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Trade Study Analysis of a Cryogenic Oxygen Architecture for Lunar Outpost Life Support

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A trade study was performed to compare the use of cryogenic liquid oxygen (LOX) with high pressure gaseous oxygen (GOX) and electrolysis approaches for Lunar outpost life support, which consists of a surface habitat and pressurized rover. This study presents the mission details pertaining to a Lunar outpost architecture, discusses the viable concept of operations for each architecture, and compares the equivalent system mass (ESM) of the cryogenic LOX, high pressure GOX, and electrolysis approaches across different parameter trades, e.g. mission duration or extravehicular activity frequency, for the single and 10-year mission architectures. For a single nominal mission, high pressure GOX is favored for short missions (< 50 days); cryogenic LOX is favored for a wide-range of mission durations (50 – 270 days); and the electrolysis approach is favored for long missions (> 270 days). However, when considering a 10-year mission architecture, each additional resupply negatively impacts cryogenic LOX due to the additional replacement tankage. Thus, over a 10-year mission, an electrolysis approach, which can provide all life support O_2 utilizing solely recovered H_2O, appears to be favored over cryogenic LOX. However, a real electrolysis system may need resupplied H_2O due to incomplete closure of the air revitalization loop. Thus, the cryogenic LOX approach was compared with the electrolysis approaches utilizing 100% resupplied or 100% recovered H_2O to approximate the resupplied to recovered H_2O ratio, i.e. the degree of loop closure, where one approach trades over the other. Additionally, gaps were identified, which are expected to affect the viability and trade of cryogenic LOX. These include the development of cryogenic pumps and vaporizers to generate high pressure GOX from LOX as well as understanding payload limitations which can affect O_2 resupply.

Nomenclature

AOGA = Advanced Oxygen Generation Assembly
CM = Crewmember
ConOps = Concept of Operations
ECLS = Environmental Control and Life Support
ESM = Equivalent System Mass
EVA = Extravehicular Activity
FSH = Foundational Surface Habitat
GOX = Gaseous O_2
ISS = International Space Station
LOX = Liquid O_2
MLI = Multilayer Insulation
NORS = Nitrogen/Oxygen Recharge System
OGA = Oxygen Generation Assembly
PLSS = Portable Life Support Subsystem
SPR = Small Pressurized Rover

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I. Introduction

Current options for supplying life support O_2 used for both the cabin and extravehicular activities (EVAs) consist of high pressure gaseous O_2 (GOX) storage or electrolysis approaches. These approaches are typically favored for contrasting mission durations.[1, 2] A high pressure GOX storage architecture tends to be favored for short missions where less infrastructure is necessary; however, over long exploration missions the required tankage tends to rapidly increase this approach's cost. For an electrolysis architecture where H_2O is converted O_2 and H_2 via an electrolysis unit, e.g. the oxygen generation assembly (OGA) or advanced oxygen generation assembly (AOGA), the initial mass, volume, and power investments tend to be very large, which tends to cause it to be disfavored for shorter missions.[1, 2, 3] However, due to the ability to utilize H_2O, which is either recovered from regenerative environmental control and life support (ECLS) subsystems or resupplied in more mass efficient water storage tanks and/or bags compared to high pressure gas tanks, electrolysis tends to trade well over long mission durations.

Over the years, significant advancements have been made to improve cryogenics for in-space satellites as well as propellant storage. Advancements such as development of a zero boiloff cryocooler and improved cryogenic tanks for the long duration storage of cryogenic propellants (O_2 and H_2) in space and on planetary surfaces[4, 5, 6] as well as cryogenics to improve in space telescope and detector sensitivities.[7] By utilizing these advanced cryogenic storage technologies to enable long term storage of LOX, it may be possible to provide life support O_2 at a fraction of the cost compared to high pressure GOX storage and with less process units compared to electrolysis options.

The objectives of this trade study are to (1) gather the latest mission and technology details pertaining to a Lunar base mission; (2) present different O_2 architectures for supplying cabin and EVA O_2 as well as their respective concept of operations (ConOps); and (3) perform an ESM analysis comparing the total costs of the cryogenic LOX, high pressure GOX, and electrolysis approaches across different parameter trades, e.g. mission duration or EVA frequency, for a single nominal mission and multi-year mission architecture. These objectives will allow for the investigation of potential mass, volume, and power savings associated with the use of cryogenic liquid O_2 (LOX). Additional insights will be provided on the technology and knowledge gaps, which may currently affect the trade of cryogenic LOX.

II. Analysis Methodology and Assumptions

Different O_2 architectures may be traded by comparing their equivalent system mass (ESM). ESM is a method to compare different physical quantities, which are representative of a system, by converting these different quantities into a single variable. Quantities such as volume, power, and thermal load can be converted to equivalent masses by utilizing appropriate equivalency factors associated with the habitat/vehicle. For example, a power-mass equivalency factor can be calculated by dividing the average power output by the mass of the power generating equipment. Equation (1) shows the calculation of an ESM, which incorporates mass, volume, power, and heat load.

$$\mathrm{ESM} = \mathrm{M} + \mathrm{V_P E_{VP}} + \mathrm{P_E E_{PE}} + \mathrm{CE_C} + \mathrm{TE_{CT}} \tag{1}$$

In the equation, ESM is the equivalent system mass (kg), M is the system/subsystem mass (kg), V_P is the pressurized volume (m^3), P_E is the electrical power usage (kW_e), C is the heat load (kW_{th}), T is the crewtime (CM-hr), and $E_{VP}/E_{PE}/E_C/E_{CT}$ are the volume/power/thermal/crewtime equivalency factors. Note that although Equation (1) contains the crewtime equivalency factor, its consideration in this analysis was not included. The reason why crew time factors were not considered is due to the complex issue of assigning specific crewtime estimates for the different oxygen architectures without a more thorough understanding of the concept of operations for the lunar outpost scenario. The equivalency factors used in this analysis are provided in Table 1.

A. Mission Assumptions

The mission under consideration for this trade study analysis is a Lunar outpost mission architecture. For the nominal mission, the assumed habitats are the foundational surface habitat (FSH) and the small pressurized rover (SPR), which are pictured in Figure 1. Nominally, there is assumed to be 4 crewmembers (CMs), 2 within the FSH and 2 within the SPR at any time. The nominal mission duration has been assumed to be 30 days; however, the mission duration will be a parameter, which will be varied, within the trade space. Additionally, this trade study both a single mission and multiyear mission architecture, which consists of 1 mission per year for 10 years. The mission location is assumed to be at the Lunar south pole with ample sunlight to facilitate a photovoltaic and battery power source.

The specific habitat details are provided in Table 1. The surface habitat is significantly larger than the pressurized rover. Space will be a premium within the pressurized rover, which affects the possible ECLS subsystems that can be kept within the rover. The electrolyzer and cryogenic LOX storage tanks are assumed to be kept solely on the surface habitat due to these volume limitations.

Based on meetings with subject matters experts, the surface habitat is nominally expected to perform less frequent (3 EVA/CM-week) and longer duration (Nominal: 6 hr/EVA) EVAs, whereas the rover is expected to perform more frequent (6 EVA/CM-week) and shorter duration (Nominal: 4 hr/EVA) EVAs.[8] The EVA descriptions are provided in Table 1. Additionally, the mode of crewmember ingress and egress from the habitat is assumed to occur via a suitport, which significantly reduces gas losses that arise in airlock operation. Note that the surface habitat is expected to contain both a suitport + airlock combination; however, the airlock is only operated for suit maintenance. The table also contains the equivalency factors for volume, power, and cooling for each habitat. Due to its size and mobility, the volume, power, and cooling costs of the SPR is greater than that of the FSH.

