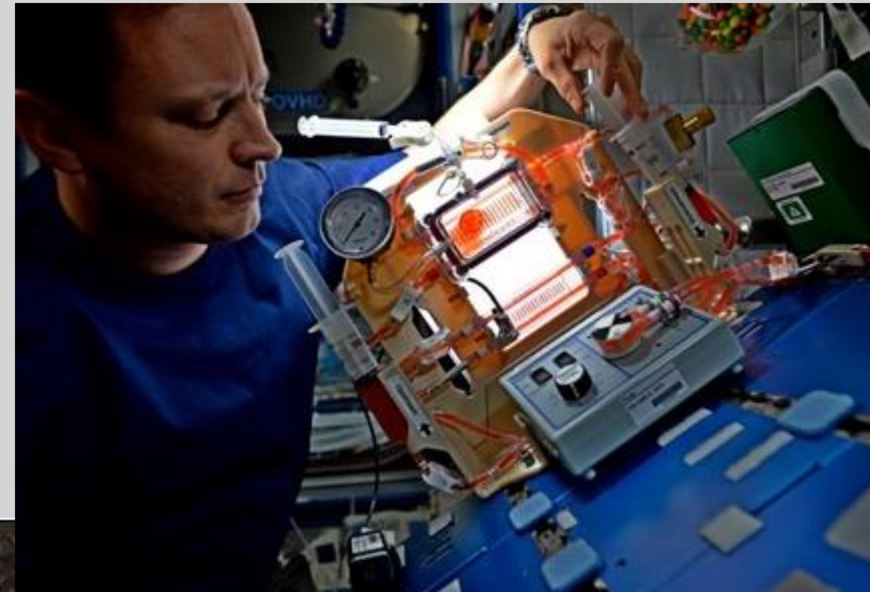
SILICON VALLEY

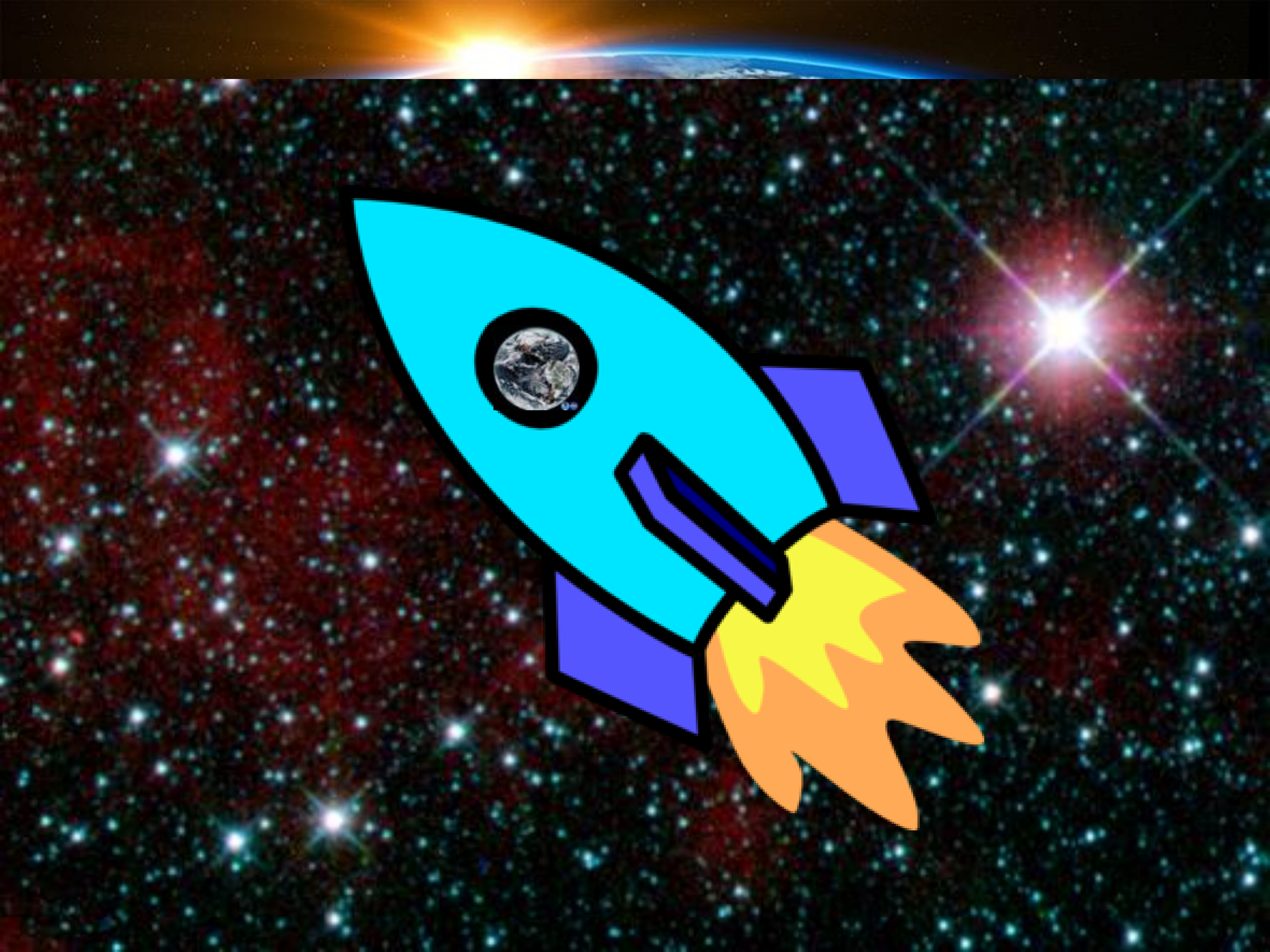
AMES RESEARCH CENTER

NASA CO_2 Removal

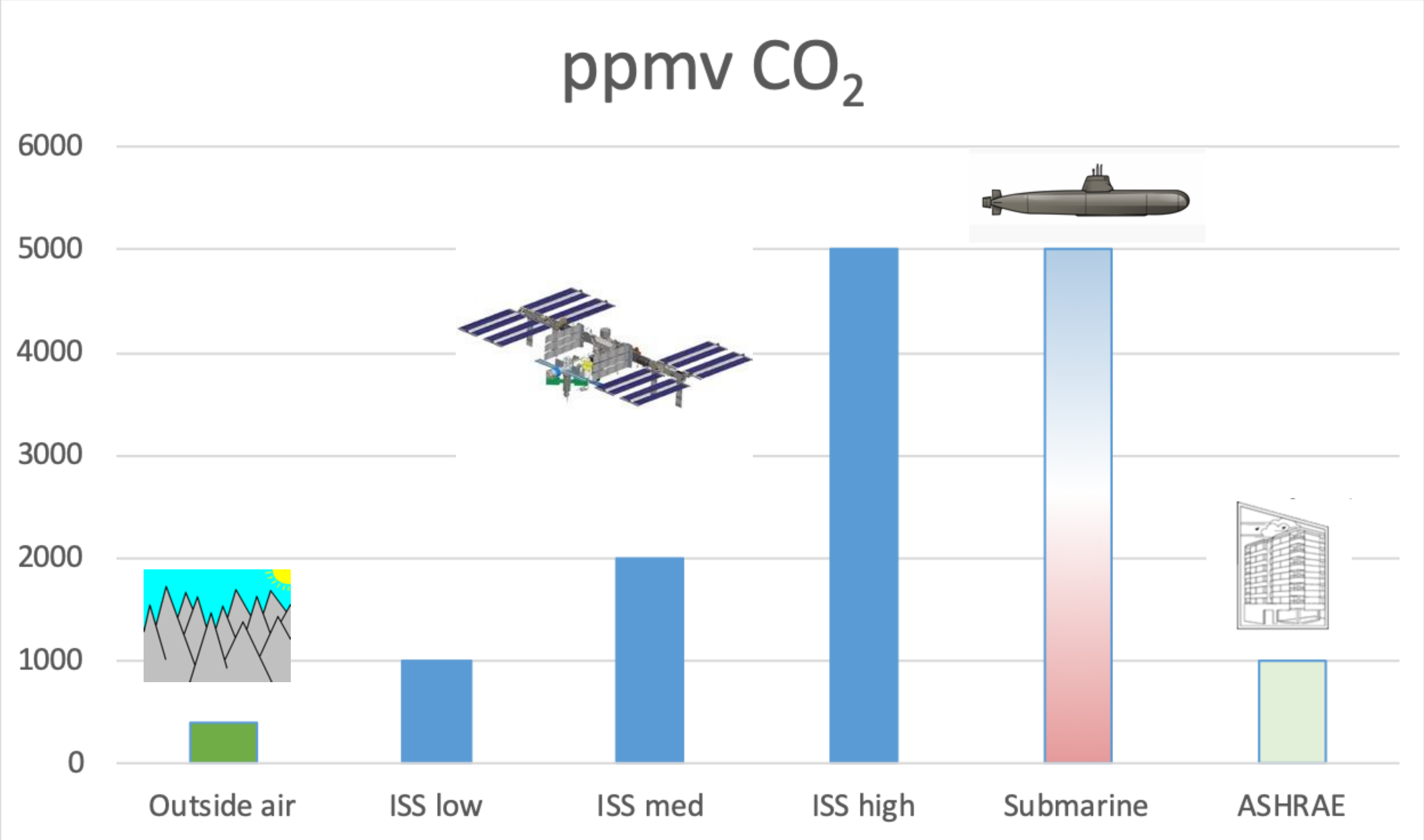
July 24, 2019
Washington, DC

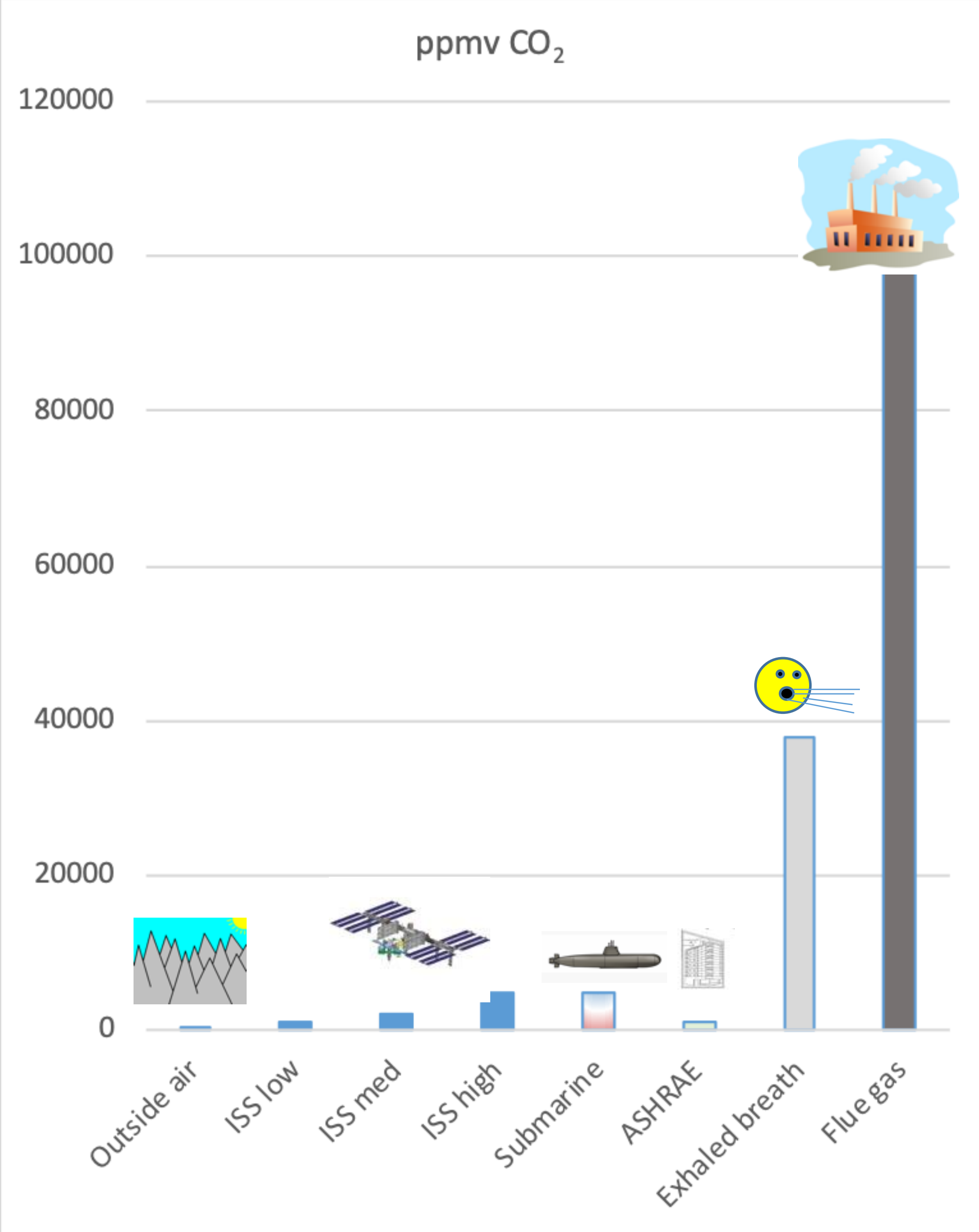
Darrell Jan, PhD
Life Support Systems CO_2 Removal Co-Lead
NASA Ames Research Center





Some comparisons




ppmv CO_2
120000
100000
80000
60000
40000
20000
0
Outside air
ISS low
ISS med
ISS high
Submarine
ASHRAE
Exhaled breath
Flue gas

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Space-specific challenges

- Liquid drops and solid particles don't fall
- Bubbles don't rise

Apollo 11 50th Anniversary

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 (1.84 lb)
- Food Solids = 0.62 kg (1.36 lb)
- Water in Food = 1.15 kg (2.54 lb)
- Food Prep Water = 0.76 kg (1.67 lb)
- Drink = 1.62 kg (3.56 lb)
- Metabolized Water = 0.35 kg (0.76 lb)
- Hand/Face Wash Water = 4.09 kg (9.00 lb)
- Shower Water = 2.73 kg (6.00 lb)
- Urinal Flush = 0.49 kg (1.09 lb)
- Clothes Wash Water = 12.50 kg (27.50 lb)
- Dish Wash Water = 5.45 kg (12.00 lb)
- Total = 30.60 kg (67.32 lb)

