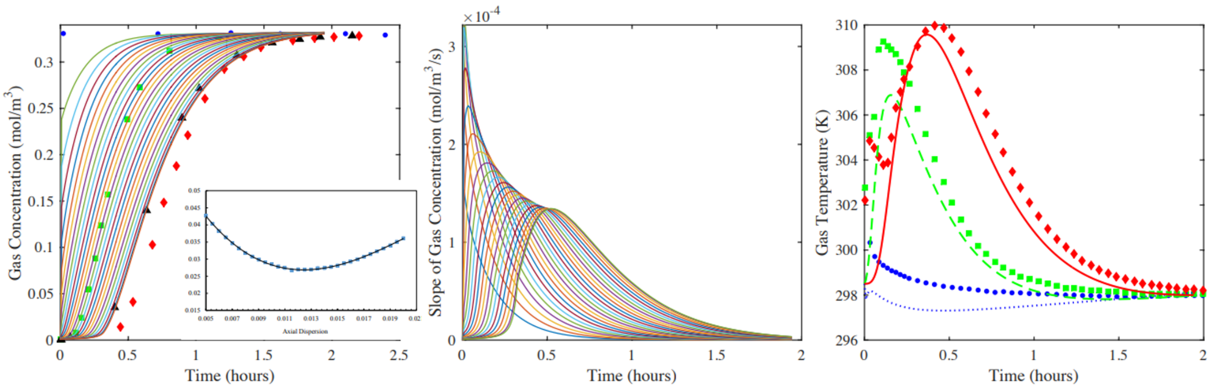


Figure 1.22: Adsorption curve of concentration vs. time pulled from literature [61], the slope of this curve, and temperature profiles from left to right. Solid lines represent results from the model using an adjusted dispersion coefficient. Squares, triangles, and diamonds show experimental data of concentration on the left and temperature on the right for values measured at 2.5%, 50%, and 97.5% down the length of the bed using centerline measurements.

Computational Fluid Dynamics (CFD), primarily employing discretized forms of the Navier Stokes equations for descriptions of the flow field along with the internal geometry of the bed, has been developed extensively for earth-based systems[90]. As a result, models for particle-to-fluid mass and heat transfer [78], as well as fluid-to-wall and wall-to-ambient mass and heat transfer[31] have been generated. Discrete methods, which treat the beads within a bed as discrete entities, have also been employed in the case of Direct Numerical Simulation (DNS)[99]. In this method, all scales of the motion of the fluid are resolved down to the no-slip boundary condition on the surface of each particle without a need for closure models. The computational grid must be smaller than the particles themselves to achieve DNS simulation results.

Within the past five years, a coupling method between CFD to model the fluid phase and the Discrete Element Method (DEM) to model the particles has gained traction [17][55][100] for turbulent packed beds. DEM, a counterpart to CFD, tracks the motion of every particle by solving the Newton equations of motion for particles with collision models. This is most applicable to earth-based fluidized beds but could also serve as useful for space-based applications to analyze the degradation of particles due to fluidization. Regarding space-specific models, NASA Glenn has performed initial investigations into packed bed flows under microgravity conditions [66].

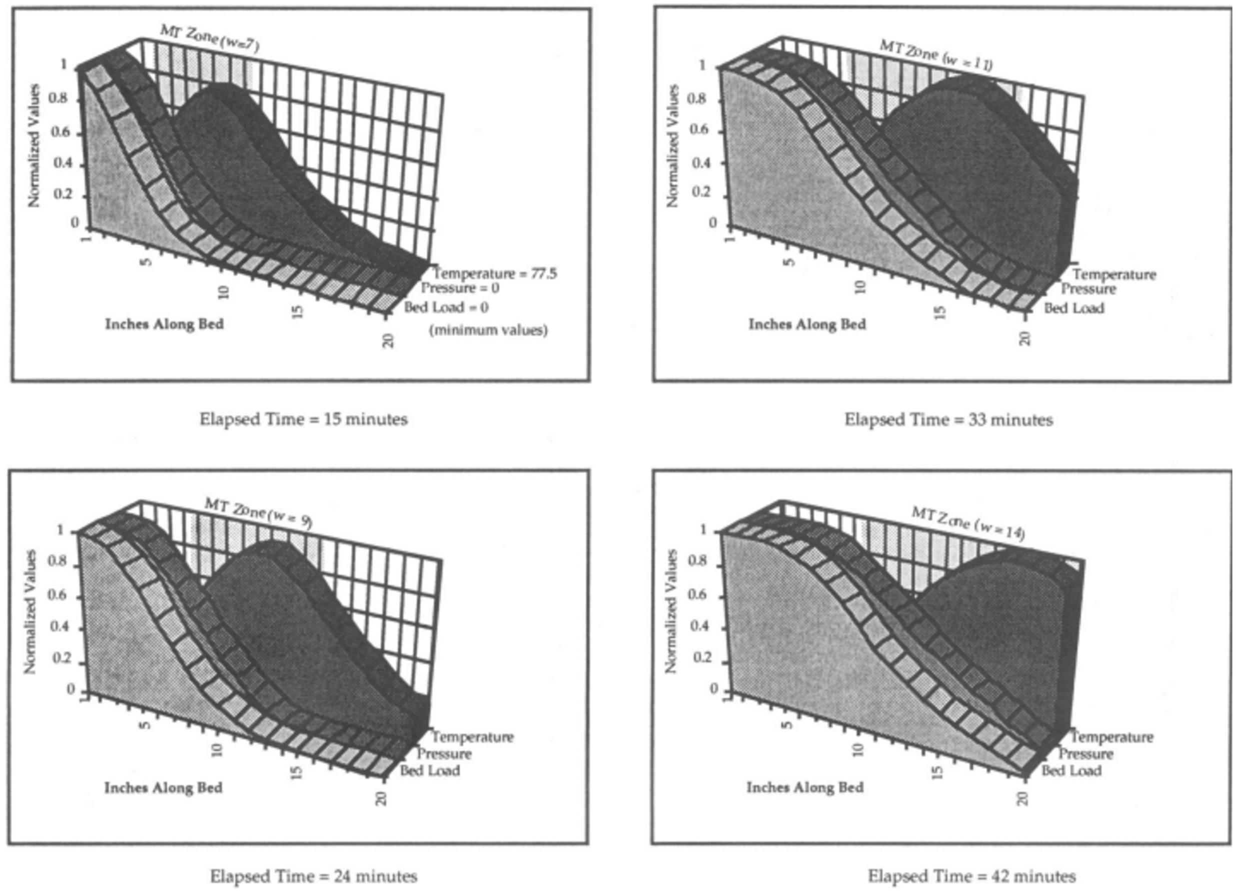


Figure 1.23: Temperature profiles at different elapsed times down the length of the bed showing packed beds vary significantly from isothermal conditions[67].

Summary of the current state of knowledge

Packed beds are primarily modeled without the use of the Navier Stokes equations, making simplifying assumptions that neglect the complex nature of flow through a pelletized structure. While these models are adequate for modeling mass transfer over the entirety of the bed, they fall short when investigating local mass transfers, heat transfers, and shear stresses, as these are all dependent on details of the flow field. The past ten years have shown an uptick in using more advanced computational methods that employ the Navier-Stokes methods. While more computationally intensive, these are more comprehensive and allow a greater understanding of the mechanics within the bed.

Experimental Methods for Packed Beds

Laser Doppler Anemometry(LDA)

Laser Doppler Anemometry is based on the concept of the Doppler shift of scattered light from a moving particle. Two laser beams intersect at a measurement volume, and the intersection of laser wavefronts in the volume generates laser interference patterns called fringes. When a particle passes through the two beams, it scatters the light; the difference in frequency in the scattered light is called the Doppler shift and is proportional to the fluid velocity. A receiver can then collect the scattered light and convert the light intensity fluctuations into voltage signal fluctuations. To generate a full-field profile of the bed, multiple measurements are made at various points throughout the bed[69]. To experimentally validate their CFD approach for a packed bed, Calis and Romkes [14] used LDA on a bed with polyethylene spheres in a structured packing to measure local velocities. Water was used at ambient conditions, seeded with 0.3 µm TiO_2 particles. The LDA results can be seen in Figure 1.24.

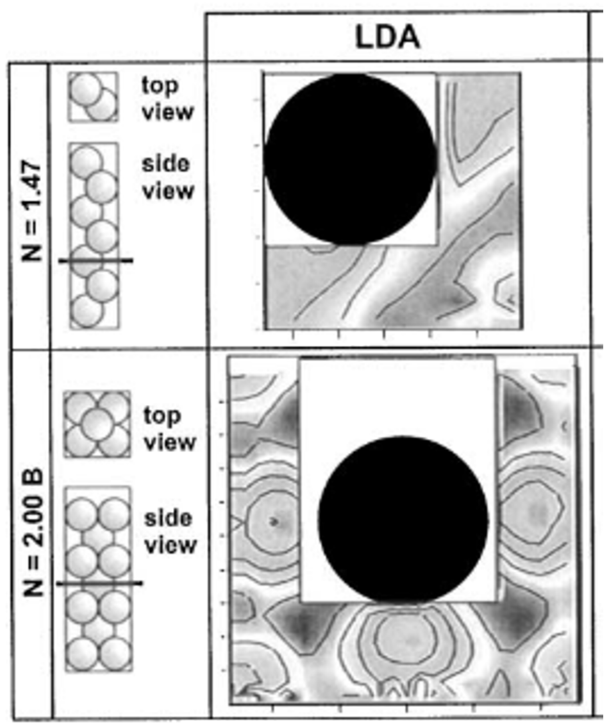


Figure 1.24: LDA Flow for different packing [14] showing a comparison of flow profiles in a horizontal cross-section through the bed (i.e., perpendicular to the longitudinal axis of the bed), obtained with LDA for channel-to-particle diameter ratios of 1.47 (top) and 2.00B (bottom). The horizontal bars in the drawings indicate the locations of the sample planes

Particle Image Velocimetry

Particle Image Velocimetry (PIV) is an optical method to visualize the velocity field of an entire region simultaneously and was created as a response to the limitations of point measurement devices such as the LDA[63]. PIV works by directing a pulsed high-energy laser through a cylindrical lens. This creates a thin planar sheet of high-intensity light, which is aligned and shone through the flow. Like LDA, the flow is seeded with light-scattering particles. The sheet of light then scatters and the images of the scattering seeds are captured by a high-speed camera. Taking two of these images, one right after the other, gives a picture of the flow at two discrete times, and these can be differenced to determine local velocity vectors.

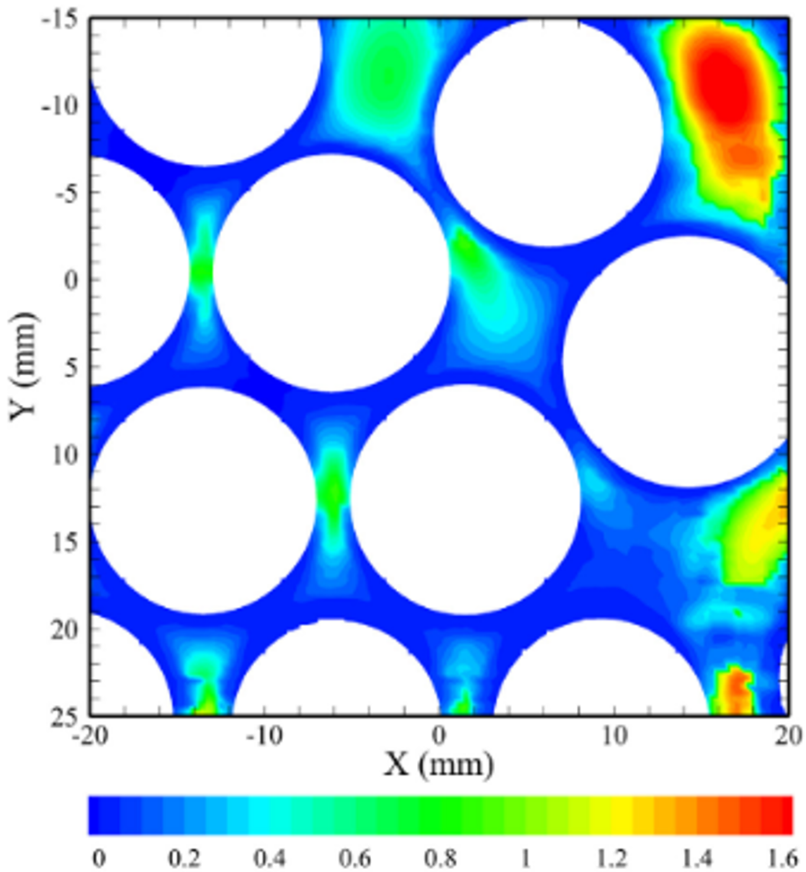


Figure 1.25: Axial velocity profile using PIV showing contour plot using velocity in (mm/s)[99]

Wood and their group at Oregon State University used PIV to image flow through a randomly packed bed of spherical beads made of optical glass[99]. To eliminate distortion from the medium, they used a solution of ammonium thiocyanate with a refractive index matched to the glass. To directly compare the PIV results with the model, the bead center locations were measured using the PIV itself, measuring the glare of the surface along with the image diameter by using the laser sheet. This resulted in a variation of magnification in each measurement plane. To reduce uncertainty from in-plane image loss, they collected 1000 images per imaged plane and used them to form 999 image pairs, from which a correlation averaging method determined particle displacements. Figure 1.25 shows the axial velocity fields through a contour plot. Normal velocity was recorded as well. The overall uncertainty was 2.6% in the streamwise direction and 7.5% in the axial direction.

Computational Methods for Packed Beds

With the help of modern CFD codes and the growth of computational modeling, it is now possible to compute detailed flow fields for the complex geometry of gas-solid packed bed systems. Models exist primarily for a low tube-to-particle diameter ratio relevant to space systems and smaller-scale reactors. For reference, some packed beds in the petroleum refining industry can reach 10 feet in diameter.

CFD Continuum Approach

Calis and Romkes, at the University of Delft, developed a validation of a flow profile in a packed bed[14], followed by a validation of particle to fluid mass and heat transfer description[78] based on a Navier-Stokes Continuum CFD approach. CFX-5.3 was employed and was shown to predict the local flow adequately; streamlines can be seen in Figure 1.26. To define the geometry of their beds, they used a structured packing system as opposed to a random packing system.

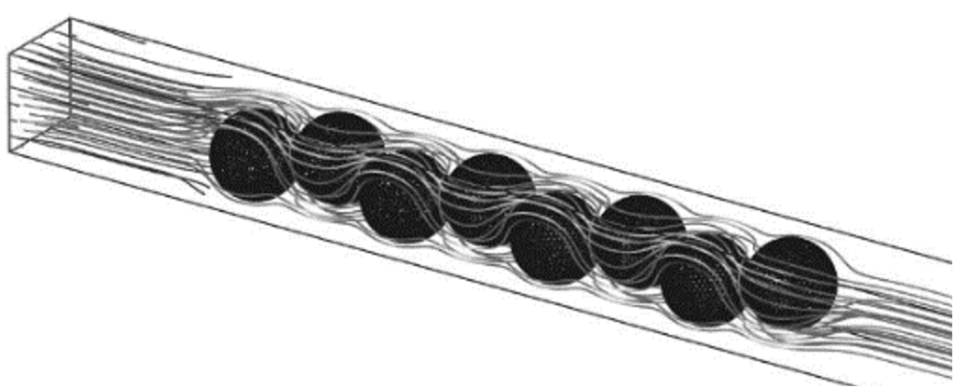


Figure 1.26: Flow profile through a packed bed [14]

In their first study, they limited the number of particles in the simulated bed to 30. Their inputs were as follows:

- Laminar, 3D, incompressible flow
- Use of an unstructured grid with about 3 million cells
- Steady flow instead of transient flow
- Second-order discretization scheme

A comparison of friction factors obtained through experiments and through the model showed that pressure drop characteristics of the packed bed could be predicted with an average error of 10%. Studies show that the CFD model trends, using particle-to-bed ratios of 1.47 and 2, agreed with the LDA experimental results, as shown in Figure 1.27. This was confirmation that the CFD model could predict local velocities adequately.

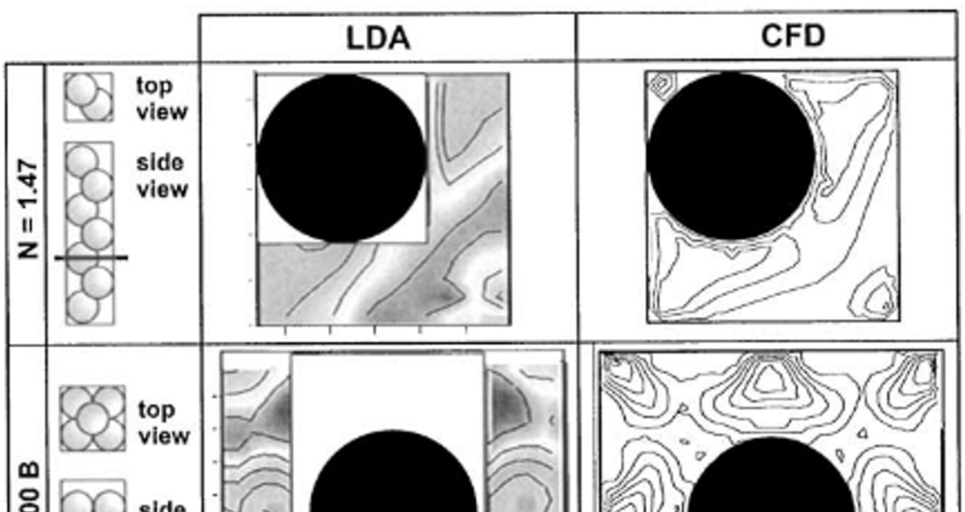


Figure 1.27: Comparison of LDA measurement for flow with CFD[14], showing comparison of flow profiles in a horizontal cross-section through the bed (i.e., perpendicular to the longitudinal axis of the bed), obtained with LDA (left) and CFD (right), for channel-to-particle diameter ratios of 1.47 (top) and 2.00B (bottom). The horizontal bars in the drawings on the right indicate the locations of the sample planes

In their subsequent study, which used the same setup, they could adequately predict the particle-to-fluid heat transfer of a single free sphere and the mass and heat transfer characteristics within 15% of experimental values pulled from literature.

Direct Numerical Simulation of Pore Scale Flow Approach

Pore-scale flow studies can be conducted using Direct Numerical Simulation (DNS), solving the Navier-Stokes equations using conventional numerical discretizations on a fine grid with an explicitly resolved substrate geometry. Experimental results calculated by the Woods group[99], shown in the section covering Particle Image Velocimetry, were used to validate a flow field predicted from DNS. They use what is referred to as a fictitious domain approach, where they apply a synthetic force around the solid regions in the bed to satisfy a desired no-slip boundary condition to generate better quality solutions near the wall. An uncertainty analysis was conducted, which generated an estimate for the number of grid points necessary per bead diameter needed to describe the flow field within 5% uncertainty for particle Reynolds numbers less than 600. The following assumptions are employed:

- Navier-Stokes equations for fluid motion extend over the entire bed, including particle regions
- Particle region is described as a Newtonian fluid (constant viscosity with shear rate proportional to shear stress)
- Incompressible
- Motion of the material inside the solid is constrained to be a rigid body motion

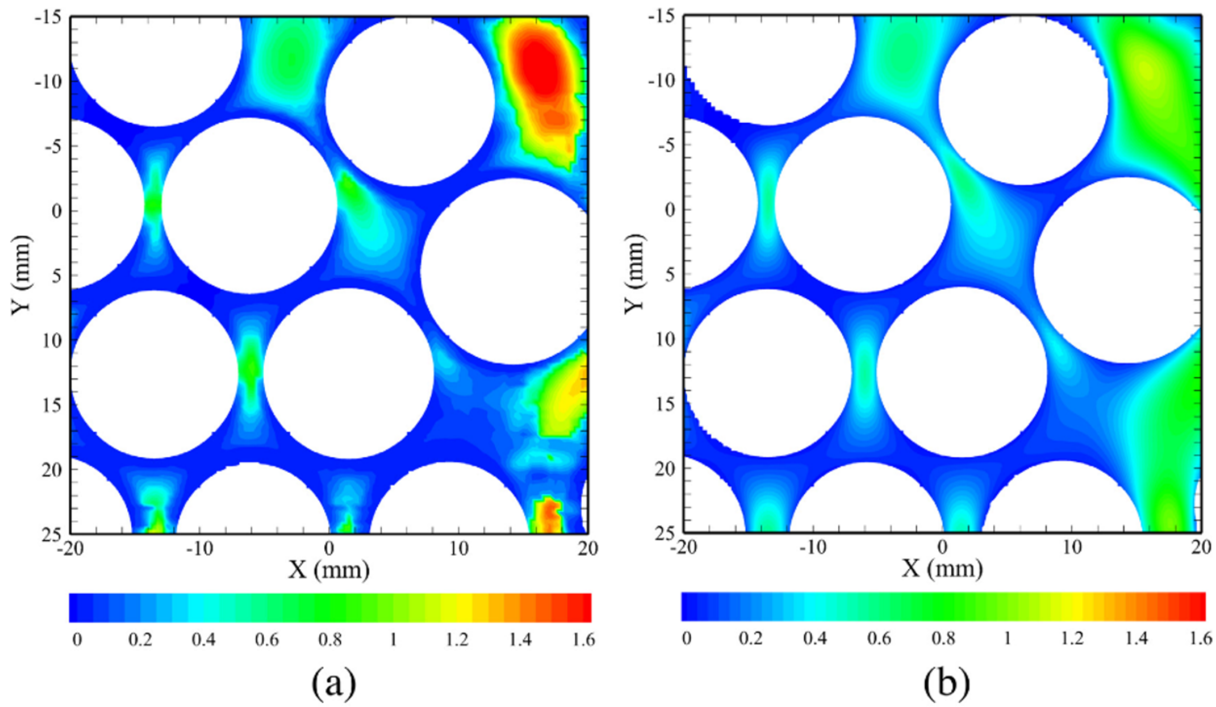


Figure 1.28: Comparison of axial velocity between PIV and DNS [99]; (a) contour plot from PIV (velocity in (mm/s)), (b) contour plot from DNS (velocity in (mm/s))

To compare the DNS velocities against experimental results, the DNS results were interpolated to the grid locations used to obtain the PIV results. Figure 1.28 shows the comparison of the axial velocity for both PIV (a) and DNS (b). The deviations between numerical and experimental results were 11.32% for axial velocity and 4.74% for streamwise velocity. The uncertainties in the DNS predictions were 2.94% for the streamwise velocity and 4.38% for the axial velocity, computed using a Global Convergence Index.

Transition and Turbulence

The distinction between true turbulent and unsteady laminar flow for packed beds is made difficult by a difference in terminology between Chemical Engineering and Mechanical and Aerospace Engineering. It is not uncommon to see turbulence referenced in Chemical Engineering texts[79] when, in fact, the flow in question is unsteady laminar. That said, there have been investigations into the true turbulent flow for randomly packed beds[54], where transition occurred at a critical particle Reynolds number between 275 and 375 when accounting for voidage, and for structured packed beds[11].

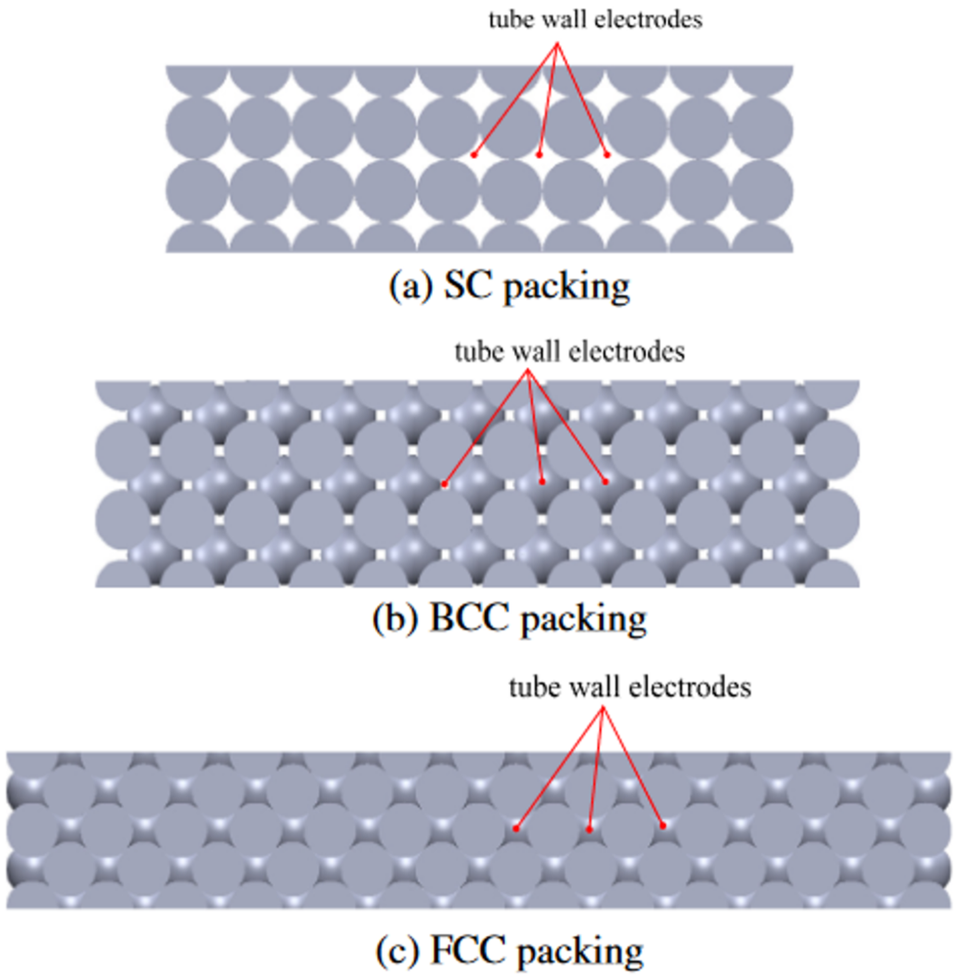


Figure 1.29: Structure of simple cubic (SC), body center cubic (BCC), and face center cubic (FCC) and corresponding placement of wall electrodes

For structured beds, Reynolds numbers were recorded by the Bu lab at Xi'an Jiaotong University [11] for three different structures, shown in Figure 1.29 with corresponding parameters in Figure 1.30, using an electrochemical technique. Microelectrodes made of nickel wire were placed at the tube wall, as shown in Figure 1.29, and at the inner particle surfaces, as shown in Figure 1.31. The packing spheres were 12 mm in diameter, and the tubing was made of plexiglass. An electrolyte composed of an aqueous solution of caustic soda, potassium ferrocyanide, and potassium ferricyanide was used, which reacted with the nickel while a constant voltage was supplied. This creates small electrochemical cells throughout the bed that produce readings recorded by a computer, with increased amplitude and frequency corresponding to the onset of turbulence. These readings were processed using the analysis of the fluctuating rate of current signals, where the onset of turbulence was determined when the behavior of turbulence flow was observed in about 80% of the electrodes (either inner or wall electrodes). Turbulence was determined by taking the instantaneous limit current, which is the sum of the average and fluctuating values, and using it to find the fluctuating rate. The power spectrum density of the fluctuating component was then determined, and previously investigated relationships between the integration domain of the power spectrum density and the Reynolds number were employed.

Packing forms	L (mm)	W (mm)	H (mm)	ε_{local}	ε
SC	120.00	36.00	36.00	0.22	0.48
BCC	164.42	41.57	41.57	0.41	0.32
FCC	215.65	33.94	33.94	0.22	0.26

Figure 1.30: Parameters for each type of bed packing structure [11]

It was found that transition for a simple cubic packed bed took place for all electrodes for Re around 260 to 430. The upper range is higher than randomly packed beds; this was attributed to a higher void fraction of 0.48 compared to 0.40 and a smaller tortuosity for simple cubic packing. Fluctuations at the wall were larger than those at the center, corresponding to a smaller void fraction at the wall for this packing.

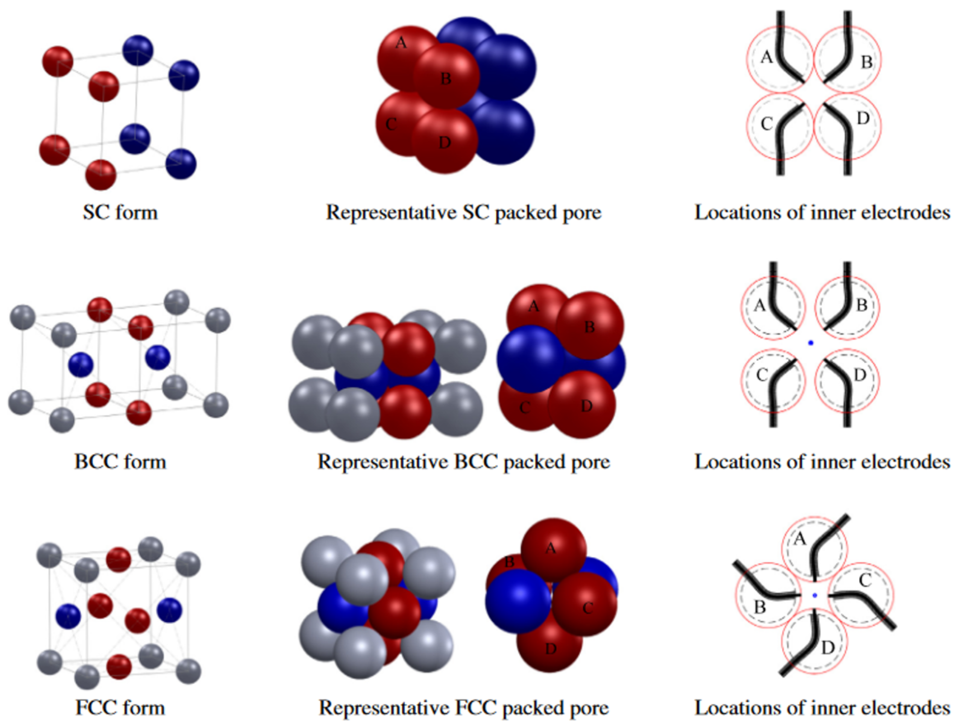


Figure 1.31: Locations of inner electrodes for each type of structure [11]

In face center cubic packed beds, turbulence occurred for all electrodes between 70 and 250, with a lower limit much smaller than that of randomly packed beds. This was attributed to an interior void fraction of 0.26, almost half that of the randomly packed bed.

For the body center cubic packed bed, the end of laminar flow occurred around 130. The onset of turbulent flow occurred at 350 for inner probes and 580 for wall probes, showing much larger fluctuations at the interior than at the exterior. This corresponded to a larger void fraction of 0.41 at the wall than at the center, where the void fraction is 0.32.

CFD-DEM Approach (Computational Fluid Dynamics -Discrete Element Method)

CFD-DEM aims to couple the DEM, which describes collision models of the discrete solid particles, with the Navier-Stokes continuum approach to describe the fluid. This approach has recently gained traction for industrial-scale modeling of turbulent packed beds. In 2009, the Dow Company published their findings[3] to improve the accuracy of catalyst reactor design. DEM generates a realistic packing structure for the bed, which is then imported into the CFD preprocessor to generate a mesh for the CFD simulation. The bed at Dow was created with 1000 spherical pellets, for which particle-particle friction and particle-wall friction were considered. An unstructured mesh was generated using tetrahedral elements. The 3D steady-state flow was then simulated using the Reynolds Averaged Navier-Stokes equations (RANS) alongside the mass conservation equation. All simulations occurred within the turbulent regime, between Reynolds numbers of 2000 and 20,000, and the closure model used was the Renormalization Group (RNG) [102]. Figure 1.32 shows the flow path lines (a), the pressure contours on particles and on the wall (b), and the velocity magnitudes on the central plane across the packed bed (c). The average error between the CFD-DEM model pressure drop and previously measured pressure drop values was 3.1%.

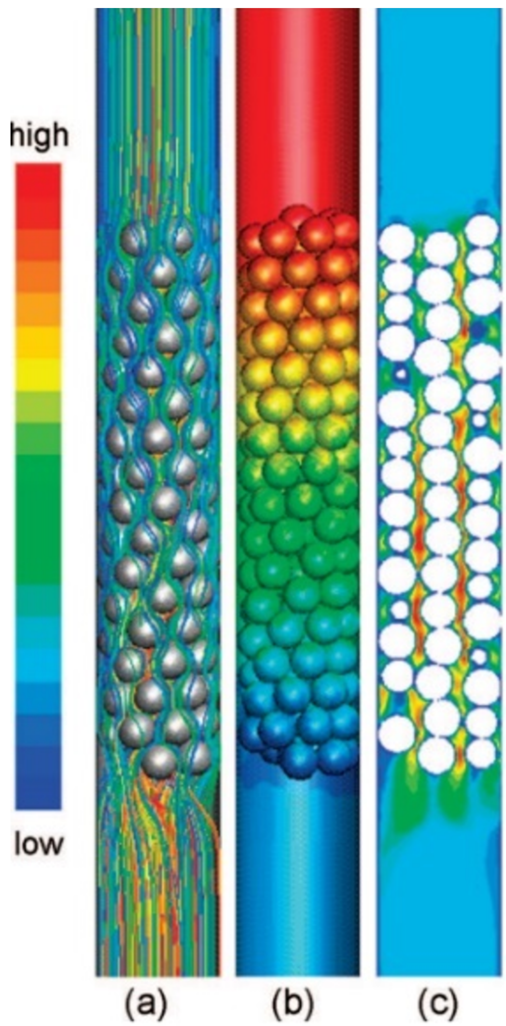


Figure 1.32: CFD-DEM model visualization (a) flow pattern shown as flow path lines, (b) pressure contours on particles and tube wall, and (c) velocity on central plane[3]

Takeaways & Research Challenges for Packed Bed Flow

Improved computational processing aids all complex flow modeling; however, the packed bed flow modeling applications are increasing. With the push for long-duration space habitation, packed bed flows in microgravity for life support systems are gaining attention. These could use the computational tools currently used by other fields, such as CFD-DEM, which could prove useful for the fluidized nature of beds in microgravity.

The above information helped solidify knowledge that would be required to focus on packed bed flow systems and solidified the choice to build a CO_2 removal testbed using a zeolite packed bed for degradation studies at the UC Davis Center for Spaceflight Research and as a result set this thesis on a clear path.

1.5 Existing Ground-Based Testbeds for Carbon Dioxide Removal in Packed Beds for Space

The following two testbeds were investigated to gain an understanding of current ground-based testbeds for space applications. The leads for the two testbeds, Dr. Knox (LINUS) and Dr. Eshima and Dr. Nabity (STEVE), were also gracious in acting as advisors both for weekly advice and in a formal capacity as reviewers of the milestones for the UC Davis-based ECLSS testbed based on zeolite packed bed technology and on an ISS CDRA/4BCO2-like system.

- LINUS: Ground-based analog to the 4BCO2/4BMS system currently serving as the prime technology within the EXPRESS rack on the ISS. Located in Huntsville, Alabama, at NASA MSFC
- STEVE: Simulation Testbed for Exploration Vehicle ECLSS. Designed based on a CDRA/4BMS/4BCO2-like system and part of the NASA HOME STRI hardware. Located in Boulder, Colorado, at CU Boulder under the direction of Dr. Jim Nabity

Linus Ground Analog to 4BCO2/4BMS at NASA MSFC

The Linus testbed at NASA Marshall Space Flight Center in Huntsville, Alabama, resides in their ECLSS high bay[58] and is a ground analog to the 4BCO2/4BMS system that was also developed by the MSFC team, led by Dr. Knox. Linus contains functionally similar hardware to the 4BCO2/4BMS currently on station, with a layout that facilitates access to all parts of the testbed.

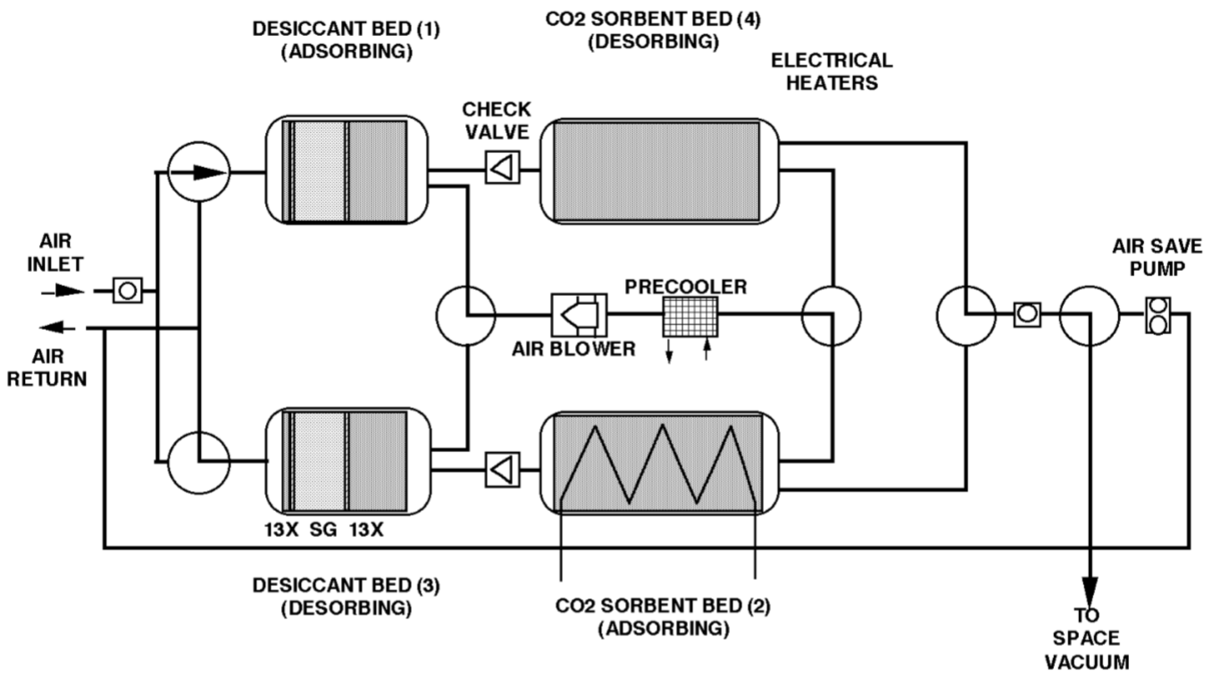


Figure 1.33: 4BMS schematic from literature [58] has a functionally similar design to the Linus ground-based testbed.

STEVE Simulation Testbed for Exploration Vehicle ECLSS at CU Boulder

The STEVE testbed at CU Boulder [34], shown in Figure 1.34, was also modeled after a CDRA/4BCO2-like system has been developed to collect nominal and off-nominal regenerable CO_2 removal system operation data. The system, operating under the HOME NASA STRI, enables the introduction of faults, including valve stiction, sorbent bed degradation, filter clogging, sensor failures, heater failures, and leaks.

As STEVE was the first ECLSS testbed developed and used for the HOME institute, it was an example for ZeoDe, which has different but complementary capabilities. While STEVE focuses on step function faults, ZeoDe focuses on degradation signals. There is much overlap between their system architecture; however, when ZeoDe was in development, it was a conscious choice to start from fundamental requirements and build out to component selection independently from the STEVE architecture since the core data generation goals of the two testbeds are different. The ZeoDe testbed also benefited immensely from STEVE through advisorship in the design and build process from the STEVE responsible engineers.

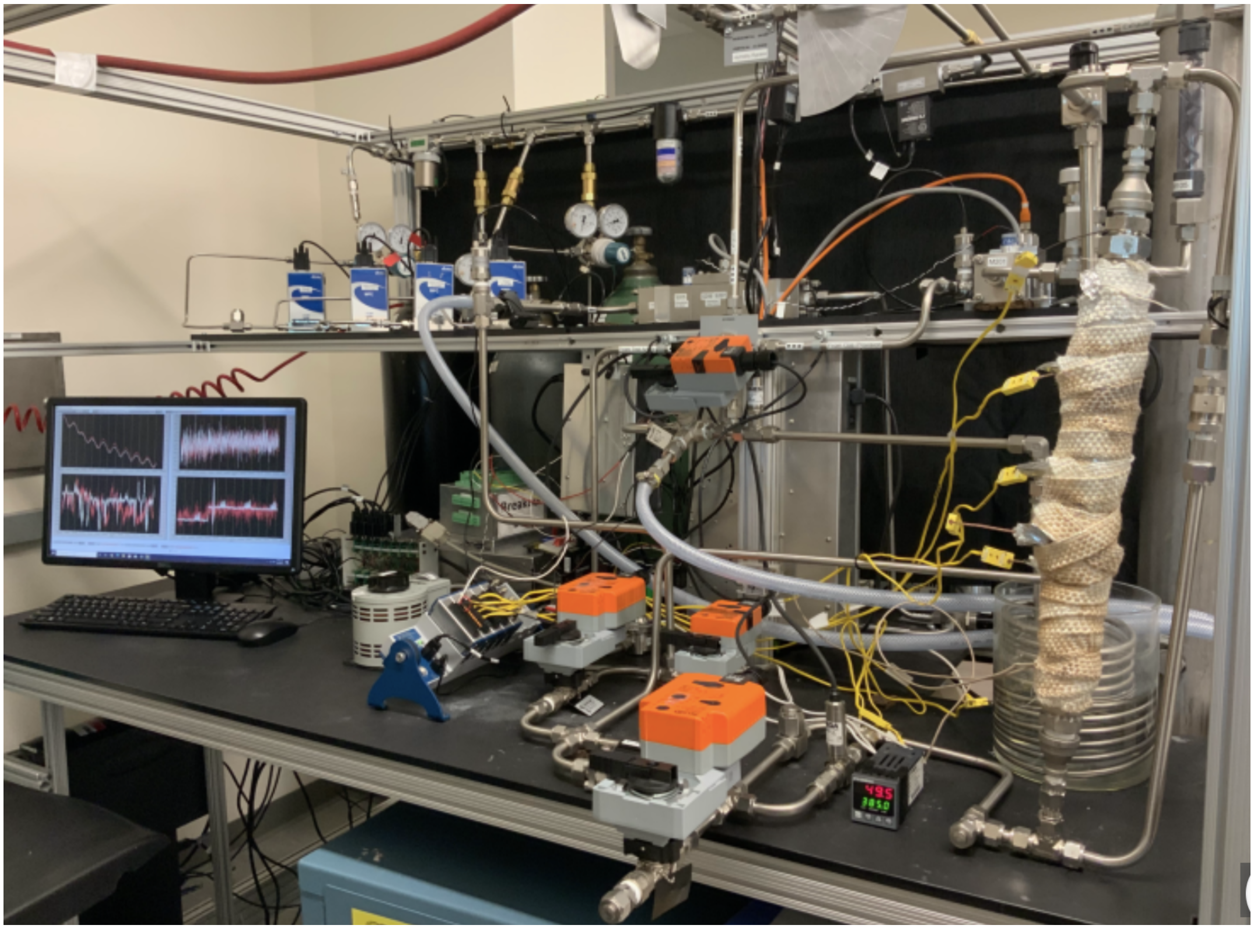


Figure 1.34: The STEVE CO_2 removal testbed at CU Boulder [34]

Takeaways from Existing Ground-Based Systems

Collaboration with teams responsible for the two existing ground-based systems listed above was paramount to a clean design for designing, building, and testing a new and novel ECLSS testbed for CO_2 removal at the UC Davis Center for Spaceflight Research. They were considered so crucial that visiting both testbeds in person was integrated into my research plan, creating a traveling preliminary design review presented in this thesis's PDR and CDR section. Collaborations with these testbeds yielded the following:

- Information on known issues for common parts such as mass flow controllers and valves
- Suggestions on procedural flow and safety considerations
- Suggestions on mitigation for common testbed issues such as leaks, electrical disconnections, and temperature control

1.6 Degradation in Space Habitats

This section explores relevant parallel fields to CO2 removal in space habitats within the context of the HOME STRI (funding source). This section provides background for what degradation means, as well as the current state of research as it relates to ECLSS

Degradation occurs in all systems - it can be attributed to normal wear and tear of nominal operations or accelerated due to off-nominal conditions. In space stations, we can't create a perfect system that won't degrade, but we have to make one that eliminates the element of surprise failures or degradation.

A key element within the HOME Institute is using machine learning to identify mean shifts in a system and predict the future state of a degrading system. This monumental effort is led by the HOME team at Georgia Tech, comprised of Heraldo Rozas, Ayush Mohanty, and Michael Ibrahim, and led by Dr. Nagi Gebraeel [35], with a focus on prognostics [38]. For example, this team at Georgia Tech has been working on prediction algorithms for a ball bearing: they can consistently predict when it will fail, with a curve showing remaining useful life (RUL) or time to failure vs the amplitude of the vibration of the part. This predictive capability becomes increasingly important in the context of deep space missions, where lead times to resupply are long, and advanced planning is key for adequate logistical support of a space station. **In off-nominal situations, understanding when a system will become dangerous to humans is of the utmost importance; therefore, being able to predict the future states of a system in deep space is critical for crew safety.**

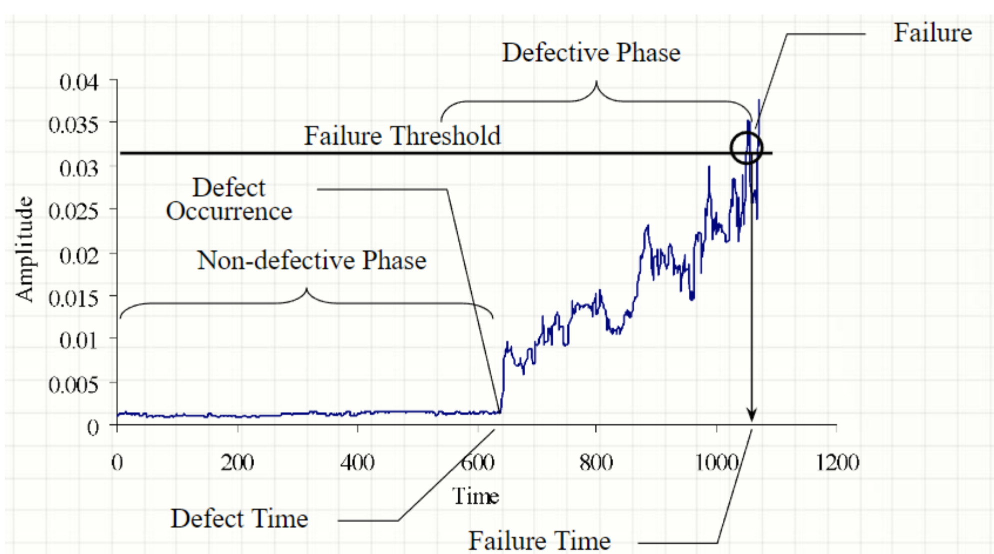


Figure 1.35: Experimental Data graciously supplied by Georgia Tech showing remaining useful life via time to failure vs. the amplitude of the vibration of a degrading ball bearing

The following is an example relevant to ECLSS, which also **showcases why the use of Machine Learning is warranted for deep space missions**. Suppose humid air is introduced into an ECLS system such as a zeolite CO_2 removal system; the CO_2 removal capacity is expected to decrease over time, eventually reducing the system capacity to below an acceptable performance threshold. The time to reach that threshold is termed the sorbent bed's remaining useful life (RUL). The prognostics algorithms being developed by the HOME STRI research community would be utilizing the onboard habitat sensors to predict the sorbent bed's RUL.

Process and measurement noise is inevitable in the data collected for a complex system with several components and sensors. Modeling this noise is crucial in predicting the RUL and requires learning their statistical distribution from the sensor data. Moreover, domain knowledge might not provide an exhaustive list of factors contributing to sorbent bed degradation. Certain covariates of the degradation model can only be learned statistically from the sensor data, which mandates using state-of-the-art machine learning algorithms. Furthermore, given the nature of cyclic operations, the parameters of the prognostics model should utilize the information of the latest cycle. This can only be achieved by re-estimating the model parameters as more operational data becomes available instead of deploying a fixed model whose parameters are estimated offline from the historical dataset of training cycles. As nominal operations change over time, a hard-coded logic would not yield accurate fault/nominal operations detection upon an updated nominal state.

To address all the aforementioned requirements, advanced machine learning techniques are utilized to monitor the performance of the CO_2 removal apparatus as a single-system analog of an autonomous deep space habitat conceptualized in HOME STRI's research efforts. The predicted CO_2 removal system zeolite bed RUL will provide a feasible replacement plan for the sorbent bed.

1.7 Maintainability of ECLSS for humans and robots

This section explores relevant parallel fields to CO_2 removal in space habitats within the HOME STRI (funding source) context. This section provides background for maintainability, a key research area within HOME, and a concept explored in collaboration with the robotics teams within HOME. What does maintainability mean? Why do we need it? What makes something maintainable?

Next-generation habitats for crewed exploration can leverage years of state-of-the-art research on the ISS and ground-based progress in academia, industry, and government research. Habitats will be further from earth support and may only be populated by crew part-time [42]. As such, the habitat system must provide greater support to habitat operators. Leveraging improvements in robotics can increase the safety, reliability, and efficiency of future missions, increasing support for habitat operators and the habitat itself while uncrewed. Support can be provided in maintenance operations and failure response. NASA has funded these efforts both internally [21], as well as within the commercial sector [77] and the academic sector [51]. Environmental Control and Life Support Systems are used as a case study to provide an example for implementation in a critical space-based subsystem.

ECLSS contains various reactors, membranes, catalysts, and sorbents used to purify CO_2-rich, contaminated air and make gray and black water usable or potable. Aside from being a human-critical system, ECLSS is an ideal case study for maintainability because this system requires significant crew maintenance time on the International Space Station [86], as seen in Figure 1.36.

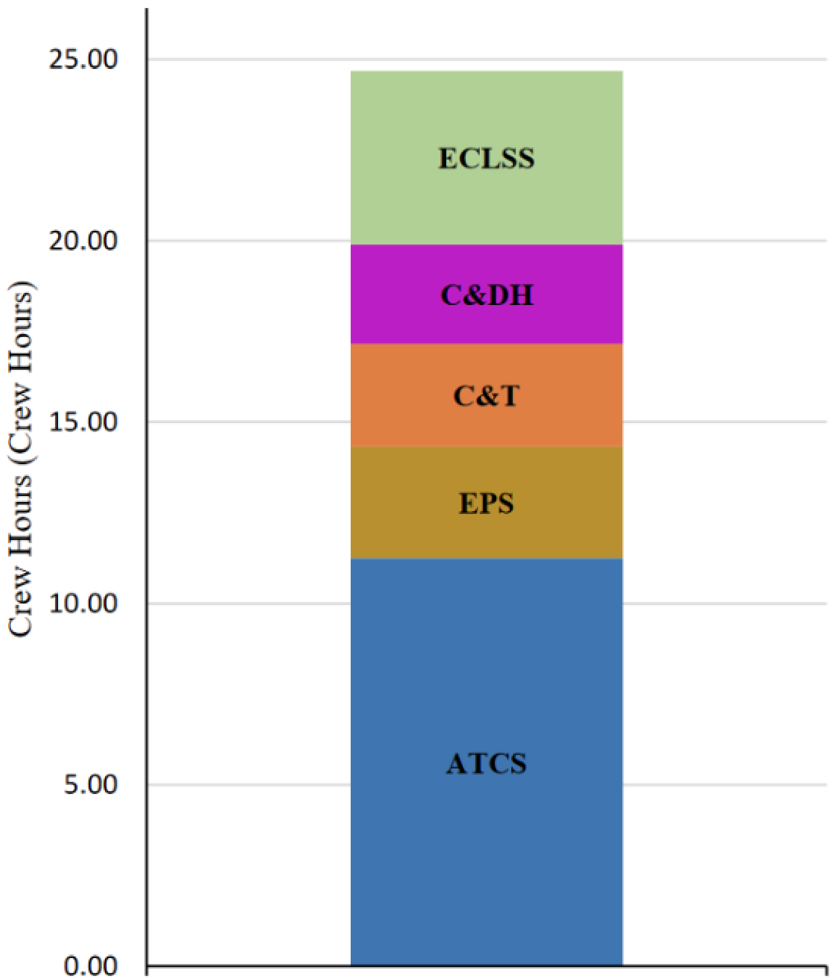


Figure 1.36: Crew hours required for maintenance of five major subsystems: ECLSS (Environmental Control & Life Support Systems), C&DH (Command and Data Handling), C&T (Communications & Tracking), EPS (Electrical Power System), and ATCS (Active Thermal Control System) [86]

The CDRA, reviewed earlier in this chapter, has undergone extensive maintenance on the ISS. As such, it was chosen as a case study within ECLSS for developing principles of robotic maintenance. Maintenance performed so far throughout CDRA's lifetime on the ISS (operational since 2002) includes fixes to the following, or related, issues [96]:

- Leaks into the system
- Pellet containment issues in both packed beds
- Zeolite dust generation from packed bed media harming internal hardware, such as valves
- Liquid water infiltration
- Heater shorts

Other examples of ECLSS subsystems that offer viable case studies for maintainability include the Sabatier system. This catalytic packed bed has been fouled by upstream hardware [15], and the Urine Processor Assembly, which has had issues with O-ring belts[95] that manage rotation slipping, as well as sensor malfunctions.

As a result of the history of maintenance requirements for ECLSS units, NASA has identified maintainability as a key design concept moving forward for next-generation space habitats[21] [10]. All of the above makes ECLSS a key candidate for maintenance studies to optimize for time and efficacy while increasing the standard for safety. Most ECLSS systems generally comprise the following components, with corresponding examples in Figure 1.37.

Component Type	Representative Components in Figure 4
Flexible Tubing	Right image, circled in orange
Hydraflow or Wiggins Quick Disconnect Couplings	Right image, circled in pink
Electrical Quick Disconnects	Left image, circled in purple; right image, circled in blue
Hard Tubing	Right image, circled in red
Hard Enclosures	Right image, circled in purple

Table 1.4: Common types of components of an ECLSS system and examples from Figure 1.37

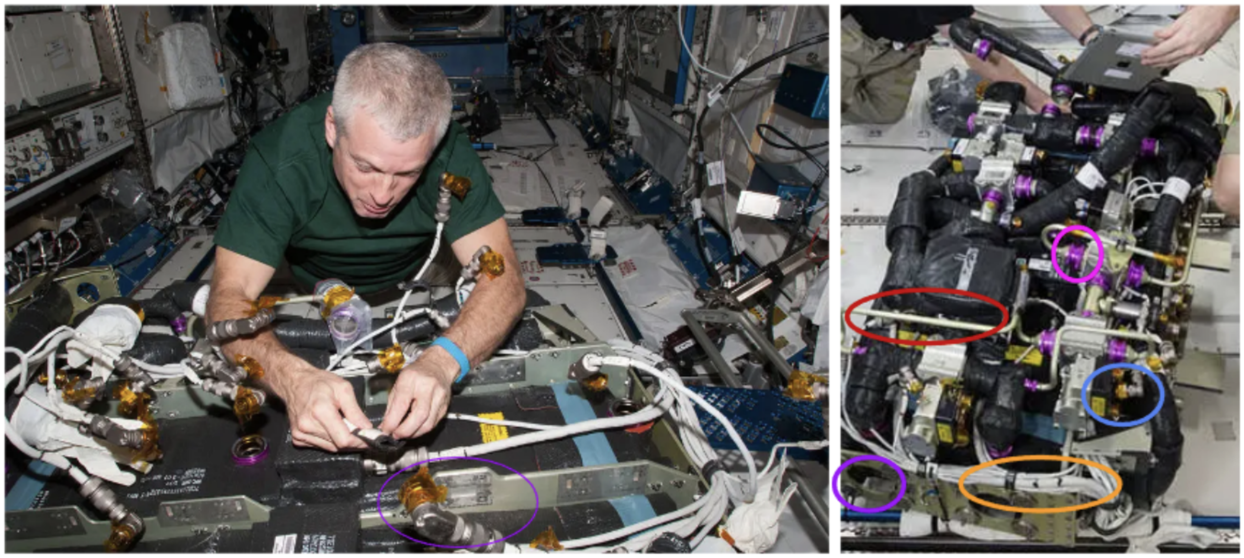


Figure 1.37: Left: NASA Astronaut performs maintenance on CDRA [71]. Right: zoomed-in image of the unit; colored circles/ellipses indicate types of components described in Table 1.4

The following pseudo-code was generated to use as a source to determine what types of tasks could and couldn't be done by a robotic agent assisting a human. The hope is that the following pseudo-code will also serve as a tool for future work in maintenance studies with applications in ECLSS. This pseudo-code procedure is followed by the open-source images used to generate the pseudo-code. Additional maintenance procedures provided by NASA that were used to inform this pseudo code can be found in the appendix.

Takeaways from Maintenance and Robotic Manipulability Review

This dive into maintenance and the start of understanding what goes into a maintainable system on earth and in space contributed to the core requirements of the ECLSS design, build, and test of ZeoDe at the UC Davis Center for Spaceflight Research. This investigation also led me to participate in a parallel project, RobInZeN (Robotically Interactive ZeoDe twiN), at UC Davis, which would duplicate the geometry of my system in a mock-up form factor to experiment with robotic manipulation of ECLSS parts. This has effort its own dedicated section in chapter 3.6.

Pseudo Code Maintenance Procedure for a Hypothetical Maintenance Task on CDRA

```
Function DataDisconnect
        Ensure connector visible & connection site accessible
        Disconnect connector using a 12 mm socket wrench
        Cover ends of connector with Kapton tape
Function DataConnect
        Ensure connector visible & connection site accessible
        Remove Kapton tape
        Connect connector using a 12 mm socket wrench
Function PowerDisconnect
        Ensure connector visible & connection site accessible
        Disconnect connector using a 12 mm socket wrench
        Cover ends of connector with Kapton tape
Function PowerConnect
        Ensure connector visible & connection site accessible
        Remove Kapton tape
        Connect connector using a 12 mm socket wrench
Function FluidDisconnect
        Ensure connector visible & connection site accessible
        Disconnect connector using a 19 mm socket wrench
        Cover ends of connector with plastic bag and rubber band
Function FluidConnect
        Ensure connector visible & connection site accessible
        Remove plastic bag & rubber band and stow
        Connect connector using a 19 mm socket wrench
Pre-stage:
                Plastic bags
                Rubber bands
                Kapton tape
                Stowage for loose fasteners
                White 5ft bands with clips
                Velcro 6in fastening straps
                12 mm socket wrench
                10 mm box end wrench
Command CDRA OFF via crew terminal
PowerDisconnect(QD1_MILC22992)
PowerDisconnect(QD2_MILC22992)
DataDisconnect(QD1_MIL1553)
DataDisconnect(QD2_MIL1553)
FluidDisconnect(Hydraflow_Air_Outlet)
FluidDisconnect(Hydraflow_Air_Inlet)

%-----------------------------------------------------------------------
%note, a small amount of air will still be flowing through the
%air inlet flexible tube that has been disconnected
%-----------------------------------------------------------------------

Unscrew 36 hex-head fasteners on CDRA front plate using a
10-mm Box end wrench and stow
Remove CDRA front plate and stow

%-----------------------------------------------------------------------
% START two crew member steps
%-----------------------------------------------------------------------

Ensure no tubing is obstructing exit path of module
Slide CDRA out of rack, sliding along guide rails
Rotate to expose SORBENT2SIDE
Translate CDRA to wall
Use velcro straps to secure CDRA corners
Use two bands to secure CDRA
%-----------------------------------------------------------------------
%END two crew member steps
%-----------------------------------------------------------------------

FluidDisconnect(Hydraflow_0.7in_3WayValveSKR_V1H)

%-----------------------------------------------------------------------
%Pipe connected via Hydraflow_C1H & Hydraflow_C2H
Obstructs the rest of the 3-way valve fittings
%-----------------------------------------------------------------------

FluidDisconnect(Hydraflow_C1H)
FluidDisconnect(Hydraflow_C1H)
Stow pipe connected to Hydraflow_C1H & Hydraflow_C2H
Ensure no obstructions to 3WayValveSKR
FluidDisconnect(Hydraflow_3WayValveSKR_V2H)
FluidDisconnect(Hydraflow_3WayValveSKR_V3H)
Unscrew fasteners 1-4 on 3WayValveSKR using a 10 mm box
end wrench
Remove 3WayValveSKR
Insert 3WayValveSKR_ORU

Hold 3WayValveSKR_ORU in place
Fasten 4 stowed fasteners on 3WayValveSKR_ORU using a 10 mm box
        end wrench
FluidConnect(Hydraflow_3WayValveSKR_V3H)
FluidConnect(Hydraflow_3WayValveSKR_V2H)
Insert pipe connected to Hydraflow_C1H & Hydraflow_C2H
FluidConnect(Hydraflow_C1H)
FluidConnect(Hydraflow_C1H)
FluidConnect(Hydraflow_0.7in_3WayValveSKR_V1H)

%-----------------------------------------------------------------------
% START two crew member steps
%-----------------------------------------------------------------------

Remove two bands that secure CDRA
Remove velcro straps that secure CDRA corners
Translate CDRA to rack
Rotate CDRA to expose SORBENT1SIDE
Slide CDRA out of rack, sliding along guide rails

%-----------------------------------------------------------------------
%END two crew member steps
%-----------------------------------------------------------------------

Insert CDRA front plate
Hold CDRA front plate in place
Screw in the previously stowed 36 hex-head fasteners using a 10-mm box
        end wrench
FluidConnect(Hydraflow_Air_Inlet)
FluidConnect(Hydraflow_Air_Outlet)
DataConnect(QD2_MIL1553)
DataConnect(QD1_MIL1553)
PowerConnect(QD2_MILC22992)
PowerConnect(QD1_MILC22992)

Command CDRA ON via crew terminal
```

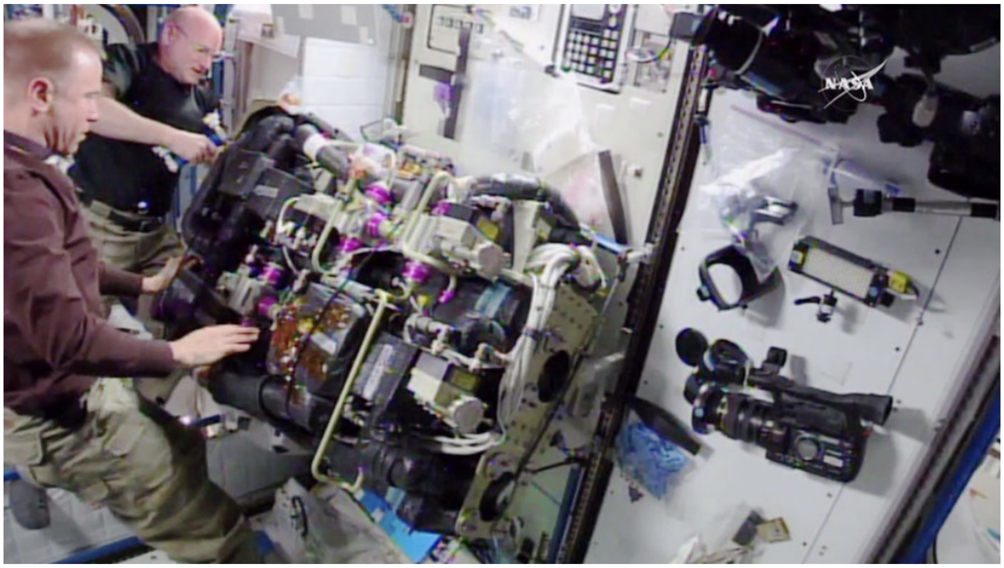


Figure 1.38: NASA-published CDRA Maintenance image for the basis of pseudo-code procedure

Figure 1.39: NASA-published CDRA Maintenance image for the basis of pseudo-code procedure

Figure 1.40: NASA-published CDRA Maintenance image for the basis of pseudo-code procedure

Chapter 2

Simulation Options for a Carbon Dioxide Removal System

This section reviews what a simulation effort might look like when modeling after the physical ECLSS system that is planned to be built. While a simulation was never fully incorporated, it is a recommended future project within the lab to explore degradation in accelerated non-time-restricted space using a system that can still be validated against physical data

Simulations are ideal for exploring trends and sensitivity analyses without the time limitation in a physical testbed. Simulation options allow the researcher to see results in an accelerated timeline, especially for degradation studies where degradation might occur over the course of years in a space habitat. Validation of the model is required to determine if it is producing realistic trends, which is why the physical testbed was the top priority over a simulation. Ideally, a simulation would have been created alongside the physical ECLSS testbed; however, this was not a possibility due to the timeline of an M.S. thesis.

2.1 Simulation Options

The following table lays out options that were initially explored for simulations and are options that still exist for future projects.

Simulation Option	Cost	Development time	Example Use Case
Matlab	Moderat	Moderate	CU Boulder, VHAB
Aspen	High	Moderate	UC Davis
COMSOL	High	Moderate	NASA MSFC
DWSIM	Free	High	Not Used

Table 2.1: Simulation options for modeling a CO_2 removal testbed

COMSOL

NASA has used the COMSOL Multiphysics software package [60] to solve the mass and energy balance equations discussed in Chapter 1. This research, conducted by Dr. James Knox, is validated by experimental setups and has, among other findings, contributed the following conclusions and tools [59].

- A new approach to fitting heat and mass transfer coefficients, which was discussed in the review section of this thesis
- Defined conditions where non-physical simulation results can arise
- Defined an approach to determine dispersion limits and lumped mass transfer coefficients.

The model described in Dr. Knox's dissertation provides a tool for modeling complex partial differential equations and has the added benefit of implementing more comprehensive modeling equations. With this model, they can replicate cyclic adsorption and desorption coupled with the energy balances within the system. Using a similar model would require the purchase and subscription of a COMSOL license.

Matlab/Simulink

Matlab, paired with Simulink and Simscape, has been used at CU Boulder by Dr. Sam Eshima [34] to model the Simulation Testbed for Exploration Vehicle ECLSS (STEVE) to simulate component failures and performance degradation. STEVE contains the necessary components to replicate the basic functionality of the ISS Carbon Dioxide Removal Assembly (CDRA). It can be used to systematically investigate operations under nominal and off-nominal conditions for CO2 removal to generate data for the HOME team. In parallel, a Simulink model of STEVE has been developed. This enables rapid data generation for conditions that STEVE cannot simulate. It uses the moist air components under the Simscape Foundation library to enable realistic inlet conditions.

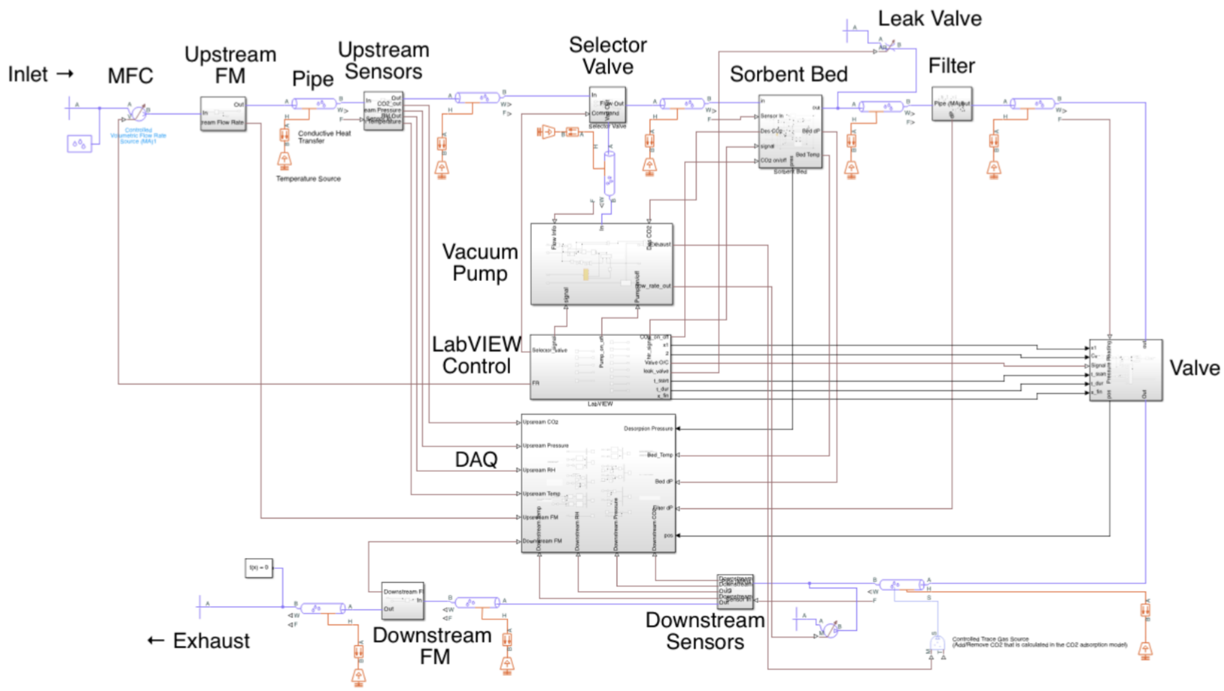


Figure 2.1: STEVE Simulink Model as reported in literature[34]

This model replicates cyclic adsorption and desorption coupled with simplified energy balances to describe the STEVE system.

Matlab has also been used by Dr.Daniel Kaschubek at Technical University Munich [56] to describe the CDRA system onboard the ISS. It uses a life support system simulation tool, Virtual Habitat (V-HAB). V-HAB has been under development at the Technical University of Munich since 2006 and was recently released as open-source code at https://github.com/v-hab/v-hab. The MATLAB-based code dynamically simulates life support systems and subsystems and adds a unit block representing crew metabolism.

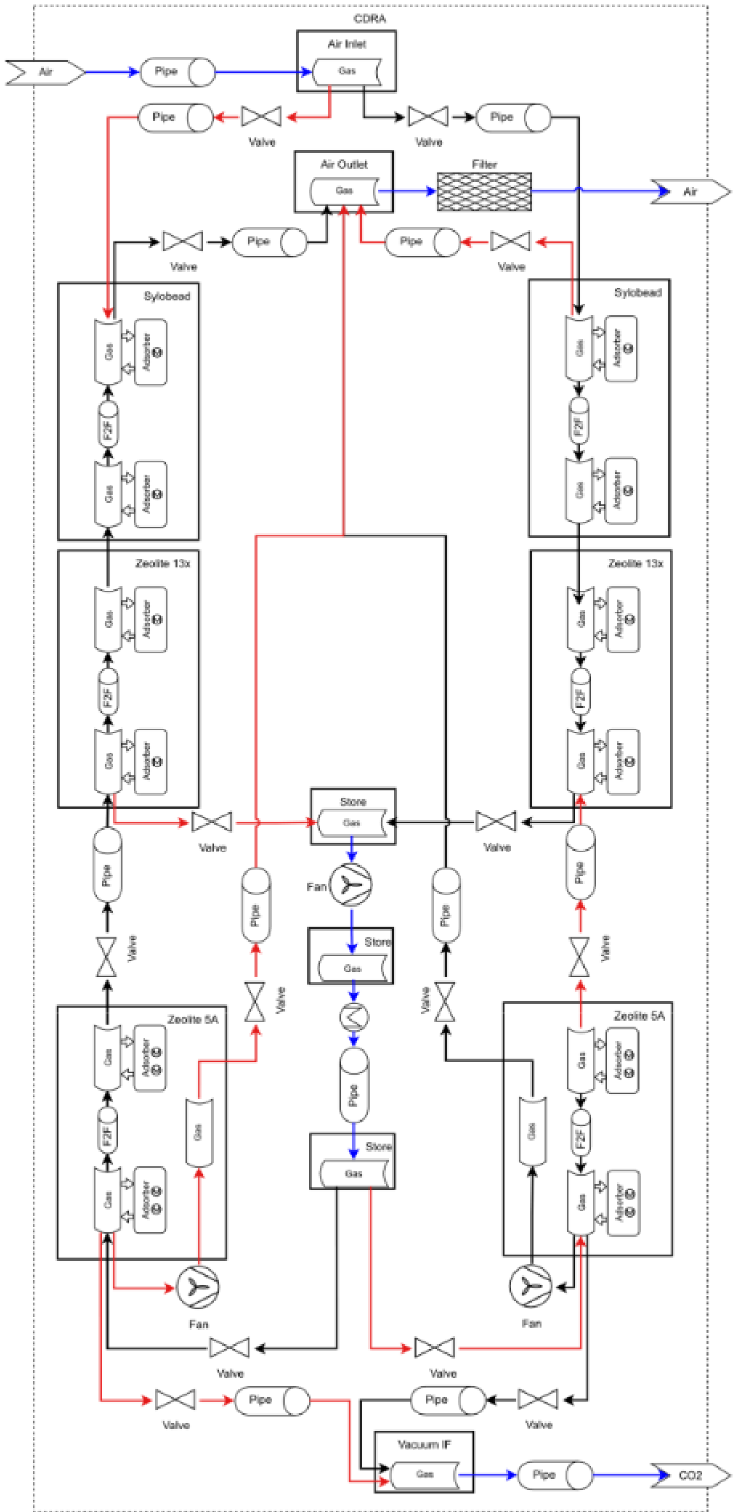


Figure 2.2: VHAB Matlab model created by Dr.Daniel Kaschubek, as reported in literature [56]

Aspen Adsorption

Monica Torralba [89] has used Aspen Adsorption at UC Davis to describe the precursor to the current ZeoDe system. The upside to Aspen Adsorption is the access to an extensive chemical library complete with thermodynamics. This is the same chemical library, with additions, as is found in the widely used Aspen Plus program. Aspen Adsorption was made because adsorption is not a chemical reaction and does not follow kinetic reaction models. It caters to the Chemical Engineering community, and the user-defined specifications are often in the form of empirical correlations, which can be pulled from the literature. For this reason, ASPEN's modularity and modifiability are not its greatest strengths. Modifications can be made using FORTRAN, but the literature on the specifics of modifications is sparse. Aspen Adsorption is an ideal option for gathering more information on the chemical side. It requires either the development of empirical correlations or the use of an experimental setup similar to others in the literature. This model also requires the purchase and subscription of an Aspen Adsorption license.

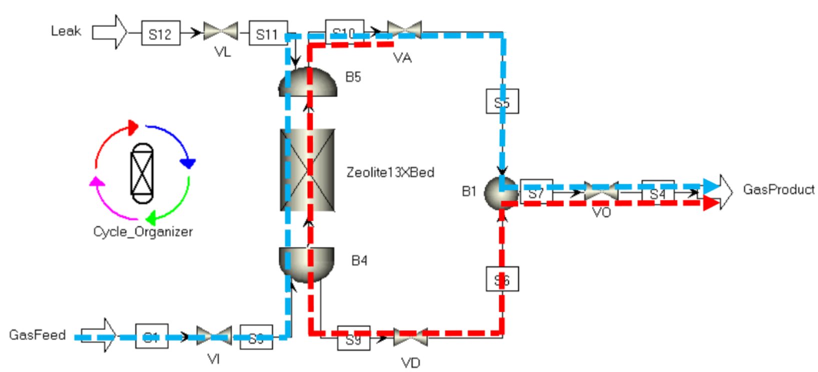


Figure 2.3: ASPEN adsorption model created by Monica Torralba at UC Davis[89]

DWSIM

DWSIM is an open-source software similar to Aspen Plus and contains a similarly extensive chemical library. Modifications can be made more easily with Python, as opposed to Fortran, in a similar manner to Simulink blocks. However, its base functions are currently focused on chemical reaction kinetics, similar to Aspen Plus, and it does not yet have an equivalent to Aspen Adsorption built in. The capabilities of Aspen Adsorption could be programmed in using Python. It can model a temperature-pressure swing adsorption system but only supports energy balances for isothermal assumptions.

Python

To model a non-isothermal system in DWSIM, it is necessary to create an adsorption block using Python that could be imported as its own function. One could separate the mass and energy balance equations to solve the PDEs numerically, as in the following example. Once running successfully within a Python compiler, it can be transferred into DWSIM similarly to the functions available in Simulink code blocks. Equation 1.40 is rearranged to solve for concentration, and subscripts are dropped for simplicity.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - \nu_i \frac{\partial C}{\partial z} - \left(\frac{1-\epsilon}{\epsilon}\right)\frac{\partial \bar{q}}{\partial t} \tag{2.1}$$

Then the finite difference method is applied, discretizing along the length of the bed

$$\frac{\partial C}{\partial t} = D\left[\frac{C_{k+1} - 2C_k + C_{k+1}}{dz^2}\right] - \frac{\nu_i \left(C_k - C_{k-1}\right)}{dz} - \left(\frac{1-\epsilon}{\epsilon}\right)\frac{\partial \bar{q}}{\partial t} \tag{2.2}$$

$$\frac{\partial C}{\partial t} = \frac{C_j^{n+1} - C_j^n}{\Delta t} \tag{2.3}$$

$$\frac{\partial c}{\partial x} = \frac{C_{j+1}^n - C_j^n}{\Delta x} \tag{2.4}$$

$$\frac{\partial^2 c}{\partial x^2} = \frac{C_{j+1}^n - 2c_j^n - C_{j-1}^n}{\Delta x^2} \tag{2.5}$$

$$C_j^{n+1} = C_j^n + D\left(\Delta t\right)\frac{C_{j+1}^n - 2c_j^n - C_{j-1}^n}{\Delta z^2} - \nu_i\left(\Delta t\right)\frac{C_{j+1}^n - C_j^n}{\Delta z} - \Delta t\frac{\partial \bar{q}}{\partial t} \tag{2.6}$$

This method, while explored within Python, has been set up as future work for focused simulation studies using DWSIM.