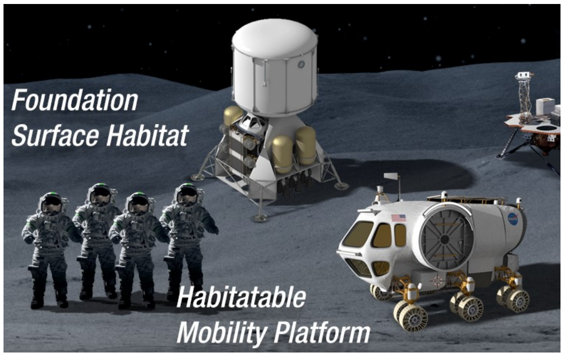

Figure 1. Illustration of the Lunar habitats.[9]

Table 1. Nominal Habitat Specific Details

Parameter	Lunar Surface Habitat	Pressurized Rover
Pressurized Volume (m^3) [10, 11, 12]	175	12.8
Cabin Environment	8.2 psia, 34% O_2	8.2 psia, 34% O_2
EVA Duration (hr) [8]	Min: 4; Average: 6; Max: 8	Min: 2; Average: 4; Max: 8
EVA Frequency (EVA/CM-week) [8]	3	6
Ingress/Egress Option	Suitport	Suitport
Volume Equivalency (kg/m^3) [12, 13]	133.1	147.3
Power Technology	Photovoltaics + Batteries	Photovoltaics + Batteries
Power Equivalency (kg/kW) [12, 13]	72.9	103.1
Cooling Technology	Radiators	Radiators
Cooling Equivalency (kg/kW) [12, 13]	102	194.8

B. Oxygen Usage Assumptions

Table 2 provides the major modes of O_2 usage, which can be categorized as cabin metabolic O_2, medical O_2, cabin leakage, and EVA O_2. Cabin metabolic consists of the crewmember metabolic O_2. Medical O_2 is a contingency supply which is assumed to be required. Currently, there is no requirement for the amount of medical O_2; however, this analysis assumes that each habitat must have 5 days equivalent of metabolic O_2 to facilitate transit from the Moon to the Earth in the case of an emergency. EVA O_2 usage depends on both the habitat and EVA duration due to the associated metabolic and suit leakage losses during the EVA as well as the pre- and post-EVA procedures.

Table 2. Different Modes of O_2 Usage [13, 14]

Operation	Units	Value
Cabin: Metabolic	kg/CM-day	0.82
Medical [a]	kg/habitat	8.2
Cabin Leakage [b]	vol%/day	0.14
EVA	--	Table 3

[a] Assume a necessary medical O_2 amount to accommodate a 5 day transit from the Moon to Earth in the case of a medical emergency at the nominal of metabolic O_2 usage.

[b] based on the ISS laboratory module.

The total EVA O_2 usages are presented in Table 3. These values were determined from the O_2 usage during EVA, which includes metabolic O_2 and suit leakages and losses; O_2 losses from suitport egress; and O_2 usage from pre- and post-EVA operations including leakage check, suit purge, depress, pre-breathe, and repress. With an exploration atmosphere (8.2 psia and 34% O_2) assumed for both the rover and habitat, a 30 minute, in-suit pre-breathe has been assumed.[15] There is a significant difference in O_2 usage between the surface habitat and pressurized rover, with the latter utilizing more O_2. The reason for this occurrence is that the surface habitat, due to its larger volume compared to the rover, may accommodate some of the expended O_2 for the pre-EVA suit purge and leakage check. Normally, these are vented into vacuum; however, it may be possible to direct these O_2 volumes to the cabin to save mass. The recycle of the suit purge and leakage check O_2 was determined to maintain the cabin O_2 concentration within its permissible bounds ($< |\pm 1\%\ O_2|$). The same, however, is not applicable to the pressurized rover. The caveat on this concept is that a design update of the suit purge valve may be necessary to allow O_2 delivery back into the cabin.

Table 3. Total O_2 Usage for EVA

Total EVA O_2 Usage (kg/CM-EVA	Habitat	EVA Duration (hr)						
		2	3	4	5	6	7	8
Low-Pressure	Surface Habitat	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090
	Pressurized Rover	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090	0.0090
High-Pressure	Surface Habitat	0.2578	0.3575	0.4572	0.5569	0.6566	0.7563	0.8560
	Pressurized Rover	0.7399	0.8396	0.9393	1.0390	1.1387	1.2384	1.3381
Total	Surface Habitat	0.2668	0.3665	0.4662	0.5659	0.6656	0.7653	0.8650
	Pressurized Rover	0.7489	0.8486	0.9483	1.0480	1.1477	1.2474	1.3471

For a nominal, 30-day mission with 4 CMs in the surface habitat (2 CMs; 3 EVA/CM-week; 6 hr/EVA) and pressurized rover (2 CMs; 6 EVA/CM-week; 4 hr/EVA) at the Lunar south pole, the total O_2 required is 159.2 kg with most of it needed for cabin metabolic O_2 (86.7 kg) and EVA (63.4 kg). Most of the EVA O_2 consists of high pressure O_2, so it is important to study the effect of different EVA scenarios which may lead to an overabundance of low pressure O_2 and undersupplying high pressure O_2 depending on the O_2 supply architecture. An additional 8.2 kg and 0.9 kg of O_2 are needed to account for medical contingency O_2 and cabin leakage.

C. General Logistics Assumptions

These assumptions have been made based on the habitat limitations or to simplify the trade study calculations.

1. An electrolysis unit (i.e. AOGA) exists solely in the surface habitat.
2. The SPR will periodically return (weekly) to the FSH for crew transfer, O_2 refill, and logistic mass transfers.
3. Cryogenic O_2 storage tanks are kept solely at the surface habitat due to limited volume in the rover.
4. The cryogenic O_2 storage tanks are kept outside, and high-pressure GOX tanks are kept inside the habitat.
5. Nominally, resupplies occur every year, and a cryogenic resupply assumes delivery of a new cryogenic tank. This assumption is partly made to simplify the analysis concept of operations, but also considers that even if it is feasible to refill an existing LOX tank at the lunar outpost, the LOX would necessarily still need to be transported from Earth to the Moon in a second cryogenic tank. Future analysis would want to explore the effect of LOX refills versus changing out the tanks.
6. In dormancy, the electrolyzer and high-pressure tanks are not functioning.
7. Refill of the GOX tanks using cryogenic LOX is assumed to take a full day where they are not useable.
8. For the nominal mission, electrolysis architectures are assumed to be using 100% recovered H_2O unless otherwise noted. This recovery efficiency is representative of a water recovery system consisting of a water processor assembly, urine processor assembly, and brine processor assembly. The 100% value was chosen as the highly idealized case of complete water loop closure. In actuality, water recovery will be lower and additional water losses, which are unrecoverable, would be expected during EVA operations.

D. Oxygen Architectures

In addition to the mission and O_2 usage assumptions, there are technology specifications needed to construct each of the O_2 supply architectures. Figure 2, Figure 3, and Figure 4 depict schematics for the different architectures: (1) high pressure GOX, (2) cryogenic LOX, and (3) electrolysis. These schematics illustrate the technologies needed for each architecture as well as the order of unit operations prior to O_2 delivery. For the cryogenic LOX architecture, two configurations are presented, a single vaporizer and recharge tank and a two-vaporizer configuration. Both configurations are going to be compared to determine viability for supplying both cabin and EVA O_2.

