Executive Summary

On Earth, our Carbon Dioxide (CO_2) levels are managed by our lungs and environment. Our lungs collect vital oxygen (O_2) through inhalation, circulate O_2 throughout our body and to vital organs via bloodstream, and then upon exhale, release CO_2 into the environment. When our respiratory system does not function nominally, either from physical or environmental limits, CO_2 can build up in our bodies (hypercapnia) and cause symptoms such as headache, dyspnea, fatigue, and in extreme cases, death. Our environment naturally eliminates CO_2 through photosynthesis of plants and trees, weathering, and other experimental CO_2 removal processes. Humans in space face hostile, enclosed environments (including vehicles and suits) that do not have the benefit of natural CO_2 removal, relying on CO_2 removal equipment (e.g., the Carbon Dioxide Removal Assembly (CDRA), lithium hydroxide, and amine systems) to help regulate CO_2 levels in the environment and help decrease risk of negative consequences of elevated CO_2 exposure.

Relevant Standards

NASA-STD-3001 Volume 1, Rev B

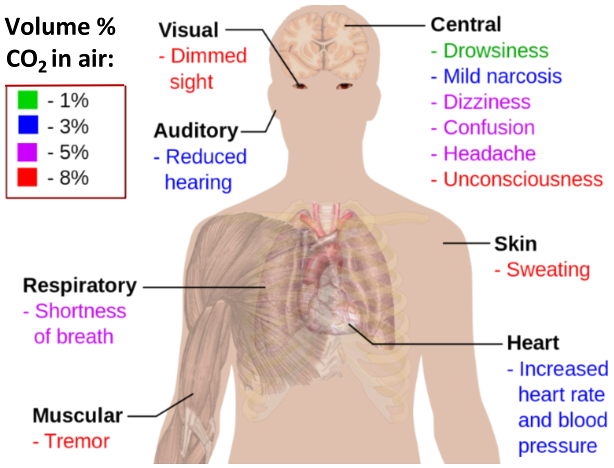
[V1 3003] In-Mission Preventive Health Care
[V1 3004] In-Mission Medical Care
[V1 5002] Astronaut Training
[V1 5009] Physiological Exposure Mission Training

NASA-STD-3001 Volume 2, Rev C

[V2 4015] Aerobic Capacity
[V2 6001] Trend Analysis of Environmental Data
[V2 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels
[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure
[V2 7041] Environmental Control
[V2 6020] Atmospheric Data Recording
[V2 6021] Atmospheric Data Displaying
[V2 6022] Atmospheric Monitoring and Alerting Parameters
[V2 6107] Nominal Vehicle/Habitat Atmospheric Ventilation
[V2 6108] Off-Nominal Vehicle/Habitat Atmospheric Ventilation
[V2 11034] Suited Atmospheric Data Recording
[V2 11035] Suited Atmospheric Data Displaying
[V2 11036] Suited Atmospheric Monitoring and Alerting
[V2 11037] EVA Suited Metabolic Rate Measurement
[V2 11038] EVA Suited Metabolic Rate Display
[V2 11039] Nominal Spacesuit Carbon Dioxide Levels

Background

Main Symptoms of CO_2 Toxicity (Hypercapnia)

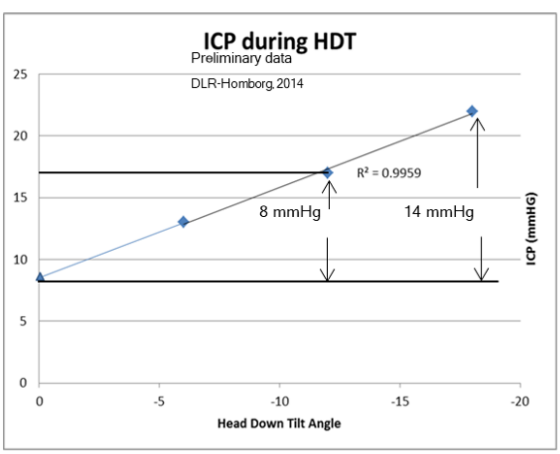


These symptoms represent potential side-effects of hypercapnia, however it is important to note that most of these symptoms have never been observed during spaceflight.

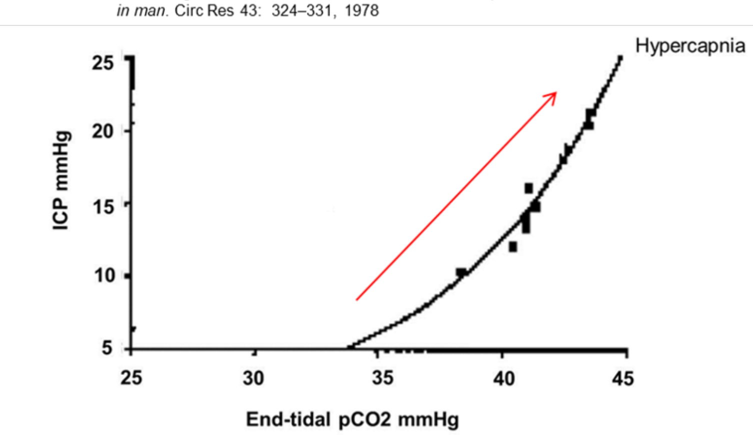
- The most common symptoms experienced during spaceflight are headaches and vision changes (Spaceflight Associated Neuro-ocular Syndrome [SANS]).
- These two symptoms are commonly linked to fluid shifts and potential increase in intra-cranial pressure (ICP) due to the microgravity environment in spaceflight.