Takeaways from Reviewing Simulation Options

While a simulation was not an endeavor I ended up taking, focusing instead on a physical testbed, I believe a simulation could generate substantial value for degradation studies within HOME or for any studies that might require either an accelerated timeline not reasonable for a physical testbed, or that might push safety limits. Cost-wise, for academia, if the institution supports Matlab, VHAB can be used, or a similar Simulink model can be developed. If Matlab is not supported, the ideal path would be to build up a Python model for adsorption, or whatever physics are desired, using complex partial differential equations for both mass and energy transfer. Transferring this into DWSIM would create a robust model based on first principles that could employ an extensive chemical library. Additional benefits of aiming straight for a Python and DWSIM simulation would be increased collaboration possibilities as both programs are open source.

Chapter 3

ZeoDe: ECLSS Carbon Dioxide Removal Testbed for Degradation Studies

This chapter gets into the hands-on portion of the project. It goes through the rigorous concept, design, build, and operations of the ZeoDe CO2 removal testbed at UC Davis

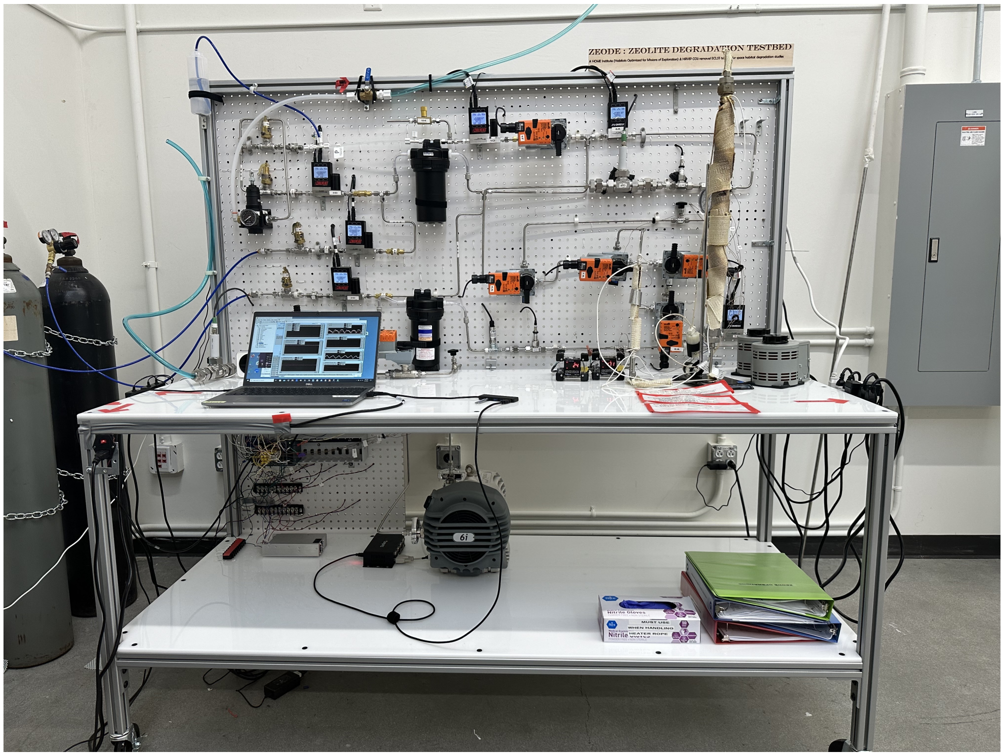


Figure 3.1: Image of the ZeoDe testbed at the UC Davis Center for Spaceflight Research

The following section describes the making of the ECLSS CO_2 Removal testbed for the studies of zeolite bed performance degradation via precise injection of humidity, which is described in detail at the end of this section. It was named ZeoDe (Zeolite performance Degradation testbed) and is a product of not just my work but also the help of an incredible team within both the NASA HOME STRI and the HRVIP lab at the UC Davis Center for Spaceflight Research. A complementary resource to what is described in this thesis is a characterization project performed by my colleague Shannon Lackey, which can be found in her portfolio at the following link: https://shannonlackey2022.wixsite.com/portfolio1 [48].

3.1 Requirements

Once the work had gone into the breadth and depth of knowledge acquisition on ECLSS and zeolite packed bed systems, the following project-level mission statement was created:
Build a CO_2 removal testbed based on packed bed technology to produce degradation data for prognosticating future states of degraded ECLSS systems to contribute to both the HOME STRI and the ECLSS research community as a whole.

The design process started with the conception of requirements. First, top-level (L1) requirements were developed. These were decomposed into L2 requirements and then into L3 requirements. The level 3 requirements are verifiable. The below requirements were compiled for the design of the testbed, beginning with the L1 requirements listed in Table 3.1.

ID	Type	Text	Rationale	In-Links	In-Link Text
L1-001	Data	The testbed shall generate degradation data for prognostics	Degradation data is being used for RT2 prognostics and RT5 Digital Twin projects.	L2-001, L2-002, L2-003, L2-004, L2-005	The degradation dataset shall have at least 3 replicates of each experiment.// The degradation dataset shall generate a degradation rate.// The testbed shall include sensors to capture degradation metrics// The degradation metrics shall include humidity.// The degradation dataset shall focus on CO2 adsorption capacity degradation
L1-002	Chemistry, Structure, Data, Environment	The testbed shall mimic the CO2 removal system aboard the ISS known as CDRA	The CO2 Removal system was found to be the prime example for prognostic implementation through a HOME ECLSS analysis.	L2-004, L2-005, L2-013, L2-014, L2-015, L2-016	The degradation metrics shall include humidity.// The degradation dataset shall focus on CO2 adsorption capacity degradation// The testbed shall be housed in an environment that allows mimicry of the CO2 removal system process aboard the ISS, known as CDRA. // The testbed sorbent bed shall be sized taking channeling into account// The testbed sorbent bed shall be sized taking the interstitial velocity of CDRA into account.// The testbed sorbent bed shall be sized to have a residence time equal to or greater than the residence time of CDRA.
L1-003	Programmatic	The testbed shall contribute to HOME's annual milestones.	The HOME community benefits from multiple sources of data generation.		
L1-004	Lifetime	The testbed shall have an expected lifetime of at least 5 years, with the exception of consumables.	The testbed should be usable for the remaining time of the HOME program. Consumables such as CO2, Nitrogen, and adsorption media (that can break down over time) can be replaced as needed	L2-007, L2-008	The testbed dolly structure shall have an expected lifetime of at least 5 years.// The testbed components shall have an expected lifetime of at least 5 years
L1-005	Safety, cost, volume properties	The testbed shall be compatible with its designated HOME, HRVIP, and university-affiliated lab space.	We want to be able to handle this in a regular lab setting.	L2-009, L2-010, L2-011, L2-012	The testbed structure shall be composed of non-hazardous materials.// The testbed chemical components shall be composed of non-hazardous materials.// The testbed footprint shall take up less than a 5'x3'x6'(length x width x height) space when assembled.// The testbed shall meet all OSHA and lab safety regulations.

Table 3.1: Level 1 Requirements for the ZeoDe testbed, with requirement ID listed in the far left column

L1-001 is tied to the HOME STRI, where a team at Georgia Tech takes the testbed data as an input to train their algorithms that predict future states of a system. L1-002 chooses the CDRA as the reference technology; the goal is not to design new CO_2 removal technology but to use a space-proven technology that will likely be used in future spaceflight. L1-003 exists because while prognostics is the main output of this testbed, the testbed should be flexible enough to meet any changing needs of the HOME program. The minimum lifetime in L1-004 was determined based on the original HOME lifetime. L1-005 is added to address the low-TRL, bench top-level scale at which academia is primed to contribute to the space community.

These top-level requirements were then decomposed into the L2 requirements in Table 3.2. L1-001 is decomposed into requirements describing the degradation data set needs, L1-002 is decomposed into elements of the testbed sorbent bed, L1-004 is decomposed into individual component lifetime requirements, and L1-005 is decomposed into general size and safety requirements.

ID	Type	Text	Rationale	In-Links	Out-Links
L2-001	Data	The degradation dataset shall have at least 3 replicates of each experiment.	3 Replicates are listed as the minimum from the Prognostics team	L3-001	L1-001
L2-002	Data	The degradation dataset shall generate a degradation rate.	Prognostics require a degradation rate deg/time.	L3-001	L1-001
L2-003	Structure, Data	The testbed shall include sensors to capture degradation metrics	Degradation metrics need sensors to sense those metrics.	L3-002, L3-003, L3-004, L3-005, L3-006	L1-001
L2-004	Data	The degradation metrics shall include humidity.	The major degradation mode of zeolite 13x is water contamination.	L3-001, L3-004, L3-005, L3-006	L1-001, L1-002
L2-005	Data	The degradation dataset shall focus on CO2 adsorption capacity degradation	The degradation modes ultimately result in decreased CO2 capacity which leads to decreased removal performance and efficiency.	L3-006	L1-001, L1-002
L2-006	Chemistry	The testbed shall implement adsorption media that mimics the chemical process of the CO2 removal system aboard the ISS, known as CDRA.	We want to mimic the chemical process itself of CO2 adsorption onto a porous media that is also prone to H2O adsorption	L3-008	
L2-007	Lifetime	The testbed dolly structure shall have an expected lifetime of at least 5 years.	We want the testbed to be designed to last for the remainder of HOME		L1-004
L2-008	Lifetime	The testbed components shall have an expected lifetime of at least 5 years	We want the testbed to be designed to last for the remainder of HOME	L3-009, L3-010	L1-004
L2-009	Safety, Structure	The testbed structure shall be composed of non-hazardous materials.	We want to be able to handle this in a regular lab setting.		L1-005
L2-010	Safety, Chemistry	The testbed chemical components shall be composed of non-hazardous materials.	We want to be able to handle this in a regular lab setting.		L1-005
L2-011	Volume properties	The testbed footprint shall take up less than a 5'x3'x6'(length x width x height) space when assembled.	We want this to fit in the lab spaces provided, and through doorways.		L1-005
L2-012	Safety	The testbed shall meet all OSHA and lab safety regulations.	In order to have a testbed in academic surge/Bainer/Spafford it needs to meet lab-specific regulations & OSHA regulations; these two encompass university regulations		L1-005
L2-013	Environment	The testbed shall be housed in an environment that allows mimicry of the CO2 removal system process aboard the ISS, known as CDRA.	Essentially, we do not want an incredibly large particle count in the air (e.g. a machine shop)	L3-007	L1-002
L2-014	Sizing	The testbed sorbent bed shall be sized taking channeling into account	We are assuming we will be scaling down, we want to make sure that channeling doesn't become a big issue due to limitations of the size of the sorbent pellets	L3-011	L1-002
L2-015	Sizing	The testbed sorbent bed shall be sized taking the interstitial velocity of CDRA into account.	We want to make sure the physics are similar to CDRA - this is determining the velocity of flow coming in since we already have a restriction on the diameter of the bed from L2-014	L3-012	L1-002
L2-016		The testbed sorbent bed shall be sized to have a residence time equal to or greater than the residence time of CDRA.	CDRA has a residence time of about 0.023. This requirement is really giving us a minimum length for our sorbent bed	L3-013	L1-002

Table 3.2: Level 2 Requirements for the ZeoDe testbed, with requirement ID listed in the far left column

These Level 2 Requirements were then decomposed into Level 3 requirements, shown in Table 3.3, which are verifiable by either analysis or test.

ID	Type	Text	Rationale	Out-Links
L3-001	Data	The degradation dataset shall vary at least one factor.	Humidity will be varied. Flow rate can be varied as well.	L2-001, L2-002, L2-004
L3-002	Data	The testbed sensors shall capture humidity measurements at the inlet and outlet of the testbed.	Degradation metrics need sensors to sense those metrics.	L2-003
L3-003	Data	The testbed sensors shall capture the temperature of the testbed.	Degradation metrics need sensors to sense those metrics.	L2-003
L3-004	Data	The testbed sensors shall capture the pressure drop throughout the testbed.	Degradation metrics need sensors to sense those metrics.	L2-003, L2-004
L3-005	Data	The testbed sensors shall capture H2O measurements at the inlet and outlet of the testbed.	Degradation metrics need sensors to sense those metrics.	L2-003, L2-004
L3-006	Data	The testbed sensors shall capture CO2 measurements at the inlet and outlet of the testbed	Degradation metrics need sensors to sense those metrics.	L2-003, L2-004, L2-005
L3-007	Environment	The testbed shall be housed in an ISO-8 environment.	We do not want particulates from the environment affecting the type of chemical process happening within the testbed	L2-013
L3-008	Chemistry	The CO2 adsorption media shall use a zeolite structure that adsorbs CO2 via weak forces and adsorbs H2O via polar attraction	We want adsorption media that has a similar affinity for CO2 and H2O	L2-006
L3-009	Lifetime	The testbed sensors shall have an expected lifetime of at least 5 years.	We want these sensors to last at least 5 years before needing replacement	L2-008
L3-010	Lifetime	When offered as an option by the manufacturer, all testbed parts shall be manufactured from corrosion-resistant material	316 Stainless steel	L2-008
L3-011	Sizing	The testbed shall use a sorbent diameter to housing diameter of at least 1:10	1:20 is best, based on Dr. Knox's dissertation, but 1:10 still minimizes channeling effects	L2-014
L3-012	Sizing	The testbed shall implement an interstitial velocity of between 0.3 and 0.4 m/s	The ISS CDRA has an interstitial velocity of 0.36 m/s. If we have a tube of 1", and a void fraction of 0.41, then this brings us to around 8-9 SLPM	L2-015
L3-013	Sizing	The testbed shall have a residence time equal to or greater than 0.023 minutes	assuming a 1" tube and 8 SLPM flow, this would be a minimum length of 14.3 inches of sorbent material in the sorbent bed	L2--016

Table 3.3: Level 3 Requirements for the ZeoDe testbed, with requirement ID listed in the far left column

3.2 Structure

Ensuring a structure for the testbed that will support testing activities as well as foreseeable future research

Design for Maintainability and Moveability by Humans and Robots

One key focus of the HOME Institute is autonomous robotic maintenance. As a result, maintainability is a common theme throughout all HOME projects and is showcased in the ZeoDe design.

The following elements are implemented into the ZeoDe design:

Design Element	Implementation 1	Implementation 2	Implementation 3
Accessibility of Parts	Single plane of parts adhered to backboard	Second level with additional parts	Electrical connections in a single plane on the backside of the backboard
Modularity	Compression fittings	Room for additional DAQ modules	Room for additional wiring
Moveability	Testbed on wheels	Sized to fit through common spaces	Quick Disconnect fluid fittings with flexible hosing for easy detachability from gas cylinders

Table 3.4: Design elements implemented into ZeoDe: accessibility of parts, modularity, and moveability

Maintainability through the accessibility of parts is an element explored in the robotics projects within HOME [51]. When parts are placed in various planes, it causes visual and physical obstructions that vastly complicate robotic tasks. This single-plane system also makes parts more maintainable by humans, not having to work around obstacles, even if we can still identify and work around them.

Modularity is introduced to facilitate design augmentation. While ZeoDe is not meant to be a fast-iteration or constantly changing testbed, allowing for augmentation of the testbed through design can open research opportunities in the future, increasing the ROI of the testbed itself. Compression fittings allow disconnection and re-connection of parts without the wear one might see on a similar NPT fitting. They also open up the possibility of augmentation by connecting a second testbed, for example, to ZeoDe. Further, leaving room for additional DAQ modules will allow additional sensors and actuators in future modifications. Moving all the wiring to the backboard enables harnessing for future design while maintaining a single plane of organized wires.

Moveability is introduced for maintenance - e.g., easily moving the testbed to expose the back side with wiring - and for future work. The ability to move the testbed into a habitat mock-up will facilitate human factors experiments. Further, moveability within or out of a building facilitates more extended distance movement where future experiments might be better suited to take place at a different site. The design of the gas cylinder connection to the testbed allows the testbed to be moved without the cylinders, only having to swap out flexible lines for different lengths.

Resulting Structural Scaffold Design

The previous aspects, when implemented, resulted in the following base structure design.

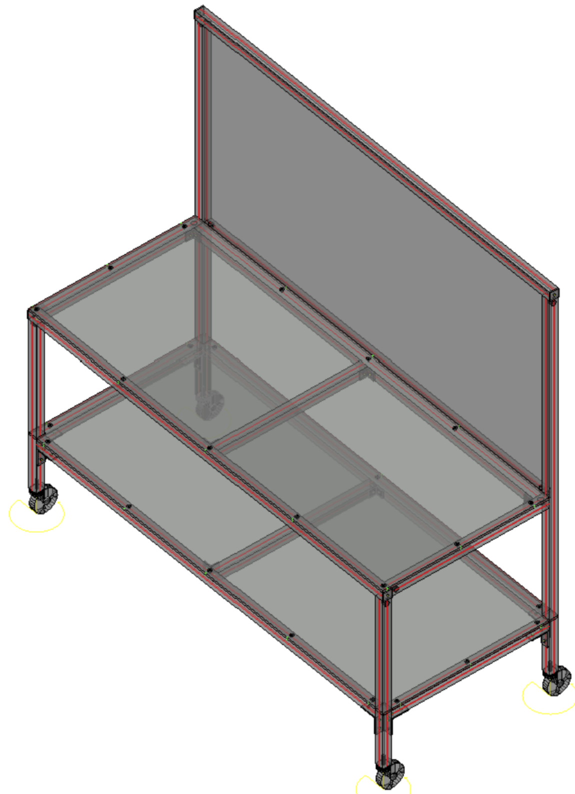


Figure 3.2: Aerial view of the testbed structure design using 80/20

The ZeoDe support structure is designed to use 80/20 to form a bench-top-like scaffold, with an added backboard and a second level below. The entire structure is on wheels.

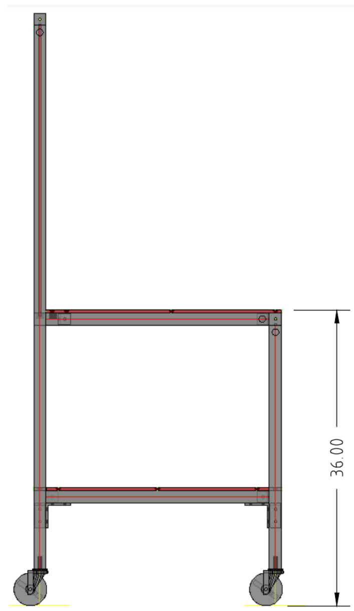


Figure 3.3: Side view of the testbed structure design using 80/20

As seen above, the bench top height was chosen based on standard benches used for chemistry benchtops. The height and width of the entire testbed were sized to be the maximum area that could fit through a standard doorway. Materials were chosen based on cost and usability in a mechanical and chemistry environment.

Aspect/Part	Size	Material	Rationale
Testbed height	6 ft	80/20	Shorter than the standard doorway height
Testbed width	2.5 ft	80/20	Shorter than the standard doorway width
Testbed length	6 ft	80/20	Both a standard size for boards of variuos materials, and short enough to increase maneuverability through doorways
Testbed structure	1.5" thick	80/20	Strong enough to support at least 200 lbs on each level
Top work bench	3/8"	HDPE	Surface that can be used both for chemistry experiments as well as mechanical or electrical projects
Lower work bench	3/8"	HDPE	Surface that can be used both for chemistry experiments as well as mechanical or electrical projects
Backboard	Up to 1/4" Thick Panel	Pegboard	Easy installation of parts

Figure 3.4: Testbed aspects/parts with their size, material, and rationale

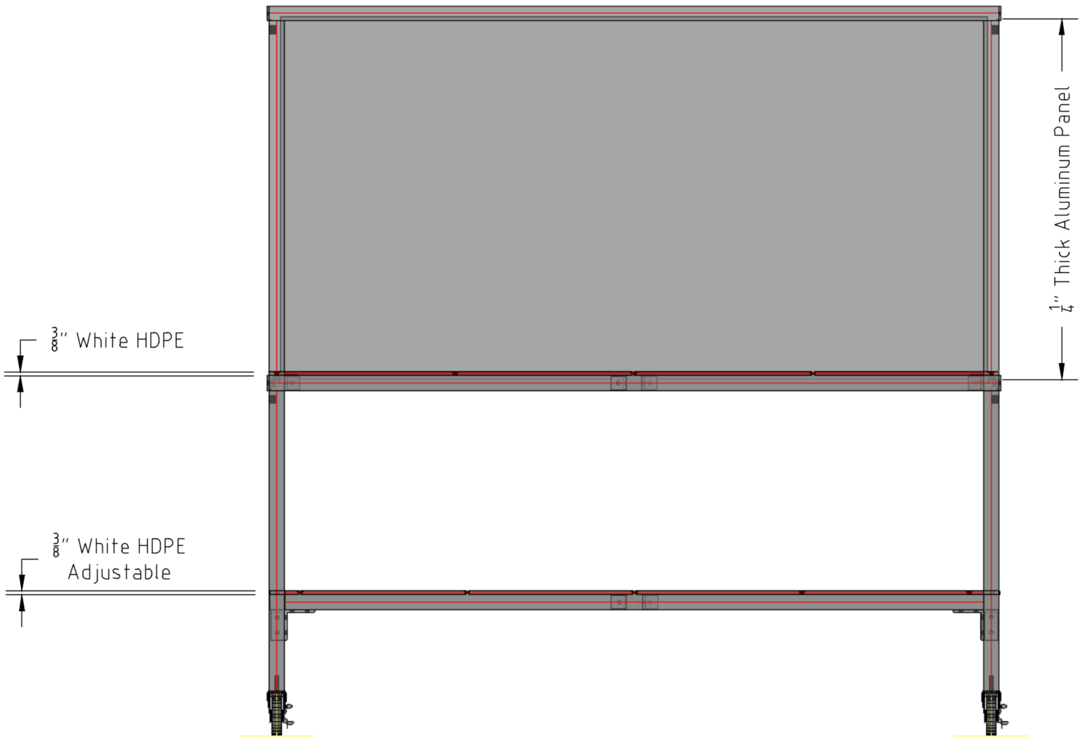


Figure 3.5: Back side view of the testbed structure design using 80/20

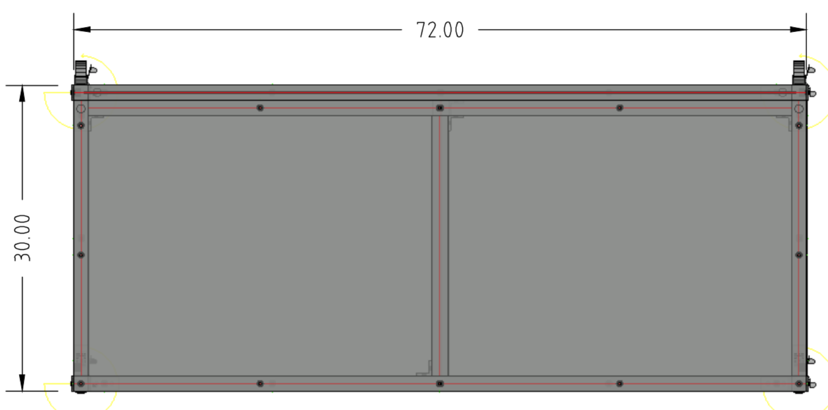


Figure 3.6: Top view of the testbed structure design using 80/20

3.3 Process

The UC Davis ZeoDe is centered around a packed zeolite bed, which undergoes a bakeout before each experiment. This is followed by adsorption and desorption cycles, with desorption taking place via pressure-temperature swing. For off-nominal testing, where degradation is investigated, humidity is introduced during the adsorption phase of the experimental cycle.

Most of the ZeoDe testbed supports fluid routing, cyclic operations, heating, humidity introduction, and sensing for the zeolite-packed bed. All temperature, flow, and humidity are controlled via a LabView interface connected to a National Instruments CompactDAQ.

The testbed comprises a 6' by 6' by 2.5' [LxHxW] structure, shown in Figure 3.2, as well as in the photo in Figure 3.7. The testbed is designed with four inlet options: dry air, humid air, nitrogen, and CO_2. Nitrogen is used to flush the system during bakeout before experiments - the flow path for this setup is shown in Figure 3.11. Air mixed with CO_2 is used during adsorption, representing a habitat-level concentration of CO_2. Humidity can be introduced to the air line by a Nafion membrane tube supplied by a small water-holding vessel - the flow path for this setup is shown in Figure 3.9. Mass Flow Controllers (MFCs) control flow rate and the air CO_2 composition. Mass Flow Transmitters (MFTs) measure flow rate and aid in leak checks. A series of 3-way and 2-way valves direct flow throughout the testbed. During desorption, a dry scroll pump is used to evacuate accumulated CO_2 from the sorbent bed in a counter-current manner. Directly upstream and downstream of the bed are identical sensor suites, measuring pressure, CO_2 levels, and dew points. The packed bed consists of a 20" long, 1" in diameter stainless steel pipe filled with zeolite 13x beads to a height of around 14" secured on either side by glass wool. During operation, this packed bed is wrapped in heater tape that brings the bed up to 350°C for bakeout and also serves as insulation for temperature regulation and operational safety.

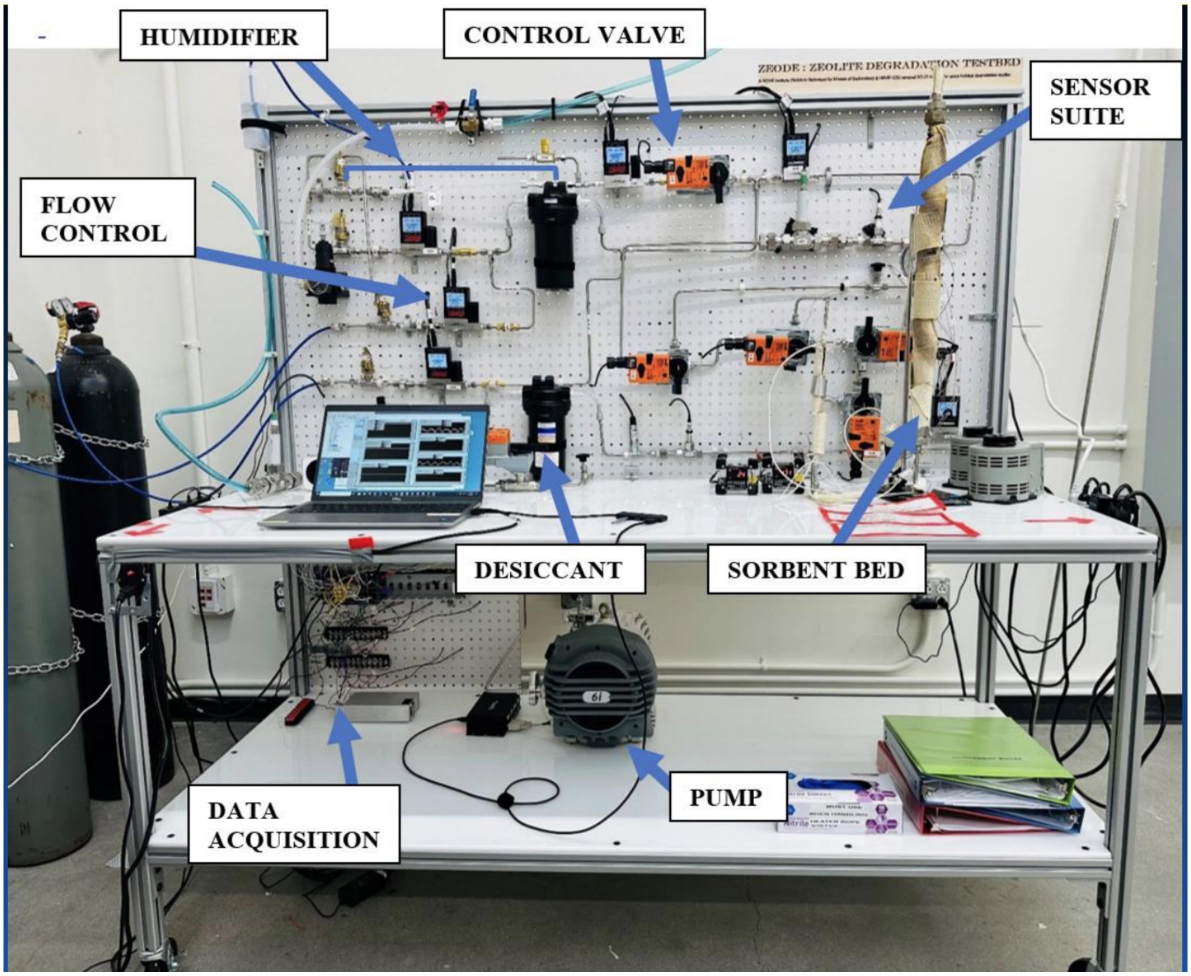


Figure 3.7: Labeled photo of the ZeoDe testbed, taken February 2024

Adsorption

Figure 3.8 highlights the flow path for dry adsorption, and Figure 3.9 highlights the flow path for humid adsorption in a piping and instrumentation diagram. During adsorption, a compressed gas line provides air to the system, and a cylinder adds CO_2 into the system; the nitrogen cylinder is shut off. Each inlet includes a pressure relief valve, filter, and mass flow controller with a check valve. The flow then passes through flow rate sensors/transmitters, followed by a sensor suite upstream of the packed bed. The flow then passes from top to bottom, through the sorbent bed, and downstream to a second identical sensor suite. One can opt for a dry or humid air stream, as shown in Figure 3.8 and Figure 3.9, where a bleed valve mitigates control issues by providing one stream in excess. Desiccants are placed upstream of the humidity introduction device and the dry scroll pump. The flow path is determined by commandable 3-way valves connected to the CompactDAQ system commanded by LabView.

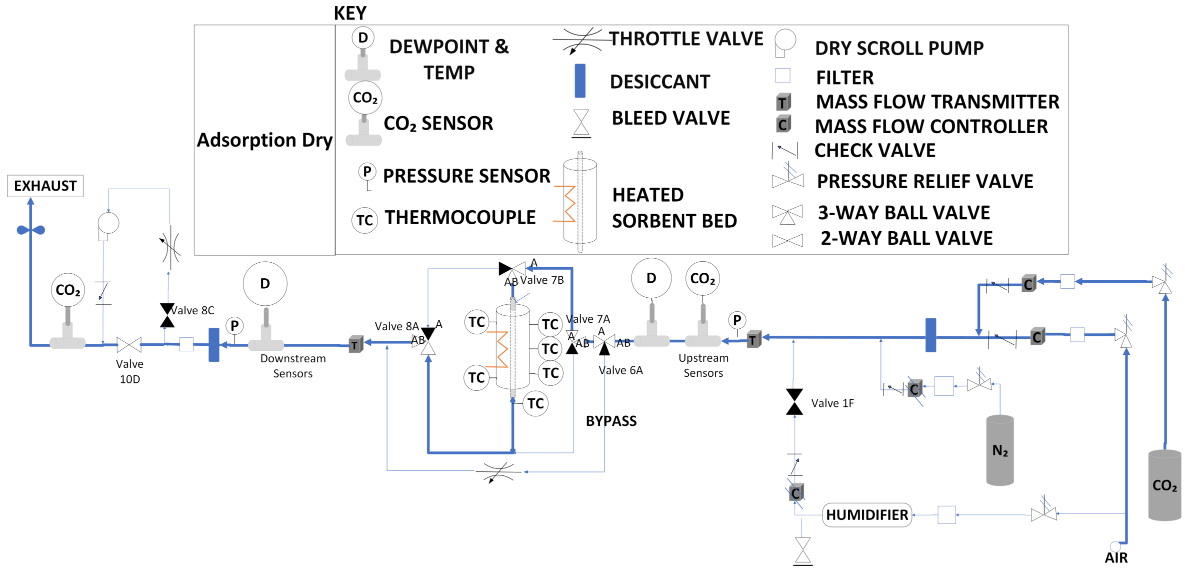


Figure 3.8: ZeoDe PNID with the dry adsorption flow path in bold

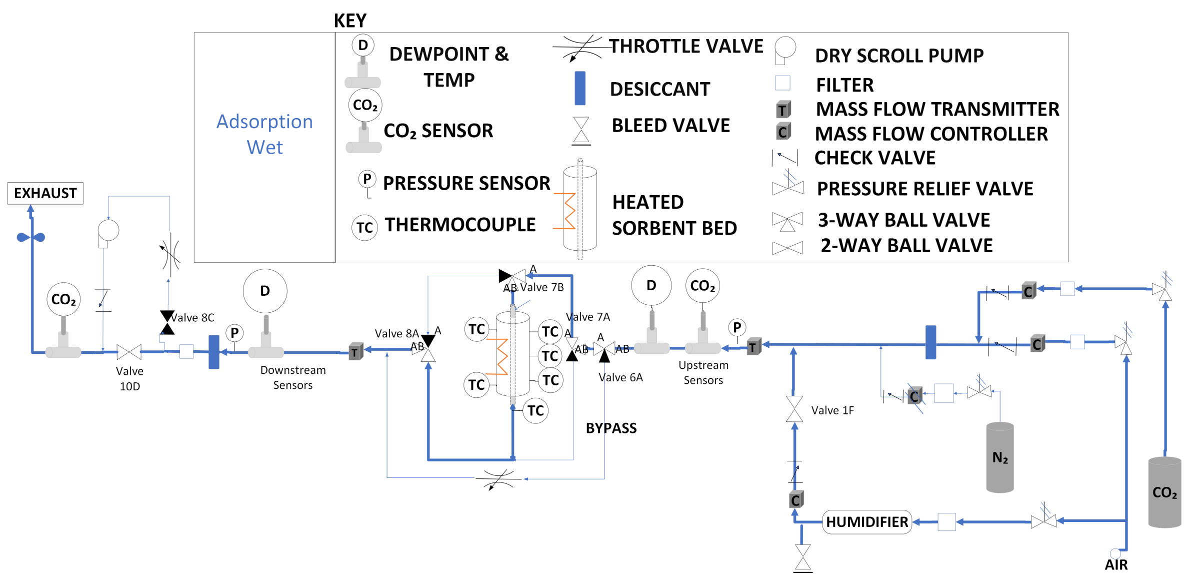


Figure 3.9: ZeoDe PNID with the humid adsorption flow path in bold

Desorption

Inlets are shut off during desorption, highlighted in Figure 3.10, and a 3-way valve restricts back-flow. Vacuum is pulled in a counter-current direction to adsorption so that CO_2 being released from the bed flows upwards through the zeolite bed and out to exhaust. Counter-current is chosen because, during adsorption, the top of the bed gets saturated first. Adsorption is not timed for full bed saturation, so the top of the bed will always have a higher concentration than the bottom. Running desorption in a counter-current manner desorbs the highest concentration first and, therefore, desorbs more efficiently.

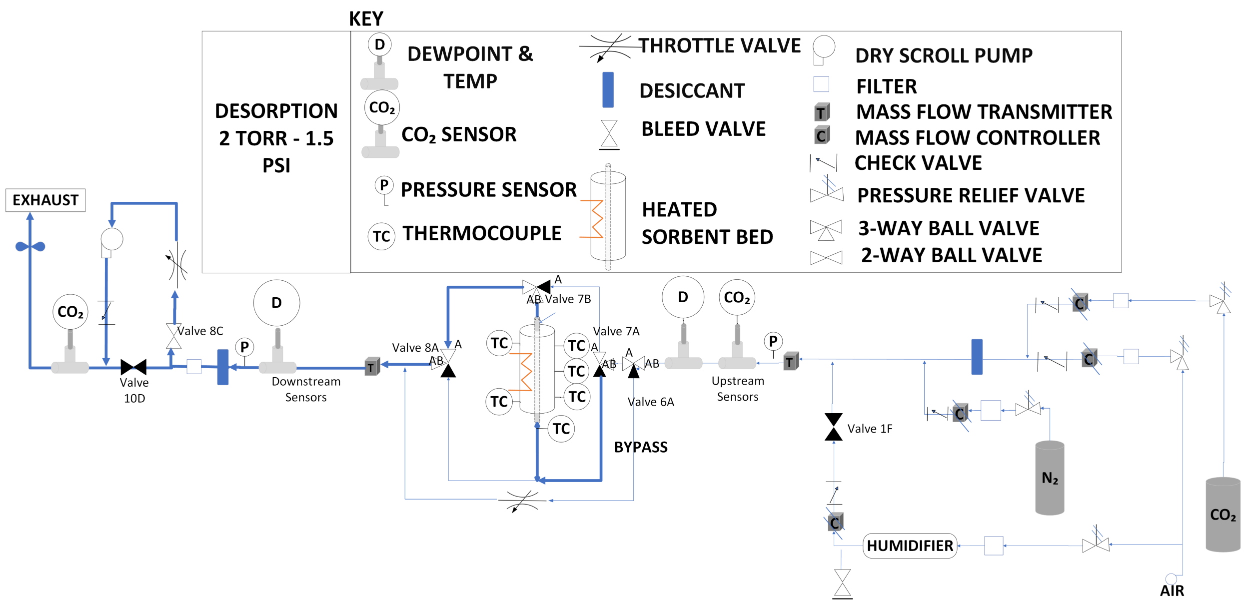


Figure 3.10: ZeoDe PNID with the desorption flow path in bold

Bake Out

Bake out, in a space-rated system, is usually only carried out once and before launch. During bakeout, the system can reach temperatures up to 350°C or use lower temperatures for longer. This process is meant to purge the zeolite of contaminants, including but not limited to CO_2 and humidity. In the ZeoDe testbed, bake-out is performed at 350°C, and nitrogen carries away contaminants. Nitrogen is more efficient at purging the bed than vacuum, as an inert gas with small molecular weight can more efficiently carry CO_2 from the bed.

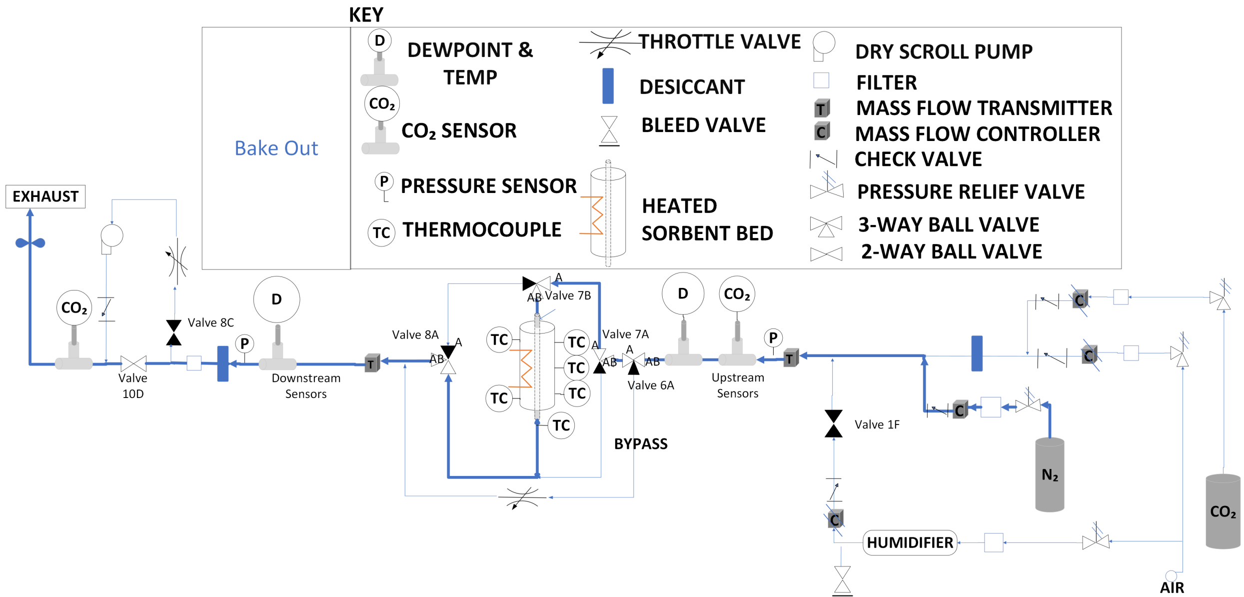


Figure 3.11: ZeoDe PNID with the bake-out flow path in bold

Sensor Checks

It is helpful to check sensors and air composition without contaminating the bed. Because of this, a bypass line was designed to flow around the bed and through both upstream and downstream sensors. The path is shown in Figure 3.12.

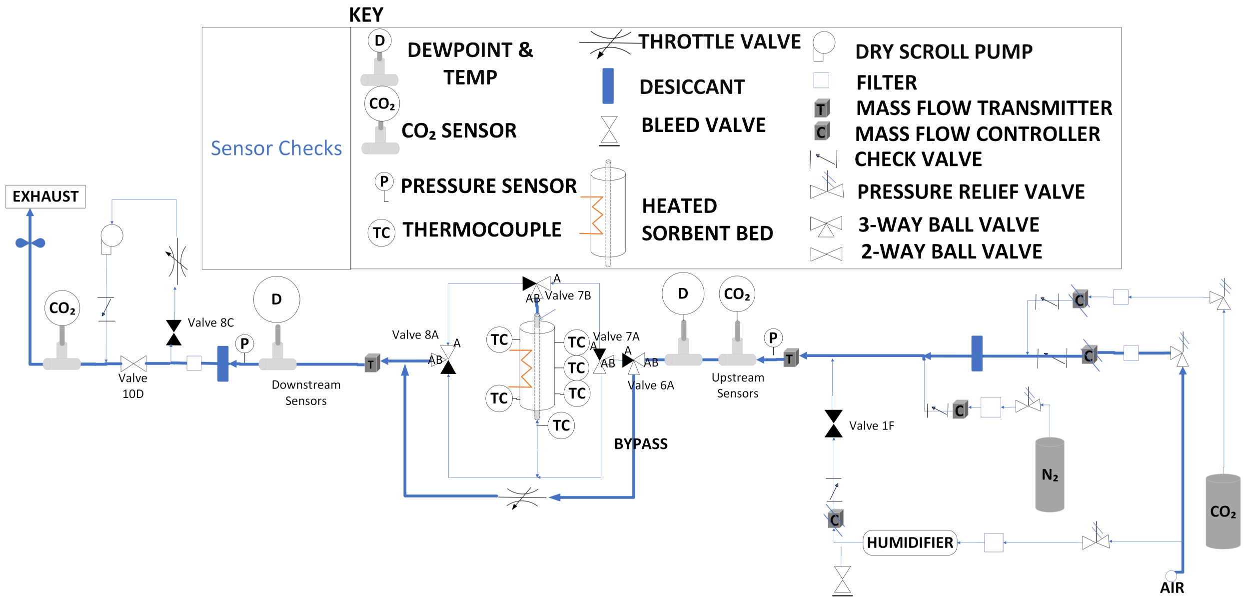


Figure 3.12: ZeoDe PNID with the sensor checks/ bypass flow path in bold

3.4 Component, Unit, Subsystem Selection

Optimizing between individual performance, performance as a system, and meeting the mission requirements.

Units were selected based on the following criteria

- Fulfillment of testbed requirements
- Advice and feedback from PDR and CDR review board
- Lead time to fit within a M.S. Thesis timeline
- Cost appropriate for low TRL development scale testbed in a university environment

Sorbent Packed Bed Sizing and contents

The sorbent media was chosen based on the following requirements:

- Requirement L3-008: The CO_2 adsorption media shall use a zeolite structure that adsorbs CO_2 via weak forces and adsorbs H_2O via polar attraction

Based on requirement L3-008, Zeolite 13X molecular sieves with an 8-12 mesh were chosen from Sigma Aldrich. These are alumino silicate structures with the following composition, with a diameter of 1-2 mm.

$$Na_{86}\,[AlO_2)_{86}(SiO_2)_{106}] \tag{3.1}$$

The sorbent bed was sized using the following requirements:

- L3-011: The testbed sorbent diameter to housing diameter ratio shall be at least 1:10
- L3-012: The testbed interstitial velocity shall be between 0.3 and 0.4 m/s
- L3-013: The testbed residence time shall be equal to or greater than 0.023 minutes

These requirements come from channeling mitigation, matching CDRA interstitial velocity, and matching CDRA residence time, respectively. The following bed was conceived from these requirements, with an 8 Standard Liters per Minute (SLPM) nominal flow, and filled with 8x12 mesh Zeolite 13X. The tube was cut to 20 in to accommodate the minimum zeolite fill height of around 14 inches to meet the residence time outlined in L3-013, plus margin. Figure 3.13 shows the interstitial velocity and packing on the left through an internal view, and on the right shows the exterior of the bed, wrapped in heater tape, thermocouples, and surrounded by insulation.

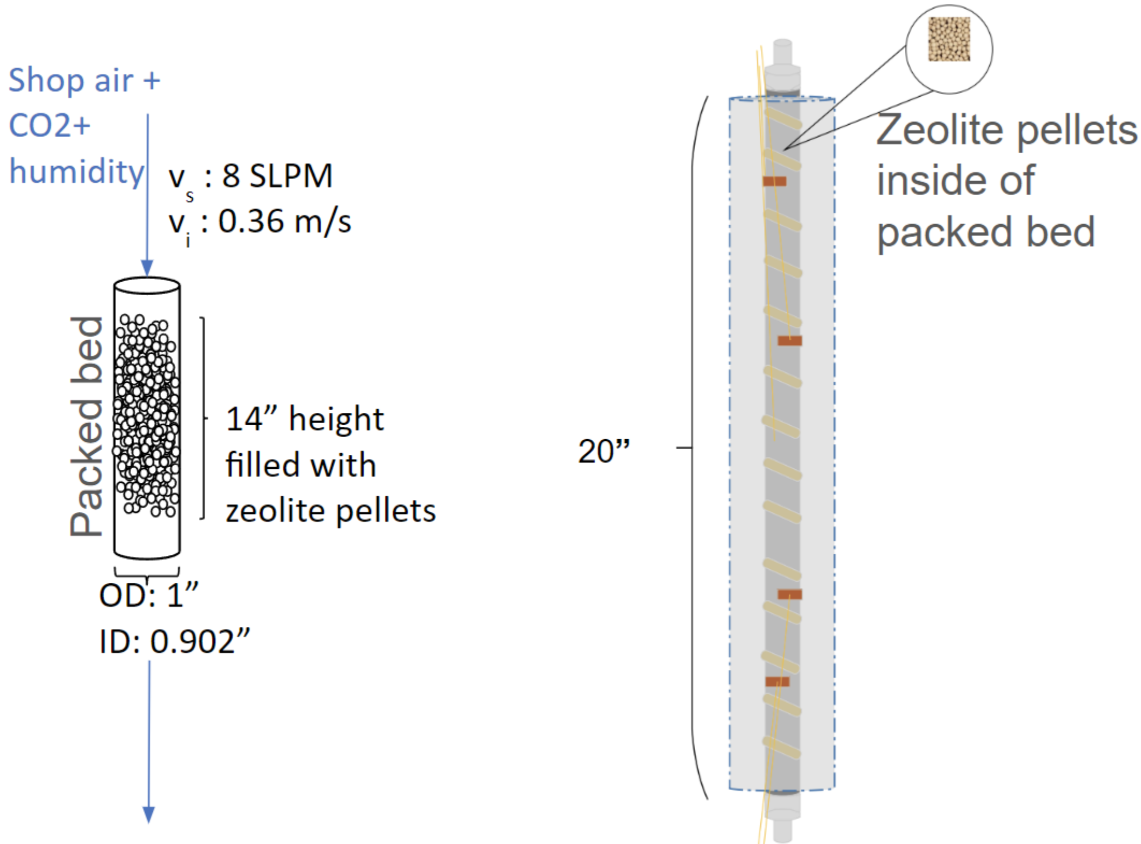


Figure 3.13: ZeoDe sorbent bed sizing depiction, with a nominal flow rate of 8 SLPM, filled with Zeolite 13x

The material for the sorbent bed met the following requirements:

- L3-010: When offered as an option by the manufacturer, all testbed parts shall be manufactured from corrosion-resistant material

Based on this, the 1” tube was sourced as 316 Steel, and the fittings on either end were sourced as 316 Steel compression fittings.

Instrumentation

The instrumentation was chosen based on the following requirements:

- L3-002: The testbed sensors shall capture humidity measurements at the inlet and outlet of the testbed.
- L3-003: The testbed sensors shall capture the temperature of the testbed.

- L3-004: The testbed sensors shall capture the pressure drop throughout the testbed.
- L3-005: The testbed sensors shall capture temperature measurements at the inlet and outlet of the testbed.
- L3-006: The testbed sensors shall capture CO_2 measurements at inlet and outlet of the testbed
- L3-014: Sensors shall be capable of sensing CO_2 levels at the inlet and outlet of the bed during adsorption and capable of providing at least part of a desorption CO_2 curve. *note* it is anticipated that the sensors may not cover the full range of a desorption curve and would top out at their upper limit*
- L3-015: Sensors shall be capable of sensing humidity levels between 10 and -30°C dew point
- L3-016: Sensors shall be capable of sensing pressure levels between 14.7 psia and 30 psia.

This led to the use of the following sensors.

Sensor	**Vendor**	Part	**Range**	**Form Factor**
Pressure Transducer	Omega	PX309-030G5V	0-30 psi	probe
CO2 Sensor	Vaisala	GMP252	0-5,000 psi upstream; 0-20,000 psi downstream	probe
Dewpoint Sensor	Vaisala	HMP060	-40°C to 60°C	probe
Thermocouple	Omega	5SC-GG-K-30-108	0°C to 482°C	wire

Table 3.5: Primary sensors on ZeoDe, with vendor, range, and form factor

Fitting the probe-type sensors into the testbed brought about two options: individual integration of each sensor into the lines or inserting all sensors into one machined sensor housing. The following solution was designed to avoid leaks from machined housing.

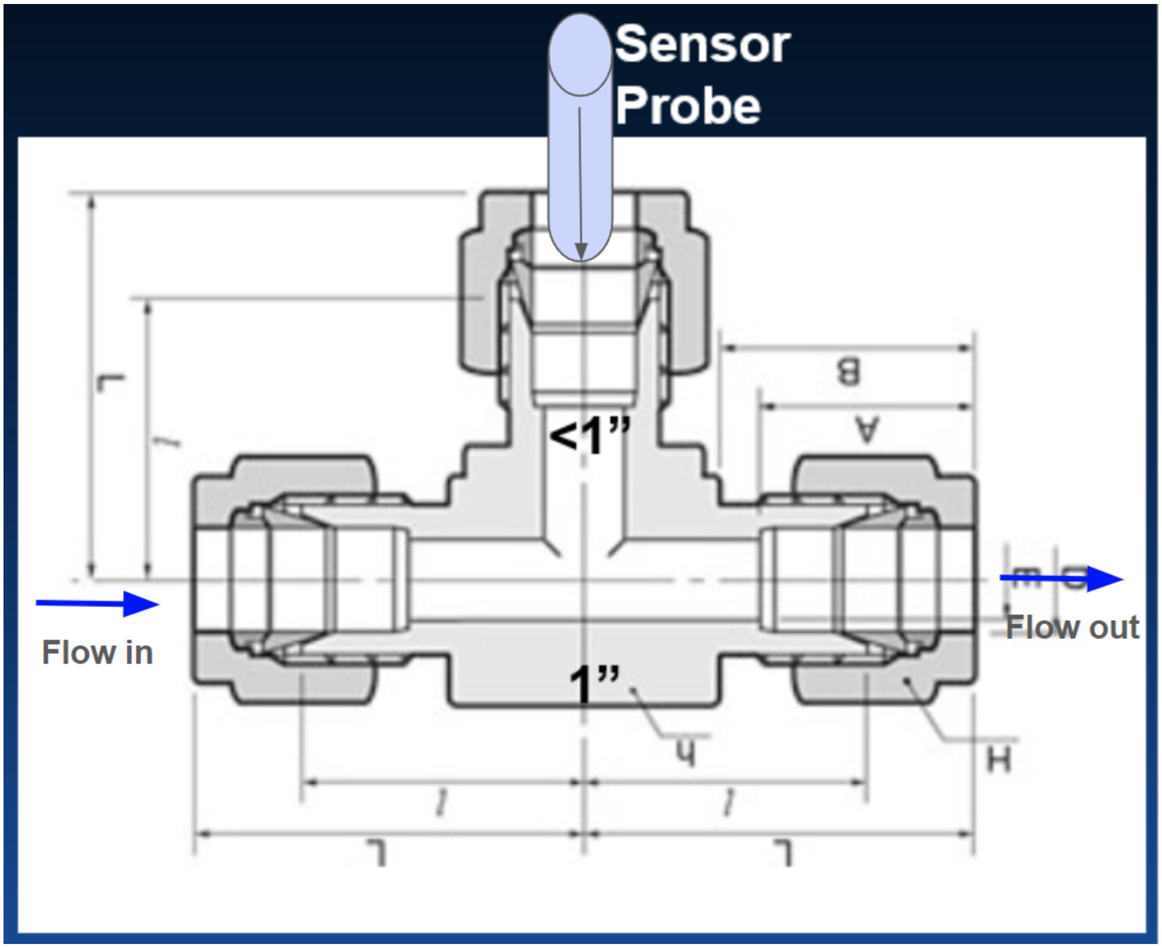


Figure 3.14: Depiction of the ZeoDe sensor housing in the form of a tee fitting, showing sizing for a sensor probe 1” in diameter

While the sensor probes in Table 3.5 are primarily designed for duct-type installation, where they are installed into a wall or open to the environment, ZeoDe requires a sealed environment and in-system measurements. The Omega pressure sensor chosen has NPT fittings and can fit into a tee with corresponding threads. However, neither Vaisala probe includes threading. Correspondingly, a tee with compression fittings that would not harm the sensors could allow a closed-system measurement. To properly fit each probe, given a smaller internal diameter than the opening diameter, modifications via machining are needed, and a Polytetrafluoroethylene (PTFE) ferrule and sleeve are required to replace the stainless steel ferrule and sleeve that comes with the compression tee.

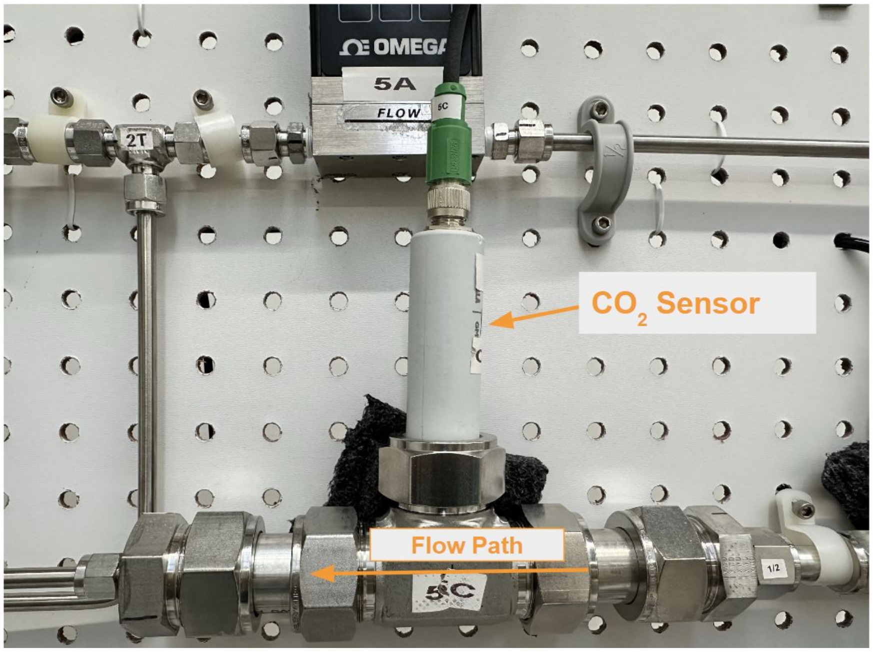


Figure 3.15: ZeoDe upstream CO_2 sensor housed within a tee fitting

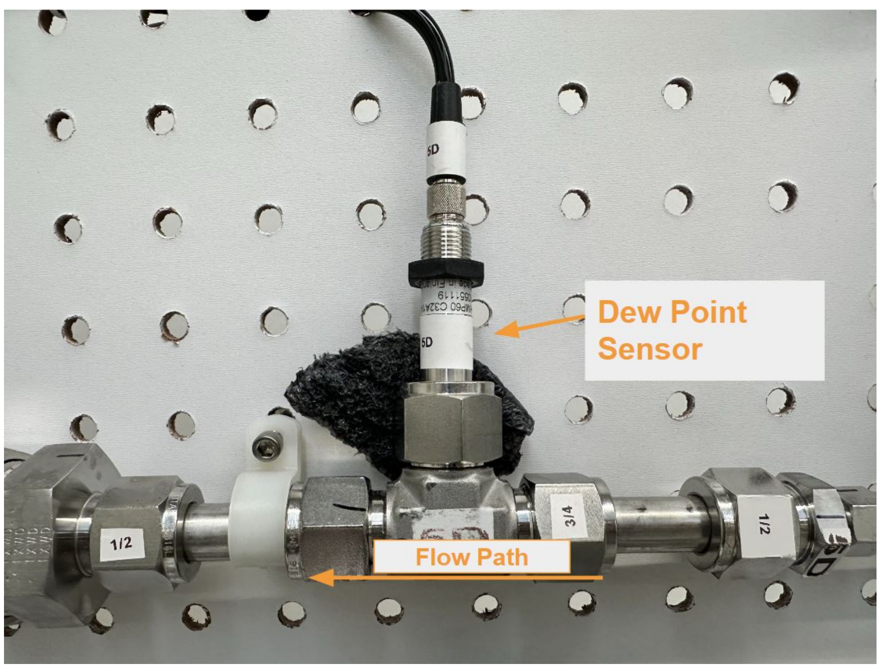


Figure 3.16: ZeoDe upstream Dew Point sensor housed within a tee fitting

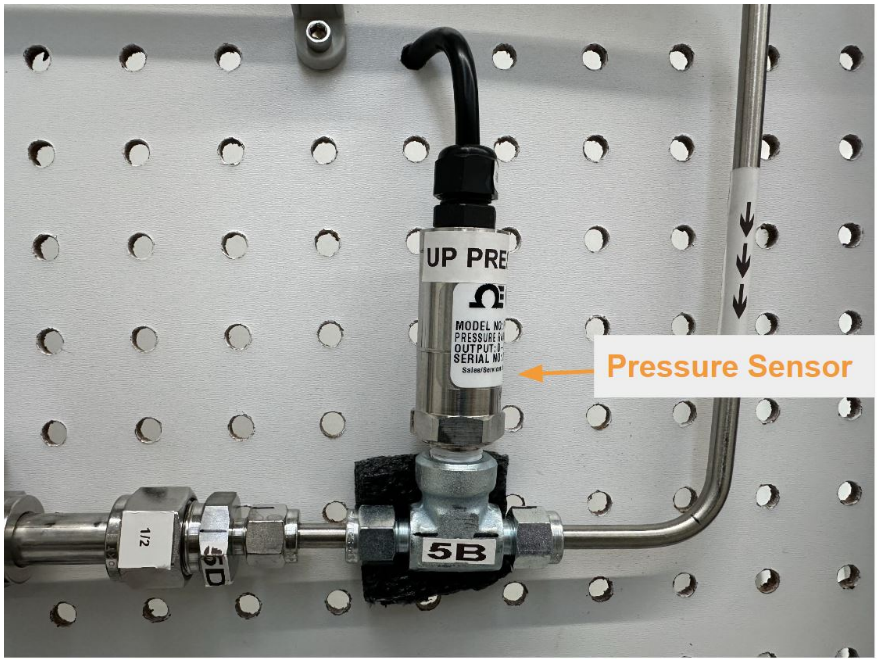


Figure 3.17: ZeoDe upstream Dew Point Sensor housed within a tee fitting

Figure 3.18: ZeoDe thermocouple form factor, with a mini-tc connection

Actuators: Valves

To support cyclic, regenerative operation with multiple gas inputs, ZeoDe requires both two-way and three-way valves. Additionally, the following requirement must be met:

• L2-019: The testbed shall use commandable actuators.

This led to the following choice.

Two-Way and Three-way Valves with actuators	
Type	Ball valve
Speed	4 seconds
Vendor	Belimo
Communication Protocol	2-10 VDC

Table 3.6: ZeoDe valve selection, with type, speed, vendor, and communication protocol

Risks carried with the valves in Table 3.6 include a 2% leak path in the 3-way valves in the AB to B direction, as well as the use of NPT threads to connect the valves to the testbed, which can be prone to leaks if re-installations occur due to worn down threading.

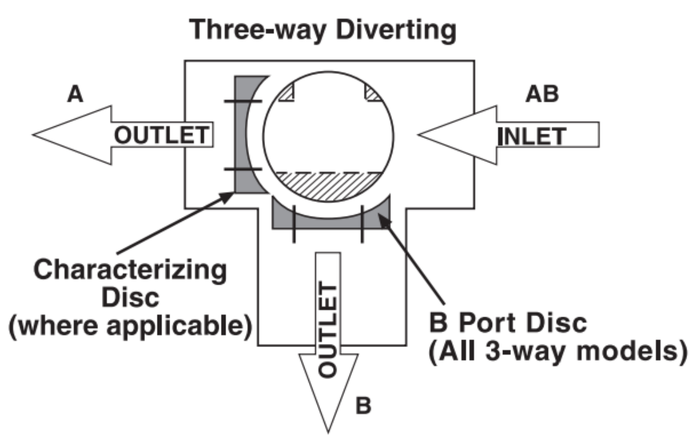


Figure 3.19: Diagram of the valve chosen for ZeoDe - the Belimo 3-way Valve - and its flow path

Figure 3.20: Photo of a Belimo 3-way valve on ZeoDe

Mass Flow Controllers

Mass Flow Controllers (MFC's) The mass flow controllers were chosen based on the following requirements:

- L3-017: Mass flow controllers shall be capable of delivering between 400 ppm and 4,000 ppm CO2 into the fluid stream.
- L3-018: Mass flow controllers shall be capable of delivering a fluid stream containing between -30°C dew point to 10°C dew point.
- L3-019: The testbed shall use commandable actuators.

This led to the following selection:

Mass Flow Controllers	
Type	Temperature Pressure
Range	0-1 SLPM ; 0-20 SLPM
Vendor	Alicat
Communication Protocol	0-5 VDC, controlled by control loop in LabView

Table 3.7: ZeoDe mass flow controller properties: type, range, vendor, and communication protocol

These mass flow controllers use pressure and temperature sensors to measure gas flow. A microprocessor uses these readings and a library of known gases to calculate the mass flow rate and regulate the gas flow by opening or closing a valve.

Figure 3.21: Photo of an Alicat mass flow controller on ZeoDe

Pump

The pump is required for desorption during cyclic operations. It needs to feed back into the system without contamination or leakage, as sensors may be required downstream of the pump outlet. As a result, an oil-less pump was required to avoid oil contamination. This led to the choice of an nXDSi Edwards vacuum pump, which meets the following requirement:

- L3-020: The testbed shall be capable of operating at 4 Torr.

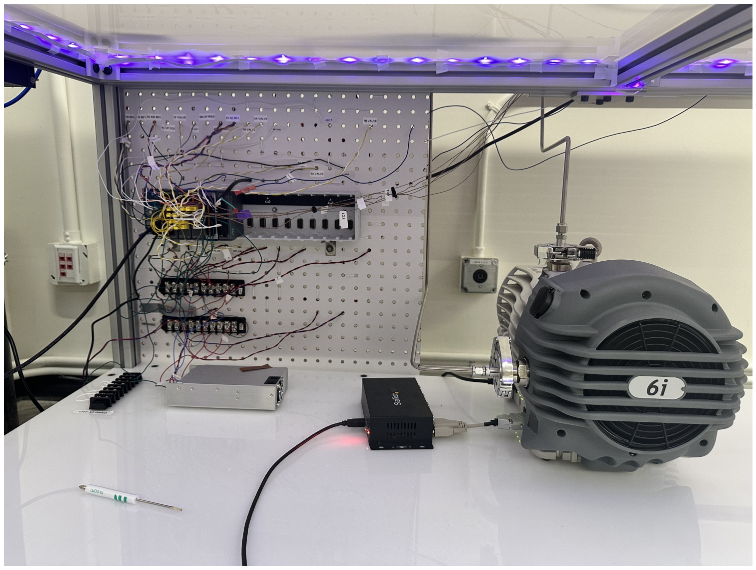


Figure 3.22: Photo of the ZeoDe pump, on the lower level bench

Humidity Introduction

The ability to induce capacity degradation into the testbed relies on precise humidity injection into the inlet stream to the sorbent bed. This system had to meet the following requirements:

- L3-018: Mass flow controllers shall be capable of delivering a fluid stream containing between -30°C dew point to 10°C dew point.

The traditional option to control humidity is a bubbler, where gas is bubbled through a chamber filled with water. The gas stream becomes saturated with water vapor. The amount of water vapor carried away by the gas stream depends on the gas's temperature and pressure and the water's temperature.

It was noted that bubblers for similar systems [34] are large and bulky and can require extensive controls to introduce precise humidity and avoid liquid introduction into the system.

Alternatives were explored, including a system currently used in the Spacex Dragon humidity control system: Nafion membranes for water vapor exchange across a membrane, with gas on one side and water on the other. This less expensive, less mass- and volume-intensive option was chosen, as it still met the system's requirements. This resulted in the following humidity introduction system.

Humidity Introduction	
Type	Sulfonic Acid Nafion Membrane
Range	10°C - 65°C dew point
Vendor	PermaPure
In conjunction with	0-20 SLPM Mass Flow Controller and PID control through LabView

Table 3.8: Table for the chosen ZeoDe humidity introduction, showing type, range, vendor, and parallel technologies on the testbed

Nafion sulfonic acid membranes are a type of polymer electrolyte membrane commonly used in fuel cells and other electrochemical applications. They are characterized by their high proton conductivity and ability to transport water vapor selectively. This makes them ideal for use in humidifying gas streams. They contain a fluorinated backbone with sulfonic acid groups (-SO3H) attached to the side chains. The sulfonic acid groups are hydrophilic, meaning they have a strong affinity for water molecules. As a result, the membranes can absorb and retain large amounts of water. When a gas stream is passed through a Nafion membrane, the water molecules in the gas stream are attracted to the sulfonic acid groups and are preferentially transported through the membrane. The dry gas that exits the membrane on the other side has a lower humidity level than the original gas stream.

The sulfonic acid groups are constantly moving due to the thermal energy of the membrane. This thermal energy is the input that transports water molecules through the membrane. The transport rate of water molecules through the membrane is proportional to the concentration gradient of water molecules across the membrane, the membrane's temperature, and the membrane's thickness. Thicker membranes will transport less water vapor than thinner membranes.

An example of a humidity introduction curve for a PermaPure Nafion membrane is shown below. Note that this humidity capability can be paired with a dry stream to achieve desired dew points.

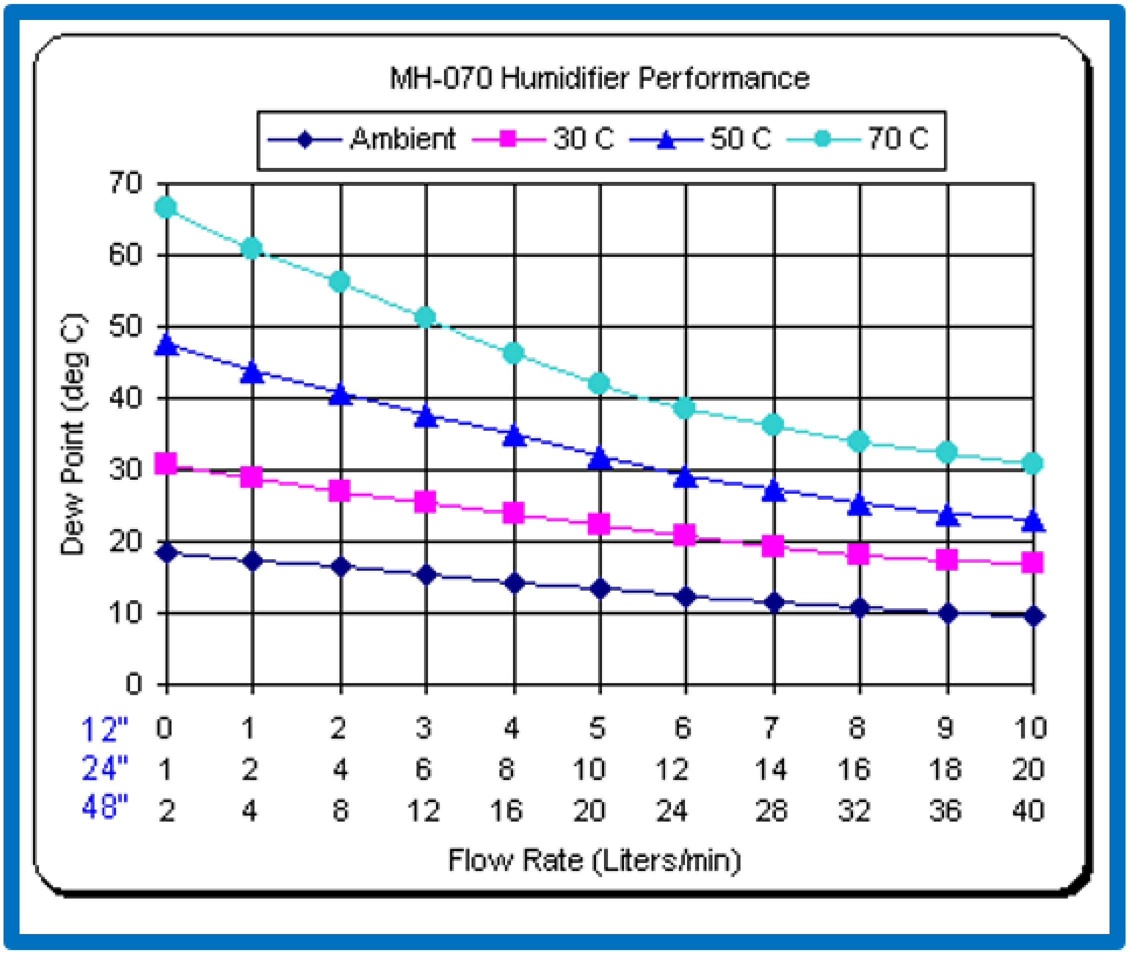


Figure 3.23: Table provided by PermaPure for the humidity introduction capability of a PermaPure Nafion membrane

Pictured below, air comes in via the light blue inlet line. After passing through a regulator, it splits into two lines. The top line feeds into a Permapure Nafion membrane, is followed by a bleed valve, and then is controlled by an Alicat MFC. The line is opened or closed by the 1F 2-way Belimo valve. The lower line produces a dry air inlet.

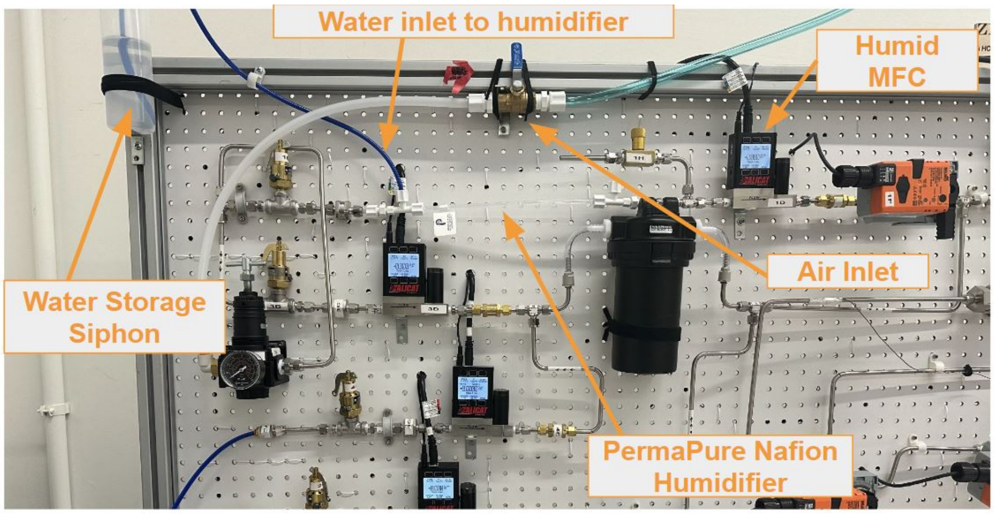


Figure 3.24: Photo of ZeoDe highlighting the humidity introduction capability via Nafion Permapure membrane, fed by a water tank, and outlet controlled by an Alicat Mass Flow Controller that is connected to a controller within LabView

Desiccant Beds

Desiccant beds are needed in two locations:

- Downstream of the air inlet, to allow for the introduction of dry air
- Upstream of the pump, to ensure no condensation of water within the pump

Upstream of the sorbent bed, the desiccant is needed to ensure a pure dry stream for nominal tests and as a part of the mixture of dry air and humid air to reach desired humidity levels. It contributes to the following requirements:

- L3-001: The degradation data set shall vary at least one factor
- L3-020: The testbed shall be capable of delivering a fluid stream with a humidity range of -30°C to 10°C dew point.

This led to the following choice of desiccant.

Desiccant Beds	
Type	CaSO4
Dew Point Temperature	-45°C
Vendor	McMaster Carr

Figure 3.25: ZeoDe desiccant bed specifications, showing type, dew point temperature, and vendor

This desiccant dries the stream to a lower dew point than in the humidity introduction trials. While a truly dry system would be brought to around -88°C [25], this design brings the dry baseline to a low dew point while maintaining a bench-top level price point and complexity.

Data Acquisition

The data acquisition requirements were not held to stringent data standards. The DAQ needed to connect to all the sensors and actuators on the testbed and produce a readable file with time histories of system states and sensor telemetry.

- L3-021: The testbed shall use programmable data acquisition and command software and hardware to command the testbed and store data.

Two main options were explored:

- Arduino/Raspberry Pi-based system
- National Instruments-based system

The pros of the Arduino/Raspberry Pi type system are that it is modifiable at every level as it is built from the ground up. However, it requires greater time and effort to build up. Conversely, National Instruments has created advanced data acquisition systems with built-in modules for different data types. This fully functional system requires less time for design and build, but it has less component flexibility and a much higher price point.

Feature	CompactDAQ	PXI	CompactRIO
Form factor	Modular	PCIe	Embedded
Size	Portable	Desktop	Embedded
Performance	Lower	Higher	High
Cost	Lower	Higher	Highest
Applications	Benchtop measurements, distributed data acquisition	High-performance testing, embedded systems	Real-time control, robotics

Table 3.9: Comparison of National Instrument DAQ Systems evaluated for the ZeoDe system

As this project was intended to be designed, built, and tested in an M.S. timeline, the upside in scheduling for the National Instruments hardware could not be ignored. The options within National instruments included those shown in Table 3.9. ZeoDe is a low TRL bench-level testbed, so it does not require more than 14 module slots, WiFi or Bluetooth connectivity, embedded systems, or high-speed control. Additionally, the modular nature of the CompactDAQ was appealing to a bench-top-level testbed. Because of this and the lower price point, the CompactDAQ was the best choice.
Once the CompactDAQ was chosen, the following hardware was designed into the system in collaboration with National Instruments engineers.

Unit/Module	Description	Use
CDAQ-9179	CompactDAQ Chassis(14-Slot USB 3.0)	Chassis to house all modules: 0-10V
NI 9210	Mini TC,24-Bit,14 S/s/ch, 4-Ch,Thermocouple C Series Module	X2 for all thermocouple data on testbed
NI 9264	Spring, 16-Ch voltage,+/-10V, 16-bit, 25kS/s/ch AO module	Analog output: 0-10V
NI 9205	Spring Terminal, 32 Ch, +/-200mv To +/-10v, 16-Bit, 250 Ks/S Ai C Series Module	Analog input: 0-10V
NI 9482	C Series Relay Output Module, 4-Ch SPST, 30/60 VDC, 250 VAC, Spring Terminal	Relay for heater systems

Table 3.10: National Instruments Data Acquisition system modules chosen for ZeoDe

This setup uses all analog modules and is standardized to work within 0-10 VDC for commands and telemetry. It also includes a relay module for the heaters, which allows control of the heater temperature by sequentially turning on and off the power inlet to the heaters to maintain specified temperatures.