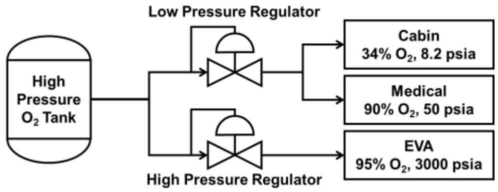

Figure 2. High pressure GOX architecture schematic

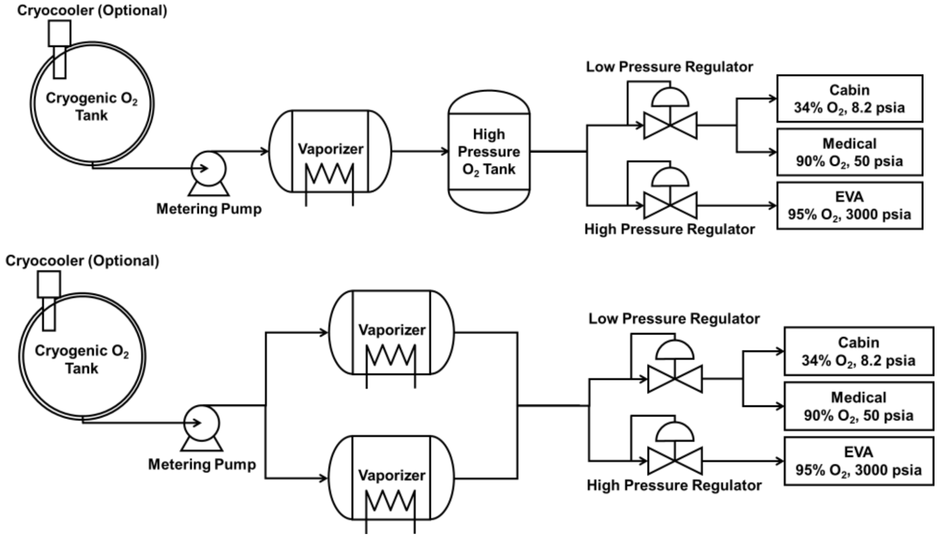

Figure 3. Cryogenic LOX architecture schematics represented by a (top) single vaporizer and recharge tank and (bottom) two-vaporizer configurations.

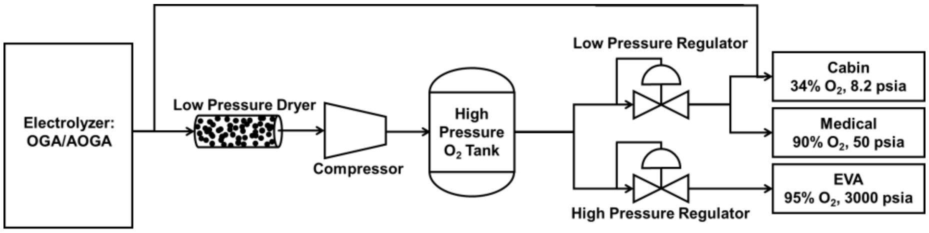

Figure 4. Electrolysis architecture schematic.

1. *Technologies for the Trade Study*

Based on the assessment of the different available technologies for each of the unit processes within the O_2 supply architectures, the following nominal technology list was selected for the trade study analysis. Some of the key units are discussed in more detail within this section including the high pressure O_2 tanks, electrolyzer, cryocooler, etc.

- **High Pressure O_2 Tank:** 4500 psia O_2 Tank
- **Cryogenic Tanks:** Cryogenic Tank with 50 MLI Layers
- **Cryocooler:** Sunpower Cryotel MT, CT, or GT Cryocooler (Cooling Capacity at 77 K = 5 – 16 W)
- **Metering Pump:** Barber Nichols Liquid O_2 Pump
- **Vaporizer:** Vaporizer Tank Conceptual Design

- **Electrolyzer:** AOGA
- **Dryer:** Consumable Desiccant Low Pressure Dryer (Nominal: 1 month lifetime)
- **Compressor:** 3-stage Oxygen Compressor

The high pressure tanks considered are based on the Nitrogen/Oxygen Recharge System (NORS) which is utilized to resupply the ISS.[16] The NORS tank can store O_2 at pressures up to 6000 psia. Thus, this tank design provides ample high pressure O_2 (> 3000 psia), which is needed for EVAs. Another 4500 psia variant is also considered, which is lighter weight at the cost of a lower proportion of high (> 3000 psia) to low (< 3000 psia) pressure O_2. A comparison of these two tank variants and their ability to maintain frequent or long EVAs will be discussed in later sections.

The electrolyzer constitutes a very important unit for a closed ECLSS where H_2O, which can be resupplied or recovered, is converted to O_2 and H_2. The OGA has been operational on the ISS since 2007. The OGA at its nominal production rate can support the oxygen needs of 4 CMs; however, at its maximum rate, it can support 11 CMs.[17, 18] Depending on the combination of EVA duration and frequency, an average O_2 production has been calculated which dictates the OGA's duty cycle, requisite O_2 production rate, and power consumption. Production in excess of the cabin metabolic is assumed to be used to maintain a full high pressure O_2 tank. Under high EVA frequency scenarios, it may be possible to have a duty cycle, which exceeds 100%. In these cases, the OGA mass, volume, power, and cooling are assumed to scale linearly with the duty cycle. In development is the AOGA which improves upon the design of the ISS OGA.[18] Some of the major differences between the AOGA and the OGA include the addition of maintainable domes, a manual flushing capability to enable dormancy, and general component upgrades to improve reliability. The hydrogen dome of the OGA, which surrounds the cell stack and the rotary separator accumulator, will be replaced with two serviceable domes around each component. This update allows maintenance within the domes and the ability to change components rather than orbital replacement units, which will reduce the spares mass. The spares analysis in this study assumes a minimum of one spare for each non-redundant component.

Cryogenic storage tanks have existed since the Apollo missions where they were utilized to supply O_2 to the ECLS system and O_2 and H_2 to fuel cells to generate power. They have also been utilized on Space Shuttle missions to the ISS in the same manner. Cryogenic tank sizing has been performed assuming 50 layers of MLI and is dependent on the type of cryogen, total cryogenic mass, tank material, environmental temperature, mission duration, and cryocooler specifications. The cryogenic tank sizing outputs include the tank mass, tank volume, boiloff mass, and heat leak. Although there have been recent cryogenic developments such as the cryogenic flux capacitor[19] and aerogel-based insulations[20], which may provide a simpler, low-pressure storage architecture or improved robustness, neither of these developments are at a high enough technology readiness level to be considered in this study, with technology readiness levels of approximately 3-4 and 5-6, respectively.

In the past decade, the development and utilization of space cryocoolers has increased dramatically.[4, 5, 6, 7] These cryocoolers are typically utilized for space probes and telescopes to cool detectors to low temperatures to improve performance. Current developments in cryocoolers at NASA have focused on state-of-the-art, large cryocoolers for propellant storage. These consist of the 20 K, 20W cryocooler for LH_2 and the 90 K, 150 W cryocooler for LOX storage.[21] In comparison to propellant masses (> 10,000 kg), life support needs for O_2 are significantly lower (~159 kg). Thus, the state-of-the-art, large cryocoolers are severely oversized for ECLSS. Instead, this analysis assumes the use of the Sunpower cryocoolers.[22] These are cryocoolers which have seen use in real space applications with technology readiness levels of 8 - 9.

Following the cryogenic storage tank, a cryogenic pump may be needed to transport LOX to the vaporizer. Although industrial cryogenic pumps, are capable of pumping at high pressures which may be necessary, they are also severely oversized compared to life support O_2 needs and tend to have limited lifetimes due to seal wear. Barber Nichols has developed a produced multiple LOX pumps for NASA related research and testing. Although, Barber Nichols has designed large rocket loading pumps for LOX with up to 200 psig outlet pressures, the development of an appropriately sized cryogenic pump, which can produce large pump head (> 100 psi) presents a technology gap.

The vaporizer converts LOX to GOX and pressurizes the O_2 so that it may be used to fill the PLSS tanks for EVAs. Industrial vaporizers do exist; however, like the cryogenic pumps, they are severely oversized. For this trade study, the conceptual design of a tank vaporizer with a built-in heater was performed. The conceptual vaporizer design consists of a high pressure gas tank, drum heater, and pressure and mass flow controllers. Depending on the external temperature, a tank containing LOX may self-pressurize; however, the built-in heater is considered to provide the crewmembers with control over the pressurization process. The details of this conceptual vaporizer design are described herein; however, it should be understood that the design used in this trade study represents just a basic, first-pass estimate. Significant effort will be needed to design and test an appropriate vaporizer.

