NASA CO$_2$ Removal

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Life Support Systems CO$_2$ Removal Co-Lead
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Some comparisons
Space-specific challenges

- Liquid drops and solid particles don’t fall
- Bubbles don’t rise
It takes a lot of rocket to get a small spacecraft to the moon!

Reducing mass (or things that result in reducing mass*) is important to reducing launch costs!

*lower power, lower volume, higher reliability, less crewtime
THE ECLS CHALLENGE

**Needs**
- Oxygen = 0.84 kg (1.8 lbs)
- Food Solids = 0.62 kg (1.38 lbs)
- Water in Food = 1.15 kg (2.54 lbs)
- Food Prep Water = 0.76 kg (1.67 lbs)
- Drink = 1.62 kg (3.58 lbs)
- Metabolized Water = 0.35 kg (0.76 lbs)
- Hand/Face Wash Water = 4.09 kg (9.04 lbs)
- Shower Water = 2.73 kg (6.09 lbs)
- Urinal Flush = 0.49 kg (1.08 lbs)
- Clothes Wash Water = 12.50 kg (27.5 lbs)
- Dish Wash Water = 5.45 kg (12 lbs)
- Total = 30.60 kg (67.1 lbs)

**Effluents**
- Carbon Dioxide = 1.00 kg (2.2 lbs)
- Respiration & Perspiration Water = 2.28 kg (5.0 lbs)
- Food Preparation, Latent Water = 0.036 kg (0.08 lbs)
- Urine = 1.50 kg (3.3 lbs)
- Urine Flush Water = 0.50 kg (1.1 lbs)
- Feces Water = 0.091 kg (0.2 lbs)
- Sweat Solids = 0.018 kg (0.04 lbs)
- Urine Solids = 0.059 kg (0.1 lbs)
- Feces Solids = 0.032 kg (0.07 lbs)
- Hygiene Water = 12.58 kg (27.8 lbs)
- Clothes Wash Water Liquid = 11.90 kg (26.9 lbs)
- Latent = 0.60 kg (1.3 lbs)
- Total = 30.60 kg (67.1 lbs)
Calculations:

- 4 crew members produce about 4 kg/day CO₂.
- To maintain 2500 ppm CO₂, we need to process at least 20 cubic feet per minute, continuously.
- At 1000 ppm, this increases to 50 cfm.
• 5A Molecular Sieve
Carbon Dioxide Utilization

Cabin Air
- ~0.25% CO₂
- ~50% Humidity

- Current technology does not completely close the loop
Potential additional options for CO$_2$ usage

Improved Oxygen recovery:
   Plasma Pyrolysis
   Bosch reaction
CO$_2$ for plant or algal growth - photosynthesis
CO$_2$ as a source for fuel production – methane, hydrocarbon liquid fuels
CO$_2$ as a feedstock for either direct utilization or through conversion to organic substrates (Microbial substrates, fish food, etc) biomanufacturing
CO$_2$ as a compressed gas for compressed gas cleaning or propulsion
CO$_2$ as a carbon and oxygen feedstock for the physicochemical synthesis of chemicals (plastics, pharmaceuticals, adhesives, etc.)
CO$_2$ as a cleaning solution or switchable polarity solvent
Carbon Dioxide Removal Assembly History

- Adsorbent bed media containment failures
- Rapid pressure drop increases
- Limited bed life
- Bed heater shorts

Current design addresses fixes
Future CO$_2$ Removal

- Updated Sorbent Bed Geometry
- Updated Heater Geometry
- Change in Sorbent Material
Mini Scrubber

https://www.nasa.gov/sites/default/files/thumbnails/image/dynetics-nextstep.png
Carbon Dioxide Removal by Freezing

Carbon Dioxide Deposition by Freezing, cont’d

• May be particularly advantageous for deep space missions.
• Can also condense out volatiles from the air.