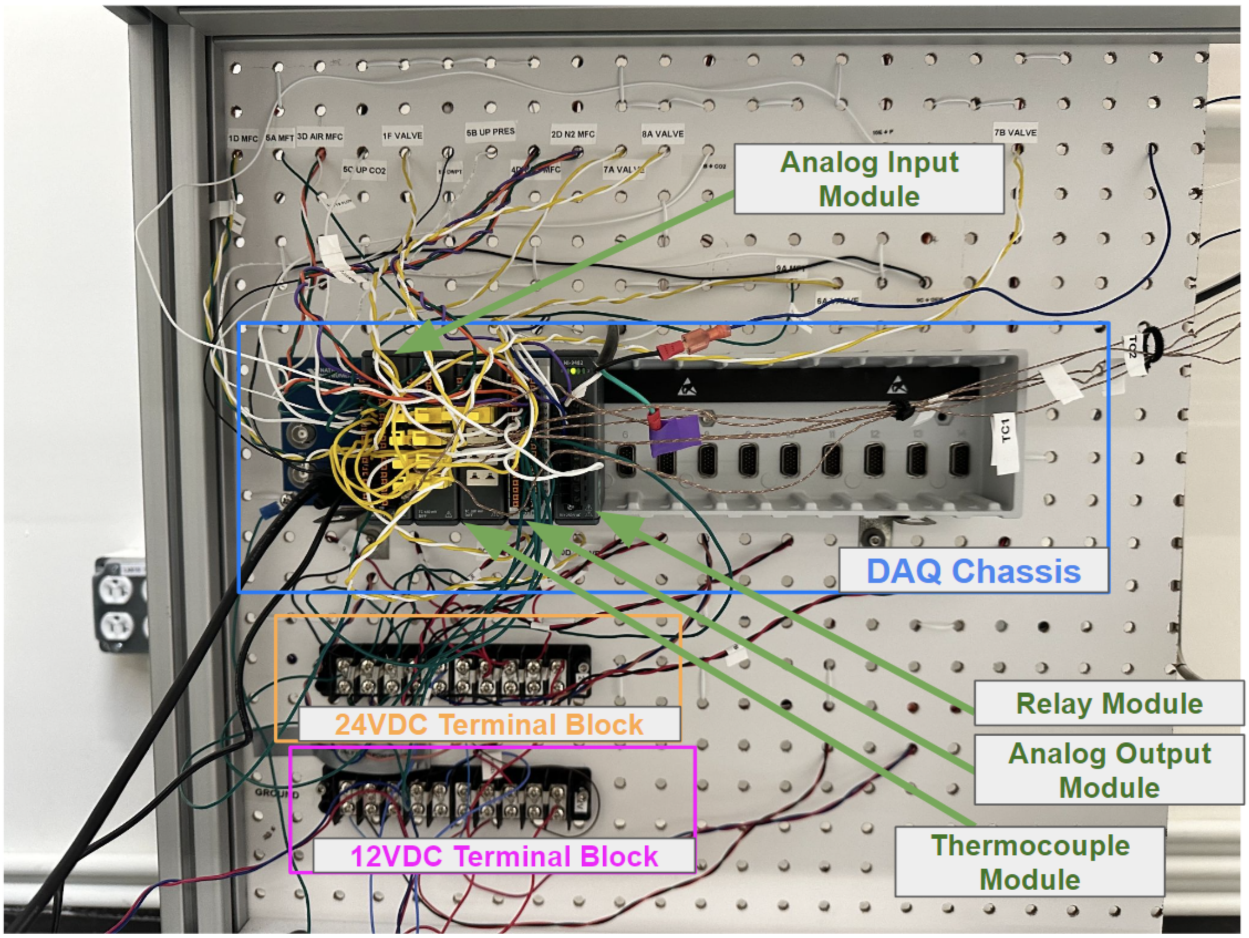


Figure 3.26: Photo of the National Instruments Data Acquisition System on ZeoDe

Figure 3.26 shows the DAQ, which is mounted to the underside of the testbed, with wiring feeding in from the backside of the testbed backboard, where it is arranged for traceability. Power and grounding terminal blocks for the DAQ and each sensor/actuator feeding into the DAQ are seen below the CompactDAQ Chassis.

Software

The software component presented several options, shown below.

Feature	LabVIEW	C/C++	Python	MATLAB
Programming language	Graphical programming language	Text-based programming language	Text-based programming language	Text-based programming language
Time to Build [for a Graduate Student]	Short	Longest	Long	Long
Performance	Slower	Faster	Faster	Faster
Flexibility	Less flexible	More flexible	More flexible	More flexible
Community	Large and active	Smaller but growing	Large and active	Large and active

Table 3.11: Software comparison table showing software that was traded for data acquisition on ZeoDe

An opportunity arose within the Lab View Environment, where ZeoDe's sister testbed at CU Boulder [34], which contained many of the same drivers, inputs, outputs, and testing protocol, had software written that could be transferred to a ZeoDe Lab View environment. This professionally written code had an intuitive user interface and could be modified easily. It was chosen as the price point and lead time for a mostly transferred package from CU Boulder, which was feasible for a university-scale bench top-level testbed.

Software	Environment	Vendor	Compatibility
MICAS-X	LabView	Original Code Consulting	National Instruments DAQ

Table 3.12: Chosen data acquisition software on ZeoDe

MICAS-X is a software framework written in LabView that allows for pre-formatted data acquisition and commands and pre-formatted control loops. It includes extensive functionality, including but not limited to the ability to create sequencing, alarming, file writing, and error and event logging. The end-users can configure all these functionalities using custom LabView software, including the modification option. An example of the result of end-user sequences programming is listed below, with commands listed sequentially as they are sent when a sequence is initiated. Sequences can also be nested within each other, allowing, for example, ten adsorption-desorption sequences to be run sequentially.

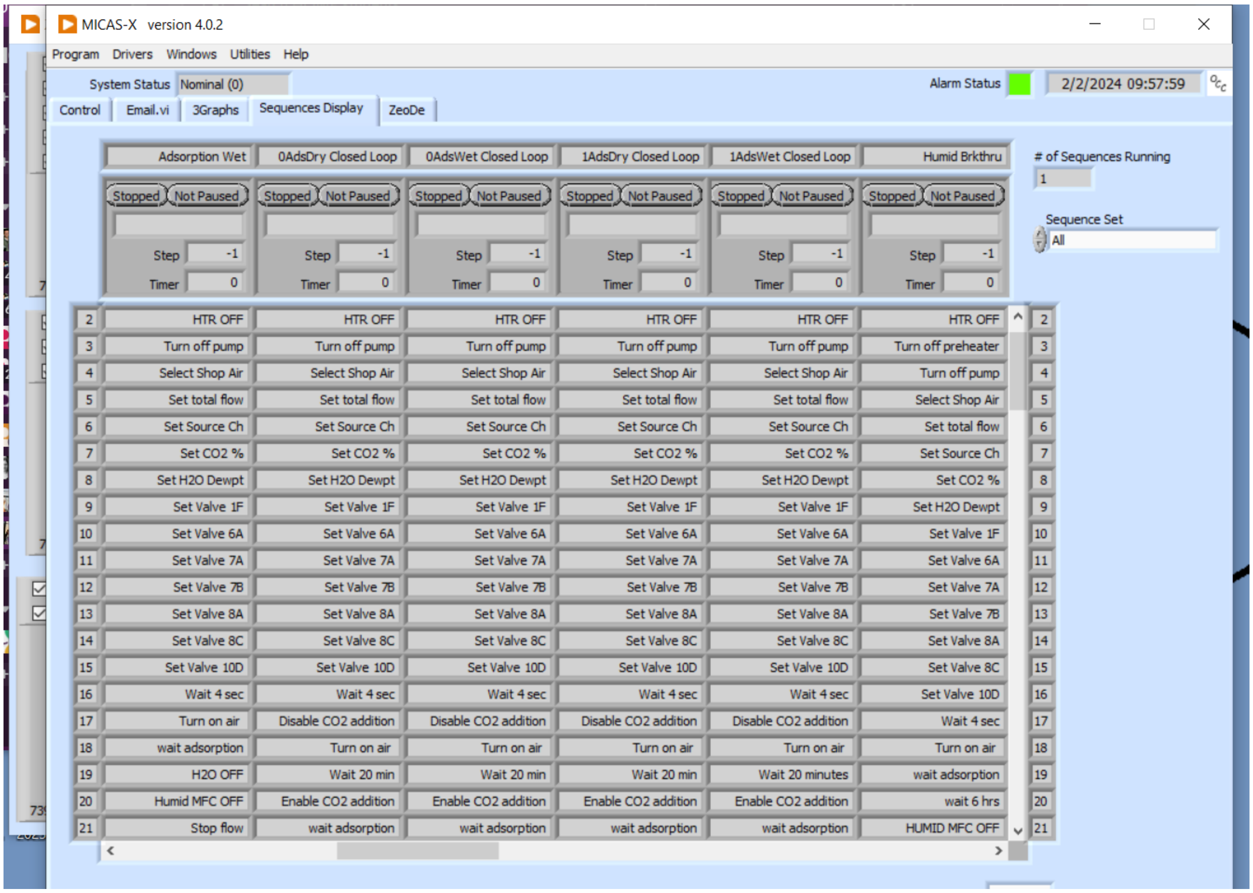


Figure 3.27: Data Acquisition Software MICAS-X that was chosen for ZeoDe: GUI example for the sequences tab, which groups a list of commands for an experiment

GUI interface is ready for the end-user, with examples below.

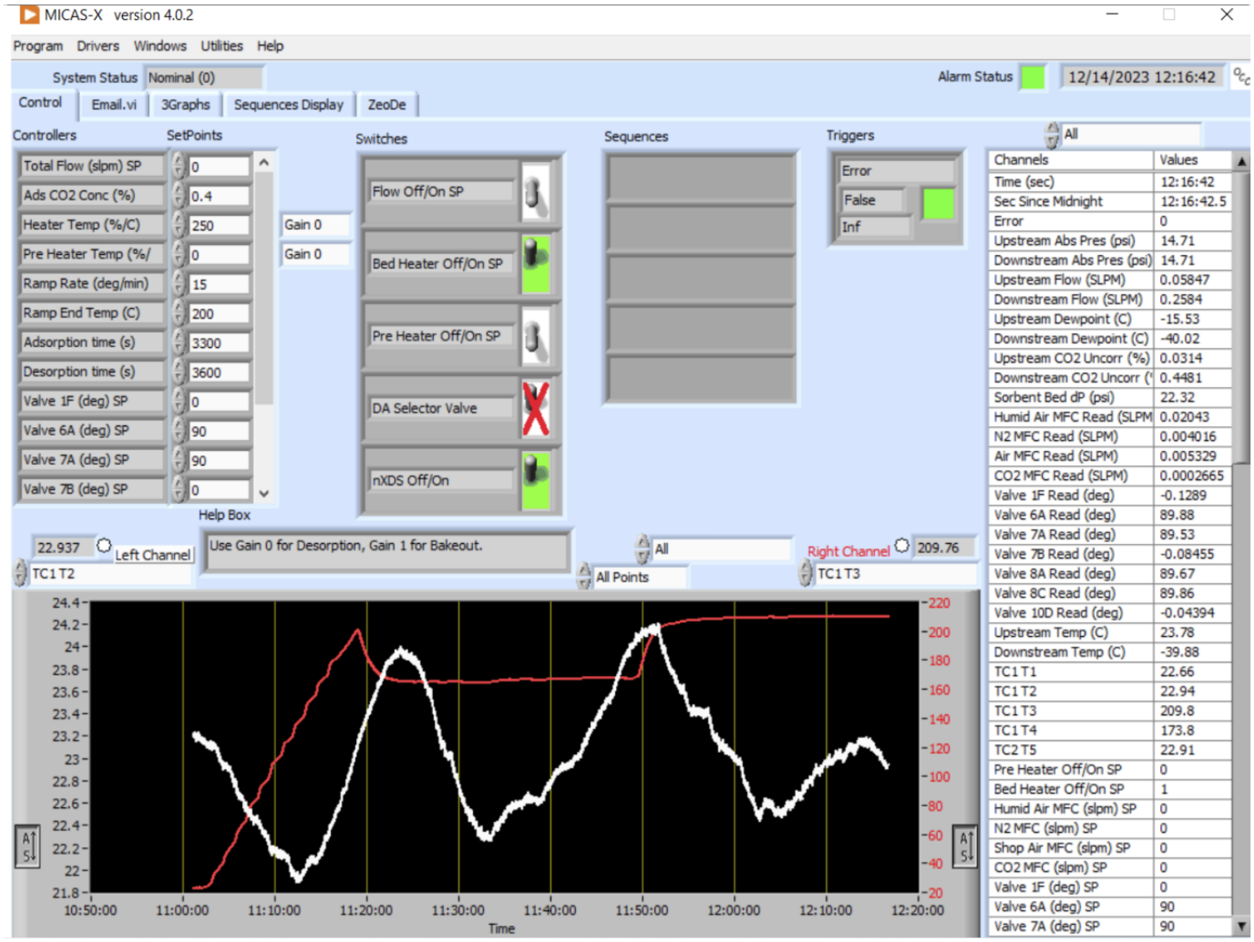


Figure 3.28: Data Acquisition Software MICAS-X that was chosen for ZeoDe: Graphical user interface for ZeoDe in the MICAS-X program

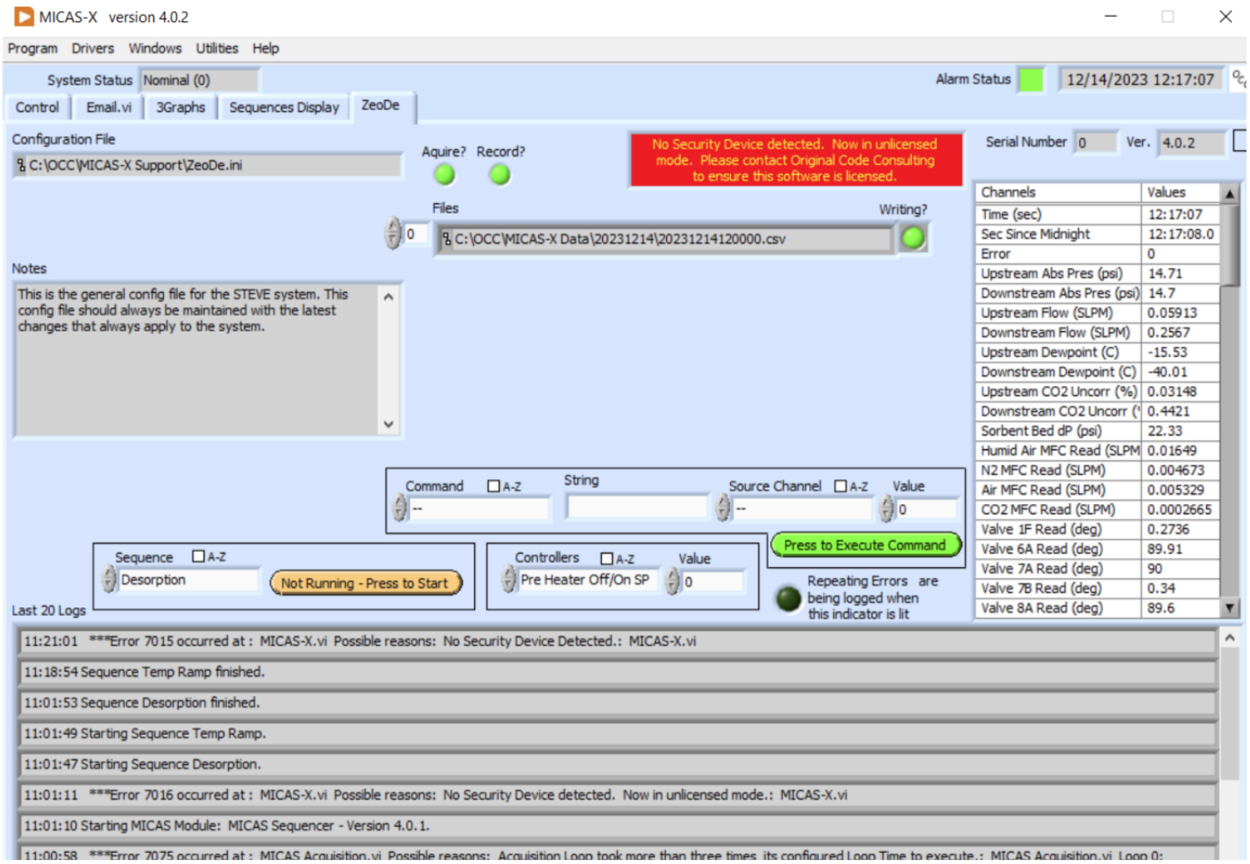


Figure 3.29: Data Acquisition Software MICAS-X that was chosen for ZeoDe: Graphical user interface for ZeoDe in the MICAS-X program

Electronics

Signals between 0 and 10V DC were chosen to align sensors and actuators. Additional electronics were required to connect them to the data acquisition system.

Part	Description	Use
8 Port USB to Serial RS232 Adapter	Converts signal from serial to usb, readable by LabView	adapter for pump command and telemetry
AC to DC Converter	Power conversion to provide 12VDC and 24VDC	power supply for sensors and actuators
Terminal Blocks	Terminal blocks for connecting multiple wires to a single bar	grounding and power supply
Outlet Plug with Fuse	Accessible AC Neutral, Live, and Ground wires	Connect power to the AC to DC converter using exposed end wires

Table 3.13: Table showing additional electronics parts incorporated into ZeoDe

Power

The instrumentation and actuators require AC, 12VDC, and 24VDC power. The power architecture is laid out here, assuming that the DAQ powers thermocouples.

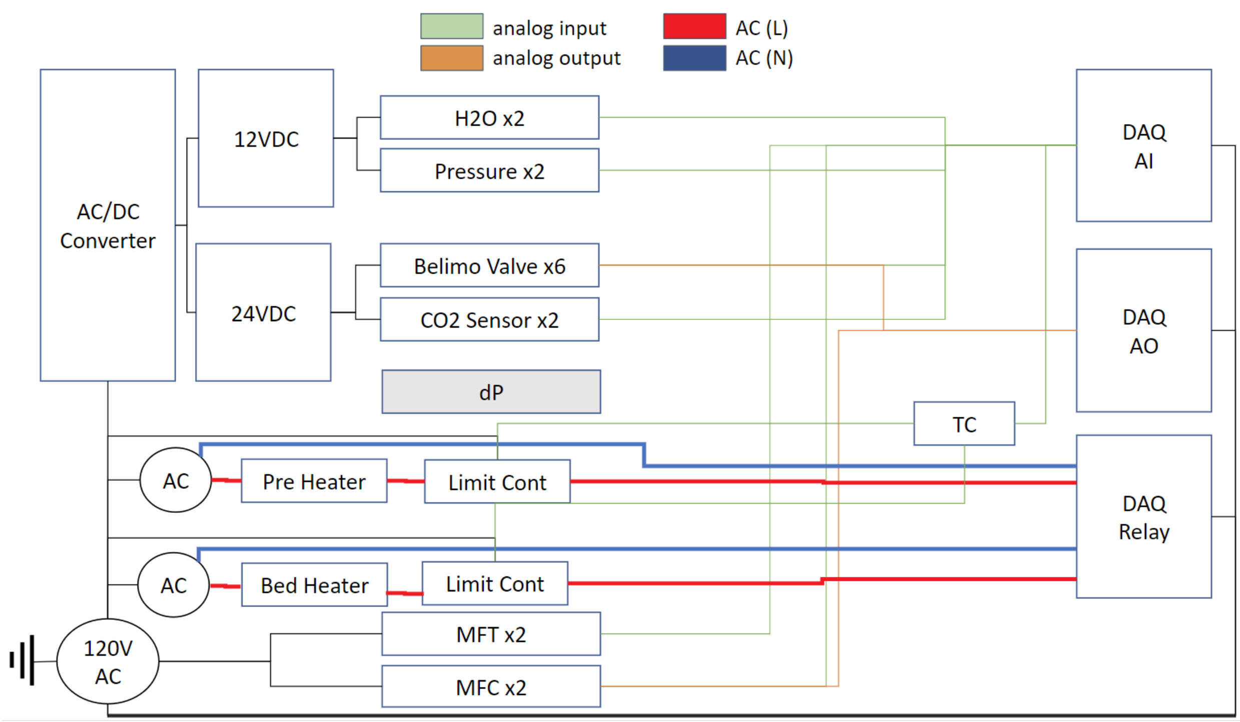


Figure 3.30: Diagram showing the power architecture of the ZeoDe instrumentation and actuators

Wires and Connectors

While some instrumentation and actuators came with power cables, they usually required extension. As a norm, 18 AWG wire was used for power for all units.

Sensors and actuators are delivered with cables ranging from 16 AWG to 20 AWG. Extensions are necessary given the ZeoDe testbed length, described in the structures section, and the distribution of the sensors and actuators. The following modes of extension and connection are designed into the system.

Part	Description	Use
18 AWG solid core wire	Copper wire, 18 AWG, colored	Wires for extension of lines to reach DAQ
Nylon Spade Quick Disconnect	Male and Female electrical quick disconnects to connect one piece of 18 AWG wire to another	Wire junctions for extension of lines to reach DAQ

Table 3.14: Table showing the types of Wires and connectors chosen for ZeoDe

All electrical systems were mapped out using Visio. The top-level electrical diagram is shown below, followed by a more in-depth diagram for the valves.

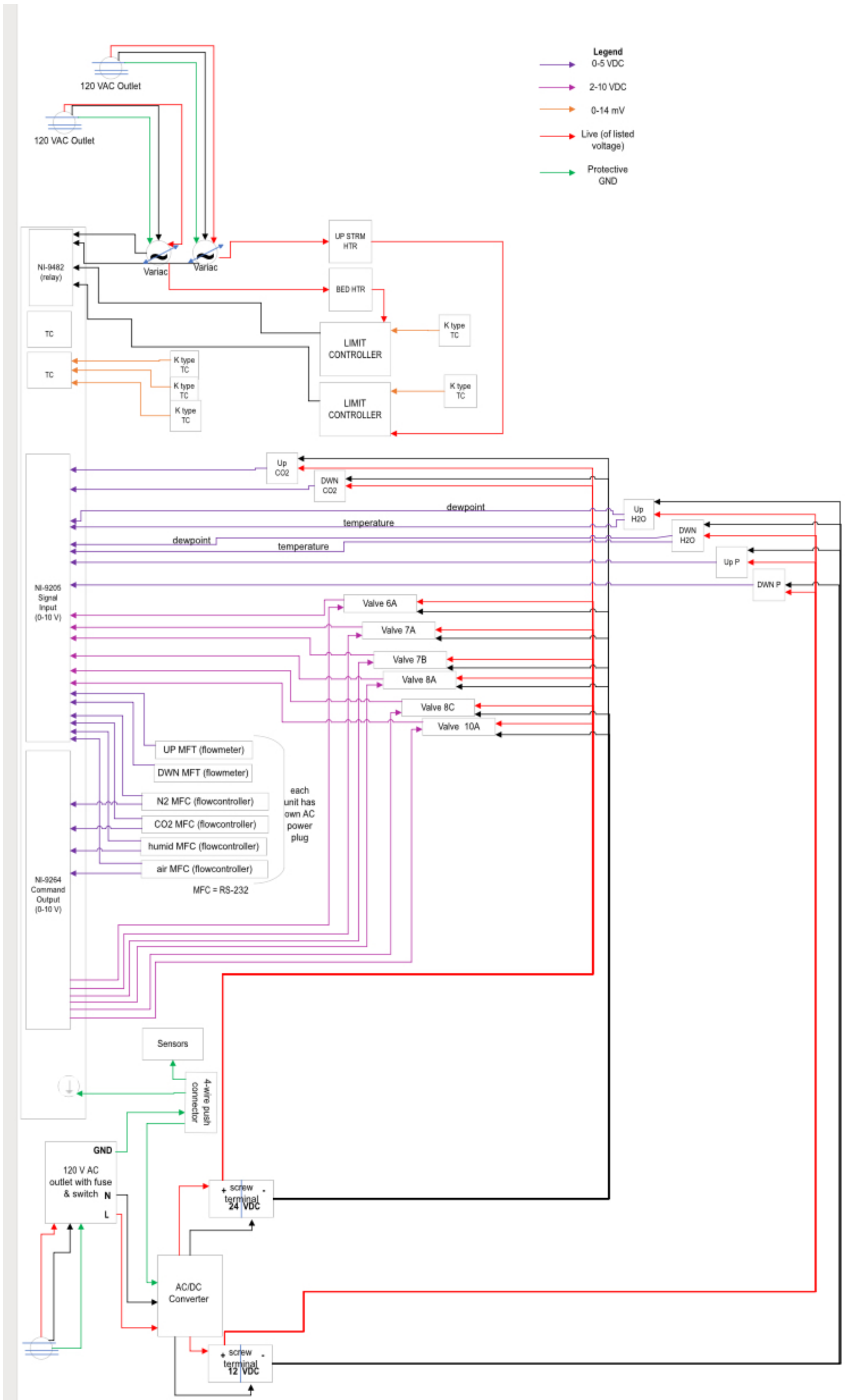


Figure 3.31: Diagram showing a top level wiring diagram for ZeoDe

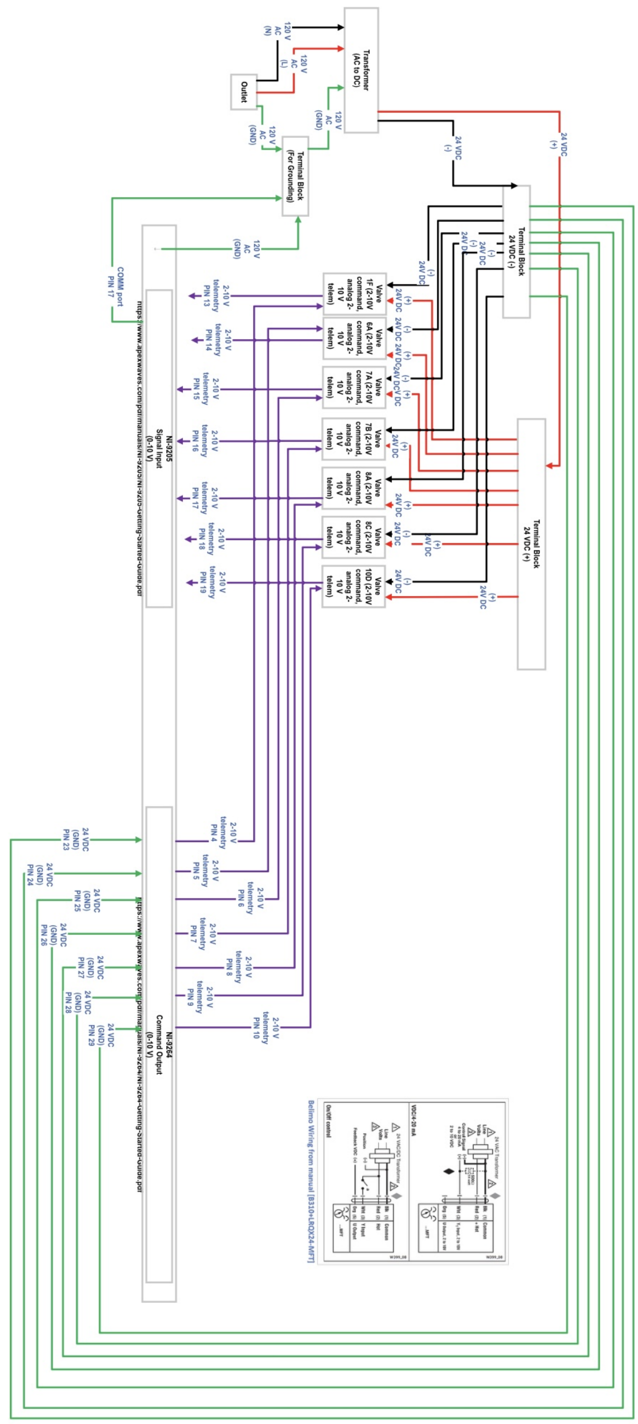


Figure 3.32: Diagram showing a more in-depth wiring diagram for ZeoDe, focused on the valve wiring

3.5 Safety

Safety is just as important on the ground as it is in space. The UC Davis Center for Spaceflight Research holds a high standard for safety, setting a precedent for our mentality when designing technologies and processes for crewed spaceflight. This section goes through some steps we took to ensure our lab mates, testbed builders, and future testbed operators are safe.

Hazards Analysis

The following risk chart was used to determine the consequences of each risk.

SCORE	1	2	3	4	5
IMPACT ON PERFORMANCE	Minimal impact on goals	Minor impact on goals	Unable to achieve a particular goal	Unable to achieve multiple goals	Unable to achieve the overall goal
IMPACT ON HUMAN SAFETY	Discomfort or nuisance	First aid	Minor injury or illness	Major injury or illness	Loss of life
IMPACT ON ASSET	No physical damage	Cosmetic damage	Functional damage but repairable	Substantial damage but repairable	Destroyed
IMPACT ON SCHEDULE	Minimal impact on schedule	Delay on some tasks not impacting overall schedule	Delay on some tasks minimally impacting overall schedule	Major slip in overall schedule	Critical milestones cannot be met
IMPACT ON COST	Minimal impact on cost	Minor impact on cost (cost variance <5%)	Medium impact on cost (5-10%)	Major impact on cost (10-15%)	Critical impact on cost (cost variance >15%)

Table 3.15: Table used for scoring and color coding of hazards/risks

The following chart shows the likelihood vs consequences model that was also used.

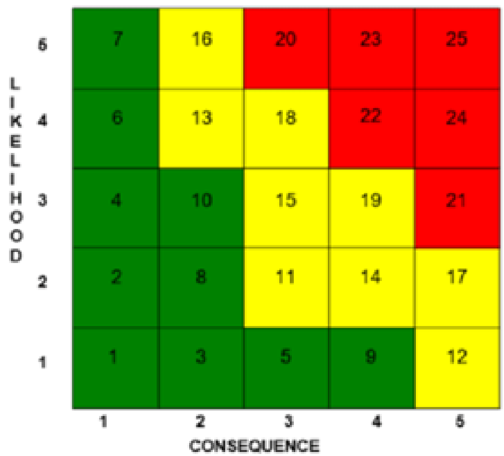


Figure 3.33: Chart used to determine the likelihood vs consequences evaluation of ZeoDe hazards and risks

Using the above resources, the following table was compiled.

Risk	LxC	Risk Title	Approach	Conditions for Occurence	Mitigations
ZeoDe -001	3x4	Over Pressure of system	Mitigate	A failed valve or mass flow controller Inlet of shop air at higher pressure than regulator is rated to	Pressure Relief valves at the beginning of each inlet line The shop air regulator has a relief valve
ZeoDe -002	3x2	Over Temp of sorbent bed	Mitigate	Failed commanding to the heater	Heater limit controller LabView alarm and shut down response as a result of sorbent bed thermocouple readings
ZeoDe -003	3x2	Over-Temp upstream of the sorbent bed	Mitigate	Failed commanding to the heater	Heater limit controller LabView alarm and shut down response as a result of sorbent bed thermocouple readings
ZeoDe -004	4x4	Electrical Discharge	Mitigate	Loose connections Ungrounded connections	Grounding the DAQChassis Grounding the testbed
ZeoDe -005	2x2	Sharp Edges	Mitigate	Sharp connections between 80/20 pieces	Sharp edges are to be smoothed or have foam attached to them.
ZeoDe -006	4x1	High CO_2	Accepted	High CO_2 can take place as exhaust is venting to the room or given a leak of the compressed gas cylinder, for example, thorough the regulator	Gas analysis: CO_2 levels will not rise to hazardous levels, given the volume of the enclosure
ZeoDe -007	1x5	Gas Tank Release	Mitigate	The compressed gas cylinders fall over, and the caps are broken off	Securing the gas cylinders at two locations each to the center of the building metal struts
ZeoDe -008	2x2	Water leak from Nafion to units	Mitigate	Water leaks from the housing down toward the mass flow controllers	The water housing uses a siphon instead of a drip system, with the opening at the top
ZeoDe -009	1x3	Electric Short	Mitigate	Exposed wires make contact	Using quick-disconnects for wire extensions
ZeoDe -010	1x1	Low O_2	Mitigate	Large quantities of gas released at once	Size of gas cylinders and size of room
ZeoDe -011	1x2	Unsecured part	Mitigate	A bolt becomes loose on the back of the pegboard	The testbed produces minimal vibrations

Table 3.16: Risk chart developed for ZeoDe, showing the risk, its risk level evaluation, and details

The above chart is based on the likelihood vs consequences chart shown in Figure 3.34.

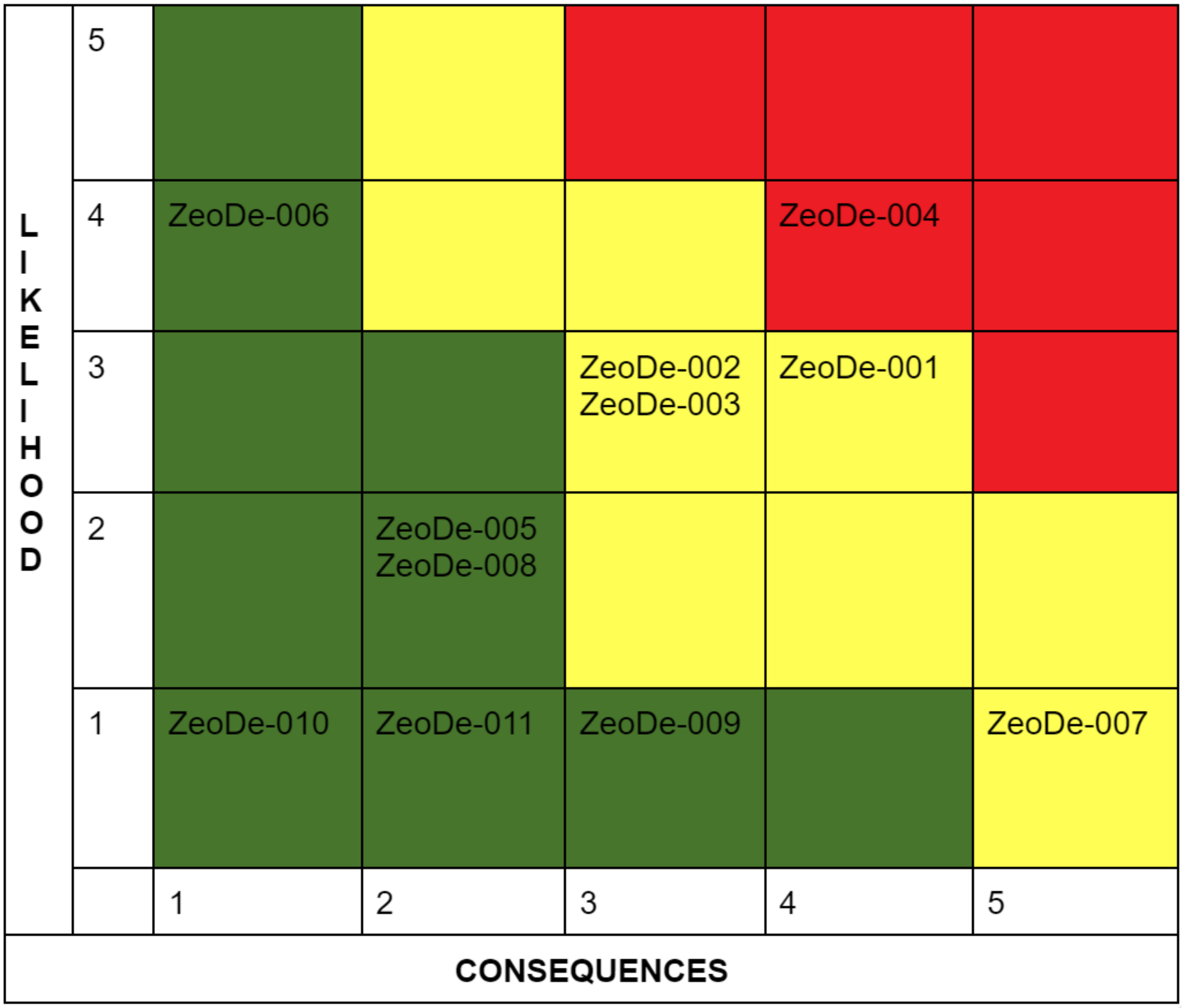


Figure 3.34: Likelihood vs consequences chart developed for ZeoDe, showing the likelihood vs consequences for each identified risk/hazard

Addressing ZeoDe-001: Pressure Relief

Pressure relief valves are designed into the inlet of each line, preset to 140 kPa.

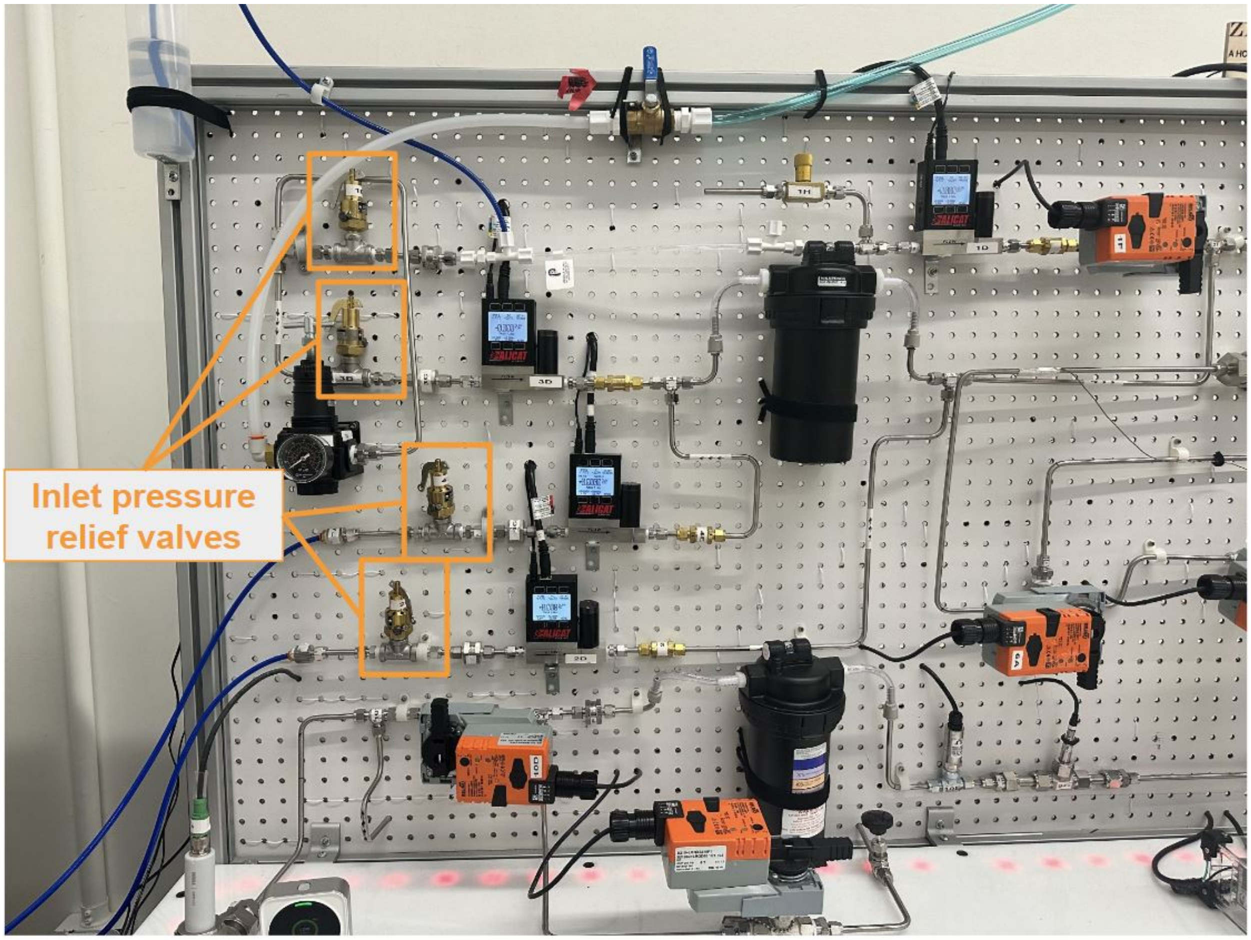


Figure 3.35: Photo of ZeoDe, highlighting the inlet pressure relief valves

Addressing ZeoDe-002: Over temperature Protection

The relay within the DAQ is commanded through LabView and programmed to shut off if the maximum temperature read by any of the thermocouples rises above a user-set threshold. The system is fault tolerant in that a separate relay for each heater has been designed into it, which is connected to its own set of thermocouples and isolated from the DAQ.

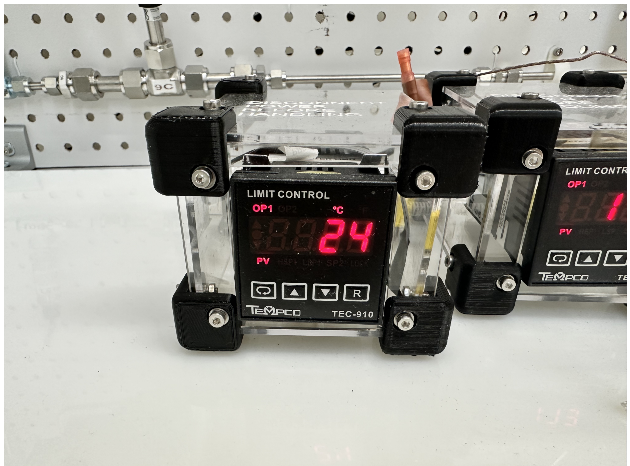


Figure 3.36: Photo of ZeoDe, highlighting the limit controller, which works in isolation from the DAQ

This limit controller itself has terminal blocks on the back end. A housing was designed using acrylic, a laser cutter, and soft-edged plastic to protect it from accidental human contact with the terminal blocks when powered.

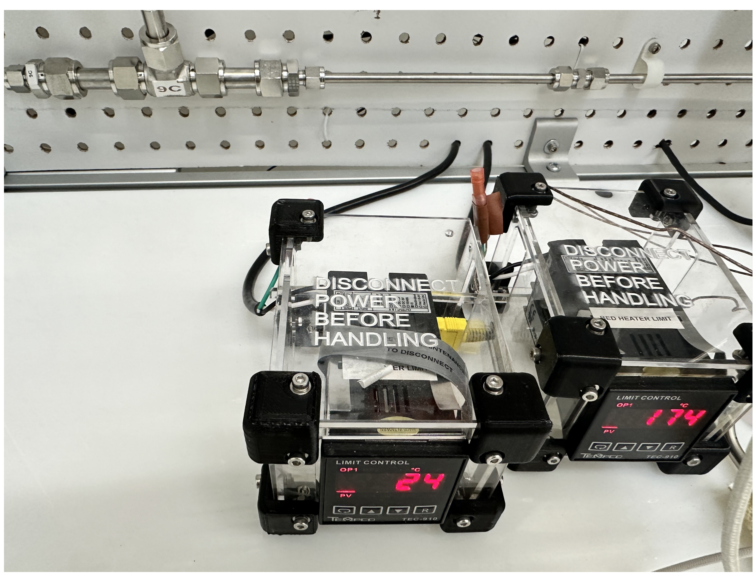


Figure 3.37: Photo of ZeoDe, highlighting the limit controller housing, ensures a touch-free zone for high voltage

The wiring diagram for the secondary heater relays is shown below.

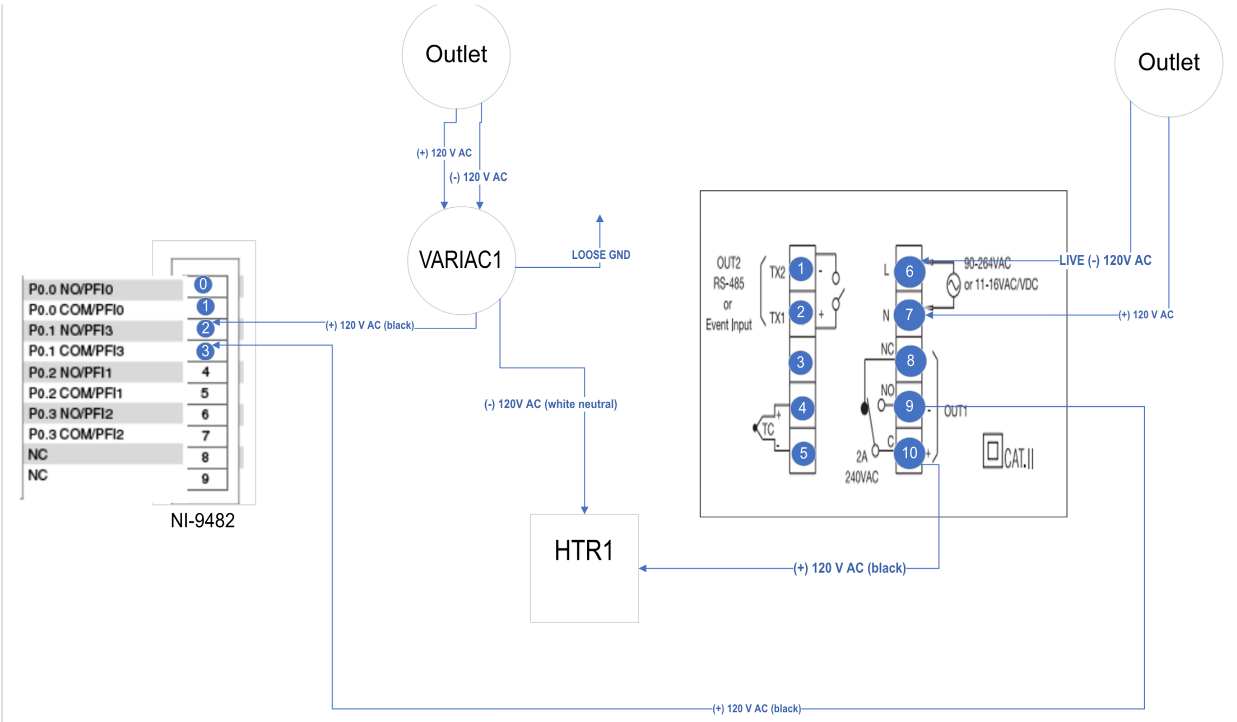


Figure 3.38: Diagram showing the wiring for the heater relay/limit controller depicted in the photos above

Addressing ZeoDe-004: Grounding

Protective grounds were employed, as well as grounding of the DAQ Chassis. Everything is designed onto a common ground to mitigate potential differences. Red electrical tape covers the grounding blocks while powered to mitigate touch hazards.

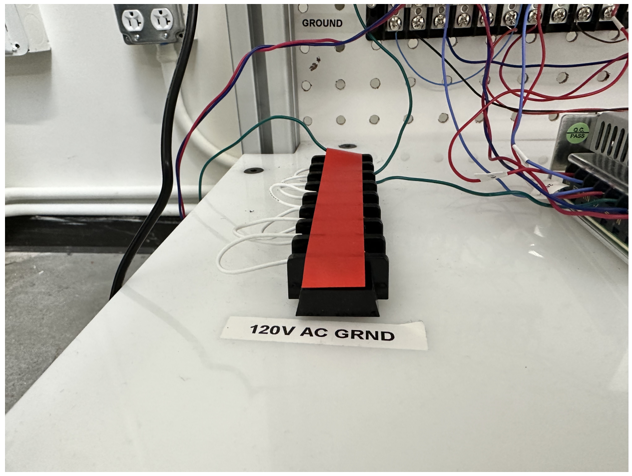


Figure 3.39: Photo of ZeoDe, highlighting the grounding block, which is covered with tape to mitigate touch hazards on high voltage

The DAQ grounding is located on the lower left corner of the DAQ Chassis and is separate from the individual module grounding that is also employed.

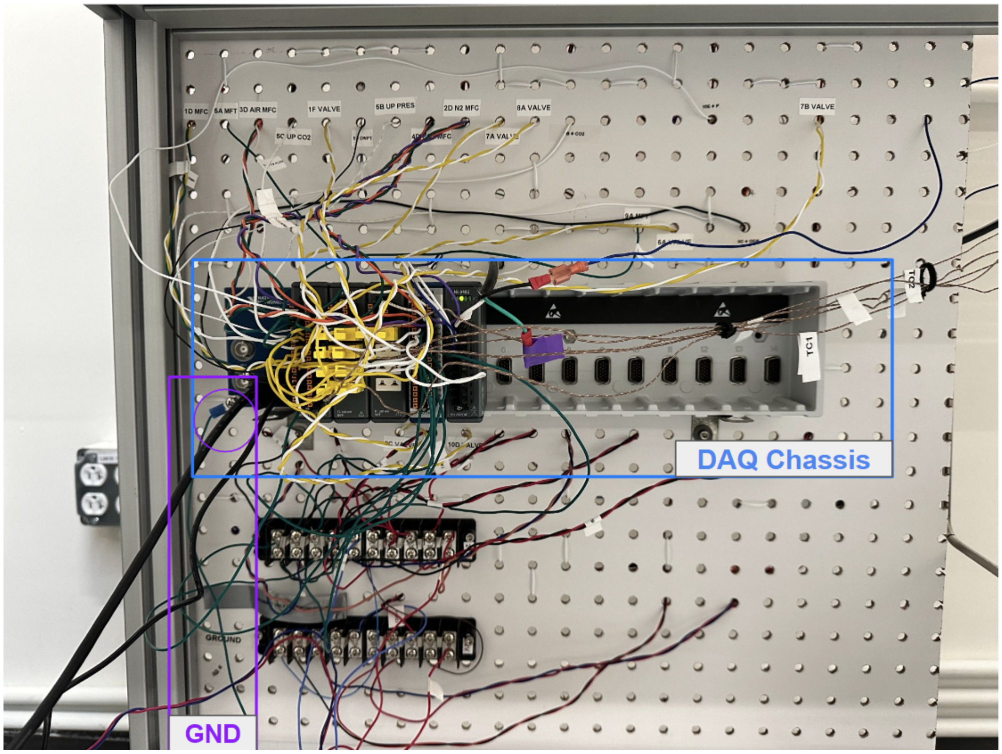


Figure 3.40: Photo of ZeoDe highlighting the DAQ Chassis grounding in the lower left corner of the Chassis, which is connected to the terminal block in Figure 3.39

Addressing ZeoDe-007: Gas Tank Securing

The gas tanks are secured to the wall at two points. The struts within the UC Davis Center for Spaceflight Research walls are made of 1.25” thick metal. To ensure adequate security in the wall, holes were drilled into the wall to ensure all drilled metal screws were inserted at the center of each strut. These metal screws secured two bars to the wall, to which both the Nitrogen and the CO_2 cylinders are chained.

Figure 3.41: Photo of ZeoDe, highlighting the CO_2 and Nitrogen cylinders, and how they are secured to the wall through a two-chain system to a bar that is adhered to the metal struts of the building

Addressing ZeoDe-008: Nafion Water leakage

Initial designs considered included attaching an inverted bottle directly to the inlet of the Nafion tube. When leakage was considered, an integrated design included instead a right-side-up water storage container secured to the structure of the testbed siphoned into the system.

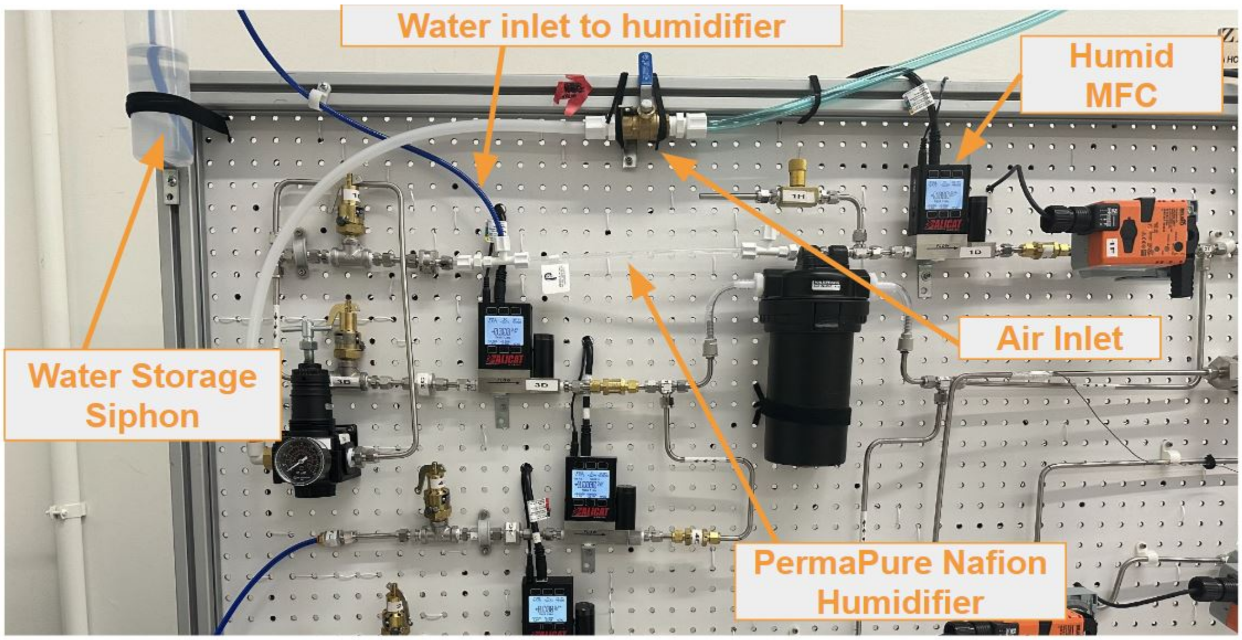


Figure 3.42: Photo of ZeoDe highlighting the leak mitigation implemented via the siphon method, with labels showing the entire humidity introduction system

Addressing ZeoDe-009: Electrical Connectors

Insulated quick disconnects were employed to mitigate electrical discharge, potentially from partially connected wires. Further, all wiring was moved to the back of the testbed, and lines were routed in lanes to avoid contact with each other or disruption.

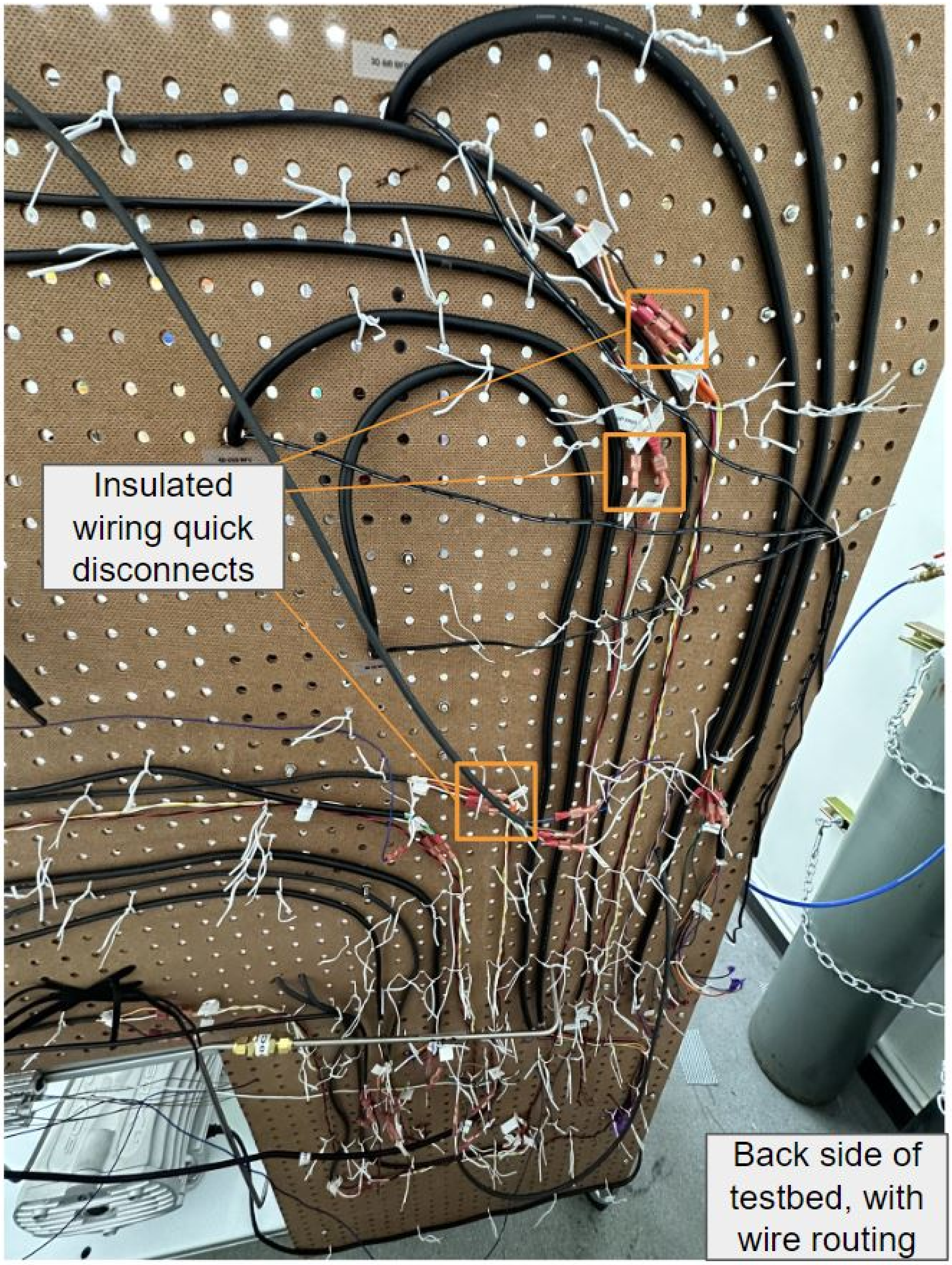


Figure 3.43: Photo of ZeoDe highlighting the wiring on the back side of the testbed, with insulated quick disconnect electrical connectors and twist ties holding routing in place

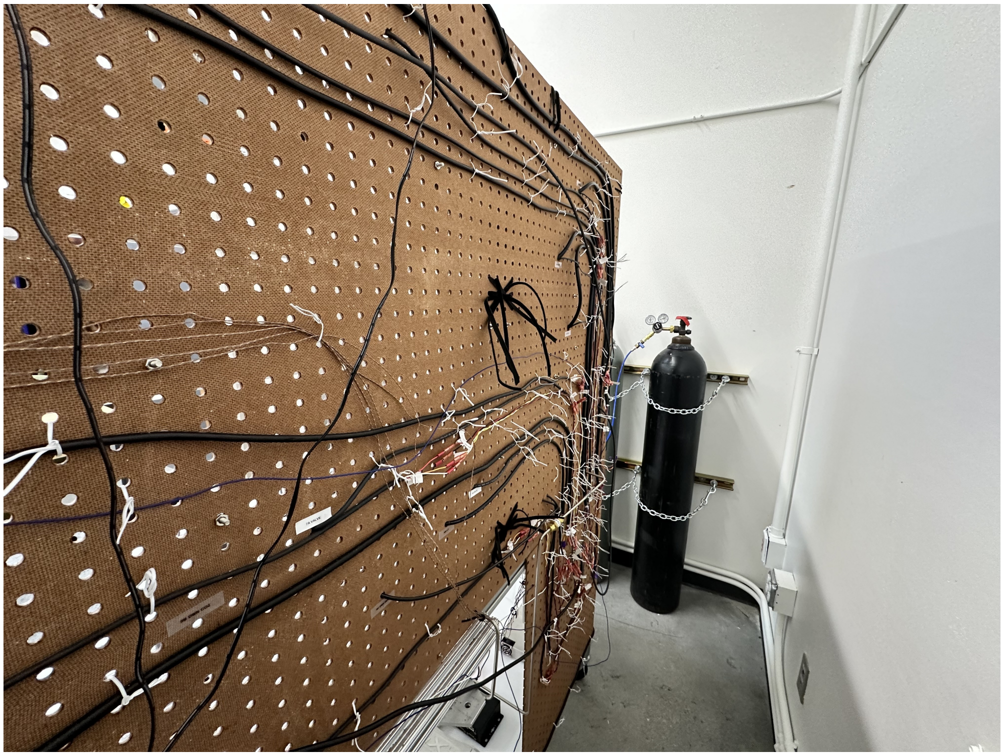


Figure 3.44: Photo of ZeoDe highlighting the wiring on the back side of ZeoDe, with insulated quick disconnect electrical connectors

Addressing ZeoDe-006 and ZeoDe-010: Gas Analysis

If both cylinders were to release all gas simultaneously, this would amount to 228 CU. FT. of Nitrogen, and 432 CU. FT. of Carbon Dioxide at 1-atmosphere room pressure. The smallest dimensions of the Spafford building are 60' x 42' x 13' (L x W x H), granting a total of 32,760 CU—FT of volume. One section of the ceiling extends to 18', so this is a conservative estimate.

- PPM CO_2 limit: 5000 PPM
- Assuming nominal ambient conditions in the room hover at a worst-case scenario of indoor air quality 1,000 PPM CO_2 (0.1%)

Assumption: pressurized to less than 880 PSIG, so in a gaseous state Cylinder Spec: Internal Pressure: 830 PSIG Internal Volume: 2038.2 in^3

$$PV = nRT \tag{3.2}$$

$$(830PSIG)\left(2038.2in^3\right) = n\,(R)\,(20C) \tag{3.3}$$

$$\frac{(5722.65kPa)(33.4L)}{(8.314LkPa/molK)(293.15K)} = n \tag{3.4}$$

Mol CO_2 inside canister: 78.4 mol

At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L. In the room, this would amount to 1462500 mol of air. If there is 0.1% CO_2 in the air, there are 1462.5 mol of CO_2 in the room. Upon release of CO_2 cylinder, this would amount to

$$\frac{(189 + 1462.5)}{(1462500 + 189)} = 0.1129 \tag{3.5}$$

Or 1,129 PPM

How long will this gaseous mixture last?
Conservative estimate: air at 0.03% CO_2, trying to bring it up to 0.3%, so air flowing at 7.784 LPM, CO_2 flowing at 0.216 LPM. Within the cylinder, we have:

$$\frac{78.4mol}{33.4L} = 2.34mol/L \tag{3.6}$$

Regulating to 40 PSIG, equivalent to 275.79 kPa

$$\frac{(275.79kPa)(0.216L/min)}{(8.314LkPa/molK)(293.15K)} = n/min\ = 0.0244mol/min \tag{3.7}$$

$$\frac{78.4mol}{(0.0244mol/min)} = 3,213.1minutes\ = 53.5hours \tag{3.8}$$

CO_2 is added for about $\frac{1}{2}$ of one complete adsorption/desorption cycle, so approximately 107.1 experiment hours, or a 4.46-day experiment

Assumption: pressurized to greater than 880 PSIG, so in a liquid state

$$1101kg/m^3 \quad [1m^3[=]1000L] \tag{3.9}$$

$$(1.101\,kg/L\,)\,(33.4L) = 36.7734\,kg \tag{3.10}$$

$$44.009g/mol \rightarrow 0.044009\,kg/mol \tag{3.11}$$

$$(36.7734\,kg)/(0.044009\,kg/mol) = 835.7\,mol \tag{3.12}$$

At STP, one mol of gas occupies a volume of 22.4 L. The room is equal to 32760000 L. In the room, this would amount to 1462500 mol of air. If there is 0.1% CO_2 in the air, there are 1462.5 mol of CO_2 in the room. Upon release of CO_2 cylinder, this would amount to

$$\frac{835.7 + 1462.5}{1462500 + 835.7} = 0.1571\% \, CO_2 \tag{3.13}$$

Or 1,571 PPM.

How long will this liquid CO_2 cylinder last?
Conservative estimate: air at 0.03% CO_2, trying to bring it up to 0.3%, so air flowing at 7.784 LPM, CO_2 flowing at 0.216 LPM
Within the cylinder, we have

$$\frac{835.7 \, mol}{33.4 \, L} = 25.02 \, mol/L \tag{3.14}$$

Regulating to 40 PSIG, equivalent to 275.79 kPa

$$\frac{(275.79kPa)(0.216L/min)}{(8.314LkPa/molK)(293.15K)} = \; n/min \; = 0.0244 \, mol/min \tag{3.15}$$

$$\frac{835.7 \, mol}{0.0244 \, mol/min} = 34,250 \, minutes \tag{3.16}$$

$$= 570.8 \, hours \tag{3.17}$$

CO_2 is added for about $\frac{1}{2}$ of one full adsorption/desorption cycle, so approximately 1,142 experiment hours, or a 45.6 day experiment

Lack of Oxygen Asphyxia limit: 19.5%

At 21% oxygen, this would be 6879.6 CU. FT. occupied by oxygen

Adding the entirety of both cylinders would amount to the equivalent of 33420 CU. FT. of gas in the room, with a resulting oxygen percentage of 20.6%
Carbon Dioxide:
Assumption: pressurized to greater than 880 PSIG, so in a liquid state

$$\left(1101 \frac{kg}{m^3}\right) \left[1m^3 \, [=] \, 1000L\right] \tag{3.18}$$

$$\left(1.101 \frac{kg}{L}\right) (33.4 \, L) = 36.7734 \, kg \tag{3.19}$$

$$44.009\frac{g}{mol} \to 0.044009\frac{kg}{mol} \tag{3.20}$$

$$\frac{36.7734kg}{0.044009\frac{kg}{mol}} = 835.7\,mol \tag{3.21}$$

Nitrogen:
Assumption: pressurized to greater than $\approx 725\,PSIG$, so in liquid state

$$0.807\frac{g}{mL}\left[1\frac{g}{mL}\,[=]\,1\frac{kg}{L}\right] \tag{3.22}$$

$$0.807\frac{kg}{L}\,(33.4L) = 26.95\,kg \tag{3.23}$$

$$28\frac{g}{mol} \to 0.028\frac{kg}{mol} \tag{3.24}$$

$$\frac{26.95kg}{0.028\frac{kg}{mol}} = 962.5\,mol \tag{3.25}$$

At STP, one mol of gas occupies a volume of 22.4 L. The room is equal to 32,760,000 L. In the room, this would amount to 1,462,500 mol of air. Assume there is 0.1% CO_2 in the air, 78% Nitrogen in the air, and 21% Oxygen in the air. There are then 6,879,600 L of Oxygen in the air.

Non-Conformances

Non-conformances were defined as off-nominal conditions that could not be easily fixed within 24 hours or that posed a safety risk. They were logged and addressed until signed off. Eight non-conformances are summarized. They are appended in full within the appendix of this thesis. The format used was designed for the critical design review and approved during the safety readiness review.

#	Title	Brief Summary	Closure
NC-001	ZeoDe Electrical Discharge	04/26/23: While testing a circuit (disconnected from the main system), a 120 V electric discharge occurred on a cable meant to be connected to the heater interrupt.	Increased labeling of electronics, additional warning labels, and new grounding standards.
NC-002	Grounding Issue	8/1/23: Valves were not operating as expected. They were all reacting in a way that showed there was residual voltage building up in the system, where they would progressively not close wholly when commanded closed and not open completely when commanded open.	Cabling was redone, grounding blocks were separated and re-labeled, and wiring diagrams were updated
NC-003	Desiccant Leak	8/11/23: While testing the airflow through the system, a leak was discovered at both ends of the 2F desiccant. Upon removal of the NPT fittings that were the source of the leak, it was found that the internal threading was irreparably damaged. The root cause was a mislabeled spec sheet stating stainless steel threading rather than aluminum threading.	New desiccant beds were received, and plastic fittings were attached instead of stainless steel. The system was run, and no leaks were detected at the desiccant beds.
NC-004	CO_2 sensor issues	9/14/23: A full-scale test was attempted. The heater powered slightly (to 45 C), heating the stream downstream of the packed bed (see NC-005). CO2 levels began reading 256%.	This NC was combined with NC-007
NC-005	Temperature increase at the bed	9/14/23: A full-scale test was attempted. Though not commanded on, the heater increased in temperature to 45 C and leveled off. It was found to be the same faulty thermocouple that later failed in NC-006.	New thermocouples were installed.
NC-006	Limit controller error reading SbnE	9/25/23: An error light flashed on one of our temperature limit controllers. The manual for TEC-910 was consulted, but this error message was not found. After consulting the manufacturer it was confirmed that the error message was due to a faulty sensor.	New thermocouples were installed

Table 3.17: Table showing a summary of the ZeoDe non-conformances, which are detailed in full within the appendix

#	Title	Brief Summary	Closure
NC-007	CO_2 Sensor issue	9/26/23: When running sensor checks on the system, it was found that the CO_2 probes were not reading correctly despite having been thought to be previously calibrated. The sensors did not respond to stimuli (0-100% CO_2 flow). Voltage checks were done to determine if the root cause was related to MICAS-X or the sensor itself. Conclusion: the sensor was stuck in an error mode.	Characterization of the sensor error modes was performed. The downstream sensor was exchanged for one with a greater range, and error modes were modified in the source programming.
NC-008	Humidity Sensor issue	9/27/23: When running the humidity sensor calibration, two problems arose. The first is that the downstream sensor did not produce readings or deflections with changes in humidity. This was hypothesized as a sensor or connectivity problem. The second issue that arose is that the Nafion manual is not a source of truth for known dew point readings, resulting in difficulty in calibrating the sensor. This could be a housing size problem (which is also currently being investigated for CO_2 sensor problems), a problem with the sensor itself, or a problem with our known dew points (indicating we need another source of truth for calibration).	The error modes for the sensor were reprogrammed, and a minimum flow rate for accurate sensor readings was established.

Table 3.18: Table showing a summary of the ZeoDe non-conformances, which are detailed in full within the appendix

3.6 RobInZeN: Robotically Interactive ZeoDe twiN

This section goes into an effort parallel to the design, build, and test of ZeoDe, which is a robotically manipulable mock-version of ZeoDe used as a testbed for exploring robotic manipulation of space systems and what might be done on both the robotics side and the ECLSS side to make robotic manipulability more feasible.

While ZeoDe was in the design phase, a second UC Davis testbed was conceptualized in collaboration with the HOME Robotics team and human-machine interface team, notably Tammer Barkouki from UC Davis and Ulubilge Ulusoy from USC. I contributed from the ECLSS design side. Ulubilge was instrumental in the system's design and construction, and Tammer Barkouki, who specializes in XAI and robotics, was also instrumental in designing and constructing the mockup and programming the robotic system.

- *Background*: Maintenance is a high priority and core concept for ZeoDe. However, it is not yet feasible to demonstrate repair/maintenance capabilities on data-generator (functional) testbeds with robotic agents and/or humans. There is a high likelihood of damaging the functionality of the testbed.

- *Definition*: Non-functional ECLSS testbed for physical manipulation of its components for task execution. It will be built using non-functional COTS and 3D-printed components. The base design will be the same as that of ZeoDe, with certain adjustments based on robot-friendly interface requirements. Additional complexity (layers - e.g., panel covers) will be added to achieve higher fidelity.

- *Purpose*: Will be utilized during the task execution of capstone demonstrations to NASA by both robotic agents and humans ("Joint execution of existing procedures for human/robot teams," also individual project experiment(s).

The results of these efforts are shown in Figure 3.45, the mockup built into a physical system at the UC Davis Center for Spaceflight Research at UC Davis.

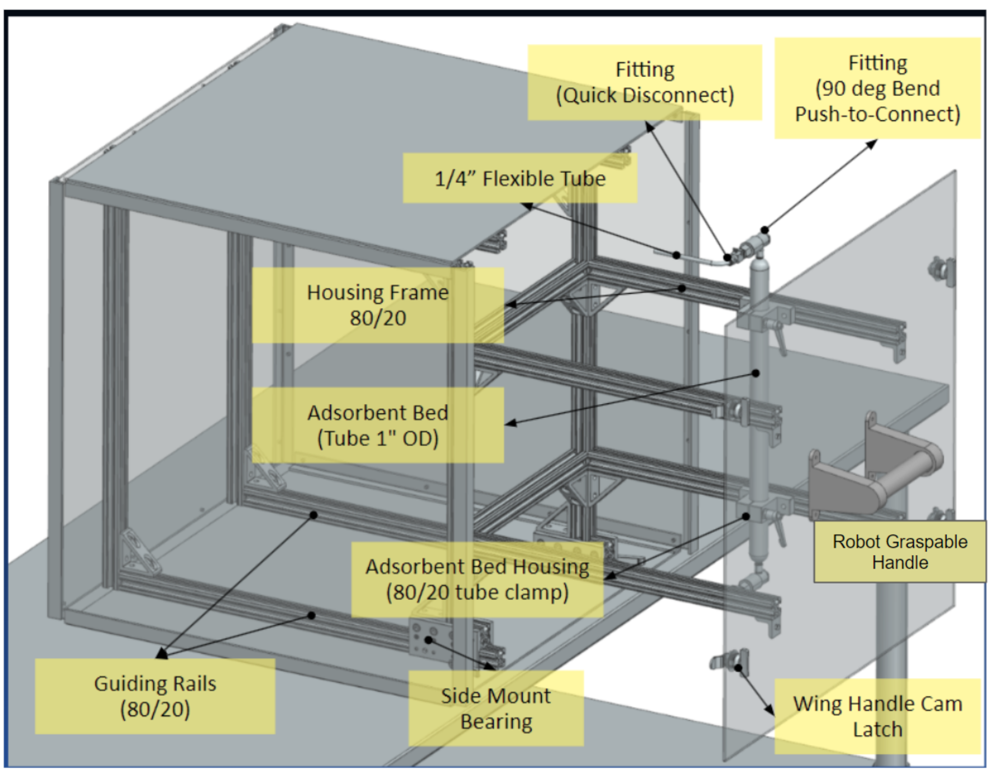


Figure 3.45: Diagram of the robotically Interactive ZeoDe Twin, produced by Ulubilge Ulusoy at USC

3.7 Preliminary Design Review Overview

A Preliminary Design Review serves as a formal review of the system and subsystem levels before the start of subsystem detail design to assure that the proposed design and associated implementation approach will satisfy the system and subsystem functional requirements. This section gives a top-level overview of how our PDR was designed

The preliminary design review was held in three locations: first, a trip to CU Boulder, where a similar testbed is located; second, a trip to Marshall Space Flight Center, where the 4BCO2 system and the CDRA teams are based; and third, a debrief of those two trips at UC Davis.

CU Boulder

Performing part of the preliminary design review at CU Boulder gave the advantage of viewing a similar testbed in an academic research setting and presenting the ZeoDe plan to researchers who were knowledgeable about a similar testbed. Over two days, the following was accomplished:

- Detailed walk-through of the STEVE testbed (similar to the ZeoDe testbed design)
- Understanding of intent behind design decisions in STEVE
- Discussion of top-level requirements for ZeoDe, broken down into specific design
- Discussions of PNIDs for different sequences for ZeoDe
- Safety features included relief valves, checklists for procedures, leak checks
- Walkthrough of the MICAS-X program within the LabView environment, which would be copied over to the ZeoDe system from STEVE
- Considerations for running cyclic testing

Marshall Space Flight Center

Performing part of the preliminary design review at Marshall Space Flight Center gave me the advantage of viewing the ground system on which ZeoDe was based. It also allowed the design of ZeoDe to be reviewed by the SMEs on the CO_2 removal systems onboard the ISS. Throughout a one-day review, the following was accomplished:

- Detailed walk-through of LINUS, the 4BCO2 ground testbed
- Broad walk-through of the MSFC ECLSS High-Bay, seeing the physical setups of a variety of ECLSS testbeds

- Viewing of ECLSS testbeds that seemed optimized for maintainability
- Viewing of ECLSS testbeds that were optimized for simulation correlation, including centerline measurements
- Presentation of the ZeoDe design to the NASA SMEs for CDRA and 4BCO2
- Feedback on a variety of sensors and actuators proposed in the ZeoDe design with which NASA has had success or issues

UC Davis

By the end of the Preliminary Design Review, the following rough design had been fine-tuned:

- General size, geometry, and parts layout
- General operating conditions, including Bakeout, Adsorption parameters, Desorption parameters, and humidity levels
- Sensors and actuators that were approved for the design and those that were rejected with suggestions on determining better options. Entirely replaced actuators due to the PDR include the 2-way and 3-way valve selection, differential pressure transducer type, pressure relief valves, and the power box.

Action items that came from the preliminary design review included

- To work further on finalizing the bill of materials
- To replace the rejected parts with new parts and perform the required analysis on these parts
- To align the bill of materials and design with that of a modular testbed encountered at MSFC with the help of MSFC engineers
- To refine the rationale behind chosen humidity levels
- To refine the rationale behind desorption pressure

Below is a visual used during the lead-up to the PDR and CDR. As units were decided or changed, their size was taken, and they were organized onto a backboard that fit the requirements of the structural system. This was handed out to each build team member, printed on large paper, and posted on the wall of the build area for orientation.