III. Analysis Results and Discussion

The following sections provide the results and discussion for the trade analyses. These include (1) a comparison of different cryogenic tank configurations and ConOps of viable operation modes; (2) ESM comparisons of a single mission; and (3) ESM comparisons over the 10-year return mission scenario.

A. Cryogenic Configuration and ConOps Analysis

1. *Single Vaporizer + Recharge Tank versus Two-Vaporizer Configuration*

The section compares the ConOps of the different vaporizer configuration shown in Figure 3. Consider a single vaporizer and recharge tank whose ConOps can be simplified as:

1. Fill the vaporizer with LOX.
2. Apply heat to the vaporizer to pressurize it to the fill pressure (4500 psia).
3. Equilibrate the vaporizer with the recharge tank.
4. Repeat steps 1 – 3 until an adequate fill level is achieved.

The ConOps are illustrated in Table 4 which provides the fill number, time (assuming 6 hrs per pressurization and equalization step), recharge tank pressure, and percent fill of the recharge tank. This calculation suggests that a significant amount of time to fill the recharge tank may be needed. To achieve a fill percentage of > 90%, 4 fills are required, which can take 24 hrs when utilizing a 200 W heater. The speed at which GOX is pressurized may be improved by utilizing a more powerful heater; however, this will require increased infrastructure to supply the necessary power. A greater concern is the large pressure gradient that a cryogenic pump will have to work against to fill the vaporizer tank. The high pressure fills on the vaporizer may be prohibitive with current cryogenic pump technologies. Technology development of an appropriate high pressure, metering cryogenic pump would be necessary for this configuration. Additionally, with a single vaporizer and recharge tank, the latter must be refilled each time the pressure drops below 3000 psia to facilitate filling of the PLSS tanks, which necessitates more periodic fills.

Table 4. Fill ConOps of a Single Vaporizer and Recharge Tank Configuration

Fill Number	Time (hr) [a]	Tank Pressure (psia)	Tank Fill Percentage (%)
1	6	2250	50%
2	12	3375	75%
3	18	3937.5	87.5%
4	24	4218.8	93.8%

[a] The vaporizer tank heater is assumed to be sized for a 6-hour pressurization.

Instead, consider the two-vaporizer configuration. By configuring the vaporizer tanks in parallel to one another, a cascading fill procedure may be implemented to provide EVA O_2. An example of the ConOps is provided.

- Tank 1 (partially filled) = 2500 psia and Tank 2 (full) = 4500 psia
- Use Tank 1 to fill the PLSS tank to 2500 psia.
- Switch to Tank 2 to fill the PLSS tank to 3000 psia.

By cascading the vaporizer tanks, low pressure O_2 (< 3000 psia) may still be utilized for high pressure O_2 refills. Using this type of scheme for supplying O_2 may allow a tank, which has dropped below the high pressure threshold of 3000 psia, to still be used for cabin metabolic and EVA O_2. If properly sized, the vaporizer tanks may alternatingly be utilized until near empty, which mitigates the LOX pumping issue against a large pressure gradient. Further analysis of this cascading ConOps is provided in Section 3: Concept of Operations for Two-Vaporizer Configuration. For the ESM analysis, the cryogenic O_2 architecture assumes the use of the two-vaporizer configuration.

2. *LOX Delivery Methods*

As indicated, an issue with LOX delivery to a vaporizer or another associated tank is the large pressure gradient (> 100 psia). This section discusses LOX delivery solutions. This is not an all-encompassing list and additional consideration is necessary to determine the best courses of action. Possible solutions for LOX delivery include:

1. Development of a cryogenic pump capable of pump heads greater than hundreds of psia
2. Re-liquefying the remaining GOX to LOX to reduce the pressure gradient
3. Pressurization of the cryogenic tank with residual GOX and a sparger in the vaporizer for cooling

4. Compressing the residual GOX to the other vaporizer tank(s)
5. Venting the remaining GOX

The first solution reiterates the points made previously that an appropriately sized cryogenic pump for life support which is also able to pump against a large pressure gradient will need to be developed. The second solution involves the liquefaction of the remaining GOX in the vaporizer to reduce its pressure. This may be enabled by delivering a controlled flow of GOX to the cryogenic storage tank and cryocooler where excess cooling capacity is used to liquefy GOX to LOX. Table 5 provides simplified calculations to show the viability of this approach. Assuming a 4500 psia vaporizer and an empty threshold of 500 psia, 958.8 kJ of cooling is needed to produce a target tank pressure of 25 psia. Utilizing the excess cooling capacity of the Cryotel cryocoolers under the worst environmental conditions for conservatism, the liquefaction process could take 14.7 hrs with the largest cryocooler. Thus, this solution may be able to refill the vaporizer tanks with LOX within one full day. Additionally, a cold environment if present can also aid in the liquefaction process. This back-of-the-envelope calculation suggests the viability of this solution; however, detailed thermal analysis and testing would be necessary to confirm this.

Table 5. Depressurization Time Estimate Calculations from Liquefaction

Initial and Target Points			
Initial "Empty" Pressure	500 psia	Target Pressure	25 psia
Initial Temperature	294.3 K	Target Temperature	90 K
Heat Load for Liquefaction			
Sensible Heat to 90 K		544.3 kJ	
Heat of Vaporization × Mass		414.5 kJ	
Excess Cooling Capacity = Cryocooler Capacity - Heat Leak			
Heat Leak at Max Temperature (300 K)		2.7 W	
Excess Cooling Capacity (Cryotel GT at 90 K)		18.1 W	
Depressurization Time		**14.7 hr**	

The third solution is to use the remaining high-pressure GOX in the vaporizer tank to pressurize the ullage of the cryogenic storage tank. An equilibrated cryogenic storage tank and vaporizer tank will allow flow to be initiated by utilizing the current cryogenic pump. Additionally, a sparger at the vaporizer tank inlet (Figure 5b) may be utilized to promote improved heat transfer and rapid cooling of the remaining GOX in the vaporizer. Rapid cooling would result in a collapse of the pressure within the vaporizer, which can stimulate flow from the cryogenic storage tank without needing to operate the cryogenic pump. A similar type of solution for producing high pressure cryogenic liquid and gas has been presented in a prior patent.[23] However, if the cryogenic tank is going to be pressurized, it will need to be designed for the maximum expected pressure, which will result in a thicker walled and heavier cryogenic tank.

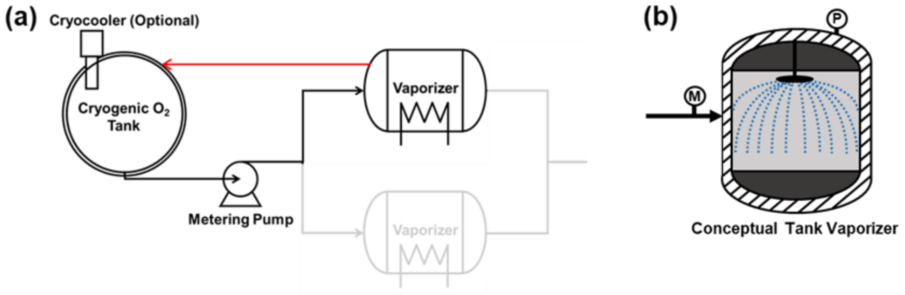

Figure 5. (a) Schematic of the two-vaporizer configuration with a direct line from the pressurized vaporizer to the cryogenic storage tank. (b) Illustration of an example of a sparger within a vaporizer tank to facilitate rapid cooling.

The fourth solution is to deliver the residual GOX from the vaporizer tank, which is considered empty, to the fuller vaporizer tank. To do so would require a compressor to not only transport the GOX but also pressurize up to the fill pressure of the other vaporizer tank. This represents another technology gap which is the development of a compressor that can accept high pressure GOX and pressurize it higher, e.g. 4500 or 6000 psia for a vaporizer design based on the high pressure O_2 tanks.

