CO_2 and Trace Contaminant Removal System for Manned Missions beyond LEO

Jordi Paredes-Garcia[1], Barry Nakazono[2], Gerald Voecks[3], Jose Rodriguez[4] and Jack Jones[5]
NASA – Jet Propulsion Laboratory, Pasadena, CA, 91109

and

Darrell Jan[6], John Hogan[7]

NASA – Ames Research Center, Moffet Fields, CA, 94035

The current spacecraft technology to remove CO_2 generated in manned missions relies on solid adsorbents in packed beds, which have experienced multiple problems over the last decades. The current solution has been to regularly replace the defective component, but this is only viable for missions close to Earth, e.g. ISS. Once humans require longer duration missions without Earth access, highly reliable CO_2 capture becomes essential. There is no current technology that has been demonstrated which will reliably maintains CO_2 levels for long duration missions.

Gaseous CO_2 can be captured cryogenically, and the different solidification temperatures between water, carbon dioxide, nitrogen and oxygen become the key parameters of this system. Cryogenic technology is a robust approach that can take advantage of the deep space thermal environment to reduce power requriements. Water and the vast majority of organic contaminants in the cabin atmosphere will freeze at a higher temperature than CO_2, meaning these contaminants will be captured prior to CO_2 solidification. The overall system therefore encompasses elements not only of CO_2 removal, but also humidity and trace contaminant control and thermal management.

Nomenclature

CAD	=	computer-aided design
CDRA	=	carbon dioxide removal assembly
CO2	=	carbon dioxide
MOXIE	=	mars oxygen ISRU Experiment
ISRU	=	*in situ* resource utilization
ISS	=	international space station
SOXE	=	solid oxide electrolysis

I. Introduction

Life support for humans in the International Space Station (ISS) has been a challenge and vital to long duration

[1] Propulsion Engineer, Propulsion And Fluid Flight Systems, MS125-228
[2] Senior Propulsion Engineer, Propulsion And Fluid Flight Systems, MS125-207
[3] Chemical Scientist, Analytical Chemistry and Materials Development, MS125-207
[4] Princiapl Engineer, Propulsion, Instrument Systems Implementation Conects and Section, MS157-316
[5] Principal Engineer, Retired, MS157-316
[6] Darrel Jan acting Life Support Branch Chief, NASA Ames Research Center, Moffett Field, CA
[7] Physical Scientist, NASA Ames Research Center, Moffett Field, CA, Bioengineering Branch, MS239-15

missions. Minimizing gas resupply is required for long term missions. To date, the ISS is the only spacecraft that has implemented O_2 recovery from CO_2. Currently a Sabatier reactor enables thermocatalytic conversion of CO_2 and H_2 into water and methane[1]. The methane is currently vented while the water is utilized for multiple purposes, such as converting into O_2 and H_2, where the oxygen can be used for life support and the hydrogen is recycled back to the Sabatier reactor. In addition to H_2, the input for the Sabatier is concentrated CO_2, which is currently provided by the ISS Carbon Dioxide Removal Assembly (CDRA).

To date, CO2 capture from cabin atmosphere is via a packed bed of sorbent material. A new system using an alternative technology to remove the CO_2 from the atmosphere and feed it into the Sabatier process is proposed. The ideal target would be a self-sustaining system that would be able to collect the CO_2 and contaminants generated by the crew and spacecraft systems, and convert the CO_2 into O_2, thereby decreasing the need for station resupply and venting of gasses.

