Equivalent System Mass Comparison of ECLSS CO_2 Removal Technologies

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Conclusion

- **For long-term human spaceflight, any CO_2 removal technology will need to integrate into existing vehicle systems and prove sufficient performance while maintaining a reasonable system-level impact**
- **Task:** Conduct an equivalent system mass (ESM) analysis to provide a comparison of competing Environmental Control and Life Support Systems (ECLSS) CO_2 removal technologies for manned space exploration
- **Approach:** Evaluation and comparison of six technologies was achieved using an existing ESM tool that formerly ranked such technologies for consideration on Gateway
    - **Carbon Dioxide Removal System (CDRS)** – TRL 7
    - **Thermal Amine Scrubber (TAS)** – TRL 9
    - **Carbon Dioxide Removal Assembly (CDRA)** – TRL 9
    - **Four-Bed CO_2 Scrubber (4BCO_2)** – TRL 9
    - **CO_2 and Humidity Control Swing Bed (CHC)** – TRL 9
    - **Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS)** – TRL 5
- Technologies were assessed using metrics of mass, volume, power and cooling requirement, CO_2 removal performance, and gas consumables

Equivalent System Mass (ESM) Approach

- **ESM analysis takes disparate sizing characteristics of technologies or subsystems and converts them into a unified, quantifiable metric that can be easily compared among multiple candidates**
  - Applies "equivalency factors" (infrastructure costs) to convert sizing and performance parameters such as volume and cooling into units of mass, which are then added to actual system mass to yield a total ESM
  - Enables a more apples-to-apples comparison of integrated system impacts across candidates rather than a simple direct comparison of component mass alone

$$\mathbf{ESM} = M_S + M_C + \gamma_V V + \gamma_P P + \gamma_Q Q$$

$\mathbf{M_S}$	System mass	kg
$\mathbf{M_C}$	Gas consumables mass (O_2 and N_2)	kg
$\mathbf{V}$	System volume	m^3
$\mathbf{P}$	Power consumption	W
$\mathbf{Q}$	Heat loss or gain (thermal control)	W
$\boldsymbol{\gamma_V}$	Volume equivalency factor	kg/m^3
$\boldsymbol{\gamma_P}$	Power equivalency factor	kg/W
$\boldsymbol{\gamma_Q}$	Thermal control equivalency factor	kg/W

Equivalent System Mass (ESM) Approach

- **Results of an ESM analysis depend on assumptions made about the operating environment, so it must be performed with a specific mission in mind**
- **Equivalency factors:** represent the degree of impact, expressed in terms of mass, that system volume, power, and cooling requirements for technologies will have on the infrastructure of habitats for different missions
  - Values depend strongly on mission architecture and are specific to mission location
  - Evaluated by NASA according to current baselines for launch vehicles, spacecraft, and supporting equipment
- **Separate comparisons of ESM values for each CO_2 removal technology performed for Lunar transit, Lunar surface, Mars transit, Mars surface, and low-Earth orbit mission habitats**

Equivalency Factors	γ_V (kg/m^3)	γ_P (kg/W)	γ_Q (kg/W)	Pressure (psia)
Lunar transit (LT)	80.8	0.136	0.0554	10.2
Lunar surface (LS)	133.1	0.076	0.102	8.4
Mars transit (MT)	79.3	0.162	0.096	14.7
Mars surface (MS)	170	0.087	0.146	10.2
Low-Earth orbit (LEO)	79	0.162	0.18	14.7

Technology Assessment

A literature review was conducted to obtain accurate information on mass, power, volume, consumables, and CO_2 removal capacity for each technology option, and principal investigators were contacted for confirmation of the most up-to-date quantitative data