The final proposed solution is the simplest, which is to vent the remaining O_2 in the vaporizer. It may be possible to minimize O_2 losses and increase mass savings just by venting the remaining O_2. For example, if the vaporizer were able to be utilized until it reaches 100 psia, this would represent the venting of 2.2% of the supplied O_2. Over a nominal 30-day mission with 159.2 kg of O_2 total, this is equal to 3.5 kg of O_2. The infrastructure to facilitate the venting of O_2 may be less than the other proposed solutions, so by venting O_2, it may be possible to produce a less costly system.

3. *Concept of Operations for Two-Vaporizer Configuration*

The ConOps for the two-vaporizer cascade have been analyzed to discuss their feasibility in different EVA scenarios. Consider the following example ConOps for a two-vaporizer cascade.

1. If Tank 1 (> 3000 psia) and Tank 2 (> 3000 psia),
    a) Use Tank 1 for cabin and EVA.
2. If Tank 1 (1500 psia < P_1 < 3000 psia) and Tank 2 (> 3000 psia),
    a) Use Tank 1 to fill PLSS tanks to P_1 and cabin, and
    b) Use Tank 2 for remaining fill.
3. If Tank 1 (500 psia < P_1 < 1500 psia) and Tank 2 (> 3000 psia),
    a) Use Tank 1 for cabin, and
    b) Use Tank 2 for EVA.
4. If Tank 1 (< 500 psia) and Tank 2 (> 3000 psia),
    a) Use Tank 2 for cabin and EVA, and
    b) Repeat steps 1 – 4 with the tanks switched after refilling Tank 1.

This ConOps was applied for a nominal mission and the resultant pressure vs. time for the tanks are presented in the figures below. When operating the two-vaporizer configuration in cascade, it is important to ensure that at all points in time there is always high pressure O_2, i.e. at no point can Tank 1 and Tank 2 be less than 3000 psia. From the analysis, the comparison of a 4500 or 6000 psia vaporizer tanks shows that the latter can maintain its pressure above 3000 psia longer. Additionally, due to the smaller habitat volume of the pressurized rover and its higher associated O_2 usage per EVA, the tank pressure decay in the rover is significantly faster compared to the surface habitat. Thus, if a higher frequency or longer duration EVAs are desired in the rover, it is likely that the number of vaporizers will need to be increased or the size of the vaporizer tanks will need to be increased.

Based on the current vaporizer tank sizes, this analysis shows that the tanks are quite large relative to the O_2 usage rate where even in the worst case, i.e. 4500 psia vaporizer in the rover, the vaporizers only need to be refilled every ~15 days. Thus, the tanks would not need to be refilled at each rendezvous between the surface habitat and rover.

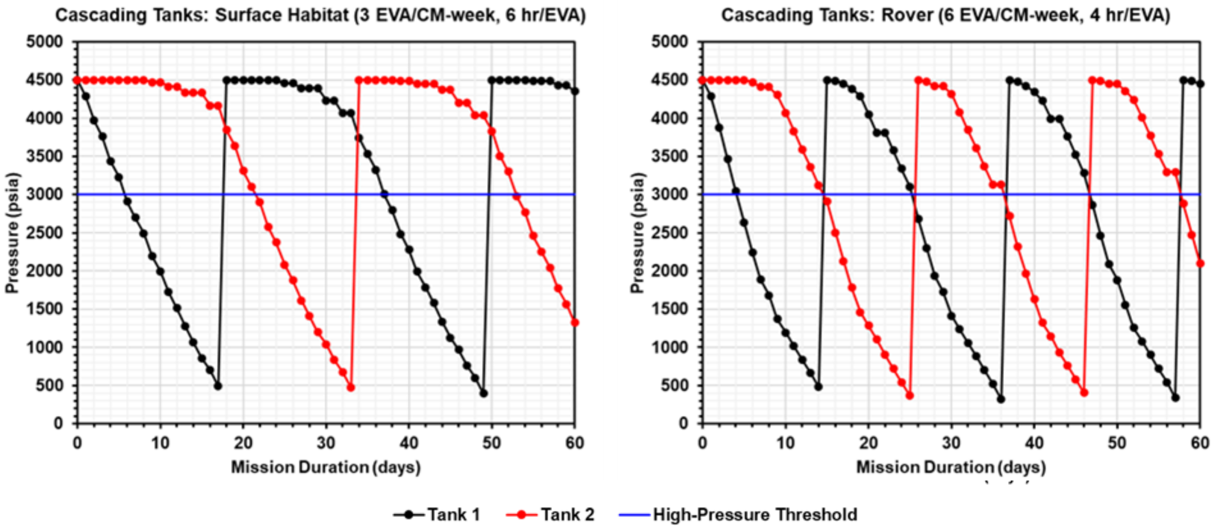

Figure 6. Pressure within vaporizer tanks with 4500 psia max fill pressure versus time.

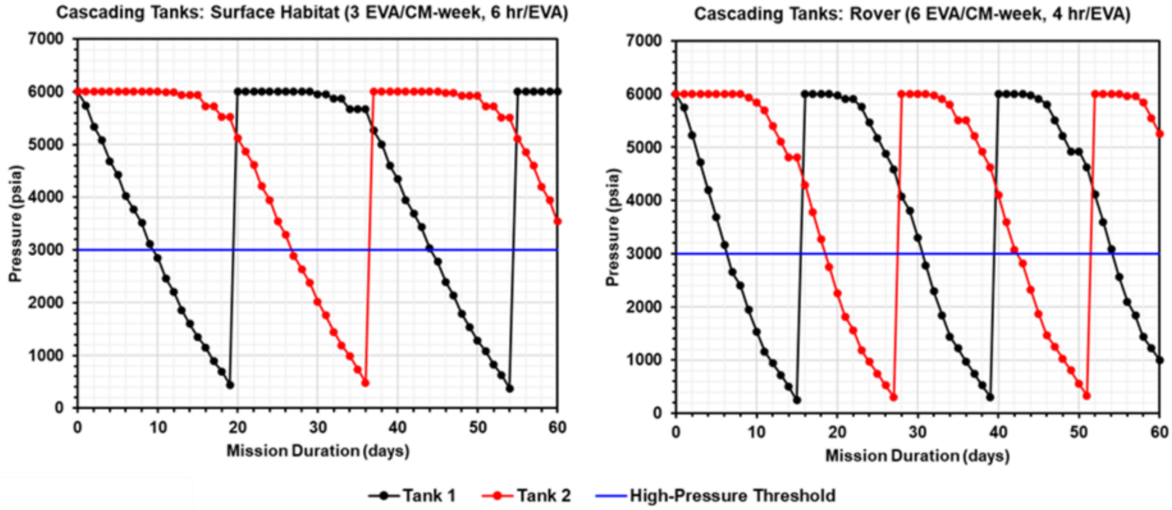

Figure 7. Pressure within vaporizer tanks with 6000 psia max fill pressure versus time.

Table 6. Number of Cascading Vaporizers Needed

EVA Frequency (EVA/week)	EVA Duration (hr/EVA)															
	2	4	6	8	2	4	6	8	2	4	6	8	2	4	6	8
	4500 psia Vaporizer								6000 psia Vaporizer							
	Surface Habitat				Rover				Surface Habitat				Rover			
2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
5	2	2	2	2	2	2	2	3	2	2	2	2	2	2	2	2
6	2	2	2	3	2	2	3	3	2	2	2	2	2	2	2	2

B. Single Mission ESM Analysis

An trade ESM analysis for a single mission is presented herein which compares the O_2 supply architectures of cryogenic LOX with and without a cryocooler, high pressure GOX tanks, and water electrolysis. The cryogenic architecture assumes a two vaporizer configuration to provide sufficient high pressure (> 3000 psia) EVA O_2. This trade considers the effect of mission duration, EVA duration and frequency, and environment temperature.