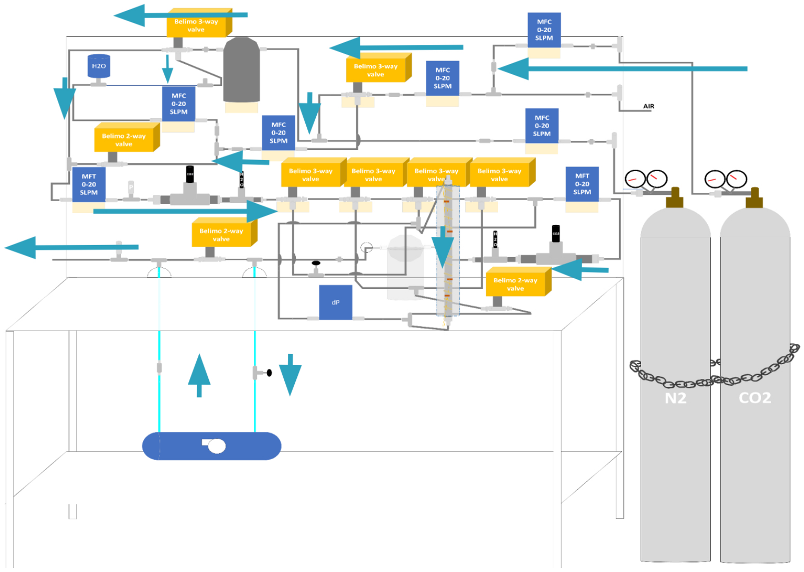


Figure 3.46: Preliminary diagram of ZeoDe, used to check volumes of units as vendors or parts were changed

3.8 Critical Design Review Overview

The CDR ensures that all design requirements have been met and that all engineering analyses have been completed. The results of engineering model tests or analyses demonstrate that the hardware and software can be built to perform as planned.

The critical design review was held in person and virtual at UC Davis. The review board consisted of the following members:

- Dr. Jim Knox, NASA MSFC Senior Principal Engineer - 4BCO2 & CDRA for Life Support Systems Branch at NASA Marshall Space Flight Center
- Diego Rojas, Advanced Farm Software Engineer and HOME robotics researcher
- Monica Torralba, Collins Aerospace PLSS life support systems engineer
- Dr. Justin Werfel, Harvard University lead for Designing Emergence Laboratory
- Jeff Sweterlitsch, NASA JSC AES/EC Life Support Systems Oxygen Generation and Recovery Element Lead [could not attend in real-time, but provided feedback on packages ahead of time]

The package has been made available online at the link below to see a representative CDR package for this type of system.

https://docs.google.com/presentation/d/1r1nskrL1A0wcqnL8XXsGFLyZ920n4XqY/edit?usp=sharing&ouid=100013162978456958863&rtpof=true&sd=true

The following was reviewed:

- Detailed walk-through of each element of the testbed and where it would fit in 3D space
- Description and rationale of all part modifications made since PDR with their rationale
- Reiew of test procedures
- Hazards and safety review
- Assembly and build plan
- Software and DAQ setup plan

Discussion included questions regarding ZeoDe that were addressed offline in a question response form, which was then sent back to reviewers for final approval. The question response form can be found in the appendix under CDR Reviewer Feedback.

3.9 Build

Volumetrically, the bulk of the testbed's construction took place during a 10-day allotted time for "build week." During build week, HOME researchers came from USC and CU Boulder and called in remotely from Georgia Tech and Huntsville, AL, to support.

Leading up to build week, preparation consisted of communicating with vendors on estimated ship and arrival dates and performing kitting as parts came in. The kitting consisted of grouping parts in build order and providing a label for each part within the BOM corresponding to a bin and plastic bag within the ZeoDe project cabinets.

All units were sized and arranged virtually before the arrival of parts onto the backboard, referred to here as the board. This helped to organize where parts would go, estimate the amount of tubing used, and how much bending would be required, which would feed into pressure drop calculations. Below is a sample of a virtual organization of parts before build week.

Task	List of Tasks	Prereqs	Min people needed
1	Wrap NPT fittings in teflon tape		1
2	Compile parts	1	1
3	Attach NPT fittings to parts	2	2
4	Attach compression fittings to parts	2	2
5	Layout parts with fittings on board based on drawing	1-4	2
6	Draw out tubing on backboard based on drawing	1-5	2
7	Measure pipe draw-outs for cuts and bends	1-6	2
8	Cut and bend tubing in order of kitting on drawings	1-7,9	3
9	After each cut, lay out tubing on board to check measurements	1-8	3
10	Lay out all parts with tubing on board	1-9	3
11	Tighten compression fittings	1-10	3
12	Secure parts to board	1-11	2
13	Attach supports under heavy parts	1-12	2
14	Vertical board test	1-13	4
15	Put scafffold of test bed together		4
16	Attach board to test bed scaffold	14,15	5

Table 3.19: Table showing a sample of the build tasks that would be updated and posted daily during build week

Pre-assembly kitting was performed by the team and organized by fellow graduate student Shannon Lackey to organize parts into logical build subsections. She organized all parts into these subsections, labeling them and sectioning them into bags and then boxes, which contained all information on the corresponding diagrams for each set of parts. Below is a sample PNID that was labeled with kitted parts. This was handed out to each build team member, printed on large paper, and posted onto the wall of the build area for orientation; below is a small snapshot of the BOM where kitted parts were labeled.

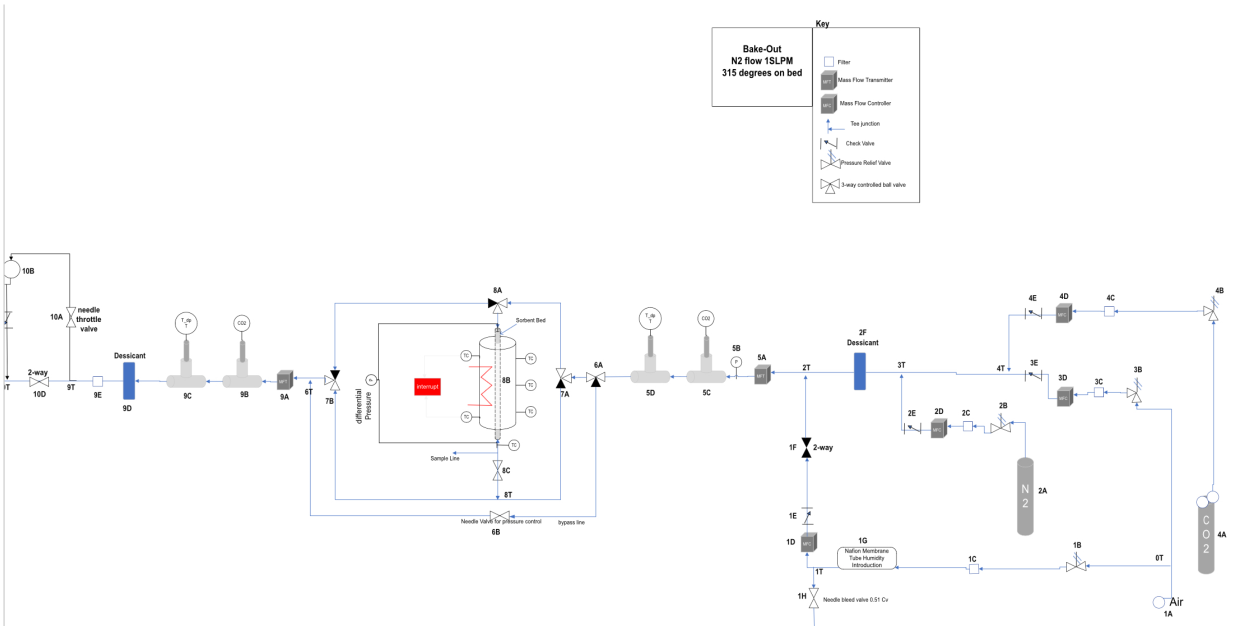


Figure 3.47: Old ZeoDe PNID with kitting designators used for build week

1	Category	KITTED	Part Confirmed in CDR	# units	vendor	part #
63	Sensors	5A	Mass Flow Transmitter	1	Omega	FMA-160 -V2
66	Sensors	5B	General Purpose, Stainless Steel Pressure Transducers 0 to 30 psi, Gauge, 0-5V mA, Cable	1	Omega	PX309-03 G5V
69	Sensors	5C	CO2 sensor	1	Vaisala	GMP252
70	Lines		Smooth-Bore Seamless 316 Stainless Steel Tubing 1" OD, 0.035" Wall Thickness 3ft	1	McMaster	89785K8
74	Lines	5D	Humidity sensor	1	Vaisala	HMP060
78	Valves	6A	B310+LRQX24-MFT 3-way valve	1	Belimo	B310+LR 24-MFT
81	Valves	6B	Stainless Steel Integral Bonnet Needle Valve, 0.37 Cv, 1/4 in. Swagelok Tube Fitting, Regulating Stem, PEEK Packing	1	Swagelok	SS-1RS4-

Figure 3.48: Small excerpt from the BOM to show kitting of the parts

The fully-assembled ZeoDe is shown below in Figure 3.49

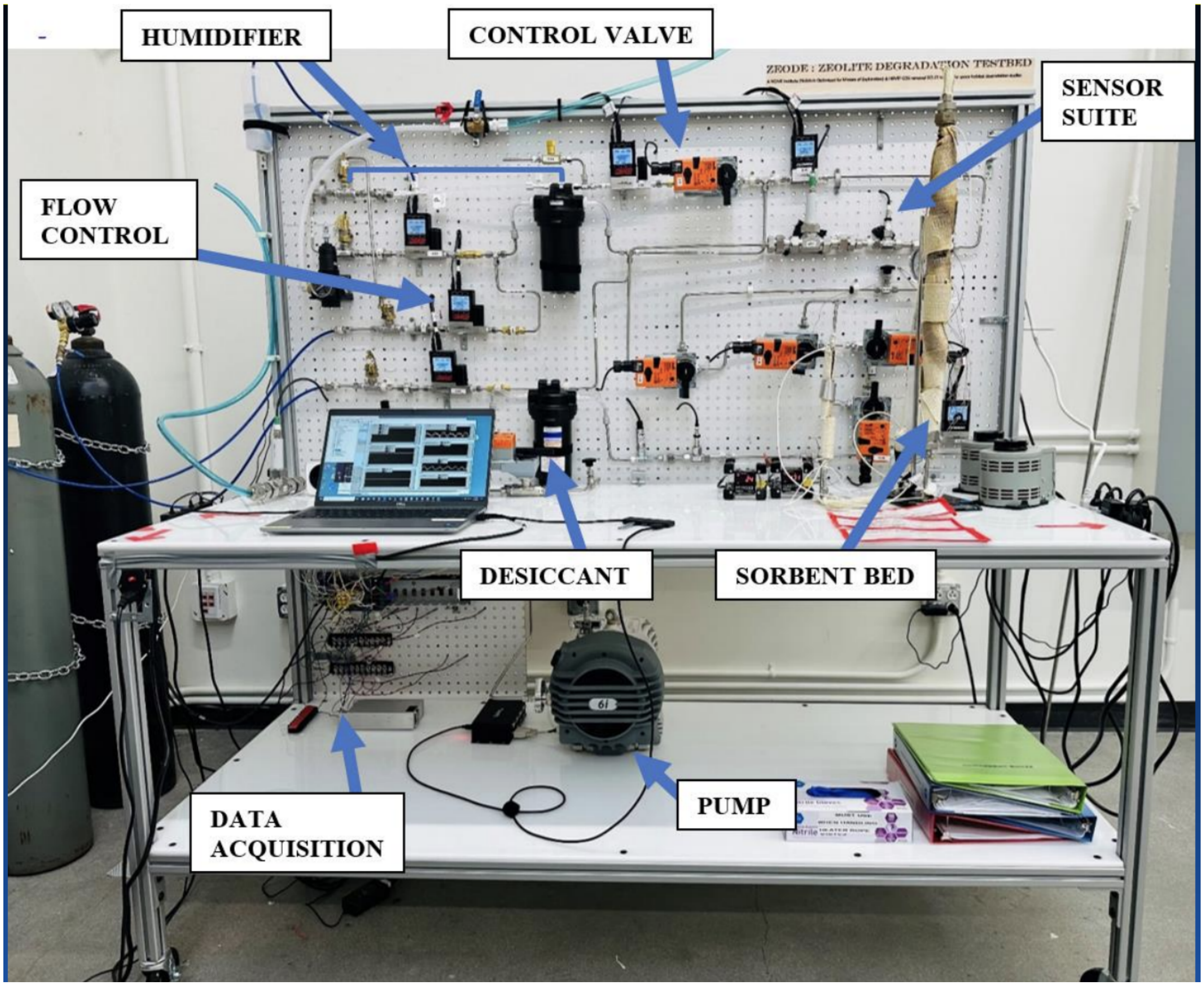


Figure 3.49: Photo of the ZeoDe testbed from February 2024, with some components referenced with arrows.

3.10 Test Readiness Review

Before the first startup, hazards, as well as specific hazard documents that would be on-site, were reviewed in detail. Particular attention was paid to the first startup checklist, included in the appendix within the operational procedure CSFR-ECLSS-003, the ZeoDe Startup Procedure.

The test plans were also reviewed, as shown in the top-level table below, which shows the types of experiments to be performed.

Task	Description	Scope of Task	Duration Estimate
Bake out	Bake-out happens prior to each test to ensure a dry bed. A 1 SLPM stream of nitrogen is passed through the bed, while the temperature is elevated to 300°C or higher.	This is expected to take at least 12 hours, so will be started the day before each test, and will run through the night.	12+ hours
Dry Breakthrough Testing Baseline	Breakthrough testing consists of running air with 0.3% CO_2 until CO_2 exits the bed (indicating that the bed is saturated)	1 breakthrough test 3 replicates of each test Total: 3 breakthrough tests *Potential to add on similar testing at 0.4% and 0.2% CO_2 for bounding purposes*	1+ weeks
Dry Cyclic Testing Baseline	Cyclic testing uses defined cycle times (adsorption & desorption) multiple cycles will make up one test	2 cyclic tests (with multiple cycles) 3 replicates of each test Total: 6 cyclic tests	1+ weeks
Humid Cyclic Testing (Degradation Testing)	Humidity is injected into the system during the adsorption portions of cyclic operations. The rate of water accumulation in the bed is determined by machine learning based on sensor data.	3 humidity levels: -30°C, -20°C, -10°C 1 cyclic test (with multiple cycles) at each humidity level 3 replicates of each test *Additional tests are expected once the first batch of test results is delivered to the HOME prognostics team. Data requirements may change accordingly.*	ongoing

Table 3.20: Description of the types of experiments developed for ZeoDe, which all use a sorbent bed 1” in diameter and 20” in length.

3.11 Operations

The following procedures were developed for the operation of the ZeoDe testbed and include a procedure for testing, a procedure that lays out the gas hazards present when using or storing the testbed, the startup procedure used for the very first start-up, a maintenance procedure outlining steps to take when performing any maintenance, hazards, and risks, an electrical document linking to electrical diagrams, a weighing procedure, and a procedure that includes steps for calibration and a record of all calibrations performed.

Document	Title	Purpose
CSFR-ECLSS-001	ZeoDe Experiment Test Plan	Lay out testing procedures and data sheets
CSFR-ECLSS-002	ZeoDe Experiment Gas Hazards Document	Analysis on gas hazards present during experiments
CSFR-ECLSS-003	ZeoDe Startup Procedure	First startup checklist with rationale
CSFR-ECLSS-004	ZeoDe Maintenance Procedure	Checklist for any maintenance performed on testbed
CSFR-ECLSS-005	Hazards and Risks Document	List and rating of all hazards and risks associated with the testbed
CSFR-ECLSS-006	ZeoDe Electrical Document	Links to all wiring diagrams *not appended*
CSFR-ECLSS-007	Zeolite Weighing	Procedure and notes for weighing out zeolite
CSFR-ECLSS-008	Sensor Calibrations	Repository of notes for any sensor calibrations

Table 3.21: Table of operations documents, which are included in the appendix with the exception of ECLSS-006, which is made up solely of links to figures that are already included in this thesis

Chapter 4

Results and Conclusions of Experimental Data

4.1 Summary of Results

The following chapter lays out experimental data collected for ZeoDe, both for characterization of the system, and for validation of initial requirements.

This chapter covers the following data:

- Nominal cyclic open loop tests [Figure 4.10]
- Nominal breakthrough tests [Figure 4.16]
- Cyclic open loop tests with induced degradation [Figure 4.5]
- Cyclic closed-loop tests with induced degradation [Figure 4.7]
- Breakthrough tests with induced degradation [Figure 4.18]
- Additional characterization testing [Section 4.4]

Novel degradation research provided by this thesis, validated by the plots in the following section, includes:

- A testbed and design of experiments that accurately demonstrates performance degradation of a CO_2 removal ECLSS system in a system representative of a CDRA or 4BCO2-like ECLSS. [Figure 4.5]
- Humidity introduction into a zeolite packed bed for CO_2 removal will result in measurable performance degradation of the packed bed [Figure 4.6, Figure 4.9]

- A nafion membrane paired with a corresponding mass flow controller can be used in a CO_2 removal ground testbed to introduce specific performance degradation via humidity introduction [Figure 4.18, Figure 4.17]
- Humidity introduction of -10 degrees Celsius into a sorbent bed will cause performance degradation due to the build-up of humidity over time, where H_2O occupies sites on the sorbent that would have otherwise been occupied by carbon dioxide [Figure 4.6]

Note that plots 4.5 through 4.15, and all subsequent plots in their likeness were graciously generated by Heraldo Rozas, a HOME colleague who is part of the Georgia Tech Prognostics team[35].

4.2 Design of Experiments and Iterative Approach

The HOME Institute offers a uniquely collaborative environment where the team at Georgia Tech working on machine learning algorithms, the receiving end of the data, is intimately involved in the design and iterative review of the experimental setup. As such, the following is one example, and specifically the most impactful, of how the design of experiments was modified after the first long-duration test data was produced.

Open Loop Testing

The experiments were initially designed to be open-loop, using the logic below. This air calculation loop determines the sorbent bed's inlet conditions set by the MFCs. The user can choose inlets of N_2 for sensor testing or air for experiments. The user also has an initial setpoint for the percentage of CO_2 desired in the inlet. Nominally, the design of experiments was meant to replicate elevated but within operational levels on the ISS of 0.4% CO_2, or 4,000 PPM. That level is maintained during the inlet during adsorption when air is selected for the experiment.

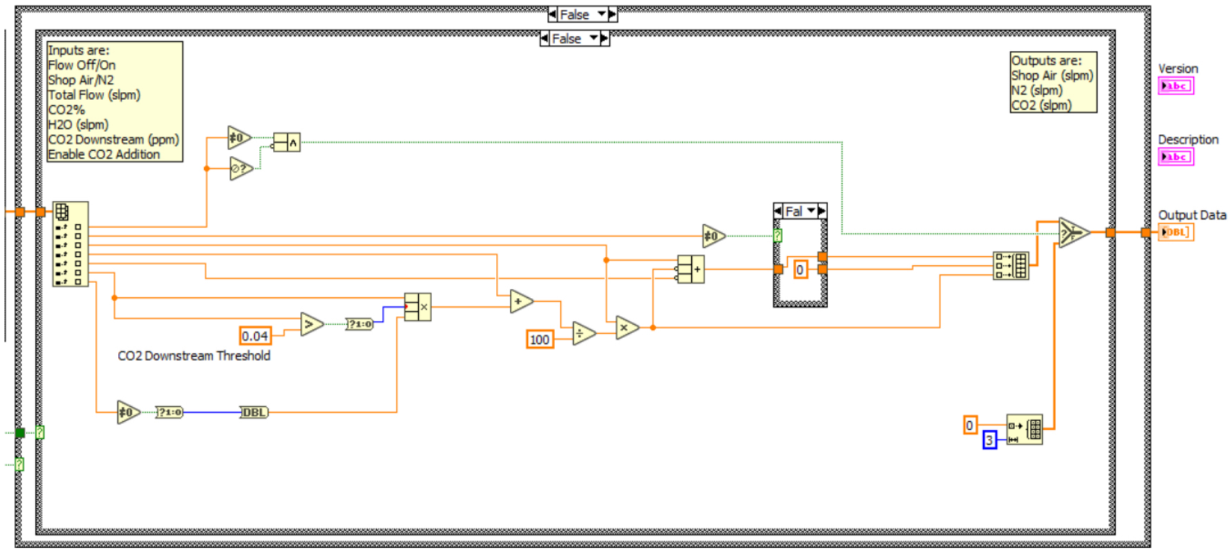


Figure 4.1: Screen-grab of the open loop Controls in the ZeoDe LabView

The data corresponding to these controls does show humidity-induced performance degradation, as seen in the following chapter. However, once this data was reviewed with Georgia Tech, it was decided collaboratively that the closed habitat system should be replicated in the experimental setup as we look at degradation in a closed habitat system. This presented a challenge illustrated in Figure 4.2 where in space, the system has two outlets - one to space (or a downstream processing unit) and one back to the habitat. At UC Davis, only one outlet was designed since a closed habitat system was not part of our top-level requirements. However, our sensors and control logic were set up to meet the top-level requirement of catering to the prognostics algorithms' needs. We knew and expected that once the first experiments were reviewed, there would need refinement and possibly changes to the experimental design. For that reason, our system was designed to be easily manipulable software-wise in the control logic and hardware-wise in the modifiability of lines with compression fittings. It was decided to attempt to make the system more closed-loop by using software controls.

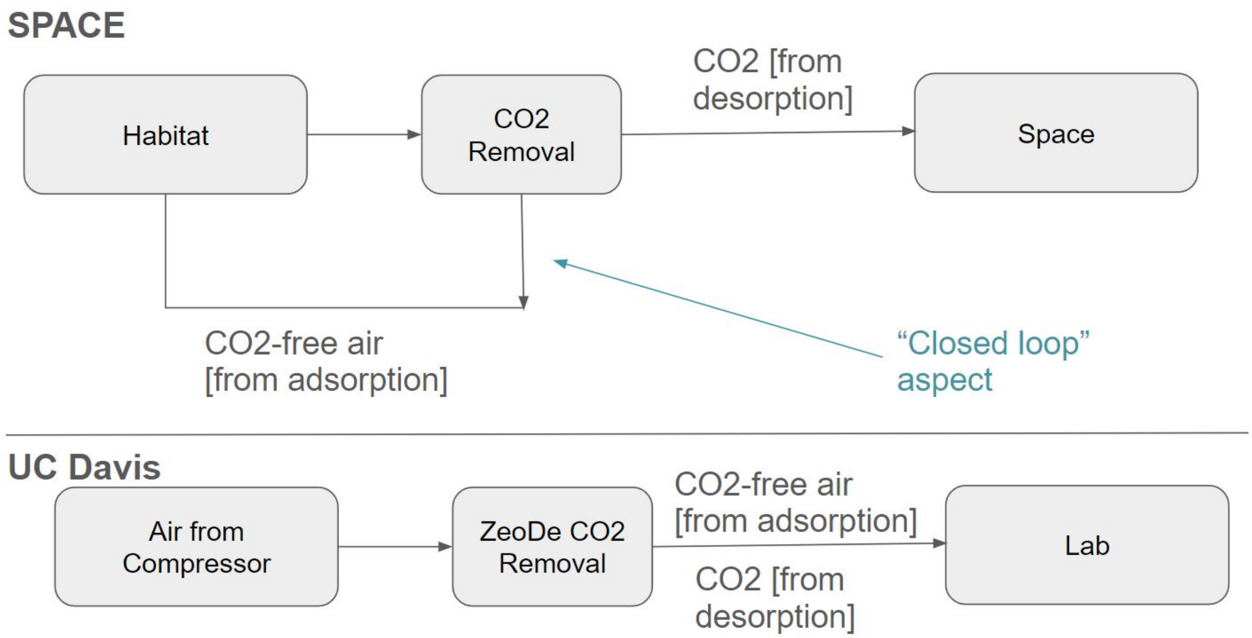


Figure 4.2: Diagram of the original open-loop experimental setup in space vs. at UC Davis

The way the non-closed-loop version manifests itself in a non-cyclic test is seen in Figure 4.3, where the maximum input CO2 will be 0.4%. So, the maximum outlet CO2 during adsorption will also be 0.4%. However, if we close the loop with PID control feeding outlet CO_2 data during adsorption back into the inlet conditions, our CO_2 can increase just as it would in a closed habitat system in space.

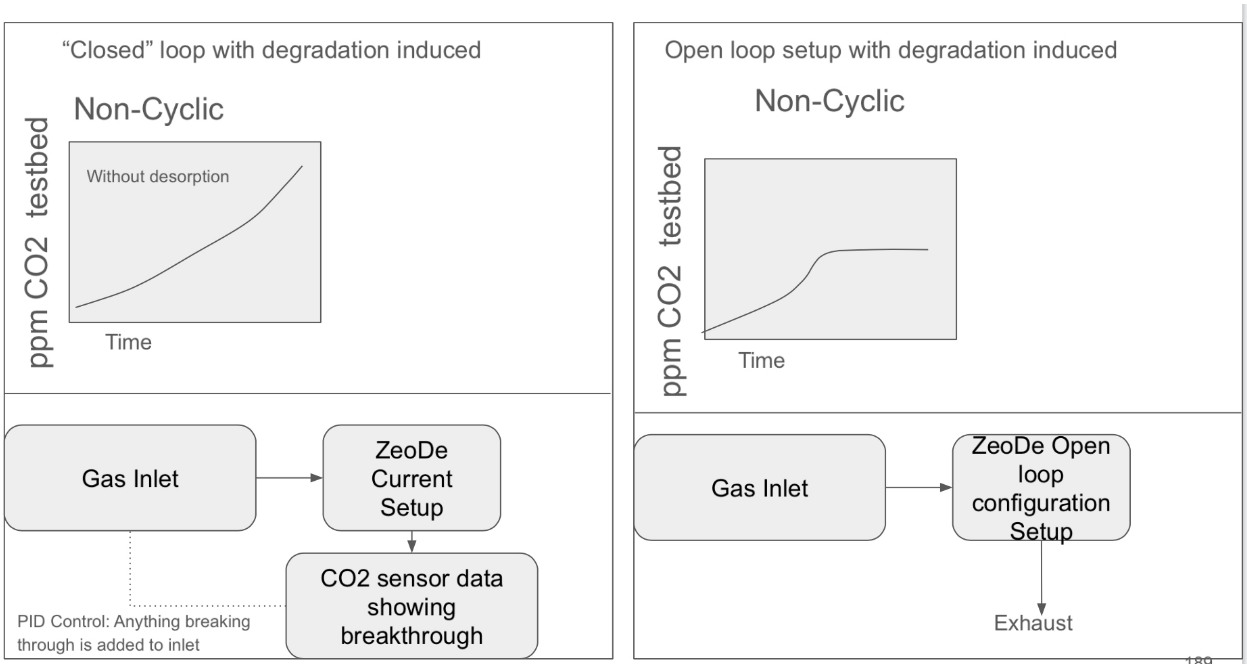


Figure 4.3: Diagram of thew closed loop vs open loop concept

Based on this logic, the following closed-loop controls were designed and implemented. The outlet CO_2 sensor data is monitored during adsorption, and if it passes above a certain threshold to account for noise, it is passed through a dilution factor to dampen in a proportional habitat volume and added back into the inlet. In this way, if a breakthrough occurs during adsorption, the inlet CO_2 levels could increase indefinitely.

Closed Loop Testing

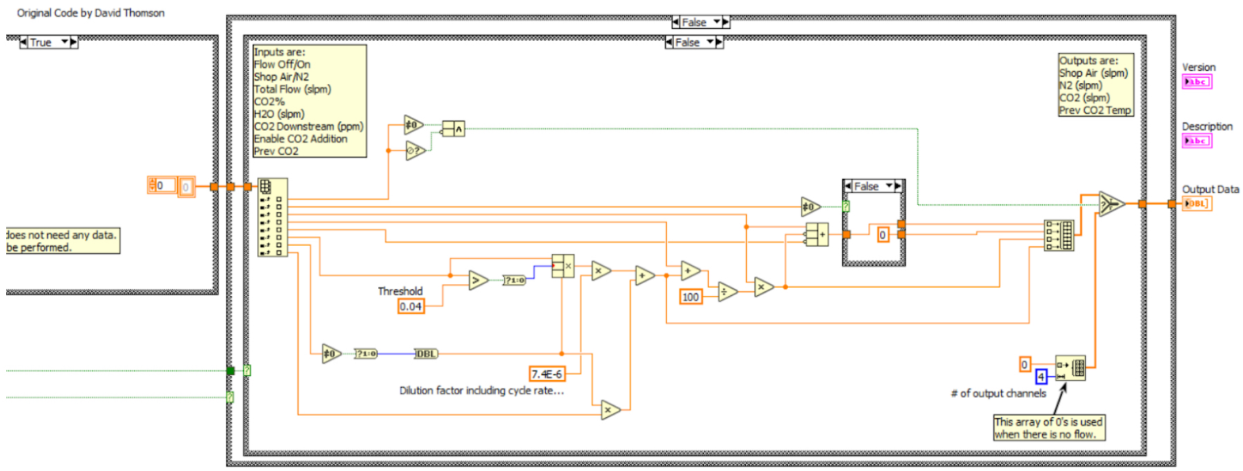


Figure 4.4: Screen grab of the ZeoDe LabView using a closed loop approach

The habitat volume dilution factor was based on the CO_2 that the system scrubs per 24-hour period and on the habitable volume recommendations from NASA for a long-duration mission of 20 m^3 per crew member. The ZeoDe testbed scrubs 0.45 kg per 24-hour period. The average astronaut on the ISS produces 1 kg per 24-hour period. With that, the scaling factor will be 45%, so the habitable volume is assumed to be 9 m^3, or 9,000 L.

4.3 Degradation Test Results

Long duration humid open loop cyclic tests

Once the testbed had been characterized for the limits of the planned testing, long-duration experiments were run. The first were open loop, as explained above. While this was not ideal for the training algorithms, it did establish a baseline for trends. By running an open loop test, one can separate potentially confounding variables of humidity addition and increased inlet CO_2. The result is that even in an open-loop scenario, the humidity does cause degradation in the system. It should be noted that the open loop experiment included here is slightly accelerated due to experimental initial conditions and, therefore, exhibits more extreme performance degradation than the closed loop test. The difference in starting experimental conditions was that the open loop testing began at a higher initial CO_2 content within the bed. This was meant to replicate a system that had already been operating in nominal steady-state conditions.

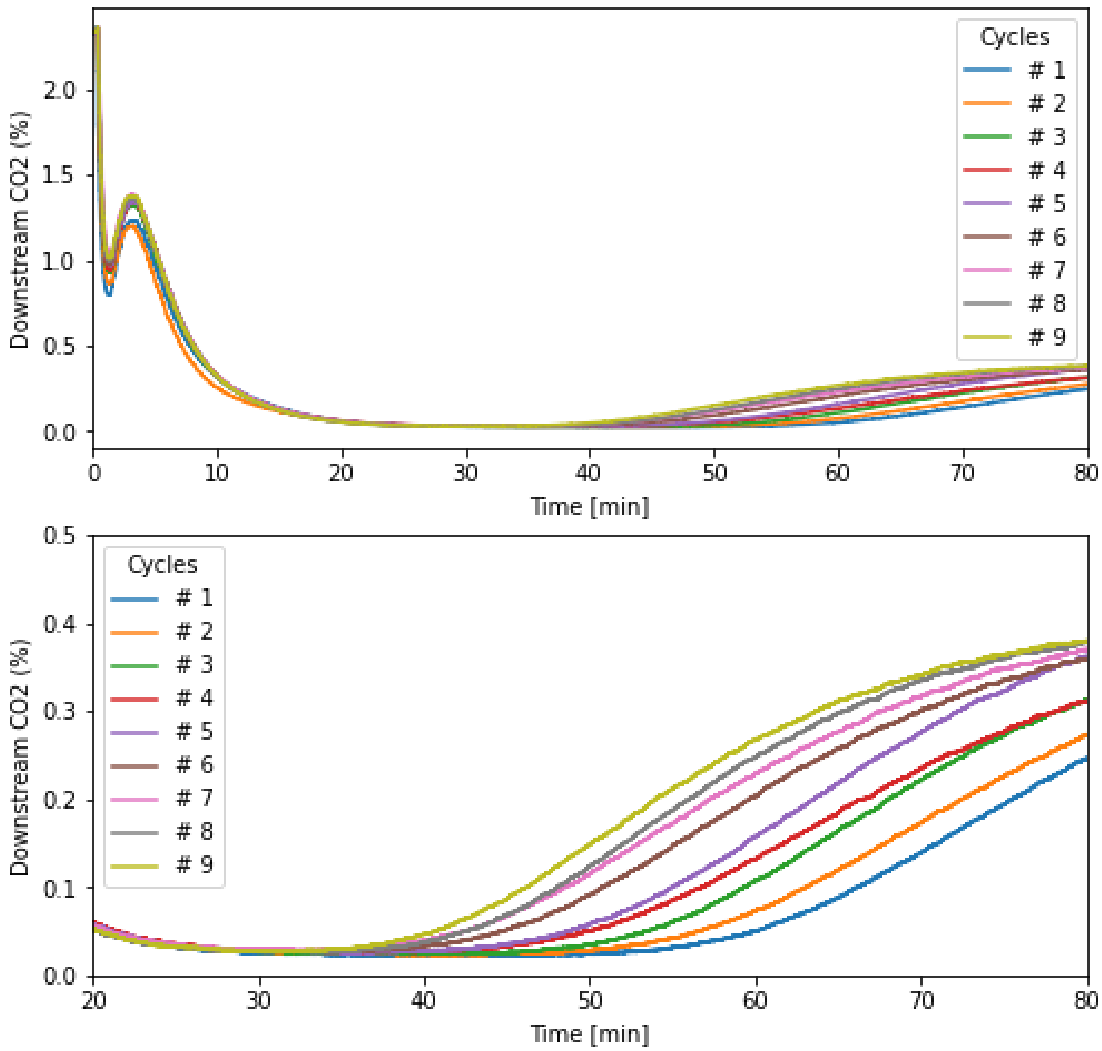


Figure 4.5: Data plot from a ZeoDe cyclic open loop test with degradation due to humidity introduction at -10 C dew point

Figure 4.5 shows the adsorption portion of each cycle. The initial bump in the first 10 minutes comes from the fact that the bed is still cooling down. Therefore, CO_2 still passes through due to the increased energy injected into the system, counteracting the attractive forces for adsorption. Around 30 minutes in, the bed cools to the point where adsorption is possible, and all the CO_2 entering the bed is adsorbed. At around 40 minutes in, we start to see a breakthrough. The different cycles are labeled chronologically from 1-9, where a desorption portion between each cycle is not shown here.

The bottom half of Figure 4.5 zooms in to view the trend of decreasing breakthrough time as the cycles progress. This difference is the visible trend of increasing degradation as the bed fills with humid air, bumping off CO_2. The open-loop nature of this test is also evident as the maximum outlet CO_2 will always be 0.4, where all the curves approach.

Figure 4.6 plots the area under the curve from the plot in Figure 4.5. First, the total area is shown. This includes the first 16 minutes, where we have a pronounced CO_2 increase due to the bed being at an increased temperature. To decouple this effect, the second plot shows only the partial area, which does not include the area under the curve of the first hump. Here, we see a linear increase in CO_2. This further de-confounds our future design of experiments to make the system more representative of a closed loop habitat because we know this increase in CO_2 is attributed to the humidity introduction and not exclusively to increased inlet CO_2 levels. **This plot validates the top-level requirements of the testbed, as well as the mission statement, reposted below:**

MISSION STATEMENT

Build a CO_2 removal testbed based on packed bed technology to produce degradation data for prognosticating future states of degraded ECLSS systems to contribute to both the HOME STRI and the ECLSS research community as a whole.

- L1-001: The testbed shall generate degradation data for prognostics
- Validation: degradation trends are validated through the test data in Figure 4.5 and 4.6
- L1-002: The testbed shall generate degradation data for prognostics
- Validation: the same trends as seen in the CDRA ISS are seen in Figure 4.5, confirmed by NASA reviewer members of HOME.
- L1-003: The testbed shall contribute to HOME annual milestones.
- Validation: Figure 4.5 partially fulfills this requirement. The test data shown in the closed loop section completes the validation of this requirement, confirmed by the prognostics team at Georgia Tech.

The top-level requirements L1-004 and L1-005 were validated by analysis and by the on-site safety manager for the UC Davis Center for Spaceflight Research during the SRR, respectively.

The third plot in Figure 4.6 shows the final value of CO_2 after each cycle. Here, the open-loop nature of this experiment is once again evident. The final values approach and level off close to the maximum inlet condition of 0.4%, or 4,000 PPM. The goal for the closed-loop version of this experiment is to see this plot increase linearly, similar to the top two plots.

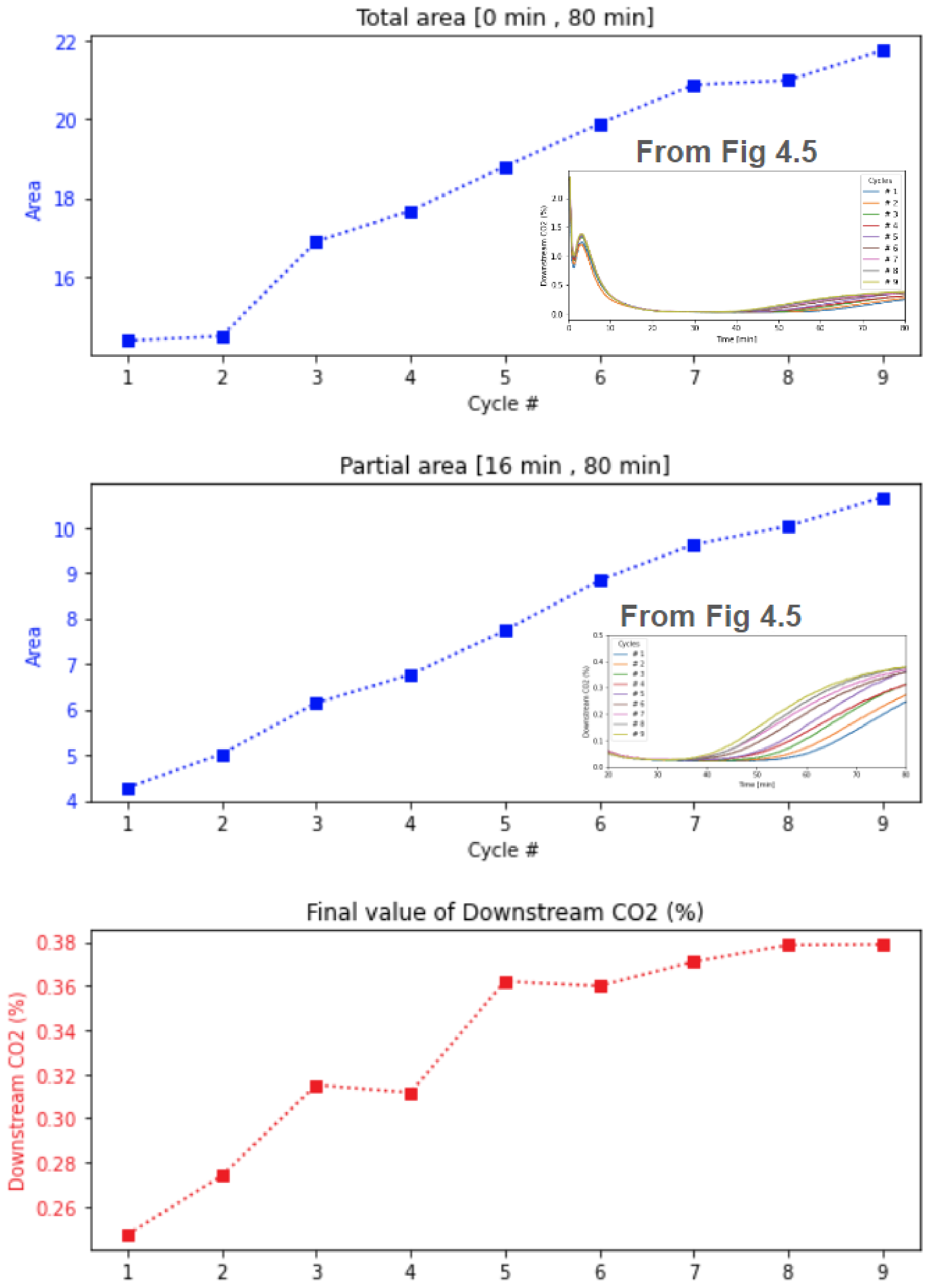


Figure 4.6: ZeoDe cyclic open loop test trends from data in Figure 4.5 where degradation is present due to the introduction of humidity at -10 C dew point

Long duration humid closed loop cyclic tests

The continuous involvement of the prognostics team during the generation of the test data presented in the open-loop section helped to define the new design of experiments for closed-loop testing. This incorporated new controls to feed broken-through CO_2 during adsorption through a dilution factor and back into the inlet setpoint for the MFCs. During the review of the open-loop testing and the planning of the open-loop testing, it was noted that due to the scaled-down nature of the ZeoDe testbed from a CDRA or 4BCO2-like system. At the same time, the physics of mass transfer is sound due to the matching of interstitial velocity and residence time, and there is a higher surface area to volume ratio of metal. This means that since the heating coils are wrapped around the tubing housing the zeolites for the ZeoDe system, heating comes from that surface area, and the cooling time is extended. Like ZeoDe, the CDRA and 4BCO2 systems do not use active cooling. Because of this increased cooling time, the hump that is seen early on in testing is representative of what is seen in a CDRA of 4BCO2-like system but is more pronounced. This artificially increases the value of CO_2 added back into the inlet. Because of this, the controls for the closed-loop system do not turn on CO_2 recirculation until 20 minutes into each adsorption cycle.

It should also be noted that the initial conditions for this closed-loop test differed from those for the open-loop test. The assumption for the open-loop initial conditions is as follows:

- CO_2 inlet conditions are set to represent a non-degraded system that has been on for some time, with a base CO_2 content within the bed that would be expected of a system that has reached an adsorption/desorption steady state.

- A system that has reached a steady state has a base level of CO_2 within the interior of the zeolite pellets that is not desorbed during the desorption cycles.

The assumption for the closed-loop initial condition is as follows.

- CO_2 inlet conditions are set to represent a fresh, non-degraded system that is just turning on for the first time. Therefore, the base content of CO_2 that would be present in a system that has reached a steady state is not present here.

- As a result, the system is slower to degrade because there is more space available at the onset that can be filled with humidity and CO_2

Further, the prognostics group requested a new condition: during the same experiment, cycles start with no humidity and then change to including humidity. This shows, without variation from experiment to experiment, that degradation is not present in the system until humidity is introduced.

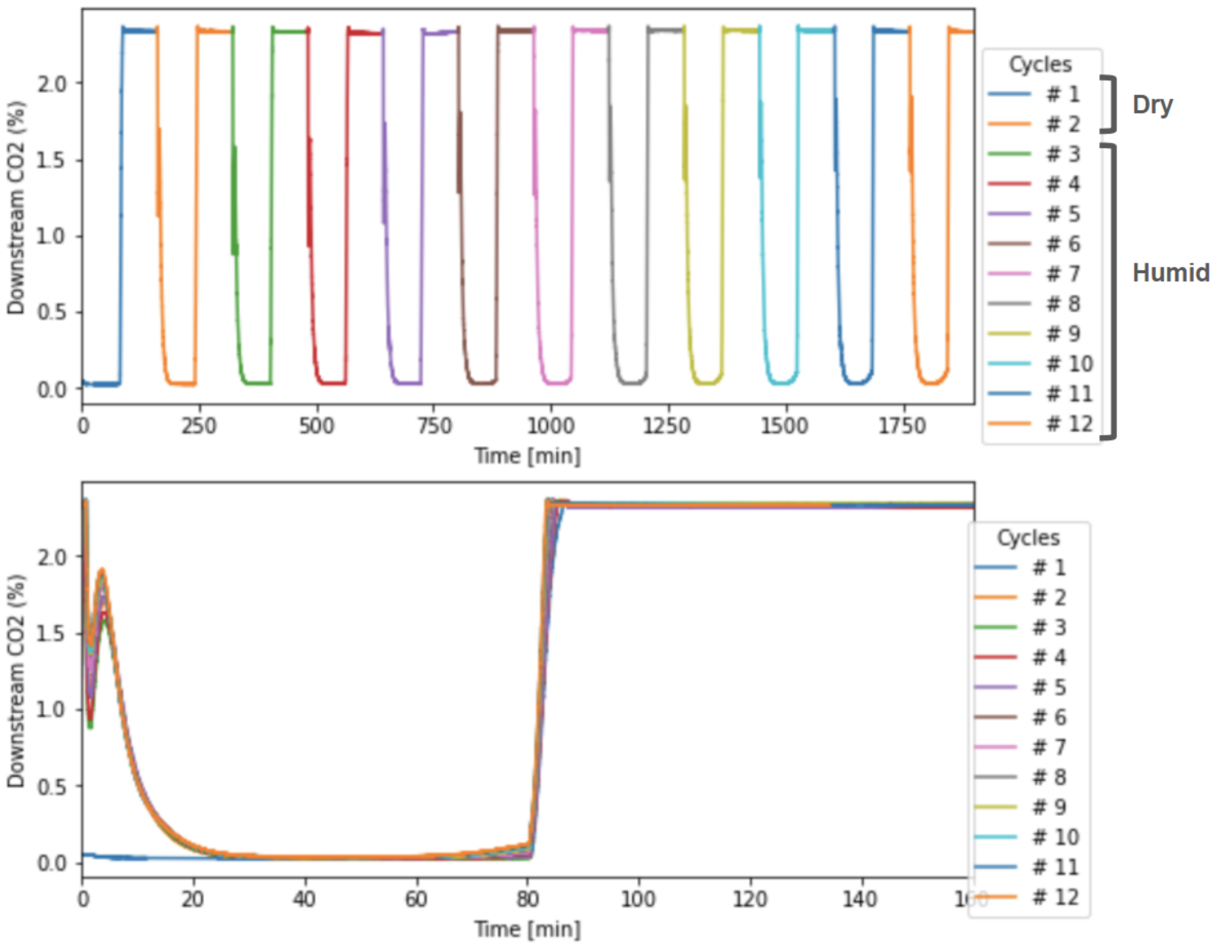


Figure 4.7: ZeoDe data plots showing humid cyclic closed loop test where degradation is present due to the introduction of humidity at -10 C dew point. The first two cycles are dry to establish a baseline.The upper plot shows cycles chronologically, and the lower plot shows all full cycles (adsorption and desorption) superimposed on each other.

Figure 4.7 shows 12 cycles, starting with two dry cycles and continuing with humid cycles at -10 degrees C dew point. The upper plot shows all cycles, and the lower plot overlaps all cycles, starting with adsorption for up to 80 minutes and continuing with desorption. Here, the desorption trend is visible where the sensor tops out at 2.33% CO_2, which is why it flattens out. The lower plot also shows a less pronounced degradation than the open loop plots, which is expected due to the different initial conditions stated above.

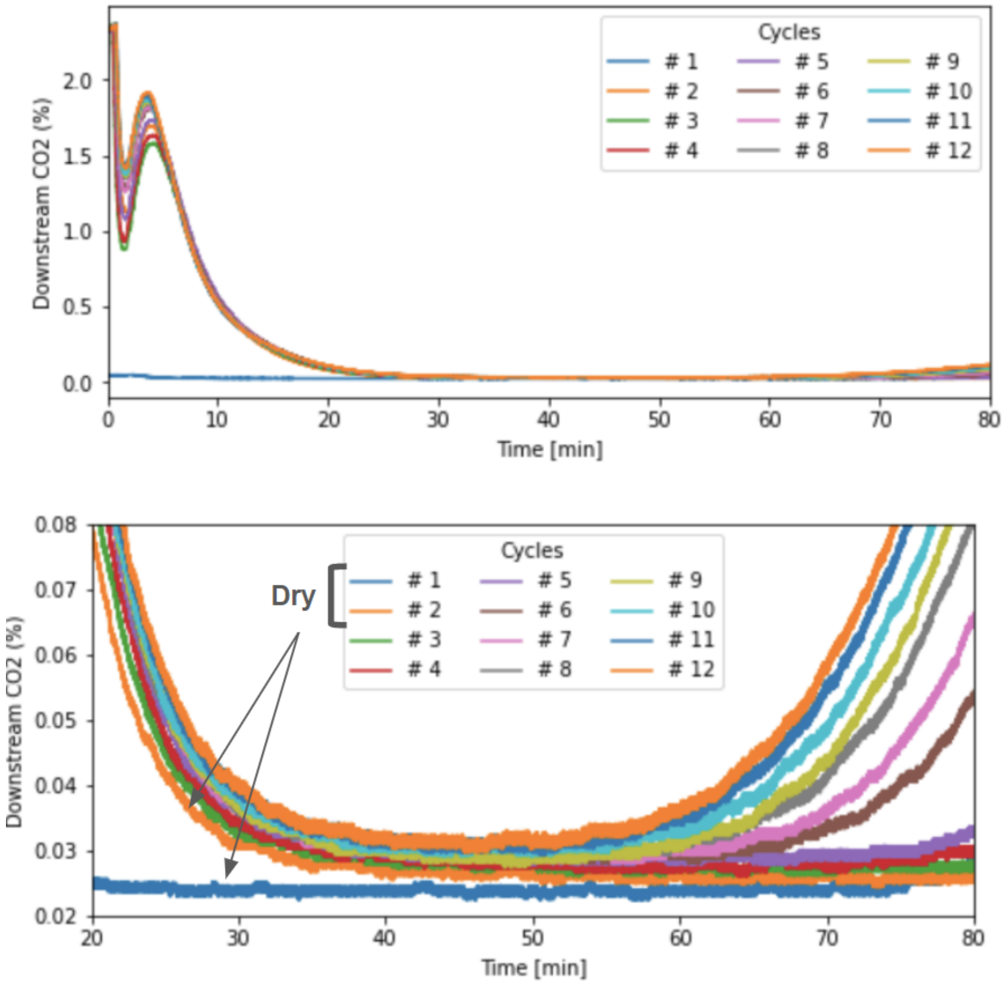


Figure 4.8: ZeoDe data plot showing humid cyclic closed loop test where degradation is present due to the introduction of humidity at -10 C dew point. The first two cycles are dry to establish a baseline.

Figure 4.8 shows just the adsorption portion shown in Figure 4.23 in the upper plot and zooms in on the last 60 minutes of adsorption in the lower plot. From 40 minutes on, we see the same degradation trends in the open-loop testing, again showing that our trends are the same for degradation in a closed-loop habitat. The degradation trends are only exhibited in the humid tests, and in the first two adsorption cycles, which were run at dry conditions, we see a flat line. This shows a direct comparison without experimental uncertainty where degradation is evident in a cycle where humidity is injected but not in a cycle where humidity is not injected. The magnitude of these trends may differ from those in the open-loop portion, but it is not verifiable here due to the differing initial conditions.

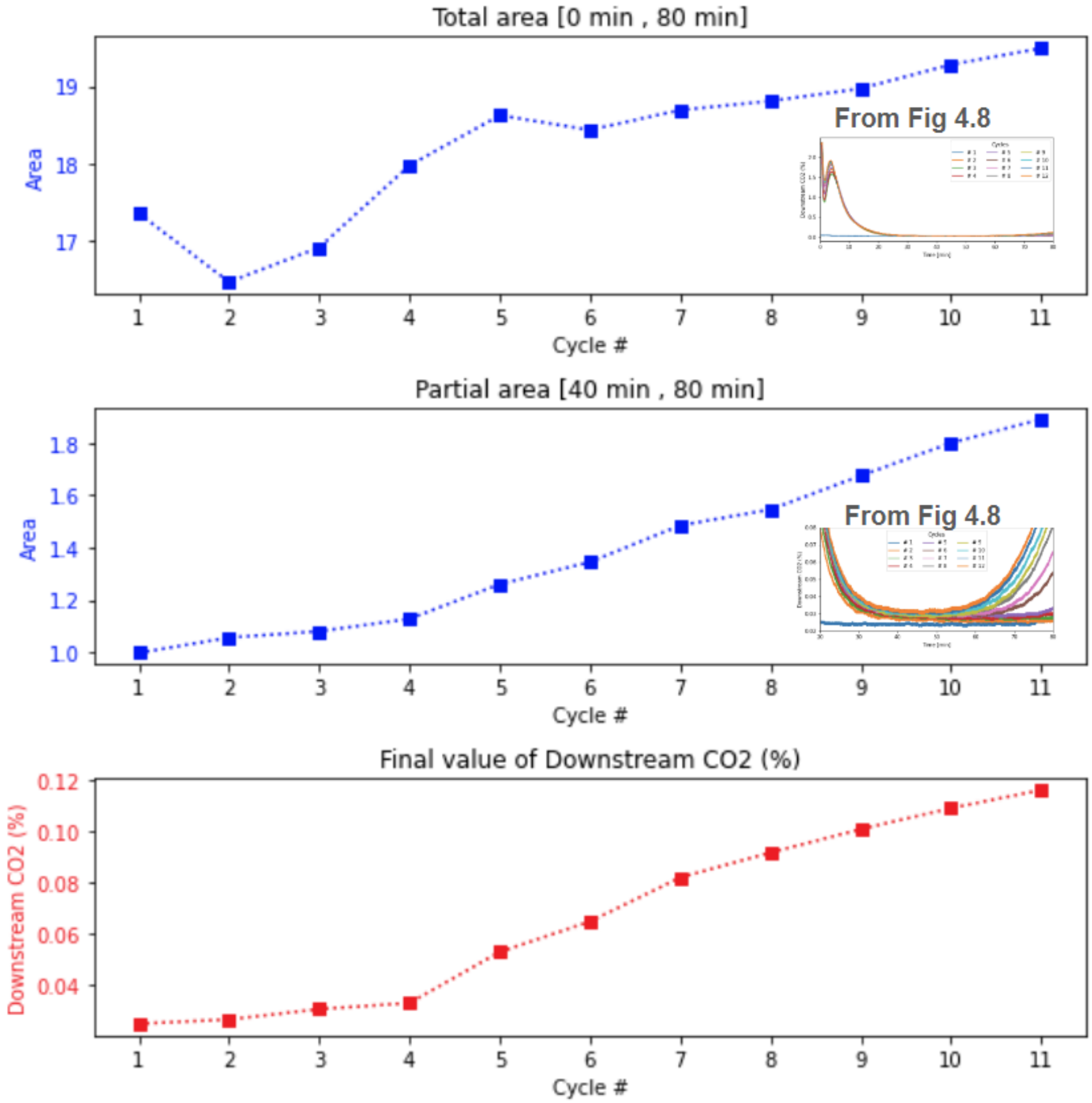


Figure 4.9: ZeoDe trends from the humid cyclic closed-loop test in Figure 4.8 where degradation is present due to the introduction of humidity at -10 C dew point. The first two cycles are dry to establish a baseline.

Figure 4.9 Shows the expected trends for degradation, where the total area under the curve and partial area are linear, except for less so during the first two dry runs. Aside from those first two runs, due to the closed-loop nature of the system, we see a linear trend in the final value of the downstream CO_2 since we are now recirculating our system to represent a closed-loop habitat and are not limited by our first inlet condition of 0.4% CO_2.

Long duration dry closed loop cyclic tests

Long-duration dry tests using the same closed-loop logic were performed to compare to the humid closed-loop experiments. This further ensures we don't see degradation-like signals in the dry cycles that could imply a faulty experimental setup for the same experiment duration.

The assumptions for the closed-loop initial conditions for the dry experiments are as follows.

- CO_2 inlet conditions are set to represent a fresh, non-degraded system that is just turning on for the first time. Therefore, the base content of CO_2 that would be present in a system that has reached a steady state is not present here.
- The system does not have humidity injected, so we expect not to see degradation signals in the downstream CO_2 readings.

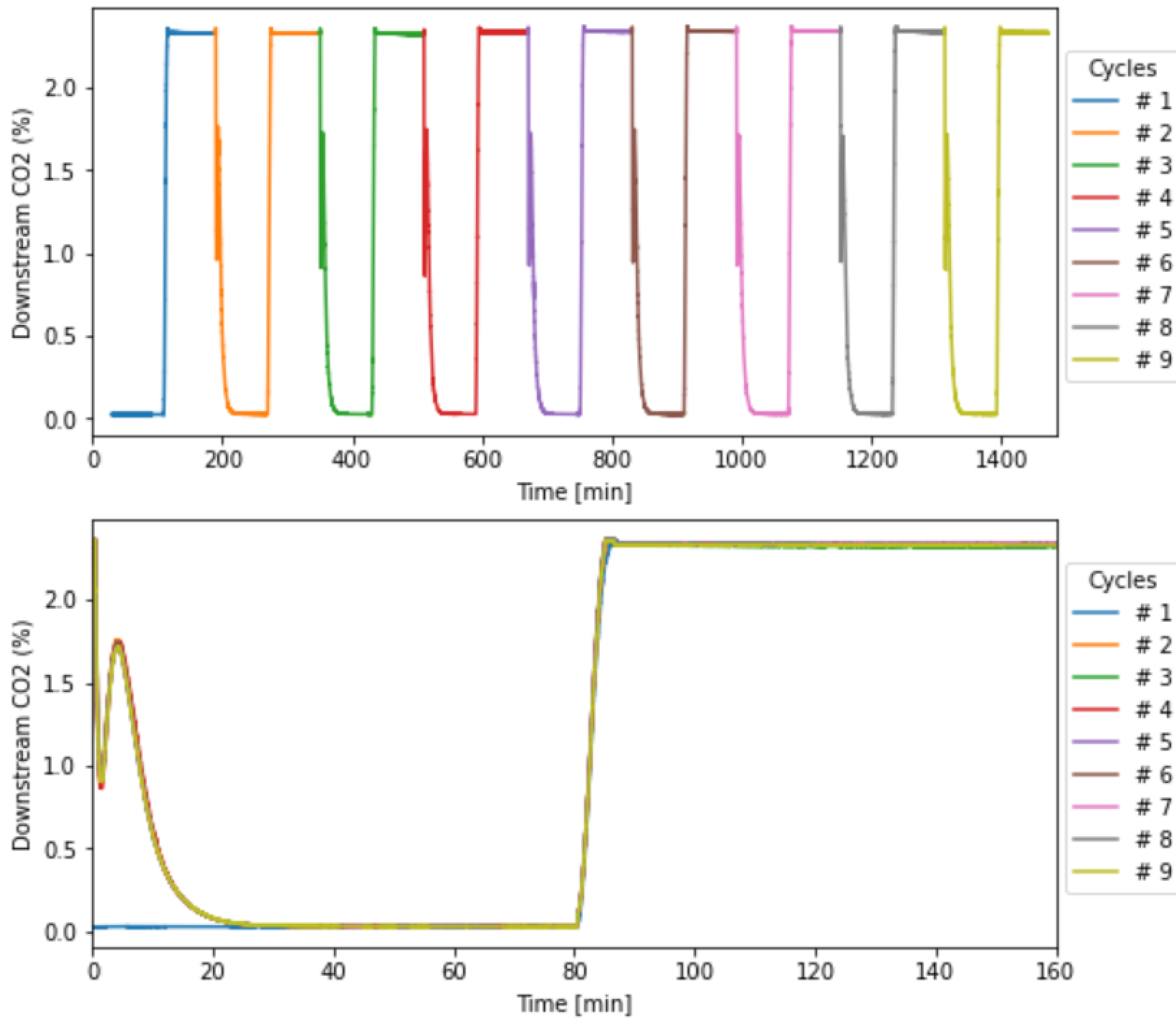


Figure 4.10: ZeoDe data plots showing a dry cyclic closed loop test to establish a baseline. The upper plot shows cycles chronologically, and the lower plot shows all full cycles (adsorption and desorption) superimposed on each other.

Figure 4.10 shows the nine cycles, with PID control set to maintain a dry condition of -40 C dew point, the system sensors' lower limit. The humid MFC remains closed for this entire dry test. The upper plot shows all cycles, and the lower plot overlaps all cycles, starting with adsorption for 80 minutes and continuing with desorption. Here, the desorption trend is visible where the sensor tops out at 2.33% CO_2, which is why it flattens out. The lower plot shows no degradation compared to the humid runs, with an entirely flat trend.

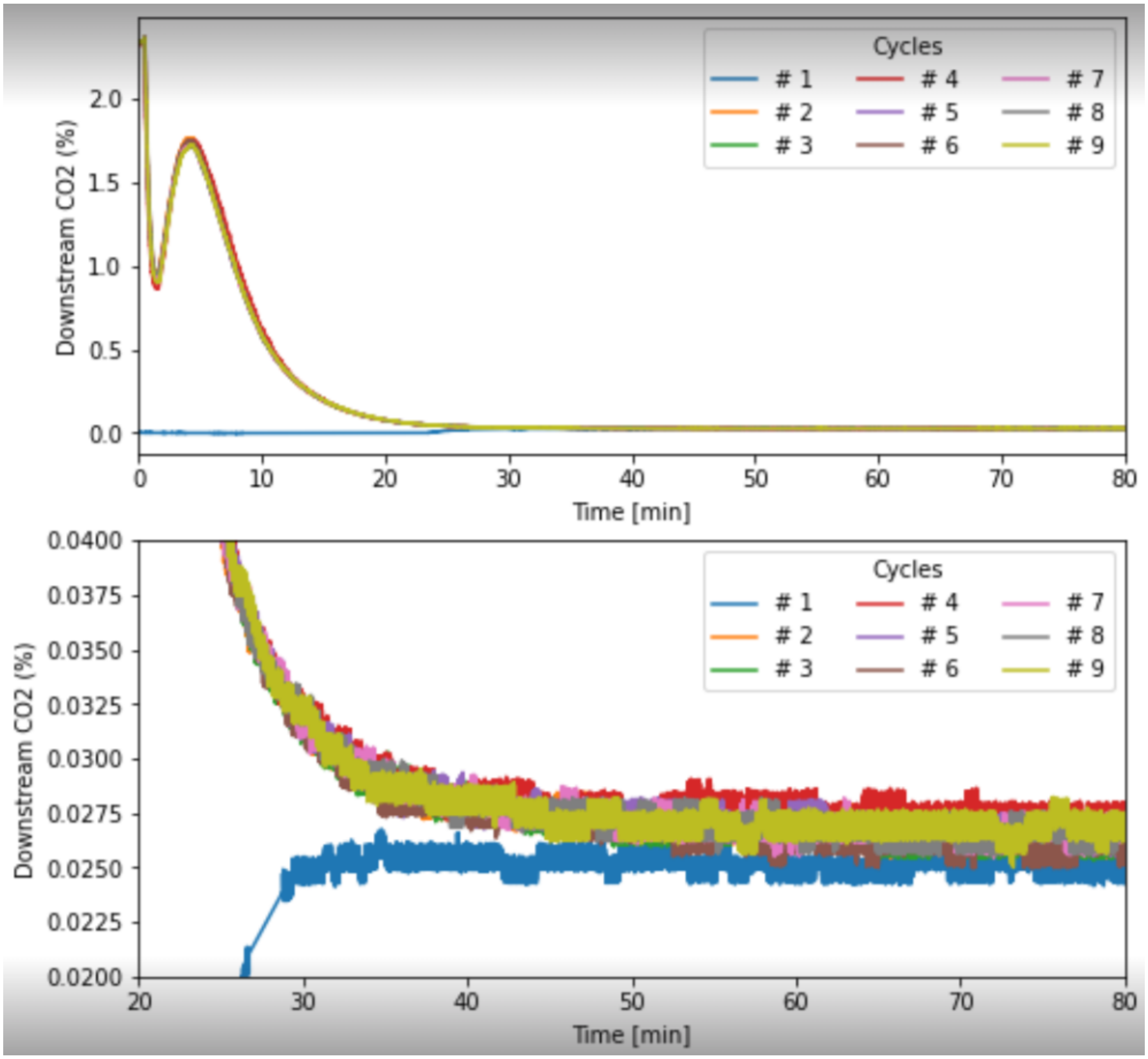


Figure 4.11: ZeoDe data plots showing a dry cyclic closed loop test to establish a baseline. The upper plot shows adsorption cycles overlayed, and the lower plot shows the same, zoomed in on the last 60 minutes of each adsorption cycle

Figure 4.11 shows just the adsorption portion shown in Figure 4.10 in the upper plot and zooms in on the last 60 minutes of adsorption in the lower plot. From 40 minutes on, it is apparent that there is no degradation, as the lines are flat and do not uptick, showing that CO_2 is being completely adsorbed by the system and is not breaking through as we see in our humid degradation experiments. As our initial conditions are the same as those in the humid experiments, with the exception of the controlled variable of humidity, this plot further proves our performance degradation injection via humidity is sound. As all lines are flat, this plot uses a different scale than the humid tests - noise has not increased in the system.

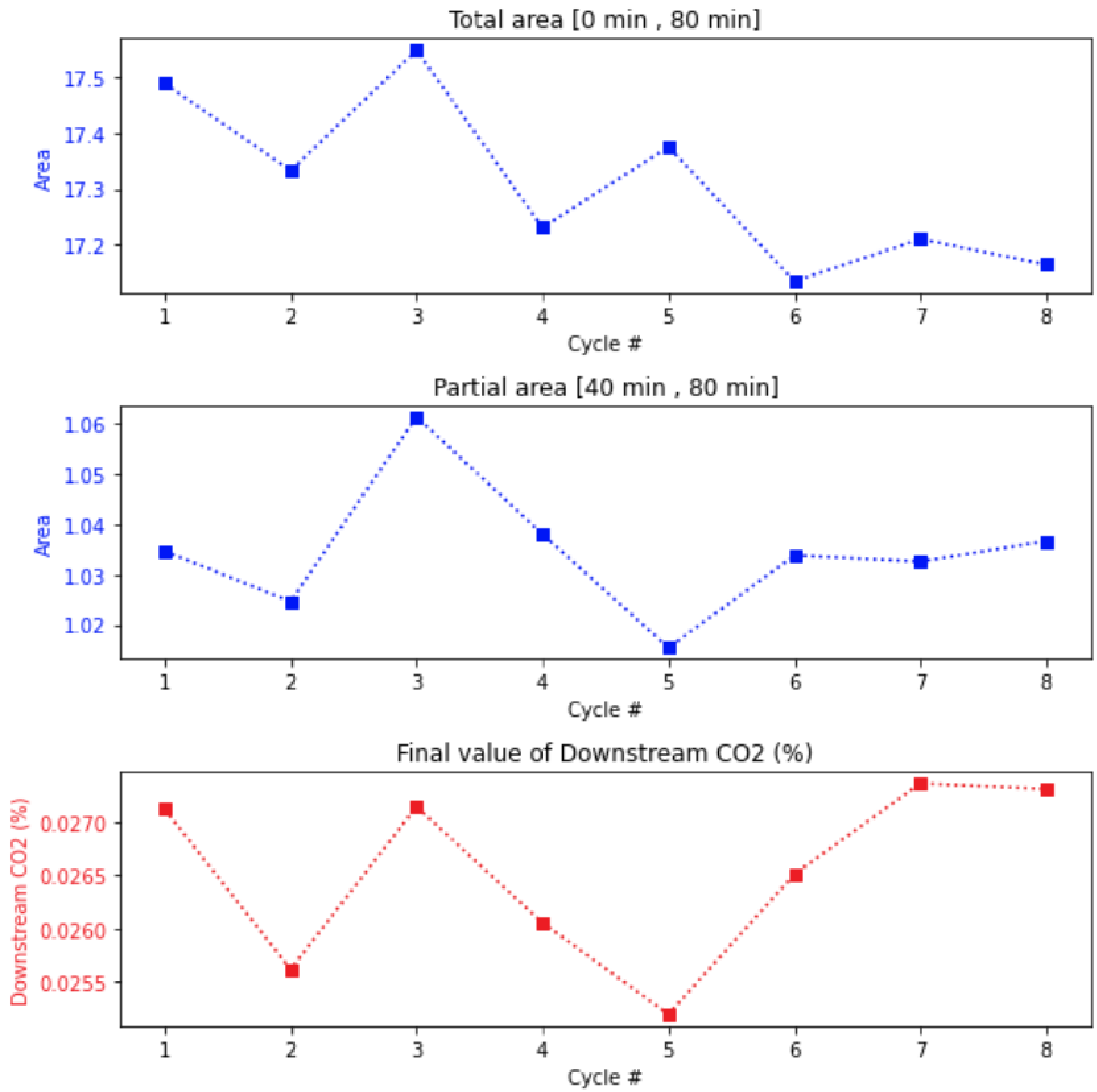


Figure 4.12: Trends from the data shown in Figures 4.10 and 4.11 for the dry cyclic closed loop test used to establish a dry baseline

Figure 4.12 Shows the expected trends for a dry experiment, where the total area under the curve and partial area are not linearly increasing like they are in humid runs and instead show representative noise expected in the system and are flat. Note that the scale for these plots differs from the humid runs, so variation in points is minimal. Even though we are still recirculating our system to represent a closed loop habitat and are not limited by our first inlet condition of 0.4% CO_2, we do not see an increase in CO_2 levels at the inlet, in our symbolic "cabin habitat CO_2" levels.

Comparison of Dry and Humid Experiments

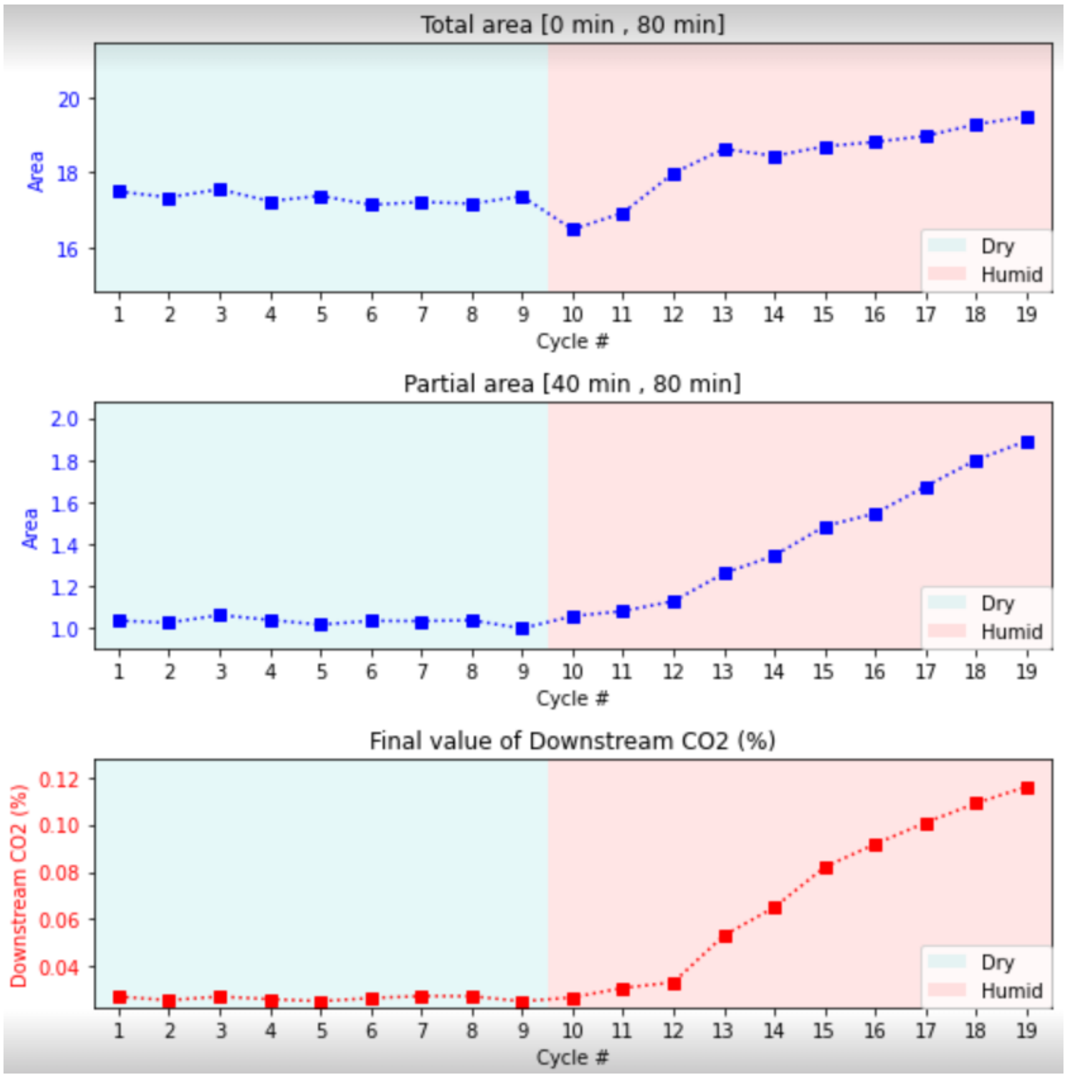


Figure 4.13: Trend plot to show the comparison of dry experiments, shown on the left, to humid experiments concatenated on the right, which have an initial first run shown that is dry. In humid runs, degradation is introduced via a set point of -10 C dew point

Figure 4.13 shows a direct comparison of trends between humid and dry experiments, with the left side showing dry results from purely dry experiments and the right side, shaded, showing concatenated humid results from purely humid experiments (with an initial dry data point). This allows a visual comparison of the flat trend without humidity introduction and, therefore, without degradation on the left-hand side and the linearly increasing trend with degradation on the right-hand side. The differing initial condition is the dew point. The remaining initial conditions are set in the same way with a freshly baked-out and cooled system, the same flowrate and initial adsorption and desorption setpoints to match ISS interstitial velocity, residence time, and desorption pressure, and the same closed-loop logic during adsorption to simulate a closed cabin habitat.

Longer Duration Experiments with Dry and Humid Cycles

After the creation of the concatenation in Figure 4.13, it was decided that the ideal experiment would be a longer duration test where at least five dry cycles are run, followed by humid cycles, with the first dry cycle consistently dropped due to its different temperature conditions since the first adsorption cycle does not follow a desorption. Figure 4.14 (a) shows the entire test, lasting 45 hours, with cycles shown chronologically. The first five cycles are dry (only four are shown as the first cycle is dropped), followed by humid cycles at a dew point of -10 C. Figure 4.14 (b) then shows this same experiment, with complete cycles superimposed (adsorption followed by desorption). One notable difference between this experiment and the previous experiments is the trend at the end of desorption and the beginning of adsorption. This was investigated, and found to be due to more complete regeneration of ZeoDe during the bake-out before testing. This is an area for future investigation and characterization as the current dew point sensors do not sense below -40 C dew point, and therefore, determining a true dry condition to signify a complete bake-out is not currently possible. This is elaborated upon in a characterization project performed by a colleague [48]. Figure 4.14 (c) zooms in on the last 60 minutes of all adsorption cycles.

Figure 4.15 shows the trends for the area under the curve and final CO_2 concentration following each adsorption from Figure 4.14. The degradation signal is visible with a linearly increasing area under the curve.