1. **Carbon Dioxide Removal Assembly (CDRA)** – Legacy four-bed molecular sieve assembly with fully regenerative thermal/pressure swing CO_2 sorption process
   - Long history of maintenance issues and obsolete core components; eventual retirement and redesign intended to address mechanical failures
2. **Four-Bed Carbon Dioxide ($4BCO_2$) Scrubber** – Potential redesign of CDRA commissioned for flight demonstration onboard ISS to prove reliability for exploration missions with no resupply and light sparing capabilities, such as Mars transport
   - New custom zeolite sorbent to improve CO_2 capacity and kinetics, decreased operational temperature and heater redesign to minimize dusting, and a cylindrical bed shape (as opposed to rectangular) to maintain compaction
   - Reduced mass, volume, and cooling requirement compared to the CDRA, but increased power consumption
3. **Thermal Amine Scrubber (TAS)** – Different alternative to CDRA, solid amine-based system that utilizes thermal regeneration, launched as a flight experiment to the ISS to further develop solid amine technology while mitigating potentially increasing CO_2 levels with arrival of additional crew members
   - At the high end of mass and power and has by far the largest volume compared to other technologies in this study

Technology Assessment

4. **Carbon Dioxide Removal System (CDRS) –** Similar to TAS, another amine-based regenerative system intended for the International Habitation Module (I-HAB) of the Gateway Lunar space station
    - Better CO_2 removal performance than the TAS and much lower system volume, but slightly larger mass, power consumption, and cooling requirement
5. **Orion Carbon Dioxide & Humidity Control (CHC) System –** Flown on Artemis I, regenerative amine dual bed system developed for use on Orion to support an extended integrated mission without the need for additional CO_2 removal-related consumables (such as lithium hydroxide canisters) or complicated humidity capture systems
    - Unlike the CDRA, $4BCO_2$, and TAS, the CHC does not require any cooling
    - More favorable than the other technology options in terms of mass, volume, and power requirements; main drawback is its large nitrogen and oxygen consumption via venting to space due to lack of an air save pump
6. **Carbon Dioxide Removal by Ionic Liquid Sorbent (CDRILS) –** Another CDRA alternative, utilizes a regenerable ionic liquid sorbent that is continuously recirculated between a scrubber and stripper
    - Venting carbon dioxide overboard as a waste product results in the loss of oxygen molecules that could be supplied back to the cabin
        - Integration of the CDRILS flight demonstration unit with Sabatier reactor has been investigated, which would enable oxygen recovery and reduce the need for resupply
        - Thermal integration of CDRILS with Sabatier would also allow for heat from the Sabatier reaction to be recovered and used to warm up the ionic liquid entering the stripper, thus saving power