Fluid shift		CO_2
Microgravity Induced Fluid Shift – Due to Decreased Venous & Lymphatic Drainage	+	Exposure to Elevated CO_2 Levels
Microgravity → ICP >6 mmHg	+	CO_2 ↑ by 1 mmHg → ICP ↑ 1-3 mmHg

Greenberg JH et al: *Local cerebral blood volume response to carbon dioxide in man.* Circ Res 43: 324–331, 1978



HDT = Head-down tilt



*Paul RL, et al: Intracranial pressure responses to alterations in arterial carbon dioxide pressure in patients with head injuries. J Neurosurg 36:714-720, 1972

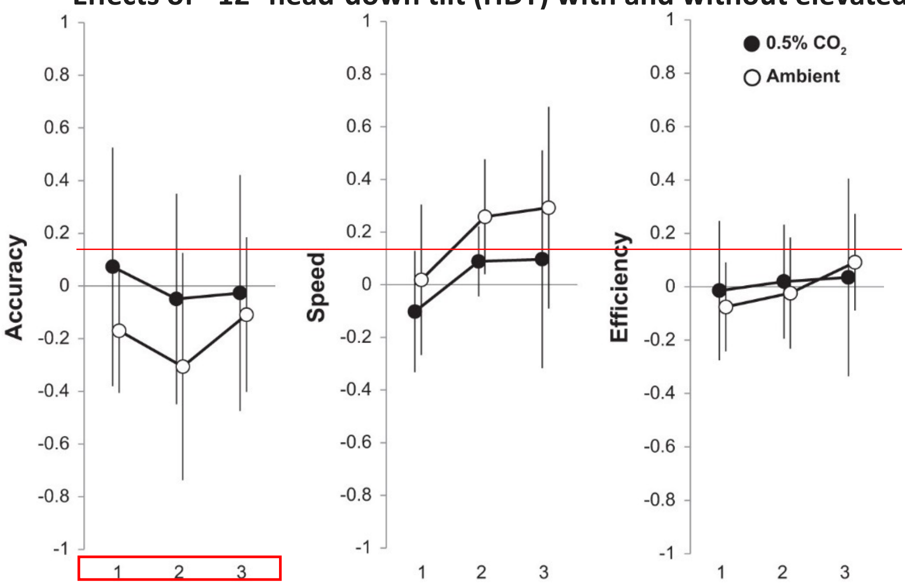
Background

Effects of CO_2 on Cognitive Functioning

Prior research offers conflicting data on CO_2 exposure and the effects on cognitive functioning, including memory, concentration, decision-making, and task performance. However, several recent terrestrial studies have shown the CO_2 exposure at levels currently maintained onboard spacecraft and submarines does not reduce cognition and performance in astronaut-like subjects or submarine officers.

- *Effects of acute exposures to carbon dioxide on decision-making and cognition in astronaut-like subjects* (Scully et al., 2019). Findings state “There were no clear dose-response patterns for performance on either Strategic Management Simulation or Cognition”.
- *Acute Exposure to Low-to-Moderate Carbon Dioxide Levels and Submariner Decision Making* (Rodehe et al., 2018). Findings state “There were no significant differences for any of the nine Strategic Management Simulation measures of decision making between CO_2 exposure conditions”.
- *Effects of -12° head-down tilt with and without elevated levels of CO_2 on cognitive performance: the SPACECOT study* (Basner et al., 2017). Findings state “There were no statistically significant time-in-CO_2 effects for any cognitive outcome”.

Effects of −12° head-down tilt (HDT) with and without elevated CO_2 on cognitive performance



The chart represents a summary of results from a subset of tests from a widely used and validated neurocognitive battery, the Penn Computerized Neurocognitive Battery, as well as a number of additional tests that have either been used extensively in spaceflight or that assess cognitive domains of particular interest in spaceflight (including spatial orientation, emotion recognition, and risk decision making).

1=0.1 hours
2= 5.2 hours
3= 21 hours
into HDT

Displayed data reflect Standard Deviation (SD) units. Error bars reflect 95% confidence intervals. A confidence interval that does not include 0 indicates a statistically significant difference relative to baseline data collection (BDC) at $P < 0.05$. The only outcomes with a significant time-in-HDT main effect in both the discrete and the continuous exposure duration models were physical exhaustion ($P = 0.0012$ and $P = 0.0043$, respectively) and mental fatigue ($P = 0.0328$ and $P = 0.0205$, respectively). The severity of these symptoms increased with increasing exposure duration. 0.5% CO_2 = 3.8 mmHg CO_2.

Source: Basner et al., 2017.

Background

Key Historical CO_2 Concentrations

% CO_2	$PPCO_2$ (mm Hg)	Note [Reference]
0.03%	0.23	Ambient outdoor CO_2 level on Earth
	2	Relief of symptoms on Expedition 6 [1]
0.3-0.7%	2.3-5.3	Typical spacecraft CO_2 concentrations [2]
0.5%	3.4	**New NIOSH Recommended Exposure Limit** [3] *
	>4	Lethargy, malaise, listlessness, and fatigue on Expedition 6 [1]
	4.9	Derived threshold corresponding to 90% negative predictive value for CO_2-related symptoms [4]
	5	Safe chronic CO_2 level in terms of performance [5] **Empiric threshold established by flight surgeons**
	2.7 to <6	Headaches on STS-112/ISS-9A [1]
	Up to 7.5	Headache on STS-113/ISS-11A [1]
1%	7.5	**NIOSH Permissible Exposure Limit** [6]
	8	**EMU EVA termination limit** with baseline Caution and Warning System [7]
1.2%	9	Slight performance decrement after chronic exposure [5]
	10	**Orlan EVA termination limit** with crew at rest [8]
	12.4	**EMU EVA termination limit** with enhanced Caution and Warning System [7]
1.99%	14.9	Maximum CO_2 concentration on Apollo 13 [9]
2%	15	Headache, exertional dyspnea start [10] **ISS Off-Nominal $ppCO_2$ Level** [11]
	20	**ISS Emergency $ppCO_2$ Level** [11] **Orlan EVA termination limit** [8]
3%	23	Sweating, resting dyspnea start [10] **NIOSH Short-Term Exposure Limit** [3]
4%	30	**NIOSH Immediately Dangerous to Life or Health limit** [3]
4-5%	30-38	Dizziness, lethargy, uncomfortable dyspnea start [10]