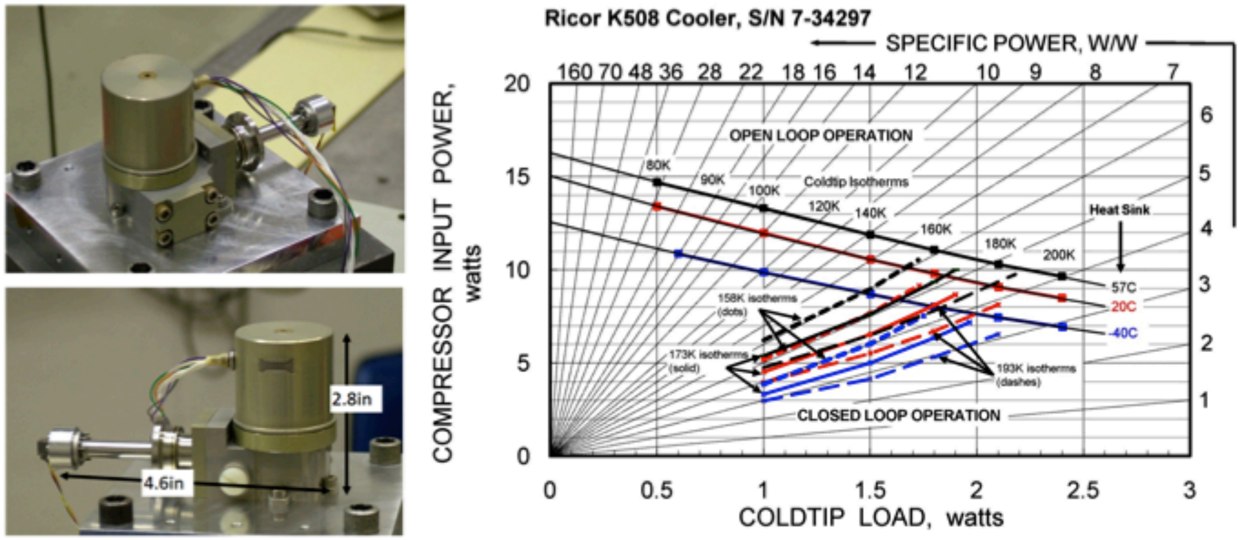
The medical community[2] has suggested an operational upper limit of 3 mmHg CO_2, or about 4000 ppm. Every astronaut generates around 1Kg CO_2 / day which needs to be continuously removed from the cabin air.

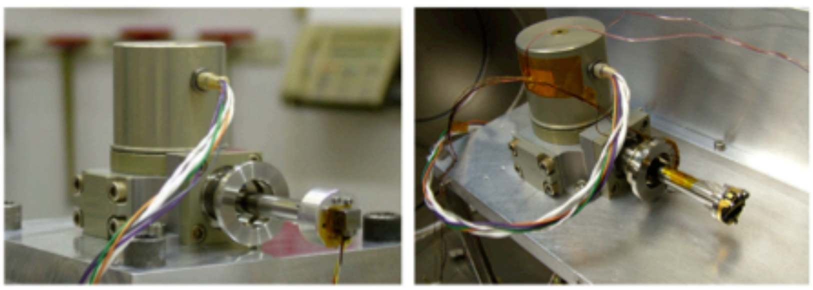
The proposed system consists of staged Two-Phase Heat Exchangers, to selectively solidify water, trace contaminants and CO_2. Deep space radiators, ideal for extended missions beyond earth orbit, provide the required cooling power, and solar heaters deliver the necessary heat to evaporate all the solidified species, during the system cycles. The energy requirements are passively collected from space, thus minimizing system electrical power required for missions beyond LEO (Only a small amount of electrical power is needed for control valves and electronics).

II. Development for Mars application

Experimental studies of cryogenic capture of CO_2 for NASA missions has been discussed before[3]. Terrestrial capture of CO_2 using Stirling coolers has also been studied[4]. This team was also attempting to address the requirement to collect and pressurize CO_2 from the Martian atmosphere. A concept was built and tested using cryocoolers in order to collect the CO_2 at the Martian partial pressure by omitting and venting the inerts which freeze at much lower temperatures than CO_2 at this pressure (5-10mbar).

The concept is simple - use a cryocooler to collect CO_2. This has proven successful using a Ricor Tactical Stirling Microcoolers - K508 back in 2014. Using copper foam attached at the cold tip of the crycooler and flowing a Mars-like gas (~95.6% CO_2, 1.9% N_2, 1.9% Ar) at 7 mbar for 30 minutes; 2 grams of CO_2 were captured while the tip stayed at 150K and the cryocooler was supplying 1.5W of cooling power. Figure 1 describes the specific operating characteristics of the Ricor K508. The three pictures in Figure 1 (left and middle bottom) are actual images of the Ricor K508 used on JPL experiments. The upper right image describes the electrical power required for a certain freezing temperature indicating the coldtip load. For the experiments performed simulating Mars atmosphere (7mbar), freezing point is around 150K and 50C heat sink which leads to approximately 12W electrical power and 1.5W at the cold tip. Bottom right table embedded in Figure 1 notes the K508 specifications.





