

# An Emergency Mitigation System for Safer Lunar Surface Exploration

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## Abstract

This paper presents the conceptual design and analysis of a rover-based mission emergency mitigation system intended to increase the range, scientific capability, and safety of manned lunar surface exploration while only requiring a modest increase in capability over the Apollo mission designs. The system is intended to enable the safe return of two astronauts back to the lunar operational base in the event of two types of failures: (1) rover failures, and (2) medical emergencies and/or suit failures. The proposed system increases fault tolerance with the addition of an emergency inflatable structure and an environmental control and life support system on the lunar rover to mitigate a wide range of suit and rover failures. The environmental control and life support system on the rover can be connected to the emergency inflatable to provide a habitable environment in the event of suit failure or connected to the astronaut's portable life support system to provide additional consumables in the event of rover failure. The mass and volume analyses of each subsystem are integrated to generate a total system mass of 24.8 kg and volume of 88.1 L, both of which can be accommodated on the Apollo Lunar Roving Vehicle design without requiring additional carrying capacity.

*Keywords:* Lunar Surface Exploration, Emergency Inflatable Structure, Environmental Control and Life Support System, Carbon Dioxide Removal, Sublimator Design, Human Space Exploration, Apollo Lunar Rover

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## 1. Introduction

### 1.1. Motivation

One of the central achievements of the Apollo program was the development of rover vehicles which significantly increased the range and scientific capabilities of lunar surface exploration. Given the mission specifications of the Apollo program—which generated a combined total of 3 days and 6 hours of lunar surface EVA time—the Apollo 15, 16, and 17 mission vehicles were designed primarily for short-duration exploration. However, as proposed future space exploration looks ahead to longer duration missions, and perhaps even to the establishment of a permanent manned lunar presence, the capabilities of unpressurized rover vehicles must be expanded, not only in terms of surface range, but also in their ability to tolerate unexpected emergency scenarios.

Since longer intervals of surface exploration result in increased risk exposure, the level of risk acceptable during Apollo will not be acceptable for more frequent, longer duration missions. Therefore, the ability of rover vehicles to meet unexpected mission contingencies and to mitigate risk will be integral to sustaining ex-

tended lunar surface exploration. To this end, this paper presents the conceptual design and analysis of a rover-based, single-day mission emergency mitigation system for manned lunar surface exploration.

During the Apollo missions, a major constraint on the rover excursions was the crew was required to remain within “walk-back” range of the Lunar Excursion Module (LEM) [1]. If the rover was disabled for any reason, the crew had to be able to walk back to the lunar lander within the time limit given by their current ECLSS consumables levels. This constraint limited the distance away from base that the astronauts could explore.

The work presented in this report is set within the context of the next generation of lunar surface exploration. The earliest future lunar missions are assumed to be comparable in capability and scope to the later Apollo missions, with modest advances. Rather than the large pressurized roving vehicles like SPRITE [2] and permanent base envisioned under the Constellation program [3], this paper assumes sortie missions with a modest increase in landing mass and surface duration compared to the Apollo missions. One of the assumed capabilities of these missions is having two rovers on

the lunar surface. This will be a critical development because it will eliminate the walk-back constraint on lunar surface exploration, dramatically increasing the reachable exploration area. This paper details the conceptual design of a system that can be integrated into the design of these lunar rovers to significantly increase exploration and scientific capabilities with a modest increase in system mass, volume, and power.

### 1.2. Top-Level System Design Overview

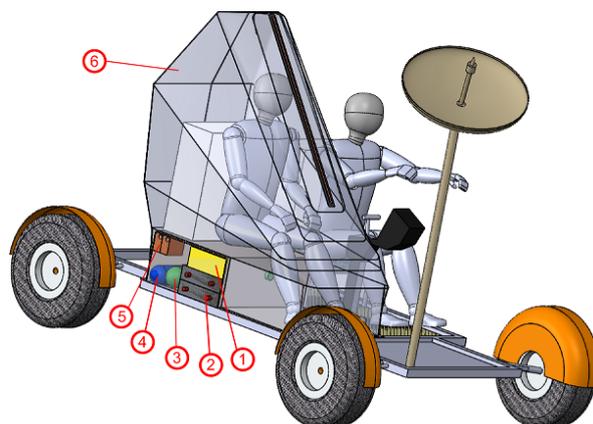
The system presented herein, called the “emergency system”, is aimed at mitigating mission risk and increasing system tolerance limitations during lunar surface exploration in open, unpressurized rovers. It was developed in conjunction with a secondary expanded operations system to improve upon both the exploration capabilities and risk mitigation abilities of existing Apollo-era rover systems (for details on this system’s operation counterpart, see [4]). This section provides a brief design overview of the emergency system, for which detailed subsystem specifications are presented in Section 3.

The first significant subsystem of the emergency mitigation system is an inflatable structure, shown in its inflated, deployed configuration in Figure 1. This inflatable structure stows around the passenger seat of the rover and can be quickly inflated to provide a safe, habitable volume for an astronaut in the case of a suit puncture or other loss of suit environmental control.