Current NASA-STD-3001 Volume 2 Rev C [V2 6004] limits the average 1-hour CO_2 partial pressure ($ppCO_2$) in the habitable volume to no more than 3 mmHg. Previous requirements accepted a larger range (3.8 to 7.5 mmHg) that has been lowered to 3 mmHg due to evidence from observed operational and research data.

*Referenced New NIOSH Recommended Exposure Limit dated 2005.

See source (NASA/TP–2010– 216126) for listed references

Anecdotal evidence from previous spaceflight missions have found the following associations between CO_2 levels and symptomology:

- Headaches at levels between 2.8-4.5 mmHg; worsening with increasing levels of CO_2 accompanied by fatigue and malaise flushing.
- Fatigue malaise, decreased sleep, and nausea reported at levels above 4.5 mmHg.
- 5th cranial nerve dysesthesia at 4.5-5.0 mmHg.
- Chronic cough, poor sleep, blurred vision, and frontal headaches reported at 3.5 mmHg.

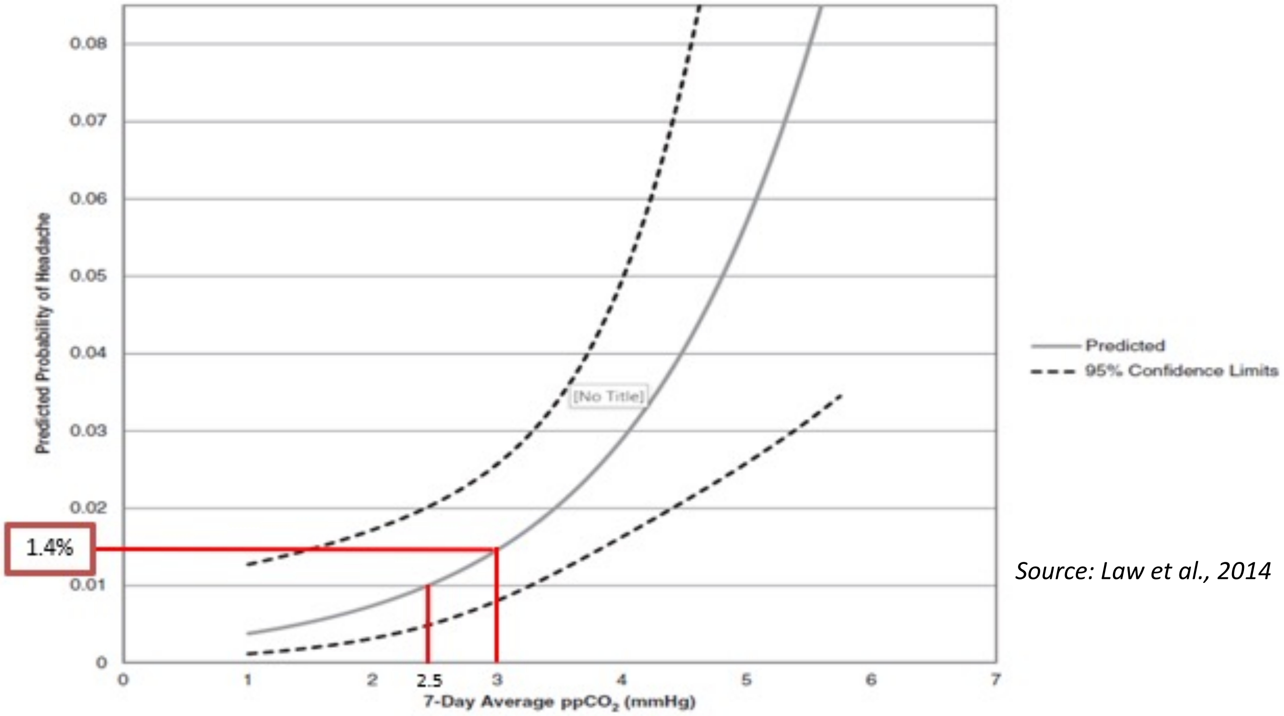
Background

CO_2-Induced Headaches

Research and past historical data has revealed an association between reported headaches and CO_2 levels among crewmembers.

- A study of data collected from Expeditions 2 to 31 (N=49) found that CO_2 level, age at launch, time in-flight, and data source were significantly associated with reported headaches on the ISS.
- 19 of the 49 astronauts reported experiencing headaches (~38.7%).
- To keep the risk of headache below 1%, average 7-day CO_2 needs to be maintained below 2.5 mmHg (current ISS range: 1 to 9 mmHg; 3001 standard requires $\leq$3 mmHg).
- Most experienced headaches were moderate intensity, requiring the use of analgesics in many cases.
- A retrospective analysis of the case reports found a total of 46 days with reported headaches and 1,670 days of non-reports (no headaches observed).
- Based on this data, the current NASA-STD-3001 Volume 2 Rev C [V2 6004] limits the average 1-hour CO_2 partial pressure ($ppCO_2$) in the habitat volume to no more than 3 mmHg to keep incidence of headaches below 1.4%.