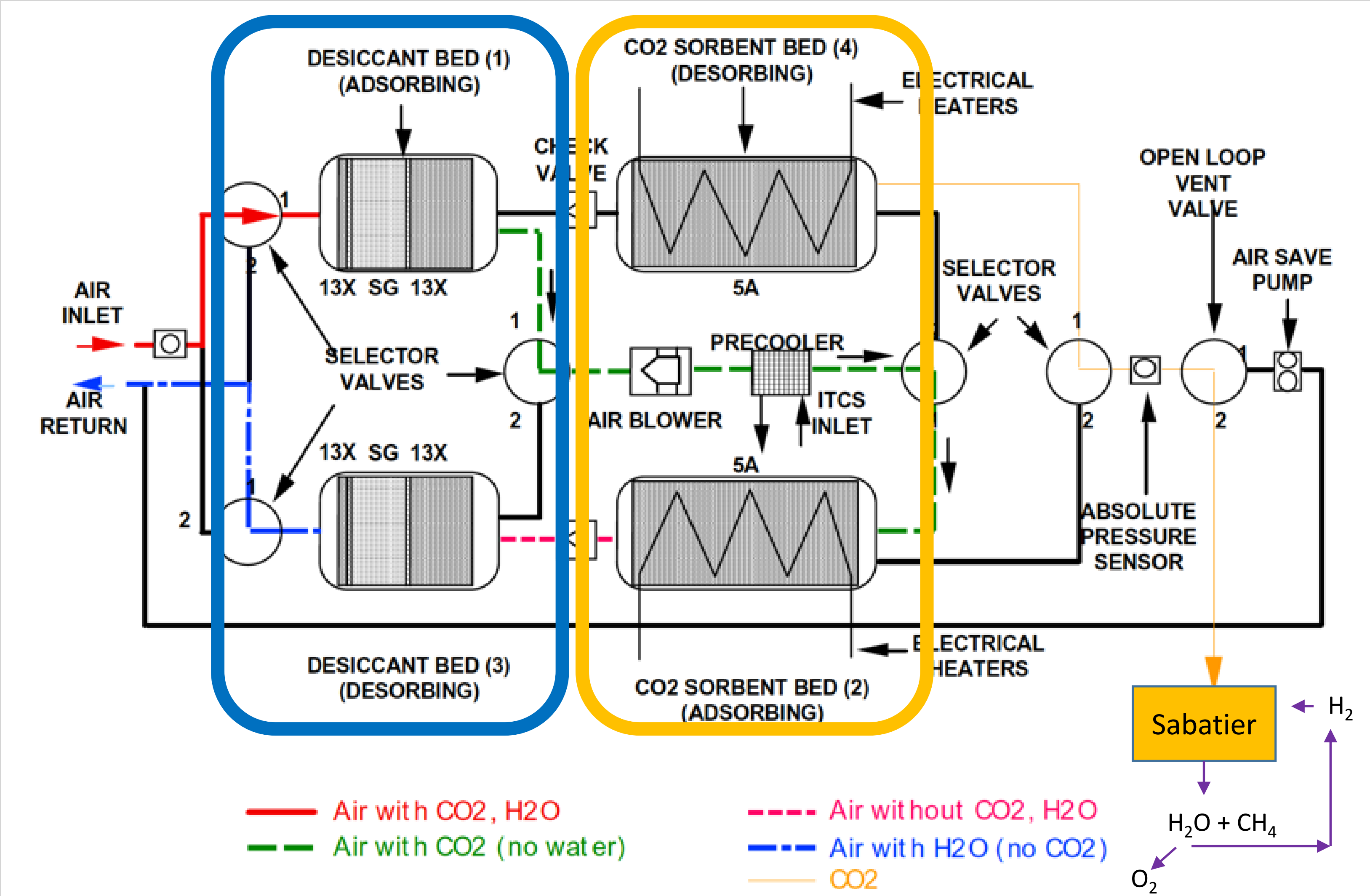
Effluents

- Carbon Dioxide = 1.00 kg (2.20 lb)
- Respiration & Perspiration Water = 2.28 kg (5.02 lb)
- Food Preparation, Latent Water = 0.036 kg (0.08 lb)
- Urine = 1.50 kg (3.31 lb)
- Urine Flush Water = 0.50 kg (1.09 lb)
- Feces Water = 0.091 kg (0.20 lb)
- Sweat Solids = 0.018 kg (0.04 lb)
- Urine Solids = 0.059 kg (0.13 lb)
- Feces Solids = 0.032 kg (0.07 lb)
- Hygiene Water = 12.58 kg (27.68 lb)
- Clothes Wash Water
  - Liquid = 11.90 kg (26.17 lb)
  - Latent = 0.60 kg (1.33 lb)
- Total = 30.60 kg (67.32 lb)

Calculations:

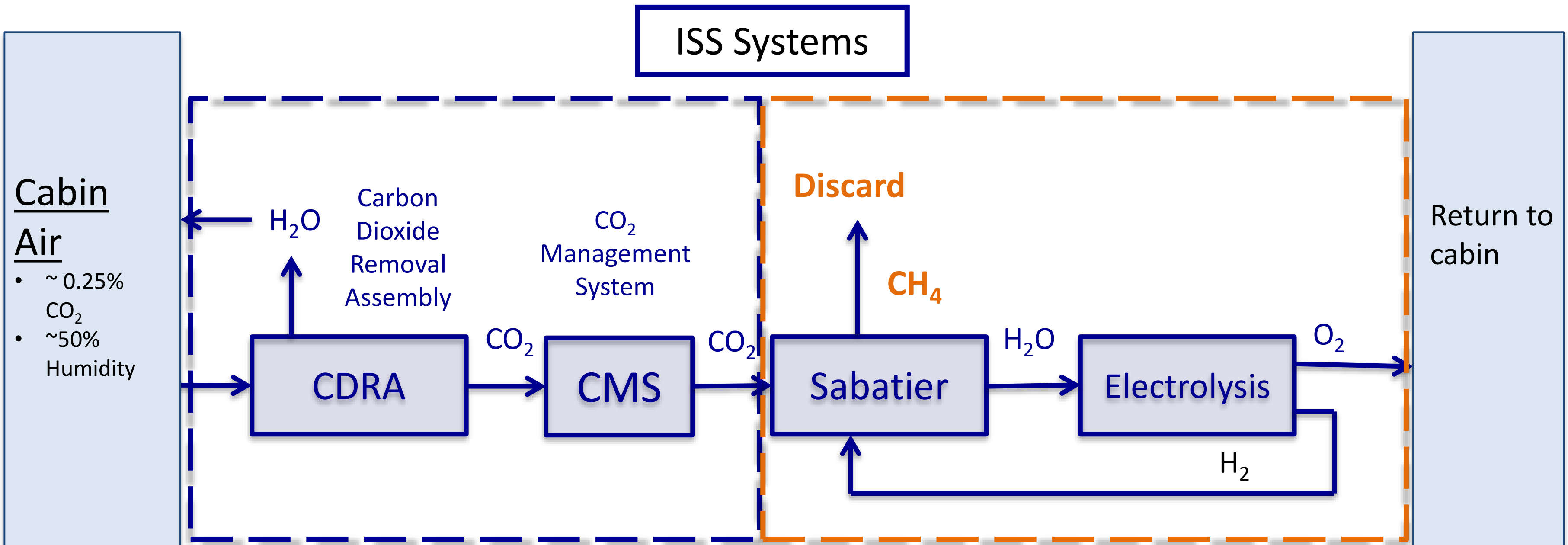
- 4 crew members produce about 4 kg/day CO_2
- To maintain 2500 ppm CO_2, we need to process at least 20 cubic feet per minute, continuously.
- At 1000 ppm, this increases to 50 cfm.

- 5A Molecular Sieve



Knox, J. C.; Campbell, M.; Miller, L. A.; Mulloth, L. M.; Varghese, M.; Luna, B., “Integrated Test and Evaluation of a 4-Bed Molecular Sieve, Temperature Swing Adsorption Compressor, and Sabatier Engineering Development Unit”. In International Conference on Environmental Systems, SAE: Norfolk, 2006, 2006-01-2271.