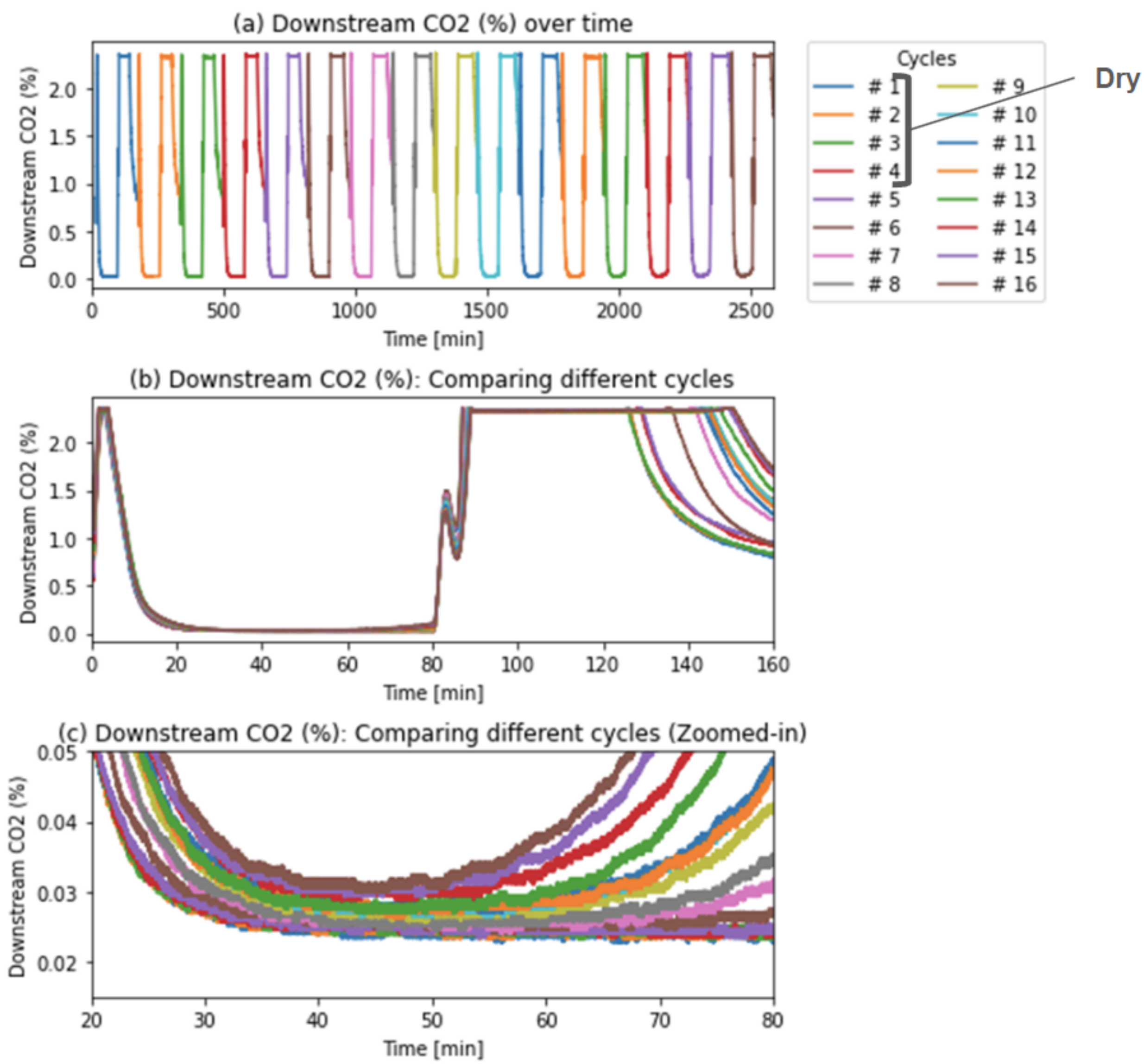


Figure 4.14: ZeoDe data plots showing a long duration experiment where five dry cycles are run (first not shown), immediately followed by humid cycles. In humid cycles, degradation is introduced via a set point of -10 C dew point

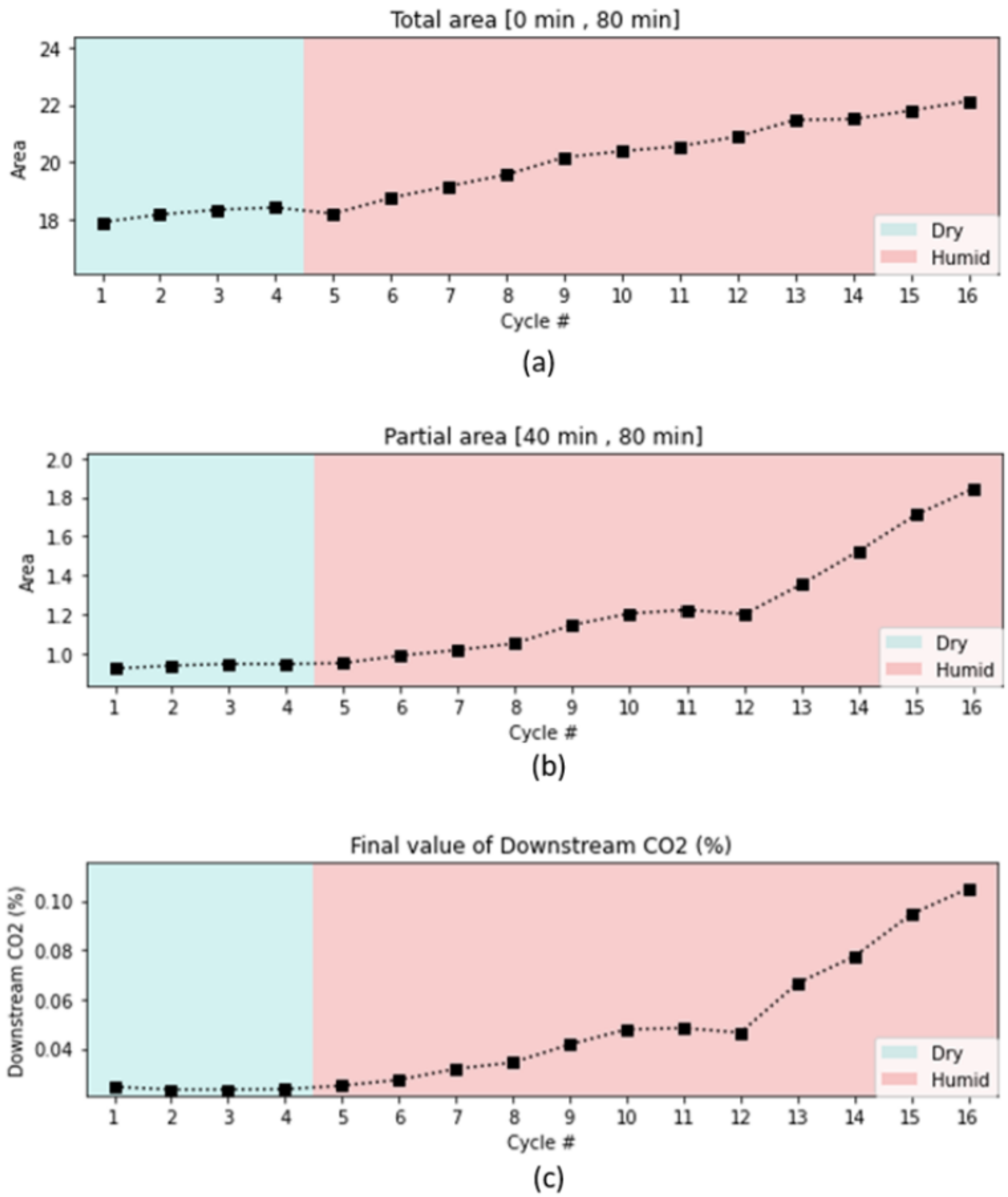


Figure 4.15: ZeoDe trend plot for the long duration experiment in Figure 4.14 where five dry cycles are run (first not shown), immediately followed by humid cycles. In humid cycles, degradation is introduced via a set point of -10 C dew point

4.4 Initial Characterization Before Degradation tests

The following plots paint a picture of some of the characterization for the boundary conditions of the experiments initially planned to verify the system was ready for long-term degradation testing.

Dry Breakthrough

The following plot shows a dry breakthrough with starting conditions of 800 PPM at the outlet from bakeout and the highest temperature measured on the testbed being 30 degrees C. This shows a breakthrough time of around 100 minutes, validating the choice of an 80-minute cycle time, which matches the cycle time of the CDRA and 4BCO2 systems. This means the internal physics of our bed, having matched residence time and interstitial velocity, are similar enough to these systems to justify the same cycle times.

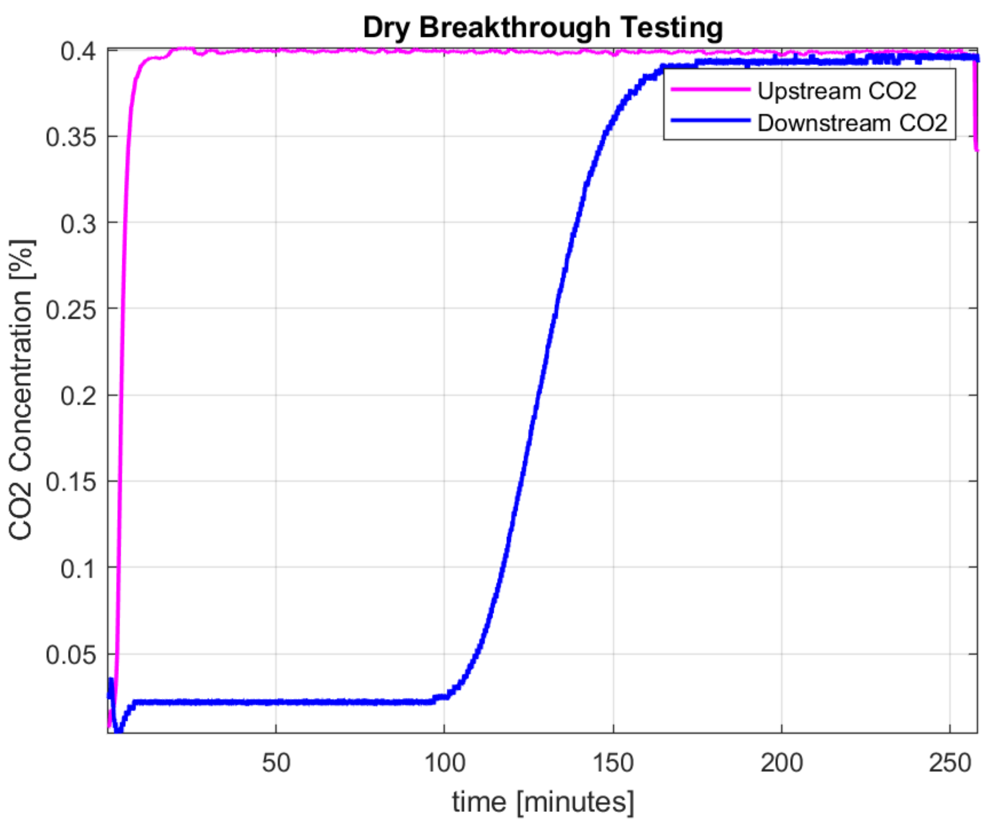


Figure 4.16: ZeoDe characterization test used to establish a dry breakthrough time

Humidity Introduction Capability

To control humidity within the system during long-term degradation studies, it is important to be able to control humidity to a set level even as inlet conditions may be changing due to:

- Increasing CO_2 levels for closed-loop testing
- Changing humidity levels outside, from which the air inlet is coming from
- Changing humidity insertion through the Nafion tube due to increased temperature and, therefore, increased humidity levels in the humid stream

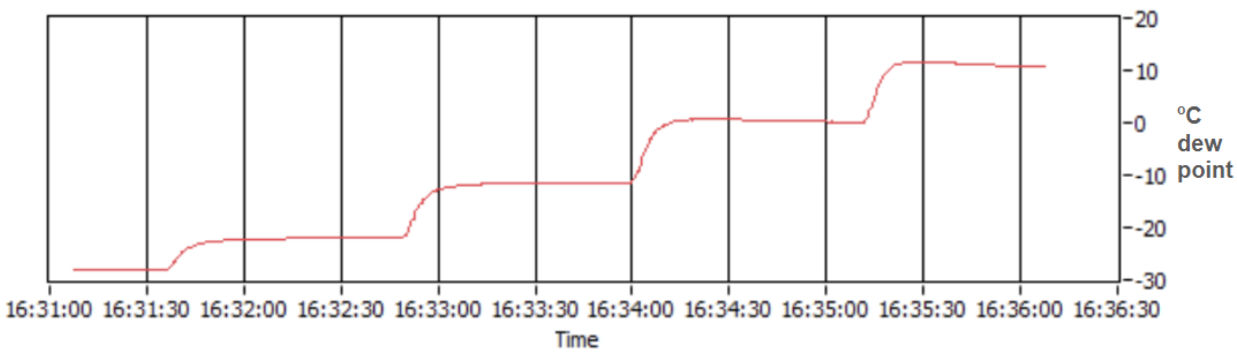


Figure 4.17: ZeoDe characterization plot used to show the capability to control the system to -30, -20, -10, 0, and 10 degrees Celsius Dew Point. Total flow was 8 SLPM, and CO_2 was at 0.4%

Humid Breakthrough

Figure 4.18 shows two humid breakthrough tests performed on different dates with the same initial conditions as those of the dry breakthrough test. We see replicability in breakthrough times, validating our experimental setup.

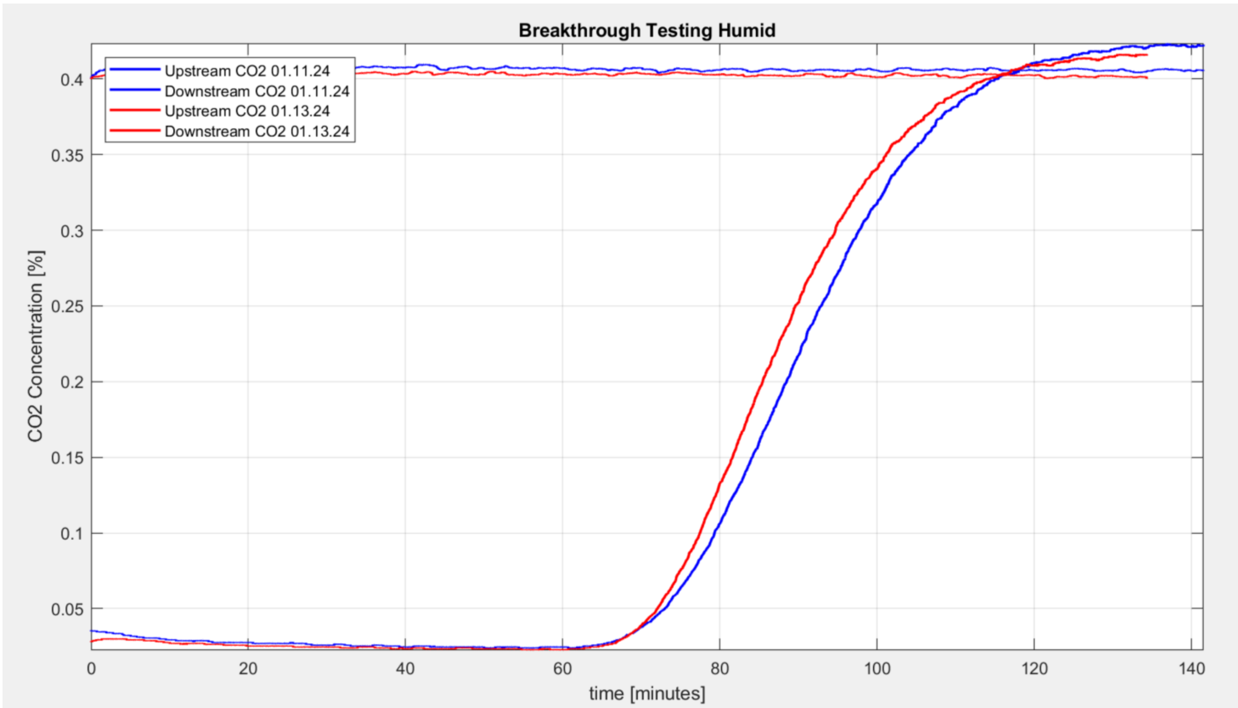


Figure 4.18: ZeoDe characterization plot used to compare two humid breakthrough experiments under the same conditions to test for replicability. This implies that the experimental design was replicable.

The experiment in Figure 4.19 compares one of the humid tests and the dry breakthrough. They use the same initial conditions, aside from the humidity injection at -10 C dew point in the humid test. The trend is that breakthroughs happen earlier in humid tests than in dry tests. This trend is replicable. This is because water molecules are up-taking sites that would have otherwise been used for CO_2. This plot is another measure of the successful implementation of performance degradation within the system through humidity injection.

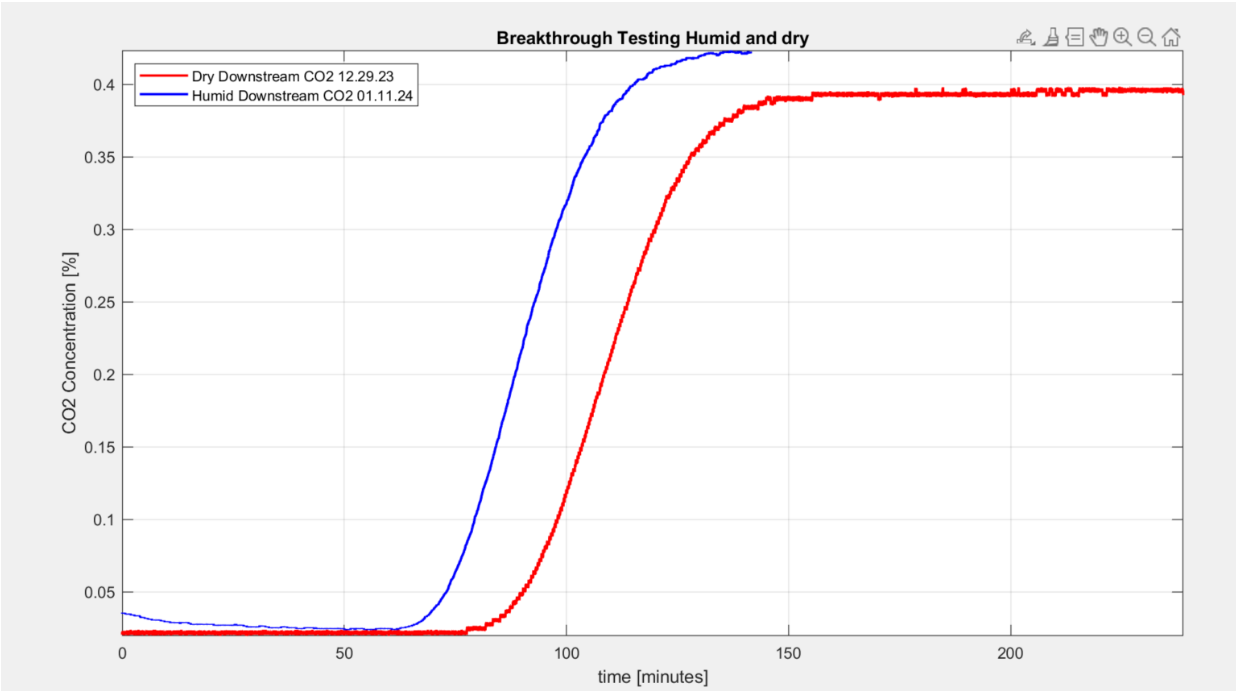


Figure 4.19: ZeoDe characterization experiment showing a comparison of a dry and humid breakthrough test to see how humidity affected breakthrough time

Degradation Experimental Data with and without Humidity

The following were initial open-loop short-term experiments conducted that showed degradation during humidity injection but not during dry experimentation. This acted as internal validation that I was on the right track toward a functional testbed that could successfully induce degradation.

Dry Cyclic Testing

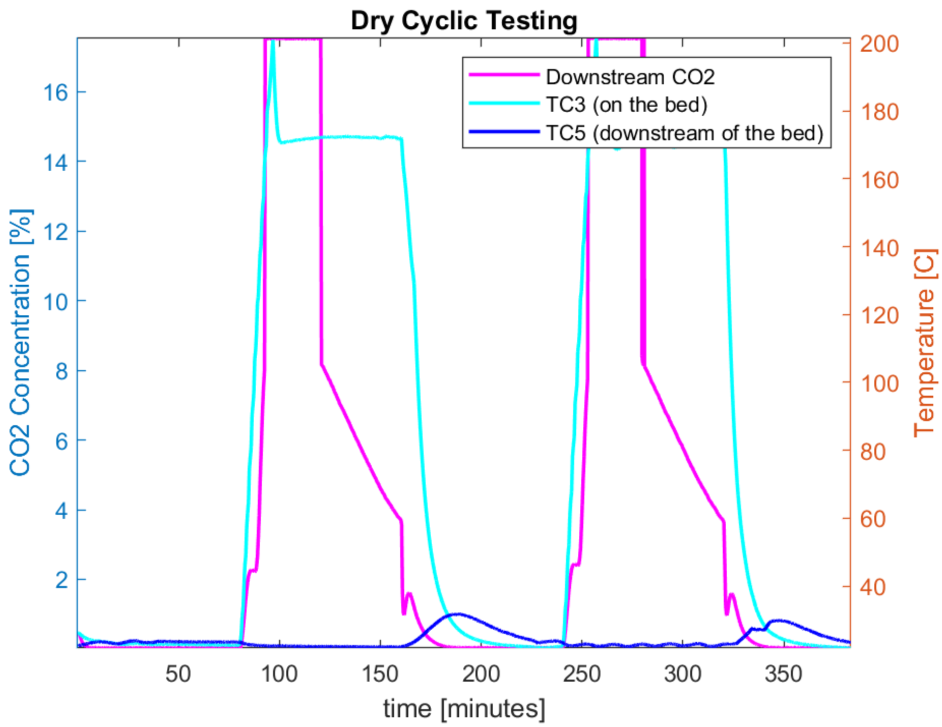


Figure 4.20: ZeoDe characterization experiment to perform a first attempt of a dry cyclic test

Here, the downstream CO_2 does not increase at the end of the adsorption cycles.

Humid Cyclic Testing

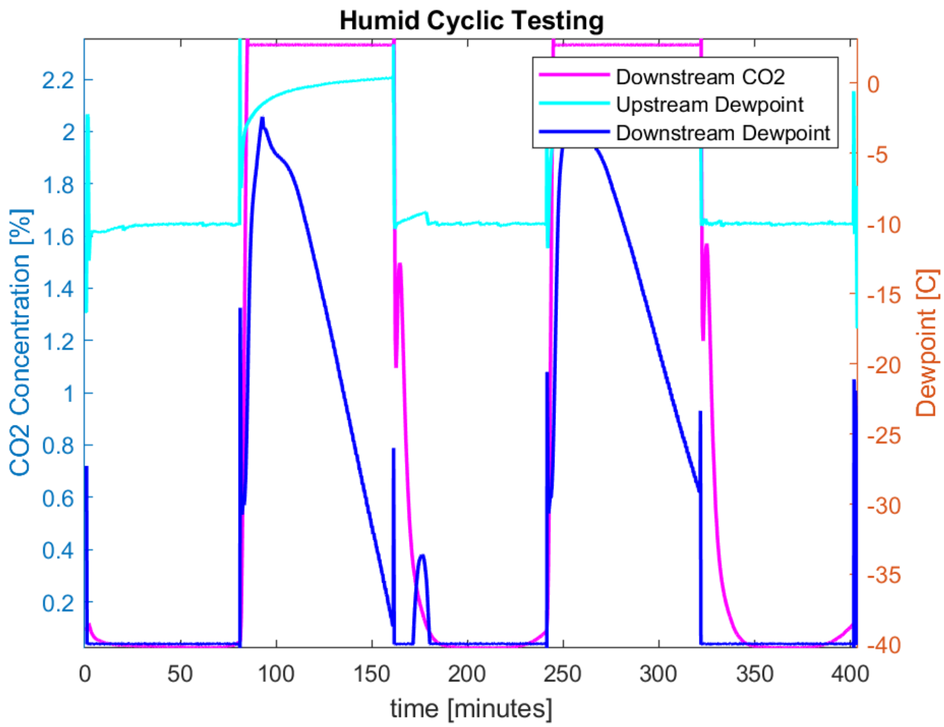


Figure 4.21: ZeoDe characterization experiment to perform a first attempt of a humid cyclic test with humidity-induced capacity degradation at -10 C dew point

Here, the downstream CO_2 does increase at the end of the adsorption cycles.

Bake Out

Below is the first test conducted at 350 degrees C, proving the system could adequately maintain these high temperatures for a bake-out session.

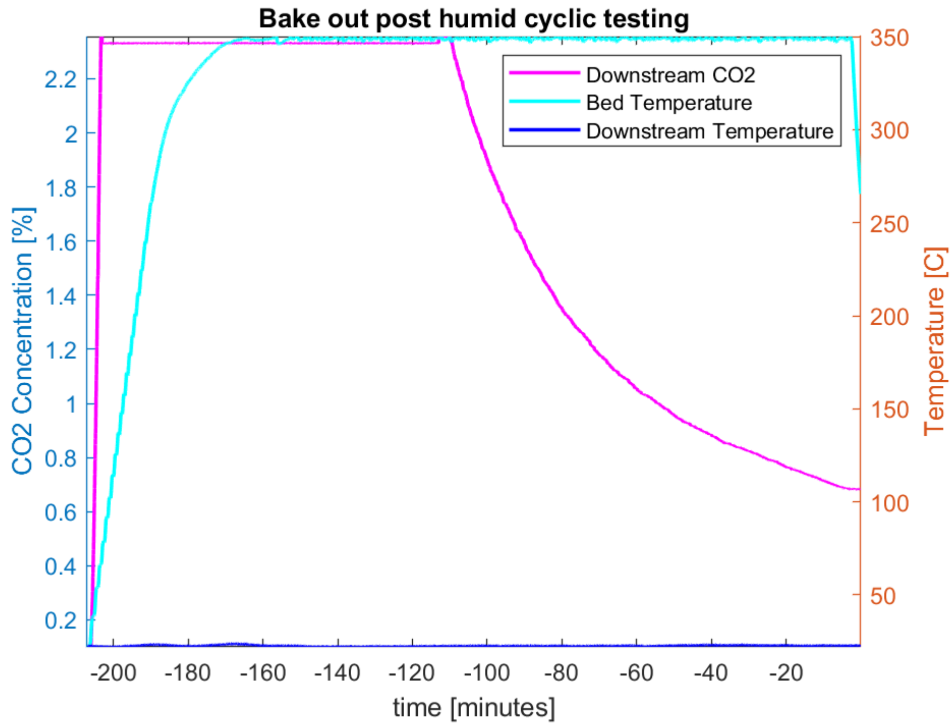


Figure 4.22: ZeoDe characterization experiment to establish the capability to perform a bake out at the upper temperature limit post humid cyclic testing

The following was an unsuccessful attempt at a long-duration cyclic humid closed-loop test. This is because they were not entirely representative in their recirculation controls of what one might see in a space habitat. As the ZeoDe system is scaled down, our packed bed's surface area to volume ratio is much higher than that of the 4BCO2 or CDRA system. Our heaters are also present on the outside of our packed bed. This means our heat during desorption is coming from the surface area. Immediately following desorption, the bed is still hot, and for the first twenty minutes of adsorption, quite a bit of CO_2 exits the bed, as shown in the zoomed-in plot in Figure 4.23. This bump of CO_2 represents a similar trend seen on the ISS, but it has a much higher magnitude than would be seen on the ISS due to the surface area to volume ratio differences. Therefore, when using a simulated closed-loop control logic, if this trend is included, it artificially speeds up the system's degradation appearance. In the below plot, the closed-loop control is turned on 20 minutes into each adsorption to avoid including this trend in the accumulation of CO_2 in the cabin. However, it was decided that even at the 20-minute cutoff, CO_2 was still elevated due to this phenomenon and could, therefore, still affect results. After this test, the closed-loop control logic was changed to enable it after 40 minutes of each adsorption, which is shown in the degradation results at the beginning of this chapter.

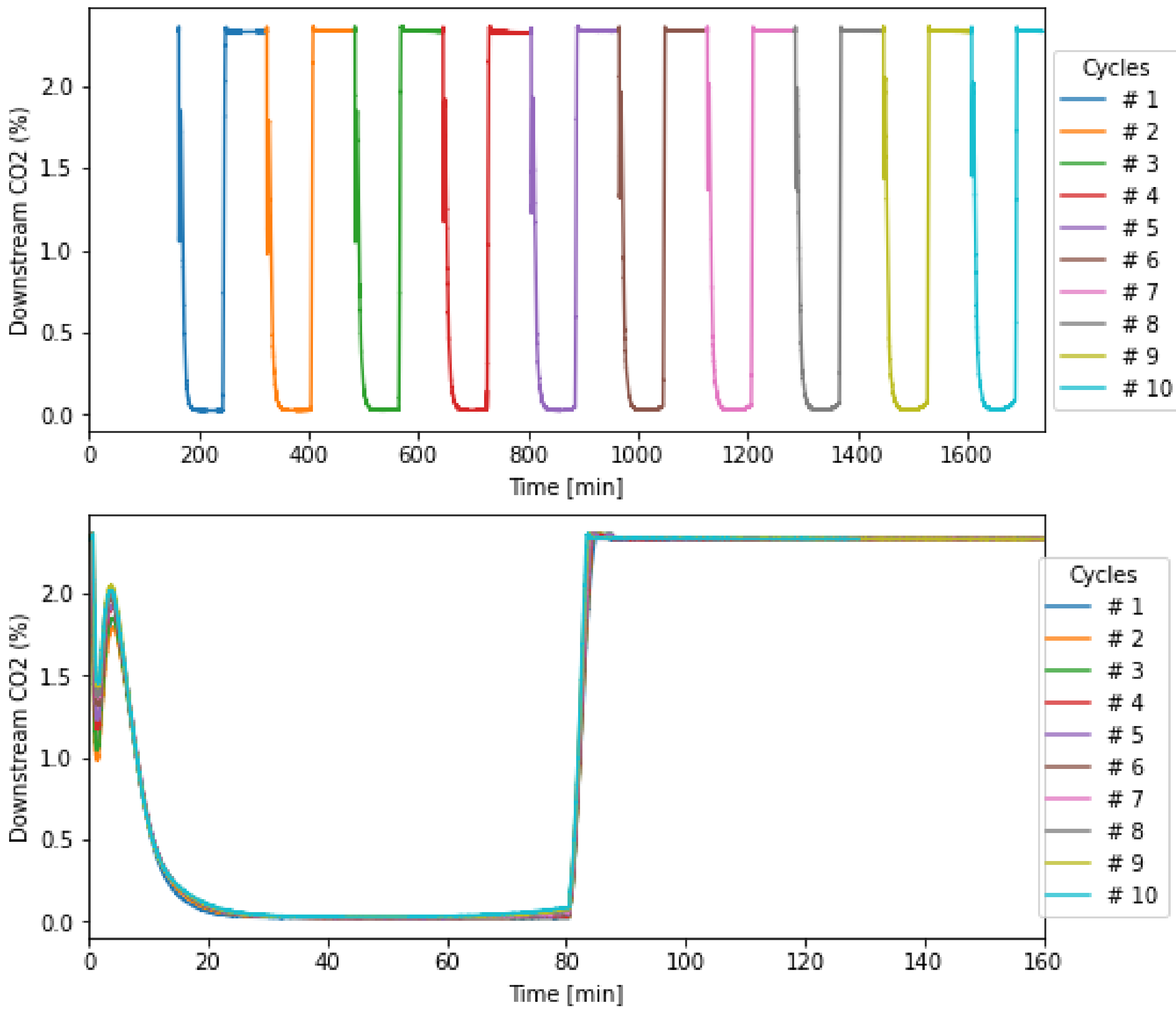


Figure 4.23: ZeoDe characterization experiment for a long duration cyclic test where humidity was introduced, after running one dry cycle, attempting to introduce closed-loop logic within labview to simulate a closed habitat. This run experiment did not represent a closed-habitat system as desired.

Figure 4.23 shows the ten cycles, starting with a dry cycle and continuing with humid cycles at -10 degrees C dew point. The upper plot shows all cycles, and the lower plot overlaps all cycles, starting with adsorption for up to 80 minutes and continuing with desorption. Here, the desorption trend is visible where the sensor caps out at 2.33% CO_2, which is why it flattens out. The lower plot also shows a less pronounced degradation than the open loop plots, which is expected due to the different initial conditions stated above.

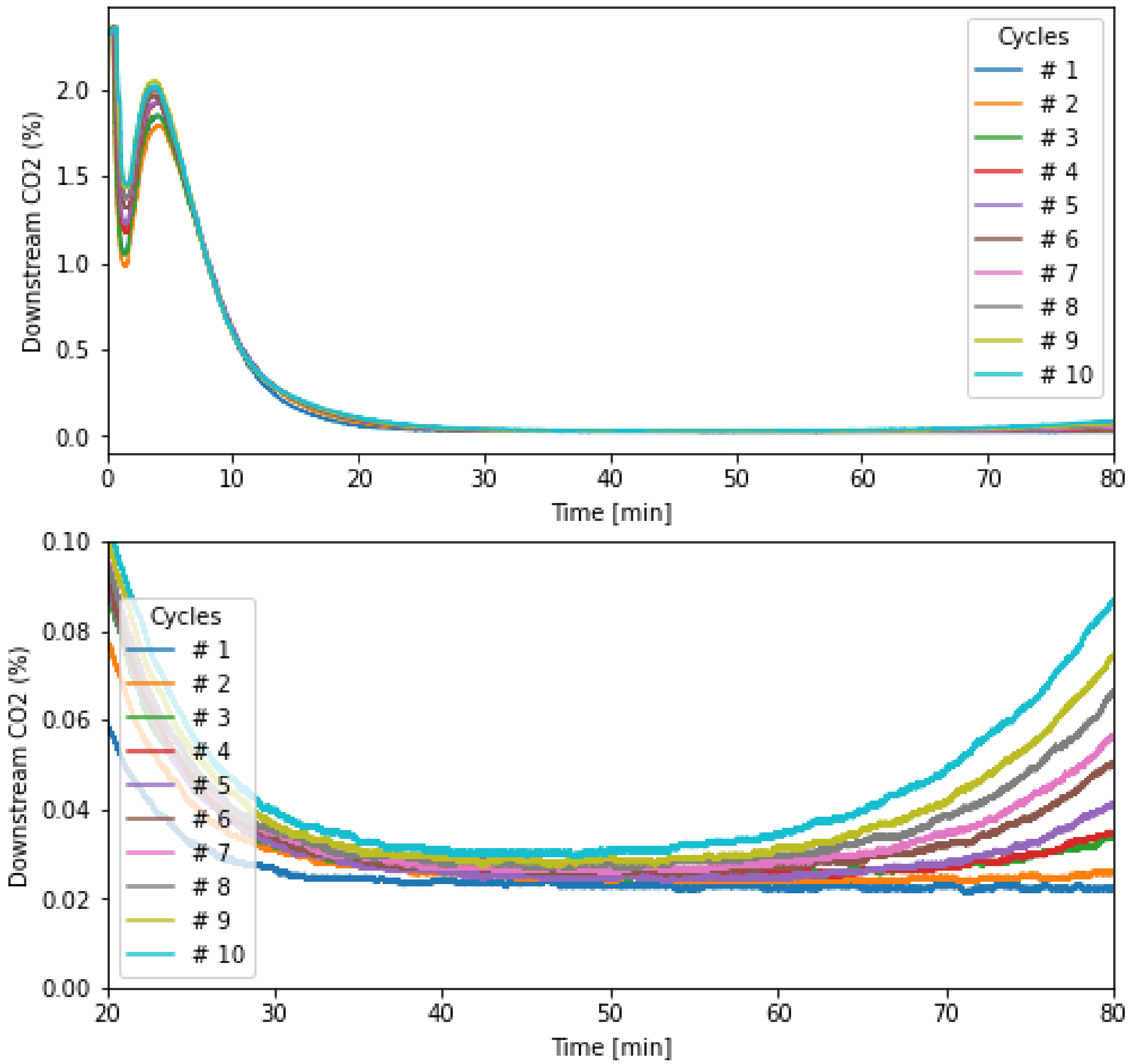


Figure 4.24: Zoom in on adsorption for the ZeoDe characterization experiment shown in Figure 4.23 for a long-duration cyclic test where humidity was introduced after running one dry cycle, attempting to introduce closed-loop logic within labview to simulate a closed habitat. This run experiment did not represent a closed-habitat system as desired.

Figure 4.24 shows just the adsorption portion shown in Figure 4.23 in the upper plot and zooms in on the last 60 minutes of adsorption in the lower plot. From 40 minutes on, we see the same degradation trends in the open-loop testing, again showing that our trends are the same for degradation in a closed-loop habitat.

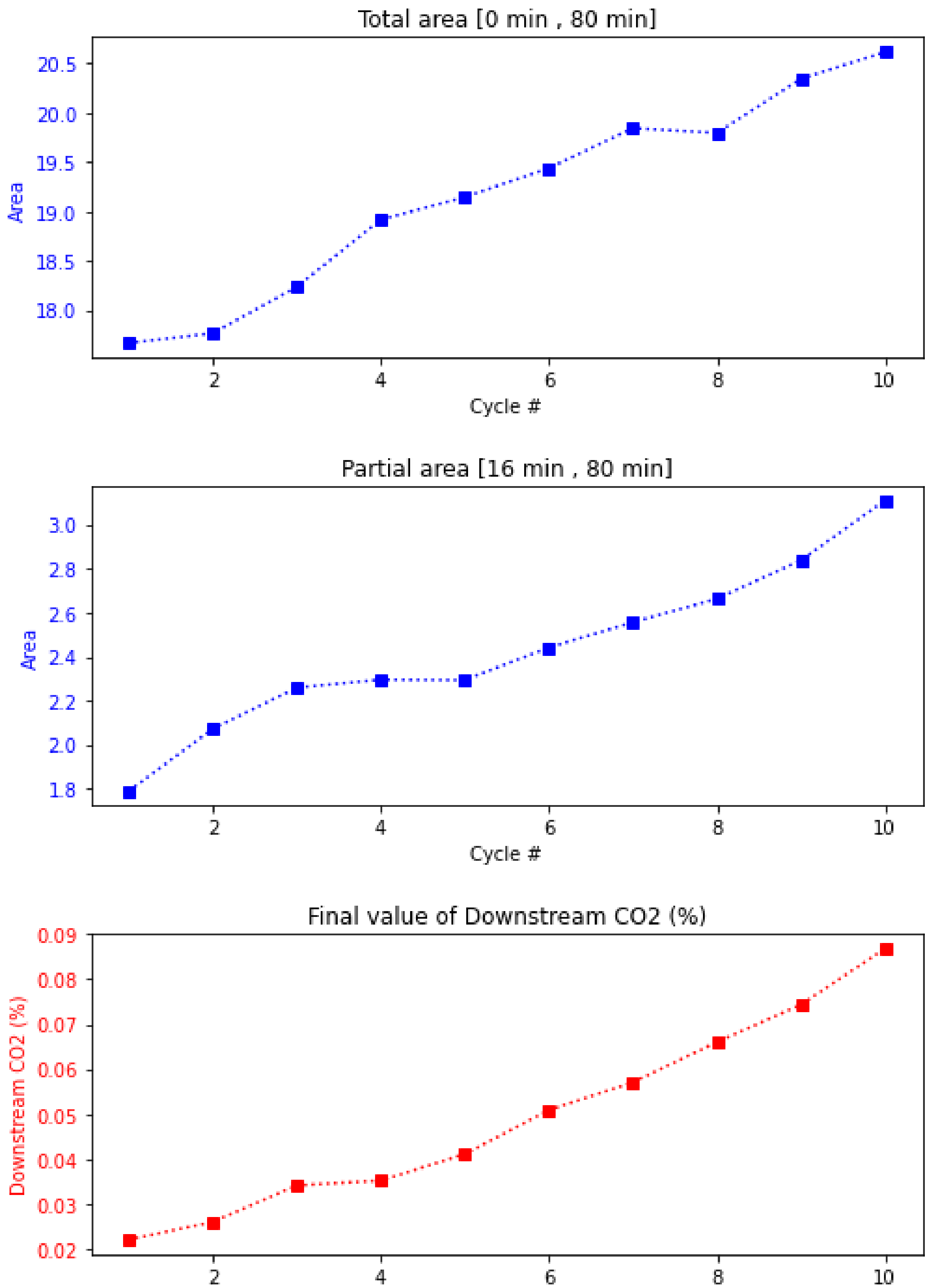


Figure 4.25: Trends for the experiment shown in Figure 4.23 and 4.24 for a long-duration cyclic test where humidity was introduced after running one dry cycle, attempting to introduce closed-loop logic within labview to simulate a closed habitat. This run experiment did not represent a closed-habitat system as desired.

Figure 4.25 Shows the expected trends for degradation, where the total area under the curve and partial area are linear. Now, due to the closed-loop nature of the system, we see a linear trend in the final value of the downstream CO_2 since we are now recirculating our system to represent a closed-loop habitat and are not limited by our first inlet condition of 0.4% CO_2. However, this trend could be intensified by the initial breakthrough of the CO_2 at the outlet due to the increased surface area to volume ratio of the scaled-down ZeoDe system. Therefore, while this experiment is stored for characterization purposes, it is not used to train the ML prognostics algorithms.

Chapter 5

HOME STRI Demonstration Work

5.1 Capstone Framework

Three Capstone demonstrations are planned for presentation at the NASA HOME STRI Year 5 Annual Review. These are meant to showcase the technologies delivered to NASA and reviewed in a summary Annual Review hard copy deliverable to NASA. They are intended to showcase developed technologies in the following three scenarios, one for each capstone.

- Capstone 1: Uncrewed self-maintenance
- Capstone 2: Transition – crew about to arrive in the transfer vehicle
- Capstone 3: Crew onboard

5.2 Capstone Involvement

I served as a co-captain for Capstone 3 and as an individual contributor, providing the ECLSS testbed and a dataset of degradation experiments on which a machine learning algorithm was trained. The following capstone summary was developed by the capstone captains together, including myself, Ulubilge Ulusoy at USC, Heraldo Rozas at Georgia Tech, and Ben Greaves at CU Boulder, and summarizes the demonstration of work performed by the entirety of the HOME Institute.

5.3 Capstone 3

The goal of Capstone 3 is to showcase the integration of several innovative technologies from the HOME STRI in a scenario that demonstrates HOME smart habitat capabilities. This scenario will integrate new capabilities with previously demonstrated research elements to convey a holistic implementation of HOME technology in a future smart habitat. This capstone scenario will demonstrate how predictive analytics can be integrated into an optimization program for computing maintenance schedules and spare parts decisions—including Additive Manufacturing spare part supplies—for critical components of ECLSS*. This capstone will also showcase how complex maintenance tasks can be planned and executed, considering collaborative work between humans and robotic/autonomous agents. The scenario allows for the demonstration of multiple enabling technologies that the STRI has created by using a scenario that allows for the natural flow of how these technologies would be used to address such problems in spaceflight.

The one-line statement goal to describe this capstone is as follows: Perform predictive maintenance of the adsorbent bed and pump bracket of ECLSS (ZeoDe Testbed) with humans and robotic/autonomous agents, thereby showcasing how intelligent optimization/planning modules can transform sensor data to actual maintenance actions. The following is the progression of the capstone step by step, considering the two vehicle states (crew-degraded and crew-nominal).

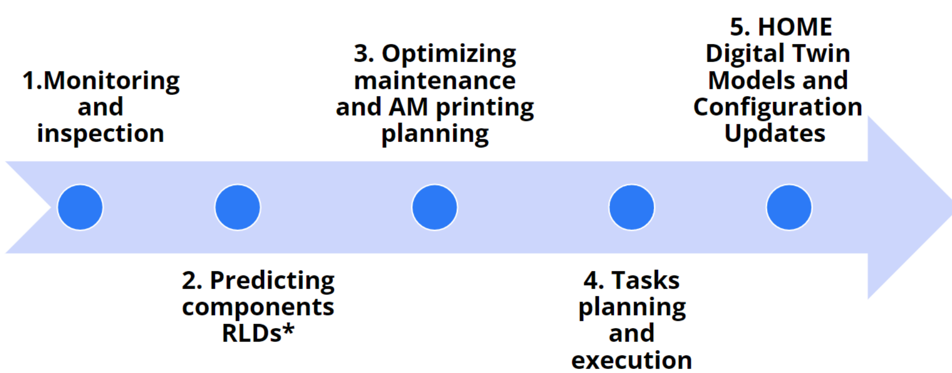


Figure 5.1: Capstone 3 Flow

Assumptions

- The habitat is crewed.
- The habitat is equipped with sensors for monitoring.
- Environmental Control and Life Support System (ECLSS) is monitored by multiple sensors, supported by machine learning algorithms that model the degradation of the sorbent bed and pump.
- The habitat has an Additive Manufacturing (AM) module capable of printing specific spare parts.

- The habitat has a robotic agent(s) that can assist in the AM printing process and conducting maintenance tasks.
- The habitat has an embedded autonomous agent (e.g., large language model-based AI system) that provides task execution support in the style of Earth's mission control.
- Habitat has highly maintainable ECLSS hardware.

Storyboard

1. Detection of accelerated degradation in sorbent bed

- The monitoring module detects accelerated ECLSS sorbent bed performance degradation.
- The accelerated performance degradation is attributed to a leak in the system, which allows humidity into the ECLSS, thus increasing the sorbent bed degradation rate.
- A crew member must investigate and identify the leak when time allows.
- A prognostic module is executed to estimate an updated RLD for the sorbent bed conditional on the new degradation rate.
- The estimated RLD is integrated into the optimization module for scheduling maintenance.
- The maintenance task will include leak detection and repair and sorbent bed replacement
- The maintenance is a complex task that demands the interaction between humans and robots
- The replaced sorbent bed will have to begin a long duration bake out at elevated temperatures to regain performance efficiency, with enhanced safety features implemented, such as off-gassing detection during the elevated operational temperatures

2. Detection of unrelated accelerated degradation in ECLSS pump

- The monitoring module also detects accelerated mechanical degradation in the ECLSS pump through elevated vibration levels.
- Since this anomalous behavior lacks a known cause, and degradation has also just been detected elsewhere in the same system (sorbent bed), it prompts human/robot inspection.
- Upon inspection, the human operator/robot agent identifies a crack in the ECLSS pump bracket. The source of the leak is also found upstream.

- A prognostic module is executed to predict an updated RLD for the cracked pump/bracket conditional on the new degradation rate.
- As this type of part is slotted for this mission to be printed as needed rather than have stored spares, the spare part will be printed using AM.

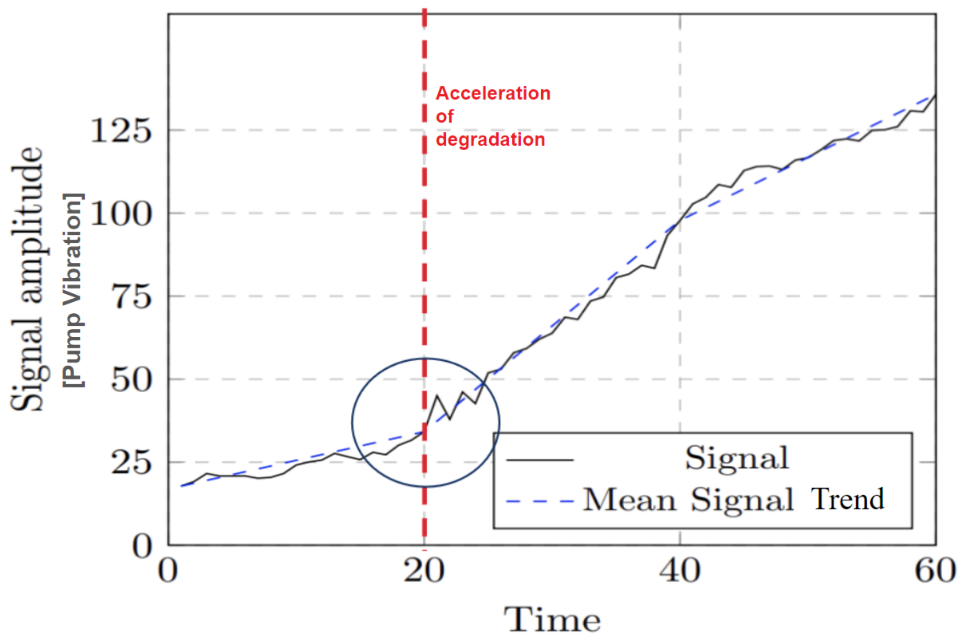


Figure 5.2: Capstone 3 Prognostics plot for pump RUL

3. Optimizing maintenance and AM printing planning :

- New estimated RLDs are integrated into a decision-making module that jointly optimizes maintenance, spare parts inventory, and AM printing schedule.

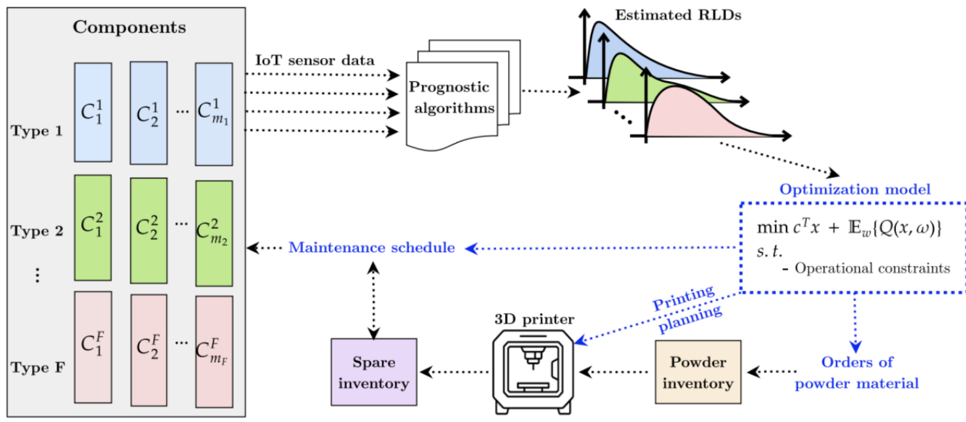


Figure 5.3: Capstone 3 Optimization maintenance and AM printing planning flow

- The optimization model encourages grouping maintenance tasks.
- In this capstone, two components of ECLSS need to be replaced. So, these two repair tasks are scheduled for the same maintenance window.
- Optimization model assigns maintenance tasks to humans and robots.

AM Printing

- A pump bracket is printed in the habitat with a robotics-friendly in-space additive manufacturing process.
- Printing method: Material extrusion and furnace-based sintering.

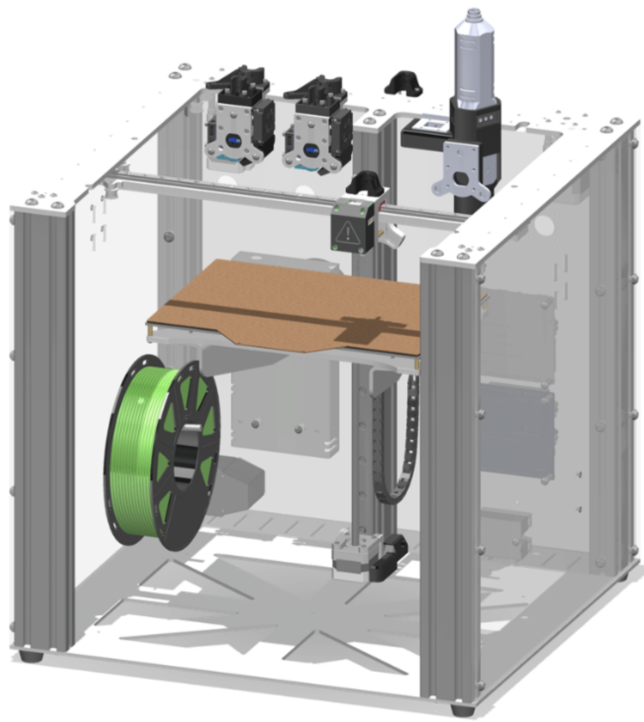


Figure 5.4: Capstone 3 AM print setup

Task Planning

The TACOMA [50]planner, developed by the Intelligent Coordination and Logistics Laboratory at CMU, generates a maintenance task execution plan for the sorbent bed and the pump bracket, considering the availability, capabilities, and limitations of humans and robotic/autonomous agents. (RT4.1)

- Robot plans constraints for symbolic planning and scheduling based on previous interactions. (RT3.3)
- Human trust modeling enables human interaction prediction and robot action planning. Measuring human trust provides a metric for understanding when humans may rely on an autonomous agent in the context of a modeled task.
- Human assistance (Human Factors Respect actions) is considered to potentially overcome the limitations of robotic and autonomous agents while planning their task execution portions. (RT3.8)

- Human Factors Respect is defined as the opportunity cost (e.g., time) incurred by humans when partnering with autonomous agents to improve the combined team's performance and assist them in overcoming their limitations. The assistance actions are categorized as consideration, cooperation, compliance, and correction.

Task Execution

The robotic agent performs a portion of the maintenance task (robotic agent executes actions) while a human crewmate provides supervision and/or assistance.

- The robotic agent provides explanations generated for humans to aid in maintaining situational awareness during supervision. (RT3.7)
- Human trust is queried through verbal interaction to be included in the trust model for the future. (RT3.3)

The human crewmate assists (Human Factors Respect Actions) with the robotic agent as needed. (A potential integration between RT3.7 & RT3.8)

- A human crewmate performs the remaining portion of the maintenance task as it is supported by an embedded autonomous agent (similar to mission control support)
- The human crewmate provides assistance (Human Factors Respect actions) to an embedded autonomous agent (e.g., language-based AI models) to enhance their support capabilities whenever necessary. (RT3.8)
- Projects involved: RT3.3, RT3.7, RT3.8

Chapter 6

Summary, Lessons Learned & Future Work

6.1 Summary

This thesis outlines the design, build, and test of a CO_2 removal testbed used for degradation studies. The testbed's novelty lies in its ability to induce performance degradation by precisely injecting humidity into a zeolite-based sorbent system. The system was validated to match the interstitial velocity and residence time of the current CO_2 removal system onboard the International Space Station. The data produced by the testbed is used to train a machine learning algorithm to predict future states of a degrading system. This capability will be critical for the next generation of deep-space habitats.

The content covered within this thesis spans the entire life cycle of this project. As a result, it includes literature reviews performed to narrow down the choice of project for the thesis to zeolite CO_2 removal packed beds, literature reviews on the state of research on packed beds, and the entire process from design through experimentation as well a demonstration of its application for space.

Key findings of this thesis include

- Zeolite-based packed beds remain a viable and reliable option for space-based CO_2 removal systems [Chapter 1]
- With the push for long-duration space habitation, packed bed flows in microgravity for life support systems are gaining attention and could benefit from the computational tools currently in use by other fields, such as CFD-DEM, which could prove useful for the fluidized nature of beds in microgravity. [Chapter 1.4]
- Chemical Engineering tools such as packed-bed mathematical descriptions and process engineering simulation tools such as Aspen can be transferred to the Aerospace sector and add value to the field of ECLSS [Chapter 1.4 and 2.1]

- A zeolite-based CO_2 removal life support system similar in physics to the 4BCO2/CDRA system with performance degradation induced via humidity introduction can produce degradation data to feed to a machine learning algorithm to predict the future state of this system/time to failure. [design & build in Chapter 3] [validation in Chapter 4]

6.2 Lessons Learned

This thesis has laid out the following

- A detailed description of the design, fabrication, and testing of a new CO_2 removal testbed for ECLSS degradation studies
- In outlining the above, this thesis provides the user with a how-to for both setting up and operating their testbeds
- Experimental data showing validation of initial requirements
- A comprehensive literature review on CO_2 removal technologies and packed bed reactors
- A guide to choosing a path for simulations of similar systems
- An introduction to the purpose and deliverables by the NASA HOME STRI, which funded this research

The following table shows the lessons learned:

Lessons Learned	Category	Actionable steps for the future
Holding a PDR and CDR mitigates risk in schedule and non conformances	Design	Hold a PDR and CDR, giving advanced notice and requests to a review board of professionals both in and outside of your professional organization if possible. NASA especially holds a vast amount of knowledge on proven parts for space-related projects and is a valuable asset on any review board.
Oversized parts shipments can delay schedule	Design	When designing with oversized parts, such as tabletops or long pieces of 80/20, ask the manufacturer how close the facility is to your build location. If possible, pick a distributor that is closer and has a pick-up option. If not, plan for a margin of at least 3 weeks shipping delays
Electrical quick disconnects are useful but connection may loosen over time	Design	If choosing a non-disconnectable connection, give extra margin for cutting off wire. If choosing quick disconnects, write into procedures to watch for error modes in signals and to check sensors against each other with regular cadence.
A BOM is the perfect location for low-tech receiving, quality, and acceptance checks and sign offs	Design & Build	The BOM should be labeled with kitting designations, and should contain a sign off location for received parts, acceptance checks, and quality checks. This also helps to keep track of overdue shipments.
Bending pipe and connecting compression fittings takes surprisingly long	Build	Add extra margin of at least 2 weeks for pipe bending and compression fittings
Dedicated software testing with help for 2+ weeks is ideal for working out bugs	Build	If receiving software support, plan a dedicated 2 week more intensive schedule around 1 month after the planned build time
Academia is lower on the priority list for vendors, and order timelines may be pushed back if check-ins are not made	Build	If schedule is a variable, ask for surge support (colleagues, labmates) to allow for someone to check in with vendors once a week at the onset, and potentially every other day leading up to shipping to ensure order fulfillment is continuing as planned.
Kitting in preparation for building proved efficient, time saving, and helped in organization after build week	Build	Kit all parts as they come in, partitioning by portion of the testbed, and labeling parts as well as the bags and boxes in which they are stored
Mechanical overtemperature relays and overpressure valves are ideal risk mitigators	Health and safety	Assuming a first line of risk mitigation of software over-temperature and pressure fault detection isolation and recovery, secondary mechanical measures are ideal and should be implemented
Sizing gas cylinders to health limits in the lab space both mitigates risk and saves schedule long term for safety training, alarm implementation, and ventilation	Health and safety	If possible, size gas cylinders so that if all gas is released at once, the lab environment is above the critical oxygen limit and below critical exposure limits to the gases in use. If flammability is a concern (for example, with O2), that sizing should be done as well though has added complexities.

Table 6.1: Lessons Learned

6.3 Future Work

This testbed has opened up many opportunities for future work. First, additional experiments are possible without changing any aspects of the testbed. These include additional data generation for degradation studies or adding fault studies into the dataset.

Opportunity Type: Experiments with current testbed setup	
Opportunity	*Description*
Additional Performance Degradation Studies	One set of degradation studies has been performed - more data is key to training machine learning algorithms in degradation detection and could continue accordingly based on ML needs.
Fault studies	In addition to degradation, the ZeoDe testbed is capable of fault simulations such as valve stiction and clogged filters. These experiments could contribute to the fault detection algorithms within the ECLSS community.

Table 6.2: Future Work with current testbed setup

Sofware projects could also expand capabilities with the current testbed setup. These could include the development of an open-source simulation model of ZeoDe, or connecting ZeoDe software to the ARS mockup that currently resides at the UC Davis Center for Spaceflight Research (described in the background of this thesis). It should be noted that if an open-source model is developed for ZeoDe, adding an in-line sampling system to the packed bed would be beneficial to get more accurate readings.

Opportunity type: Software related to current testbed setup	
Opportunity	*Description*
Development of Open-Source Model	The simulation options section of this thesis describes current models/simulations in use for systems like ZeoDe. All current options require a subscription to software. That section also lays out a path towards programming adsorption mass and energy balances using Python, and inputting them into DWSIM. This would create an open source software that can both be used by and contributed to by the ECLSS community.
Connecting ARS Mockup to ZeoDe	The ARS Mock-up, described in the ground-based testbeds section of this thesis, currently resides in the UC Davis Center for Spaceflight Research. This system has the capacity to be built up with internals for ECLSS processes, and potentially connected to the ZeoDe DAQ system.

Table 6.3: Future work related to software

Additional value added could be gained from augmentations to the current testbed setup. On station, CO2 can be vented or sent downstream for further processing. That processing can be added as a secondary or tertiary testbed downstream of ZeoDe. The extra slots with the CompactDAQ within ZeoDe would allow additional testbeds to be connected to the same data collection system, simplifying integration.

Opportunity type: Augmentation of current testbed setup	
Opportunity	*Description*
Swap-out for different packed beds	The modularity of ZeoDe presents a unique opportunity in the realm of research on packed beds. Many life support systems use packed beds, and the form factor of this system would allow for either re-packing the current bed with a different substrate, such as a MOF, solid amines, or a catalyst, or swapping the tube out for a differently packed tube. Additional swap outs could be done with membrane based systems or liquid systems. What remains is that ZeoDe allows for the automated cyclic flow of a representative space habitat environment through a life support system.
Addition of a downstream process	The current ZeoDe setup acts as a CO2 removal system. On station, CO2 can either be vented to space, or it can be sent downstream for Oxygen recovery. The modularity and moveability of the ZeoDe setup would allow for an additional Oxygen recovery device to be added downstream and connected to the same DAQ.
Addition of a plant system	Additional add-ons could include plant systems. This would allow for ground based studies on the optimization of a physiochemical system with a plant-based system.

Table 6.4: Future work related to testbed augmentations

Bibliography

[1] Morgan Abney et al. "Comparison of Exploration Oxygen Recovery Technology Options Using ESM and LSMAC". eng. In: (July 2020). Accepted: 2020-07-30T00:30:07Z Publisher: 2020 International Conference on Environmental Systems. URL: `https://ttu-ir.tdl.org/handle/2346/86428` (visited on 04/20/2022).

[2] Julia Badger and Jeremy D. Frank. "Spacecraft Dormancy Operational Design for a Crewed Martian Reference Mission". In: *2018 AIAA SPACE and Astronautics Forum and Exposition*. AIAA SPACE Forum. American Institute of Aeronautics and Astronautics, Sept. 2018. DOI: `10.2514/6.2018-5117`. URL: `https://arc.aiaa.org/doi/10.2514/6.2018-5117` (visited on 04/17/2022).

[3] Hua Bai et al. "A Coupled DEM and CFD Simulation of Flow Field and Pressure Drop in Fixed Bed Reactor with Randomly Packed Catalyst Particles". In: *Industrial & Engineering Chemistry Research* 48.8 (Apr. 2009). Publisher: American Chemical Society, pp. 4060–4074. ISSN: 0888-5885. DOI: `10.1021/ie801548h`. URL: `https://doi.org/10.1021/ie801548h` (visited on 06/05/2022).

[4] Grace Belancik et al. "Evaluating Capabilities of the Carbon Dioxide Deposition System". eng. In: (July 2020). Accepted: 2020-07-30T00:57:35Z Publisher: 2020 International Conference on Environmental Systems. URL: `https://ttu-ir.tdl.org/handle/2346/86446` (visited on 04/20/2022).

[5] Byron Bird. *Transport Phenomena*. John Wiley & Sons, Inc., 2007.

[6] Vincent Blay et al. *Zeolites and Metal-Organic Frameworks From Lab to Industry*. Apr. 2018. ISBN: 978-94-6298-556-8.

[7] Klaus Bockstahler et al. "Design Status of the Advanced Closed Loop System ACLS for Accommodation on the ISS". eng. In: (July 2016). Accepted: 2016-07-28T19:41:25Z Publisher: 46th International Conference on Environmental Systems. URL: `https://ttu-ir.tdl.org/handle/2346/67723` (visited on 04/20/2022).

[8] Klaus Bockstahler et al. "Status of the Advanced Closed Loop System ACLS for Accommodation on the ISS". en. In: *th International Conference on Environmental Systems* (2017).

[9] Brittany R. Brown et al. "Utilizing Ionic Liquids to Enable the Future of Closed-Loop Life Support Technology". In: NTRS Author Affiliations: NASA Marshall Space Flight Center, Qualis Corp., AZ Technology, Inc., Auburn Univ. NTRS Report/Patent Number: M18-6698 NTRS Document ID: 20180006334 NTRS Research Center: Marshall Space Flight Center (MSFC). Albuquerque, NM, July 2018. URL: https://ntrs.nasa.gov/citations/20180006334 (visited on 04/20/2022).

[10] Zach Bryant, Andrew Choate, and David Howard. "Environmental Control and Life Support (ECLS) System Options for Mars Transit and Mars Surface Missions". eng. In: (July 2023). Accepted: 2023-06-20T15:07:17Z Publisher: 2023 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/94687 (visited on 09/25/2023).

[11] Shanshan Bu et al. "Experimental study of flow transitions in structured packed beds of spheres with electrochemical technique". en. In: *Experimental Thermal and Fluid Science* 60 (Jan. 2015), pp. 106–114. ISSN: 0894-1777. DOI: 10.1016/j.expthermflusci.2014.09.001. URL: https://www.sciencedirect.com/science/article/pii/S0894177714002167 (visited on 05/29/2022).

[12] D. G. Bunnell et al. "Effective Thermal Conductivities in Gas-Solid Systems". In: *Industrial & Engineering Chemistry* 41.9 (Sept. 1949). Publisher: American Chemical Society, pp. 1977–1981. ISSN: 0019-7866. DOI: 10.1021/ie50477a033. URL: https://doi.org/10.1021/ie50477a033 (visited on 06/02/2022).

[13] Amy B. Button and Jeffrey J. Sweterlitsch. *Amine Swingbed Payload Testing on ISS*. eng. Accepted: 2014-10-20T18:40:55Z. 44th International Conference on Environmental Systems, July 2014. ISBN: 978-0-692-38220-2. URL: https://ttu-ir.tdl.org/handle/2346/59626 (visited on 04/20/2022).

[14] H. P. A. Calis et al. "CFD modelling and experimental validation of pressure drop and flow profile in a novel structured catalytic reactor packing". en. In: *Chemical Engineering Science*. 16th International Conference on Chemical Reactor Engineering 56.4 (Feb. 2001), pp. 1713–1720. ISSN: 0009-2509. DOI: 10.1016/S0009-2509(00)00400-0. URL: https://www.sciencedirect.com/science/article/pii/S0009250900004000 (visited on 06/05/2022).

[15] Joyce Carpenter et al. "Poisoning Evaluation of On-Orbit Sabatier Assembly". eng. In: (July 2020). Accepted: 2020-07-30T01:53:28Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86470 (visited on 10/16/2023).

[16] *Cfd Simulation Of Catalytic Converter*. en. Jan. 2022. URL: https://www.learncax.com/knowledge-base/blog/by-category/cfd/cfd-simulation-of-catalytic-converter (visited on 02/01/2024).

[17] *CFD-DEM: Modeling the Small to Understand the Large*. en. Sept. 2017. URL: https://www.aiche.org/resources/publications/cep/2017/september/cfd-dem-modeling-small-understand-large (visited on 06/05/2022).

[18] Amanda Childers et al. "Chemical Vapor Deposition Methane Pyrolysis Enables Closed-Loop Oxygen Recovery: Reducing System Consumables". eng. In: (July 2021). Accepted: 2021-06-23T16:37:10Z Publisher: 50th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/87052 (visited on 04/20/2022).

[19] T. H. Chilton and A. P. Colburn. "Mass Transfer (Absorption) Coefficients Prediction from Data on Heat Transfer and Fluid Friction". en. In: *Industrial & Engineering Chemistry* 26.11 (Nov. 1934), pp. 1183–1187. ISSN: 0019-7866, 1541-5724. DOI: 10.1021/ie50299a012. URL: https://pubs.acs.org/doi/abs/10.1021/ie50299a012 (visited on 06/01/2022).

[20] Lisa Chu et al. "Development of the Liquid Amines Ground-Based Test System". eng. In: (July 2021). Accepted: 2021-06-24T14:25:47Z Publisher: 50th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/87118 (visited on 04/20/2022).

[21] James Clawson et al. "NextSTEP Appendix A Modular ECLSS Effort Lessons Learned". eng. In: (July 2023). Accepted: 2023-06-20T15:40:17Z Publisher: 2023 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/94726 (visited on 09/25/2023).

[22] Gregory Cmarik. "Co-Adsorption of Carbon Dioxide on Zeolite 13X in the Presence of Preloaded Water". eng. In: (July 2018). Publisher: 48th International Conference on Environmental Systems. URL: http://hdl.handle.net/2346/74024 (visited on 01/31/2024).

[23] Gregory Cmarik and James Knox. "CO2 Removal for the International Space Station – 4-Bed Molecular Sieve Material Selection and System Design". eng. In: (July 2019). Accepted: 2019-06-20T16:21:16Z Publisher: 49th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/84429 (visited on 04/20/2022).

[24] Gregory Cmarik, James Knox, and Timothy Huff. "Analysis of Performance Degradation of Silica Gels after Extended use Onboard the ISS". eng. In: (July 2018). Publisher: 48th International Conference on Environmental Systems. URL: http://hdl.handle.net/2346/74023 (visited on 01/31/2024).

[25] Gregory Cmarik, James Knox, and Warren Peters. "4-Bed CO2 Scrubber – From Design to Build". eng. In: *49th International Conference on Environmental Systems, 2020*. Accepted: 2020-07-30T00:53:01Z. 2020 International Conference on Environmental Systems, July 2020. URL: https://ttu-ir.tdl.org/handle/2346/86440 (visited on 04/20/2022).

[26] Marc M Cohen et al. "Water Walls Life Support Architecture: 2012 NIAC PHase I Final Report". en. In: (2012), p. 54.

[27] Tom Crotzer and Ryan Hooper. "Development of a Proof-of-Concept Laser Pyrolysis Assembly (LPA)". eng. In: (July 2020). Accepted: 2020-07-30T01:42:20Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86467 (visited on 04/20/2022).

[28] Gisela Detrell et al. "PBR@LSR: the Algae-based Photobioreactor Experiment at the ISS – Operations and Results". eng. In: (July 2020). Accepted: 2020-07-27T13:54:06Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86331 (visited on 04/20/2022).

[29] S. Dey and Niraj Mehta. "Automobile pollution control using catalysis". In: *Resources, Environment and Sustainability* 2 (Dec. 2020), p. 100006. DOI: 10.1016/j.resenv.2020.100006.

[30] Meili Ding and Hai-Long Jiang. "Improving Water Stability of Metal–Organic Frameworks by a General Surface Hydrophobic Polymerization". en. In: *CCS Chemistry* 3.8 (Aug. 2021), pp. 2740–2748. ISSN: 2096-5745. DOI: 10.31635/ccschem.020.202000515. URL: http://www.chinesechemsoc.org/doi/10.31635/ccschem.020.202000515 (visited on 02/16/2022).

[31] Anthony G. Dixon and Michiel Nijemeisland. "CFD as a Design Tool for Fixed-Bed Reactors". In: *Industrial & Engineering Chemistry Research* 40.23 (Nov. 2001). Publisher: American Chemical Society, pp. 5246–5254. ISSN: 0888-5885. DOI: 10.1021/ie001035a. URL: https://doi.org/10.1021/ie001035a (visited on 06/01/2022).

[32] P. N. Dwivedi and S. N. Upadhyay. "Particle-Fluid Mass Transfer in Fixed and Fluidized Beds". In: *Industrial & Engineering Chemistry Process Design and Development* 16.2 (Apr. 1977). Publisher: American Chemical Society, pp. 157–165. ISSN: 0196-4305. DOI: 10.1021/i260062a001. URL: https://doi.org/10.1021/i260062a001 (visited on 06/01/2022).

[33] T. Eppinger, K. Seidler, and M. Kraume. "DEM-CFD simulations of fixed bed reactors with small tube to particle diameter ratios". en. In: *Chemical Engineering Journal* 166.1 (Jan. 2011), pp. 324–331. ISSN: 13858947. DOI: 10.1016/j.cej.2010.10.053. URL: https://linkinghub.elsevier.com/retrieve/pii/S1385894710010089 (visited on 05/29/2022).

[34] Samuel Eshima et al. "Generating Anomalous Regenerable CO2 Removal System Data for Environmental Control and Life Support System Self-Awareness". eng. In: (July 2022). Publisher: 51st International Conference on Environmental Systems. URL: https://hdl.handle.net/2346/89798 (visited on 01/02/2024).

[35] *Facilities at the Analytics and Prognostics Systems Laboratory — Predictive Analytics and Intelligent Systems (PAIS)*. URL: https://pais.scl.gatech.edu/facilities (visited on 03/14/2024).

[36] Michael T Flynn. "WATER WALLS ARCHITECTURE:" en. In: (), p. 138.

[37] Scott Fogler. *Elements of Chemical Reaction Engineering*. Pearson Education, Inc., 2006.

[38] Nagi Gebraeel et al. "Prognostics and remaining useful life prediction of machinery: advances, opportunities and challenges". In: *Journal of Dynamics, Monitoring and Diagnostics* (2023), pp. 1–12. URL: https://ojs.istp-press.com/dmd/article/view/148 (visited on 03/14/2024).

[39] D. J. Gunn, M. M. Ahmad, and M. N. Sabri. "Radial heat transfer to fixed beds of particles". en. In: *Chemical Engineering Science* 42.9 (Jan. 1987), pp. 2163–2171. ISSN: 0009-2509. DOI: 10.1016/0009-2509(87)85037-6. URL: https://www.sciencedirect.com/science/article/pii/0009250987850376 (visited on 06/02/2022).

[40] Mengzhi Guo et al. "A Highly Efficient and Stable Composite of Polyacrylate and Metal–Organic Framework Prepared by Interface Engineering for Direct Air Capture". en. In: *ACS Applied Materials & Interfaces* 13.18 (May 2021), pp. 21775–21785. ISSN: 1944-8244, 1944-8252. DOI: 10.1021/acsami.1c03661. URL: https://pubs.acs.org/doi/10.1021/acsami.1c03661 (visited on 02/16/2022).

[41] Loura Hall. *Water Walls: Highly Reliable and Life Support Architecture*. und. Text. Mar. 2019. URL: http://www.nasa.gov/directorates/spacetech/niac/2012_Phase_I_water_walls (visited on 02/16/2022).

[42] Danny W Harris et al. "Moon to Mars (M2M) Habitation Considerations". en. In: (2022).

[43] Joseph Hartvigsen, S. Elangovan, and Lyman Frost. "MOXIE Development Driven Prospects For ISRU and Atmosphere Revitalization". eng. In: (July 2018). Accepted: 2018-07-07T22:01:26Z Publisher: 48th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/74181 (visited on 04/20/2022).

[44] Harald Helisch et al. "Non-axenic microalgae cultivation in space – Challenges for the membrane µgPBR of the ISS experiment PBR@LSR". eng. In: (July 2018). Accepted: 2018-07-07T16:46:21Z Publisher: 48th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/74157 (visited on 02/16/2022).

[45] Phoebe Henson et al. "An Environmental Control and Life Support System (ECLSS) for Deep Space and Commercial Habitats". eng. In: (July 2021). Accepted: 2021-06-24T15:19:53Z Publisher: 50th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/87157 (visited on 04/20/2022).

[46] Phoebe Henson et al. "Carbon Dioxide Removal by Ionic Liquid System (CDRILS): Continuous Operation and Full-Scale Brassboard Testing". eng. In: (July 2021). Accepted: 2021-06-24T15:19:06Z Publisher: 50th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/87156 (visited on 04/20/2022).

[47] Paul E. Hintze et al. “Self-Cleaning Boudouard Reactor for Full Oxygen Recovery from Carbon Dioxide”. eng. In: (July 2016). Accepted: 2016-07-28T19:19:44Z Publisher: 46th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/67644 (visited on 04/20/2022).

[48] *Home — Shannon Lackey*. en. URL: https://shannonlackey2022.wixsite.com/portfolio1 (visited on 03/15/2024).

[49] Weixin Huang et al. “Enhanced Catalytic Activity for Methane Combustion through *in Situ* Water Sorption”. en. In: *ACS Catalysis* 10.15 (Aug. 2020), pp. 8157–8167. ISSN: 2155-5435, 2155-5435. DOI: 10.1021/acscatal.0c02087. URL: https://pubs.acs.org/doi/10.1021/acscatal.0c02087 (visited on 05/30/2022).

[50] *Intelligent Coordination and Logistics Laboratory - Robotics Institute Carnegie Mellon University*. URL: https://www.ri.cmu.edu/robotics-groups/intelligent-coordination-and-logistics-laboratory/ (visited on 03/15/2024).

[51] Daniela Ivey et al. “Design, Build, Test of a CO2 Removal Testbed and Twin Robotically Manipulable Testbed: Sensing Degradation and Performing Maintenance with Robot/Human Teaming”. eng. In: (July 2023). URL: https://ttu-ir.tdl.org/handle/2346/94645 (visited on 09/05/2023).

[52] Ambalavanan Jayaraman et al. “Demonstration of a Closed-Loop CO2 Removal System for Deep-Space ECLSS”. eng. In: (July 2020). Accepted: 2020-07-30T00:35:49Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86434 (visited on 04/20/2022).

[53] Ambalavanan Jayaraman et al. “Highly Efficient Closed-Loop CO2 Removal System for Deep-Space ECLSS”. eng. In: (July 2019). Accepted: 2019-06-20T17:50:26Z Publisher: 49th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/84463 (visited on 04/20/2022).

[54] K. R. Jolls and T. J. Hanratty. “Transition to turbulence for flow through a dumped bed of spheres”. en. In: *Chemical Engineering Science* 21.12 (Dec. 1966), pp. 1185–1190. ISSN: 0009-2509. DOI: 10.1016/0009-2509(66)85038-8. URL: https://www.sciencedirect.com/science/article/pii/0009250966850388 (visited on 05/29/2022).

[55] Nico Jurtz. “Particle-resolved CFD as tool for multi-scale design exploration for process intensification in slender fixed-beds”. PhD thesis. Feb. 2022. DOI: 10.14279/depositonce-14894.

[56] Daniel Kaschubek and James Nabity. “Modeling and Simulation of Component Degradation and Faults in the Carbon Dioxide Removal Assembly”. eng. In: (July 2022). Accepted: 2022-06-21T00:14:39Z Publisher: 51st International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/89758 (visited on 10/16/2023).

[57] M Kaviany. *Principles of Heat Transfer in Porous Media*. en. 1995. URL: https://link.springer.com/book/10.1007/978-1-4612-4254-3 (visited on 06/04/2022).

[58] James Knox, Warren Peters, and Gregory Cmarik. "Optimization of the 4-Bed CO2 Scrubber Performance Based on Ground Tests". eng. In: (July 2021). Publisher: 50th International Conference on Environmental Systems. URL: https://hdl.handle.net/2346/87078 (visited on 02/01/2024).

[59] James C. Knox. *Finite Difference Modeling and Experimental Investigation of Carbon Dioxide Adsorption on a Molecular Sieve Sorbent Material Used in Spacecraft Carbon Dioxide Removal Systems.* 1992.

[60] James C. Knox. "Predictive Simulation of Gas Adsorption in Fixed-Beds and Limitations due to the Ill-Posed Danckwerts Boundary Condition". In: *Dissertation, Alabama University* (2016).

[61] James C. Knox et al. "Limitations of Breakthrough Curve Analysis in Fixed-Bed Adsorption". In: *Industrial & Engineering Chemistry Research* 55.16 (Apr. 2016). Publisher: American Chemical Society, pp. 4734–4748. ISSN: 0888-5885. DOI: 10.1021/acs.iecr.6b00516. URL: https://doi.org/10.1021/acs.iecr.6b00516 (visited on 05/29/2022).

[62] B Koning. "Heat and Mass Transport in Tubular Packed Bed Reactors at Reacting and Non-Reacting Conditions". en. In: (), p. 297.