The second subsystem is an Environment Control and Life Support System (ECLSS) on the lunar rover that essentially replicates the functionality of the space suit portable life support system (PLSS). The rover ECLSS contains a sublimator or evaporator to reject excess heat, two CO<sub>2</sub> scrubbing cartridges to remove carbon dioxide from the atmosphere, a “slurper” to remove humidity from the atmosphere, an oxygen tank to supply oxygen for respiration, a water tank to feed the sublimator or evaporator and provide crew hydration, and a backup power system. All these items are stored beneath the passenger seat for easy access.

## 2. Emergency Scenarios and Requirements

Requirements for the proposed emergency mitigation system were derived using a historical survey of the emergency scenarios encountered during space exploration throughout the last fifty years. This analysis revealed the need for redundancy against four major failure categories: suit failures, medical emergencies, rover failures, and environmental concerns. It is evident that



**Figure 1:** The proposed emergency mitigation system shown on the Apollo Lunar Roving Vehicle. The system consists of a (1) sublimator/evaporator, (2) 2 CO<sub>2</sub> scrubbers, (3) an O<sub>2</sub> tank, (4) a H<sub>2</sub>O tank, (5) batteries, and (6) inflatable emergency shelter in its inflated configuration.

all four of these major categories could occur during a lunar rover mission. The results of this analysis show that potential failures result in two main categories of hardware and consumables requirements:

1. **Rover failure:** if the rover becomes nonfunctional (for instance, due to a power system or drive train failure, or a driving accident), the crew must be able to survive long enough for the second rover to be dispatched from the base, arrive at their location, and return to the base. They are assumed to remain in their EVA suits and obtain additional consumables via an umbilical connection to the emergency system mounted on the rover.
2. **Suit failure or medical emergency:** if one of the crew’s suit sustains substantial damage and loses life support capability, or if that crew member must remove their suit to access injuries, that crew member must be able to survive in the pressurized emergency shelter long enough for the second crew member to drive the rover back to the base. The crew member with the injury or suit failure is expected to utilize the emergency system for ECLSS requirements, while the other crew member continues to use his or her suit PLSS and drives the rover back to base.

A set of conceptual emergency scenarios in the context of future lunar exploration was generated to determine the worst-case scenarios for the purpose of designing the emergency mitigation system. The worst-case scenario is related to the maximum travel distance at the time of the emergency. Assuming an 8-hr total one-day

EVA, two astronauts may drive the rover for three hours directly away from the lunar base to the exploration site, conduct up to two hours of science, and plan to return directly. Emergencies at this point in time comprise the set of worst-case scenarios.

In the case that the rover is compromised and the astronauts must await rescue, the ECLSS on the rover can interface with the suit PLSS's to support both astronauts for the extended mission duration. For this failure scenario, the worst-case timeline occurs 5 hours into the mission (at the maximum distance from base with the least consumables remaining). It would involve two astronauts driving the rover for three hours to the exploration site, conducting up to two hours of science, and, when attempting to return, finding the rover to be non-functional, preventing them from returning to base. At this point in time, the crew would contact the second rover for rescue, which would take approximately one hour to dispatch, three hours to reach the exploration site, two hours to prepare to return to base, and four hours to drive back to base. The timeline below was used to generate the requirements for the emergency mitigation system.

- (T+0) Mission begins with astronauts driving rover to operation site
- T+3 – Team arrives at operation site
- T+5 – Site operations complete
- T+5 – Lunar rover unable to return
- T+5 – Backup rover notified
- T+6 – Backup rover departs base
  - Assumes 1 hour required to prepare 2nd rover for departure
- T+9 – Backup rover arrives
  - 1 hour spent on scientific transfer or attempted rover repairs
- T+10 – Backup rover departs with 3 astronauts
- T+14 – Rover arrives at base
  - Assumes 1 hour extra travel time due to increased rover load

From this timeline it can be seen that the initial crew would require 6 hours of life support beyond their PLSS capability, in addition to 1 hour of life support for the rescue crew member beyond his PLSS capability, for a

total of 13 crew-member-hours (CM-h) of life support requirements. It is assumed that both the main and rescue rovers will have identical emergency systems, allowing those 13 CM-h to be split evenly between the two rovers. This gives a requirement for 6.5 CM-h of life support consumables per rover. It should also be noted that once the rescue rover arrives and all the crew in onboard, the remaining ECLSS in the failed rover is no longer accessible.

In the case that one of the space suits becomes compromised, the emergency mitigation system can be used to return the astronaut safely back to base. For this suit failure or medical emergency scenario, the worst-case scenario also happens at a mission time of 5 hours. During this scenario, the astronaut can sit in the passenger seat of the rover, deploy the inflatable structure, zip it closed, and open the O<sub>2</sub> tank valve to fill the inflatable structure with breathable oxygen. In case of a modest-sized suit puncture, the suit's emergency oxygen supply should be able to maintain pressure until the emergency structure is deployed and pressurized. Connecting the ECLSS on the rover to the emergency inflatable provides critical life support functionality for the three-hour return trip to the lunar base. Additional consumables would also be provided for the driver for any unplanned mission extension related to the initial suit malfunction. The second timeline below was also used to generate the requirements for the emergency mitigation system.