RICOR K508		
Cooler Technology	Rotary Stirling, w/lubricated bearings; close contact expander	
Max Power Input	15W	
Mass	450grams	
Max Cooling Capacity	1650 mW	at 150K
	500 mW	at 80K
Drive Frequency	25 - 70 Hz	
Exported Vibration	60mN at 53.9Hz	

Figure 1: Ricor Tactical Stirling Microcooler - K508

The tests successfully operated over multiple 30 to 40 minute operations until accumulating a total of 6 grams of CO_2 in 140 min. The accumulated CO_2 was analyzed and had no traces of Argon or Nitrogen.

Figure 2 describes the first data collected of frozen CO_2 (green line), superposed onto the red CO_2 phase diagram. The blue lines indicate the water phase diagram for reference. The tests started at ambient temperature (20ºC, Step 1) and approximately 7mbar of pressure. The CO_2 flowed while the cryocooler started decreasing temperature (1 to 2). The oscillations of the pressure are due to the regulator keeping up with the decrease of pressure on the reservoir to simulate Martian pressure (2 to 3). Once the temperature crossed the solidifaction curve, solid CO_2 ice was formed at the cryocooler tip. When a predetermined time was reached, the cryocooler was stopped and the pressure and temperature passively increased following the solidification curve until the triple point was achieved (3 to 4). A sharp increase of pressure was observed, which is expected to be caused by liquid CO_2 dropping down from the cryocooler tip that evaporated rapidly in contact with the outer accumulator, which was at ambient temperature (4 to 1).

This process was repeated multiple times, displacing the pressurized CO_2 from the small cryo accumulator to a 500cc accumulator using solenoid valves. In 140 min and 4 cycles, the 500cc accumulator had a pressure ratio increase from 0.1psi to 300psi. Currently, there is no other compressor that can accomplish a 3000:1pressure ratio with 12W of electrical power (1.5W of cooling power at 150K).