[63] W. A. S. Kumara et al. "Comparison of Particle Image Velocimetry and Laser Doppler Anemometry measurement methods applied to the oil–water flow in horizontal pipe". en. In: *Flow Measurement and Instrumentation* 21.2 (June 2010), pp. 105–117. ISSN: 0955-5986. DOI: 10.1016/j.flowmeasinst.2010.01.005. URL: https://www.sciencedirect.com/science/article/pii/S0955598610000130 (visited on 06/05/2022).

[64] Max Leva. *Fluid Flow Through Packed and Fluidized Systems*. en. Google-Books-ID: 8T8ixAEACAAJ. U.S. Government Printing Office, 1951. ISBN: 978-0-598-89369-7.

[65] Chi-Hsiung Li and B. A. Finlayson. "Heat transfer in packed beds—a reevaluation". en. In: *Chemical Engineering Science* 32.9 (Jan. 1977), pp. 1055–1066. ISSN: 0009-2509. DOI: 10.1016/0009-2509(77)80143-7. URL: https://www.sciencedirect.com/science/article/pii/0009250977801437 (visited on 06/04/2022).

[66] Yongsheng Lian, Brian Motil, and Enrique Rame. "Investigation of Multiphase Flow in a Packed Bed Reactor under Microgravity Conditions". en. In: *46th AIAA Fluid Dynamics Conference*. Washington, D.C.: American Institute of Aeronautics and Astronautics, June 2016. ISBN: 978-1-62410-436-7. DOI: 10.2514/6.2016-4274. URL: https://arc.aiaa.org/doi/10.2514/6.2016-4274 (visited on 06/05/2022).

[67] Habib Mohamadinejad et al. "Hardware-Independent Mathematical and Numerical Modeling of a Four Bed Molecular Sieve - Part 1: Modeling and Verification of Gas Adsorption on Zeolite 5A". In: *SAE Transactions* 105 (1996). Publisher: SAE International, pp. 349–361. ISSN: 0096-736X. URL: https://www.jstor.org/stable/44725522 (visited on 06/04/2022).

[68] O. Molerus and K. E. Wirth. *Heat Transfer in Fluidized Beds*. en. Google-Books-ID: x5N9CAAAQBAJ. Springer Science & Business Media, Dec. 2012. ISBN: 978-94-011-5842-8.

[69] Nader Montazerin, Ghasem Akbari, and Moastafa Mahmoodi. *Developments in Turbomachinery Flow: Forward Curved Centrifugal Fans*. en. Google-Books-ID: kZKDBAAAQBAJ. Woodhead Publishing, July 2015. ISBN: 978-1-78242-193-1.

[70] Faith Morrison. "An Introduction to Fluid Mechanics". en. In: *Cambridge University Press* (2013), p. 946.

[71] NASA. *Astronaut Steve Swanson Performs CDRA Maintenance - NASA*. en-US. 2014. URL: https://www.nasa.gov/image-article/astronaut-steve-swanson-performs-cdra-maintenance/ (visited on 10/17/2023).

[72] William Papale et al. "An Advanced CO2 Removal System using Regenerable Solid Amines". eng. In: (July 2016). Accepted: 2016-07-28T18:20:57Z Publisher: 46th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/67557 (visited on 04/20/2022).

[73] L. J. Petrovic and George Thodos. "Mass Transfer in Flow of Gases through Packed Beds. Low Reynolds Number Region". In: *Industrial & Engineering Chemistry Fundamentals* 7.2 (May 1968). Publisher: American Chemical Society, pp. 274–280. ISSN: 0196-4313. DOI: 10.1021/i160026a016. URL: https://doi.org/10.1021/i160026a016 (visited on 06/01/2022).

[74] Holden Ranz, Steven Dionne, and John Garr. "A Thermally-Regenerated Solid Amine CO2 Removal System Incorporating Water Vapor Recovery and Ullage Air Recovery". en. In: *th International Conference on Environmental Systems* (2019), p. 13.

[75] Holden Ranz, Steven Dionne, and John Garr. "Thermal Amine Scrubber – Space Station Installation and Start-Up". eng. In: (July 2020). Accepted: 2020-07-30T00:56:04Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86444 (visited on 04/20/2022).

[76] Tanya Rogers et al. "Selection and Characterization of a Liquid Sorbent for CO2 Removal in Advanced Exploration Systems". eng. In: (July 2017). Accepted: 2017-07-07T16:03:51Z Publisher: 47th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/72943 (visited on 04/20/2022).

[77] Jake Rohrig, Jonathan O'Neill, and Tom Stapleton. "In-Flight Maintenance Design Philosophy for Gateway and Deep-Space Life Support Systems". In: 49th International Conference on Environmental Systems, 2019.

[78] S. J. P Romkes et al. “CFD modelling and experimental validation of particle-to-fluid mass and heat transfer in a packed bed at very low channel to particle diameter ratio”. en. In: *Chemical Engineering Journal*. Festschrift Prof. Cor M. van den Bleek 96.1 (Dec. 2003), pp. 3–13. ISSN: 1385-8947. DOI: 10.1016/j.cej.2003.08.026. URL: https://www.sciencedirect.com/science/article/pii/S1385894703002328 (visited on 06/01/2022).

[79] Douglas M. Ruthven. *Principles of Adsorption and Adsorption Processes*. John Wiley & Sons, Inc., 1984. ISBN: 0-471-86606-7.

[80] Masato Sakurai et al. “Preliminary Study of CO2 Electrolysis in Ionic Liquid”. eng. In: (July 2019). Accepted: 2019-06-28T20:13:14Z Publisher: 49th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/84916 (visited on 02/16/2022).

[81] Laura A Shaw et al. “International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2020 Status”. en. In: (), p. 12.

[82] H. L. Shulman and J. J. DeGouff. “Mass Transfer Coefficients and Interfacial Areas for 1-Inch Raschig Rings”. In: *Industrial & Engineering Chemistry* 44.8 (Aug. 1952). Publisher: American Chemical Society, pp. 1915–1922. ISSN: 0019-7866. DOI: 10.1021/ie50512a048. URL: https://doi.org/10.1021/ie50512a048 (visited on 06/01/2022).

[83] Nevin Smalls et al. “Implementation of Advanced Sorbents in a Pressure-Swing Carbon Dioxide Removal System”. eng. In: (July 2020). Accepted: 2020-07-30T00:19:45Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86424 (visited on 04/20/2022).

[84] Christine Stanley et al. “Alternative Carbon Formation Reactors for the Series-Bosch System”. eng. In: (July 2018). Accepted: 2018-07-06T19:40:24Z Publisher: 48th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/74039 (visited on 04/20/2022).

[85] Christine Stanley et al. “Evolving Maturation of the Series-Bosch System”. eng. In: (July 2017). Accepted: 2017-07-07T21:59:21Z Publisher: 47th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/73016 (visited on 04/20/2022).

[86] Chel Stromgren et al. “Assessment of Crew Time for Maintenance and Repair Activities for Lunar Surface Missions”. en. In: *2022 IEEE Aerospace Conference (AERO)*. Big Sky, MT, USA: IEEE, Mar. 2022, pp. 01–10. ISBN: 978-1-66543-760-8. DOI: 10.1109/AERO53065.2022.9843431. URL: https://ieeexplore.ieee.org/document/9843431/ (visited on 09/25/2023).

[87] Motoyuki Suzuki. *Adsorption Engineering: Motoyuki Suzuki*. en. Google-Books-ID: IR2itQEACAAJ. Elsevier, 1990. ISBN: 978-0-444-41295-9.

[88] Aaron Thornton et al. “Developing Metal-Organic Frameworks (MOF) to Achieve Earth-Like CO2 Levels for Advanced Space Exploration”. eng. In: (July 2020). Accepted: 2020-07-30T01:00:25Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86450 (visited on 04/20/2022).

[89] Monica Torralba. “Modeling and Simulation of Carbon Dioxide Removal for Environmental Control and Life Support Systems for Deep Space Habitats”. en. M.S. Mechanical & Aerospace Engineering. University of California, Davis, 2022. URL: https://www.proquest.com/openview/f9be5010d1029a2c79916d67750854c2/1?pq-origsite=gscholar&cbl=18750&diss=y (visited on 05/14/2023).

[90] Evangelos Tsotsas. “M7 Heat and Mass Transfer in Packed Beds with Fluid Flow”. en. In: *VDI Heat Atlas*. VDI-Buch. Berlin, Heidelberg: Springer, 2010, pp. 1327–1342. ISBN: 978-3-540-77877-6. DOI: 10.1007/978-3-540-77877-6_100. URL: https://doi.org/10.1007/978-3-540-77877-6_100 (visited on 05/30/2022).

[91] J. J Van Deemter. “Heat and Mass Transport in a Fixed Catalyst Bed During Regeneration”. en. In: *Industrial & Engineering Chemistry* 46.11 (1954), p. 3.

[92] N. Wakao and T. Funazkri. “Effect of fluid dispersion coefficients on particle-to-fluid mass transfer coefficients in packed beds: Correlation of sherwood numbers”. en. In: *Chemical Engineering Science* 33.10 (Jan. 1978), pp. 1375–1384. ISSN: 0009-2509. DOI: 10.1016/0009-2509(78)85120-3. URL: https://www.sciencedirect.com/science/article/pii/0009250978851203 (visited on 06/01/2022).

[93] Richard Wheeler et al. “Plasma Pyrolysis Assembly (PPA) Zero-g Flight Experiment Development”. eng. In: (July 2018). Accepted: 2018-07-06T23:09:27Z Publisher: 48th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/74078 (visited on 04/20/2022).

[94] Richard R Wheeler et al. “Results from the Plasma Pyrolysis Assembly (PPA) Zero-g Flight Experiment”. en. In: (), p. 13.

[95] Jill Williamson et al. “Upgrades to the International Space Station Urine Processor Assembly”. eng. In: (July 2019). Accepted: 2019-06-26T14:08:56Z Publisher: 49th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/84727 (visited on 10/16/2023).

[96] Dale Winton et al. “Carbon Dioxide Removal Technologies for Space Vehicles - Past, Present, and Future”. eng. In: (July 2016). Accepted: 2016-07-28T19:41:26Z Publisher: 46th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/67727 (visited on 10/16/2023).

[97] Johannes Witt et al. “On-orbit Testing of the Advanced Closed Loop System ACLS”. eng. In: (July 2020). Accepted: 2020-07-30T01:58:59Z Publisher: 2020 International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/86479 (visited on 04/20/2022).

[98] Marek A. Wojtowicz et al. "Pressure-Swing Adsorption of Trace Contaminants Using Carbon Sorbent Monoliths". eng. In: (July 2021). Accepted: 2021-06-24T20:50:19Z Publisher: 50th International Conference on Environmental Systems. URL: https://ttu-ir.tdl.org/handle/2346/87272 (visited on 06/01/2022).

[99] B. D. Wood et al. "A comparison of measured and modeled velocity fields for a laminar flow in a porous medium". en. In: *Advances in Water Resources* 85 (Nov. 2015), pp. 45–63. ISSN: 0309-1708. DOI: 10.1016/j.advwatres.2015.08.013. URL: https://www.sciencedirect.com/science/article/pii/S0309170815001992 (visited on 06/05/2022).

[100] Zhouzun Xie, Shuai Wang, and Yansong Shen. "CFD-DEM modelling of the migration of fines in suspension flow through a solid packed bed". en. In: *Chemical Engineering Science* 231 (Feb. 2021), p. 116261. ISSN: 0009-2509. DOI: 10.1016/j.ces.2020.116261. URL: https://www.sciencedirect.com/science/article/pii/S0009250920307934 (visited on 06/05/2022).

[101] Sakae Yagi, Daizo Kunii, and Noriaki Wakao. "Studies on axial effective thermal conductivities in packed beds". en. In: *AIChE Journal* 6.4 (1960). _eprint: https://onlinelibrary.wiley.com pp. 543–546. ISSN: 1547-5905. DOI: 10.1002/aic.690060407. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/aic.690060407 (visited on 06/04/2022).

[102] Victor Yakhot and Steven A. Orszag. "Renormalization group analysis of turbulence. I. Basic theory". en. In: *Journal of Scientific Computing* 1.1 (Mar. 1986), pp. 3–51. ISSN: 1573-7691. DOI: 10.1007/BF01061452. URL: https://doi.org/10.1007/BF01061452 (visited on 03/14/2024).

[103] Mustafa Alper Yildiz et al. "Direct Numerical Simulation of the Flow Through a Randomly Packed Pebble Bed". In: *Journal of Fluids Engineering* 142.4 (Jan. 2020). ISSN: 0098-2202. DOI: 10.1115/1.4045439. URL: https://doi.org/10.1115/1.4045439 (visited on 06/05/2022).

Chapter 7

Appendix

This appendix includes:

- 7.1 Glossary
- 7.2 Technology Readiness Level
- 7.3 Operational Procedures
- 7.4 Non-conformances
- 7.5 CDR Reviewer Questions and Responses
- 7.6 NASA Maintenance Procedures

7.1 Glossary

Acronym	Definition	Note
4BCO2	4 Bed CO2 removal system	Same as 4BMS
4BMS	4 Bed Molecular Sieve	Same as 4BCO2
ACLS	Advanced Closed Loop System	
AM	Additive Manufacturing	
ARS	Air Revitalization System	
CAMRAS	CO2 and Moisture Removal Amine Swing-Bed	
CBOS	Continuous Bosch Reactor	
CCA	Carbon Capture Assembly	
CDEP	Carbon Dioxide Deposition System	
CDRA	Carbon Dioxide Removal Assembly	
CDRILS	Carbon Dioxide Removal by Ionic Liquid System	
CFD	Computational Fluid Dynamics	
CFR	Carbon Formation Reactor	
CFR	Carbon Formation Reactor	
CHX	Heat Exchanger	
DEM	Discrete Element Method	
DNS	Direct Numerical Simulation	
ECLSS	Environmental Control & Life Support Systems	
EXPRESS	Expedite the PRocessing of Experiments to Space Station	
HEPA	High Efficiency Particulate Air filter	
HMT	Human Machine Teaming	
HOME	Habitats Optimized for Missions of Exploration	
ICES	International Conference on Environmental Systems	
ISS	International Space Station	
JAXA	Japan Aerospace Exploration Agency	
LDA	Laser Doppler Anemometry	
LPM	Liters Per Minute	
MFC	Mass Flow Controller	
MOFs	Metal Organic Frameworks	
NASA	National Astronautics and Space Administration	
NASA KSC	NASA Kennedy Space Center	

NASA MSFC	NASA Marshall Space Flight Center	
NPT	National Pipe Thread	
OGA	Oxygen Generation Assembly	
PDE	Partial Differential Equation	
PID	Proportional Integral Derivative	
PIV	Particle Image Velocimetry	
ppm	parts per million	
psi	Pounds per Square Inch	
PTFE	Polytetrafluoroethylene	
RANS	Reynolds Averaged Navier-Stokes equations	
Re	Reynolds Number	
rH	Relative Humidity	
RNG	Renormalization Group	
ROI	Return On Investment	
RTs	Research Thrusts	
RUL	Remaining Useful Life	
RWGS	Reverse Water Gas Shift reactor	
SLPM	Standard Liters Per Minute	
SME	Subject Matter Expert	
STEVE	Simulation Testbed for Exploration Vehicle ECLSS V&V - Verification and validation	
STP	Standard Temperature & Pressure	
STRI	Space Technology Research Institute	
TAS	Thermal Amine Scrubber	
TRL	Technology Readiness Level	
UPA	Urine Processing Assembly	
WPA	Water Processing Assembly	
WPS	Water Processing System	
ZeoDe	Zeolite performance Degradation testbed	

7.2 Technology Readiness Level

The below has been published by NASA as a guide to Technology Readiness Levels (TRLs) and was used in the air revitalization technology review in this thesis.

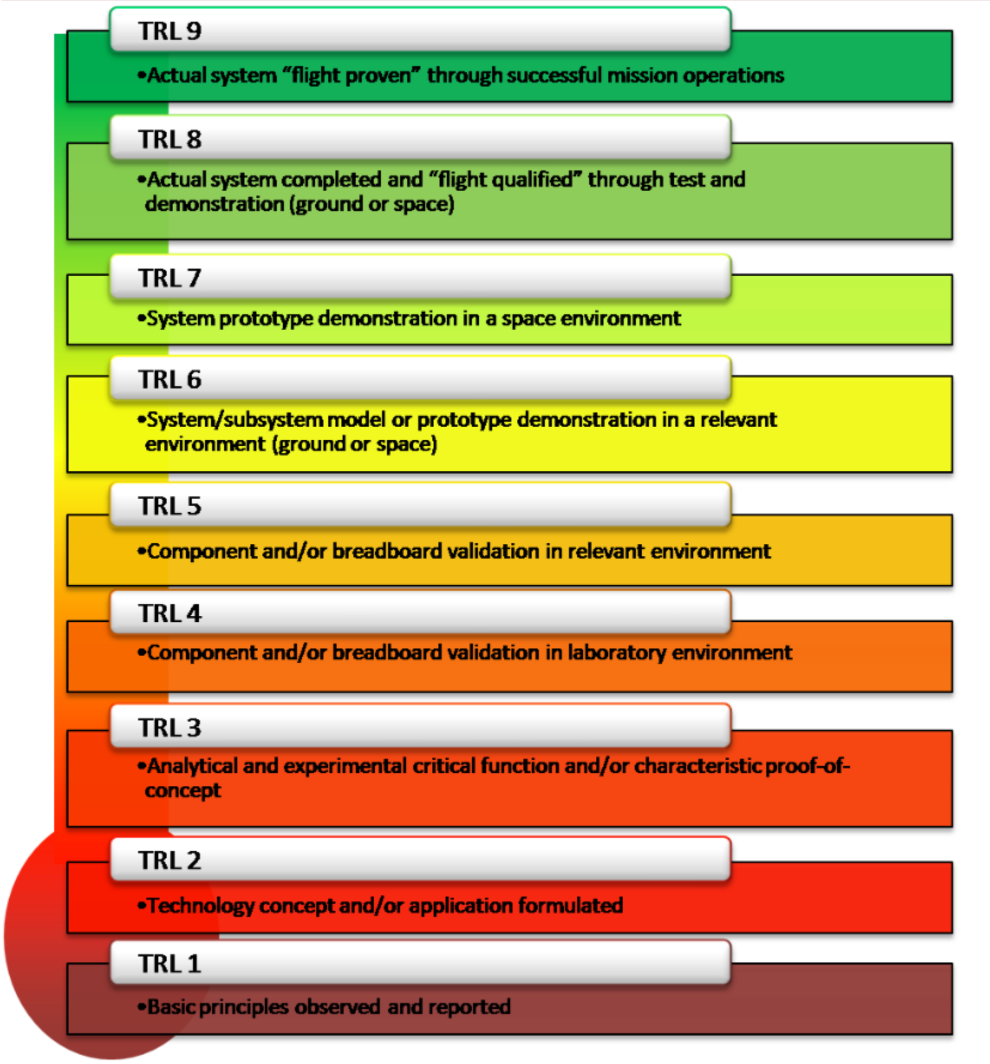


Figure 7.1: TRL levels, as defined by NASA

7.3 Operational Procedures

Document	Title	Purpose
CSFR-ECLSS-001	ZeoDe Experiment Test Plan	Lay out testing procedures and data sheets
CSFR-ECLSS-002	ZeoDe Experiment Gas Hazards Document	Analysis on gas hazards present during experiments
CSFR-ECLSS-003	ZeoDe Startup Procedure	First startup checklist with rationale
CSFR-ECLSS-004	ZeoDe Maintenance Procedure	Checklist for any maintenance performed on testbed
CSFR-ECLSS-005	Hazards and Risks Document	List and rating of all hazards and risks associated with the testbed
CSFR-ECLSS-006	ZeoDe Electrical Document	Links to all wiring diagrams *not appended*
CSFR-ECLSS-007	Zeolite Weighing	Procedure and notes for weighing out zeolite
CSFR-ECLSS-008	Sensor Calibrations	Repository of notes for any sensor calibrations

Table 7.1: Table of operations documents, which are included in the appendix with the exception of ECLSS-006, which is made up solely of links to figures that are already included in this thesis

ZeoDe Procedures

CSFR-ECLSS-001: ZeoDe Experiment Test Plan

UC Davis Center for Spaceflight Research

Habitats Optimized for Missions of Exploration (HOME) Institute

Points of Contact: Ivey, Daniela dbivey@ucdavis.edu; Robinson, Dr. Stephen K stephen.k.robinson@ucdavis.edu ; Shannon Lackey sjlackey@ucdavis.edu

Objective & Scope

The objective of these tests is to generate degradation data for the HOME prognostics modeling team. The scope of this test plan is performance degradation testing using the ZeoDe (Zeolite performance Degradation) testbed by injecting humidity into the system, as well as supplementary testing and maintenance that supports this goal.

Required Training

- [ ] Review of SafetyNet#60 Compressed Gas Safety
- [ ] Review of CSFR-ECLSS-002 ZeoDe Experiment Gas Hazard Document
- [ ] In-person review with SatLab within CSFR of electronics hazards
- [ ] Review of Drierite SDS
- [ ] Review of heater rope SDS

Important Reference Documents

- ZeoDe testbed Overview

Required PPE

- Nitrile Gloves when handling heater rope
- Safety Glasses when performing mechanical or electrical work where eye damage could occur - for example: stripping wires behind the testbed
- Hair back
- Long pants when working with heater rope
- Closed toed shoes when performing mechanical or electrical work

Revision History

Revision #	Date	Reason for New Revision	Changes	POC making edits
1	May 2022	Initial Draft	-	Daniela Ivey; Monica Torralba
2	December 2022	New testbed; CDR held for new testbed with suggested changes	Rewording for new testbed	Daniela Ivey
3	May 2023	Ahead of Safety Briefing	Enhanced safety notes	Daniela Ivey
4	March 6, 2024	Refined testing procedures with enhanced checklists based on experience in testing and things that have been unclear	Added checklists to each test Broke up testing into sections, with corresponding more detailed checklists	Daniela Ivey

Important Notes/Lessons Learned

- Need to have one of the dry/humid air streams in excess or may experience controller infighting
  - Source: Dr. Knox
- The Vaisala dew point sensors have an automatic purge function that heats up the probe once every 24 hours to self-clean the sensor head, but you can disable this function.
  - Source: Dr. Sweterlitsch
- Make sure to fully close the ballast knob on the Edwards pump to ensure the strongest vacuum possible.
  - Source: Dr. Sweterlitsch
- Water creep in zeolite is a gradual phenomenon and can take many cycles before achieving cyclic steady state.
  - Source: Dr. Knox
- Regarding the GMP 252 CO_2 sensor, you may want to run a test where you expose the sensor to a constant CO_2 concentration at a constant flow rate for at least 5 hours.
  - Source: Dr. Sweterlitsch

FailSafe testing

Over Temperature

- ☐ Ensure limit controller has been set to switch its relay at 350C
- ☐ Command temperature to 360 C, with a ramp up
- ☐ Monitor

Over Pressure

- ☐ Ensure pressure relief valves are not engaged
- ☐ Command pressure to 30 psi using regulator
- ☐ Monitor

High CO_2

- ☐ Ensure the Environmental alarm is plugged in, and you can monitor it both from its screen and from the Honeywell application on your phone
- ☐ Set CO2 levels to 5% higher than alarm setpoint
- ☐ Monitor

Bake Out

Bake-out is performed before experiments to clean the sorbent bed of water, CO2, and any other contaminants. In a space system analog, this process would only be done on the ground. It uses high temperature and pressure vacuum (Temperature pressure swing) first to heat up the system to break apart any bonds, and then pull a pressure differential to pull all of the freed molecules out of the system.

Time commitment:
Bake out for the ZeoDe system takes place in two parts, due to optimization of resource use. The first part of bake-out uses the pump, can take place overnight, and does not need to be supervised once operating temperatures are reached. The second part of bake out uses nitrogen, and may take anywhere between 1 and 4+ hours, and should be supervised.

Required materials for pump bake-out (part 1)

- [ ] Functioning pump
- [ ] Functioning heaters
- [ ] The mechanical/piping system downstream of valve 6A needs to be fully connected and secured

Required materials for Nitrogen bake-out (part 2)

- [ ] Nitrogen cylinder that is above 500 psi
- [ ] Functioning heaters
- [ ] The mechanical/piping system of the entire testbed needs to be fully connected and secured

Sequence for PART 1 - Pump Bake Out

[estimate 12 hours, requires supervision for the first 15 minutes]

- [ ] Ensure Nafion membrane is fully hydrated and does not look dried out (it should be twisted inside the straight tube, and some bubbles should be visible)
- [ ] Ensure no loose wires are present in the system
- [ ] Ensure the system downstream of valve 6A is fully closed and connected
- [ ] Ensure plugs for AC PWR1 and ACPWR2 are connected to the wall
- [ ] Ensure the plug for the CO2 monitor is connected to the wall
- [ ] Ensure that the bypass needle valve is completely closed
- [ ] Turn on BED HTR Variac
- [ ] Plug DAQ USB into the computer
- [ ] Plug Pump USB into the computer
- [ ] Turn on AC PWR1
- [ ] Turn on AC PWR2
- [ ] Turn on DC PWR
- [ ] Open LabView

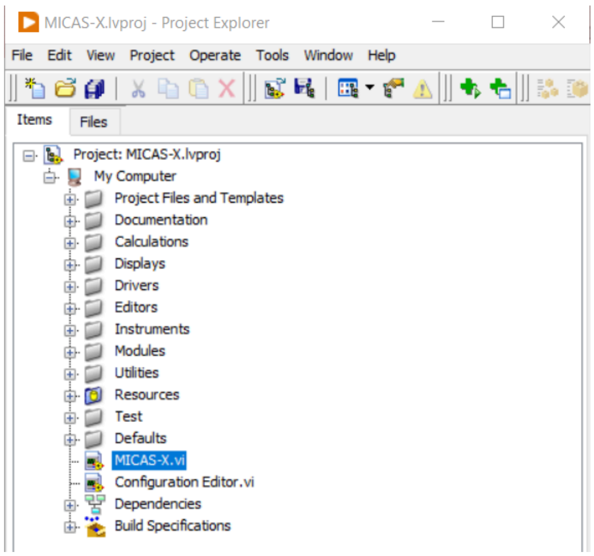
- ☐ Open MicasX project
- ☐ Run MICASX project
- ☐ Wait for the system to start up
- ☐ Check that the system looks nominal
- ☐ Run ZeoDe Bake Out PUMP sequence
- ☐ Log start time in the experimental notebook
- ☐ Monitor system for 15 minutes:
    - ☐ Ensure the temperature of the bed is ramping up by monitoring TC3 and TC4
    - ☐ Ensure the over-temp relay for the sorbent bed is showing an increase in temperature (it will be lower than the bed heaters, by about 70 degrees)
    - ☐ Ensure the upstream Mass Flow Transmitter is reading 0.002 SLPM or below
        - ☐ If not, your needle valve is probably not completely closed, CLOSE NEEDLE VALVE
    - ☐ Ensure the upstream Mass Flow Transmitter is reading around 14.7 psia
        - ☐ If not, your needle valve is probably not completely closed, CLOSE NEEDLE VALVE
    - ☐ Ensure the temperature reaches 350C and holds there
- ☐ After monitoring period
    - ☐ Turn flashing lights on for the testbed
    - ☐ If leaving the testbed, put a clearly visible note on top of the computer stating TESTING IN PROGRESS with your contact information
    - ☐ If leaving the lab, inform other members present in the lab that you are leaving, that there is testing in progress, and that no action is needed on their part
- ☐ Once the sequence stops, around 12 hours later you can move on to part two

Sequence for PART 2 - Nitrogen Bake Out

[estimate 1-3+ hours, requires supervision via intermittent check-ins to ensure Nitrogen cylinder does not empty]

- ☐ Ensure Nafion membrane is fully hydrated and does not look dried out (it should be twisted inside the straight tube, and some bubbles should be visible)
- ☐ Ensure no loose wires are present in the system
- ☐ Ensure the Nitrogen regulator valve is closed (counterclockwise to close!)
- ☐ Open ball valve downstream of Nitrogen regulator
- ☐ Open Nitrogen cylinder
- ☐ Ensure pressure reads at or above 500 psia
    - ☐ If above 100 psia, you can run the following procedure, monitoring closely, until reaching 20 psia, then stop and mark the cylinder EMPTY with tape and sharpie
- ☐ Ensure the entire system is fully closed and connected [e.g. there are no holes in the testbed or missing components]

- ☐ Ensure plugs for AC PWR1 and ACPWR2 are connected to the wall
- ☐ Ensure the plug for the CO2 monitor is connected to the wall
- ☐ Ensure that the bypass needle valve is completely closed
- ☐ Ensure BED HTR Variac is turned on
- ☐ Ensure the DAQ USB is plugged into the computer
- ☐ Ensure the Pump USB is plugged into the computer
- ☐ Ensure AC PWR1 is ON
- ☐ Ensure AC PWR2 is ON
- ☐ Ensure DC PWR is ON
- ☐ Ensure LabView is open
- ☐ Ensure MicasX project is open
    - ☐ Navigate to MICAS-X. Make sure to to hit the arrow!



- ☐ Check that the system looks nominal
- ☐ Run ZeoDe Bake Out sequence
- ☐ Log the start time of the sequence in the experimental notebook
- ☐ While monitoring Nitrogen MFC
    - ☐ Open nitrogen regulator until Nitrogen MFC reads 23 psia (to OPEN, turn CLOCKWISE)
    - ☐ Ensure flow is 4 SLPM without noise
    - ☐ Ensure the setpoint is 4 SLPM
- ☐ Closely monitor the system for 15 minutes:
    - ☐ Ensure the temperature of the bed is ramping up by monitoring TC3 and TC4
    - ☐ Ensure the over-temp relay for the sorbent bed is showing an increase in temperature (it will be lower than the bed heaters, by about 70 degrees)
    - ☐ Ensure the upstream Mass Flow Transmitter is reading close to 4 SLPM
    - ☐ Ensure the downstream Mass Flow Transmitter is reading close to 4 SLPM

- [ ] Ensure the upstream Mass Flow Transmitter is reading between 14.7 psia and 18 psia
    - [ ] If not, your inlet pressures may be too high or too low
- [ ] Ensure the temperature reaches 350C and holds there

- [ ] After the close monitoring period
  - [ ] Turn flashing lights on for the testbed
  - [ ] If leaving the testbed (e.g. going to the other side of the room and watching remotely from your computer), put a clearly visible note on top of the computer stating TESTING IN PROGRESS with your contact information
  - [ ] You can leave the lab, but only for a short period within reason, and taking into consideration how much Nitrogen you have left
    - [ ] If leaving the lab, inform other members present in the lab that you are leaving, that there is testing in progress, and that no action is needed on their part
- [ ] Monitor the system until either
  - [ ] you run out of nitrogen (you will have to rerun bake out when you have replaced nitrogen)
  - [ ] OR you reach -40 dewpoint at the outlet and at or below 0.005% CO_2 at the oulet
  - [ ] NOTE* if humid tests were run prior to this bake out, you should see humidity coming off the bed during the nitrogen PART 2. If you do not see any come off, your dewpoint sensor may be malfunctioning and you may have to:
    - [ ] restart the system/check connections and resume the test again
    - [ ] **OR if you have enough Nitrogen, you can run the Nitrogen bake out for a total of 5 hours. This is equivalent to the longest bake out we have had to run plus margin, so should remove all contaminants**
- [ ] If one of the above two conditions are met
  - [ ] Stop the sequence, and log time
  - [ ] Run STOP ALL, and log time
  - [ ] Ensure any notes on the experiment are in the experimental notebook
- [ ] If bake out has been successful, and experiments are desired, let the system cool down
  - [ ] One can speed up the cool down process by placing the fan on the testbed
  - [ ] Cool down is considered completed when the highest temperature thermocouple reading on the system is at or below 30 degrees Celsius
  - [ ] *note, it is best to run cyclic or breakthrough experimentation soon after the cooldown is completed - since it is not a perfectly sealed system, over time air will seep in and your starting conditions will not be the same.

Cyclic Testing

Cyclic testing *is performed with an 80-minute adsorption cycle, then an 80-minute desorption cycle, then an 80-minute adsorption cycle, and then an 80-minute desorption cycle, continuing in this way until the desired number of cycles, time, or end conditions are met. The 80-minute half-cycles for the ZeoDe*

testbed match with the 80-minute half-cycles of the 4BCO2 and CDRA cycles on the ISS. It is possible to match these times even in a scaled-down system because we matched our interstitial velocity and residence times to the ISS systems.
***Adsorption** is run at 8SLPM through a 1" bed packed with 14.3 inches high of sorbent. Temperatures at the onset of testing are below 30 degrees Celsius and normally do not increase much past that. There is no active heating or cooling during adsorption.*
***Desorption** is run at a vacuum of an estimated 5 Torr, with added heating bringing the exterior of the sorbent bed to 200 degrees C.*

Time commitment:
Cyclic testing can take anywhere from 160 minutes (one full cycle), to 48+ hours (18 full cycles). If leaving the lab, it is recommended to monitor remotely intermittently. It is OKAY to not monitor the system overnight, BUT regardless of when you are running it, carve out around 180 minutes after beginning the experiment to ensure you have checked in on the system either in person or remotely for both the adsorption and desorption cycles to ensure nominal operations. At a minimum, excluding nighttime operations, check the system once every 4 hours. Since the system is not fully sealed, it is not uncommon for pressure from the CO_2 cylinder to have to be readjusted, or for the Nafion membrane to dry out.

Required materials

- [ ] Functioning pump
- [ ] Functioning Nafion Membrane (for humid tests)
- [ ] Functioning heaters
- [ ] The mechanical/piping system of the entire testbed needs to be fully connected and secured
- [ ] CO2 cylinder that is above 200 psi
- [ ] Dry desiccant beds (blue)

Sequence for DRY cyclic test

[requires observation for first 180 minutes, intermittent check-ins after that, with at least 1 in-person check-in each day]

- ☐ Ensure Nafion membrane is fully hydrated and does not look dried out (it should be twisted inside the straight tube, and some bubbles should be visible)
- ☐ Open up desiccant beds and check that they are dry enough for the duration desired
  - ☐ Completely blue for dry tests
- ☐ Ensure CO_2 regulator is closed (to close, turn COUNTER CLOCKWISE)
- ☐ Ensure ball valve downstream of CO_2 regulator is open
- ☐ Open CO_2 cylinder (COUNTER CLOCKWISE)
  - ☐ Verify that PSI is above 200 psi
  - ☐ If not, then you may not be able to run this test
- ☐ Ensure no loose wires are present in the system
- ☐ Ensure the system is fully closed and connected
- ☐ Ensure plugs for AC PWR1 and ACPWR2 are connected to the wall
- ☐ Ensure the plug for the CO_2 monitor is connected to the wall
- ☐ Ensure that the bypass needle valve is completely closed
- ☐ Ensure BED HTR Variac is turned on
- ☐ Ensure the DAQ USB is plugged into the computer
- ☐ Ensure the Pump USB is plugged into the computer
- ☐ Ensure AC PWR1 is ON
- ☐ Ensure AC PWR2 is ON
- ☐ Ensure DC PWR is ON
- ☐ Ensure LabView is open
- ☐ Ensure MicasX project is open
- ☐ Check that the system looks nominal
- ☐ Run ClosedLoopDryCyclic1 sequence
  - ☐ NOTE this uses a “closed habitat” adsorption cycle that will *virtually* recycle outlet CO_2 into the inlet, so CO_2 inlet concentration will build up over time
- ☐ Log the start time of the sequence in the experimental notebook
- ☐ While monitoring Air MFC, CO_2 MFC, and Humid Air MFC
  - ☐ Open CO_2 nitrogen regulator until Nitrogen MFC reads 26 psia (to OPEN, turn CLOCKWISE)
  - ☐ Open Air Valve
  - ☐ Open Air regulator until Air MFC reads 21 psia
  - ☐ Re-check and readjust both CO_2 regulator and air regulator until
    - ☐ **CO_2 MFC reads 26-28 psia**
    - ☐ **Air MFC reads 20-21 psia**
  - ☐ Ensure flow of air in MFC is around 7.9 SLPM without noise

- ☐ Ensure the setpoint of air in MFC is around 7.9 SLPM without noise
    - ☐ Ensure the flow of CO_2 in MFC is around 0.024 SLPM without noise
    - ☐ Ensure the setpoint of CO_2 in MFC is around 0.024 SLPM without noise
    - ☐ FOR DRY TEST ** Ensure the humid MFC setpoint is at 0 SLPM
    - ☐ FOR DRY TEST ** ensure humid MFC readback is at 0 SLPM
- ☐ Closely monitor the system for 15 minutes:
    - ☐ Ensure the temperature of the bed is not increasing in the sorbent bed
    - ☐ Ensure the over-temp relay for the sorbent bed is not showing an increase in temperature
    - ☐ Ensure the upstream Mass Flow Transmitter is reading close to 8 SLPM
    - ☐ Ensure the downstream Mass Flow Transmitter is reading close to 8 SLPM (will be a bit lower than the upstream since our system is not perfectly sealed around the sensors)
    - ☐ Ensure the upstream Mass Flow Transmitter is reading between 14.9 psia and 18 psia
        - ☐ If not, your inlet pressures may be too high or too low
    - ☐ Ensure the temperature is not increasing drastically (normally increases to around 31 degrees C)
- ☐ After the close monitoring period
    - ☐ Turn flashing lights on for the testbed
    - ☐ If leaving the testbed (e.g. going to the other side of the room and watching remotely from your computer), put a clearly visible note on top of the computer stating TESTING IN PROGRESS with your contact information
    - ☐ You can leave the lab, but only for a short period within reason, and should be back at the start of the second half cycle, or monitoring closely ready to come back to the lab and intervene if there is off-nominal telemetry
        - ☐ If leaving the lab, inform other members present in the lab that you are leaving, that there is testing in progress, and that no action is needed on their part
- ☐ During intermittent checks, note down in experimental notebook times of checks and how the data looks
- ☐ Put screengrabs of the telemetry graphs into the experimental notebook during intermittent checks
- ☐ If anything looks off-nominal, first
    - ☐ Examine data, write everything down
    - ☐ Likelihood of a catastrophic event is low, so it may be worth it to continue gathering data even if faulty to be able to understand the issue as a whole after the test is done
    - ☐ If things look to be a safety hazard, take note, then
        - ☐ Stop the sequence, and log time
        - ☐ Run STOP ALL, and log time

- [ ] Ensure any notes on the experiment are in the experimental notebook

Sequence for HUMID cyclic test

[requires observation for first 180 minutes, intermittent check-ins after that, with at least 1 in-person check-in each day]

- [ ] Ensure Nafion membrane is fully hydrated and does not look dried out (it should be twisted inside the straight tube, and some bubbles should be visible)
- [ ] Open up desiccant beds and check that they are dry enough for the duration desired
    - [ ] Mostly blue for all humid tests
- [ ] Ensure CO2 regulator is closed (to close, turn COUNTER CLOCKWISE)
- [ ] Ensure ball valve downstream of CO2 regulator is open
- [ ] Open CO2 cylinder (COUNTER CLOCKWISE)
    - [ ] Verify that PSI is above 200 psi
    - [ ] If not, then you may not be able to run this test
- [ ] Ensure no loose wires are present in the system
- [ ] Ensure the system is fully closed and connected
- [ ] Ensure plugs for AC PWR1 and ACPWR2 are connected to the wall
- [ ] Ensure the plug for the CO2 monitor is connected to the wall
- [ ] Ensure that the bypass needle valve is completely closed
- [ ] Ensure BED HTR Variac is turned on
- [ ] Ensure the DAQ USB is plugged into the computer
- [ ] Ensure the Pump USB is plugged into the computer
- [ ] Ensure AC PWR1 is ON
- [ ] Ensure AC PWR2 is ON
- [ ] Ensure DC PWR is ON
- [ ] Ensure LabView is open
- [ ] Ensure MicasX project is open
- [ ] Check that the system looks nominal
- [ ] Run ClosedLoopDryCyclic1 sequence
    - [ ] NOTE this uses a “closed habitat” adsorption cycle that will *virtually* recycle outlet CO2 into the inlet, so CO2 inlet concentration will build up over time
- [ ] Log the start time of the sequence in the experimental notebook
- [ ] While monitoring Air MFC, CO2 MFC, and Humid Air MFC
    - [ ] Open CO2 nitrogen regulator until Nitrogen MFC reads 26 psia (to OPEN, turn CLOCKWISE)
    - [ ] Open Air Valve
    - [ ] Open Air regulator until Air MFC reads 21 psia
    - [ ] Re-check and readjust both CO2 regulator and air regulator until
        - [ ] **CO2 MFC reads 26-28 psia**

- [ ] **Air MFC reads 20-21 psia**
- [ ] Ensure flow of air in MFC is around 7.9 SLPM without noise
- [ ] Ensure the setpoint of air in MFC is around 7.9 SLPM without noise
- [ ] Ensure the flow of CO_2 in MFC is around 0.024 SLPM without noise
- [ ] Ensure the setpoint of CO_2 in MFC is around 0.024 SLPM without noise
- [ ] FOR DRY TEST ** Ensure the humid MFC setpoint is at 0 SLPM
- [ ] FOR DRY TEST ** ensure humid MFC readback is at 0 SLPM

- [ ] Closely monitor the system for 15 minutes:
    - [ ] Ensure the temperature of the bed is not increasing in the sorbent bed
    - [ ] Ensure the over-temp relay for the sorbent bed is not showing an increase in temperature
    - [ ] Ensure the upstream Mass Flow Transmitter is reading close to 8 SLPM
    - [ ] Ensure the downstream Mass Flow Transmitter is reading close to 8 SLPM (will be a bit lower than the upstream since our system is not perfectly sealed around the sensors)
    - [ ] Ensure the upstream Mass Flow Transmitter is reading between 14.9 psia and 18 psia
        - [ ] If not, your inlet pressures may be too high or too low
    - [ ] Ensure the temperature is not increasing drastically (normally increases to around 31 degrees C)
- [ ] After the close monitoring period
    - [ ] Turn flashing lights on for the testbed
    - [ ] If leaving the testbed (e.g. going to the other side of the room and watching remotely from your computer), put a clearly visible note on top of the computer stating TESTING IN PROGRESS with your contact information
    - [ ] You can leave the lab, but only for a short period within reason, and should be back at the start of the second half cycle, or monitoring closely ready to come back to the lab and intervene if there is off-nominal telemetry
        - [ ] If leaving the lab, inform other members present in the lab that you are leaving, that there is testing in progress, and that no action is needed on their part
- [ ] During intermittent checks, note down in experimental notebook times of checks and how the data looks
- [ ] Put screengrabs of the telemetry graphs into the experimental notebook during intermittent checks
- [ ] If anything looks off-nominal, first
    - [ ] Examine data, write everything down
    - [ ] Likelihood of a catastrophic event is low, so it may be worth it to continue gathering data even if faulty to be able to understand the issue as a whole after the test is done
    - [ ] If things look to be a safety hazard, take note, then

- [ ] Stop the sequence, and log time
- [ ] Run STOP ALL, and log time
- [ ] Ensure any notes on the experiment are in the experimental notebook

Breakthrough Testing

Breakthrough testing *is performed at the same inlet conditions as is planned for the adsorption cycles of the cyclic testing. It is performed to test the limits of the sorbent bed. As a result, while the cyclic testing is time-limited to 80-minute adsorption half-cycles followed by 80-minute desorption cycles, the breakthrough testing runs until a clear curve is established under adsorption conditions. Breakthrough is when during an adsorption, CO2 begins to "break through" the outlet of the sorbent bed, in effect that the sorbent bed is no longer efficiently performing its role as it has been saturated and cant adsorb anymore CO2. Breakthrough can be accelerated in the presence of humidity, as the humidity will take up sites that otherwise would have been occupied by CO2, and eventually starts kicking CO2 molecules off of the sorbent bed.*
Dry breakthrough *is essentially non-time-restricted dry adsorption and is run at 8SLPM through a 1" bed packed with 14.3 inches high of sorbent. Temperatures at the onset of testing are below 30 degrees Celsius and normally do not increase much past that. There is no active heating or cooling during adsorption.*
Humid breakthrough *is essentially non-time-restricted humid adsorption and is run at 8SLPM through a 1" bed packed with 14.3 inches high of sorbent. Temperatures at the onset of testing are below 30 degrees Celsius and normally do not increase much past that. There is no active heating or cooling during adsorption.*

Time commitment:
The actual breakthrough time for dry conditions lies around 100 minutes, after which one should wait about an hour for a fully developed curve. Under humid conditions breakthrough will vary depending on the level of humidity. More humidity will mean a faster breakthrough. If leaving the lab, it is recommended to monitor remotely intermittently. A breakthrough should not be run overnight as it is such a short test. Since the system is not fully sealed, it is not uncommon for pressure from the CO_2 cylinder to have to be readjusted, or for the Nafion membrane to dry out.

Required materials

- [ ] Functioning Nafion Membrane (for humid tests)
- [ ] The mechanical/piping system of the entire testbed needs to be fully connected and secured
- [ ] CO2 cylinder that is above 200 psi

Sequence for DRY Breakthrough

[requires thorough observation for first 15 minutes, and should not be run overnight]

- ☐ Ensure Nafion membrane is fully hydrated and does not look dried out (it should be twisted inside the straight tube, and some bubbles should be visible)
- ☐ Open up desiccant beds and check that they are dry
    - ☐ Completely blue for dry tests
- ☐ Ensure CO2 regulator is closed (to close, turn COUNTER CLOCKWISE)
- ☐ Ensure ball valve downstream of CO2 regulator is open
- ☐ Open CO2 cylinder (COUNTER CLOCKWISE)
    - ☐ Verify that PSI is above 200 psi
    - ☐ If not, then you may not be able to run this test
- ☐ Ensure no loose wires are present in the system
- ☐ Ensure the system is fully closed and connected
- ☐ Ensure plugs for AC PWR1 and ACPWR2 are connected to the wall
- ☐ Ensure the plug for the CO2 monitor is connected to the wall
- ☐ Ensure that the bypass needle valve is completely closed
- ☐ Ensure BED HTR Variac is turned on
- ☐ Ensure the DAQ USB is plugged into the computer
- ☐ Ensure the Pump USB is plugged into the computer
- ☐ Ensure AC PWR1 is ON
- ☐ Ensure AC PWR2 is ON
- ☐ Ensure DC PWR is ON
- ☐ Ensure LabView is open
- ☐ Ensure MicasX project is open
- ☐ Check that the system looks nominal
- ☐ Run Dry Brkthru sequence
    - ☐ NOTE this doesn't use the “closed habitat” adsorption cycle used in the cyclic testing that will *virtually* recycle outlet CO2 into the inlet, so CO2 inlet concentration will stay the same over time
- ☐ Log the start time of the sequence in the experimental notebook
- ☐ While monitoring Air MFC, CO2 MFC, and Humid Air MFC
    - ☐ Open CO2 nitrogen regulator until Nitrogen MFC reads 26 psia (to OPEN, turn CLOCKWISE)
    - ☐ Open Air Valve
    - ☐ Open Air regulator until Air MFC reads 21 psia
    - ☐ Re-check and readjust both CO2 regulator and air regulator until
        - ☐ **CO2 MFC reads 26-28 psia**
        - ☐ **Air MFC reads 20-21 psia**

- ☐ Ensure flow of air in MFC is around 7.9 SLPM without noise
- ☐ Ensure the setpoint of air in MFC is around 7.9 SLPM without noise
- ☐ Ensure the flow of CO_2 in MFC is around 0.024 SLPM without noise
- ☐ Ensure the setpoint of CO_2 in MFC is around 0.024 SLPM without noise
- ☐ FOR DRY TEST ** Ensure the humid MFC setpoint is at 0 SLPM
- ☐ FOR DRY TEST ** ensure humid MFC readback is at 0 SLPM

- ☐ Closely monitor the system for 15 minutes:
  - ☐ Ensure the temperature of the bed is not increasing in the sorbent bed
  - ☐ Ensure the over-temp relay for the sorbent bed is not showing an increase in temperature
  - ☐ Ensure the upstream Mass Flow Transmitter is reading close to 8 SLPM
  - ☐ Ensure the downstream Mass Flow Transmitter is reading close to 8 SLPM (will be a bit lower than the upstream since our system is not perfectly sealed around the sensors)
  - ☐ Ensure the upstream Mass Flow Transmitter is reading between 14.9 psia and 18 psia
    - ☐ If not, your inlet pressures may be too high or too low
  - ☐ Ensure the temperature is not increasing drastically (normally increases to around 31 degrees C)
- ☐ After the close monitoring period
  - ☐ Turn flashing lights on for the testbed
  - ☐ If leaving the testbed (e.g. going to the other side of the room and watching remotely from your computer), put a clearly visible note on top of the computer stating TESTING IN PROGRESS with your contact information
  - ☐ You can leave the lab, but only for breakthroughs as they are so short, it is not unwise to monitor the system at least intermittently remotely
    - ☐ If leaving the lab, inform other members present in the lab that you are leaving, that there is testing in progress, and that no action is needed on their part
- ☐ During intermittent checks, note down in the experimental notebook the times of checks and how the data looks
- ☐ Put screengrabs of the telemetry graphs into the experimental notebook during intermittent checks
- ☐ If anything looks off-nominal, first
  - ☐ Examine data, write everything down
  - ☐ The likelihood of a catastrophic event is low, so it may be worth it to continue gathering data even if faulty to be able to understand the issue as a whole after the test is done
  - ☐ If things look to be a safety hazard, take note, then
    - ☐ Stop the sequence, and log the time
    - ☐ Run STOP ALL, and log the time

- ☐ Ensure any notes on the experiment are in the experimental notebook
- ☐ The stopping criteria are a well-developed plot, with breakthrough and at least 1 hour of data collection post-breakthrough.

Sequence for HUMID Breakthrough

[requires constant supervision if running above -10C dewpoint. For -10C dewpoint, is it acceptable to leave the lab and come back based on the estimated time of completion of the experiment]

- ☐ Ensure the Nafion membrane is fully hydrated and does not look dried out (it should be twisted inside the straight tube, and some bubbles should be visible)
- ☐ Open up desiccant beds and check that they are dry enough for the duration desired
    - ☐ Mostly blue for a humid test
- ☐ Ensure the water container for Nafion has sufficient water so that the outlet tube is well below the water level
- ☐ Ensure the CO2 regulator is closed (to close, turn COUNTER CLOCKWISE)
- ☐ Ensure the ball valve downstream of the CO2 regulator is open
- ☐ Open CO2 cylinder (COUNTER CLOCKWISE)
    - ☐ Verify that PSI is above 200 psi
    - ☐ If not, then you may not be able to run this test
- ☐ Ensure no loose wires are present in the system
- ☐ Ensure the system is fully closed and connected
- ☐ Ensure plugs for AC PWR1 and ACPWR2 are connected to the wall
- ☐ Ensure the plug for the CO2 monitor is connected to the wall
- ☐ Ensure that the bypass needle valve is completely closed
- ☐ Ensure BED HTR Variac is turned on
- ☐ Ensure the DAQ USB is plugged into the computer
- ☐ Ensure the Pump USB is plugged into the computer
- ☐ Ensure AC PWR1 is ON
- ☐ Ensure AC PWR2 is ON
- ☐ Ensure DC PWR is ON
- ☐ Ensure LabView is open
- ☐ Ensure MicasX project is open
- ☐ Check that the system looks nominal
- ☐ Run Humid Brkthru sequence
    - ☐ NOTE this does NOT use the “closed habitat” adsorption cycle that is used in cyclic tests, so CO2 inlet concentration will remain constant
- ☐ Log the start time of the sequence in the experimental notebook
- ☐ While monitoring Air MFC, CO2 MFC, and Humid Air MFC

- ☐ Open CO_2 nitrogen regulator until Nitrogen MFC reads 26 psia (to OPEN, turn CLOCKWISE)
- ☐ Open Air Valve
- ☐ Open Air regulator until Air MFC reads 21 psia
- ☐ Re-check and readjust both CO_2 regulator and air regulator until
    - ☐ **CO_2 MFC reads 26-28 psia**
    - ☐ **Air MFC reads 20-21 psia**
- ☐ Ensure flow of air in MFC is around 7.9 SLPM without noise
- ☐ Ensure the setpoint of air in MFC is around 7.9 SLPM without noise
- ☐ Ensure the flow of CO_2 in MFC is around 0.024 SLPM without noise
- ☐ Ensure the setpoint of CO_2 in MFC is around 0.024 SLPM without noise
- ☐ FOR HUMID TEST ** Ensure the humidity upstream is being maintained at the setpoint (PID set to -10, or -20, or -15 etc.)
- ☐ FOR HUMID TEST ** ensure humid MFC setpoint is not increasing dramatically

    ***this most likely signifies that the Nafion tube is dried out, and test should be stopped immediately and Nafion should be rehydrated**

☐ Closely monitor the system for 15 minutes (for the entirety of the test if doing a humid test above -10C dewpoint)

- ☐ Ensure the temperature of the bed is not increasing in the sorbent bed
- ☐ Ensure the over-temp relay for the sorbent bed is not showing an increase in temperature
- ☐ Ensure the upstream Mass Flow Transmitter is reading close to 8 SLPM
- ☐ Ensure the downstream Mass Flow Transmitter is reading close to 8 SLPM (will be a bit lower than the upstream since our system is not perfectly sealed around the sensors)
- ☐ Ensure the upstream Mass Flow Transmitter is reading between 14.9 psia and 18 psia
    - ☐ If not, your inlet pressures may be too high or too low
- ☐ Ensure the temperature is not increasing drastically (normally increases to around 31 degrees C)

☐ After the close monitoring period

- ☐ Turn flashing lights on for the testbed
- ☐ If leaving the testbed (e.g. going to the other side of the room and watching remotely from your computer), put a clearly visible note on top of the computer stating TESTING IN PROGRESS with your contact information
- ☐ You can leave the lab, but only for a short period within reason, and should be back at the start of the second half cycle, or monitoring closely ready to come back to the lab and intervene if there is off-nominal telemetry
    - ☐ If leaving the lab, inform other members present in the lab that you are leaving, that there is testing in progress, and that no action is needed on their part

        - ☐ Exception to leaving the lab: humid tests are riskier, for risk of drying out Nafion. If running a humid test above -10C dewpoint, one should not leave the lab
- ☐ During intermittent checks:
    - ☐ note down in the experimental notebook the times of checks and how the data looks
    - ☐ Ensure that the Nafion tube still looks hydrated
- ☐ Put screengrabs of the telemetry graphs into the experimental notebook during intermittent checks
- ☐ If anything looks off-nominal, first
    - ☐ Examine data, write everything down
    - ☐ The likelihood of a catastrophic event is low, so it may be worth it to continue gathering data even if faulty to be able to understand the issue as a whole after the test is done
        - ☐ The only exception to this is the Nafion tube: if the Nafion is drying out TEST SHOULD BE TERMINATED IMMEDIATELY and the Nafion tube should be removed from the system and rehydrated
    - ☐ If things look to be a safety hazard or a hazard to the Nafion, take note, then
        - ☐ Stop the sequence, and log the time
        - ☐ Run STOP ALL, and log the time
        - ☐ Ensure any notes on the experiment are in the experimental notebook

Template for Experiment Notebook

Date/Title: XX.XX.XX /TITLE

Start Time: End Time (when all equipment was turned off):
Experimenter:

Daily Goals:

- [ ] Goal 1
- [ ] Goal 2

Actions taken:

Experiments Conducted:

Time	Experiment	Sub-Experiments	Notes
			-
			-
			-
			-
			-
			-
			-
			-
			-
			-

Notes:

Data Collected:

Data	Notes	Link to Experimental Data

		Folder

Link to Documentation:

-

Action items for next time:

Issues Encountered:

-

Non-Conformance Links:

-

End of day checklist - ORDER DOES MATTER, complete sequentially

- [ ] Check that gas cylinders are still above 30 bar
- [ ] Bubbles are present in Nafion membrane
- [ ] Gas cylinders have been depressurized
- [ ] System has been depressurized (all MFCs reading at or close to zero)
- [ ] STOP ALL has been run in LabView
- [ ] CO2 valve closed
- [ ] N2 Valve Closed
- [ ] Shop Air Valve Closed
- [ ] AC PWR 1 OFF
- [ ] DC PWR OFF
- [ ] AC PWR 2 OFF
- [ ] VARIAC1 & VARIAC2 OFF
- [ ] Superfluous outlets unplugged (everything except for CO2 environmental sensor, AC power strips, and computer power
- [ ] No noises
- [ ] No loose wires
- [ ] CO2 Environmental Sensor Plugged In to PWR
- [ ] USB's unplugged from computer
- [ ] Uploaded Necessary Data documents to Google Drive

Supplementary Testing

Packing Procedure

- Insert glass wool in the steel 1” diameter bed
- Using a funnel with a grid at the outlet, pour pre-weighted zeolite spheres into the 1” steel tubing

TGA Experimental Procedure (for Runnebaum lab)

TGA Monday, April 11 2022

- As pellets are large, crush two pellets with mortar and pestle
- Mass of Crucible:140.4 mg
- Mass of crushed Zeolite: 33.0 mg

· Hold lift and lock button simultaneously

· Note stem very delicate (there is a hand rest rail)

· Place crucible in center of stem

· Lower with lock and lower button

· Name file definition

· Select forward

· Click start standby

· Set up mass spec measurement file (it will communicate with TGA run)

· Name mass spec measurement file same as TGA file (it will have different extension)

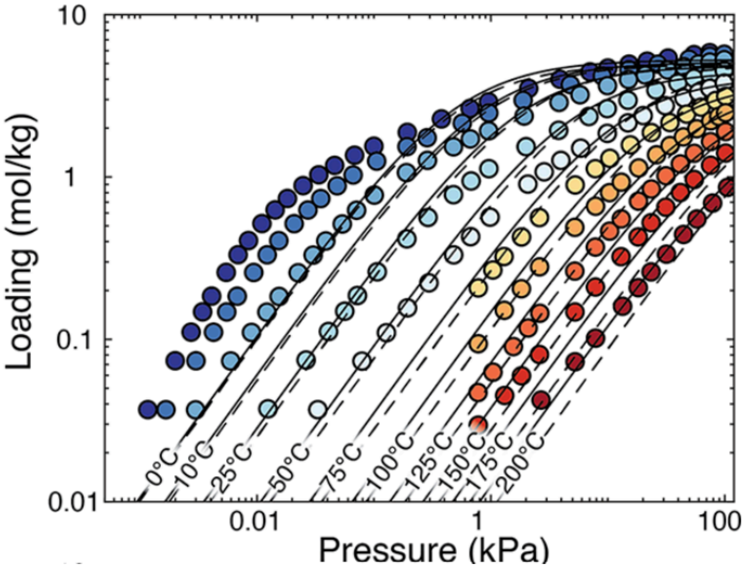
Adsorption and Desorption:

- Saturate with CO2 (partial pressure doesnt matter)
- Desorb at increments of 50 degrees C up to 500
- Flowrate wont really matter, just note what the flowrate is
- Export data from initial bakeout

TGA CO2 uptake:

- Sample mass 31.3 mg (subtracted from mass degassed)
- Crucible mass 140.4 mg
- Because minimum constraint from TGA is 4 mL/min, we opted for 1% CO2 input with 196 ml/min purge plus 200 ml/min N2 protective flows which total 396 ml/min N2. We checked if 1% is a major or minor difference to 0.1% CO2 via the adsorption isotherm and found that there is a minor difference so we may expect that in the results - we just

can't get lower than 1% CO_2 in the TGA. For the plot below, looking at the 50C line (the lightest blue data points) and comparing the loading at 0.1 kPa and 1kPa, the CO_2 uptake is approx. 0.1 mol/kg and 1 mol/kg respectively.

- 

- Source: https://pubs.acs.org/doi/pdf/10.1021/acs.jced.8b00019
- Desorption: we ramped from 30C to 120, 200, 250, 300, 350, 400 with standby at each temperature for 2 hours each and 5C/min increments for the ramps. This is to capture TG signal across the operational temperature on STEVE at 250C and beyond, max of 400C which can be used for full bakeout (pre-test). The flow rate was chosen to be 20 ml/min N_2 purge and 20 ml/min N_2 protective for a total of 40 ml/min N_2 to match the bakeout flow rate. We want the effect of CO_2 desorption to be temperature based rather than due to high flow.

CSFR-ECLSS-002: ZeoDe Experiment Gas Hazards Document

UC Davis Center for Spaceflight Research

Habitats Optimized for Missions of Exploration (HOME) Institute

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Objective

This document outlines the hazards involved with the handling and use of compressed gases.

- Shop Air
- Carbon Dioxide
- Nitrogen

Compressed gases are defined by the U.S. Department of Transportation (DOT) as any materials or mixtures in containers having an absolute pressure in excess of 40 psi at 20 C (70 F) or in excess of 104 psi at 54.5 C (130 F).

Scope

This procedure covers employee safety during the handling and use of compressed gas cylinders, as well as the shop air inlet.

Revision History

Revision #	Date	Reason for Change	List of Changes	Responsible Engineer
1	January 2023	Initial Draft Based on the following UC Davis SafetyNet#60 Compressed Gas Safety Document and the MIT gas safety document	-	Daniela Ivey
2	May 2023	Addition of shop air section	Shop air	Daniela Ivey

3	July 2023	Addition of Teflon warning, along with other bold faced warnings from UC Davis Safety Net 60		Daniela Ivey

Safety Analysis

Handling of compressed gases may be considered more hazardous than the handling of liquid and solid materials because of the following properties: high pressure, ease of diffusion, low ignition points for flammable gases, low boiling points, and in some cases lack of visual and/or odor detection of hazardous gases. Because of these properties, failure to follow proper procedures can result in both personal and property damage.
Following are some of the hazards associated with the improper handling and use of compressed gases:

Using Gas Cylinders

• Do not use a cylinder with unidentified contents. Read the label on the cylinder before using. If the label is illegible or missing, return the cylinder to the supplier. Do not rely on stenciling or the color of the cylinder.
• Keep cylinders upright. Never lay cylinders on their sides, unless the cylinder is specifically designed to be stored horizontally. Consult the manufacturer's instructions.
• Inspect the cylinder and valve condition before using. If a gas cylinder valve is damaged, the contents can exit with great force.
• Select the gas piping and regulator recommended for use with your cylinder. The pressure, purity, and corrosive properties of the gas will determine the correct piping and regulator. Never attempt to use a cylinder without a regulator or some other pressure-reducing device in place. Always inspect the regulator prior to each use. Regulators shall only be repaired (if needed) by a party authorized by the manufacturer.
• **Never use Teflon tape on a gas cylinder regulator. Regulators are designed to make metal-to-metal contact with cylinders to create a leak-proof connection.**
• Follow safe handling procedures. When preparing to withdraw gas from a high-pressure cylinder, close the regulator first. Open the main cylinder valve until it stops and adjust the gas flow rate using the regulator. For cylinders containing fuel gases, open the cylinder valve one-quarter turn,
adjusting the regulator as above.
• Follow safe shut-off procedures. When you are finished using a compressed gas system, turn off
the main cylinder valve, bleed the regulator and lines, and close the regulator. Do not leave the

regulator under pressure by closing down the flow from the regulator without shutting off the main
cylinder valve.
• Follow lockout/tagout procedures. Be sure to lock out upstream gas lines leading to equipment prepared for maintenance. Compressed gases are a hazardous energy source requiring lockout/tagout procedure. Adequately purge lines following lockout procedures and before beginning maintenance.
• Do not drain a cylinder completely. Air can be sucked back through the valve, contaminating the
cylinder or creating an explosive mixture.

General Hazards

1. Explosion hazards may arise as a result of equipment failure or leakage from systems that are not pressure tight. Explosion can also occur if the compressed gas is used to pressurize system elements such as tubing, vacuum vessels, or any other type of containment beyond their design ratings.
2. Diffusion of leaking gases may cause rapid contamination of the atmosphere, giving rise to toxicity, anaesthetic effects, asphyxiation, and rapid formation of explosive concentrations of flammable gases.
3. The ignition point of a flammable gas under pressure is always lower than the ambient or room temperature. Leaking gas can, therefore, rapidly form an explosive mixture with air.
4. Low-boiling point materials can cause frostbite on contact with living tissue. This is common among cryogenic liquids, such as nitrogen and oxygen, but it also can result from contact of the liquid phase of liquified gases, such as carbon dioxide, fluorocarbons and propylene.

The procedures adopted for the safe handling of compressed gases are based on containment of the material so as to prevent its escape into the atmosphere and to maintain proper flow and pressure. The specific hazards of compressed gases used at the PSFC are as follows:

Gas Threshold, flammability, and major hazards table

GAS	THRESHOLD LIMIT VALUE (TLV) PPM	FLAMMABILITY LIMITS IN AIR (% BY VOLUME)	MAJOR HAZARDS
CARBON DIOXIDE	5000	none	asphyxiant
NITROGEN	not established.	none	asphyxiant

Definitions

Asphyxiant gas - A gas which has little or no positive toxic effect but which can bring about unconsciousness and death by replacing air and thus depriving an organism of oxygen.

Flammable gas - A gas mixture of 13% or less by volume with air that is ignitable at 14.7 psia or has a flammable range with air of at least 12% regardless of the lower limit.
Pyrophoric gas - A highly flammable and reactive gas that may spontaneously burn or explode when released into the air.
Oxidizing gas - A gas that, in the presence of an ignition source and a fuel, supports and may vigorously accelerate combustion.

Threshold Limit Value (TLV) - The time-weighted average concentration for a normal 8-hour workday and a 40 hour work week, to which nearly all workers may be repeatedly exposed without adverse effects.

Explosive or Flammable Limits or Range (Lower & Upper - LEL & UEL) - The minimum and maximum concentration of a gas or vapor in air within which a substance will burn or explode when exposed to an ignition source.

Responsibilities

The supervisor or responsible person shall designate and train employees who are required to handle and use compressed gases. The supervisor or responsible person shall ensure that necessary safety equipment is available. The supervisor or responsible person shall ensure that compressed gases are handled in accordance with good work practices. It is the supervisor's responsibility to verify that employees using compressed gases understand the proper procedures.

Assumptions

The supervisor or responsible person shall be familiar with the hazards associated with compressed gases and the appropriate procedures and equipment necessary for proper handling as outlined in this document.

Procedures

The following procedures define the proper receiving, transporting, handling and use and disposal of compressed gases.

RECEIVING

1. When a cylinder is received from a supplier it should have a valve protection cap, a DOT label, the date of the last hydrostatic test and labels identifying the contents.
2. Cylinders received with only color coding should NOT be accepted, as there is no universal color code for identifying gas cylinders.
3. Cylinders must be secured against falling upon receipt, or transferred to the point of use and secured there.

STORAGE

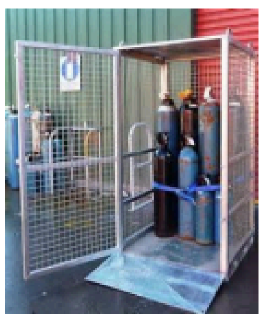
1. Compressed gas cylinders should be stored in a level, dry fire resistant area that is well ventilated. The storage area should be separated from the area where the gas cylinders are used by distance or by physical barriers.
2. Label storage area with hazard warning and/or precautionary sign.
3. Never store cylinders under stairways or in hallways designated for emergency exit.
4. Store cylinders away from sources of ignition or excessive heat. Pressure-relief devices are installed on flammable gas cylinders and most other cylinders to prevent cylinder rupture in the event of fire or high temperatures.
5. Store oxygen away from flammable gases. Oxygen should be stored at least 25 feet away from flammable gases or separated by a five ft. high non-combustible wall.
6. Do not store cylinders near elevators, gangways or in locations where moving objects may strike or fall on them.
7. Cylinders must be chained or strapped in place to prevent them from falling over. A falling cylinder may shear off its valve causing the escape of high pressure gas resulting in an explosion or the rapid projection of the bottle and/or valve. A 250 cu . ft. cylinder pressurized at 2500 psi, with the valve broken off, becomes a rocket and attains a speed of 35 MPH in 0.1 second. Store cylinders with valve caps securely attached whenever cylinders are not in use.
8. Corrosive gases should be stored for the shortest possible time period to prevent corrosion of valves, labels and regulators, and to avoid potential leakage.

Acceptable Securing and Storage of Gas Cylinders

Dual bracing

Cylinder rack w/dual bracing

Cylinder rack/frame

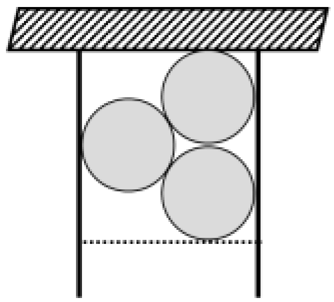


Cylinder cage w/ incline

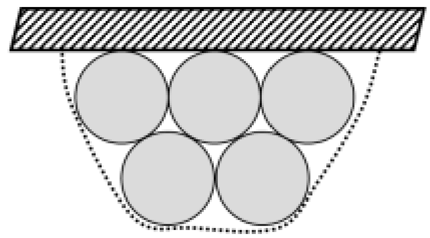
Cylinder cage w/sign

Nesting compressed gas cylinders is defined as each cylinder having three points of contact with either a wall or other gas cylinders.

Chains: One chain is required (two are recommended) when in the storage rack to provide the third point of support.



Storage rack



Nested wall support. Cylinders still need to be chained.

TRANSPORTING

1. Always use a hand truck to transport cylinders. Do not drag, roll or slide cylinders. Leave the valve protection cover ON until cylinders are secured and ready to use. Do not transport a cylinder with the regulator installed. Do not use a transport device to hold a cylinder in use unless it is adequately secured from falling.
2. Do not transport compressed gases in closed vehicles. Cylinders must be chained or otherwise secured during transporting in a open or well ventilated vehicle.
3. Flammable gases and oxygen should not be transported in the same vehicle.
4. Always handle cylinders as if they were full. Accidents have occurred when containers were under partial pressure and were thought to be empty.
5. If it is necessary to transport gas bottles with a crane, forklift, or other lifting fixture, an approved carrier designed for that purpose must be used.
6. Never try to catch a falling cylinder. Some cylinders can weigh over 200 pounds.
7. Use freight elevators when transporting filled cylinders, when possible. Avoid transporting cylinders in occupied elevators. Here is a link to a fact sheet on transporting hazardous materials through public spaces.

HANDLING AND USE

1. Before use, an evaluation of the operation should be made and appropriate safeguards instituted. The major hazard of compressed gas is often a function of how and where it is used.
2. The cylinder valve should be positioned so that it is accessible at all times. The main valve MUST be closed when the cylinder is not in active use. NEVER use wrenches or pliers to open the main valve unless it is a specially designed key provided by the supplier. Most cylinders are equipped with a hand wheel valve. If the valve is not operational, return to supplier labeled "inoperable".

3. NEVER crack open valves on unregulated cylinders. The main valve on a regulated cylinder should be opened slowly. **The main valve should NOT be opened all the way.** Never face a gauge while opening a cylinder. Stand to the side in case of a malfunctioning valve.
4. With the cylinder valve open and the flow control valve in the closed position, set the desired delivery pressure by turning the delivery pressure and adjusting the screw clockwise until the desired pressure is reached. While the function of the regulator is to set and maintain a given gas delivery pressure, flow control is achieved by the use of the flow control valve located at the regulator outlet or by a supplementary needle valve.
5. Always turn off the cylinder by **first closing the main cylinder valve and then the regulator.** The pressure gauges should be brought back to zero.
6. When cylinders containing different gases are manifolded, one-way or check valves should be placed in line to prevent accidental gas mixtures due to pressure differences.
7. NEVER strike an electric arc on or direct a flame at a cylinder.
8. Appropriate personal protective equipment (goggles, face shields, gloves) should be worn with compressed gases.
9. Never pressurize a sealed system unless a pressure relief valve is installed on the system or it is rated to take the full bottle pressure without explosion.
10. Process piping must be provided in accordance with NFPA 55 and ANSI B-31.1. CGA fittings should be used. Manifolding should be constructed by a certified pipe fitter qualified to work with high pressure systems.
11. Do not use a transport device to hold a cylinder in use unless it is adequately secured from falling.
12. Installation video: https://www.youtube.com/watch?v=HNvsc4DzDys
13.

ADDITIONAL CONSIDERATIONS FOR TOXIC AND FLAMMABLE GASES

1. Toxic, flammable and corrosive gases should be used in a well-ventilated area or fume hood. Gases with a health hazard label of 3 or 4 must be used in an approved gas cylinder cabinet. Pyrophoric gases must be used in an approved gas cylinder cabinet equipped with a sprinkler system.
2. Users of flammable gas cylinder sizes in laboratories must consider fuel loading when choosing the size and number of cylinders. The amount of cylinder gas necessary to stay below the lower explosive limit should be evaluated.
3. Ground all cylinders and piping containing flammable gases to prevent the hazards caused by the buildup of static electricity.
4. NEVER use oil or grease on valves or gages intended for oxygen cylinders. Use only oxygen service regulators and components.

LEAK DETECTION

1. Suspected cylinder leakage should be tested by covering the cylinder with soapy water. A leak will be indicated when bubbles of escaping gas pass through the soap film.
2. Keep connections to piping, regulators, and other appliances tight.

3. Check that the hoses are in good condition.
4. If a gas cylinder is leaking, the supplier should be notified for advice on how to handle the leak until the supplier can remove it from the laboratory.
5. If a leaking cylinder is judged safe to handle, it may be placed in a hood or moved to an outside location.

LEAKS

In case of catastrophic failure of a compressed gas cylinder or a large and uncontrolled release, evacuate area and call 9-1-1.

In case of slow and continuous cylinder leaks that cannot be stopped by tightening the hand wheel, do the following:

- For hazardous gases: (CO_2)
  - Leave the room, closing the door behind you
  - Secure the room to prevent entry
  - Sound the fire alarm
  - Call 911
- For inert gases (N_2)
  - Replace the cylinder cap
  - Leave the room, closing the door behind you
  - Secure the room to prevent entry
  - Contact vendor for removal. If ordered from Central Storehouse, send an email to afscylinders@ucdavis.edu; they will contact the vendor.
  - Notify EH&S (530-752-1493) as soon as possible during work hours (M-F, 8-5) or nonemergency campus dispatch (530-752-1727) to reach the after-hours on-call EH&S representative for further guidance.

DISPOSAL

1. Mark empty cylinders "empty" and store them separately from full ones. NEVER refill a cylinder. A cylinder is empty at 25 psi. DO NOT EMPTY COMPLETELY as suction and backflow can occur contaminating the cylinder.

ANALYSIS

If both cylinders were to release all air at once, this would amount to 228 CU. FT. of Nitrogen, and 432 CU. FT. of Carbon Dioxide.

The smallest dimensions of the spafford building are 60’ x 42’ x 13’ (L x W x H), granting a total of 32,760 CU. FT of volume. One section of the ceiling extends to 18’, so this is a conservative estimate.

PPM CO2 limit: 5000 PPM
Assuming ambient conditions at 1,000 PPM, or 0.1% CO2

Assumption: pressurized to less than 880 PSIG, so in gaseous state
Cylinder Spec:
Internal Pressure: 830 PSIG
Internal Volume: 2038.2 in3

PV=nRT
(830 PSIG)(2038.2 in3) = n(R) (20 C)
(5722.65 kPa)(33.4 L) /((8.314 L kPa/mol K)(293.15 K))= n
Mol CO2 inside canister: 78.4 mol

At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L
In the room, this would amount to 1462500 mol of air. If there is 0.1% CO2 in the air, there are 1462.5 mol of CO2 present in the room.
Upon release of CO2 cylinder, this would amount to (189 + 1462.5) / (1462500 +189)= 0.1129% CO2,
Or **1,129 PPM.**

How long will this gaseous mixture last?