- T+0 – Mission begins with astronauts driving rover to operation site
- T+3 – Team arrives at operation site
- T+5 – Site operations complete
- T+5 – Suit damage noticed
- T+5 – Astronaut at base notified of emergency, possibility of driving backup rover out to help
- T+5.5 – emergency shelter/chair operational, rover departs for base
- T+8.5 – Rover arrives at base

From this timeline it can be seen that the crew member with the functioning suit would be on EVA for 30 minutes longer than planned, which is within the emergency safety margin of the suit PLSS. It can also be seen that the emergency system must be able to support the other crew member for 3.5 hours in the emergency shelter. This gives a total requirement of 3.5 CM-h of

**Table 1:** Life support consumables for single-day excursion emergency.

	Rover Failure	Suit Failure
O <sub>2</sub>	0.49 kg	0.50 kg
CO <sub>2</sub> Scrubbing	0.60 kg	0.28 kg
H <sub>2</sub> O (hydration)	2.37 kg	1.28 kg
H <sub>2</sub> O vapor removal	1.91 kg	1.02 kg

life support consumables on the rover, in addition to the oxygen required to inflate the emergency shelter. In this scenario, the backup rover could possibly also be dispatched to meet enroute for additional support, but that does not effect the requirements of the primary rover and so is not included in the timeline.

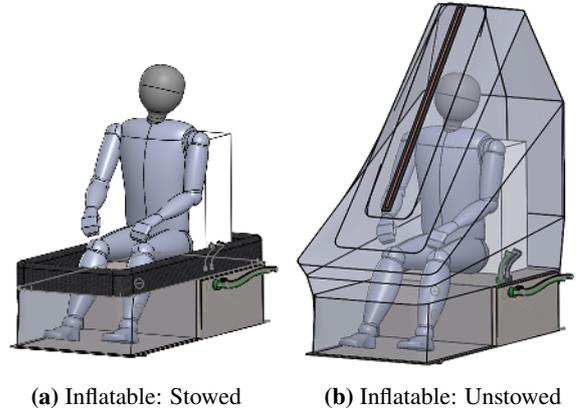
The total life support consumables requirements for these two scenarios can be calculated using the volume of the emergency shelter, the CM-h of life support required, and the baseline consumable values shown in Table 1.

### 3. Emergency Passenger Chair Design

#### 3.1. Emergency Inflatable

In the case of a suit or medical emergency, the emergency inflatable shelter will be deployed with the impaired astronaut inside. The ECLSS on the rover is connected to the emergency inflatable shelter as shown in Figure 3. The unimpaired astronaut will continue to draw PLSS-based consumables as normal while driving back to base. Only one inflatable shelter is proposed for the rover, which means that the astronauts might have to switch places in case of an emergency.

The emergency inflatable shelter is mounted and stowed around the base of the rover passenger chair, as seen in Figure 2a. For our design calculations, we assumed a fabric made up of layers in a similar configuration to the outer surface of the Apollo A7L Space Suits, minus the Liquid Cooling Garment (LCG) and comfort layer [5]. Starting from the outside thermal garment and moving inwards, the first layer of the emergency inflatable shelter fabric is woven from glass fibers (Beta fabric) and coated with Teflon. An insulation layer composed of sandwiched Beta fabric between two aluminized Kapton surfaces lies beneath the outer surface and above layers of Mylar film and non-woven Dacron (as spacer material). The pressure portion (bladder layer) is Neoprene-coated Nylon. Finally, the innermost layer is composed of lightweight Nomex fabric and is used primarily as abrasion protection for the bladder layer. The fabric is folded in accordion form around



**Figure 2:** Emergency Inflatable Shelter configurations showing O<sub>2</sub> (green) and power (black) lines permanently attached to the MIB chair base, one pair inside the inflatable, one pair outside

the astronaut's seat. It is covered with a nomex fabric cover and uses Velcro to hold the entire folded inflatable shelter in place while stowed.

To inflate, the Velcro is pulled off and the inflatable fabric is lifted up over the astronaut. A double-headed, airtight zipper, similar to what was used to seal the Apollo space suits, located directly in front of the astronaut is pulled from top (head) to bottom (near the knees). This is to ensure that the astronaut inside the emergency inflatable shelter can visually check that the zipper has closed all the way. Incorporating a double-headed zipper allows the healthy astronaut to zip up the emergency inflatable shelter in the event that the injured astronaut is physically unable. Once sealed, the bag is inflated using O<sub>2</sub> from the rover ECLSS through a valve coming out of the base between the astronaut's legs (Figure 2b).

The total volume inside the empty inflatable shelter is 0.94 m<sup>3</sup>. The shelter was designed to take up the same amount of surface area on the rover as the original seats on the Apollo rover. Using this baseline, the height of the shelter was adjusted to reach a volume that satisfied the human life support requirements to sustain one astronaut inside this volume for the amount of time specified in the requirements in Section 2. The surface area, calculated from computer-aided design models of the inflatable shelter, is 5.12 m<sup>2</sup>.