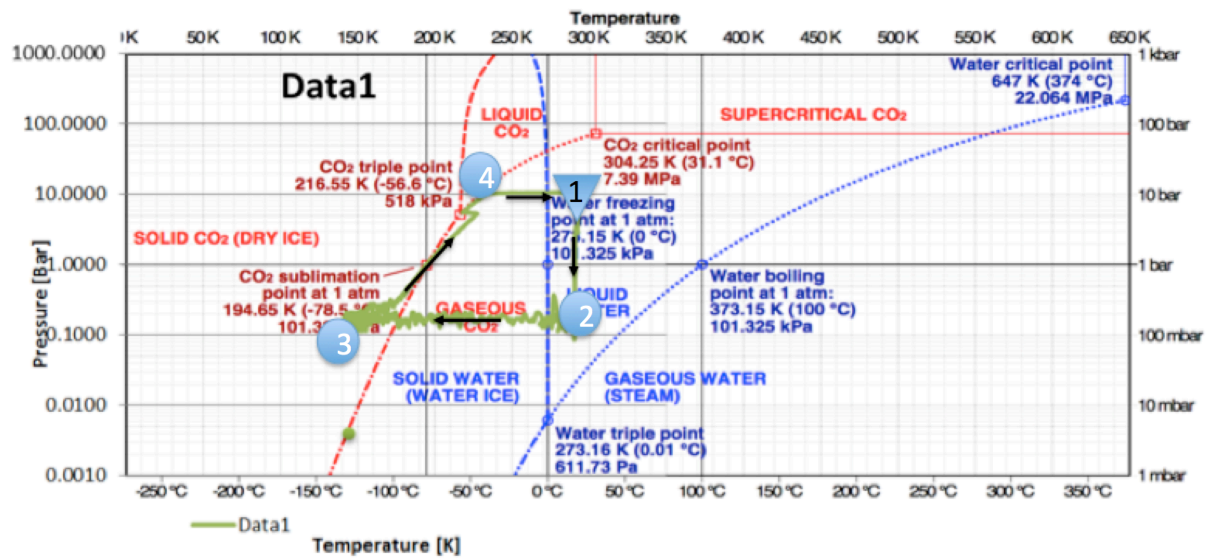


Figure 2: First CO2 collection at 150K using Ricor K508 @ JPL

This experimental research was used as a baseline to support the Mars Oxygen ISRU Experiment proposal, which involved the development of a low power and compact method to collect CO_2. This proposal was awarded to fly in the Mars rover scheduled to launch in 2020 (M2020). The cryogenic acquisition is not only a thermal method to isolate CO_2, it is also a low power pressurization system that has many practical applications. The collected CO_2 from the Martian atmosphere is pressurized to 50 bar and proposed to be delivered at 1bar to the Solid Oxide Electrolysis (SOXE) subassembly, where it would be dissociated from CO_2 to CO/O^-, and the O^- ions arerecombined into O_2, using an electrical potential while operating at 800 C.

The success of this initial experiment opened numerous applications for this type of technology, and one of them is CO_2 collection for cabin air, similar to CDRA.

III. Development for Cabin Atmosphere Revitalization

The challenge of applying this technology to a cabin atmosphere revitalization as compared to the Martian atmoshpere is concentration of CO_2. Mars is ~96% CO_2, while the Earth atmosphere has currently 400ppm of CO_2 (0.04%), and as we have seen, the crew habitat often ranges from 3000 to 4000 ppm. Even the partial pressures of CO_2 on Mars (4mbar) and on Earth (6.4mbar) are comparable, "Cryo collecting" CO_2 from the Mars atmosphere is simpler than on Earth or crew cabins. The reasoning for this statement if the percentage of CO_2 in each atmosphere. The cryocooler tip is not selective per gas in cooling (it is in freezing), but while on Earch all the nitrogen and all oxygen also need to be cooled down to 150K, on Mars 96% of the atmosphere is already CO_2. This is why cooling down on Mars for CO_2 is more efficient than on Earth, which lead to the sequential heat exchanger design to recover the N_2 and O_2 energy lost in cooling them down. Over multiple iterations and analysis, our team developed a theoretical methodology to simulate the cryo collection for cabin air in an energy efficient matter, while operating in a manner similar to current CDRA.

Two-Phase Recuperative Heat Exchangers are designed with an inner and outer tube. The flow decreases temperature and species solidify in the Heat Exchanger inner tubes, while the outer tube recirculates the cold flow. Inlet flow accesses the system through the first heat exchanger with an exit temperature of 233°K. The temperature of the second heat exchanger goes down to 133°K and the last one to 117°K. The flow then recirculates through the outer tubes of the previous heat exchanger to recover the cooling power. The solidified particles accumulate in the inner tube of the heat exchangers until the next cycle, when the cooling mode switches to heating mode. The system is cycled from cooling mode to heating mode and back (Cycle A to Cycle B, refer to Figure 3 and Figure 4) every time the selective heat exchangers are full of water and contaminants, and, independently, carbon dioxide. This is why the system consists of two sets of three heat exchangers which alternate cooling and heating mode. The solidified CO_2 is collected in the coldest heat exchanger, [133K - 117K] and pressurized in a separate vessel during heating mode. The target design is a closed system, with no water lost during the CO_2 removal process. The collected water from a previous cycle is evaporated by the dry air exit flow from the cooling mode.