Conservative estimate: air at 0.03% CO2, trying to bring it up to 0.3%, so air flowing at 7.784 LPM, CO2 flowing at 0.216 LPM

Within cylinder, we have 78.4 mol / 33.4 L = 2.34 mol/L

Regulating to 40 PSIG, equivalent to 275.79 kPa
(275.79 kPa)(0.216 L/min) /((8.314 L kPa/mol K)(293.15 K))= n/min
= 0.0244 mol/min

78.4 mol / (0.0244 mol/min) = 3,213.1 minutes

= 53.5 hours

CO_2 is added for ~½ of one full adsorption/desorption cycle, so approximately 107.1 experiment hours, or a 4.46 day experiment

Assumption: pressurized to greater than 880 PSIG, so in liquid state
1101 kg/m^3   [1 m^3 [=] 1000 L]
1.101 kg/L (33.4 L) = 36.7734 kg
44.009 g/mol → 0.044009 kg/mol
(36.7734 kg) / (0.044009 kg/mol) = 835.7 mol

At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L
In the room, this would amount to 1462500 mol of air. If there is 0.1% CO_2 in the air, there are 1462.5 mol of CO_2 present in the room.
Upon release of CO_2 cylinder, this would amount to (835.7 + 1462.5) / (1462500 +835.7)= 0.1571% CO_2,
Or **1,571 PPM.**

<u>**How long will this liquid CO_2 cylinder last?**</u>
Conservative estimate: air at 0.03% CO_2, trying to bring it up to 0.3%, so air flowing at 7.784 LPM, CO_2 flowing at 0.216 LPM

Within cylinder, we have 835.7 mol / 33.4 L = 25.02 mol/L

Regulating to 40 PSIG, equivalent to 275.79 kPa
(275.79 kPa)(0.216 L/min) /((8.314 L kPa/mol K)(293.15 K))= n/min
= 0.0244 mol/min

835.7 mol / (0.0244 mol/min) = 34,250 minutes

= 570.8 hours

CO_2 is added for ~½ of one full adsorption/desorption cycle, so approximately 1,141.6 experiment hours, or a 45.6 day experiment

Lack of Oxygen Asphyxiant limit: 19.5%
At 21% oxygen, this would be 6879.6 CU. FT. occupied by oxygen

Adding the entirety of both cylinders would amount to the equivalent of 33420 CU. FT. of gas in the room, with a resulting oxygen percentage of **20.6 %**

CO2:
Assumption: pressurized to greater than 880 PSIG, so in liquid state
1101 kg/m^3   [1 m^3 [=] 1000 L]
1.101 kg/L (33.4 L) = 36.7734 kg
44.009 g/mol → 0.044009 kg/mol
(36.7734 kg) / (0.044009 kg/mol) = 835.7 mol

Nitrogen:
Assumption: pressurized to greater than ~725 PSIG, so in liquid state
0.807 g/mL [1 g/mL [=] 1 kg/ L]
0.807 kg/L (33.4 L) = 26.95 kg
28 g/mol → 0.028 kg/mol
(26.95 kg) / (0.028 kg/mol) = 962.5 mol

At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L In the room, this would amount to 1462500 mol of air. Assume there is 0.1% CO2 in the air, 78% Nitrogen in the air, and 21% Oxygen in the air. There are then 6879600 L oxygen in the air.

CSFR-ECLSS-003: ZeoDe Startup Checklist

UC Davis Center for Spaceflight Research

Habitats Optimized for Missions of Exploration (HOME) Institute

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Objective

The objective of this checklist is to ensure a safe startup, both for the engineers and the hardware

Scope

This covers checklists to be used at the startup of the ZeoDe testbed

Required Training

- Review of SafetyNet#60 Compressed Gas Safety
- Review of CSFR-ECLSS-002 ZeoDe Experiment Gas Hazard Document
- In-person review with SatLab within CSFR of electronics hazards
- Review of Drierite SDS

Required PPE

- Nitrile Gloves when handling Drierite

Revision History

Revision #	Date	Reason for Change	List of Changes	Responsible Engineer
1	May 2023	Initial Draft based on experimental test plan CSFR-ECLSS-001	-	Daniela Ivey

Hardware

- [ ] Gas cylinder CO_2 - secured to the wall

- [ ] Gas cylinder N2 - secured to the wall
- [ ] Regulator shop air line - secured to the wall
- [ ] Pressure relief valves - no visible issues
- [ ] Piping connections throughout the testbed - no visible issues
- [ ] Hardware units - no visible sagging that could indicate loose bolts
- [ ] Tabletop - no loose units on the tabletop that could present a hazard
- [ ] Bottom level tabletop - no loose units on tabletop that could present a hazard
- [ ] Insulation - insulation is tightly wound in place around hot points, bed and upstream of bed

Electrical - Pre DAQ

- [ ] Power plugs - all plugs are disconnected from outlets
- [ ] Wiring at temperature limit controller - no loose or disconnected wires
- [ ] Wiring at temperature limit controller - no exposed wires where they could be accidentally handled
- [ ] Wiring at DAQ chassis - no loose or disconnected wires
- [ ] Wiring at DAQ chassis - no exposed wires where they could be accidentally handled
- [ ] Wiring at DC ports, both 12V and 24V below DAQ - no loose or disconnected wires
- [ ] Plug DAQ into power at the wall

Temp Checks

- [ ] Temperature - ensure readings coming from thermocouples are within 10C of ambient temperature
- [ ] Ensure no sequences are currently selected

Electrical - Post DAQ

- [ ] Ensure DAQ is still powered via AC power outlet
- [ ] Note: after plugging any unit, wait at least 5 seconds for signs of off-nominal cases, such as lound noises or sparks
- [ ] Taking the previous note into account, proceed with one by one in the following order plugging in each AC power cable
    - [ ] Mass flow controllers
    - [ ] Mass flow transmitters
    - [ ] AC power cable
    - [ ] Pump

Gas

- ☐ Open Carbon Dioxide tank valve
- ☐ Check Carbon Dioxide regulator - nominal readings
- ☐ Open NItrogen tank valve
- ☐ Check Nitrogen regulator - nominal readings
- ☐ Set shop air regulator to desired pressure - ensure nominal response

Sensor Checks

- ☐ Flow Nitrogen at 1 SLPM through the bed
- ☐ Check sensor response - nominal
- ☐ If no alarms or off-nominal readings present
    - ☐ Begin experiment

Post-Experiment Start

- ☐ Monitor readings closely for 5 minutes after start - expected response from sensors

CSFR-ECLSS-004: ZeoDe Maintenance Procedure

UC Davis Center for Spaceflight Research

Habitats Optimized for Missions of Exploration (HOME) Institute

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Objective & Scope

The objective of this procedure is to call out notes or warnings tied to hazards associated with specific maintenance, along with applicable checklists

Required Training

- ☐ Review of SafetyNet#60 Compressed Gas Safety
- ☐ Review of CSFR-ECLSS-002 ZeoDe Experiment Gas Hazard Document
- ☐ In-person review with SatLab within CSFR of electronics hazards
- ☐ Review of Drierite SDS
- ☐ Review of heater rope SDS

Important Reference Documents

Required PPE

- Nitrile Gloves when handling heater rope
- Safety Glasses when performing mechanical or electrical work where eye damage could occur - for example: stripping wires behind the testbed
- Hair back
- Long pants when working with heater rope
- Closed toed shoes when performing mechanical or electrical work

Revision History

Revision#	Date	Reason for Change	List of Changes	Responsible Engineer
1	May 2023	Initial Draft	-	Daniela Ivey
2	March 2024	Second Draft	Increased detail and added checklists	Daniela Ivey

Maintenance

Wiring

WARNING exercise caution when performing electrical work. 120VAC can cause serious injury or death.

Before performing any wiring re-work:

- [ ] Turn off AC PWR1
- [ ] Turn off AC PWR2
- [ ] Turn off DC PWR
- [ ] Unplug all outlets from wall

Before turning the system back on, after performing any wiring rework:

- [ ] Ensure no wires are left disconnected
- [ ] Ensure all wires have secure connections
- [ ] If any wires were required to be secured by temporary, non-secure connections such as alligator clips then:
    - [ ] Write a visible note and leave on top of testbed saying that there are unsecure connections present

After turning the system back on, run the following systems check

- [ ] While watching all valve readbacks, command valve 6A 90 degrees from its current position
- [ ] While watching all valve readbacks, command valve 7A 90 degrees from its current position
- [ ] While watching all valve readbacks, command valve 8A 90 degrees from its current position
- [ ] While watching all valve readbacks, command valve 7B 90 degrees from its current position
- [ ] While watching all valve readbacks, command valve 10A 90 degrees from its current position

If any other positions were affected, there is most likely a loose connection within your system. It is easy to use the valves as a case study as you can both monitor their readbacks, and see any changes in their position, or if they did not reach their final commanded position.

Mechanical

- [ ] If undoing or redoing any fittings:
    - [ ] Ensure you are securing the fastener in the correct location to eliminate back-torque
- [ ] For NPT fittings:

- [ ] The seal is made by the threads - the more you tighten it the more secure it will be
- [ ] The more you undo and redo fittings, the more the threads will wear, and the less likely a secure seal is
- [ ] Thick gloves are recommended to avoid hand fatigue

- [ ] For compression fittings:
    - [ ] The seal is made by the compression of the ferrule and the sleeve around the pipe
    - [ ] Once secured for the first time, one does not need to tighten the fitting with great force, like with an NPT fitting
- [ ] For Heater Rope
    - [ ] Ensure temperature readings are within 10C from ambient before handling
    - [ ] Wear nitrile gloves to mitigate risk of fiberglass on hands

CSFR-ECLSS-005: ZeoDe Hazards & Risks Document

UC Davis Center for Spaceflight Research

Habitats Optimized for Missions of Exploration (HOME) Institute

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Objective

This document outlines the risks associated with the ZeoDe testbed

Scope

Risks are identified and placed in a risk chart

Revision History

Revision#	Date	Reason for Change	List of Changes	Responsible Engineer
1	May 2023	Initial Draft	-	Daniela Ivey; Shannon Lackey

Risk assessment

The following risk chart was used in order to determine the consequences of each risk.

SCORE	1	2	3	4	5
IMPACT ON PERFORMANCE	Minimal impact on goals	Minor impact on goals	Unable to achieve a particular goal	Unable to achieve multiple goals	Unable to achieve the overall goal
IMPACT ON HUMAN SAFETY	Discomfort or nuisance	First aid	Minor injury or illness	Major injury or illness	Loss of life
IMPACT ON ASSET	No physical damage	Cosmetic damage	Functional damage but repairable	Substantial damage but repairable	Destroyed
IMPACT ON SCHEDULE	Minimal impact on schedule	Delay on some tasks not impacting overall schedule	Delay on some tasks minimally impacting overall schedule	Major slip in overall schedule	Critical milestones cannot be met
IMPACT ON COST	Minimal impact on cost	Minor impact on cost (cost variance <5%)	Medium impact on cost (5-10%)	Major impact on cost (10-15%)	Critical impact on cost (cost variance >15%)

The following chart shows the likelihood vs consequences model that was used in this analysis.

LIKELIHOOD \ CONSEQUENCE	1	2	3	4	5
5	7	16	20	23	25
4	6	13	18	22	24
3	4	10	15	19	21
2	2	8	11	14	17
1	1	3	5	9	12

Risks

Risk	LxC	Risk Title	Approach
ZeoDe-001	**3x4**	Over Pressure of system	Mitigate
ZeoDe-002	**3x2**	Over Temperature of sorbent bed	Mitigate
ZeoDe-003	**3x2**	Over Temperature upstream of sorbent bed	Mitigate
ZeoDe-004	**4x4**	Electrical Discharge	Mitigate
ZeoDe-005	**2x2**	Sharp Edges	Migate
ZeoDe-006	**4x1**	High CO2	Accepted
ZeoDe-007	**1x5**	Compressed Gas Tank Release	Mitigate
ZeoDe-008	**2x2**	Water leak from Nafion to electrical components	Mitigate
ZeoDe-009	**1x3**	Electric Short	Mitigate
ZeoDe-010	**1x1**	Low O2	Mitigate
ZeoDe-011	**1x2**	Unsecured part	Mitigate

LIKELIHOOD	5					
	4	ZeoDe-006			ZeoDe-004	
	3			ZeoDe-002 ZeoDe-003	ZeoDe-001	
	2		ZeoDe-005 ZeoDe-008			

	1	ZeoDe-010	ZeoDe-011	ZeoDe-009		ZeoDe-007
		1	2	3	4	5
CONSEQUENCES						

Risk	LxC	Risk Title	Approach	Conditions for Occurence	Mitigations
ZeoDe -001	3x4	Over Pressure of system	Mitigate	A failed valve or mass flow controller Inlet of shop air at higher pressure than regulator is rated to	Pressure Relief valves at the beginning of each inlet line The shop air regulator has a relief valve
ZeoDe -002	3x2	Over Temp of sorbent bed	Mitigate	Failed commanding to the heater	Heater limit controller LabView alarm and shut down response as a result of sorbent bed thermocouple readings
ZeoDe -003	3x2	Over-Temp upstream of the sorbent bed	Mitigate	Failed commanding to the heater	Heater limit controller LabView alarm and shut down response as a result of sorbent bed thermocouple readings
ZeoDe -004	4x4	Electrical Discharge	Mitigate	Loose connections Ungrounded connections	Grounding the DAQChassis Grounding the testbed
ZeoDe -005	2x2	Sharp Edges	Mitigate	Sharp connections between 80/20 pieces	Sharp edges are to be smoothed or have foam attached to them.
ZeoDe -006	4x1	High CO_2	Accepted	High CO_2 can take place as exhaust is venting to the room or given a leak of the compressed gas cylinder, for	Gas analysis: CO_2 levels will not rise to hazardous levels, given the volume of the enclosure

				example, thorough the regulator	
ZeoDe -007	1x5	Gas Tank Release	Mitigate	The compressed gas cylinders fall over, and the caps are broken off	Securing the gas cylinders at two locations each to the center of the building metal struts
ZeoDe -008	2x2	Water leak from Nafion to units	Mitigate	Water leaks from the housing down toward the mass flow controllers	The water housing uses a siphon instead of a drip system, with the opening at the top
ZeoDe -009	1x3	Electric Short	Mitigate	Exposed wires make contact	Using quick-disconnects for wire extensions
ZeoDe -010	1x1	Low O_2	Mitigate	Large quantities of gas released at once	Size of gas cylinders and size of room
ZeoDe -011	1x2	Unsecured part	Mitigate	A bolt becomes loose on the back of the pegboard	The testbed produces minimal vibrations

Further description:

ZeoDe-001	**3x4**	Over Pressure of system	Mitigate

The over-pressurization of the system could take place under the following conditions

- A failed valve or mass flow controller
- Inlet of shop air at higher pressure than regulator is rated to

Mitigations:

- Pressure Relief valves at the beginning of each inlet line
- Shop air regulator has a relief valve

ZeoDe-002	**3x2**	Over Temperature of sorbent bed	Mitigate

The over-temperature of the sorbent could take place under the following conditions

- Failed commanding to the heater
- Inlet of shop air at higher pressure than regulator is rated to

Mitigations:

- Heater limit controller

- LabView alarm and shut down response as a result of sorbent bed thermocouple readings

ZeoDe-003	**3x2**	Over Temperature upstream of sorbent bed	Mitigate

The over-temperature upstream of the sorbent could take place under the following conditions
- Failed commanding to the heater
- Inlet of shop air at higher pressure than regulator is rated to

Mitigations:
- Heater limit controller
- LabView alarm and shut down response as a result of sorbent bed thermocouple readings

ZeoDe-004	**4x4**	Electrical Discharge	Mitigate

Electrical discharge could take place under the following conditions
- Failed commanding to the heater
- Inlet of shop air at higher pressure than regulator is rated to

Mitigations:
- Grounding the DAQChassis
- Grounding the testbed

ZeoDe-005	**2x2**	Sharp Edges	Migate

Sharp edges are to be smoothed, or have foam attached to them.

ZeoDe-006	**4x1**	High CO2	Accepted

High CO2 can take place as exhaust is venting to the room, or given a leak of the compressed gas cylinder, for example thorough the regulator

Accepted:
- See CSFR-ECLSS-002 for the gas hazards analysis - CO2 levels will not rise into hazardous levels given the volume of the enclosure

ZeoDe-007	**1x5**	Compressed Gas Tank Release	Mitigate

Compressed gas releasecould take place under the following conditions
- The compressed gas cylinders fall over, and the caps are broken off

Mitigations:

- Securing the gas cylinders at two locations each to the center of the building metal struts

ZeoDe-008	**2x2**	Water leak from Nafion to electrical components	Mitigate

A water leak could take place under the following conditions

- Water leaks from the housing down towards the mass flow controllers

Mitigations:

- A putty has been employed, and applied to entire bottom of the water housing

ZeoDe-009	**1x3**	Electric Short	Mitigate

An electrical short could take place under the following conditions

- Exposed wires make contact

Mitigations:

- Using quick-disconnects for wire extensions

ZeoDe-010	**1x1**	Low O2	Mitigate

Low O2 is not possible given the volume of the enclosure - mitigation steps included ensuring that the cylinders used would not be capable of releasing enough gas to lower the O2 to hazardous levels.

- See CSFR-ECLSS-002 for the gas hazards analysis

ZeoDe-011	**1x2**	Unsecured part	Mitigate

A part could fall off the testbed given the following conditions

- A bolt becomes loose on the back of the pegboard

Mitigations:

- The testbed produces minimal vibrations

CSFR-ECLSS-007: ZeoDe Zeolite Weighing

UC Davis Center for Spaceflight Research

Habitats Optimized for Missions of Exploration (HOME) Institute

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Objective

The objective of this document is to lay out the weighing of the zeolite beads for experiments

Scope

This covers the procedures and provides a template to be filled out here when weighing is completed

Revision History

Revision #	Date	Reason for Change	List of Changes	Responsible Engineer
1	September 2023	-	-	Daniela Ivey

Procedure

Materials:

- Unopened zeolite container
- Scale
- Clean jars for storage
- Sharpie for labeling
- Computer to fill out data sheet.

Objective/Background:

Once zeolite is exposed to air, its weight can change by 30-40% due to contamination. The weight that is used in modeling of the system is the uncontaminated weight. This is what weight would be read after a bakeout. However, weighing after bakeout would require a scale on the testbed itself, which would require a scale that handles both high weight and high precision. An alternative to costly scales is to partition all zeolite when the bin is first opened.

Procedure:

Weigh each jar, without the lid, note the weight, then fill with approximately 80 g of zeolite. Then label the jar with weight of zeolite, weight of the jar, and weight of the jar with the lid. Copy the data sheet below, paste below, and fill out.

Date: 9/13/2023

Zeolite PCode	Zeolite Source Code	CAS-No	Part No.	Weight unopened	Weight without zeolite	Calculated weight of Zeolite	Scale Used
1003401419	MKCQ4436	63231-69-6	208647-1KG	1196.9 g	196.1	1000.8	Amir in sat lab 3000g X 0.1g

Jar #	Weight of Jar without lid	Weight of Jar with lid	Weight of zeolite inserted into jar	labeled	Scale Used	notes
[#]	[g]	[g]	[g]	[x]	[#]	
1	243.50	257.40	115.06	x	G Dealer Scale in Sat Lab 500g x 0.01g	
2	243.46	257.35	115.09	x	“	
3	244.32	258.17	116.78	x	“	
4	244.41	258.48	115.28	x	“	
5	244.47	258.50	115.92	x	“	
6	244.11	258.12	115.38	x	“	
7	244.36	258.27	115.33	x	“	
8	243.46	257.38	115.06	x	“	
9	244.16	258.27	77.21	x	“	Some fell on table and I wiped it into the jar with hands (contamination) and lost a few beads on the floor (maybe 1 gram worth)
Sum			1001.11			Therefore about 0.31 g contamination as measured, but with lost zeolite pieces, most likely around 1 g of contamination OR scale margin of error.

Date: 00/00/0000

Zeolite PCode	Zeolite Source Code	CAS-No	Part No.	Weight unopened	Weight without zeolite	Calculated weight of Zeolite	Scale Used

Jar #	Weight of Jar without lid	Weight of Jar with lid	Weight of zeolite inserted into jar	labeled	Scale Used	notes
[#]	[g]	[g]	[g]	[x]	[#]	

CSFR-ECLSS-008: ZeoDe Sensor Calibrations

UC Davis Center for Spaceflight Research

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Objective

The objective of this document is to take notes on the sensor calibrations performed

Scope

Notes should be taken here when sensor calibrations are performed

Revision History

Revision #	Date	Reason for Change	List of Changes	Responsible Engineer
1	October 2023	-	-	Daniela Ivey

Procedure

Materials:

- Sensor Cables

Objective/Background:

Log sensor calibrations performed or looked up for the system

Procedure:

Unit	Formula	Link to documentation	Implemented in MICAS-X
Humidity	DP={(V-0 / 5) x 100} -40 = 20V -40	Formula - Anal…	
Upstream CO2 (0-5V)	PPMCO2 = {V-0 / 5) x 5000 =1000V + 0 %CO2	Formula - Anal…	
Downstream CO2 (0-10V)	PPMCO2 = {V–0 / 10) * 20,000 = 2000V + 0 %CO2 = PPMCO2*0.0001 %CO2 = 0.2V + 0		
Downstream CO2 (0-10V) but what if 100,000 ppm max	PPMCO2 = {V–0 / 10) * 100,000 = 10,000V + 0 %CO2 = PPMCO2*0.0001 %CO2 = 1V + 0		
Pressure	P = {(V-0 / 5) x 30 } =6V		
TEMP (from humidity probe)	T = { V-0 / 5) x 100} -40 =20V-40		

Old humidity (from STEVE)

Upstream Dewpoint (C)	Polynomial	-78.586	37.878	0	0	4	0 to 5 V
Downstream Dewpoint	Polynomial	-78.586	37.878	0	0	5	0 to 5 V

Old Pressure

Name	Scaling	(Offset	Linear	Quadratic	Cubic)	Channel	Range
Upstream Abs Pres (psi)	Polynomial	14.7	41.3686	0	0	0	0 to 5 V
Downstream Abs Pres	Polynomial	14.7	41.3686	0	0	1	0 to 5 V

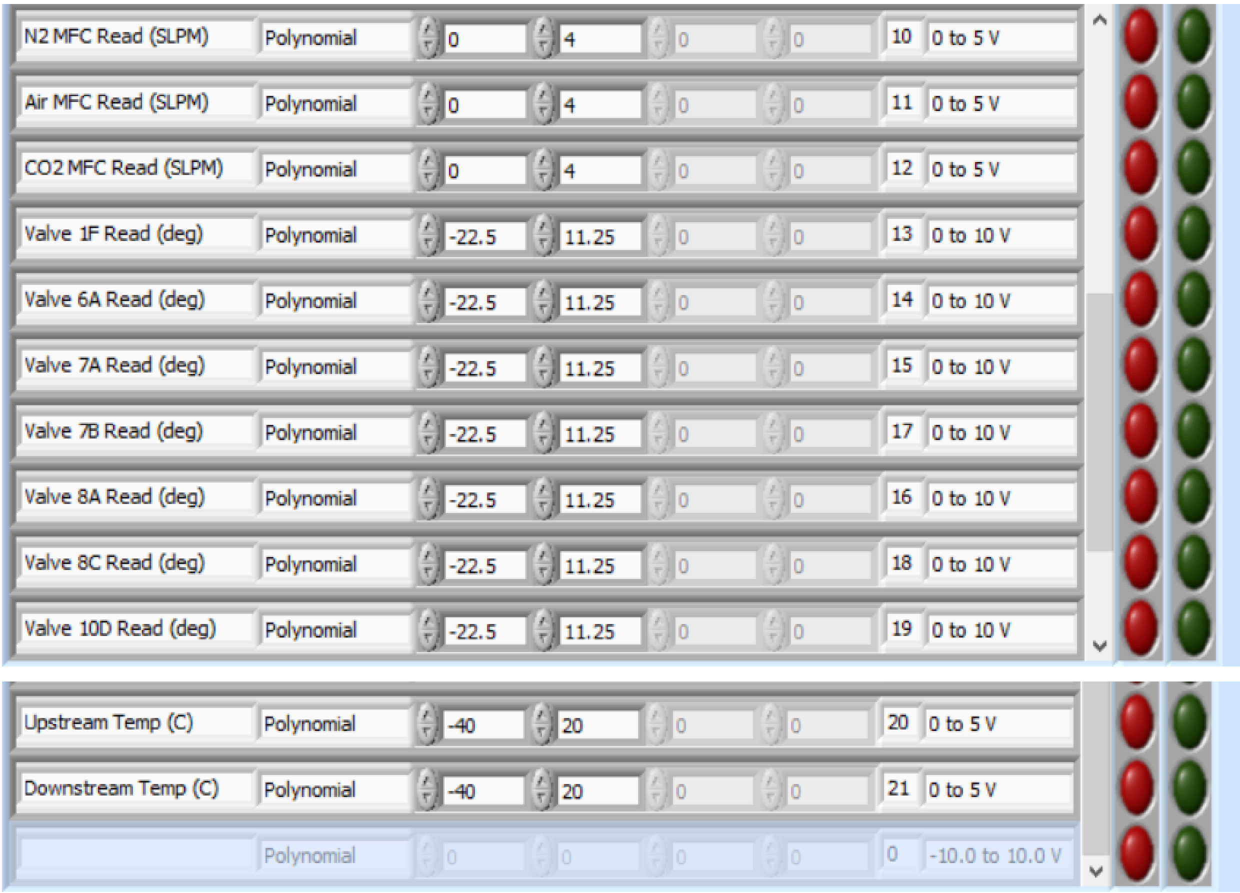
Old temp:

Upstream Temp (C)	Polynomial	-30.885	26.8034	0	0	20	0 to 5 V

(was 0-10V)

Inserted curves:

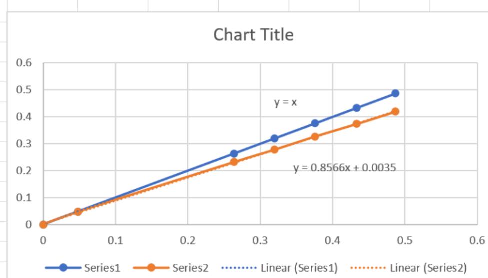
Name	Scaling	(Offset	Linear	Quadratic	Cubic)	Channel	Range
Upstream Abs Pres (psi)	Polynomial	0	6	0	0	0	0 to 5 V
Downstream Abs Pres	Polynomial	0	6	0	0	1	0 to 5 V
Upstream Flow (SLPM)	Polynomial	0	2	0	0	2	0 to 5 V
Downstream Flow (SLPM)	Polynomial	0	2	0	0	3	0 to 5 V
Upstream Dewpoint (C)	Polynomial	-40	20	0	0	4	0 to 5 V
Downstream Dewpoint	Polynomial	-40	20	0	0	5	0 to 5 V
Upstream CO2 Uncorr	Polynomial	0	1000	0	0	6	0 to 5 V
Downstream CO2 Uncorr	Polynomial	0	1000	0	0	7	0 to 5 V
Sorbent Bed dP (psi)	Polynomial	0	3	0	0	8	0 to 10 V
Humid Air MFC Read	Polynomial	0	4	0	0	9	0 to 5 V



N2 MFC Read (SLPM)	Polynomial	0	4	0	0	10	0 to 5 V
Air MFC Read (SLPM)	Polynomial	0	4	0	0	11	0 to 5 V
CO2 MFC Read (SLPM)	Polynomial	0	4	0	0	12	0 to 5 V
Valve 1F Read (deg)	Polynomial	-22.5	11.25	0	0	13	0 to 10 V
Valve 6A Read (deg)	Polynomial	-22.5	11.25	0	0	14	0 to 10 V
Valve 7A Read (deg)	Polynomial	-22.5	11.25	0	0	15	0 to 10 V
Valve 7B Read (deg)	Polynomial	-22.5	11.25	0	0	17	0 to 10 V
Valve 8A Read (deg)	Polynomial	-22.5	11.25	0	0	16	0 to 10 V
Valve 8C Read (deg)	Polynomial	-22.5	11.25	0	0	18	0 to 10 V
Valve 10D Read (deg)	Polynomial	-22.5	11.25	0	0	19	0 to 10 V
Upstream Temp (C)	Polynomial	-40	20	0	0	20	0 to 5 V
Downstream Temp (C)	Polynomial	-40	20	0	0	21	0 to 5 V
	Polynomial	0	0	0	0	0	-10.0 to 10.0 V

Downstream CO2 calibration

Flowrate	upco2 copied	Upstream CO2	Downstream CO2	Setpoint
	0	0	0	
8 SLPM	0.0483	0.0483	0.0472	0
8 SLPM	0.264	0.264	0.232	0.2
8 SLPM	0.32	0.32	0.278	0.25
8 SLPM	0.376	0.376	0.327	0.3
8 SLPM	0.433	0.433	0.373	0.35
8 SLPM	0.487	0.487	0.419	0.4



Max CO2 Conc.	Adjusting for difference in measurements		
0.2	0.233481205	0.236043904	-0.0071
1	1.167406024		
1.5	1.751109036		
2	2.334812048		
2.5	2.91851506		
4	4.669624095		

7.4 Non-Conformances

#	Title	Brief Summary	Closure
NC-001	ZeoDe Electrical Discharge	04/26/23: While testing a circuit (disconnected from the main system), a 120 V electric discharge occurred on a cable meant to be connected to the heater interrupt.	Increased labeling of electronics, additional warning labels, and new grounding standards.
NC-002	Grounding Issue	8/1/23: Valves were not operating as expected. They were all reacting in a way that showed there was residual voltage building up in the system, where they would progressively not close wholly when commanded closed and not open completely when commanded open.	Cabling was redone, grounding blocks were separated and re-labeled, and wiring diagrams were updated
NC-003	Desiccant Leak	8/11/23: While testing the airflow through the system, a leak was discovered at both ends of the 2F desiccant. Upon removal of the NPT fittings that were the source of the leak, it was found that the internal threading was irreparably damaged. The root cause was a mislabeled spec sheet stating stainless steel threading rather than aluminum threading.	New desiccant beds were received, and plastic fittings were attached instead of stainless steel. The system was run, and no leaks were detected at the desiccant beds.
NC-004	CO_2 sensor issues	9/14/23: A full-scale test was attempted. The heater powered slightly (to 45 C), heating the stream downstream of the packed bed (see NC-005). CO2 levels began reading 256%.	This NC was combined with NC-007
NC-005	Temperature increase at the bed	9/14/23: A full-scale test was attempted. Though not commanded on, the heater increased in temperature to 45 C and leveled off. It was found to be the same faulty thermocouple that later failed in NC-006.	New thermocouples were installed.
NC-006	Limit controller error reading SbnE	9/25/23: An error light flashed on one of our temperature limit controllers. The manual for TEC-910 was consulted, but this error message was not found. After consulting the manufacturer it was confirmed that the error message was due to a faulty sensor.	New thermocouples were installed

#	Title	Brief Summary	Closure
NC-007	CO_2 Sensor issue	9/26/23: When running sensor checks on the system, it was found that the CO_2 probes were not reading correctly despite having been thought to be previously calibrated. The sensors did not respond to stimuli (0-100% CO_2 flow). Voltage checks were done to determine if the root cause was related to MICAS-X or the sensor itself. Conclusion: the sensor was stuck in an error mode.	Characterization of the sensor error modes was performed. The downstream sensor was exchanged for one with a greater range, and error modes were modified in the source programming.
NC-008	Humidity Sensor issue	9/27/23: When running the humidity sensor calibration, two problems arose. The first is that the downstream sensor did not produce readings or deflections with changes in humidity. This was hypothesized as a sensor or connectivity problem. The second issue that arose is that the Nafion manual is not a source of truth for known dew point readings, resulting in difficulty in calibrating the sensor. This could be a housing size problem (which is also currently being investigated for CO_2 sensor problems), a problem with the sensor itself, or a problem with our known dew points (indicating we need another source of truth for calibration).	The error modes for the sensor were reprogrammed, and a minimum flow rate for accurate sensor readings was established.

NC-001

Title: ZeoDe Electrical Discharge
Date: 04/26/2023
Filed by: Daniela Ivey; dbivey@ucdavis.edu

Severity: Medium

Summary

On 4/26/2023 4:00 PM while testing a circuit (disconnected from the main system), a 120 V electric discharge occurred on a cable meant to be connected to the heater interrupt. Live wires were not being handled, though they were laid out on the ground to view configurations. The purpose of the heater interrupt is to break a circuit supplying power to the heaters in the case of an over temperature event. The cable that experienced the discharge had just been disconnected from the heater interrupt. It was connected on one end to a 120V outlet, and had open wires on the other end. No hardware or people were harmed as a result of the discharge. A diagram of the heater interrupt device is shown following the investigation section

Root Cause

Root Cause Category: Human Error; Electrical Diagram Misinterpretation

See diagram following investigation section: in this test, both black and red cables (120 V AC power cables) were incorrectly disconnected from their terminals. This was due to human error in misinterpretation of the circuit diagram. As the cables were not connected to ground, this created a 120V electrical discharge to ground. The black and red cables (connected to terminals 6 and 7 respectively) should not have been disconnected, as they would not experience disconnection in any scenario during routine operations or off-nominal operations.

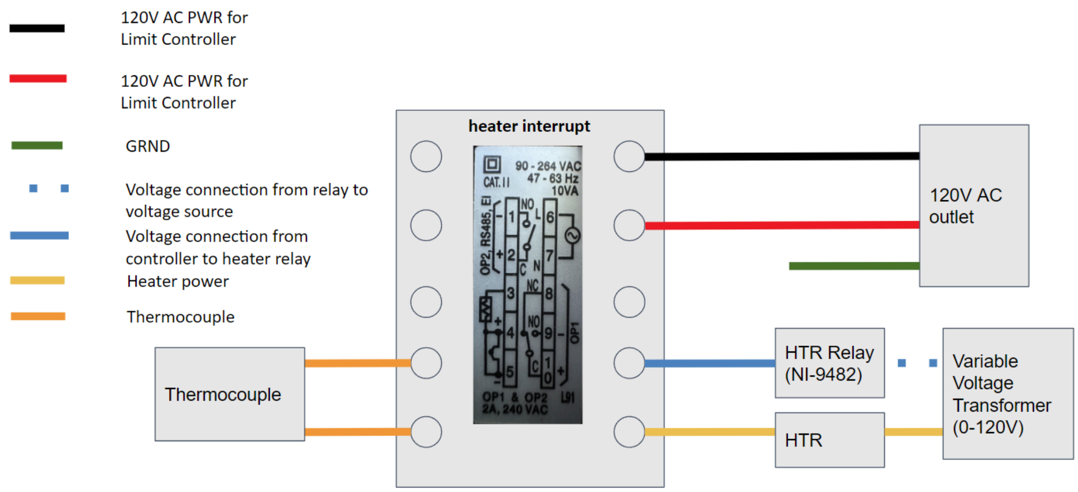
The end of this package contains a power diagram of the entire system for reference.

Investigation

Investigators: Daniela Ivey (on-site engineer), Sam Eshima (RE on similar system at CU Boulder, Grad Student)

The circuit was investigated with the help of Sam Eshima from CU Boulder, who runs a similar system on the STEVE testbed. There was initially a concern that if this was a situation that could be seen during an over temperature event, that since the CU Boulder STEVE testbed is also not connected to ground, they might be at risk of a discharge event.

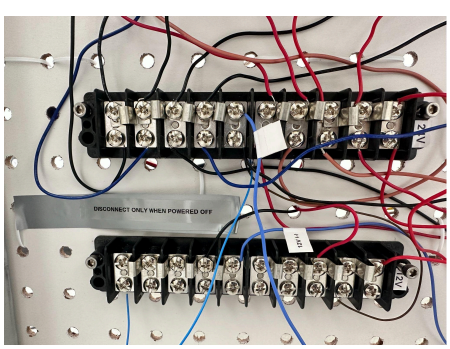
It was concluded, after reviewing the diagram, that this is not a critical concern under nominal operations as well as under an over temperature event, as terminals 6 and 7 would not in fact be disconnected. Instead, terminals 8 and 10 would be disconnected from each other. A discharge event would not take place under this configuration. The risk exclusively lies in maintenance activities.



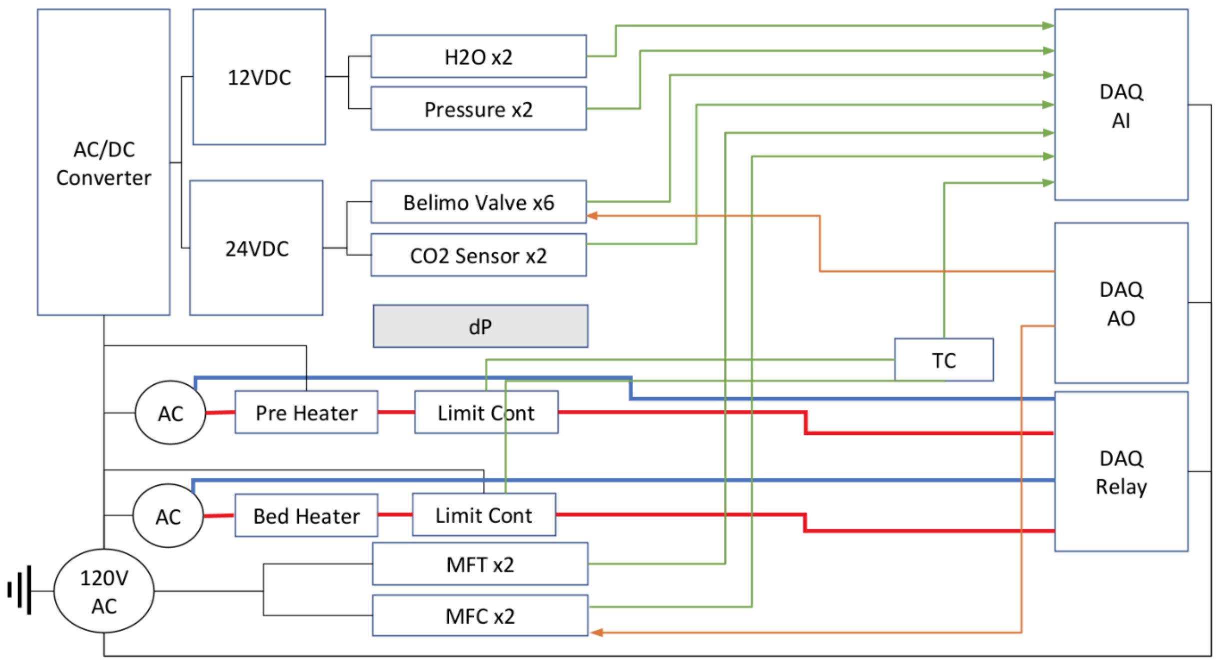
Path forward/recommendation

After discussing the wiring diagram, it was concluded that the current configuration itself would not result in a similar discharge event under nominal operations, or during an over-temperature event. The risk of electrical discharge lies in performing maintenance on wiring. It is recommended that the ground cable (green, currently not connected) be connected to facility ground to avoid the possibility of a discharge event during maintenance. If this is not possible, we recommend placing labels on each cable throughout ZeoDe that if disconnected, could produce a discharge, as well as an overview of these labeled cables with the team. The way to avoid this discharge would be to first disconnect from the outlet prior to unscrewing terminals. An additional recommendation has been to place limit controllers in a housing - plans have been put into place to 3D print this housing.

This warning will also be placed into the procedures for ZeoDe experiments, with the recommendation to create a separate procedure for maintenance that calls out warnings such as these. This appears in the first section of the experimental test plan, with “WARNING” note added.



The two images here show the warning labels placed on disconnection sites. The above is for DC power, which has a less severe safety concern than the image below, for AC power.



Closure

Engineer On-Site: ___________________________

Signature: ______________________ Date: _____________

Lab Safety Officer: ________________________

Signature: _______________________ Date: ______________

Lab Principal Investigator: ________________________

Signature: _______________________ Date: ______________

NC-002

Title: ZeoDe Grounding
Date: 08/01/2023
Filed by: Daniela Ivey; dbivey@ucdavis.edu

Safety Severity: Low

Cost Severity: Low

Operational Severity: Medium

Summary

Valves were not operating as expected. They were all reacting in a way that showed there was residual voltage building up in the system, where they would progressively not close completely when commanded closed, and not open completely when commanded open.

Root Cause

Root Cause Category: Grounding Issues

We had an AC ground cable connected to the DC grounding terminal block. This resulted in a build-up of voltage that accumulated each time a signal was sent

Investigation

Investigators: Daniela Ivey (on-site engineer), Zane Hayes (Erickson Lab), Jill Brigham

It was determined that issue could be one of the following:

1. Grounding
2. EMI
3. Unit Hardware Issue
4. Wiring issue

Testing was done to narrow it down:
https://docs.google.com/spreadsheets/d/1Tka-_uGk7_5Eu1D6cjDFkxP8YwYuIFt7CUJur_L8xQY/edit?usp=sharing

It was determined that it was most likely a grounding issue based on the fact that it built up over time as more commands were sent.

Tracing wires to our grounding block showed that we had placed an AC grounding wire into the DC grounding block, which caused a build-up of current in the system.

Wiring diagram:

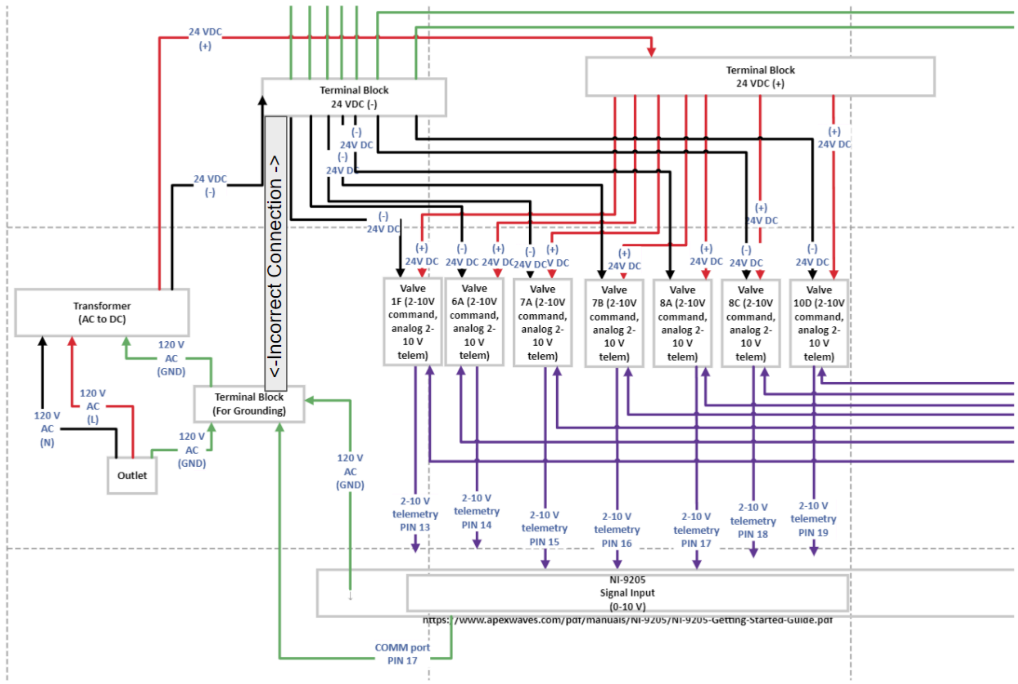


Figure 1: Incorrect configuration. A wire was connecting the AC terminal grounding block to the 24VDC terminal grounding block.

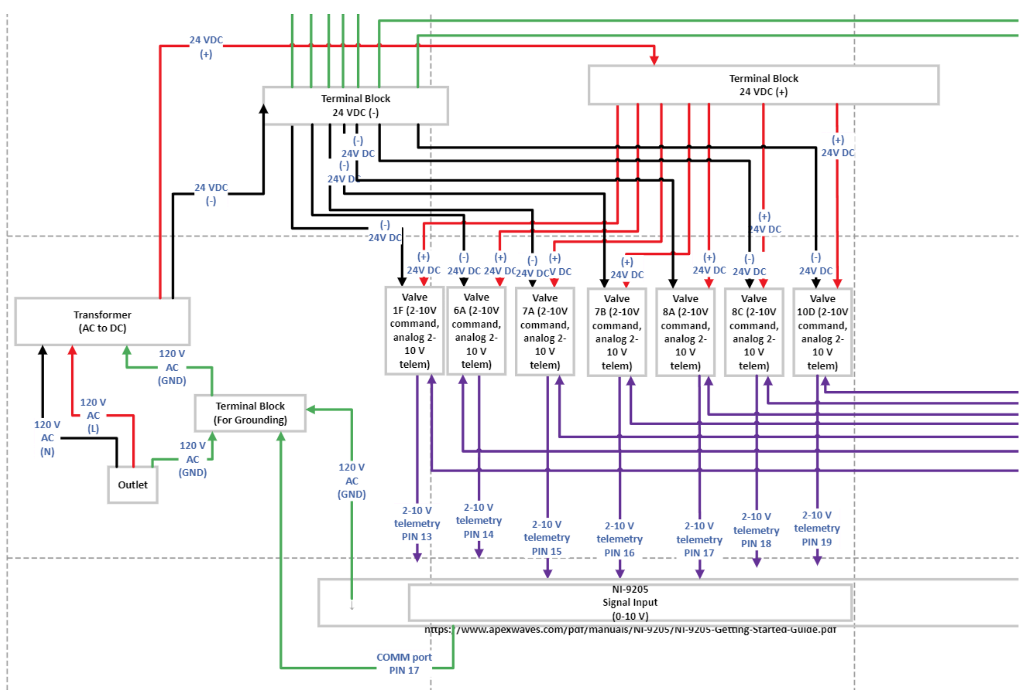


Figure 2: Diagram that shows the correction, where the connection from the AC grounding block to the DC grounding block was removed.

Path forward/recommendation

Cabling was redone, grounding blocks were separated and relabled, and wiring diagrams were updated.

Closure

Engineer On-Site: __________________________

Signature: _____________________ Date: ____________

Lab Principal Investigator: _______________________

Signature: ______________________ Date: ____________

NC-003

Title: ZeoDe Desiccant leak
Date: 08/11/2023
Filed by: Daniela Ivey; dbivey@ucdavis.edu

Safety Severity: Low

Cost Severity: Medium

Summary

The week of 08/11/2023 while testing flow of air through the system, a leak was discovered at both ends of the 2F desiccant. Upon removal of the NPT fittings that were the source of the leak, it was found that the internal threading was irreparably damaged.

Desiccant Part number: 5163K22

McMaster Carr Order number: 7227172

Fittings: stainless steel yorlok adapters: ¼" NPT to ¼ compression

Root Cause

Root Cause Category: Documentation Misinterpretation

When ordering the desiccant bed, it was believed that the threading was made from stainless steel based on the documentation provided.

After speaking with McMaster Carr, they confirmed that the material of the female threads on the desiccant body was not stainless steel, but aluminum. They also confirmed that the documentation was not clear, and that it could be misinterpreted as a stainless steel threading.

Investigation

Investigators: Daniela Ivey (on-site engineer), McMaster Carr

McMaster Carr was contacted to investigate female thread material. They confirmed it was aluminum.

The NPT male fittings that were used originally used two layers of Teflon tape for the fitting. A 9/16 wrench was used to remove the fittings, and the use of a vice was employed to keep the desiccant body in place.

They informed us that the material of the female threads was in fact aluminum and that the spec made it appear it was made of stainless steel. As a result, they sent us two replacement desiccant beds for free.

They sent us one new desiccant bed of the exact same type (¼” female NPT threads), but that was the last one in immediate stock. They did have a ½” female NPT thread desiccant of the same type, so we accepted their offer to sent that instead. We now have one desiccant with ¼” fittings and one desiccant with ½” fittings.

Purchased ¼” NPT and ½” NPT to barbed plastic fittings (shark bite brand) from Ace Hardware, installed them, ran the system, and did not encounter any leaks. Flexible hosing was connected to the barbed fittings, and then an ACE Hardware shark bite barbed to metal compression adapter was attached to the flexible tubing to make a connection to the stainless steel tubing.

Figure 1: Image of the desiccant bed, from the front, disconnected from system.

Figures 2 & 3 &4 : Photos of the thread galling on desiccant 1, on each side. Galling was not as significant in desiccant 2, but still present. Far right, photo of the stainless steel NPT male to compression fittings. One can make out on the NPT side that entered the desiccant remnants of the aluminum that were torn off when the fittings were removed.


Figure 5: New plastic fitting type that was installed, with NPT on one end and barbed fitting on the other end to connect flexible tubing. This was the easiest and least expensive option for the overall goal of connecting a plastic fitting in the desiccant to the metal tubing throughout the rest of the testbed system.

Figure 6 & 7: Upstream desiccant, with ½” NPT plastic fittings to ¼” (ID) barbed fittings, connected to ¼” (ID) flexible tubing, connected to a fitting with ¼” barbed fitting adapter to a compression fitting for metal tubing. Far right: Downstream desiccant with the same connections as the upstream desiccant, but with ¼” NPT threads inside the desiccant.

Path forward/recommendation

New desiccant beds were received, and plastic fittings were attached. The system was run, and no leaks were detected at the desiccant beds.

Closure

Engineer On-Site: ___________________________

Signature: ______________________ Date: _____________

Lab Principal Investigator: ________________________

Signature: _______________________ Date: ____________

NC-004

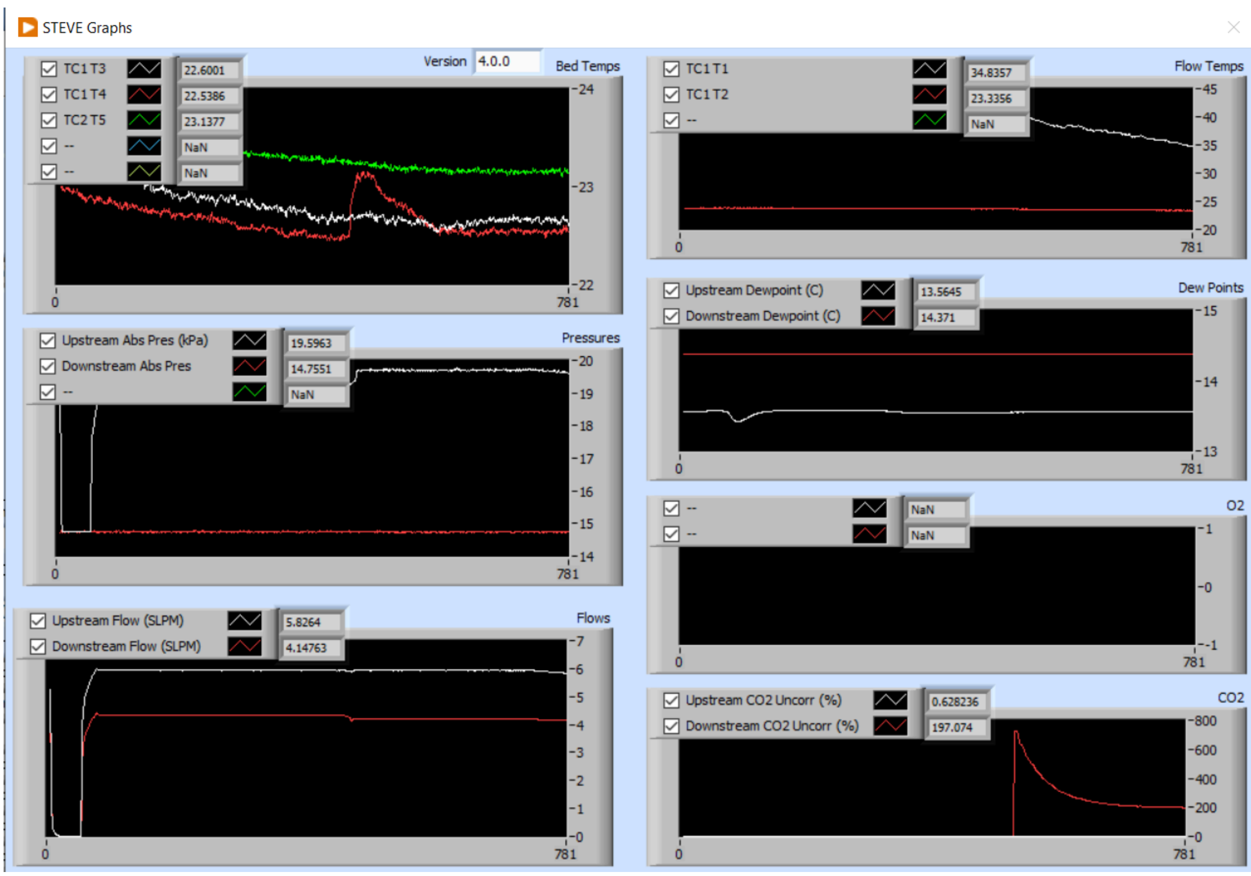
Title: ZeoDe CO2 sensor calibration/compensation issue
Date: 09/14/2023
Filed by: Daniela Ivey; dbivey@ucdavis.edu

Safety Severity: Low

Cost Severity: Low

Summary

On Thursday, 9/14/2023 a full scale test was attempted. The heater powered slightly (to 45 C) which heated the stream downstream of the packed bed (see NC-005). CO2 levels began reading 256%



Path forward/recommendation

Moving this NC into NC-007 as they concern the same unit and issue.

NC-005

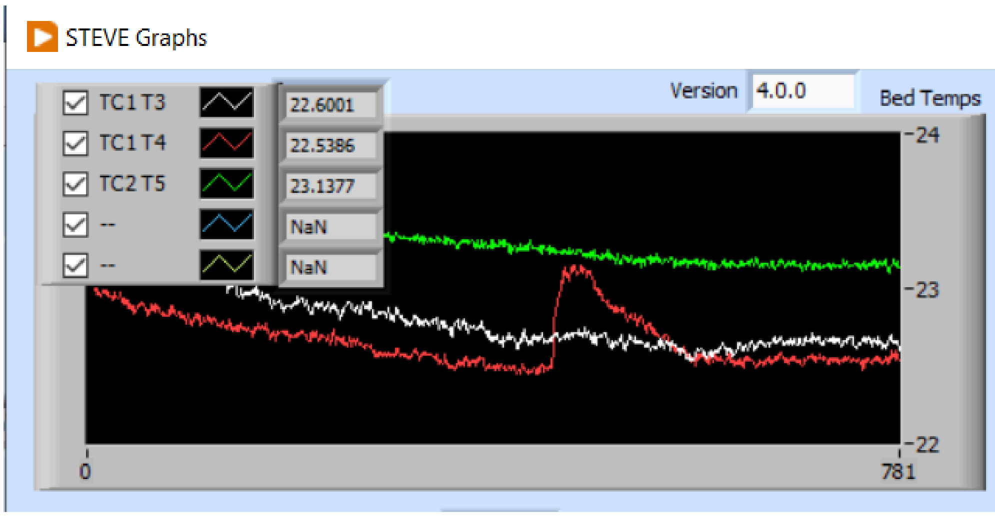
Title: ZeoDe Heater Issue
Date: 09/14/2023
Filed by: Daniela Ivey; dbivey@ucdavis.edu

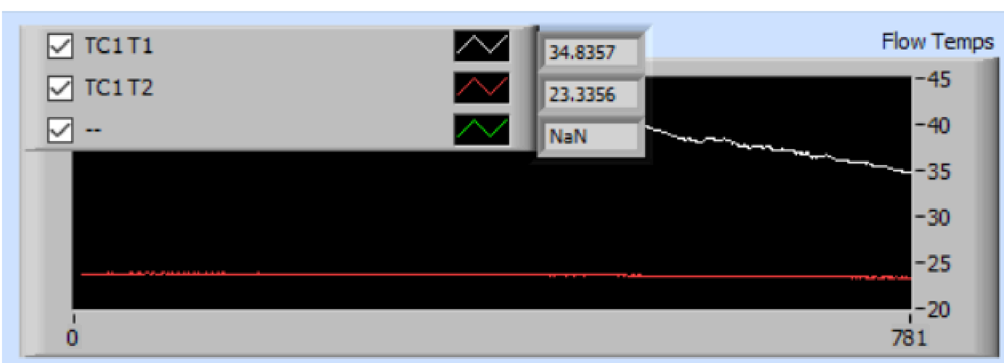
Safety Severity: Low

Cost Severity: Low

Summary

On Thursday, 9/14/2023 a full scale test was attempted. The temperature in the bed, though the heater was not commanded on, increased in temperature to 45 C and leveled off.





Root Cause

Root Cause Category: Thermocouple

The thermocouple reporting high values subsequently failed, which leads us to believe it was a faulty thermocouple. The thermocouple was replaced and the issue has not presented itself again.

Investigation

Investigators: Daniela Ivey (on-site engineer), Ben, Sam

List of potential checks that would have been performed if issue re-presented itself

- Repeating again and seeing if it happens again, if it does see how temperature changes over time as well as checking voltage to see if voltage remains constant or
- Were PID controllers active? (none were activated / heaters were selected as off)
    - Could be limiting power
- Check if relay was opened or closed (NI Max pin checking)
- Checking voltage at pin/terminal between temperature limit controller and the relay
- Putting interferences in the circuit while constantly checking temperature
-

However, issue resolved upon swapping of the thermocouple.

Path forward/recommendation

New thermocouple installed.

Closure

Engineer On-Site: ___________________________

Signature: ______________________ Date: _____________

Lab Principal Investigator: ________________________

Signature: _______________________ Date: ______________

NC-007

Title: ZeoDe CO_2 sensor problem
Date: 09/25/2023
Filed by: Shannon Lackey: sjlackey@ucdavis.edu Daniela Ivey; dbivey@ucdavis.edu

Safety Severity: Low

Cost Severity: Medium

Summary

On Tuesday, 9/26 when running sensor checks on the system, it was found that the CO_2 probes were not reading properly, despite having been thought to be previously calibrated. The output on both sensors (upstream and downstream CO_2) did not change as CO_2 percentage was changed through a range of values from 0% CO_2 (100% N_2) - 100% CO_2. They were reading in the mV range when expected output was 0-5 VDC. Voltage checks were completed to determine whether the actual unit was outputting off-nominal data, or if it was being disrupted downstream in wiring, in the DAQ from National Instruments, or in LabView. These checks led us to believe the problem is with the sensor. Talks with the vendor led to the conclusion that the sensors are experiencing an error mode (internal alarms) that cannot be identified or reprogrammed without a cable that is sold separately. A suggested BOM is included in path forward. We also have reason to believe that STEVE is encountering a similar error mode based on an email received on 10/2/2023.

Root Cause

Root Cause Category: hardware/software within hardware

Root cause is an error mode within the CO_2 sensors themselves. Exact cause of error is unknown, and a cable that allows acces to the insight software is needed to diagnose it. The current hypothesis is that it could be either high CO_2 levels or obstruction of the sensor via the housing.

Related NC's: NC-004 which was closed as it had a similar issue and same unit.

Investigation

Investigators: Daniela Ivey, Shannon Lackey (on-site engineers); Chris Keenan (Vaisala) @303-436-2369

- See Experiment notebook page 4 (Tues 09.26.2023/TempLimit Controller & Sensors & CO_2 Sensor Troubleshooting) through pg 19
- Experiment Notebook

Conversation with Vaisala:

- Sensor was in an error mode
- To detect what kind of error mode you are in, you need an additional cable from Vaisala
- Error modes can be set with that additional cable

We were able to exit the error mode. When we first hooked up one sensor, the second sensor (disconnected) was reading similar values as the first one. This caused us to think we might have an issue in MICAS-X - however we got the answer below from Dave

From Dave Thompson's email:

Here's another likely part of the puzzle. When a channel is disconnected and you use LabVIEW to measure a set of channels (e.g. scan through them), the disconnected channel will show a voltage similar to the immediately previous channel measured. This is because there is only one A/D converter on the card, and the channels are multiplexed through it. When a channel is measured that has no signal on it, it will still mostly have the voltage of the previous channel, due to stray capacitance. This isn't how MAX works, though, since in MAX you are measuring only one channel at a time. So a disconnected channel will do something weird, like slowly float down to a negative voltage, since there is no "previous" channel to bias it to anything.

Testing conducted on 9/29 showed that as soon as we increased CO2 levels to 10%, the sensors went into their error mode

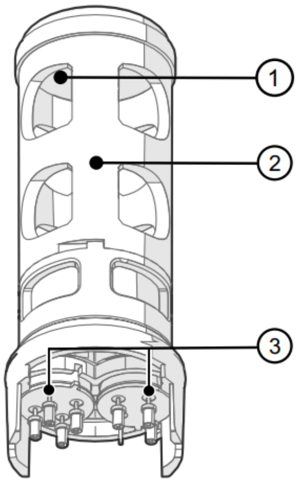
Recommendation from this is to get the cable for diagnosing and editing error modes.

Continued testing, see Thursday 9/29 section in the lab report

Based on testing (see 9/29 in LabNotebook), it seems that the following could be sources of the error, which is characterized by a 5V spike followed by readings solely in the mV range:

1. Obstruction of the Tee Housing mixed with flow of air caused the unit to go into an error mode
    a. Based on the image below from the GMP252 manual, we hypothesize there could be obstruction against the mirror within the unit. While compression was initially being considered as a root cause, the installation manual in GMP252 does include a compression device, which makes this less likely.
    b. Or it could be visual obstruction from proximity of the metal sides to the sensor.
2. High CO2 readings, according to Vaisala, could be the source of the errors, though blow tests (taking the sensor out of its housing and blowing on it for increased CO2 rather than introducing CO2 from the compressed gas cylinder) did not show any errors.

2.3. Operating Principle of CO_2 Measurement



The Vaisala CARBOCAP® sensor used in the probe is a silicon-based, nondispersive infrared (NDIR) sensor for the measurement of gaseous carbon dioxide in air-like gases.

Figure 2 Probe Cuvette with Mirror and Sensor Chips

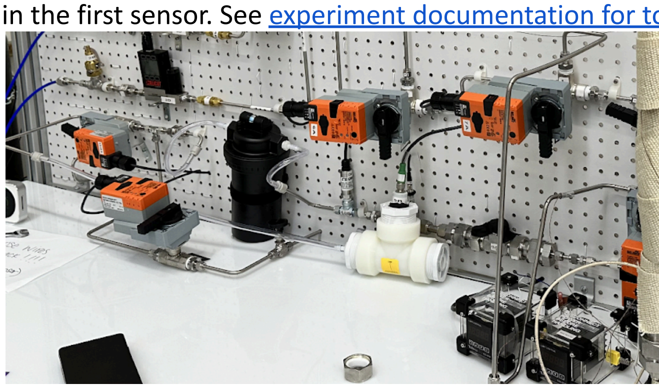
1. Mirror
2. Cuvette
3. Sensor chips under TO5 package

The sensitivity to carbon dioxide is based on absorption of infrared light at a characteristic wavelength. During measurement, infrared light is routed through the cuvette that contains the gas to be measured. A mirror reflects the light from the cuvette to a thermopile detector that measures the light intensity at a wavelength determined by a Fabry–Pérot interferometer (FPI) and a band pass filter.

An alternate housing could be constructed from the below McMaster Carr order, shown in a suggested BOM.

Friday, October 13, 2023

Tested new sensor housing, with success. Tested only on one sensor, so was able to see the error mode in the first sensor. See experiment documentation for today



Cable purchase is recommended as it will both help us identify the root cause of the error, and reprogram the probe to remove the error mode. We also recommend an alternate housing, as testing implies that the sensor enters into the error mode when it is placed inside of the housing. Recommended BOM is also printed below in tabular format. It has also been recommended to Vaisala that for future purchases, especially for universities, it would be helpful to include information on the existence of the error modes within the manual, as well

as in the purchase description.

*****A note: items 2, 3, 4 would need to be purchased again for the second sensor if the use of this housing is found to be adequate.*****

Part	Rationale	Link	Price
USB Service Cable	To identify error and allow us to reprogram the probe to remove the error mode	https://store.vaisala.com/en/spares/242659	$102
Plastic tee (2") Adapter 2" → ½" Adapter ½" NPT plastic to ¼" compression stainless steel Adapter 2" NPT → 1" NPT plastic for probe	Housing that increases interior from 1" to 2", and moves the compression fitting on the sensor up from the middle of the sensor to the top of the sensor to address potential optical occlusion	McMaster Carr Order	$56.63
Plastic 1" NPT to 1" compression to secure the sensor to the housing	This performs the same role as the current compression fitting on the metal tee within the system	US Plastic Compression Fitting Link Alternates: First Second	$9.95
Stainless Steel Reducing Union ½" - ¼"	Fill in portion of testbed that was used by CO2 sensor tee	TitanFittingsLink	$26.88

The alternate housing was tested, with the exception of the plastic 1" NPT to 1" compression, as it was not ordered but bought at Home Depot instead for $6.50. It did not fit as expected, so to seal the sensor we used tape. It did function acceptably. However, after running the sensors through a suite of tests, and putting them back into their original housing, we did not read any error modes. It is unclear if power cycling + bringing the sensor in and out of the error mode reset the sensor in some way, but for now we will stick to the stainless steel housing. The secondary housing is useful for troubleshooting purposes, and will be kept as well.

When running tests with the sensor, it was noticed that the sensor was not capable of reading values when upstream of the pump during desorption. When we switched to N_2 desorption, readings increased as expected.

The cable has been purchased, and is arriving 10/24/2023
The cable will be used to reset the error modes so that instead of dropping down to 0% CO_2 upon high CO_2 errors, they will remain at 5V, or full scale readings.

Sensor Responses:

Action	Typical Sensor Response	Notes
CO_2 PPM above 6,000	Drop into an error mode	We have observed the downstream sensor going all the way to 18,000 ppm on 10/23/2023 without issue or dropping into an error mode, and previously during initial calibration testing, readings were observed all the way up to 100% CO_2. Therefore, this is classified as an intermittent fault.
Low pressure	No change in readings	When the sensor is reading during desorption and is placed upstream of the pump, it will not change its readings. However, when the same CO_2 is carried out from the sorbent bed via an N_2 stream, readings go up as expected.

Path forward/recommendation

Characterization of the sensor error modes was performed. The new sensor housing was found to be adequate, however upon testing with the new cable, it was found that we could reset the error mode, and the sensor could be placed back into its original housing. The downstream sensor was exchanged for one with a greater range, and error modes were modified in the source programming. The sensor still errors with high CO_2, but does not remain in an error mode after CO_2 lowers, so we still get adequate curves for desorption, just with flat tops where the sensor reaches its limit.

Closure

Engineer On-Site: ___________________________

Signature: ______________________ Date: _____________

Lab Principal Investigator: ________________________

Signature: _______________________ Date: ______________

NC-008

Title: ZeoDe Humidity Sensor Problem
Date: 10/02/2023
Filed by: Shannon Lackey: sjlackey@ucdavis.edu Daniela Ivey; dbivey@ucdavis.edu

Safety Severity: Low

Cost Severity: Low

Summary

Attempting to calibrate the humidity sensor on 9/27/2023 resulted in unexpected and unusable results. Testing details and data are included in the experimental notebook from that day Experiment Notebook (see page 8 - wed 09.27.2023/CO2 sensor troubleshooting & humidity sensor calibration). Testing included a run with dry air, and 3 runs with humid air at 0.5 slpm, 4 slpm, and 6 slpm respectively. The plan was to use these for flow vales to draw known humidity readings from the Nafion manual MH-Manual.pdf.

There are 2 issues that arise from this calibration. The first being that the downstream humidity sensor did not read any values or deflections as expected with changes in humidity. This could be a sensor issue or a connectivity issue. The second problem is that the results from the upstream sensor did not match expectations. The curve produced from the sensors did not match the shape of the curve produced from known values. The two lines trended in opposing directions indicating that this is not just a calibration issue. This could be an issue with the sensor, or more likely that the data from the Nafion manual is not reliable enough to be used for a calibration. Further testing on the CO2 sensor (which has also not been giving reliable data) has led us to believe that the housing is too small. This could be a similar issue for the humidity sensor

Root Cause

Root Cause Category: hardware/software within hardware

Root cause for the upstream sensor could be too small of a sensor housing, a malfunction or error with the sensor itself, or data that is not reliable enough for calibration from the Nafion manual.

Investigation

Investigators: Daniela Ivey, Shannon Lackey (on-site engineers); Chris Keenan (Vaisala)

Investigation routes include: connectivity, recalibration with a new method that does not use the Nafion manual, and removing sensor from housing to see if it produces expected readings.

Path forward/recommendation

Similar to the CO2 sensor there is a cable that would allow us to see if the sensor is in an error state. This would be a *different* cable than the one needed for the CO2 sensors as the connection point for the sensors is different. Purchasing this cable would speed up the troubleshooting process and allow us to see the error mode, if there is one. Additionally it is recommended that one, if not both investigations are performed

1) **Removing sensor from housing to see if expected results are produced**
2) **Recalibrate with a new method**

This was performed, and the error mode was reprogrammed. The sensor is now performing as expected. It is noted that the ideal flow for this sensor and the CO2 sensor was found to be at or above 4 SLPM.

Part	Rationale	Link	Price
USB Service Cable	To identify error and allow us to reprogram the probe to remove the error mode	https://store.vaisala.com/en/spares/219690	$100
Plastic tee (2”) Adapter 2” → ½” Adapter ½” NPT plastic to ¼” compression stainless steel Adapter 2” NPT → 1” NPT plastic for probe	Housing that increases interior from 1” to 2”, and moves the compression fitting on the sensor up from the middle of the sensor to the top of the sensor to address potential optical occlusion	McMaster Carr Order	$56.63
Adapter 1” NPT → 1/2” NPT plastic for probe	Adapt down for humidity sensor	https://www.mcmaster.com/4880k348/	$2.27
Plastic 1/2” NPT to compression to secure the sensor to the housing	This performs the same role as the current compression fitting on the metal tee within the system	1/2" PVC male compression fitting	$4.20

Closure

Engineer On-Site: ___________________________

Signature: ______________________ Date: _____________

Lab Principal Investigator: ________________________

Signature: _______________________ Date: ___________

7.5 CDR Reviewer Questions and Responses

The CDR ensures that all design requirements have been met and that all engineering analyses have been completed. The results of engineering model tests or analyses demonstrate that the hardware and software can be built to perform as planned.

The critical design review was held in person and virtual at UC Davis. The review board consisted of the following members:

- Dr. Jim Knox, NASA MSFC Senior Principal Engineer - 4BCO2 & CDRA for Life Support Systems Branch at NASA Marshall Space Flight Center
- Diego Rojas, Advanced Farm Software Engineer and HOME robotics researcher
- Monica Torralba, Collins Aerospace PLSS life support systems engineer
- Dr. Justin Werfel, Harvard University lead for Designing Emergence Laboratory
- Jeff Sweterlitsch, NASA JSC AES/EC Life Support Systems Oxygen Generation and Recovery Element Lead [could not attend in real-time, but provided feedback on packages ahead of time]

The package has been made available online at the link below to see a representative CDR package for this type of system.

`https://docs.google.com/presentation/d/1r1nskrL1A0wcqnL8XXsGFLyZ92On4XqY/edit?usp=sharing&ouid=100013162978456958863&rtpof=true&sd=true`

The following was reviewed:

- Detailed walk-through of each element of the testbed and where it would fit in 3D space
- Description and rationale of all part modifications made since PDR with their rationale
- Reiew of test procedures
- Hazards and safety review
- Assembly and build plan
- Software and DAQ setup plan

Discussion included questions regarding ZeoDe that were addressed offline in a question response form, which was then sent back to reviewers for final approval. This is found below.

ZeoDe CDR Reviewer Questions and Answers

Carbonic Acid	
Question	I think the main thing I see is that CO2 + air are humidifying at the same time. Would you want to add CO2 after the humidification of the air stream? To prevent carbonic acid.
Response	Given the low dew points, between -20 C and -80 C, and the presence of water in vapor form, we do not believe this will be a concern for the current testbed design. One advantage of adding gasses simultaneously will be better mixing upstream of the sensor suite.

Packing Procedure	
Question	What is your take on the packing procedure?
Response	The same procedure that STEVE uses will be followed, where a funnel feature with a cross-sectional grid will be employed to funnel zeolite into the bed. The packing procedure has been implemented in the CSFR-ZeoDe-001 document under supplementary testing.

Desorption	
Question	In what direction is desorption?
Response	Counter-current

Timeline	
Question	What is the time scale of the build and software implementation?
Response	The timeline is present within the CDR package. The software implementation time is cut down due to using the same software source as the STEVE testbed.

Pressure Drop across Desiccant and Nafion Tube

Question	What are the estimated pressure drops across the desiccants and Nafion tube? Is there any concern regarding pressure drop prior to flow into the sorbent beds?
Response	See the question on ¼” tubing vs ½” tubing for pressure drop estimates. Below are the pressure drop calculations across the packed bed. Analysis: Poiseuille Equation $\Delta p = \frac{8\mu L Q}{\pi R^4} = \frac{8\pi\mu L Q}{A^2}$ Ergun Equation: $\Delta p = \frac{150\mu\, L}{D_p^2}\frac{(1-\epsilon)^2}{\epsilon^3}v_s + \frac{1.75\, L\, \rho}{D_p}\frac{(1-\epsilon)}{\epsilon^3}v_s\lvert v_s\rvert.$ Δp is the pressure drop across the bed, L is the length of the bed (not the column), D_p is the equivalent spherical diameter of the packing, ρ is the density of fluid, μ is the dynamic viscosity of the fluid, v_s is the superficial velocity (i.e. the velocity that the fluid would have through the empty tube at the same volumetric flow rate) ϵ is the void fraction (porosity) of the bed. Assumptions: - Length of bed: 24” = 0.6096 m - 1” tubing = 0.0254 m - Viscosity of air at 20 C: $1.6\ x\ 10^{-5}\ m^2/s$ - Viscosity of air at 20 C: $1.204\ x\ 10^{-5}\ kg/m^3$ - Volumetric flow rate of 8SLPM = 0.000133333 m^3/s - Cross-sectional area of tubing: 1” = 0.0254 m $\rightarrow \pi D^2/4\ =\ 0.00016129\pi$ - Void fraction of about 0.41 - Superficial velocity of $0.000133333\ m\hat{}3/s\ /\ 0.00016129\pi\ =\ 0.263136$ - $D_p\ =\ 0.002\ m$ $ZeoDe\ \Delta P\ across\ bed\ =$ $150(\mu)(L)(1\ -\ \epsilon)^2 v_s / ((D_p^{\ 2})(\epsilon^3))\ \ +\ 1.75(L)(\rho)(1\ -\ \epsilon)v_s\lvert v_s\rvert\ /\ (D_p)(\epsilon^3)$ $ZeoDe\ \Delta P\ across\ bed\ =$ $150(1.6\ x\ 10^{-5}\ m^2/s\ )(0.6096\ m)(1\ -\ 0.41)^2\ \ *\ 0.263136/\ ((0.002\ m^{\ 2})(0.41^3))$ $+\ 1.75(0.6096)(1.204\ x\ 10^{-5}\ kg/m^3\ )(1\ -\ 0.41)0.263136\lvert 0.263136\rvert\ /\ (0.002)(($ $=\ 486\ Pa$

Zeolite

Question	If looking to match 4BCO2, obtain Grace Davison 544 13X. I have a supplier.
Response	Hargo Corporation Zeolite 13X has been added to BOM, line 79. Order sheet from NASA MSFC is attached.

Desorption Pressure	
Question	Vacuum should be below 8 torr (not kPa) to match 4BCO2. Estimate 2-3 torr based on ground testing. To be clear 8 torr what we see on orbit but not the reality because of the sensor, in reality, 2-3 torr on ground and orbit
Response	The CDR package, as well as CSFR-ECLSS-001 - the ZeoDe Experiment Test Plan - have been modified to reflect 2-3 torr instead of 8 kPa.

Oil-less compressor	
Question	Recommend oil-less compressor for air inlet if possible to avoid possible oil contamination completely
Response	EA-4000 compressor specifications have been included in the package. The current compressor choice is oil-less

Pressure head for flow controllers	
Question	Make sure flow controllers selected do not require a pressure head .
Response	The ZeoDe mass flow controllers do not require pressure head - MKS controllers match the STEVE system

Desiccant and regeneration	
Question	What is the desiccant used in the desiccant bed? How is it regenerated?
Response	The desiccant is heritage from STEVE. It is a color changing Drierite that can be regenerated via bake out. The composition is ≥98% $CaS04$, <2% $CoCl2$. The specification for this drierite has been attached.

	The humidity stream dryness will be tested during nominal testing for short term degradation. A line item (line 6 under short term degradation testing) has been added accordingly to CSFR-ECLSS-001. As the dewpoint sensors used for STEVE have been able to read -40 C dewpoint, thus far it is confirmed that the drierite can bring the system down to this level of dryness.

Dry/humid air ratio, controller infighting	
Question	Need to have one of the dry/humid air streams in excess or may experience controller infighting
Response	This note has been added to CSFR-ZeoDe-001 under a new section labeled *Important Notes/Lessons Learned*

Pre-heater for consistent temperature during bakeout	
Question	Will need a pre-heater for consistent temperatures during bakeout
Response	This has been added to the BOM in line items 85-88. These correspond to the heater for the bed itself, and have been doubled. The heater rope section for pre-heating is half the length of the heater rope for the bed itself.

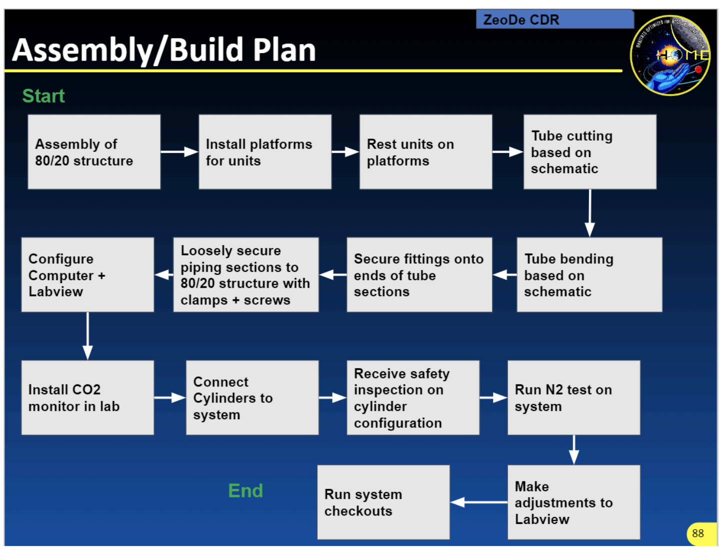
Heat damage of components	
Question	Beware of downstream component damage during 300C (sensors, valves)
Response	Temperature sensors are to be installed upstream of downstream sensor suite. There is approximately 25” of planned piping between the outlet of the bed and the beginning of the sensor suite. This includes the length passing through a mass flow controller. The thermocouples can be placed at any point within that section.