The packed volume of the stowed shelter is 0.05 m<sup>3</sup> and was determined using the surface area of the inflatable shelter, using the thickness of the layers that comprise the fabric, and using a conservative packing factor of two. This packed volume assumes the shelter is folded in an accordion form for easy deployment and

storage around the seat. Finally, the total mass of the shelter of 6 kg was calculated using the surface density of the material and the total surface area obtained from the computer-aided design models. The total volume inside the emergency inflatable shelter satisfies the human life support consumables found in Table 1 for the worst-case scenario of each failure mode described in Section 2.

### 3.2. Chair Base and Connections

During nominal operations, the astronaut not driving the rover will step over the stowed emergency inflatable, sit on the solid base, and connect to the rover ECLSS to trickle charge his O<sub>2</sub> tank and batteries. The driving astronaut's O<sub>2</sub> and power lines are fixed to the side of the passenger chair base, allowing the driving astronaut to remain connected and continue trickle charging whether the emergency inflatable is deployed or not (Figure 2b). The passenger astronaut's O<sub>2</sub> and power lines are fixed to the top of the base of the emergency chair. This allows the stowed inflatable to be deployed without the need to disconnect from the rover ECLSS. This is particularly useful in the event that an emergency happens near the end of an EVA when the astronaut's consumables are running low. The ability to stay connected to the rover ECLSS while the emergency shelter is inflated provides the astronaut the ability to continue using any working functions of his damaged suit, which may include the LCG and communication system. Of course, if the driver needs to use the emergency inflatable, then the two will have to change places, which will require temporary hose reconfiguration.

## 4. Rover ECLSS System Design

The design of the proposed system relies heavily on a deep understanding of the requirements for human life support. These requirements dictate acceptable temperature ranges, pressure levels, O<sub>2</sub> levels, relative humidity, etc. These requirements vary greatly based on level of activity. However, for this paper, we focused on extra-vehicular activity. (For ECLSS System requirements on longer, overnight missions, refer to [4]). Values for extra-vehicular activity (and other scenarios) have been published by NASA in its Advanced Life Support Baseline Values and Assumptions Document [6] and its Human Integration Design Handbook [7].

### 4.1. Baseline Consumable Values

The following tables give the human life support requirements for various substances (consumed and produced) for extra-vehicular activity (shown in moles and

kilograms). All values are directly provided by or derived from [6] and [7]. In addition, food requirements were also considered but not included in this paper due to the scope of a one-day EVA mission (Although NASA provides a food stick inside the space suit, our personal communication with NASA astronauts suggested that not eating for 8 hours was common if enough drink was provided and a good breakfast was had).

**Table 2:** Human life support values. Positive values are consumed; negative values are produced.

Compound	EVA (per CM-h)	
	mol	kg
O <sub>2</sub>	2.344	0.075
CO <sub>2</sub>	-2.114	-0.093
H <sub>2</sub> O (hydration)	20.278	0.365
H <sub>2</sub> O (res-/perspiration)	-16.343	-0.294
H <sub>2</sub> O (urine)	-3.935	-0.071

An additional role of the ECLSS system is to provide a tolerable atmosphere for humans to live in. The habitable ranges for the three most important gasses in an artificial atmosphere as well as the habitable range of total pressure are shown in Table 3. These values come from the Human Integration Design Handbook [7].