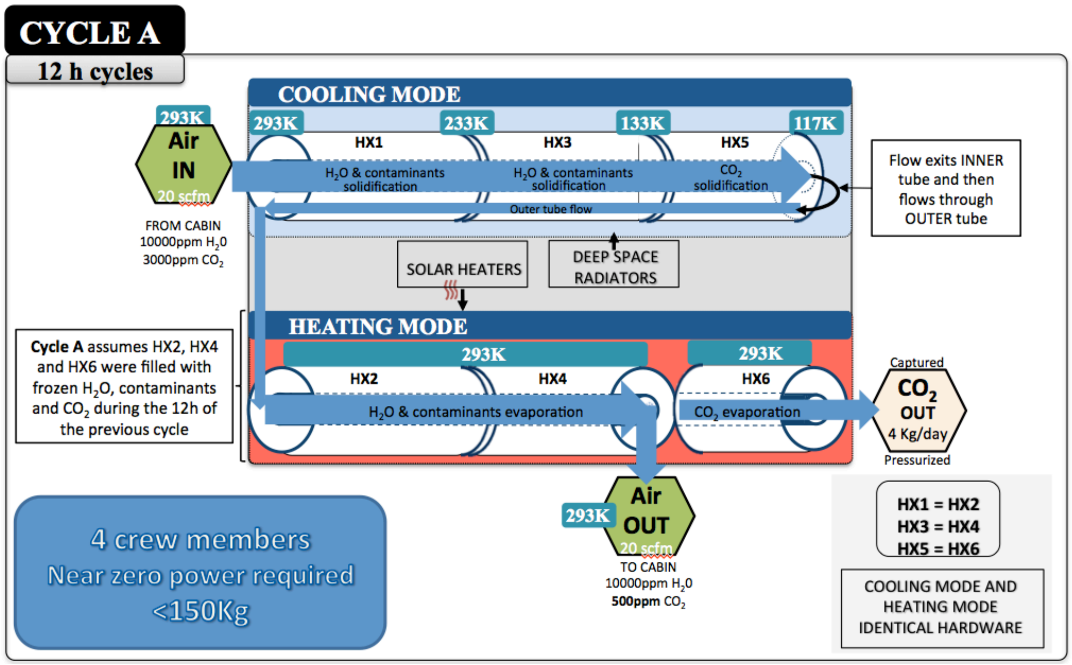


Figure 3: Cycle A of current CO_2 collection system (concept)

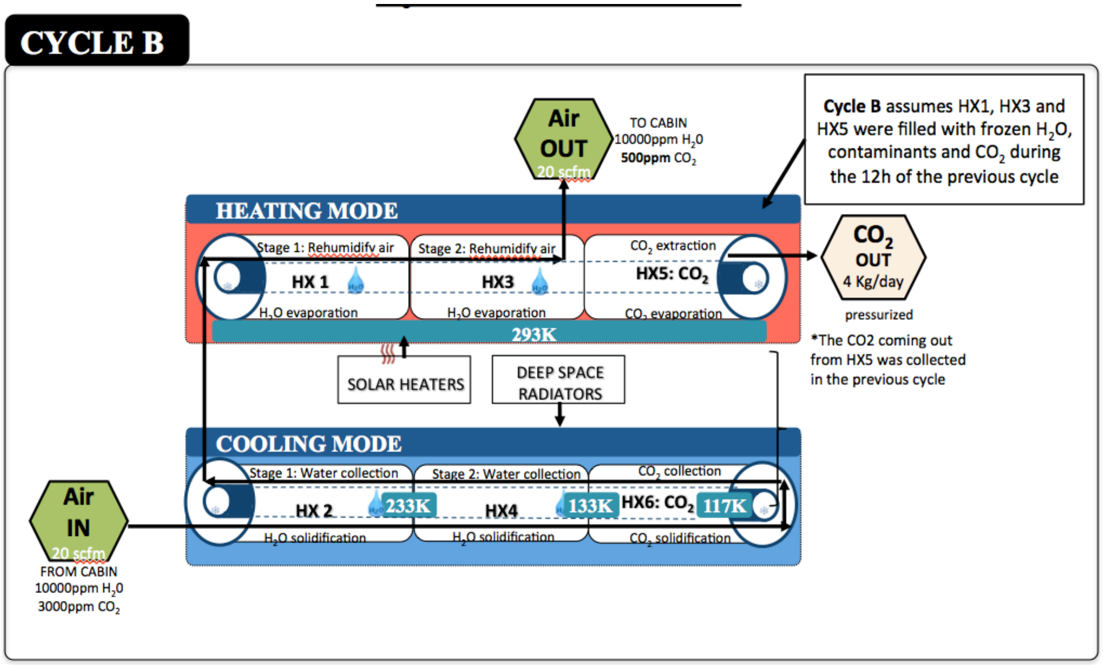


Figure 4: Cycle B of current CO_2 collection system (concept)