Carbon Dioxide Utilization



- 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

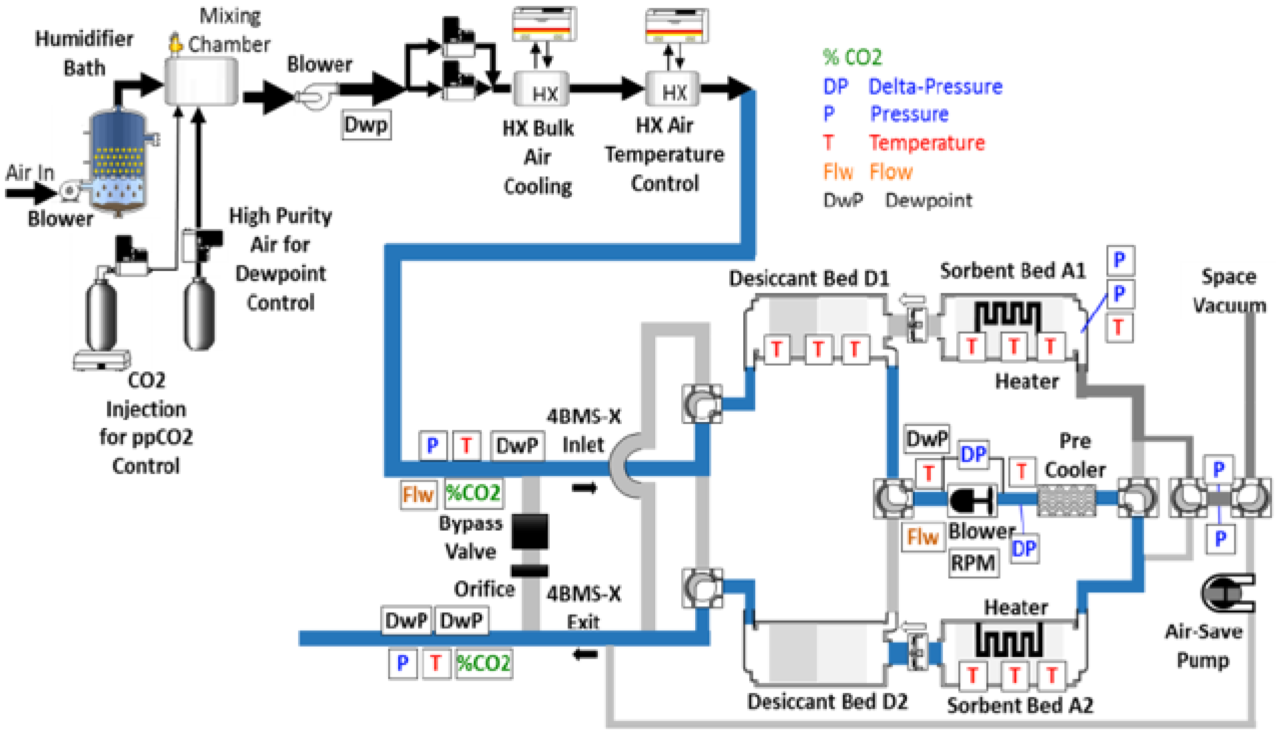
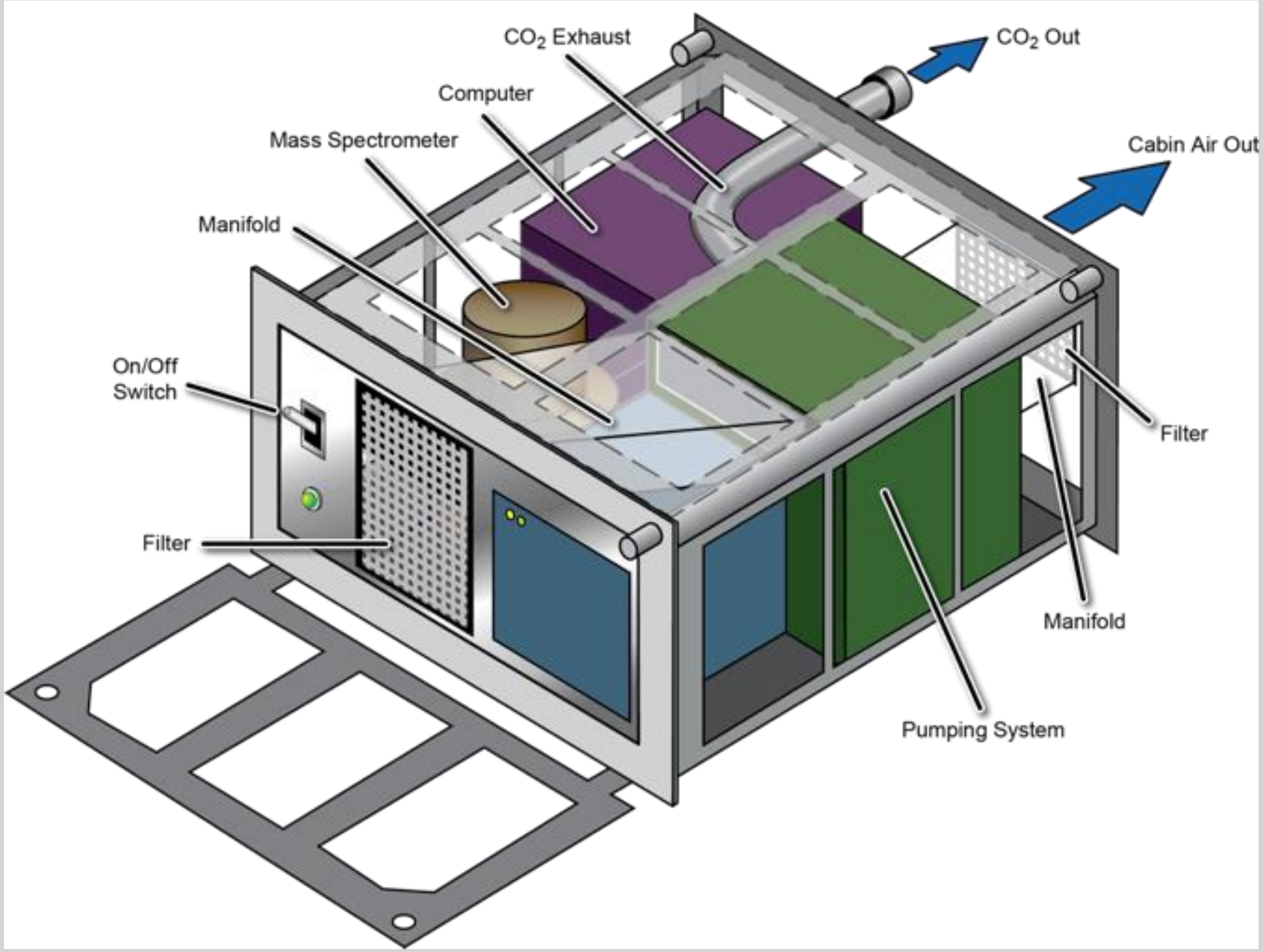


Figure 1. 4BMS-X Integrated with Conditioned Air Facility

- **Updated Sorbent Bed Geometry**
- **Updated Heater Geometry**
- **Change in Sorbent Material**

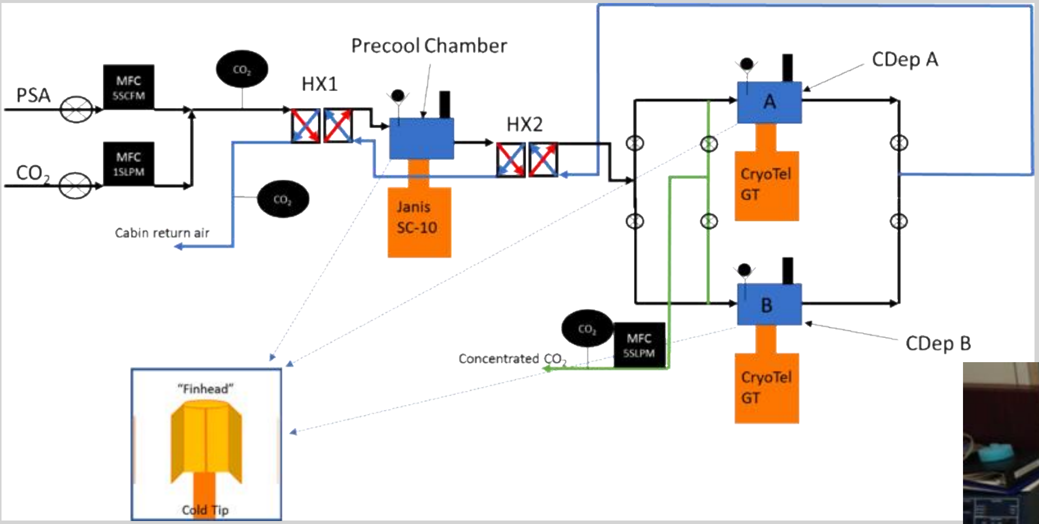
"4BMS-X Design and Test Activation," W. T. Peters and J. D. Knox, 47th International Conference on Environmental Systems, ICES-2017-240.