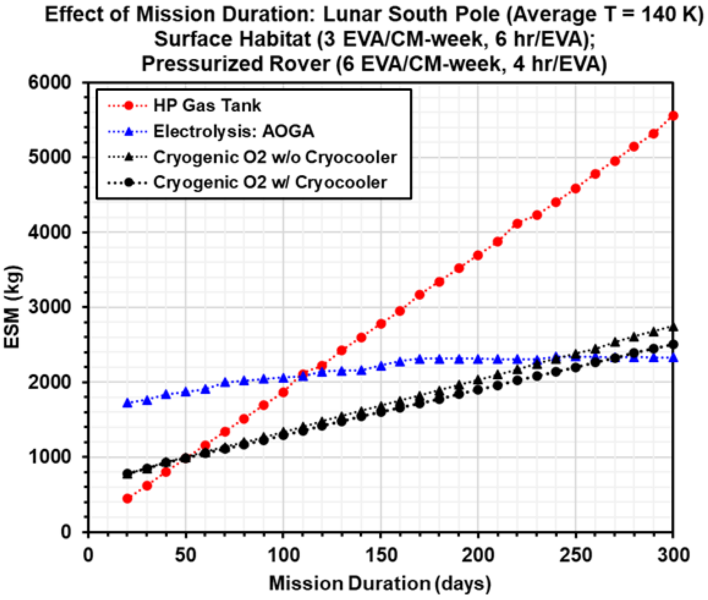

Figure 8. ESM versus mission duration for the O_2 architectures.

1. *Effect of Mission Duration*

The effect of mission duration was examined for a single mission with a surface habitat (3 EVA/CM-week, 6 hr/EVA) and a pressurized rover (6 EVA/CM-week, 4 hr/EVA). The ESM versus mission duration is shown in Figure 8. The results show three different regimes where each O_2 supply architecture is most favorable. For short duration (< 50 days) missions, the high pressure GOX tank architecture is favored since this uses the least amount of equipment. It is also the simplest to operate. However, as the mission duration increases, the ESM for the high pressure GOX tank architecture rapidly increases due to the heavy tankage.

For medium and some long duration missions (50 – 270 days) cryogenic O_2 storage is favored. The figure shows a trendline for both cryogenic storage with and without a cryocooler. In all cases, the configuration without a cryocooler is more costly than with a cryocooler due to the O_2 boiloff over the course of the mission. The cryogenic LOX trends linearly like the high pressure tank architecture; however, its slope is significantly shallower because of its greater mass efficiency, i.e. mass of the cryogenic tank versus O_2 capacity, compared to high pressure tanks.

Over long missions (> 270 days), the electrolysis architecture with 100% recovered water is favored. Interestingly, the ESM for electrolysis is not linear like the other architectures but plateaus as the mission duration increases and even tends to slightly decrease. This result is caused by the ESM per kg of recovered H_2O correlation, which was applied from French *et al.* (2019) [24], which decreases as mission duration increases. This trend appears to indicate that the initial cost for electrolysis is quite high; however, as the mission duration increases, or potentially as more missions are performed to a Lunar base, the tradeoff will eventually become favorable towards electrolysis. A breakdown of the ESM is provided for the mission durations of 50 and 270 days in the Appendix: Table 8.

2. *ESM Breakdown for a Single Mission*

An ESM breakdown for some of the 30-day, single mission scenarios is provided in Figure 9, which includes the min, average, and max EVA duration. In all cases, the largest ESM component by far is the launched mass for all the necessary equipment as well as the consumables. This is followed by the volume, power, and cooling costs. When comparing the ESM breakdown for electrolysis with the other architectures, it is evident that for a single, short mission (30-days) the mass, volume, power, and cooling investment for electrolysis is very significant where the entire AOGA rack must be provided as well as the spares and maintenance items and requisite infrastructure to power the unit. Also, electrolysis requires other downstream units including the consumable dryers, compressor, and intermediate storage tanks.

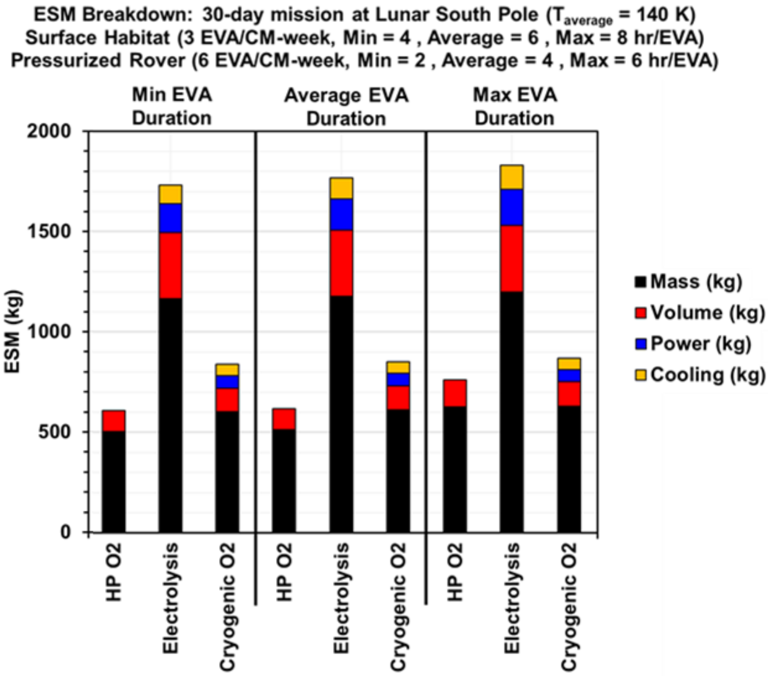

Figure 9. ESM breakdown for a single mission. The cryogenic O_2 architecture includes the cryocooler.

In comparison, high pressure tanks and cryogenic storage require much less power. Cryogenic storage does utilize power for eliminating boiloff and heating the vaporizer; however, due to how capable MLI is at minimizing heat leaks, the cryocooler chosen can be the smallest Cryotel MT with 5 W cooling capacity, which requires just 80 W of power to operate, a small fraction of the power requirement of the AOGA. The tradeoff between the electrolysis and other architectures essentially comes down to the initial equipment mass for the AOGA and spares versus the tankage cost for high pressure GOX or cryogenic LOX and their resupply over long or multiple missions.

3. *Effect of EVA Duration and Frequency*

To study the effect of EVA duration and frequency, this analysis focused specifically on the rover, which performs more EVAs and can accommodate less excess O_2 from EVA procedures. Figure 10 shows the effect of EVA duration and frequency, respectively. These figures tend to show two major implications. The first is that EVA frequency has a greater effect on ESM than EVA duration due to not only increasing the amount of O_2 usage during the EVA but also increasing the number of pre- and post EVA operations. The second observation is there appearing to be a transitional point with the high pressure GOX and cryogenic LOX architectures where a step change in the ESM is observed. This occurs when the EVA frequency increases from 4 to 5 EVA/CM-week and from 5 to 6 EVA/CM-week for the high pressure GOX and cryogenic LOX architectures, respectively. These step changes are indicative of transitions which cause the system to be high pressure O_2 limited where the ratio of high to low pressure O_2 supplied by the tanks and vaporizers may not be able to accommodate EVA needs. Thus, these transitions are accompanied by increases in the number of tanks and vaporizers for each respective configuration. Additional care should be taken to ensure that the O_2 supply architecture can meet high pressure O_2 demands.