IV. Operational

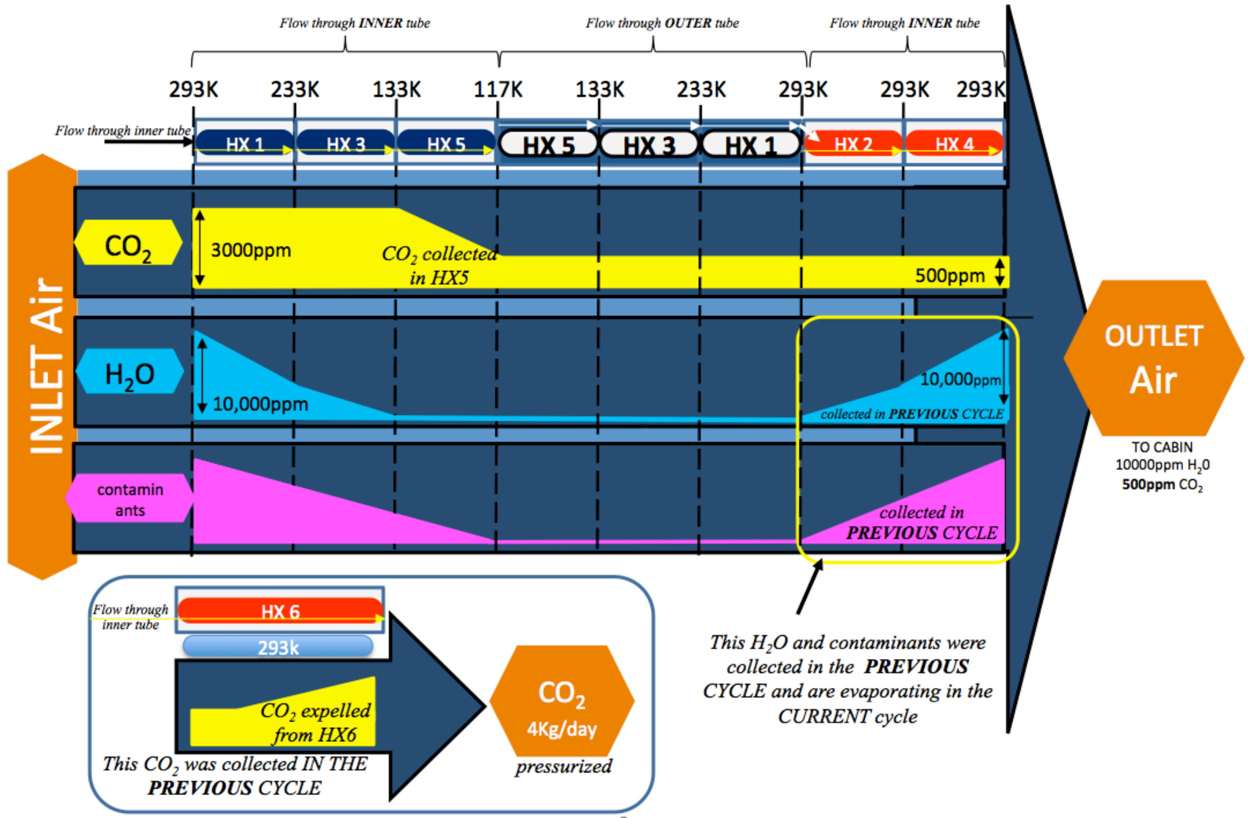


Figure 5: Diagram for gas elements through out the system

The following procedure uses freezers and crycoolers to simulate provide the cooling energy provided by the deep space radiators in space. The goal is to demonstrate both operations in this detailed description to not the Earth test and the actual flight. Same methodology with all the heaters descrived bellow, Earth test uses Electrical Heaters to simulate the Solar Heaters that would be used on flight.
This procedure and methodology could also be used in a station where the sun/dark spacecraft areas are not constantly oriented, like the ISS, which could use electrical power instead (freezers/cryocoolers and heaters)