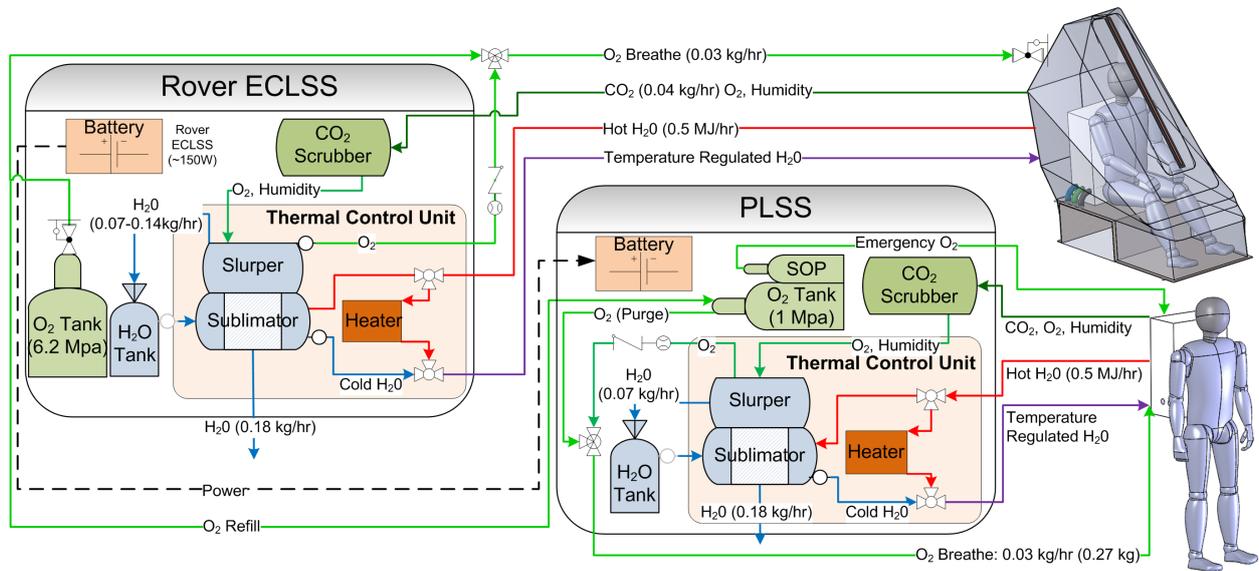
### 4.2. Carbon Dioxide Removal

#### 4.2.1. Overview: LiOH vs. MetOx vs. RCA

The CO<sub>2</sub> produced through respiration must be scrubbed from the atmosphere in order to maintain acceptable CO<sub>2</sub> levels for the astronauts. NASA has developed two CO<sub>2</sub> scrubbing technologies, or Contaminant Control Cartridges (CCC): a single EVA lithium hydroxide (LiOH) CCC which can be replaced between EVAs and a reusable metal oxide (MetOx) CCC which can be regenerated using a special oven, which requires considerable power and would most likely be situated on the lander/habitat. Both systems have canister life spans of 8 to 12 hours. A third option currently under development is Rapid Cycle Amine (RCA), which is a continuous-operation system that does not require canister replacement. These three CO<sub>2</sub> scrubbing technologies are discussed and compared in the following sections.

#### 4.2.2. Lithium Hydroxide (LiOH): Specifications and Drawbacks

Lithium Hydroxide technology utilizes a chemical reaction in which carbon dioxide reacts with lithium hydroxide to form water and an innocuous compound,



**Figure 3:** Configuration of connections during an emergency requiring the use of the Emergency Inflatable Shelter

**Table 3:** Atmospheric partial pressure limits. \*Nominal value used on the Space Shuttle

Compound	Minimum (kPa)	Preferred (kPa)	Maximum (kPa)
O <sub>2</sub>	17.2	22.1*	60.7
CO <sub>2</sub>	0	0.653	1.03
H <sub>2</sub> O	0.827	1.31	1.86
Total	20.7	29.6	117.2

lithium carbonate. Using this technology, carbon dioxide is removed from the atmosphere by flowing carbon dioxide laden air through a canister containing a packed bed of lithium hydroxide granules. The spent LiOH is not regenerated and the canisters are returned to Earth for replenishment with fresh absorbent.

The amount of LiOH required to remove the average daily output of carbon dioxide by one person is 1.35 kg/day. The removal capacity of one LiOH CCC is 0.55 kg of carbon dioxide with an enthalpy change of -100,834 J/mol carbon dioxide [8]. The dimensions of one EMU LiOH canister are: 25.4 cm height x 34.19 cm width x 8.71 cm depth, and the mass of one full/mission-ready LiOH CCC is 2.9 kg. The mission timeline was analyzed to determine the total amount of CO<sub>2</sub> that needed to be scrubbed. Using the size, mass, and enthalpy change for the LiOH CCC's listed above, a total requirement of 4 LiOH CCC's was calculated. This total includes the 2 CCC's in the suit PLSS, which results in only 2 CCC's being located on the rover (and thus inside the system boundary). This corresponds to a mass of 16.13 kg for the 4 LiOH CCC's.

#### 4.2.3. Metal Oxide (MetOx): System Specifications and Drawbacks

MetOx is an on-orbit regenerative carbon dioxide removal system. The MetOx flight system consists of two assemblies; a metal oxide sorbent canister and a regeneration assembly. The canister removes the carbon dioxide and also contains charcoal to remove the trace contaminants from the vent loop, the same as the LiOH system. After the canister is spent, it can be placed in a MetOx regenerator. This regenerator is a special oven housed at a central location with a mass of 47.63 kg [8]. This requires crew time and significant power (over 1 kW for up to 14 hours), and the enthalpy of reaction is -81,491 J/mol CO<sub>2</sub> for MetOx.

The metal oxide canister consists of metal sheet assemblies, a charcoal bag containing active charcoal, and a cover panel. The charcoal and bag construction are the same as those used in the LiOH CCC, meaning that the MetOx canisters designed for the EMU are interchangeable with the EMU LiOH CCC's. However, the MetOx CCC is significantly heavier than the LiOH CCC at 14.52 kg per container. The scrubbing capacity is

nearly identical at 0.54 kg/CCC before recharging [8]. The mission timeline was analyzed to determine the total amount of CO<sub>2</sub> that needed to be scrubbed. Using the size, mass, and enthalpy change for the MetOx CCC's listed above, a total requirement of 4 CCC's was calculated. This total includes the 2 CCC's in the suit PLSS, which results in only 2 CCC's being located on the rover (and thus inside the system boundary). This corresponds to a mass of 62.6 kg for the 4 MetOx CCC's.

#### 4.2.4. Rapid Cycle Amine (RCA): System Specifications and Drawbacks

Rapid Cycle Amine (RCA) is currently being developed by NASA as a new technology for carbon dioxide scrubbing and humidity control. The RCA design consists of alternating absorbing and de-sorbing beds that contain amine coated pellets mounted in an aluminum foam substrate. This alternating design allows a single RCA CCC to continuously scrub CO<sub>2</sub> without need for replacement. The amine used in the swing bed also removes water vapor from the suit ventilation loop, eliminating the need for a condensing heat exchanger, slurper, and rotary separator. The weight of one RCA CCC is 7.26 kg and does not require replacement during the mission.