Figure: Predicted probability of headache on the basis of average 7-day CO_2 levels



Source: Law et al., 2014

Some observations suggest that what appears to be increased CO_2 sensitivity during spaceflight may actually be attributed to individual predisposition to CO_2 retention, adaption to microgravity, and local fluctuations of CO_2 that are not measured by fixed sensors (Law, Watkins, & Alexander, 2010). Fluid shift due to decreased venous and lymphatic drainage in microgravity largely contributes to symptoms similar to CO_2 over-exposure, including headaches.

Reference Information

Contributors to CO_2 Levels During Spaceflight

- On earth, average indoor air contains CO_2 concentrations between 0.08% to 0.1% (0.608 to 0.76 mmHg).
- NASA-STD-3001 Volume 2 Rev C [V2 6004]: The system shall limit the average one-hour CO_2 partial pressure (P_ICO_2) in the habitable volume to no more than 3 mmHg. *Note: P_ICO_2 is a calculation for 14.7 psi.*

Crew-Induced Metabolic Loads for a Standard Mission Day with Exercise

crewmember Activity Description	Duration of Activity (hr)	O_2 Consumption kg/min 10-4 (lbm/min 10-4)	CO_2 Output kg/min 10-4 (lbm/min 10-4)
Sleep	8	3.60 (7.94)	4.55 (10.03)
Nominal	0.25	5.68 (12.55)	7.2 (15.87)
Exercise 0-15 min at 75% VO_2max	0.25	39.40 (86.86)	49.85 (109.90)
Exercise 15-30 min at 75% VO_2max	0.25	39.40 (86.86)	49.85 (109.90)
Recovery 0-15 min post 75% VO_2max	0.25	5.68 (12.55)	7.2 (15.86)
Recovery 15-30 min post 75% VO_2max	0.25	5.68 (12.55)	7.2 (15.86)
Recovery 30-45 min post 75% VO_2max	0.25	5.68 (12.55)	7.2 (15.86)
Recovery 45-60 min post 75% VO_2max	0.25	5.68 (12.55)	7.2 (15.86)
Total Per Day	24	0.82 (1.80)	1.04 (2.29)
Total Per Day (no exercise)	24	0.72 (1.59)	0.91 (2.00)

Source: Human Integration Design Handbook (HIDH) NASA (2014)

- Respiratory quotient (RQ) is used in calculations of basal metabolic rate when estimated from CO_2 production. It is calculated from the ratio of CO_2 produced to O_2 consumed by the body (**RQ** = $CO_{2\ eliminated}$ / $O_{2\ consumed}$). The RQ value is linked to intake of macronutrients (carbohydrates, fats, and proteins). An RQ of 0.92 is assumed for the O_2 consumption and CO_2 output determinations in the table above. Modifying crew diet can help lower the environmental CO_2 output levels (example: consuming more protein and less carbohydrates).

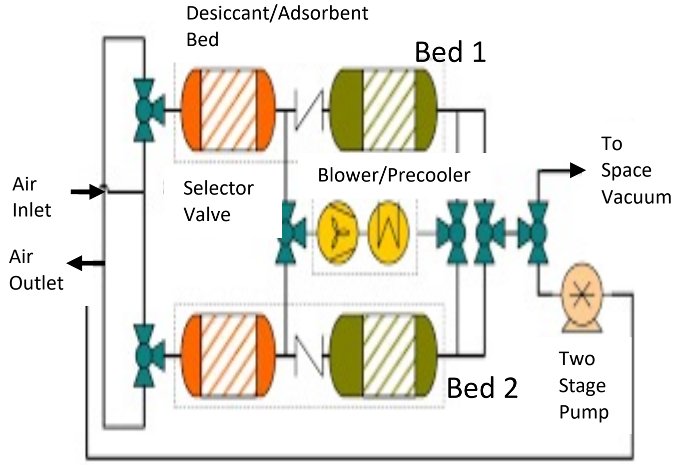
Application – Existing Technology

Carbon Dioxide Removal Assembly (CDRA) on the ISS (International Space Station)

- CDRA continuously removes six person-equivalent of CO_2, when operating with both CO_2 removal beds (dual beds functioning).
- Minimum ISS CO_2 removal rate is based on the equation for human equivalent unit (HEU) with the CO_2 partial pressure ranging from 2.0 to 3.9 mmHg.
- The CDRA houses a four-bed molecular sieve (4BMS) that utilize zeolite crystals composed of silicon, aluminum, and oxygen to remove excess carbon dioxide exhaled by the crew.

Process:

- Air enters CDRA, it passes through 1st bed where water is removed via desiccant portion of Bed 1.
- The Dry air is then routed to the zeolite portion of Bed 2 for CO_2 removal.
- The Scrubbed air flows over the previously saturated desiccant portion of Bed 2 absorbing previously removed moisture and returning it to cabin.
- Simultaneously, the isolated Adsorbent portion of Bed 1 is exposed to space vacuum and heated, causing the adsorbed CO_2 to be released and vented to space.
- When the adsorbent portion of Bed 2 becomes saturated the valves are reconfigured and the beds switch roles allowing the saturated Bed 2 to replace Bed 1 and vent CO_2 into space.
- Advantages/Disadvantages:
  Pros – Closed loop (does not require consumables other than power); conserves water while removing CO_2.
  Cons – Significant volume, replacement parts, and maintenance required. Risk of zeolite dust potentially affecting seals and mechanical parts/function.