Pressurize to check leaks

Question	Why not pressurize to check leaks? Much easier. You pressurize all systems and close areas and introduce nitrogen, watch the decay of the system, if holds the pressure then it is good, if not then you can snoop to find the leak.
Response	This has been added to CSFR-ZeoDe-001 : ZeoDe Experiment Test Plan. It has been added under the pre-run check section.

Order of assembly for valves and piping

Question	Consider placing components (valves, beds, etc) first and to get precise tubing lengths and locations
Response	The assembly process has been modified in the CDR package to reflect this



Water creep timeline

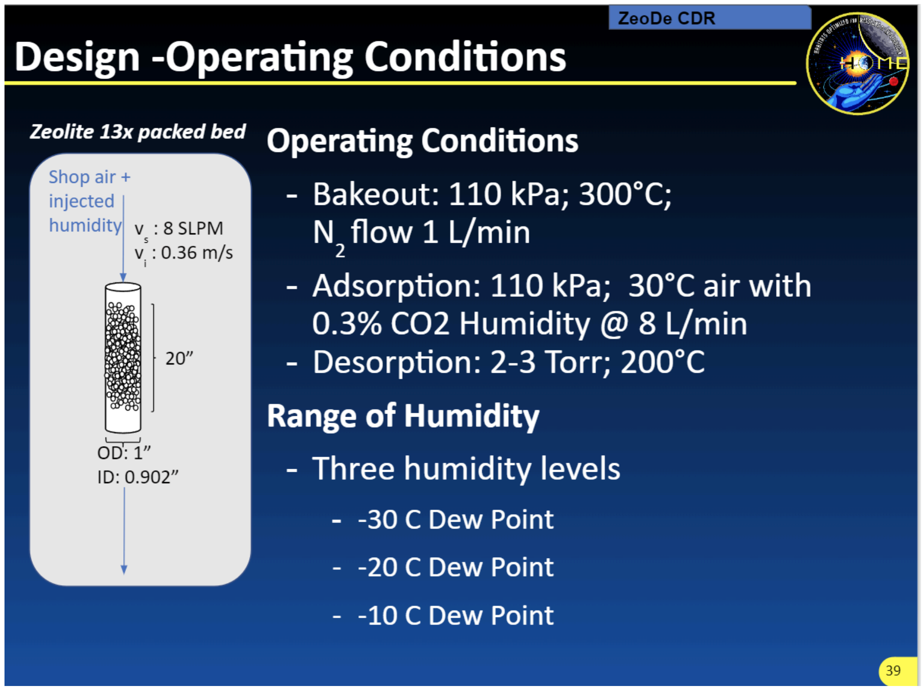
Question	Water creep in zeolite is a gradual phenomenon and can take many cycles before achieving cyclic steady state. Are you expecting it to occur over a single cycle?
Response	This note is being carried under *Important Notes/Lessons Learned.* The first humidity run will be a test to determine what our sensors and, correspondingly, what our prognostics team can sense as a rate.

O2 Sensing	
Question	What do you learn from O2 concentration? It does not contribute to CO2 adsorption (CO2 dominant over O2 in competitive adsorption).
Response	The CDR package has been corrected to reflect the choice of not including O2 sources or sensing within the ZeoDe testbed

Desiccant protects downstream CO2 sorbent beds from water	
Question	As a reminder, there are desiccant beds as part of the 4BCO2 CO2 scrubber to protect the downstream CO2 sorbent beds from water (not getting air from humid cabin)
Response	Two desiccant beds are included in the ZeoDe system, one upstream of the sorbent bed, and one upstream of the pump.

DAQ software	
Question	Why two DAQ software systems? Seems like focusing on learning one would be better.
Response	Clarification: the MICAS-X software lies within the LabView environment

Humidity Sensor Range	
Question	The HMP60 only goes down to -40C dewpoint. The DMT152 goes down to -80C dewpoint.
Response	DMT152 has been reviewed, and while it is able to go down to lower dewpoints, the cost may be prohibitive for the current purposes. We propose maintaining new humidity levels above -40C - the CDR package has been updated accordingly, where -40C dewpoint is considered our dry condition, though it is expected that our dry air stream will be closer to -80C dewpoint.



Gas Leak Analysis	
Question	Gas leak analysis needed
Response	If both cylinders were to release all air at once, this would amount to 228 CU. FT. of Nitrogen, and 432 CU. FT. of Carbon Dioxide. The smallest dimensions of the spafford building are 60’ x 42’ x 13’ (L x W x H), granting a total of 32,760 CU. FT of volume. One section of the ceiling extends to 18’, so this is a conservative estimate. **PPM CO2 limit: 5000 PPM** Assuming ambient conditions at 1,000 PPM, or 0.1% CO2 *1. Assumption: pressurized to less than 880 PSIG, so in gaseous state* Cylinder Spec: Internal Pressure: 830 PSIG Internal Volume: 2038.2 in3

	PV=nRT (830 PSIG)(2038.2 in3) = n(R) (20 C) (5722.65 kPa)(33.4 L) /((8.314 L kPa/mol K)(293.15 K))= n Mol CO2 inside canister: 78.4 mol At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L In the room, this would amount to 1462500 mol of air. If there is 0.1% CO2 in the air, there are 1462.5 mol of CO2 present in the room. Upon release of CO2 cylinder, this would amount to (189 + 1462.5) / (1462500 +189)= 0.1129% CO2, Or **1,129 PPM.** **<u>How long will this smaller, gaseous mixture last?</u>** **Conservative estimate: air at 0.03% CO2, trying to bring it up to 0.3%, so air flowing at 7.784 LPM, CO2 flowing at 0.216 LPM** **Within cylinder, we have 78.4 mol / 33.4 L = 2.34 mol/L** **Regulating to 40 PSIG, equivalent to 275.79 kPa** **(275.79 kPa)(0.216 L/min) /((8.314 L kPa/mol K)(293.15 K))= n/min = 0.0244 mol/min** **78.4 mol / (0.0244 mol/min) = 3,213.1 minutes** **= 53.5 hours** **CO2 is added for ~½ of one full adsorption/desorption cycle, so approximately 107.1 experiment hours, or a 4.46 day experiment** *2. Assumption: pressurized to greater than 880 PSIG, so in liquid state* 1101 kg/m^3 [1 m^3 [=] 1000 L] 1.101 kg/L (33.4 L) = 36.7734 kg 44.009 g/mol → 0.044009 kg/mol (36.7734 kg) / (0.044009 kg/mol) = 835.7 mol At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L In the room, this would amount to 1462500 mol of

	air. If there is 0.1% CO_2 in the air, there are 1462.5 mol of CO_2 present in the room. Upon release of CO_2 cylinder, this would amount to (835.7 + 1462.5) / (1462500 +835.7)= 0.1571% CO_2, Or **1,571 PPM.** **<u>How long will this liquid CO2 cylinder last?</u>** **Conservative estimate: air at 0.03% CO_2, trying to bring it up to 0.3%, so air flowing at 7.784 LPM, CO_2 flowing at 0.216 LPM** **Within cylinder, we have 835.7 mol / 33.4 L = 25.02 mol/L** **Regulating to 40 PSIG, equivalent to 275.79 kPa** **(275.79 kPa)(0.216 L/min) /((8.314 L kPa/mol K)(293.15 K))= n/min = 0.0244 mol/min** **835.7 mol / (0.0244 mol/min) = 34,250 minutes** **= 570.8 hours** **CO_2 is added for ~½ of one full adsorption/desorption cycle, so approximately 1,141.6 experiment hours, or a 45.6 day experiment** **Lack of Oxygen Asphyxiant limit: 19.5%** At 21% oxygen, this would be 6879.6 CU. FT. occupied by oxygen Adding the entirety of both cylinders would amount to the equivalent of 33420 CU. FT. of gas in the room, with a resulting oxygen percentage of **20.6 %** **CO_2:** *Assumption: pressurized to greater than 880 PSIG, so in liquid state* 1101 kg/m^3 [1 m^3 [=] 1000 L] 1.101 kg/L (33.4 L) = 36.7734 kg 44.009 g/mol → 0.044009 kg/mol (36.7734 kg) / (0.044009 kg/mol) = 835.7 mol **Nitrogen:** *Assumption: pressurized to greater than ~725 PSIG, so in liquid state* 0.807 g/mL [1 g/mL [=] 1 kg/ L] 0.807 kg/L (33.4 L) = 26.95 kg 28 g/mol → 0.028 kg/mol (26.95 kg) / (0.028 kg/mol) = 962.5 mol

	At STP, one mol of gas occupies a volume of 22.4 L at STP. The room is equal to 32760000 L In the room, this would amount to 1462500 mol of air. Assume there is 0.1% CO_2 in the air, 78% Nitrogen in the air, and 21% Oxygen in the air. There are then 6879600 L oxygen in the air. Upon release of both the CO_2 cylinder and the Nitrogen cylinder, this would amount to (962.6 mol)(22.4 L/mol) = 21548.8 L Nitrogen (835.7 mol)(22.4 L/mol) = 18719.7 L CO_2 (6879600 L oxygen)/(32760000 L + 21548.8 L Nitrogen +18719.7 L CO_2) = 0.209 → **20.9% Oxygen**

Applicability of test case	
Question	Is the introduction of humidity into the system implausible? If so, is the testbed worth pursuing?
Response	There is always the risk of introducing humidity; there are multiple failure points besides the desiccant bed failing. The ability to detect degradation due to humidity is still believed to be a valuable study.

¼” tubing vs ½” tubing	
Question	There is concern that STEVE has more ½” tubing, and ZeoDe only includes ¼” tubing - this could affect pressure drop
Response	Poiseuille Equation $\Delta p = \frac{8\mu LQ}{\pi R^4} = \frac{8\pi\mu LQ}{A^2}$ <u>Pressure drop comparison for STEVE and ZeoDe</u> Assumptions: - ZeoDe contains about 75% of the tubing length as STEVE - ZeoDe radius is ½ that of most of the STEVE testbed tubing radius - Viscosity comparable in ZeoDe and STEVE

	- Volumetric flow rate is the same (8SLPM) $ZeoDe\ \Delta P : STEVE\ \Delta P\ =\ 8\mu(0.75)Q/\pi(0.5^4) :\ 8\mu Q/\pi$ $ZeoDe\ \Delta P : STEVE\ \Delta P\ =\ 12 :\ 1$ <u>Approxiate pressure drop across system due to viscosity:</u> Assumptions: - Tubing length based on to-scale schematic (tubing lengths can be found by right clicking on a tube section, and selecting "formatting options", and viewing length) - ¼" tubing = 0.00635 m - Viscosity of air at 20 C : $1.6\ x\ 10^{-5}\ Pa\ *\ s$ - Volumetric flow rate of 8SLPM = 0.000133333 m^3/s - Length of tubing: ~380" = 9.652 m $ZeoDe\ \Delta P\ across\ bed\ =\ 8\mu LQ/\pi R^4$ $ZeoDe\ \Delta P\ across\ bed\ =$ $8(1.6\ x\ 10^{-5}\ Pa\ *\ s)(9.652\ m)(0.000133333\ m^3/s)/\pi(0.00635\ m\ )^4$ $=\ 32.1682\ Pa\ =\ 0.0321682\ kPa$

Failure Injection	
Question	STEVE Testbed, what is "Failure Injection"?
Response	The list of failure injection used for the STEVE testbed has been added to the list of backup slides in tabular format, and has been pasted below as well.

Condition	STEVE			
	ML Usage	Data Type (Discrete: Manual intervention needed Continuous:Failures can be pre-programmed)	Method	Time to Generate Data for one experiment including bakeout (expectation = 3 trials of one experiment & 1-4 severities)
Leak	Detection, Diagnostics, and possibly Prognostics	Continuous	Command leak valve position	Detection & Diagnostics: ~2 days Prognostics: unknown
Sorbent CO2 Removal Capacity Degradation due to humidity	Will have capability (in case STEVE is ever seriously overloaded) But not planned			
Screen Blinding	Detection, Diagnostics	Discrete	Manually change filter mesh size	Detection & Diagnostics: ~2 days
Heater Failure	Detection, Diagnostics, and possibly Prognostics	Continuous for relay command Discrete for heater power	Preprogrammed command to relay Manually adjust variac power setting	Detection & Diagnostics: ~2 days Prognostics: unknown
Check Valve Failure	Detection, Diagnostics, and possibly Prognostics	Continuous or Discrete	Command valve position	Detection & Diagnostics: ~2 days Prognostics: unknown

Condition	STEVE			
	ML Usage	Data Type	Method	Time to Generate Data
Ball Valve Failure	Detection, Diagnostics, and possibly Prognostics	Continuous	Command valve	Detection & Diagnostics: ~2 days Prognostics: unknown
CO2 and/or O2 Sensor Failure	Detection, Diagnostics, and possibly Prognostics	Discrete	Manually re-install bad sensor	Detection & Diagnostics: ~2 days Prognostics: unknown
Blower Failure	Detection, Diagnostics, and possibly Prognostics	Continuous	Command flow rate set point	Detection & Diagnostics: ~2 days Prognostics: unknown
Vacuum Failure	Detection, Diagnostics, and possibly Prognostics	Continuous	Adjust vacuum pump throttle	Detection & Diagnostics: ~2 days Prognostics: unknown
Varying Inlet Flow Rate	Detection, Diagnostics, and possibly Prognostics	Continuous	Command flow rate set point	Detection & Diagnostics: ~2 days Prognostics: unknown
Varying Inlet %CO2	Detection, Diagnostics, and possibly Prognostics	Continuous	Command %CO2 set point	Detection & Diagnostics: ~2 days Prognostics: unknown

Verification Method

Question	Strictly speaking, verifications are either by Test, Inspection, or Analysis, or some combination. I recommend verification by Design to Analysis.
Response	Verification previously denoted Design has been changed to list Analysis

Swagelok fittings vs AN style fittings	
Question	You plan on using Swagelok compression fittings. Is this test bed going to be installed and uninstalled multiple times of the 5-year planned life of the test stand? If so, you might consider AN-style fittings if you have personnel that are trained to flare tubing, as it is less prone to leakage from repeated mating/demating of fittings.
Response	This testbed may be modified during its lifetime. AN-style fittings were reviewed as a substitute for swagelok and yor-lok fittings. Based on the review, it was confirmed that while fittings may occasionally have to be undone, the overall design is not expected to change drastically over the next 5-year period.

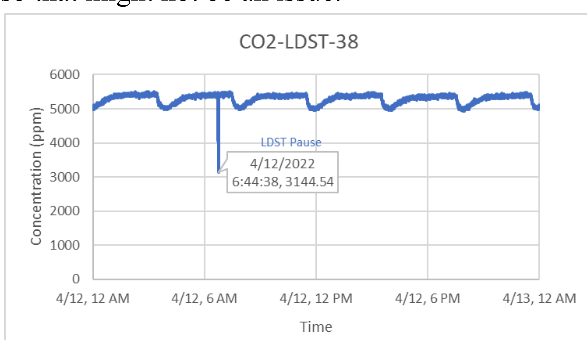
Heater Temperature Limits	
Question	if the Rubber Heater Tape can go up to 218°C (is that what it means), how do you get to 300°C as shown on Slide 9?
Response	This comment has been addressed: The heater has been switched to a fiberglass heating tape, consistent with the STEVE testbed.

Heater Temperature Limits	
Question	Swagelok sells proportional pressure relief valves, but at the same time specifically advertise that they are not certified to ASME or any other code because they do not have a capacity rating. I recommend against Swagelok pressure relief valves. I’ve used Circle Seal, Parker and Generant brand valves, but there are other brands available as well.
Response	This information was confirmed through the Swagelok Proportional Relief Valves, R Series Catalog

	Applications R series relief valves are proportional relief valves that open gradually as the pressure increases. Consequently, they do not have a capacity rating at a given pressure rise (accumulation), and they are not certified to ASME or any other codes. ⊠ **Some system applications require relief valves to meet specific safety codes. The system designer and user must determine when such codes apply and whether these relief valves conform to them.** ⊠ **Swagelok proportional relief valves should never be used as ASME Boiler and Pressure Vessel Code safety relief devices.** ⊠ **Swagelok proportional relief valves are not "Safety Accessories" as defined in the Pressure Equipment Directive 2014/68/EU.** **Operation** R series relief valves OPEN when system pressure reaches the set pressure and CLOSE when system pressure falls below the set pressure. ■ High-pressure R3A and R4 series—select and install the spring that covers the required set pressure; apply the matching label to the cap. ■ Low-pressure RL3 and RL4 series—the spring is already installed. ⊠ **For valves not actuated for a period of time, initial relief pressure may be higher than the set pressure.** Our relief system is planned to be set to 140 kPa (20 PSIG), slightly higher than that set in CU Boulder due to elevation difference. We have identified the following replacement, through the Parker catalog: https://ph.parker.com/us/en/6000-psi-relief-valve-r-series Lines They are available in compression fitting connectors. The corresponding BOM line item is modified to reflect this (lines 18-20)

Shop Air source	
Question	I see that N2 and CO2 come from compressed gas cylinders, but is "shop air" from a compressed source?
Response	Yes, shop is air can be pulled either from a compressor in lab or from a compressed air line. The slides have been modified to highlight this. The specifications for the compressor have been attached.

Humidity Source	
Question	You mention testing at three different dew points, but how do you control the dew point with the Nafion membrane setup?
Response	Additional slide material has been added. A nafion membrane adds humidity, and the stream is then mixed with a dry air stream (with dry air in excess). Mass flow controllers control the flow, and a humidity sensor downstream provides feedback control capability.

<table>
<tr><th colspan="2">GMP 252 potential for faulty signal response</th></tr>
<tr><td>Question</td><td>Regarding the GMP 252 CO2 sensor, you may want to run a test where you expose the sensor to a constant CO2 concentration at a constant flow rate for at least 5 hours. I was involved with a test that used a GMT 221 CO2 sensor, and it had a funny signal response when operating for long periods of time (see below image) We reached out to the manufacturer, who admitted they have seen that response before, but they don’t know why. The 252 is a newer model of sensor, so that might not be an issue.

</td></tr>
<tr><td>Response</td><td>This note has been added to our important notes/lessons learned section in CSFR-ECLSS-001. The test will be run during checkouts.</td></tr>
</table>

Vaisala Dew Point Sensors	
Question	The Vaisala dew point sensors have an automatic purge function that heats up the probe once every 24 hours to self-clean the sensor head, but you can disable this function.
Response	This has been added to the Important Notes/ Lessons Learned section of CSFR-ZeoDe-001

Edwards Pump ballast knob	
Question	Make sure to fully close the ballast knob on the Edwards pump to ensure the strongest vacuum possible.
Response	This has been added to the Important Notes/ Lessons Learned section of CSFR-ZeoDe-001

Edwards Pump throttling	
Question	why are you wanting to throttle your vacuum?
Response	The vacuum is overpowered for our purposes, but based on CU Boulder testing, it meets the requirements for recirculation through the system without leakage.

Vacuum pump missing selector valve to avoid recirculation	
Question	the incorporation of the vacuum pump doesn't quite make sense. You need to install a shut-off valve or selector valve or similar valve between the two horizontal tees, otherwise the pump will just recirculate the same air in the loop.
Response	This design modification has been incorporated, and can be seen in both the CDR slide package as well as the figure within Visio.

Gas release hazards	
Question	What will a CO sensor tell you about a release of CO_2? Having a CO_2 sensor can provide an indication of a release, but what is the test team response if the alarm is enunciated? Do you have an O_2 area monitor in the case of a N_2 release, or is the laboratory large enough that the oxygen levels cannot drop below the OSHA limit of 19.5% O_2? Are there any safe handling procedures for the Zeolite 13X or Drierite that you need to follow – do you have the SDS's on hand? Are there electrical hazards that you need to address (workmanship, utilization of GFCI, grounding issues, exposed connections)?
Response	CSFR-ECLSS-002 ZeoDe Experiment Gas Hazards Document, included in supplementary documents, now covers emergency response. Gas release analysis can be found in separate question.. The SDS's will be in hard copy on the floor. The laboratory is large enough that with an N_2 release the levels cannot drop below the OSHA limit of 19.5% O_2. We will plan to follow the same electrical hazards training provided to the Satellite Lab within the same building, which deals heavily with electrical connections. A required training section has been added to CSFR-ECLSS-001 ZeoDe Experiment Test plan that outlines these requirements. Based on SDS for Drierite (in supplementary documents), nitrile gloves will be used for handling Drierite, which is now called out in CSFR-ECLSS-001 ZeoDe Experiment Test Plan.

Discrepancy in pressure relief valves	
Question	you use Swagelok Pressure Relief valves but slide 43 mentions Alicat pressure relief valves with Swagelok fittings. Seems like a discrepancy.
Response	Swagelok pressure relief valves are currently incorporated. This slide error has been corrected.

7.6 NASA Maintenance Procedures

The pseudo-code presented in chapter 1 of this thesis was generated to use as a source to determine what types of tasks could and couldn't be done by a robotic agent assisting a human. It also serves as a tool for future work in maintenance studies with applications in ECLSS. It is presented in Chapter 1 alongside NASA open-source images used to generate the pseudo-code. Additional maintenance procedures, generously provided by NASA, were used to inform this pseudo code can be found below.

Takeaways from Maintenance and Robotic Manipulability Review

Chapter 1's dive into maintenance and the start of understanding what goes into a maintainable system on earth and in space contributed to the core requirements of the ECLSS design, build, and test of ZeoDe at the UC Davis Center for Spaceflight Research. This investigation also led me to participate in a parallel project, RobInZeN (Robotically Interactive ZeoDe twiN), at UC Davis, which would duplicate the geometry of my system in a mock-up form factor to experiment with robotic manipulation of ECLSS parts. This has effort its own dedicated section in chapter 3.6.

3.1.312 HEPA AND CHARCOAL FILTER R&R - LAB - Charcoal Only (XTP)

(ISS IFM/E69 - ALL/FIN 1/HC/REAL-TIME 69-0753/XTP 219/16:16:01)

ORIGINAL PROCEDURE:

3.1.312 HEPA AND CHARCOAL FILTER R&R - LAB

OBJECTIVE: To remove and replace six expended Lab HEPA and/or Charcoal Filters, one Standoff at a time, completing replacement of all Port side filters first, then moving to Starboard filters. Filter assemblies contain a HEPA Filter and a Charcoal Filter attached together. The whole assembly may be replaced at one time, or just the HEPA Filter or Charcoal Filter.

LOCATION:

LAB Standoffs LAB1PD1,3,5 and LAB1SD1,3,5

DURATION:

1 hour 45 minutes (HEPA or Charcoal Filter R&R) or 2 hour 15 minutes (both HEPA and Charcoal Filter R&R) Total Crew Time

15 minutes Removing Smoke Detector (step 2)

5 minutes Port Filter R&R Prep (step 3)

1 hour HEPA Filter only replacement (step 4)

1 hour Charcoal Filter only replacement (step 5)

1 hour 30 minutes Charcoal and HEPA Filter replacement (step 6)

5 minutes Starboard Filter R&R Prep (step 7)

15 minutes Replacing Smoke Detector (step 8)

5 minutes Post Maintenance (step 9)

CREW:

One

PARTS:

HEPA Filter P/N F0905281 (six)
Charcoal Filter P/N F0905282 (six)

MATERIALS:

Gray Tape
Kapton Tape
Sharpie
Dry Wipes (if required)
Wet Wipes
24" x 24" Ziplock Bag (six)

TOOLS:

AC Dry Vacuum Cleaner ("Nominal Ops Cleaning Only")
AC Dry Vacuum Hair Clipper Hose P/N SEG33124048-301
AC Dry Vacuum Crevice Tool P/N SEG33123990-303
Dust Mask
Safety Glasses or Goggles

Digital Camera
Static Wrist Tether
Scissors (if required)
ISS IVA Toolbox:
  Drawer 2:
    Ratchet, 1/4" Drive
    (10-50 in-lbs) Trq Wrench, 1/4" Drive
    10" Ext, 1/4" Drive
    5/16" Socket, 1/4" Drive
  Drawer 4:
    Connector Pliers (if required)

1. SAFING

WARNING
During this procedure, crew is prime for smoke detection in Lab.

CAUTION
1. To maintain air circulation in the LAB, R&R filter one Standoff at a time, completing all Port filter R&Rs first, then moving on to Starboard filters.
2. Fan speed must be decreased before closing CCAA Return Manual Damper Valve. Failure to decrease fan speed will violate flow limits through filters.

✓**MCC-H** to confirm the following:
  Operating LAB CCAA fan speed set to 4000 rpm
  LAB1SD5 and LAB1PD1 Smoke Detectors deactivated
  RPCM LA2B_D RPC 02 – Op, Cl cmd Inh
  RPCM LA1B_H RPC 03 – Op, Cl cmd Inh

2. <u>REMOVING SMOKE DETECTOR (15 minutes)</u>

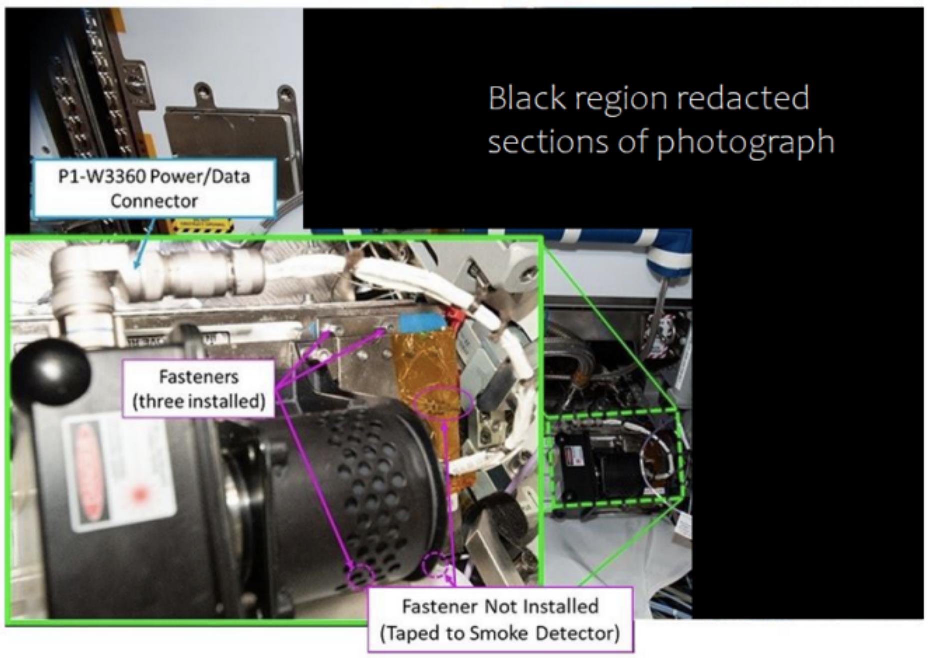


Figure 1. LAB1PD1 Smoke Detector on Bracket.

2.1 <u>Removing LAB1PD1 Smoke Detector Bracket</u>

2.1.1 Don Static Wrist Tether.
Secure to unpainted, unanodized metal surface, except stowage racks.

2.1.2 Inspect Area Smoke Detector for FOD.
If FOD present, clean with Vacuum Cleaner.

2.1.3 P1-W3360 ←|→ J1 on Smoke Detector
Cover exposed connectors with Kapton Tape. (Figure 1)

<u>NOTE</u>
Lower right fastener on the LAB1PD1 Smoke Detector bracket will not engage due to stripping of the bottom threads. Three of four fasteners are sufficient to secure the LAB1PD1 Smoke Detector. The fourth fastener is taped to the bracket and the installation hole is covered by Kapton Tape to prevent airflow bypassing the filter.

2.1.4 Remove fasteners (three) securing Smoke Detector Bracket to Standoff [Ratchet, 1/4" Drive; 10" Ext; 5/16" Socket].
Temporarily stow removed Smoke Detector/Bracket..

(Figure 1)

2.1.5 Doff Static Wrist Tether.

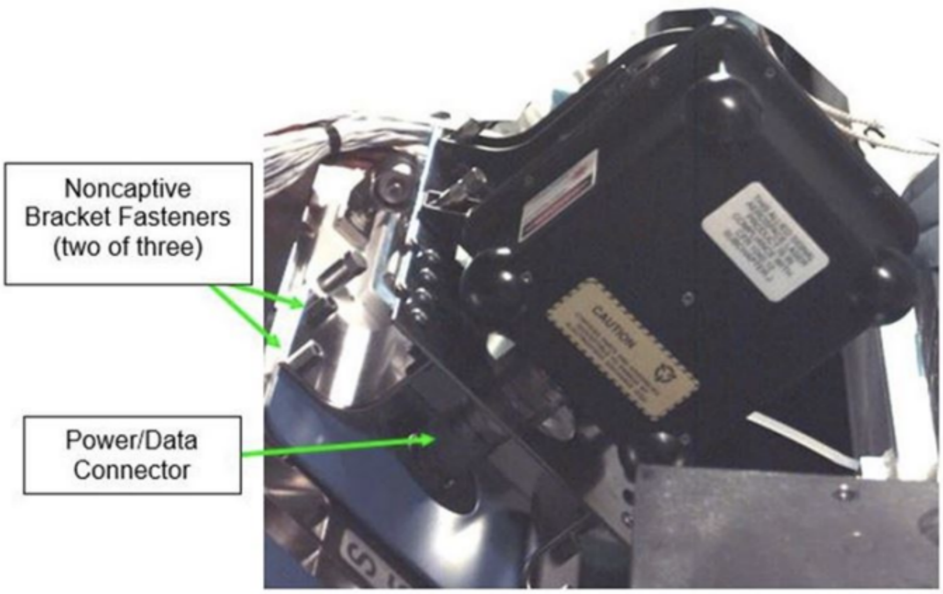


Figure 2. LAB1SD5 Smoke Detector on Bracket.

2.2 Removing LAB1SD5 Smoke Detector Bracket

2.2.1 Don Static Wrist Tether.
Secure to unpainted, unanodized metal surface, except stowage racks.

2.2.2 Inspect Area Smoke Detector for FOD.
If FOD present, clean with Vacuum Cleaner.

> NOTE
>
> 1. LAB1SD5 Smoke Detector is installed on a bracket. The bracket will be removed from structure with the attached Smoke Detector. The bracket only has three of four fasteners. All three are noncaptive.
> 2. Due to interference between structure and access to the Smoke Detector harness, the Smoke Detector on its bracket will be removed from structure prior to demating the harness connector.

2.2.3 While holding the Smoke Detector in place, disengage noncaptive fasteners (three) securing Smoke Detector Bracket to Standoff [Ratchet, 1/4" Drive; 10" Ext; 5/16" Socket]. (Figure 2)

Temporarily restrain noncaptive fasteners (three) to Smoke Detector Bracket [Kapton Tape].

2.2.4 P1-W3219 ←|→ J1 [Connector Pliers (if required)]
Cover exposed connectors with Kapton Tape. (Figure 2)

2.2.5 Remove Smoke Detector Bracket with attached Smoke Detector.
Temporarily stow.

2.2.6 Doff Static Wrist Tether.

> NOTE
>
> Eye Protection is to protect against liberated FOD, which is Hazard Level 0. Any Safety Glasses or Goggles are acceptable.

2.3 Don Safety Glasses or Goggles, Dust Mask.

2.4 Clean filters (six) to prevent excess FOD from entering cabin [Vacuum Cleaner].
Photo document filters [Digital Camera].
LAB1PD1
LAB1PD3
LAB1PD5
LAB1SD1
LAB1SD3
LAB1SD5

3. PORT FILTER R&R PREP (5 minutes)

Figure 3. CCAA Return Manual Damper Valve Control Knob, One Each Standoff (LAB1PD6 Shown).

> **CAUTION**
>
> CCAA Return Manual Damper Valve must be closed during this procedure to prevent circulation of contaminants into operating CCAA.

NOTE

1. The Port Standoff Return Manual Damper Valve will be closed first, allowing for R&R of the Port side filters. That Damper Valve will then be opened and the Starboard Standoff Return Manual Damper Valve will then be closed for Starboard side filter R&Rs.
2. The LAB1PD6 CCAA Return Manual Damper Valve must be pushed forward to engage the pin in the hole in the panel.

LAB1PD6

3.1 Pull up, rotate LAB1PD6 CCAA Return Manual Damper Valve to CLOSED. (Figure 3)

3.2 Perform filter R&R (step 4 , step 5, or step 6 as required) for all Port side filters first, one Standoff at a time (LAB1PD1, LAB1PD3, LAB1PD5), then proceed to step 7.

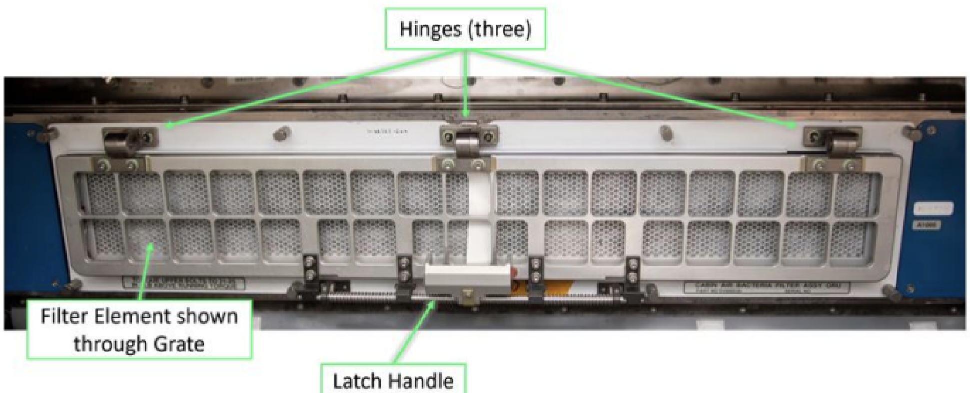


Figure 4. View of Filter Assembly Door.

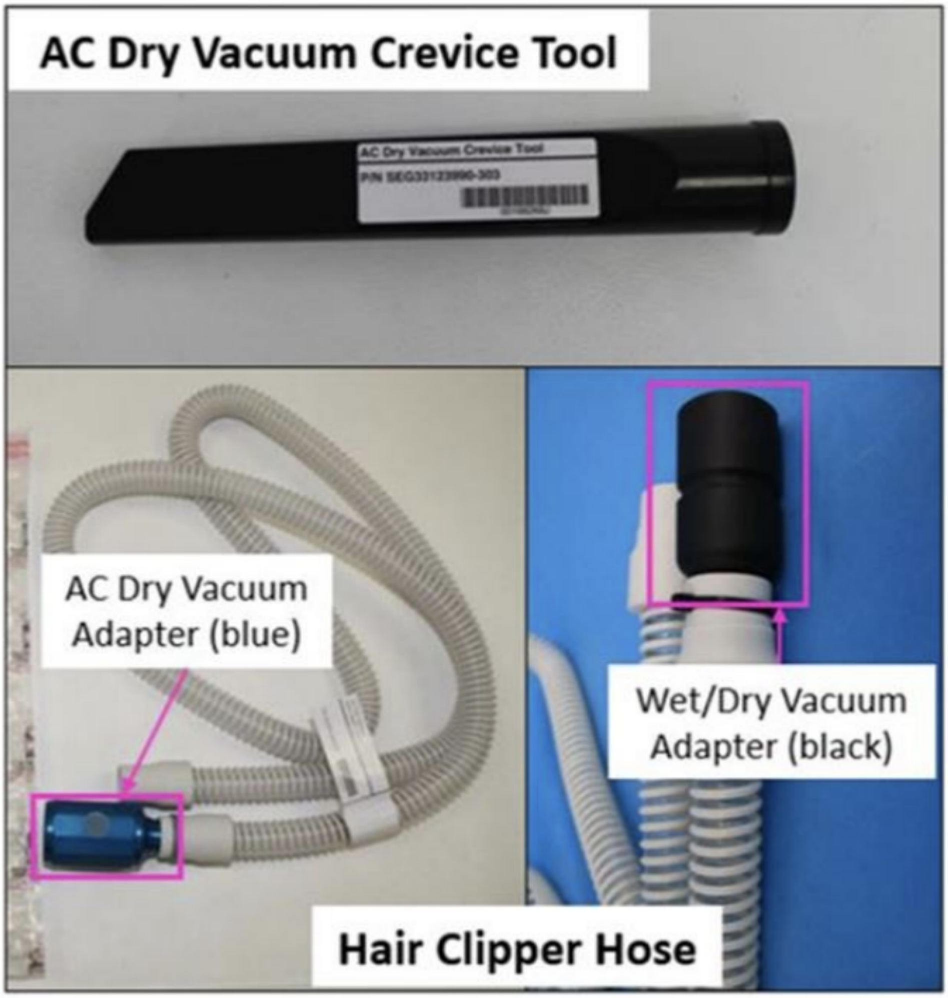


Figure 5. AC Dry Vacuum Cleaner Attachments - Crevice Tool and Hair Clipper Hose.

Figure 6. Integrated Filter Assembly.

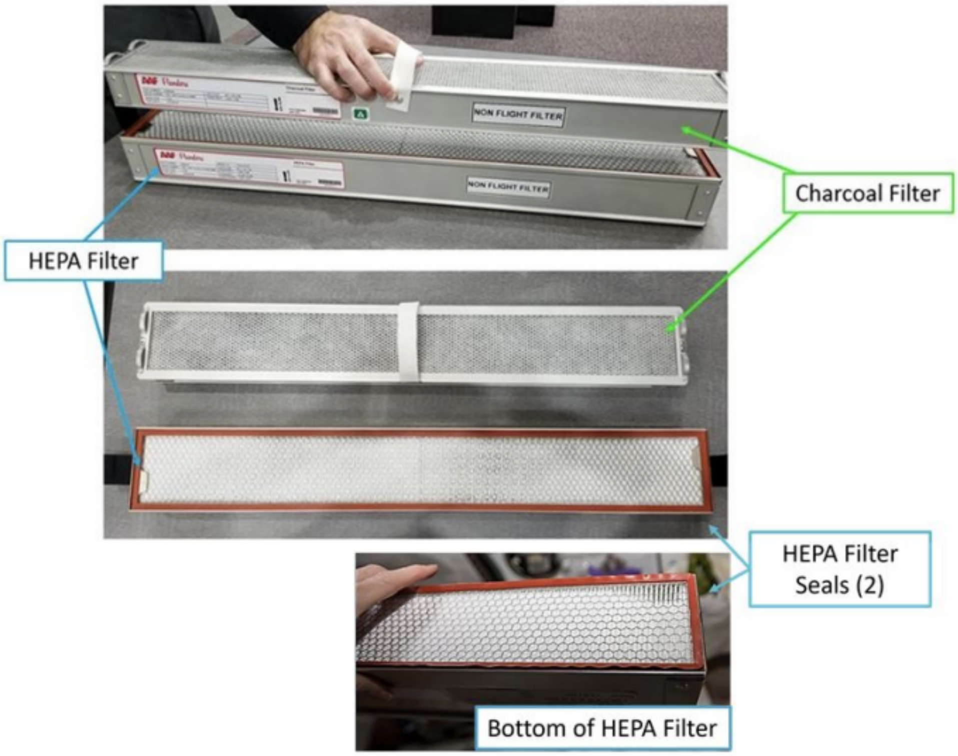


Figure 7. Integrated Filter Assembly (Not Assembled).

Figure 8. Airflow Arrows on Charcoal and HEPA Filters.

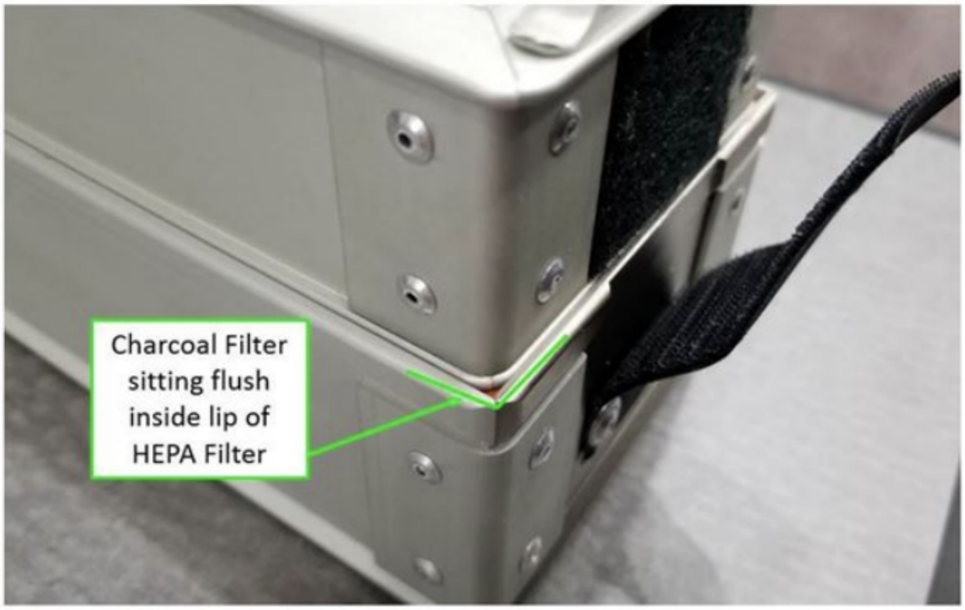


Figure 9. Charcoal Filter Installed on HEPA Filter.

5. CHARCOAL FILTER ONLY R&R (1 hour)

5.1 Record S/N of new Charcoal Filter at LAB1PD1: ______________
Record S/N of new Charcoal Filter at LAB1PD3: ______________
Record S/N of new Charcoal Filter at LAB1PD5: ______________
Record S/N of new Charcoal Filter at LAB1SD1: ______________
Record S/N of new Charcoal Filter at LAB1SD3: ______________
Record S/N of new Charcoal Filter at LAB1SD5: ______________

CAUTION
1. For cleaning the Charcoal Filter: The Hair Clipper Hose should be used with a gentle dabbing motion to prevent damage to the filter and to the Hair Clipper Hose.
2. For cleaning the HEPA Filter: The Crevice Tool should be used with a gentle side-to-side motion to prevent damage to the filter and to the Crevice Tool.
3. For Cleaning the HEPA Filter: The orange colored seals around the perimeter of the HEPA Filter (both inlet and outlet side) are delicate. Avoid these areas to prevent damage to the seals.

NOTE
Previous reports from crew indicate that the Wet/Dry Vacuum Hair Clipper Hose adapter (black) is taped to the end of the AC Dry Vacuum Cleaner. For cleaning with the AC Dry Vacuum Cleaner, the black adapter should be removed before attaching the AC Dry Vacuum Crevice Tool and the AC Dry Vacuum Hair Clipper Hose.

5.2 Open Filter Assembly Door using latch handle. (Figure 4)

Clean filter to prevent FOD from entering cabin [Vacuum Cleaner; Hair Clipper Hose]. (Figure 5)

5.3 Remove Integrated Filter Assembly by pulling up on filter handle. (Figure 6)

5.4 Remove expended Charcoal Filter from HEPA Filter by releasing two Velcro straps. (Figure 6) (Figure 7)
Clean HEPA and Charcoal filters to prevent excess FOD from entering cabin [Vacuum Cleaner; Hair Clipper Hose; Crevice Tool]. (Figure 5) (Figure 6) (Figure 7)

5.5 Photo document all sides of HEPA and Charcoal Filters [Digital Camera]. (Figure 7)

Temporarily Stow HEPA Filter to be reused in step 5.9.

CAUTION
Filters contain a handle and seals. Avoid use of Scissors near the middle of the filter and the edges to avoid inadvertently cutting handle or seal.

5.6 Remove new Charcoal Filter from Containment Bag, temporarily stow [Scissors (if required)].

5.7 Remember S/N of expended Charcoal Filter, then seal in Containment Bag with Gray Tape.
Gather and label 24" x 24" Ziplock Bag, "Expended - GMT XXX - Lab Charcoal Filter S/N XXXX" [Sharpie].
Place Charcoal Filter in labeled 24" x 24" Ziplock Bag.
Temporarily stow.

5.8 Record S/N of expended Charcoal Filter from LAB1PD1:

____

Record S/N of expended Charcoal Filter from LAB1PD3:

____

Record S/N of expended Charcoal Filter from LAB1PD5:

____

Record S/N of expended Charcoal Filter from LAB1SD1:

____

Record S/N of expended Charcoal Filter from LAB1SD3:

____

Record S/N of expended Charcoal Filter from LAB1SD5:

____

NOTE
1. Damage to filters includes: i. Excessive fuzzing, denoting severe filter deterioration and/or tearing. ii. Noticeable holes in the filters. iii. Rips, tears, or cuts in or missing portions of the seals of the filters. iv. Deformation of the filter casing, including dents, warping, and bending. 2. Cleaned surfaces must be completely dry before mating and reinstalling filters. Drying can be achieved by: i. Air drying. ii. Wiping with a Dry Wipe.

5.9 Inspect HEPA Filter (one) for damage. Inspect seals on HEPA filter for FOD or damage. (Figure 7)

If damage is present
  Photo document.
  Notify **MCC-H**.

5.10 Gently clean seals on HEPA filter [Wet Wipes]. (Figure 7)

5.11 Clean inside of Cabin Air Bacteria Filter Assy ORU [Vacuum Cleaner; Wet Wipes].

5.12 ✓All cleaned surfaces are dry [Dry Wipes (if required)]

Place new Charcoal Filter on top of HEPA Filter.
Ensure air flow arrows on label of each filter are pointing in the same direction. (Figure 8)
Ensure Charcoal Filter is fully seated inside lip of HEPA Filter. (Figure 9)

5.13 Fasten Velcro (two) to secure Charcoal Filter and HEPA Filter halves together.

5.14 Use filter handle to reinstall HEPA and Charcoal Filter into Cabin Air Bacteria Filter Assy ORU. (Figure 6)

5.15 Close filter assembly door using latch handle. (Figure 4)

7. STARBOARD FILTER R&R PREP (5 minutes)

CAUTION
CCAA Return Manual Damper Valve must be opened before increasing fan speed.

7.1 After R&R of Port side filters is complete, pull up, rotate LAB1PD6 CCAA Return Manual Damper Valve to OPEN.

LAB1SD6 7.2 Pull up, rotate LAB1SD6 CCAA Return Manual Damper Valve to CLOSED. (Figure 3)

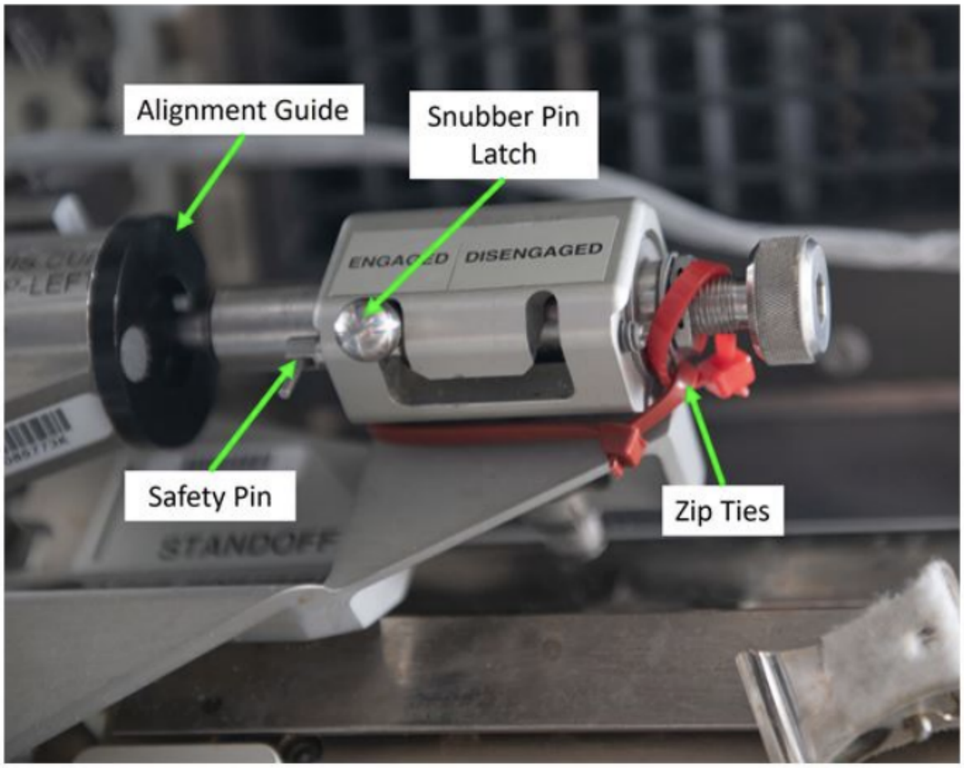


Figure 10. Snubber Assembly Shown in Proper Configuration for Step 7.3.

LAB1S3 7.3 ✓Alignment Guides (three of four) installed

✓Snubber Pin Latch is in the Engage Position for all four Snubber Pins

✓Safety Pin is locked for all four Snubber Pins

✓Snubber Assemblies (four) are secured with Zip Ties (two per Snubber Assembly)

(Figure 10)

7.4 Perform filter R&R (step 4 , step 5, or step 6 as required) for three Starboard side filters, one Standoff at a time (LAB1SD1, LAB1SD3, LAB1SD5), then proceed to the next step.

7.5 Pull up, rotate LAB1SD6 CCAA Return Manual Damper Valve to OPEN.

7.6 Doff Safety Glasses or Goggles, Dust Mask.

8. REPLACING SMOKE DETECTOR (15 minutes)

8.1 For LAB1PD1 Smoke Detector

NOTE
Lower right fastener on the LAB1PD1 Smoke Detector bracket will not engage due to stripping of the bottom threads. Three of four fasteners are sufficient to secure the LAB1PD1 Smoke Detector. The fourth fastener is taped to the bracket and the installation hole is covered by Kapton Tape to prevent airflow bypassing the filter.

8.1.1 Don Static Wrist Tether.
Secure to unpainted, unanodized metal surface, except stowage racks.

8.1.2 Replace Smoke Detector Bracket at Standoff location.
Tighten, torque fasteners (three) to 20 in-lbs [Ratchet, 1/4" Drive; 10" Ext; 5/16" Socket; (10-50 in-lbs) Trq Wrench]. (Figure 1)

8.1.3 Remove Kapton Tape, then mate:
P1-W3360 →|← J1

8.1.4 Doff Static Wrist Tether.

8.1.5 Check for FOD around work area within 1 meter radius.

8.2 For LAB1SD5 Smoke Detector

8.2.1 Don Static Wrist Tether.
Secure to unpainted, unanodized metal surface, except stowage racks.

8.2.2 Replace Smoke Detector Bracket at Standoff location. (Figure 2)

8.2.3 Remove Kapton Tape, then mate:
P1-W3219 →|← J1

8.2.4 Tighten, torque noncaptive fasteners (three) to 20 in-lbs [Ratchet, 1/4" Drive; 10" Ext; 5/16" Socket; (10-50 in-lbs) Trq Wrench].

8.2.5 Doff Static Wrist Tether.

8.2.6 Check for FOD around work area within 1 meter radius.

9. POST MAINTENANCE (5 minutes)

9.1 Photo document installed filters [Digital Camera].

9.2 ISS ⇓ **MCC-H**, "Task complete. Ready for LAB Smoke Detector activation and to increase LAB CCAA Fan Speed."

9.3 Stow tools, parts, and materials per Stowage Note.

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5.1.301 NODE 2 HEPA AND CHARCOAL FILTER AND SMOKE DETECTOR INSPECT AND CLEAN

(ISS IFM/E66 - ALL/FIN 3) Page 1 of 13 pages

OBJECTIVE:

To inspect and clean Node 2 HEPA and Charcoal Filters and Node 2 Smoke Detectors using Vacuum Cleaner. Also includes steps for an invasive I-level cleaning of Smoke Detectors using N2 cartridges.

LOCATION:

NOD2D3

DURATION:

30 minutes Nominal Cleaning

90 minutes Invasive Cleaning

CREW:

One

Please note: Trade names and trademarks used in this procedure are for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

MATERIALS:
Dust Mask
Safety Goggles
Dry Wipes (if required)
Wet Wipes
Nitrile Gloves
Sharpie

TOOLS:
Digital Camera
AC Dry Vacuum Cleaner ("Nominal Ops Cleaning Only")
AC Dry Vacuum Hair Clipper Hose P/N SEG33124048-301 (if required)
AC Dry Vacuum Crevice Tool P/N SEG33123990-303 (if required)
ISS IVA Toolbox:
  Drawer 2:
    5/32" Hex Head, 1/4" Drive
    Rachet, 1/4" Drive
    5/16" Deep Socket, 1/4" Drive
    (5-35 in-lbs) Trq Driver, 1/4" Drive
    5/16" Socket, 1/4" Drive
    4" Ext, 1/4" Drive
IVA Connector Cleaner Tool Kit P/N SJG33114991-303:
  Connector Cleaner Tool P/N CCT8128-100
  IVA N2 Cartridge P/N SDG33114990-801

1. SAFING

1.1 ✓**MCC-H** to confirm the following
Node 2 CCAA is deactivated
Node 2 Smoke Detectors 1, 2: Monitor INH (may remain powered)
JPM IMV Stbd Aft Fan is deactivated.

1.2 Inform all crew that automatic smoke detection and ventilation is lost in Node 2 until informed otherwise by **MCC-H**.

2. <u>ACCESSING</u>

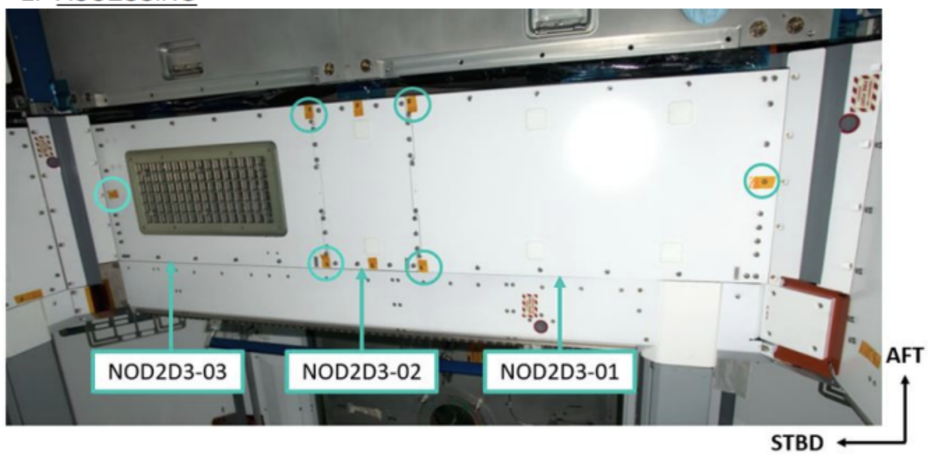

Figure 1. View of Closeout Panels.

2.1 Don Dust Mask and Safety Goggles.

2.2 Remove the following Closeout Panels [Ratchet, 1/4" Drive; 5/32" Hex Head]:
NOD2D3-01, fasteners (three)
NOD2D3-03, fasteners (three)
(Figure 1)

2.3 Clean Closeout Panels, workspace (as required) [Vacuum Cleaner; Crevice Tool].
Temporarily stow Closeout Panels.

3. INSPECTING AND CLEANING AREA SMOKE DETECTOR

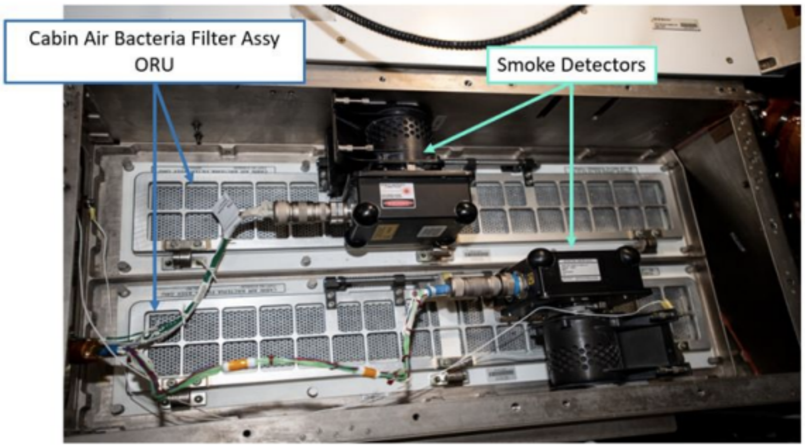

Figure 2. Bacteria Filters (Discontinued) and Smoke Detectors Installed with NOD2D3-03 Panel Removed.

NOTE
Smoke Detector connections will remain mated for the duration of this procedure. For this reason, electrical safing is not required. The Smoke Detectors will be inhibited to prevent false fire alarms caused by dislodged dust.

3.1 Detach Node 2 Smoke Detectors 1 and 2 from Velcro on volume side wall. (Figure 2)

3.2 Inspect, clean external surfaces for each Area Smoke Detector (two) [Vacuum Cleaner; Hair Clipper Hose].

3.3 Visually inspect wire harnesses (two) of Smoke Detectors for nicks, cuts, or abrasions.

If damage is present
Photo document [Digital Camera].
Notify **MCC-H**.

4. INVASIVE SMOKE DETECTOR CLEANING (IF REQUIRED)

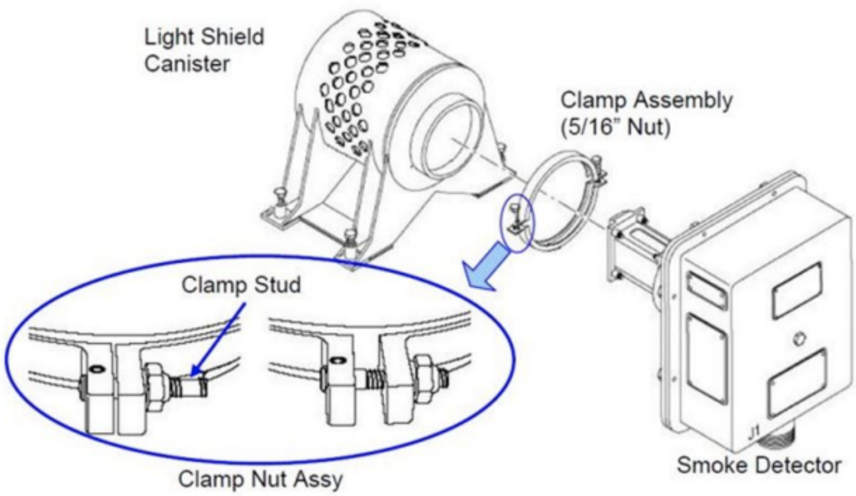

Figure 3. Smoke Detector Assembly.

CAUTION
1. Noncaptive hardware: Clamp Assembly Nuts will become noncaptive if loosened beyond the Clamp Stud.
2. When separating the Light Shield Canister Assembly from the Smoke Detector Assembly, keep the Light Shield centered and perpendicular to the Detector Assembly to avoid damage to coating on the Smoke Detector Assembly.
3. Throughout this procedure, avoid direct skin contact with the interior surfaces of the Light Shield and Detector Assemblies.

4.1 Don Nitrile Gloves.

4.2 Loosen Clamp Assembly 5/16-inch nuts (two) until the nuts spin freely on the clamp studs [Ratchet, 1/4" Drive; 5/16" Deep Socket]. (Figure 3)

4.3 Remove Light Shield Canister from Smoke Detector Assembly. (Figure 3) Photo document Smoke Detector [Digital Camera].

Figure 4. IVA Connector Cleaner Kit.

NOTE
Once black reference line is no longer visible, the IVA N2 Cartridge has been punctured by the tool.

4.4 Actuate Cleaner Tool trigger three times before installing IVA N2 Cartridge to prevent an inadvertent discharge.

4.5 Screw the IVA N2 Cartridge ↷ into Cleaner Tool retainer until black reference line is no longer visible on the IVA N2 Cartridge. (Figure 4)

WARNING
Protect eyes and skin from injury due to the compressed gas (1500 psi at 1150 ft/sec flow rate with 0.0092 Lbm/sec at nozzle point).

CAUTION
1. To prevent damage to the Smoke Detector components and coatings, avoid direct blasts of pressurized gas at close range. Hold nozzle no closer than two inches from the target surface and depress the trigger about 1/2 to 3/4 of full travel. Discharge gas in short controlled bursts. Use first three bursts to clean the Light Shield.
2. Vacuum or Dry Wipes are not to be used for cleaning any Smoke Detector interior surfaces, including Photodiode Assemblies. Interior surfaces have non-reflective coating that could be damaged hindering functionality.

NOTE

1. The goal is to reduce false smoke detection alarms. Smoke Detector may be deemed clean when relatively few visible particles remain on the surfaces.
2. There will be a total of 10 to 12 bursts available from the IVA N2 Cartridge. The first 3 bursts should be expended on the Light Shield Canister away from the Smoke Detector to reduce the pressure from the bottle before cleaning the mirrors and diodes. Save sufficient gas to clean the mirrors and diodes (about 5 to 6 bursts).
3. The Connector Cleaner Tool should be utilized near the HEPA and Charcoal Filters, avoiding the other Smoke Detector. This allows the debris to be picked up by the filters instead of the Area Smoke Detector.

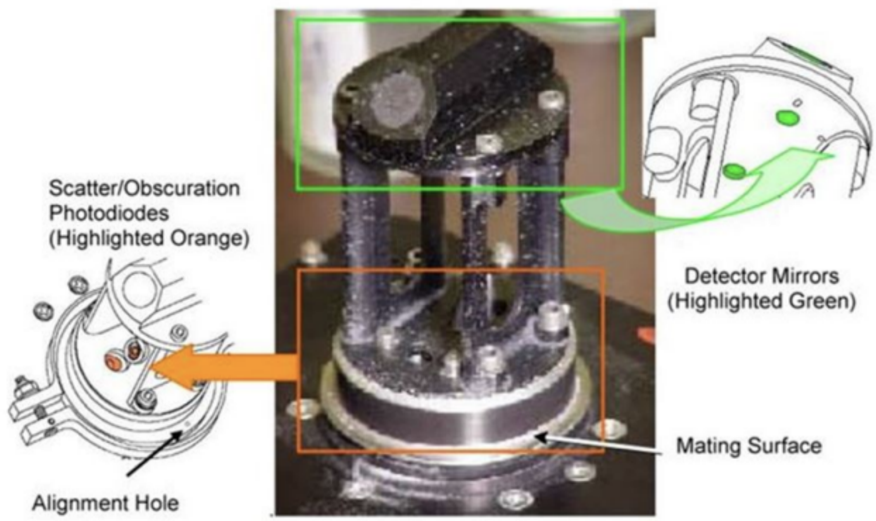

Figure 5. Contaminated Smoke Detector.

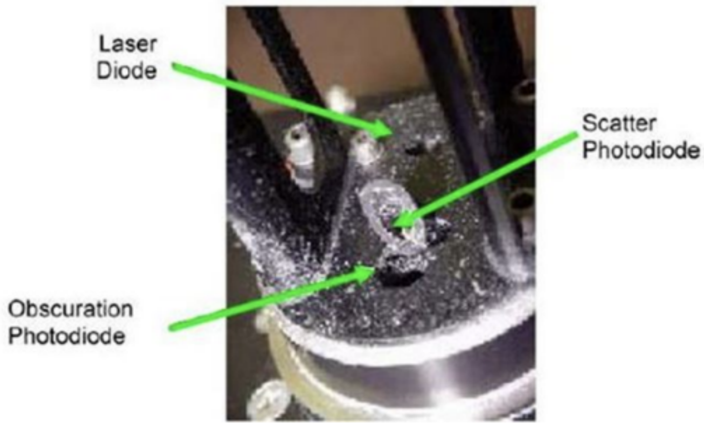

Figure 6. Contaminated Scatter and Obscuration Photodiodes.

4.6 Directing the Connector Cleaner Tool away from Smoke Detector, expend first 3 bursts to clean Light Shield Canister.
Hold Connector Cleaner Tool no closer than 2 inches away from area to be cleaned.

At HEPA and Charcoal Filters, blow (5 to 6 bursts) particulate matter off of Mirrors, Laser Diode, and Obscuration and Scatter Photodiode surfaces in a sweeping motion.

If FOD remains on any of these areas
| Use additional bursts to remove. (Figure 5) (Figure 6)

Exterior surfaces of Smoke Detector and at install location can be cleaned with Dry Wipes.

4.7 Verify N2 has been completely expelled from Connector Cleaner Tool, IVA N2 Cartridge.
Remove IVA N2 Cartridge from Connector Cleaner Tool.
Label IVA N2 Cartridge "Expended" [Sharpie].
Temporarily stow.

4.8 Attach Light Shield Canister onto Smoke Detector Assembly.
✓No gaps at mating surface between Light Shield Canister and Smoke Detector Assemblies

Tighten, torque fasteners (two) to 12 in-lbs securing band clamp over flange [(5-35 in-lbs) Trq Driver, 1/4" Drive; 4" Ext; 5/16" Socket]. (Figure 3)

4.9 Temporarily stow Smoke Detector.

4.10 Repeat step 4 for other Smoke Detector.

4.11 Doff Nitrile Gloves.

5. INSPECTING AND CLEANING FILTER

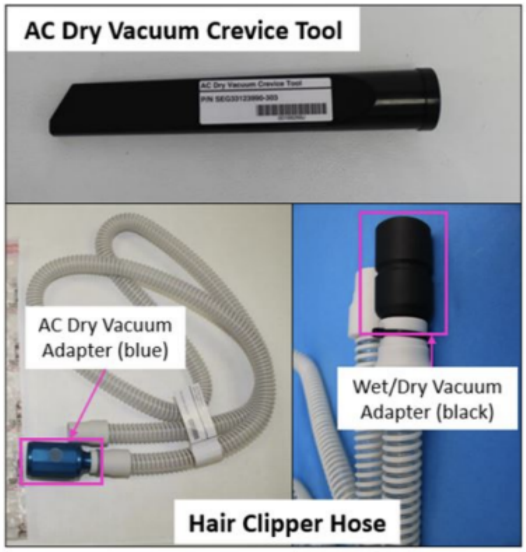

Figure 7. AC Dry Vacuum Cleaner Attachments - Crevice Tool and Hair Clipper Hose.

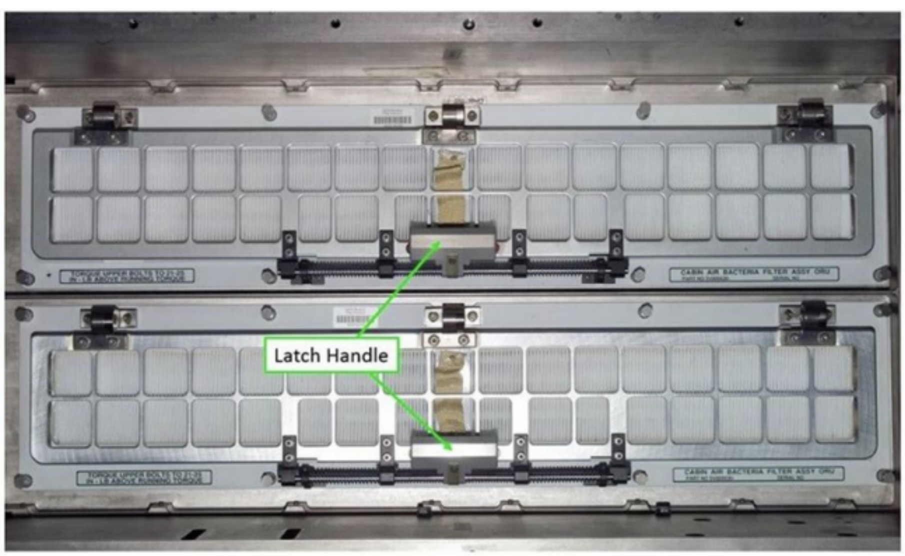

Figure 8. View of Cabin Air Bacteria Filter Assy ORU Door.

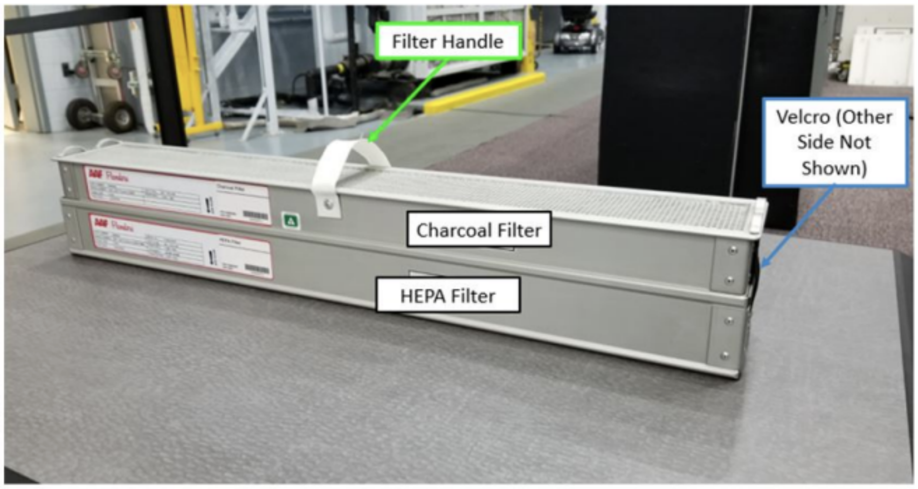

Figure 9. HEPA and Charcoal Filters Assembled.

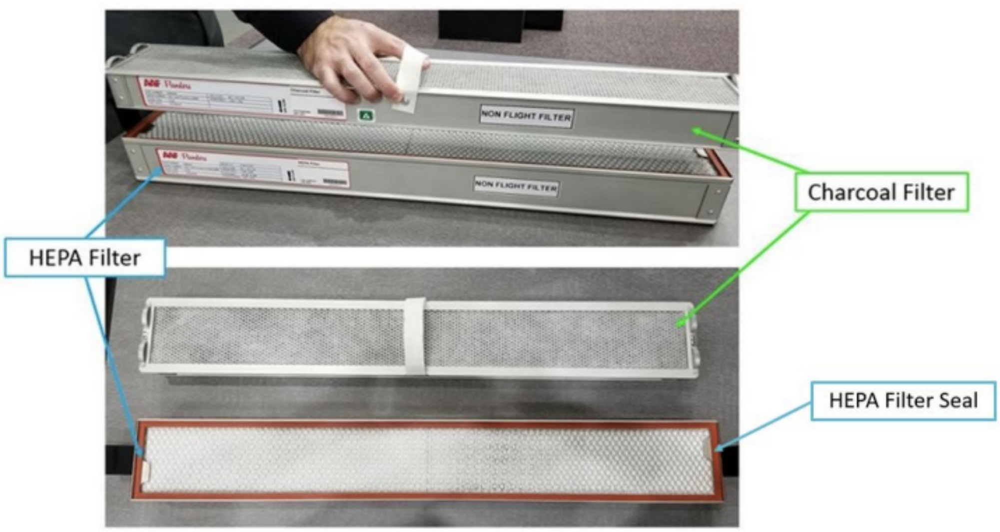

Figure 10. HEPA and Charcoal Filters Not Assembled.

Figure 11. Cabin Air Bacteria Filter Assy ORU Without Filters.

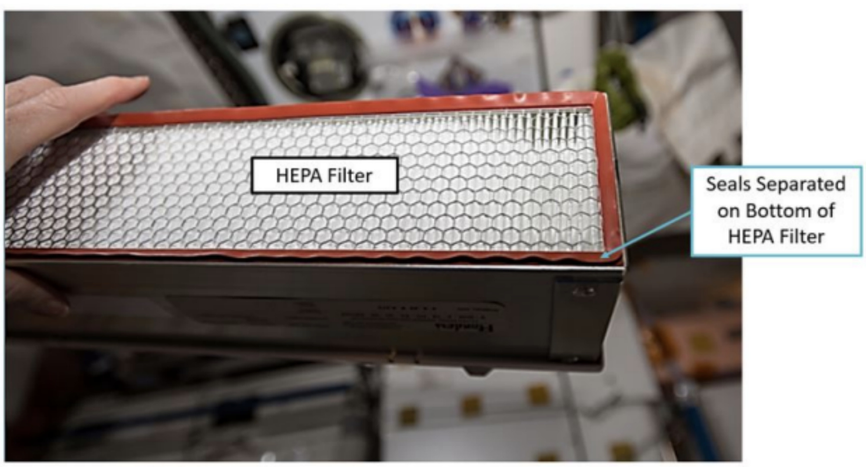

Figure 12. HEPA Filter Seal that Rests Against the Cabin Air Bacteria Filter Assy ORU.

Figure 13. Airflow Arrows on Charcoal and HEPA Filters.

CAUTION
1. For cleaning the Charcoal Filter: The Hair Clipper Hose should be used with a gentle dabbing motion to prevent damage to the filter and to the Hair Clipper Hose.
2. For cleaning the HEPA Filter: The Crevice Tool should be used with a gentle side-to-side motion to prevent damage to the filter and to the Crevice Tool.
3. For Cleaning the HEPA Filter: The orange colored seals around the perimeter of the HEPA Filter (both inlet and outlet side) are delicate. Avoid these areas to prevent damage to the seals.

NOTE
Previous reports from crew indicate that the Wet/Dry Vacuum Hair Clipper Hose adapter (black) is taped to the end of the AC Dry Vacuum Cleaner. For cleaning with the AC Dry Vacuum Cleaner, the black adapter should be removed before attaching the AC Dry Vacuum Crevice Tool and the AC Dry Vacuum Hair Clipper Hose.

5.1 Vacuum outer surfaces of filter assembly door. (Figure 7) (Figure 8)

5.2 Open filter assembly door using Latch Handle. (Figure 8)
Clean filter to prevent FOD from entering cabin [Vacuum Cleaner; Hair Clipper Hose]. (Figure 7)

5.3 Remove HEPA and Charcoal Filter by pulling up on Filter Handle. (Figure 9)

5.4 Disassemble HEPA and Charcoal Filter by releasing Velcro Straps.
Clean HEPA and Charcoal filters (two) to prevent excess FOD from entering cabin [Vacuum Cleaner; Hair Clipper Hose; Crevice Tool].
(Figure 7) (Figure 9) (Figure 10)

NOTE
Damage to filters includes: 1. Excessive fuzzing, denoting severe filter deterioration and/or tearing. 2. Noticeable holes in the filters. 3. Rips, tears, or cuts in or missing portions of the seals of the filters. 4. Deformation of the filter casing, including dents, warping, and bending.

5.5 Inspect HEPA and Charcoal Filter (one) for damage.

If damage is present
| Photo document.
| Notify **MCC-H**.

5.6 Photo document all sides of filters. (Figure 10)

NOTE
Cleaned surfaces must be completely dry before mating and reinstalling filters. Drying can be achieved by: 1. Air drying. 2. Wiping with a Dry Wipe.

5.7 Inspect seals on HEPA filter for FOD or damage. (Figure 10)

If FOD is present
| Clean [Wet Wipes].

If damage is present
| Photo document.
| Notify **MCC-H**.

5.8 Clean the face of the Charcoal Filter that mates with the HEPA Filter [Wet Wipes]. (Figure 10)

5.9 Clean inside of Cabin Air Bacteria Filter Assy ORU [Wet Wipes]. (Figure 11)

5.10 Separate the two layers of the HEPA Filter seal that rests against the Cabin Air Bacteria Filter Assy ORU gently with fingers. (Figure 12)

5.11 ✓All cleaned surfaces are dry
Reattach HEPA Filter to Charcoal Filter and secure with Velcro Straps, ensuring airflow arrows are oriented in the same direction. (Figure 9) (Figure 13)

5.12 Use Filter Handle to reinstall HEPA and Charcoal Filter into Cabin Air Bacteria Filter Assy ORU. (Figure 9)

5.13 Close filter assembly door and Latch Handle. (Figure 8)

5.14 Repeat step 5.1 to step 5.13 for other HEPA and Charcoal Filters (three).

5.15 Doff Dust Mask and Safety Goggles.

6. CLOSEOUT

6.1 Reattach Node 2 Smoke Detectors to Velcro on volume side walls. (Figure 2)

6.2 Install Closeout Panel NOD2D3-01, NOD2D3-03 fasteners (three) [Ratchet, 1/4" Drive; 5/32" Hex Head]. (Figure 1)

6.3 ISS ⇓ **MCC-H**, "Node 2 Smoke Detector and HEPA and Charcoal Filter Cleanings complete. GO for Node 2 CCAA Activation and Smoke Detector Activation."

6.4 Stow tools, materials per ASN.

Note from the author:

Thank you for reading! Putting this thesis together has been a rewarding journey, and I hope you may have found some part of it similarly rewarding. Let's keep sharing our knowledge and push the boundaries of what's possible. The future is bright when humanity works together.