Due to the continuous operation capability, each astronaut and the rover only require one RCA CCC, for a total of three canisters. Each CCC has a CO<sub>2</sub> scrubbing rate of 0.15 kg CO<sub>2</sub>/hr. The dimensions of one RCA canister are the same as MetOx and LiOH. Thus the interchangeability of all three systems still remains an option for future missions.

#### 4.2.5. Systems Comparison and Integration

Overall, the RCA and LiOH systems have significantly lower weight than the regenerative MetOx system. Table 4 shows that RCA measures carbon dioxide removal by kg/hr/CCC because it is a continuous system whereas LiOH and MetOx measure removal as kg/CCC.

**Table 4:** The required number of CCC's for the lunar surface mission, including the two CCC's in each astronaut's PLSS.

	Mass of CCC (kg)	Recommended Total CCC	Total System Mass (kg)
LiOH	2.90	4	16.13
MetOx	14.52	4	62.6
RCA	7.26	3	26.3

At 14.52 kg as opposed to 2.9 kg per CCC and a life-span no longer than LiOH, MetOx is the definitive third choice for this mission. However, the ability for

regeneration during the mission makes MetOx a superior system to LiOH in long duration missions such as on the ISS, where the mass of the regeneration oven is not a significant drawback. For shorter missions there are no significant benefits to having the MetOx system over LiOH. However, since the LiOH and MetOx canisters are interchangeable in the same ECLSS system, this decision could be easily changed later if mission duration increases. Alternatively, although LiOH is a proven technology to ensure carbon dioxide is removed from the environment, the canisters are not rechargeable, so empty canisters (0.75 kg/canister) are cumbersome to return to Earth if they are to be replenished. And finally, one of the drawbacks of RCA is that the presence of a faint ammonia smell in the ventilation loop occasionally causes discomfort to the astronaut.

There are benefits to using LiOH over MetOx for this type of mission and RCA over both LiOH and MetOx, but it is important to remain flexible. In the future, should there be some change in mission requirements or operational capabilities, this flexibility gives decision makers and mission planners more options. RCA weighs more than LiOH, but the advantage of not needing to change cartridges during EVA, eliminating the need for a time-consuming activity that is potentially dangerous and difficult, is more important than the additional mass required (4.36 kg additional/CCC). RCA is the better choice for the ECLSS system, but as a next-generation technology that is still under development and has not yet been flight-tested, this paper uses LiOH for the chosen system in all mass estimates and the concept of operations. The interchangeability of the systems means that it will be easy to switch to RCA later if/when the technology becomes mature.

#### 4.3. Sublimator Design

While cooling is typically the main concern for lunar exploration mission, during certain times of the lunar day a situation may arise that requires heat transfer to keep the astronauts warm. To allow the water running through the LCG to be heated, rather than cooled, a bypass valve in the LCG transport loop can be actuated by the astronauts. A diagram of this setup (Thermal Control Unit) is shown inside the Rover ECLSS in Figure 3. This setup is similar to the design used in the Apollo PLSS backpack which allowed different bypass levels depending on amount of cooling needed by the astronauts. The PLSS bypass line simply allowed a lower flow of the LCG water over the sublimator. Here, the bypass valve when opened will allow water to bypass the sublimator hot plate and instead flow to a heat exchanger which is exposed to direct sunlight.

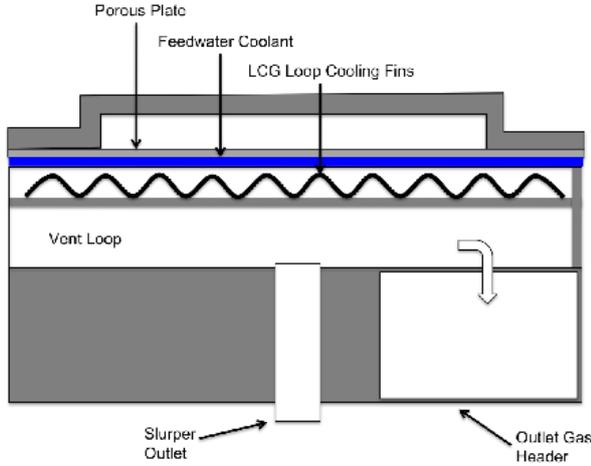


Figure 4: Cross section of sublimator

The internal design of the sublimator housing and its components, shown in Figure 4, is very similar to the Apollo PLSS design [9] and was taken to be the base model for this analysis. While future missions may use an alternate means of heat rejection, such as evaporators, basing this analysis upon proven technology provides an upper bound on mission mass while minimizing technology requirements for real world application.