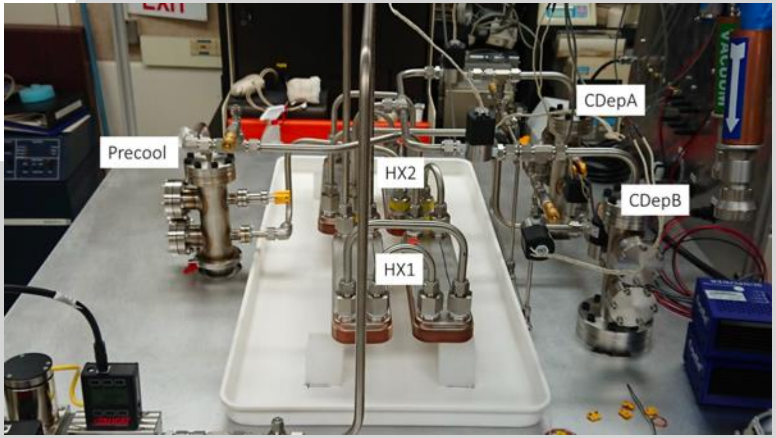
Mini Scrubber



https://www.nasa.gov/sites/default/files/thumbnails/image/dynetics-nextstep.png

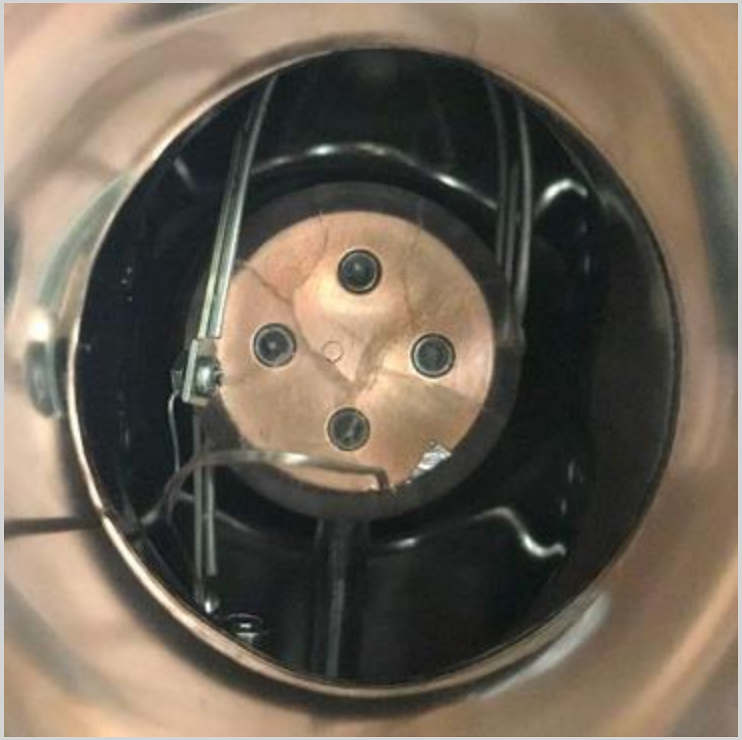
Carbon Dioxide Removal by Freezing





"Spacecraft Carbon Dioxide Deposition Subscale System Design and Test," G. Belancik, D. Jan, R. Huang, 49th International Conference on Environmental Systems, ICES-2019-041.

Carbon Dioxide Deposition by Freezing, cont'd

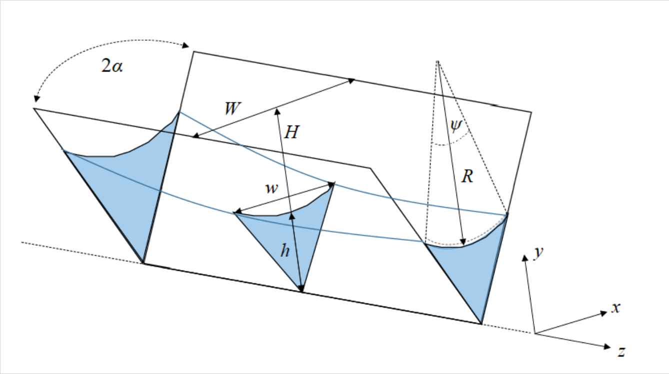


- May be particularly advantageous for deep space missions.
- Can also condense out volatiles from the air.

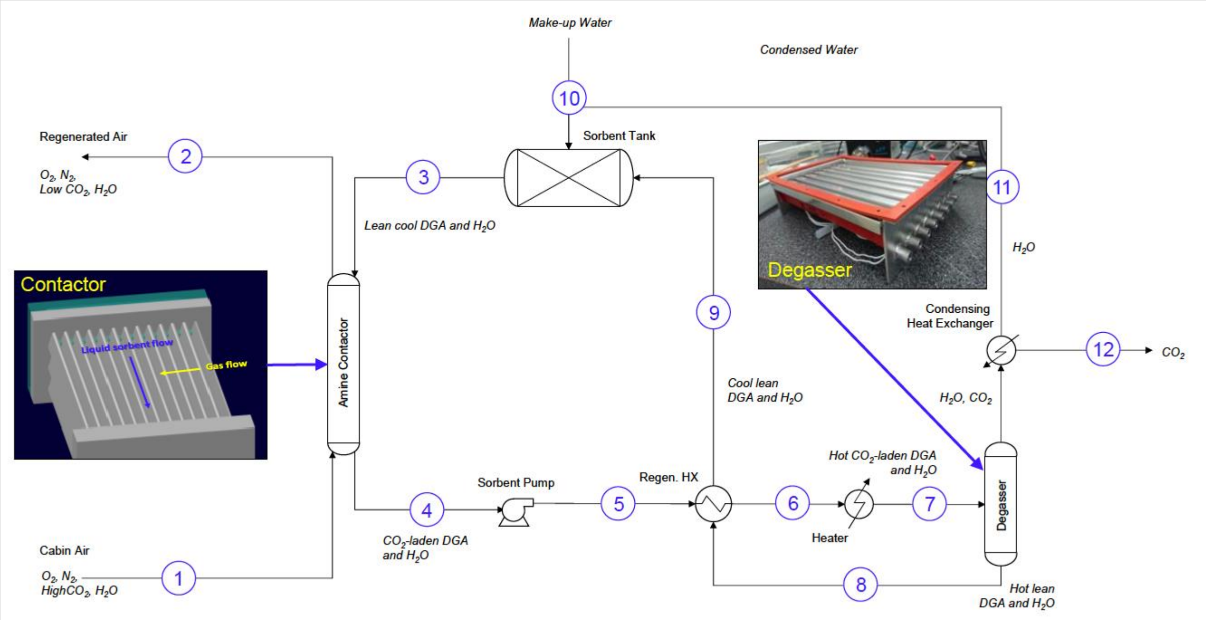
~2mm thick layer of frozen transparent CO_2

"Analysis of Spacecraft Cabin Carbon Dioxide Capture via Deposition," G. Belancik, D. Jan, R. Huang, 48th International Conference on Environmental Systems, ICES-2018-228.

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.

49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-5

CO_2 Removal for the International Space Station – 4-Bed Molecular Sieve Material Selection and System Design

Gregory E. Cmarik[1] and James C. Knox[2]
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Efforts over the past three years have focused on the study of candidate sorbent materials for use in a 4BMS molecular sieve system. The accumulation of knowledge has been invaluable for further decisions and for reflecting on the conclusions of past decisions. The goal of the next generation CO_2 removal system is continuous, failure-free operation for nearly 20,000 hours, but no complex life support system has yet reached this lofty goal. In addition to reliability, CO_2 removal performance improvements have been intensively studied. The achievements toward this end include highly detailed isotherm measurements which drive system simulations as well as testing physical design improvements. Looking back on the successes and failures of past systems, correlating data from long-duration tests, and carefully projecting future results are all needed for the success of the next system. This work intends to reveal the path we have taken and illuminate the steps to come for CO_2 removal life support with the 4BCO2 flight demonstration.