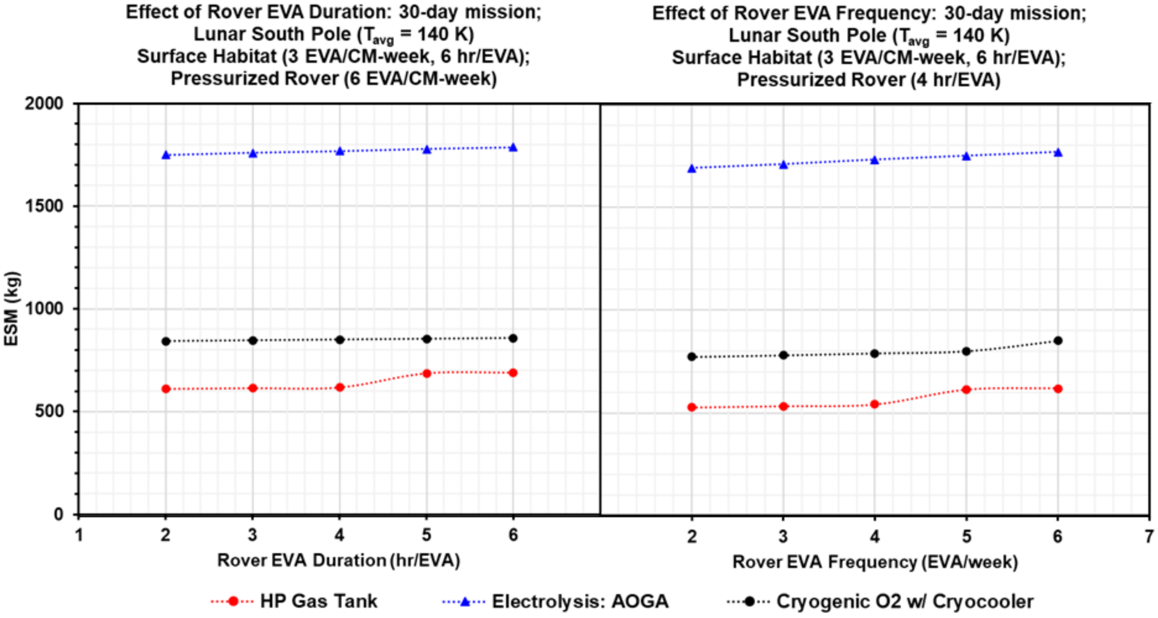

Figure 10. ESM versus EVA duration and frequency in the pressurized rover for different O_2 architectures.

4. *Effect of the Environmental Temperature*

When examining the effect of the environmental temperature, this analysis focuses solely on the cryogenic architecture with the cryocooler since the case without the cryocooler has been shown to be significantly more costly due to the boiloff masses, which will be inherently affected by the environmental temperature. Figure 11 shows the ESM versus mission duration results for a cryogenic LOX architecture with a cryocooler. The cryogenic LOX architecture with a cryocooler sees the ESM trendlines essentially collapsing onto one another. This occurs because even at the maximum environmental temperature, the smallest Cryotel MT cryocooler with 5 W cooling capacity is still oversized for the heat leaks. Thus, with active cooling implemented, it is possible to have indefinite storage of LOX under different Lunar conditions.

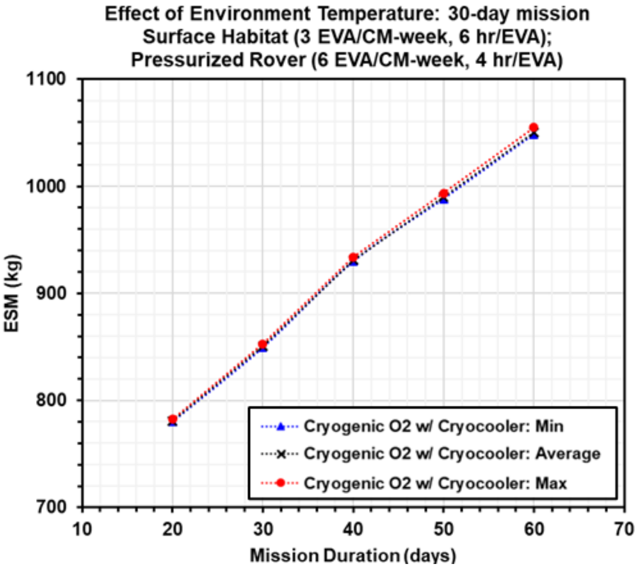

Figure 11. ESM at the min (70 K), average (140 K), and max (300 K) Lunar south pole temperature.

C. 10-year Mission ESM Analysis

1. *Effect of Dormancy on Boiloff*

When looking at a multi-year mission additional options are presented for the long-term storage of cryogenic LOX, which may be needed for the dormancy periods. Table 7 below presents the cryogenic LOX tank mass and O_2 boiloff for different resupply intervals, which range from 1 to 5 years, and for the configuration with and without a cryocooler. In the case of a 1-year resupply, each mission will provide the total life support O_2 for the single mission without concern of the dormancy period. This is illustrated by the small amount of boiloff (10 kg) without the cryocooler. However, as soon as any type of dormancy is incurred, the amount of O_2 boiloff becomes severe without a cryocooler. Even with a 2-year resupply interval, the boiloff mass (309 kg) nearly equals the total life support O_2 mass for 2 missions (313 kg). The amount of boiloff worsens with increasing resupply interval if no cryocooler is used and can be multiple times the total life support O_2 amount. This suggests that active cooling is favored for long missions.

Table 7. Effect of Dormancy on Tank and Boiloff Mass: 30-day mission; Lunar South Pole (T_{avg} = 140 K); Surface Habitat: 3 EVA/week; Rover: 6 EVA/week

Resupply Interval (years)	With Cryocooler			Without Cryocooler			
	Tank Mass (kg)	Tank Volume (m^3)	O_2 Capacity (kg)	Tank Mass (kg)	Tank Volume (m^3)	O_2 Capacity (kg)	Boiloff (kg)
1	62	0.20	159	63	0.21	169	10
2	68	0.38	313	80	0.71	621	309
5	85	0.87	772	123	2.01	1857	1086

2. *Effect of Mission Duration on the 10-year ESM*

The ESM analysis for the different O_2 supply architectures was performed over a nominal 10-year mission with yearly resupply. Figure 12 shows the ESM versus the individual mission duration. Note that the electrolysis architecture is shown for a configuration with 100% recovered or 100% resupplied H_2O. The electrolysis architecture with 100% recovered H_2O is found to be most favorable across all mission durations. This contrasts with the single mission analysis where cryogenic LOX was favored between 50 – 270 day missions. The difference between the single and 10-year missions is that resupplies negatively affect architectures which require additional tank deliveries. Electrolysis with 100% recovered water need only account for the additional recovered water needed with increasing duration, whereas the cryogenic LOX architecture must provide a resupply of LOX as well as the cryogenic tank to contain it. A breakdown of the ESM is provided in the Appendix: Table 9.

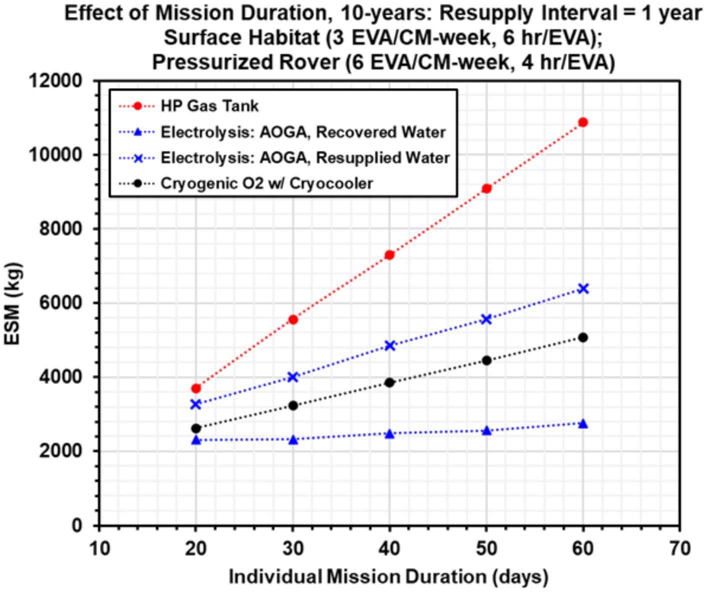

Figure 12. 10-year mission ESM versus single mission duration for different O_2 supply architectures.