The size of the sublimator is based primarily on the maximum and minimum heat loads it will have to handle. The sublimator is sized such that the ice layer will not melt at the maximum heat load, which would cause a “blowby” effect of the feedwater through the porous plate. Further, at the minimum heat load the ice layer in the sublimator must not exceed the separation distance from the porous plate, or else the expansion of the ice would crack the sublimator housing. The sublimator sizing equations used to develop this sizing model were based on [10]. Here we consider the following to be variables that the sublimator designer can set: overall heat rejection rate ( $Q$ ), heat flux from cooling loop to sublimator ( $q_A$ ), thickness of the porous plate ( $t$ ), and temperature of the water coming from the cooling garment to the sublimator ( $T_0$ ). The output of the model provides approximate volume and mass of sublimator system in addition to the expendable water supply requirements. Applying the above equations we can generate a point design for both the operational and emergency missions.

#### 4.4. Oxygen Storage System on Rover

The oxygen storage system consists of one large tank that holds gaseous oxygen and supporting connection

Table 5: Sublimator maximum requirements for one 12 hr mission at any point during lunar day.

Property	System Total
Total Sublimator System Volume	6.0 L
Sublimator Housing Mass	1.1 kg
Water Required for Sublimator	5.9 kg
Total Sublimator System Mass	7.0 kg

hoses. The design specifications of the oxygen storage tank were adapted from the oxygen tank design detailed in the Space Shuttle EMU Handbook [8]. The oxygen storage tank was designed as a cylinder with hemispherical end caps. To simplify the analysis, the ratio of tank height to diameter was set at three (that is, the tank height was three times the diameter of the tank). Given this assumption, for a given volume ( $V$ ), the diameter of the tank ( $D$ ) can be calculated as:

$$D = \left( \frac{V}{\pi} \cdot \frac{1}{\frac{3}{4} + \frac{1}{6}} \right)^{\frac{1}{3}} \quad (1)$$

Equation 1 allows the oxygen tank to be adaptively sized given the volume of oxygen required for the mission. The tank wall was assumed to be 0.65 mm thick and made out of 301 stainless steel, in accordance with the Space Shuttle EMU Handbook [8].

For this emergency system design, the total oxygen requirement was translated to tank mass and volume using the tank specifications described above. Two additional assumptions made (from the Space Shuttle EMU Handbook [8]) were the internal tank pressure (6.2 MPa) and temperature (295.15 K). An internal tank temperature of 295.15 K was determined to be achievable given the thermal environment. Radiation from the regolith and sun can be mitigated via multi-layer insulation (MLI). The thermal balance on the  $O_2$  tank confirmed the initial assumption that it could maintain an internal temperature of 295.15 K. A summary of  $O_2$  tank mass and volume can be found in Table 6.

To account for the valves, pressure regulators, and piping associated with the oxygen storage system, a margin of 20% was added to the mass and volume of the system [11]. These margins are not shown in Table 6 for clarity.

#### 4.5. Water Storage System on Rover

The water storage system was designed in a manner similar to the oxygen storage system. That is, the water tank was designed to have a height-to-diameter ratio of three and a 301 stainless steel wall that was 1.0 mm

**Table 6:** Oxygen Requirements and Storage System Sizing

	Emergency System
O <sub>2</sub> Required	0.5 kg
O <sub>2</sub> Tank Mass	1.1 kg
O <sub>2</sub> Tank Volume	6.2 L

thick. Table 7 shows the H<sub>2</sub>O storage system mass and volume for the emergency system.

To account for the valves, pressure regulators, and piping associated with the water storage system, a margin of 20% was added to the mass and volume of the system [11]. These margins are not shown in Table 7 for clarity.

**Table 7:** Water Requirements and Storage System Sizing

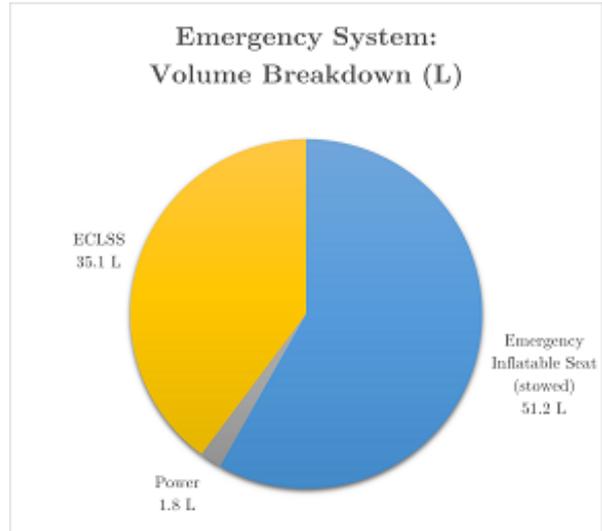
	Emergency System
H <sub>2</sub> O Required (kg)	4.4 kg
H <sub>2</sub> O Tank Mass (kg)	1.3 kg
H <sub>2</sub> O Tank Volume (L)	4.4 L

## 5. Results and Discussion

The total mass breakdown for the emergency system described in Sections 3 and 4 can be found in Figure 5. The right side of Figure 5 shows a detailed breakdown of the "ECLSS Consumables" slice, which includes the CO<sub>2</sub> scrubbing system, the water and oxygen storage tanks, the sublimator, a margin to account for pumps and hoses, and the mass of food and packaging.