~2mm thick layer of frozen transparent \( \text{CO}_2 \)

Liquid Thermal Amine Microgravity Control

- Submarines spray liquid amines to remove CO$_2$.
- Microgravity environment requires methods to control liquid behavior to use liquid amines in the space environment.
Recent work reported at the 49th International Conference on Environmental Systems, July 2019.
Versions of 13x have exceptional attrition resistance.
Continued Development of a Liquid Amine Carbon Dioxide Removal System for Microgravity Applications

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Carbon dioxide (CO₂) can rapidly accumulate in spacecraft, creating a dangerous breathing environment if not properly controlled. Traditionally, solid adsorbents have been used to capture and release the CO₂ generated by crew metabolic activity. Liquid absorbents have generally been avoided, due to the added complexity of handling fluids in a microgravity environment. However, with the advent of advanced manufacturing techniques using three-dimensional printing, a capillary-based gas/liquid contantor and degasser system has been developed and tested. Test data and an accompanying mathematical model have been developed for the contantor portion of the system. Flux rate data were then used to size a concept for application in a spacecraft. Finally, an integrated test stand was configured with the degasser and thermal control equipment. The integrated test stand was operated in a
A Thermally-Regenerated Solid Amine CO₂ Removal System Incorporating Water Vapor Recovery and Ullage Air Recovery

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The Thermal Amine Scrubber (TAS) flight experiment was developed under contract with NASA/JSC with the goal to demonstrate a Technology Readiness Level 5 (TRL5) prototype advanced carbon dioxide (CO₂) removal system based on a thermally-regenerated solid amine adsorbent. The TAS was designed to fit within two double lockers within an ISS EXPRESS Rack, consisting of a Water Save subsystem (H₂O Locker), a CO₂ Removal subsystem (CO₂ Locker), and an ISIS drawer for the system controller. The H₂O Locker incorporates a passive water save desiccant canister technology capable of recovering ~90% of the incoming humidity present in the process air stream. A supplemental desiccant wheel boosts the overall water recovery to ~97%. The CO₂ Locker receives dry air from the H₂O Locker and splits flow between two pairs of CO₂ removal beds containing the solid amine. Each pair of beds is restricted to one adsorbing bed and one desorbing bed, the latter of which is isolated from the process air and exposed to vacuum during thermal regeneration. A valve assembly redirects flow back to the regenerated bed at a regular interval, but first ~96% of the ullage air from the previous adsorbing bed is evacuated using a scroll compressor in an intermediary valve state. This design allows for a removal rate of ~3.7 kg/day of CO₂ at 2 mmHg partial pressure CO₂ in the process air, which corresponds to approximately a 4 crewmember equivalent.

The TAS will provide an additional means of removing CO₂ from the ISS, potentially providing additional capacity for time periods with increased crew size. Addition of a vacuum compressor, residual water separator, and accumulator downstream of TAS will enable integration with a CO₂ reduction system, provided the desorbed gas has acceptable CO₂ purity, and is directly applicable to exploration missions requiring oxygen recovery.

Nomenclature

AC = alternating current
AEL = Advanced Engineering Laboratory at Collins Aerospace
CD01 = Thermal Amine Scrubber carbon dioxide sensor
CDRA = Carbon Dioxide Removal Assembly
Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) System Development

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Using a liquid absorbent like an ionic liquid eliminates many of the disadvantages of solid adsorbent systems for carbon dioxide (CO\textsubscript{2}) removal from air in deep space missions. Systems built around a liquid absorbent avoid complicated valve networks to switch between absorbing and desorbing beds. Continuous flow processing delivers an even flow of product carbon dioxide and has the potential to provide a more robust system overall. Ionic liquids are particularly desirable for space applications since they are non-volatile, non-odorous, and have high oxidative stability. The CDRILS system pairs hollow fiber membrane contactors with ionic liquid absorbent to provide rapid, continuous CO\textsubscript{2} capture and recovery of pure CO\textsubscript{2} from the liquid.

Significant progress has been made in the development of the CDRILS system for use in life support applications. Membrane contactors have been designed that provide high surface area without allowing escape of the liquid, and the long-term reliability of both contactors and ionic liquid has been assessed. Using measured CO\textsubscript{2} and water capacities and mass transfer coefficients, alternative system designs have been evaluated to identify those that maximize performance while minimizing weight, volume and power consumption. Because water is strongly absorbed by most ionic liquids, water management is a key focus in designing the closed-loop system. Determination of optimized operating conditions and the optimum system design will allow scale up of lab-scale experiments to a full-size unit capable of removing 4.16 kg/day of CO\textsubscript{2}.