ISS CO_2Removal Assembly (CDRA)

Astronaut performing maintenance on ISS CDRA

Application – Existing Technology

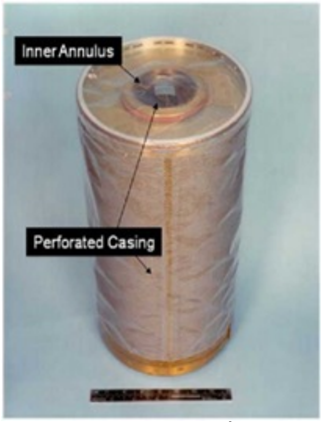
Vozdukh Russian CO_2 Removal System

- Primary Russian segment CO_2 removal system aboard ISS (located in Service Module).
- Has two desiccant beds and three adsorbent beds.
- Cabin air is drawn into Vozdukh, passed through the desiccant beds, moisture is removed, and CO_2 is absorbed.
- As one bed becomes saturated, second bed is placed in line. The saturated bed is heated, and captured CO_2 is released to space.
- If necessary, two beds can be used simultaneously and a third bed acts in CO_2 regeneration mode.
- ISS utilizes both Vozdukh and CDRA in CO_2 removal capacity.

Vozdukh

Lithium Hydroxide (LiOH)

- Primary CO_2 removal system aboard Apollo and the Space Shuttle, and currently used as backup CO_2 removal system on ISS. (CDRA is primary CO_2 removal system on ISS.)
- Currently used as one option for CO_2 removal during space walks (regenerative Metal Oxide – METOX is the other method.)
- The removal of carbon dioxide is accomplished by a chemical reaction using lithium hydroxide (LiOH) adsorbent. This method relies on the exothermic reaction of lithium hydroxide with carbon dioxide gas to create more innocuous compound lithium carbonate (Li2CO_3) solid, and water (H_2O).
- LiOH material arranged in air-permeable canisters such that cabin air flowing through canisters facilitates removal of CO_2.

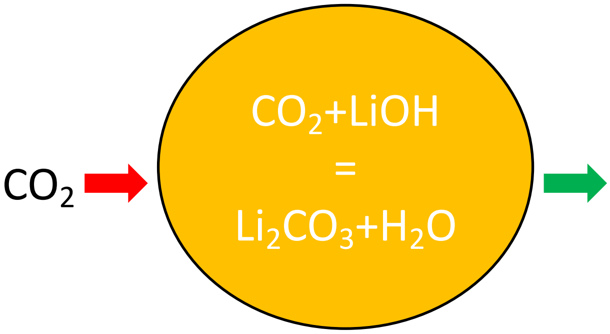


LiOH Cartridge

Advantages/Disadvantages:

- Pros – Simple and effective; highly reliable.
- Cons – Canisters are not regenerated so may only be used once (mass, stowage volume).

Lithium Hydroxide Cartridge Exchange



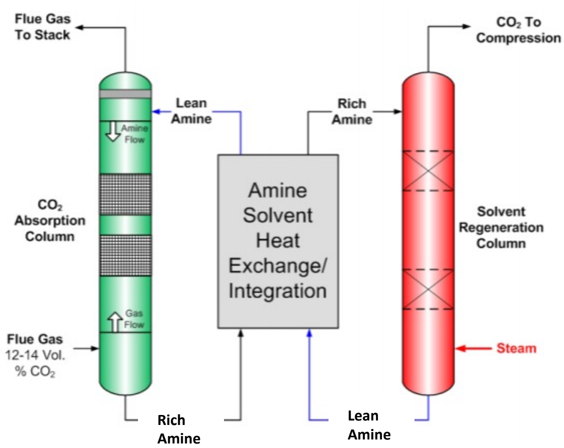
CO_2 and LiOH Chemical Reaction

Application – Emerging Technology

Thermal Amine Scrubber (TAS)

CO_2 removal system based on thermally regenerated solid amine adsorbent. TAS cycles between one adsorbing bed and one desorbing bed to remove CO_2 and regenerate bed simultaneously. Desorbing bed is isolated from the process air and exposed to vacuum during thermal regeneration.

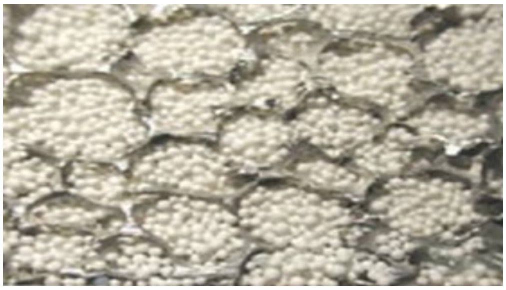
- Water locker has passive water save desiccant canister and can recover 90% of incoming humidity in process air stream, secondary desiccant wheel increases humidity recovery to 97%.
- CO_2 locker receives dry air and splits flow between 2 CO_2 removal beds.
- CO_2 is removed from one bed containing solid amine while the other bed is regenerated.
- During regeneration cycle the non-adsorbing bed is exposed to vacuum to purge CO_2.
- 96% of ullage air from adsorbing bed is evacuated using scroll compressor; removal rate of CO_2 is 3.7 kg/day at 2 mmHg partial pressure.



Thermal Amine Scrubber

Carbon Dioxide & Moisture Removal Amine Swing-bed (CAMRAS)

- Pair of interleaved-layer beds filled with SA9T, a sorbent system, of highly porous plastic beads coated with an amine. SA9T is an effective CO_2 sorbent and has an affinity for water vapor.
- A linear multi ball valve rotates 270 degrees back and forth to control flow of air and vacuum to adsorbing and desorbing beds.
- Air flows into the Amine Swing bed, a regenerable desiccant wheel dries and heats the air; air is later re-cooled by noncondensing heat exchangers.
- Scrubbed air comes out of the CAMRAS and flows back into the double locker; flows through a blower, through an electric heater, and through the opposite side of the desiccant wheel for cooling and rehydration.
- Air is returned to cabin through another filter and long hose that routes return air away from supply air inlet to prevent short circuiting of process air.
- CAMRAS sorbent beds are regenerated by exposure to space vacuum via direct connection to the ISS vacuum system.