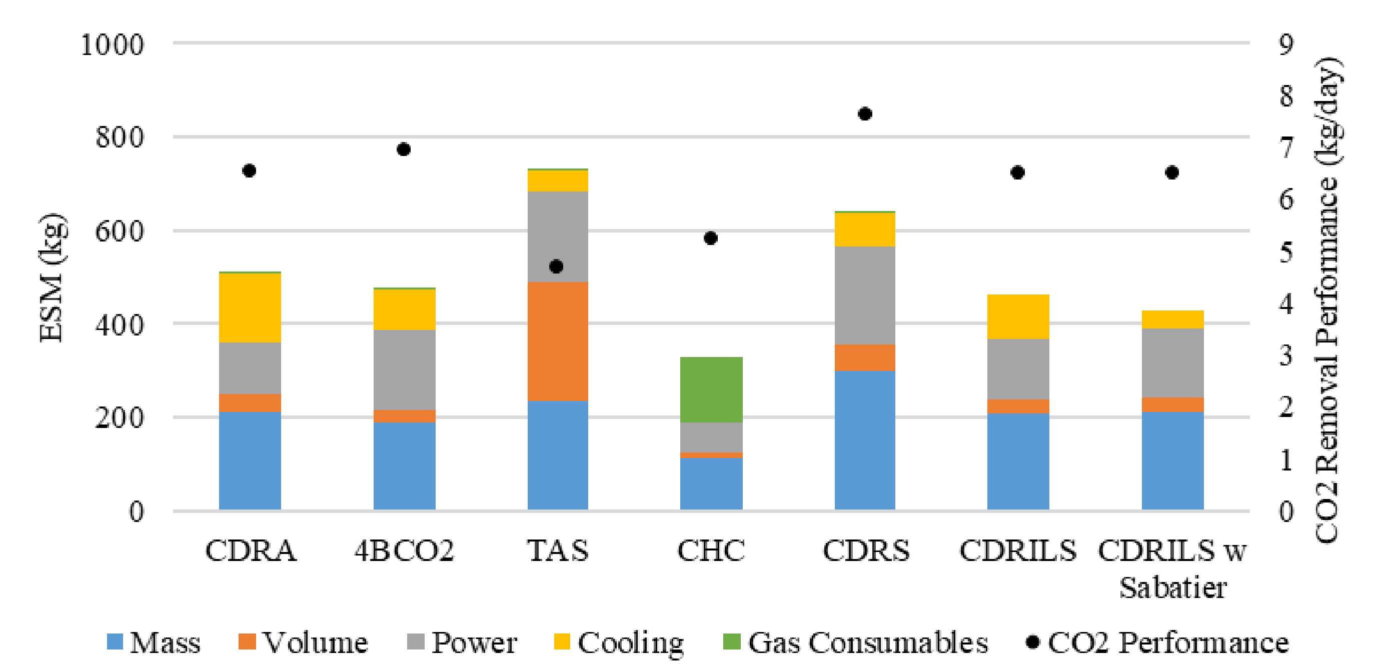
CO_2 Removal Performance & ESM

- **Calculated ESMs of the technologies in each mission habitat are presented, along with available information on CO_2 removal performance at different CO_2 concentrations**
  - Quantitative values that are not publicly available have been omitted (marked as "N/A")
- **ESMs include cumulative gas consumption over a mission period of 1 year**
  - O_2 and N_2 lost from the CO_2 removal process – does not include any recovery or regeneration from downstream processes
  - For all technologies except CDRILS, it is assumed that CO_2 is vented to space rather than recovered for downstream processing

Technology	CO_2 removal capacity (kg/day)		ESM with gas consumables mass (kg) *Mission Habitat*				
	@ 2 mmHg	*@ 3 mmHg*	*LT*	*LS*	*MT*	*MS*	*LEO*
CDRA	4.2	6.5	429	483	508	576	636
$4BCO_2$	4.5	6.9	410	406	473	470	549
TAS	3.8	4.7	682	798	728	949	766
CDRS	N/A	N/A	573	568	636	641	699
Orion CHC	3.9	5.3	277	245	331	272	331
CDRILS without Sabatier	5.0	N/A	402	419	462	485	543
CDRILS with Sabatier			389	375	429	418	464