Nomenclature

4BCO2	=	4BMS Carbon Dioxide Scrubber Flight Demonstration
4BMS	=	4BMS Molecular Sieve
ASRT	=	Allied-Signal Research & Technology
CO_2	=	Carbon Dioxide
CDRA	=	Carbon Dioxide Removal Assembly
EXPRESS	=	EXpedite the PRocessing of Experiments to Space Station
NASA	=	National Aeronautics and Space Administration
MSFC	=	Marshall Space Flight Center

- Versions of 13x have exceptional attrition resistance.

49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2018-320

Continued Development of a Liquid Amine Carbon Dioxide Removal System for Microgravity Applications

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Jacobs Technology, Inc., Houston, Texas, 77058

Geoff DeGraff[2]
Barrios Technology, Inc., Houston, Texas, 77058

Michael J. Swickrath[3]
HX5, LLC, Houston, Texas, 77058

Grace Belancik[4]
NASA, Moffett Field, CA, 94035

and

Jeffrey J. Sweterlitsch[5]
NASA Johnson Space Center, Houston, TX, 77058

Carbon dioxide (CO_2) 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 CO_2 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 contactor and degasser system has been developed and tested. Test data and an accompanying mathematical model have been developed for the contactor 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

- Aqueous diglycolamine.

49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-174

A Thermally-Regenerated Solid Amine CO_2 Removal System Incorporating Water Vapor Recovery and Ullage Air Recovery

Holden Ranz[1], Steven Dionne[2]
Collins Aerospace, Windsor Locks, CT, 06096-1010

and

John Garr[3]
National Aeronautics and Space Administration/Johnson Space Center, Houston TX, 77058

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 (CO_2) 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 (H_2O Locker), a CO_2 Removal subsystem (CO_2 Locker), and an ISIS drawer for the system controller. The H_2O 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 CO_2 Locker receives dry air from the H_2O Locker and splits flow between two pairs of CO_2 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 CO_2 at 2 mmHg partial pressure CO_2 in the process air, which corresponds to approximately a 4 crewmember equivalent.

The TAS will provide an additional means of removing CO_2 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 CO_2 reduction system, provided the desorbed gas has acceptable CO_2 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

- Uses solid amine sorbent.

48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico

ICES-2018-17

Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) System Development

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Honeywell Aerospace Advanced Technology, Des Plaines, IL, 60017

Phoebe Henson[3] and Ted Bonk[4]
Honeywell Aerospace Defense and Space, Glendale, AZ, 85308

Using a liquid absorbent like an ionic liquid eliminates many of the disadvantages of solid adsorbent systems for carbon dioxide (CO_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_2 capture and recovery of pure CO_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_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_2.

Nomenclature

BMIM Ac	=	*1-butyl-3-methylimidazolium acetate*
BMIM BF4	=	*1-butyl-3-methylimidazolium tetrafluoroborate*
CDRA	=	*Carbon Dioxide Removal Assembly*
CDRILS	=	*Carbon Dioxide Removal by Ionic Liquid Sorbent*
CMS	=	*Carbon Dioxide Management System*

- Uses countercurrent membrane contactor
- Humidity control approach TBD

49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-41

Spacecraft Carbon Dioxide Deposition Subscale System Design and Test

Grace Belancik[1] and Darrell Jan[2]
NASA Ames Research Center, Moffett Field, CA 94035-1000

and

Roger Huang[3]
Independent, Mountain View, CA 94040

To further expand the human presence in space on missions to the moon and beyond, new cabin atmosphere CO_2 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 CO_2. Generating a cold surface on which to deposit and store CO_2 for downstream processing is a highly reliable process, achievable via cryogenic coolers or thermal radiators. This method of CO_2 capture may support humidity and/or trace contaminant capture as well. The goal of the CO_2 Deposition system development unit is to demonstrate continuous CO_2 removal from an airstream scaled at approximately 1 crew member without humidity control (1 kg CO_2/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 CO_2 removal. Dry air flows through the system at varied flow rates and CO_2 concentrations, and the amount of CO_2 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

- Uses cold surfaces to condense CO_2 out of the air

49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-153

Electrochemical Solutions for Advanced Life Support

Robert J. Roy[1], Christopher Ellithorpe[2], Karen E. Murdoch[3], Timothy D. Myles[4], Ashley Wilson[5]
Skyre, Inc., East Hartford, CT, 06108

and

John C. Graf[6]
NASA Johnson Space Center, Houston, TX, 77058

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. Skyre 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

49th International Conference on Environmental Systems
7-11 July 2019, Boston, Massachusetts

ICES-2019-250

Highly Efficient Closed-Loop CO_2 Removal System for Deep-Space ECLSS

Ambal Jayaraman[1], Margarita Dubovik[2], and Sarah Devoss[3]
TDA Research, Inc., Wheat Ridge, CO 80033, USA

Arturo J. Hernandez-Maldonado[4], Bethzaely Fernandez-Reyes[5], Silvana Urcia-Romero[6], Paola A. Baldaguez-Medina[7], and Carlos E. Galiano-Haddock[8]
University of Puerto Rico – Mayaguez, Mayaguez, PR 00681-9000, USA

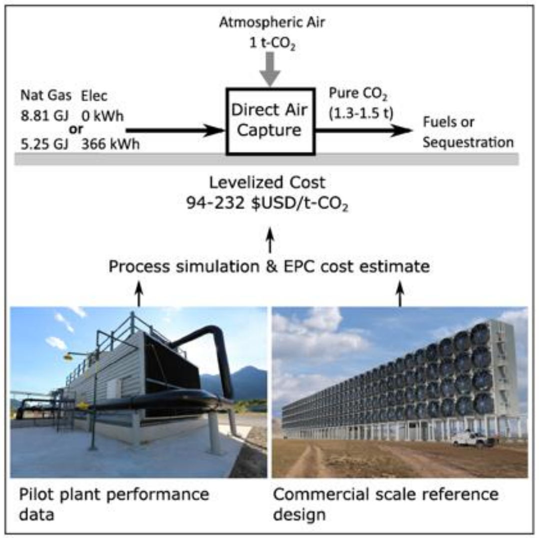
In current International Space Station (ISS) and other low orbit missions, the metabolically generated CO_2 is removed from the cabin air via adsorption and vented into space, resulting in a net loss of O_2. However, a closed-loop cabin Atmosphere Revitalization System (ARS) is crucial to NASA's mission 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.

Joule
CellPress

Article

A Process for Capturing CO_2 from the Atmosphere



First direct air capture paper for which all major components are either drawn from well-established commercial heritage or described in sufficient detail to allow assessment by third parties. Includes energy and materials balances, commercial engineering cost breakdown, and pilot plant data. When CO_2 is delivered at 15 MPa, the design requires either 8.81 GJ of natural gas, or 5.25 GJ of gas and 366 kWhr of electricity, per ton of CO_2 captured. Levelized cost per t-CO_2 from atmosphere ranges from 94 to 232 $/t-$CO_2$.

David W. Keith, Geoffrey Holmes, David St. Angelo, Kenton Heidel

keith@carbonengineering.com

HIGHLIGHTS

Detailed engineering and cost analysis for a 1 Mt-CO_2/year direct air capture plant

Levelized costs of $94 to $232 per ton CO_2 from the atmosphere

First DAC paper with commercial engineering cost breakdown

Full mass and energy balance with pilot plant data for each unit operation

Keith et al., Joule 2, 1–22
August 15, 2018
Published by Elsevier Inc.
https://doi.org/10.1016/j.joule.2018.05.006

- 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

CrossMark
click for updates

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

Oscar Alvizo[a,1], Luan J. Nguyen[b], Christopher K. Savile[a], Jamie A. Bresson[a], Satish L. Lakhapatri[c], Earl O. P. Solis[b], Richard J. Fox[d], James M. Broering[e], Michael R. Benoit[a], Sabrina A. Zimmerman[f], Scott J. Novick[a], Jack Liang[a], and James J. Lalonde[a]

[a]Codexis, Inc., Redwood City, CA 94063; [b]Calysta Energy, Inc., Menlo Park, CA 94025; [c]Siluria Technologies Inc., San Francisco, CA 94158; [d]Pioneer Hi-Bred International, Inc., Johnston, IA 50131; [e]Novozymes Inc., Franklinton, NC 27525; and [f]BP Biofuels, San Diego, CA 92121

Edited* by Chi-Huey Wong, Academia Sinica, Taipei, Taiwan, and approved October 7, 2014 (received for review June 23, 2014)

PNAS

16436–16441 | PNAS | November 18, 2014 | vol. 111 | no. 46 www.pnas.org/cgi/doi/10.1073/pnas.1411461111

"…Increase in thermostability and alkali tolerance translates to a 4,000,000-fold improvement over the natural enzyme."