\textbf{Nomenclature}

\begin{itemize}
\item BMIM Ac = 1-butyl-3-methylimidazolium acetate
\item BMIM BF\textsubscript{4} = 1-butyl-3-methylimidazolium tetrafluoroborate
\item CDRA = Carbon Dioxide Removal Assembly
\item CDRILS = Carbon Dioxide Removal by Ionic Liquid Sorbent
\item CMS = Carbon Dioxide Management System
\end{itemize}
Spacecraft Carbon Dioxide Deposition Subscale System Design and Test

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To further expand the human presence in space on missions to the moon and beyond, new cabin atmosphere CO₂ removal systems that improve reliability over the state-of-the-art are required. Multiple pathways providing incremental improvement over the current sorbent-based technology are currently being explored, but the method described in this paper leverages the phase change temperatures of air constituents to selectively remove CO₂. Generating a cold surface on which to deposit and store CO₂ for downstream processing is a highly reliable process, achievable via cryogenic coolers or thermal radiators. This method of CO₂ capture may support humidity and/or trace contaminant capture as well. The goal of the CO₂ Deposition system development unit is to demonstrate continuous CO₂ removal from an airstream scaled at approximately 1 crew member without humidity control (1 kg CO₂/day) utilizing lessons learned from heritage systems and proof of concept testing. This development unit consists of 3 total free-piston Stirling engine coolers: 1 to precool the airstream and 2 operating in parallel, alternating fashion to achieve continuous CO₂ removal. Dry air flows through the system at varied flow rates and CO₂ concentrations, and the amount of CO₂ captured, temperatures achieved, and power required to operate are measured to characterize performance. This development unit successfully demonstrates cyclic, continuous operation and establishes a proposed concept of operations for a future developmental or flight unit. The dependence on the effectiveness of the air-to-air heat exchangers to reduce the total power requirement will be the main focus in future designs.

Nomenclature
Electrochemical Solutions for Advanced Life Support

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The Oxygen Generating Assembly (OGA) on-board the International Space Station (ISS) employs a polymer electrolyte membrane (PEM) water electrolysis cell stack to electrochemically dissociate water into its two components – oxygen and hydrogen. Oxygen is provided to the cabin atmosphere for crew respiration while the hydrogen is delivered to a carbon dioxide reduction system to recover oxygen as water. The design of the OGA evolved over a number of years to arrive at the system solution that is currently operational on ISS.

Future manned missions to space will require advanced technologies that eliminate the need for resupply from earth and feature in-situ resource utilization to sustain crew life and to provide useful materials to the crew. The architects planning such missions should consider all potential solutions at their disposal to arrive at an optimal vehicle solution that minimizes crew maintenance time, launch weight, installed volume and energy consumption demands. Skrye is developing new technologies through funding from NASA, the Department of Energy, and internal investment based on PEM technology that could become an integral part of these new vehicle solutions. At varying stages of Technology Readiness Level (TRL) are: an oxygen concentrator and compressor that can separate oxygen from an air stream and provide an enriched oxygen resource for crew medical use and space suit recharge without any moving parts in the pure oxygen stream; a regenerative carbon dioxide removal system featuring a PEM-based sorbent regenerator; a carbon dioxide reduction system that electrochemically produces organic compounds that could serve as fuels or as a useful intermediary to more beneficial compounds; and an electrochemical hydrogen separator and compressor for hydrogen recycle. The technical maturity of these projects is presented along with pertinent performance test data that could be beneficial in future study efforts.

• Electrochemical regeneration of potassium carbonate to potassium hydroxide.
• Funded in part by ARPA-E
Highly Efficient Closed-Loop CO$_2$ Removal System for Deep-Space ECLSS

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In current International Space Station (ISS) and other low orbit missions, the metabolically generated CO$_2$ is removed from the cabin air via adsorption and vented into space, resulting in a net loss of O$_2$. However, a closed-loop cabin Atmosphere Revitalization System (ARS) is crucial to NASA’s mission architectures for future long duration human space exploration to the Moon and Mars and other deep space missions. TDA Research, Inc. (TDA) is developing a highly efficient CO$_2$ removal system for closed-loop space craft cabin air re-vitalization during deep space missions. The key to TDA’s system is a strontium exchanged silico-alumino-phosphate (Sr-SAPO-34) zeolite. The system delivers a continuous flow of CO$_2$ allowing uninterrupted, steady-state operation of the downstream processes that produce propellants and/or life support consumables; this greatly reduces the overall system size and complexity. The Sr-SAPO-34 can be regenerated at a much lower temperature than the 5A zeolite (currently used in ISS), which provides significant energy savings. We have successfully demonstrated that the Sr-exchanged SAPO-34 sorbent can effectively remove CO$_2$ from simulated spacecraft cabin atmosphere and the sorbent maintains its working capacity over 170 cycles in fixed bed tests, elevating the TRL to 3. In a current Small Business Technology Transfer (STTR) Phase II project, we are scaling up the sorbent production and developing the sorbent system. The results from the STTR project will be presented at the meeting.