The mass of the proposed emergency mitigation system was estimated to be 24.8 kg. It is important to note that this estimate does not include any margin to account for the low maturity of the design. With that said, the predicted mass of 24.8 kg fits well within the loose constraint imposed by the limits of the carrying capacity of the Apollo lunar roving vehicle (~105 kg), indicating that the proposed emergency system would not place any additional mass carrying capacity requirements on the new lunar rover design.

In addition, Figure 6 depicts the volumetric breakdown of the emergency system. It should be noted that, even when not inflated, the inflatable shelter accounts for a majority of the system volume. However, the ECLSS and ECLSS consumables slices shown in Figure 5 (all of the components typically included in a portable life support system) account for 3/4 of the system mass. Thus, the inflatable structure did not play as large a role in system mass as it did in system volume.



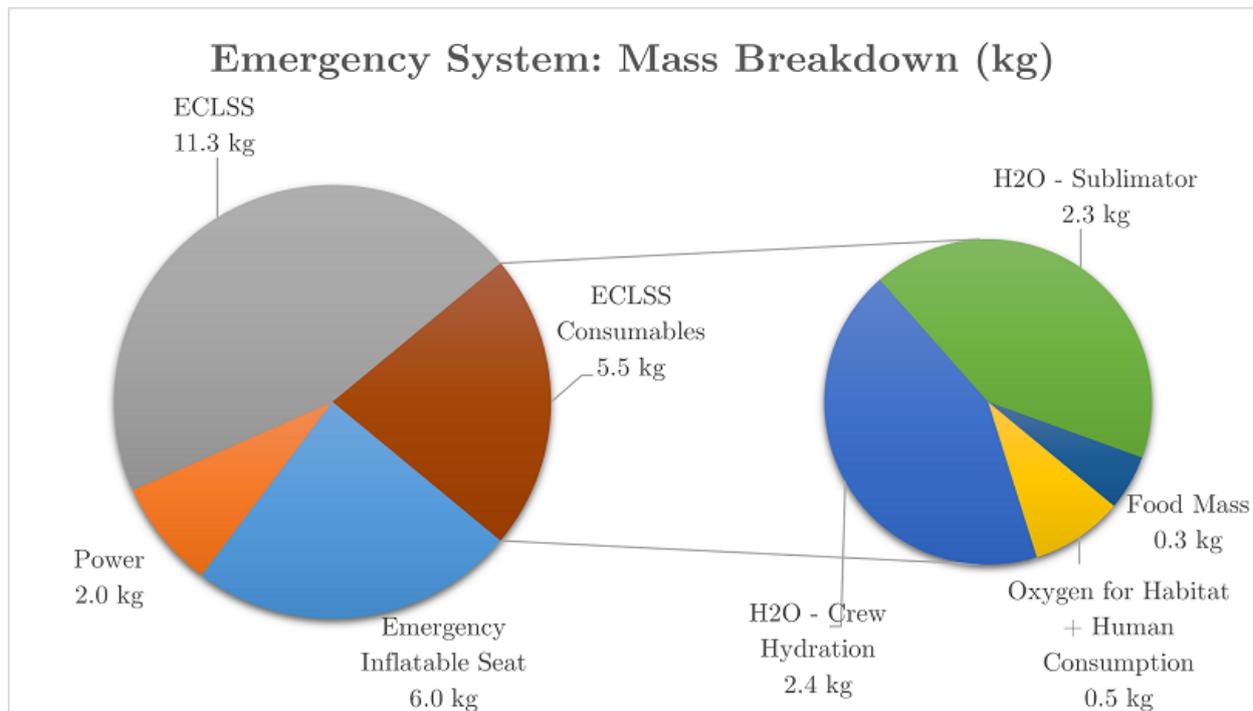
**Figure 6:** The volumetric breakdown of the subsystems within the emergency system.

This may be due to the conservative estimate of an inflatable packing factor of two. Further research could focus on designing an inflatable structure that is thinner and has a lower packing factor, to reduce the volume occupied by the stowed inflatable system.

Besides the reduction of the inflatable structure thickness and packing factor, an area of future work of this emergency system would be the design of the system and the conops for transferring the astronaut from the inflatable structure into the safety of the LEM upon return of the mission. A return from mission after a rover failure scenario would simply require all three astronauts to enter the LEM under existing conops. However, a return from mission after a suit failure or a medical emergency that requires the injured astronaut to remain in the safety of the inflatable structure, is beyond the scope of the design of this emergency system and requires further investigation.

## 6. Conclusion

The analysis presented in this work provides a preliminary assessment of a proposed system to extend safe lunar surface EVA range and scientific capabilities. The approach detailed herein described an emergency mitigation system. This system contains an ECLSS on the rover and a small inflatable shelter around the passenger seat that can be inflated with an astronaut inside if necessary. The proposed emergency system has the potential to expand EVA capabilities by providing single-



**Figure 5:** The mass breakdown of the subsystems within the emergency system.

fault tolerance in the face of a wide variety of suit and rover failure modes.

The viability of this proposed system was evaluated and found to be compatible with the Apollo lunar roving vehicle design. Assuming that future rovers have a larger carrying capacity than the Apollo era rovers, this demonstrates that both the mass and volume of these proposed systems can be accommodated by the rover to greatly increase the range and capability of science and exploration missions on the lunar surface.

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