Directed Evolution task underway at NASA Ames.

NASA Early Career Faculty (ECF) awards

Metal Organic Frameworks (MOF) and Ionic Liquids/Membrane Technologies for Advanced CO_2 Removal Applications

Jeffrey Alston
North Carolina Agricultural & Technical State University, Greensboro
"Novel CO_2 Removal with Magnetocaloric Pumping Augmentation of Hybrid Paramagnetic Ionic Liquid - SLMs"

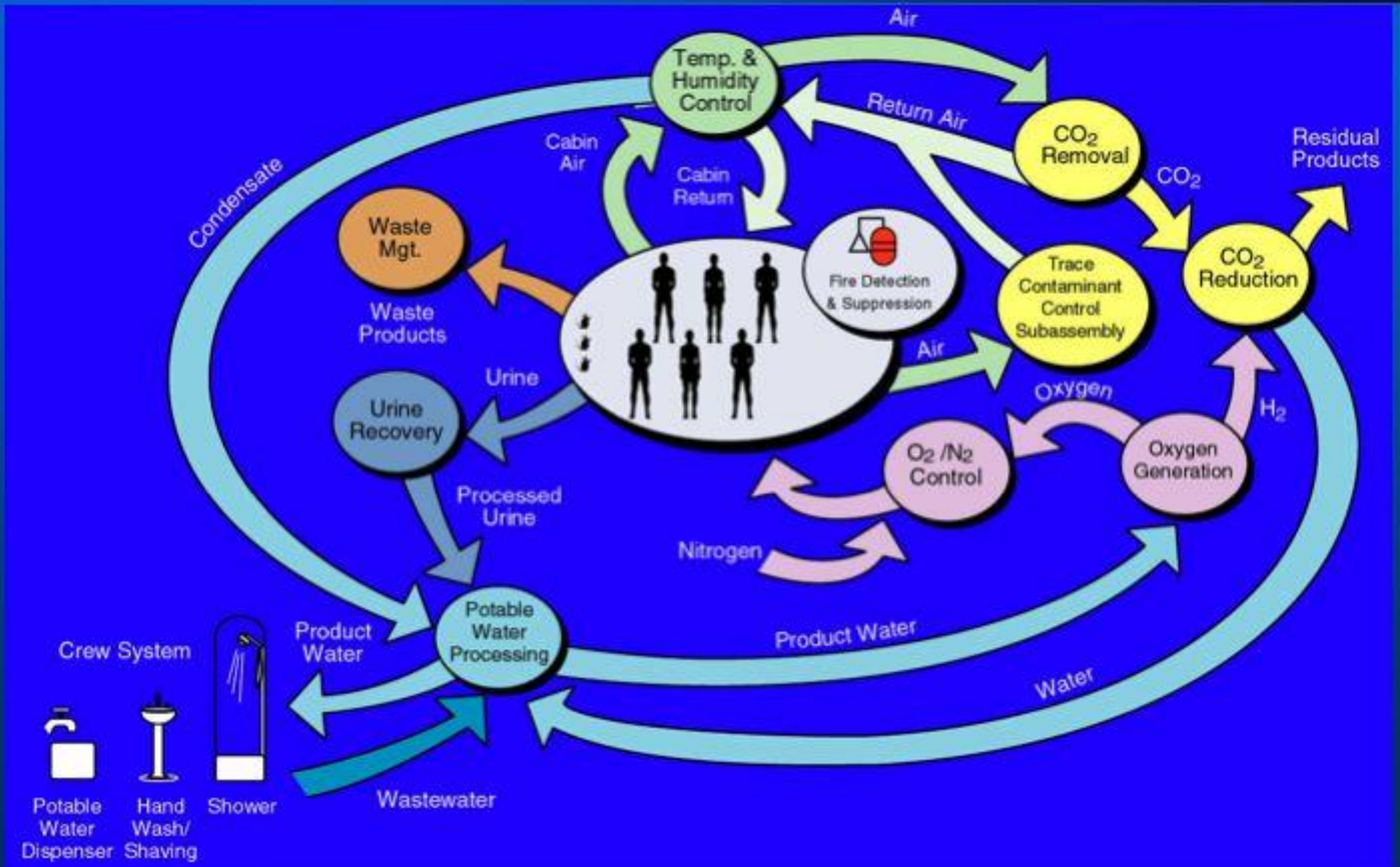
Matthew Green
Arizona State University, Tempe
"Scalable Membrane-supported IL CO_2 capture and removal systems"

Burcu Gurkan
Case Western Reserve University, Cleveland
"Poly(ionic liquid)-ionic liquid membranes reinforced by graphene sheets for CO_2 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



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

CO_2 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.

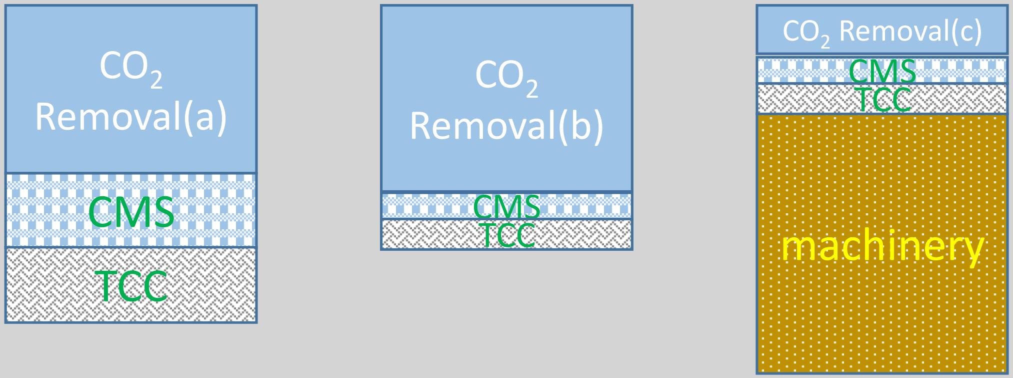
"Evaluation Criteria for CO2 Removal System Technological Assessment (FY17)," NASA. https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=565739/solicitationId=%7B21E0270C-BC1F-EFC4-3D87-30713B5FF373%7D/viewSolicitationDocument=1/CO2%20Removal%20System%20Technological%20Assessment%20Requirements.pdf [cited 25 April 2017].