• Strontium exchanged silico-alumino-phosphate (Sr-SAPO-34) zeolite.
Informal discussions with Geoff Holmes and others of Carbon Engineering, and Eric Rasmussen and Dennis Schnell of SPX. SPX sent samples of cooling tower fill.
Carbonic Anhydrase

Directed evolution of an ultrastable carbonic anhydrase for highly efficient carbon capture from flue gas


Directed Evolution task underway at NASA Ames.

“...Increase in thermostability and alkali tolerance translates to a 4,000,000-fold improvement over the natural enzyme.”
NASA Early Career Faculty (ECF) awards

Metal Organic Frameworks (MOF) and Ionic Liquids/Membrane Technologies for Advanced CO2 Removal Applications

Jeffrey Alston
North Carolina Agricultural & Technical State University, Greensboro
“Novel CO2 Removal with Magnetocaloric Pumping Augmentation of Hybrid Paramagnetic Ionic Liquid - SLMs”

Matthew Green
Arizona State University, Tempe
“Scalable Membrane-supported IL CO2 capture and removal systems”

Burcu Gurkan
Case Western Reserve University, Cleveland
“Poly(ionic liquid)-ionic liquid membranes reinforced by graphene sheets for CO2 capture and conversion in microgravity”

Casey Wade
The Ohio State University, Columbus
“Biomimetic strategies for selective carbon dioxide capture with metal-organic frameworks”
Backup slides
SPACECRAFT LIFE SUPPORT

Diagram showing the flow of life support systems in a spacecraft, including temperature and humidity control, CO₂ removal, CO₂ reduction, trace contaminant control subassembly, oxygen generation, nitrogen control, processed urine, waste products, and wastewater.
Carbon Dioxide Removal Assembly

CDRA Mass: 450 pounds
CDRA Power: 1000 watts
CDRA volume: 19 cubic feet
CDRA Heat rejection: 620 watts to TCS and 500 watts to Avionics Air

CO₂ removal performance:
4.16 kg/day assuming crew of 4
ppCO₂ at 2.0 mmHg
-> ~ 26 CFM air flow

Expected Mean Time Between Failure: 3+ years.

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Value to NASA Missions

- As noted earlier, these are valuable characteristics:
  - Reduction in mass and power compared to current systems
  - Improved reliability over current systems

**Improvements must be manifested over the complete system**

Hypothetical Comparison:

- CO$_2$ Removal(a)
- CO$_2$ Removal(b)
- CO$_2$ Removal(c)
Related topics
Sorbent characterization

Figure 2. Plot a) shows a single sample through multiple CO₂ analysis runs. In the low pressure region < 0.1 kPa, the data deviates and is inconsistent. Plot b) shows that this issue was resolved by performing the activation procedure directly on the analysis port, removing the need to transfer the sample from degas to analysis port. The analysis temperature for both plots was 25°C.

ISS Carbon Dioxide Management System (CMS)

The SAC ORU
- An oil-free reciprocal piston compressor with vibration isolators, mounting plate, an acoustic enclosure.
- Cooled with Moderate Temperature Loop (MTL) coolant water.
- Tested for 7000hrs for 2 years maintenance free.
- Mass: 125lbs (57kg).
- Volume: 17.8in x 12.6in x 7.8in, 1ft³.
- Power (average): 288Watts.

Accumulator
- Consists of 6 tanks.
- The 4 larger tanks:
  - 4.94 lbs (2.2 kg)
  - 15” L x 5” dia.
- The 2 smaller tanks:
  - 2.28 lbs (1.0kg)
  - 14” L x 3.5” dia.
- Total mass of 41.22 lbs (18.2 kg).
- Total volume 0.7ft³.

Sorbent-based CO$_2$ management systems

Air Cooled (AC) and Thermally Coupled (TC) Temperature Swing Adsorbent Compression (TSAC) system give considerable mass and power savings.