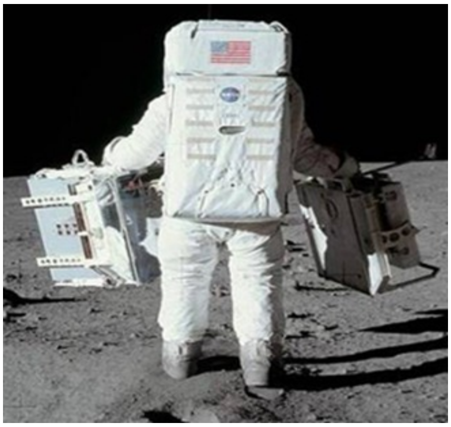


Amine based filter beads

Application - Existing Technology

Extravehicular Mobility Unit (EMU) CO_2 Removal

- When astronauts go on a Spacewalk/EVA (extravehicular activity), they build up CO_2 levels from breathing into a small closed space.
- The spacesuit has a backpack system aboard called the Portable Life Support System (PLSS), which controls the environment of the spacesuit.
- One of the key functions of the PLSS is to remove and control CO_2 delivered to the crewmember.
- CO_2 washout is a method in which CO_2 levels are controlled within the spacesuit helmet to limit the amount inhaled by a crewmember.
- The PLSS utilizes LiOH or METOX cartridges to absorb and eventually disperse the excess CO_2.
- The lithium hydroxide cells are not regenerable and are exchanged after each EVA.
- The METOX cells are regenerable. They contain CO_2 absorbent material. After each EVA they are placed into a vehicle oven that heats off the CO_2 from adsorbent beds and vents it to the vehicle.
- The CDRA then absorbs the CO_2 from the vehicle and vents into space.
- The spacesuit helmet also has an emergency purge valve to vent CO_2 in emergency situations. This can adversely affect the O_2/CO_2 balance



Portable Life Support System PLSS

Portable Life Support System PLSS

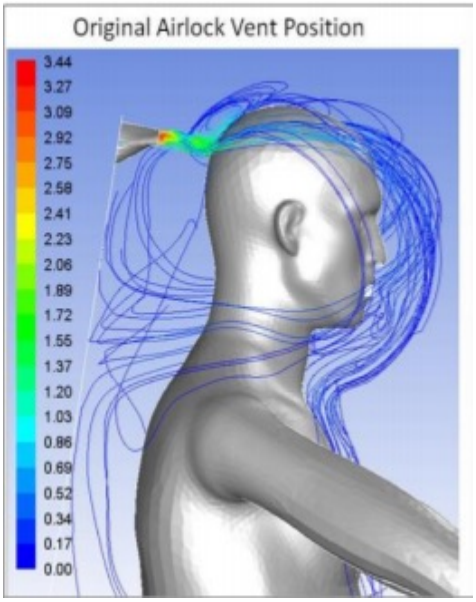
EMU Helmet

EMU Helmet Assembly

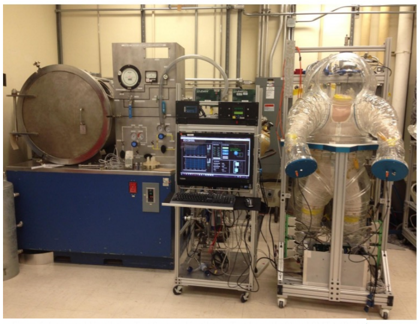
- Consists of: Transparent shell, Neck Ring, Vent Pad, Purge Valve and adjustable Valsalva Device.
- The Vent assembly diffuses incoming gas over the astronaut's face.
- Under the EMU helmet, astronauts wear the communications carrier assembly, A.K.A. Snoopy Cap.

Application – CO_2 Washout System

- Carbon Dioxide washout describes the process of removing CO_2 in an enclosed space. For the purpose of this brief, we are discussing CO_2 washout in a spacesuit and space helmet.
- CO_2 is a significant concern as the consequence of inadequate CO_2 removal can result in hypercapnia and related symptoms ranging from headache and fatigue to impaired cognitive function and death.
- CO_2 removal in a space helmet is challenging as it is difficult to ensure the quantity of CO_2 that is removed from the suit and not forming pockets in any area of the suit or helmet. It is also important to ensure when CO_2 is purged, it does not disrupt the critical breathable oxygen balance.
- Fresh air outlet from the PLSS is located at the rear base of the helmet. Air flow is directed from the back of the crewmember's head over their head and face into the suit where it exits the suit and flows into the PLSS for filtration. This provides a continuous airflow, so the exhaled CO_2 is entrained with the fresh air loop from the PLSS. This mixed air then flows down into the suit to where it exits the suit and flows back into the PLSS.
- Exhaled air including CO_2 is flowed through an adsorbent charcoal bed and contamination control cartridges composed or either LiOH or METOX. This removes CO_2, trace gases, and odors. The LiOH cartridges are stored on the vehicle and replaced on the ground, the METOX cartridges can be regenerated on orbit. Either of these are installed in the PLSS prior to EVA.
- To address the life support challenges, especially when considering future, longer space missions, NASA is developing an advanced portable life support system (APLSS) spacesuit for exploration. The ventilation loop of the APLSS is designed to assist with CO_2 washout using a regenerable rapid cycle amine (RCA) removal system, efficient fan and heat exchange systems, and trace contaminant control (TCC) unit placed inside the suit hatch that allows for easy filter exchange.
- NASA has also developed a new system called the Integrated Ventilation Test System (IVTS) designed to study CO_2 washout.
- The IVTS has a ventilation test loop as found in APLSS and suited manikin test apparatus (SMTA). The purpose is to supplement human testing, optimize CO_2 removal efficiently, validate CO_2 washout, evaluate spacesuit nitrogen efficiencies, and optimize the rapid cycle amine (RCA) performance for scrubbing CO_2.