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

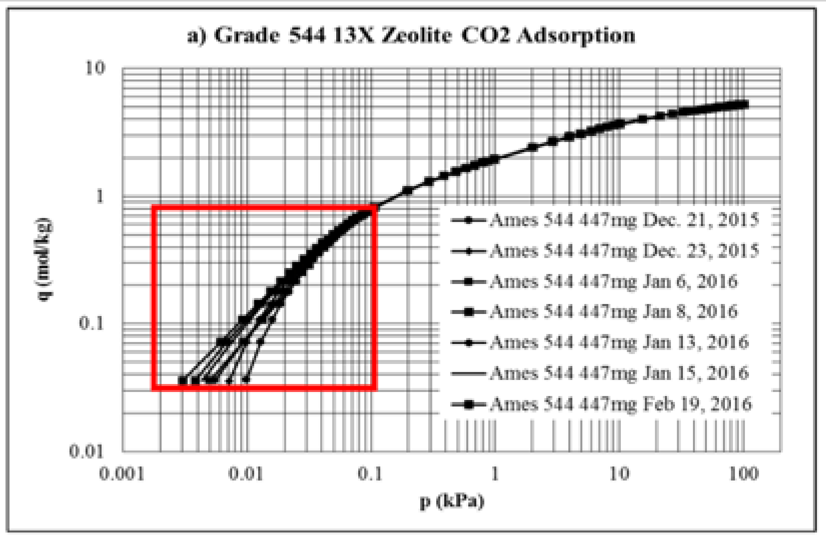
Improvements must be manifested over the complete system

Hypothetical Comparison:



Related topics

Sorbent characterization



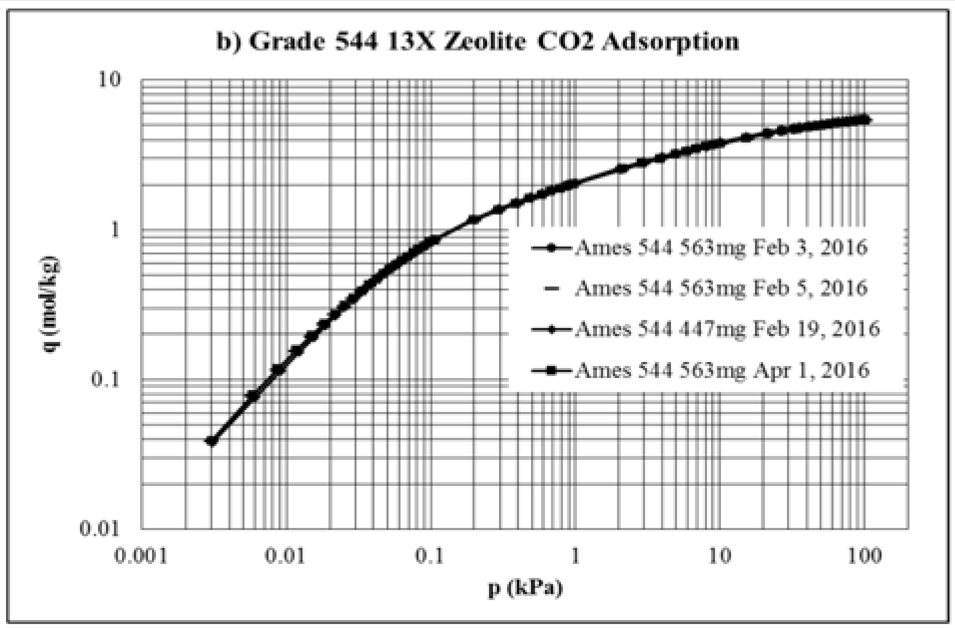


Figure 2. Plot a) shows a single sample through multiple CO_2 analysis runs. In the low pressure region < 0.1 kPa, the data deviates and is inconsistent. Plot b) shows that this issue was resolved by performing the activation procedure directly on the analysis port, removing the need to transfer the sample from degas to analysis port. The analysis temperature for both plots was 25°C

Huang, R., Belancik, G., Jan, D., Cmarik, G., Ebner, A. D., Ritter, J., and Knox, J. C. "CO2 Capacity Sorbent Analysis using Volumetric Measurement Approach," 47th International Conference on Environmental Systems. Charleston, 2017, ICES-2017-116.

ISS Carbon Dioxide Management System (CMS)

The SAC ORU

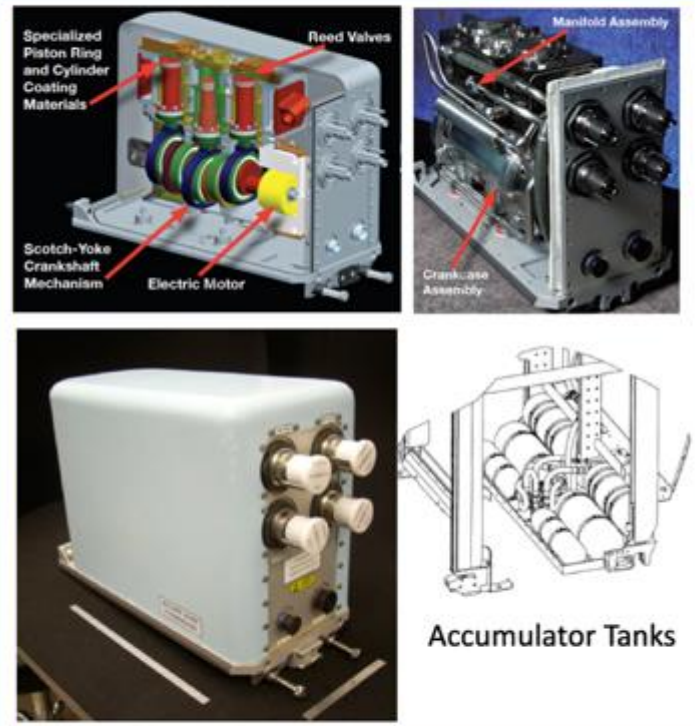
- an oil-free reciprocal piston compressor with vibration isolators, mounting plate, an acoustic enclosure.
- Cooled with Moderate Temperature Loop (MTL) coolant water.
- Tested for 7000hrs for 2 years maintenance free
- Mass: 125lbs (57kg)
- Volume: 17.8in x 12.6in x 7.8in, $1 ft^3$
- Power(average): 288Watts

Reference: UTC Aerospace Systems, *Sabatier Compressor Performance Summary.* 10/2/2017.

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. (18.2kg)
- Total volume $0.7 ft^3$

Reference: MSFC mass properties report (SLS-JA21-012D (2005)

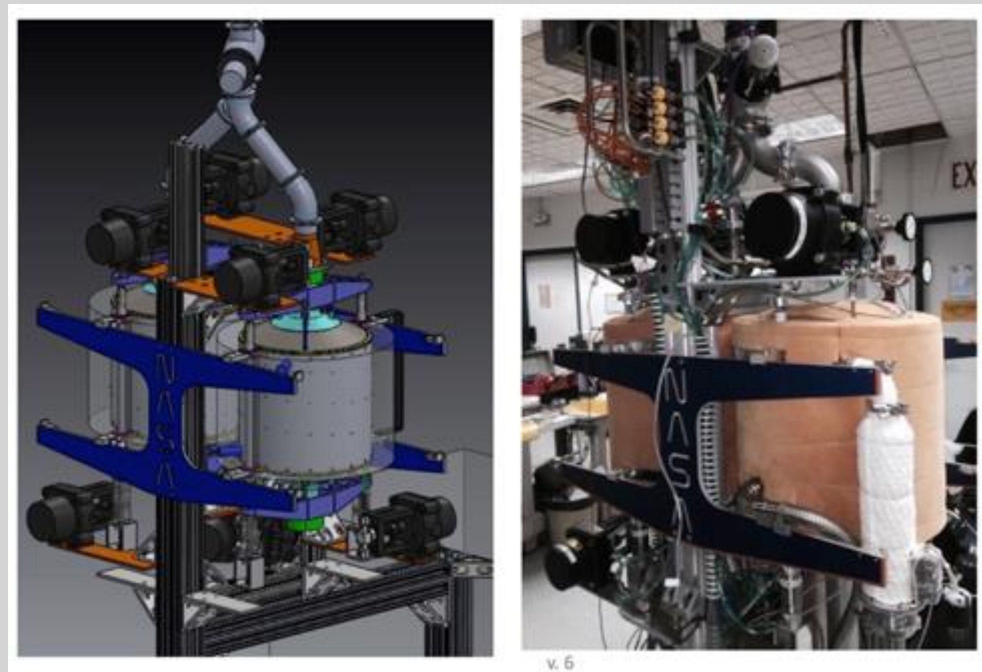


Accumulator Tanks

Reference: UTC Aerospace Systems, *Sabatier Compressor Performance Summary.* 10/2/2017.

"A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process," T.J. Richardson and D.L. Jan, 48th International Conference on Environmental Systems, ICES -2018-332.

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.

“A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process,” T.J. Richardson and D.L. Jan, 48th International Conference on Environmental Systems, ICES -2018-332.