ESM Comparison

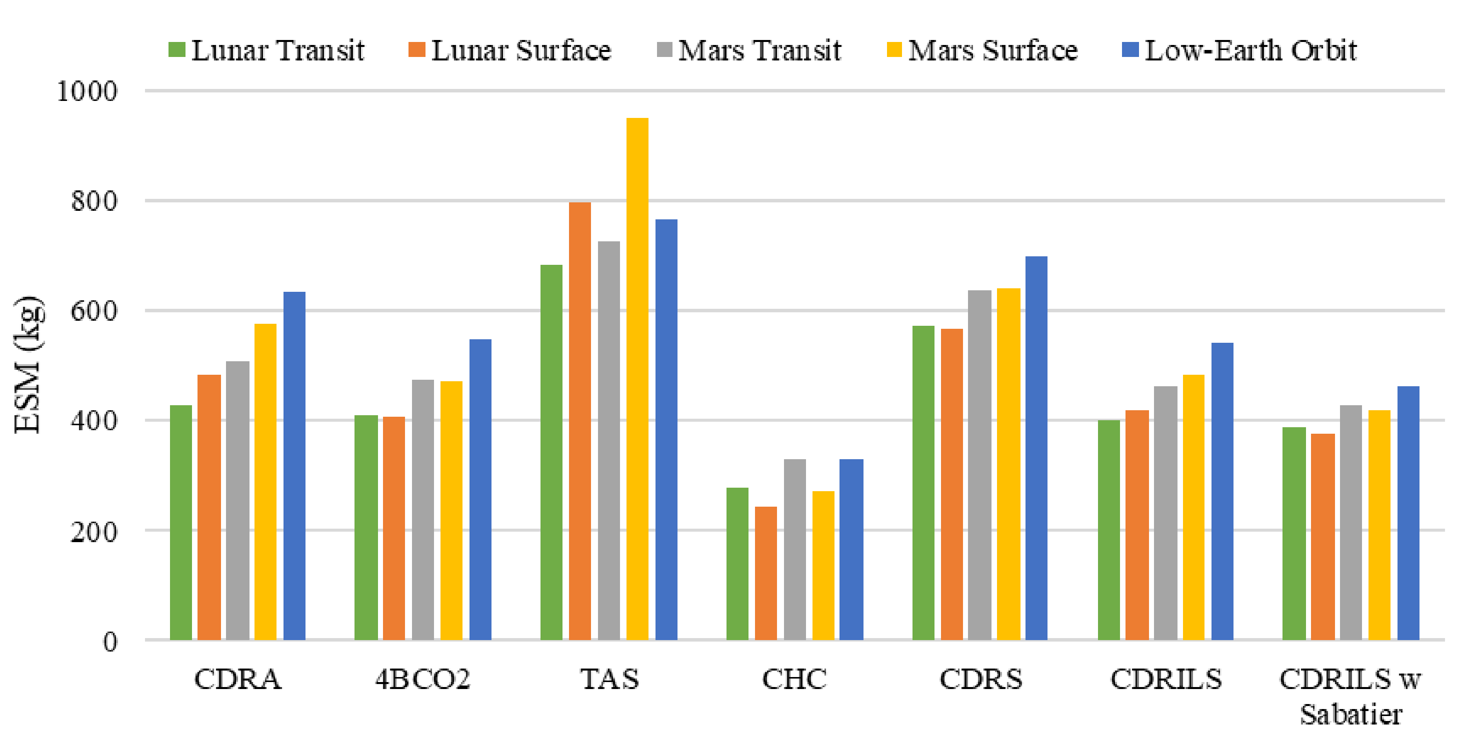
- **CHC unit consistently has lowest ESM** across all the technologies, **but has substantial gas consumables losses**
- Despite its larger mass and power draw than CHC, **CDRILS has no gas consumables losses**, making it potentially more appropriate for a long duration mission where consumables are at a premium
- **TAS and CDRS** solid amine options **have the highest ESMs** of all the technologies
  - TAS trades poorly due to large volume and CO_2 removal performance being below average
  - CDRS has a tradeoff in that it has the best overall CO_2 removal performance, but is currently at a lower TRL than the ISS proven technologies
- With only a change in bed design, the **4BCO$_2$ scrubber can achieve lower mass, volume, and cooling requirements than CDRA while increasing CO_2 removal performance**
- For most missions, the **CDRILS ESM is comparable to that of the 4BCO$_2$**
- **No clear tradeoff between CO_2 removal performance and ESM, with some technologies having better CO_2 removal with a lower equivalent mass, and vice versa**



Comparison of ESMs for each CO_2 removal technology in Mars transit habitat

ESM Comparison

- **Technologies that have high volume, power, or thermal control requirements will have more impact on habitats with higher corresponding equivalency factors**
  - CDRILS trades better than 4BCO_2 in Lunar transit, Mars transit, and LEO
  - 4BCO_2 trades better than CDRILS in Lunar and Mars surface habitats
- **LEO habitat has high power and thermal control equivalency factors** compared to the other habitats, **leading to the highest ESMs** among most of the CO_2 removal technologies
- **Mars surface habitat has a high volume equivalency factor** compared to the other habitats, yet it **does not yield higher ESMs than the LEO habitat in any technology except for the TAS**, which has a significantly larger volume than any of the other systems
  - Power and cooling requirements appear to be the more dominant contributors to the total ESM
- **Overall trends suggest technologies well suited for one mission environment may not trade well in another**



Comparison of ESMs including gas consumables mass for each CO_2 removal technology in each mission habitat

Conclusion

- **The performance and ESM of current spacecraft CO_2 removal systems has been evaluated and compared for Lunar, Mars, and low-Earth orbit habitats**

- **These ESM results can be used as a guide to assist programs in their selection of a CO_2 technology best suited for a specific vehicle and mission**
  - Analysis does not capture the overall logistical impacts of technologies and is not sufficient for informing technology down-selection on its own
  - Given the constant evolution of infrastructure costs and the ongoing testing and characterization of some of these candidates, the data presented here may shift over time and should be periodically revised to reflect the latest as technologies or operations advance

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Questions?

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