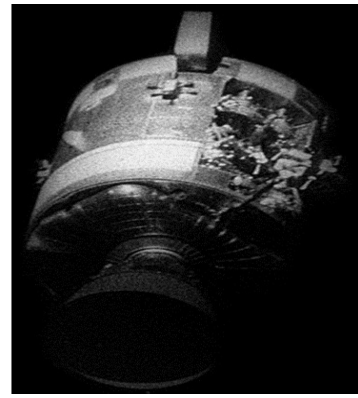
Integrated Ventilation Test System



Mishaps

Apollo 13 – April 11-17, 1970

- Apollo 13 began their mission to land on and discover new information about the moon on April 11, 1970.
- Two days into their mission, a stir of the Service Module (SM) oxygen tank resulted in an electrical short causing the tank to explode, leaving the crew without adequate life support.
- The Lunar Module (LM), originally supplied for 2 of the crew to use for 2 days on the lunar surface, became a lifeboat supporting 3 crew for 4 days due to the SM's inability to power the CM.
- CO_2 levels quickly rose (14.9 mmHg) and it became apparent the LM did not have enough LiOH cylinders to support the crew for 4 days.
- Ground support identified that the CM had usable remaining LiOH cartridges, but they were not the same type/shape as the LM filters.
- The astronauts were instructed to use plastic bags, duct tape, and a suit hose to modify the filters, enabling them to absorb CO_2 and support the 3-person crew. The CO_2 levels dropped to 1 mmHg.
- The crew rationed supplies and water and used the minimum amount of power possible, allowing them to survive in the cold, dark LM for 4 days during their return to Earth.
- The objective of visiting the moon was aborted, but with significant ground support planning, the crew was able to transfer back to the CM and safely land.



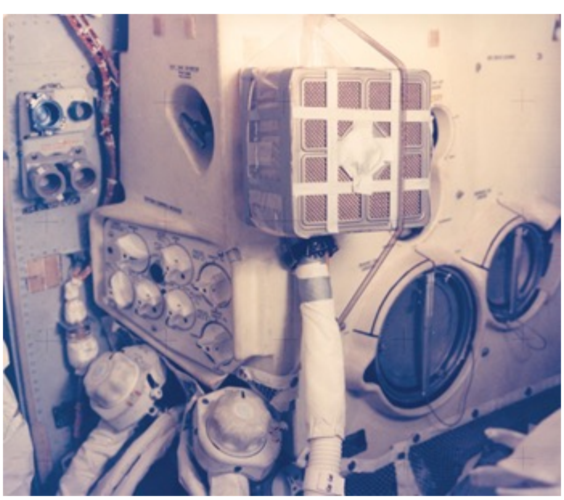
Damaged Apollo 13 Service Module

Relevant Standards
NASA-STD-3001 Volume 2 Rev C

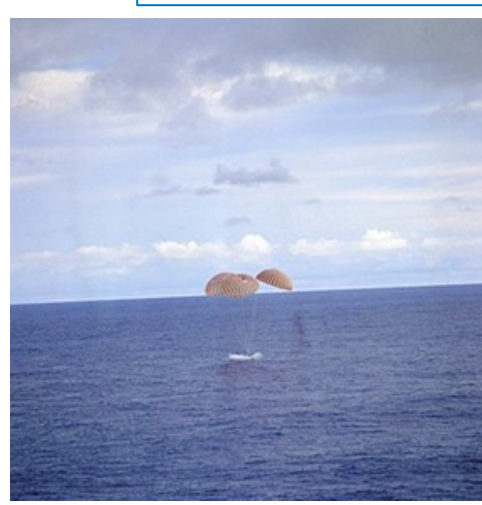
[V2 6004] The system shall limit the average 1-hour CO_2 partial pressure in the habitable volume to no more than 3 mmHg.

[V2 9001] Hardware and equipment performing similar functions shall have commonality of crew interfaces.

[V2 10012] Procedures for performing similar tasks shall be consistent.



Apollo 13 Re-designed CO_2 filter



Apollo 13 Safe landing!

Mishaps

Soyuz 23 – October 14, 1976

- The Soyuz 23 had an automatic docking system malfunction during the final approach to Salyut 5 due to an electronics failure.
- Cosmonauts had less than two days of battery power remaining and missed the landing opportunity for the day, so they powered down systems to conserve power.
- A blizzard was active in the landing zone forcing a lake rather than land landing.
- The descent module lowered in the dark on a single parachute which rocked as it entered the high winds of the landing area.
- They splashed down into the freezing water of Lake Tengiz, making recovery efforts extremely difficult.
- The cosmonauts stayed in the capsule with systems shut off to save power.
- As the capsule floated, the pressure equalization valve above the waterline provided air.
- The salt water from the lake caused the secondary chutes to deploy by shorting out the sensors, the parachute filled with water and dragged the capsule below the surface.
- The ventilation had to be closed to prevent water entering the vehicle.
- Finally, a helicopter, which could not lift the capsule due to water weight, was able to drag Soyuz 23 to the lake edge.
- The crew was found alive but incapacitated due to high CO_2 levels inside the capsule.