1. Ambient air (293K) comes in the *cooling mode* starting at HX1 at 20scfm 7°C dew point.
2. HX1 captures water & contaminants at T_{exit}=233°K. The commercial **freezer** provides the cooling required by the efficiency loss of HX1.
3. HX3 captures the rest of water and contaminants: T_{exit}=133°K cooled by one of the **Cryocoolers** (Thales LPT9710)
4. HX5 collects high purity CO_2: T_{exit}=117°K cooled by 2 Cryocoolers Thales LPT9710
5. Air with no water, CO_2 nor contaminants flows back through HX5, HX3, HX1 transferring the cooling power to the new inlet flow.
6. Output HX1 warm air drives through the ***Heating Mode***; HX2 and HX4 return the humidity. The heat generated by the freezer and the cryocoolers during their normal cooling operation is used to evaporate the water and CO_2.
7. The CO_2 in HX6 provides high pressure CO_2 for processing (at the desired pressure): For a Sabatier, no compressor is required in this case.
8. After a 12h cycle of capturing water, contaminants and CO_2 in the cooling mode. **Modes are switched** and HX1, HX3 and HX5 become part of the Heating Mode and HX2, HX4 and HX6 become part of the Cooling Mode

V. Discussion and Future Work.

They key advantages of this concept are the minimizationof of moving parts and no particulate generation. These characteristics yield to high reliability (>10,000h) and no resupply required, as well as low power required when using the solar thermal power / deep space radiators. (Alternative electrical power sources have also been investigated. The power required without solar heating and deep space radiators is similar to current CDRA).

This new self-contained system does not require scheduled replacement parts. No replacement filters are required and every component has been flown in a spacecraft previously. Space qualified cryocoolers have life times exceeding 10,000 hours. There is no current similar system using temperature to collect CO_2. Since nearly all volatile organics are captured as well, the trace contaminant control system can be considerably smaller, and designed mostly to capture small amounts of small molecules such as methane and carbon monoxide (which freeze at a lower temperature than CO_2.)

Compared to the current zeolite sorbent systems that fly in the International Space Station, the advantage of the system are **reliability**, flexibility and nearly no power required. This new system will open a whole new window of options for human missions beyond LEO, like transit missions to Mars. No current system is reliable enough to enable such a long mission without significant resupply requriements. The system is flexible in terms of CO_2 removed. The CO_2 removed from the system is roughly linear with inlet flow, power and temperature of the third heat exchanger. If more CO_2 needs to be removed, the temperature of the third heat exchanger can be set to a lower value, decreasing the CO_2 further. Consequently, if the medical community affirms that the current CO_2 levels are responsible for creating health issues cor the crew, forcing the CO_2 levels to go well below current levels (even as low as below 600ppm), this system can perform that task. It is not constrained like the current systems which are limited by their adsorption kinetics, thermal cycles, and high energy requirements.

The energy efficiency of this system relies on the deep space thermal environment. Some mission scenarios, such as a planetary base, may not be suitable for this approach. In this case there could be different architectures for CO_2 removal for the planetary base, as opposed to the deep space transit mission. There is thus a lack of hardware architecture commonality for the two mission segments. This may or may not be an advantage, but should be considered.

The proposed approach encompasses the functions of CO_2 removal, CO_2 storage, CO_2 delivery, and the analogous functions for trace contaminant control and water vapor. System studies should be performed which compare the mass, power and reliability of systems comprising *all* these functions.

VI. Conclusion

NASA requires an improvement and completely new technology for CO_2 management on long duration misions. Current systems have been proven to be not reliable for the long term, due to media life limitations and particle generation. This new technology opens a whole new world of possibilities in terms of human exploration creating a reliable and flexible system, which will allow astronauts to collect their expelled CO_2, for further processing. Spacecraft's needs a methodology to revitalize the cabin air with a closed system; loosing ties with Earth will allow human interplanetary exploration to grow to a new level.

Acknowledgments

Some of this work was performed at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA). The authors thank Dr. Enid Contes-De-Jesus for valuable discussions.

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