Relevant Standards
NASA-STD-3001 Volume 2 Rev C
[V2 6004] The system shall limit the average 1-hour CO_2 partial pressure in the habitable volume to no more than 3 mmHg.
[V2 6006] The system shall maintain the pressure to which the crew is exposed to between 26.2 kPa < pressure ≤ 103 kPa (3.8 psia < pressure ≤ 14.9 psia) for indefinite human exposure without measurable impairments to health or performance.

Back-Up

Major Changes Between Revisions

Original → Rev A

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev C.

Referenced Standards

NASA-STD-3001 Volume 1 Revision B

[V1 3003] In-Mission Preventive Health Care All programs shall provide training, in-mission capabilities, and resources to monitor physiological and psychosocial well-being and enable delivery of in-mission preventive health care, based on epidemiological evidence-based probabilistic risk assessment (PRA) that takes into account the needs and limitations of each specific design reference mission (DRM), and parameters such as mission duration, expected return time to Earth, mission route and destination, expected radiation profile, concept of operations, and more. The term "in-mission" covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth. In-mission preventive care includes, but is not limited to: (see NASA-STD-3001, Volume 1 Rev B for full standard).

[V1 3004] In-Mission Medical Care All programs shall provide training, in-mission medical capabilities, and resources to diagnose and treat potential medical conditions based on epidemiological evidence-based PRA, clinical practice guidelines and expertise, historical review, mission parameters, and vehicle-derived limitations. These analyses should consider the needs and limitations of each specific DRM and vehicles. The term "in-mission" covers all phases of the mission, from launch, through landing on a planetary body and all surface activities entailed, up to landing back on Earth. In-mission capabilities (including hardware and software), resources (including consumables), and training to enable in-mission medical care, are to include, but are not limited to: see NASA-STD-3001, Volume 1 Rev B for full standard).

[V1 5002] Astronaut Training Beginning with the astronaut candidate year, general medical training, including first aid, cardiopulmonary resuscitation (CPR), altitude physiological training, carbon dioxide exposure training, familiarization with medical issues, procedures of space flight, psychological training, and supervised physical conditioning training shall be provided to the astronaut corps.

[V1 5009] Physiological Exposure Mission Training Physiological training designed to assist crewmembers with pre-mission familiarization to in-flight exposures (i.e., carbon dioxide [CO_2] exposure training, hypoxia training/instruction, centrifuge, and high-performance aircraft microgravity adaptation training) in preparation for space flight shall be provided.

NASA-STD-3001 Volume 2 Revision C

[V2 4015] Aerobic Capacity The system shall be operable by crewmembers with the aerobic capacity as defined in NASA-STD-3001, Volume 1.

[V2 6001] Trend Analysis of Environmental Data The system shall provide environmental monitoring data in formats compatible with performing temporal trend analyses.

[V2 6004] Nominal Vehicle/Habitat Carbon Dioxide Levels The system shall limit the average one-hour CO_2 partial pressure (P_ICO_2) in the habitable volume to no more than 3 mmHg.

Referenced Standards

[V2 6006] Total Pressure Tolerance Range for Indefinite Crew Exposure The system shall maintain the pressure to which the crew is exposed to between 26.2 kPa < pressure ≤ 103 kPa (3.8 psia < pressure ≤ 14.9 psia) for indefinite human exposure without measurable impairments to health or performance.

[V2 7041] Environmental Control The system environmental control shall accommodate the increased O_2 consumption and additional output of heat, CO_2, perspiration droplets, odor, and particulates generated by the crew in an exercise area.

[V2 6020] Atmospheric Data Recording For each isolatable, habitable compartment, the system shall automatically record pressure, humidity, temperature, ppO_2, and $ppCO_2$ data continuously.

[V2 6021] Atmospheric Data Displaying The system shall display real-time values for pressure, humidity, temperature, ppO_2, and $ppCO_2$ data to the crew locally and remotely.

[V2 6022] Atmospheric Monitoring and Alerting Parameters The system shall alert the crew locally and remotely when atmospheric parameters, including atmospheric pressure, humidity, temperature, ppO_2, and $ppCO_2$ are outside safe limits.

[V2 6107] Nominal Vehicle/Habitat Atmospheric Ventilation The system shall maintain a ventilation rate within the internal atmosphere that is sufficient to provide circulation that prevents CO_2 and thermal pockets from forming, except during suited operations, toxic cabin events, or when the crew is not inhabiting the vehicle.

[V2 6108] Off-Nominal Vehicle/Habitat Atmospheric Ventilation The system shall control for ppO_2, $ppCO_2$, and relative humidity during off-nominal operations, such as temporary maintenance activities in areas not in the normal habitable volume.

[V2 11034] Suited Atmospheric Data Recording Systems shall automatically record suit pressure, ppO_2, and $ppCO_2$.

[V2 11035] Suited Atmospheric Data Displaying Suits shall display suit pressure, ppO_2, and $ppCO_2$ data to the suited crewmember.

[V2 11036] Suited Atmospheric Monitoring and Alerting Suits shall monitor suit pressure, ppO_2, and $ppCO_2$ and alert the crewmember when they are outside safe limits.

[V2 11037] EVA Suited Metabolic Rate Measurement The system shall measure or calculate metabolic rates of suited EVA crewmembers.

[V2 11038] EVA Suited Metabolic Rate Display The system shall display metabolic data of suited EVA crewmembers to the crew.

[V2 11039] Nominal Spacesuit Carbon Dioxide Levels The spacesuit shall limit the inspired CO_2 partial pressure (P_ICO_2) in accordance with Table 35, Spacesuit Inspired Partial Pressure of CO_2 (P_ICO_2) Limits.

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