In consideration of a real electrolysis architecture, recovered water may not be able to solely supply all life support O_2 needs. This is especially true of the rover operations, which will not have its own closed ECLSS. Some of the key performance parameters of the water recovery system is a >98% from urine and 95% from brine utilizing the water, urine, and brine processor assemblies. [25] Considering a system with 98% water recovery, a crewmember may receive or generate 4.47 kg/CM-day of water as potable water, water from food, and metabolic water.[13] That mass of water is output as fecal water, respiration, perspiration, and urine. If the water recovery system recycles 4.38 kg/CM-day of water, then 3.22 kg/CM-day of that is used for food prep, drinking water, and makeup water due to perspiration from exercise. The excess 1.16 kg/CM-day of recovered water may be used for electrolysis. In comparison, a 30-day mission with 3 EVA/CM-week from the surface habitat amd 6 EVA/CM-week from the rover requires 1.30 kg/CM-day and 1.83 kg/CM-day of water, respectively. Thus, this excess recovered water alone does not provide 100% of the water necessary for electrolysis. Trash processing provides an additional means of recovering excess water. Waste is generated at 1.45 kg/CM-day with a water concentration of 36.5%. [26] This additional water recovery may provide a total excess water recovered of 1.68 kg/CM-day, which could completely support the crew's O_2 needs.

Thus, the electrolysis with 100% recovered H_2O provides the lower bound ESM and the electrolysis with 100% resupplied H_2O provides the upper bound ESM. As seen in the figure, cryogenic LOX lies between the lower and upper bounding electrolysis architectures. Thus, there are missions depending on the ratio of recovered to resupplied H_2O where cryogenic LOX may be deemed favorable and less costly over the 10-year mission timeline. If the ESM from the lower bound, recovered H_2O case to the upper bound, resupplied H_2O case is assumed to correlate linearly with the ratio of recovered to resupplied H_2O then the relative position of the cryogenic LOX ESM in between the lower and upper bounds is indicative of the ratio of recovered to resupplied H_2O where electrolysis begins to be favored over cryogenic LOX. With this assumption, the results suggest that at lower individual mission durations cryogenic LOX is more likely to be favored even with a significant proportion of life support O_2 being supplied from recovered H_2O and vice versa for the high individual mission durations. For the nominal, 30-day individual mission, electrolysis appears to become more favorable when recovered H_2O can produce 46% of the total life support O_2. This threshold is lower for longer missions where a 60-day individual mission lowers the threshold to 36% of the total life support O_2 being supplied by recovered H_2O. This analysis indicates how well cryogenic LOX can trade over long, multi-year missions and indicates that there may be ambiguity on the best architecture over long Lunar missions.

3. *ESM Breakdown for a 10-year Mission*

The ESM breakdown for the 10-year mission is provided in Figure 13, which displays the mass, volume, power, and cooling costs depending on the resupply interval. These results show, the high pressure O_2 and electrolysis architectures to essentially be unaffected by the resupply interval since the former contains many high pressure O_2 tanks, and in the latter, the only resupplies are the spares and maintenance items, all of which can be partitioned easily across resupply missions. In contrast, the resupply interval has a significant effect on the cryogenic LOX approach assuming the tanks are scaled. With a longer resupply interval, i.e. less resupplies, the cryogenic LOX ESM decreases due to mass savings associated with the tankage. If cryogenic tanks are resupplied more frequently an additional tank is delivered with each resupply resulting in a greater mass and volume cost. However, despite the mass savings with a long resupply on the cryogenic LOX tanks, more frequent resupplies may be more feasible. Smaller cryogenic tanks, which are still quite heavy when including the LOX mass, are easier for crewmembers to maneuver, whereas large cryogenic LOX tanks with multiple missions worth of life support O_2 may be unwieldly. An additional consideration and knowledge gap is an understanding of what the available payloads on future cargo vehicles may be. Despite the significant mass and volume savings, if the crew are not able to maneuver the tank to the habitat or if the cargo vehicle is unable to accommodate such a heavy tank, then it is unfeasible.

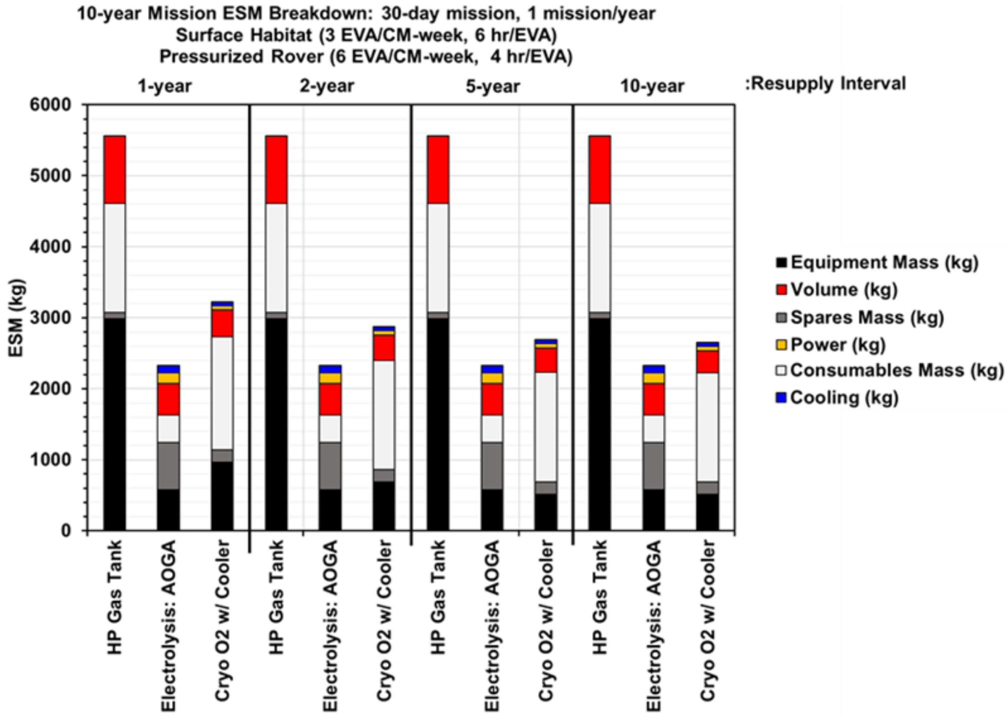

Figure 13. 10-year mission ESM breakdown with nominal single missions at different resupply intervals (1-, 2-, 5-, and 10-year resupply interval). The electrolysis architecture shown utilizes 100% recovered H_2O.

IV. Conclusion

A trade study was performed to compare different O_2 supply architectures (high pressure GOX storage, cryogenic LOX storage, and electrolysis). This study provides not only an ESM analysis of the final O_2 system architecture but also presents the mission and technology assumptions and an analysis cryogenic specific ConOps. From the analysis, it was shown that for a single, nominal mission (30 days), high pressure GOX tanks were favored; however, long, multi-year missions greatly favored either cryogenic or electrolysis architectures due to the heavy tankage associated with the storage of GOX. Although cryogenic LOX was found to be favorable over a wide range of individual mission durations (50 – 270 days), when considering a 10-year mission with multiple resupplies, each resupply affected the cryogenic LOX architecture negatively due to the associated resupplied tank masses and volumes. The results of the 10-year ESM analysis shows that cryogenic LOX can be competitive with electrolysis options; however, their trade is not necessarily clear depending on the degree and feasibility of having a closed ECLSS system to provide sufficient recovered H_2O to produce life support O_2 via electrolysis. The favorability of the cryogenic LOX or electrolysis approaches depends on multiple factors including proportion of the total life support O_2 which can be produced via recovered H_2O and mission duration. In addition, to the ESM conclusions, this analysis presents several gaps which can affect the cryogenic architecture including: (1) development of a high pressure, cryogenic metering pump; (2) viable strategies for filling pressurized tanks with LOX; (3) detailed thermal analysis of cryogenic and vaporizer tanks in Lunar environments; (4) design and analysis of cryogenic vaporization technologies; (5) risk mitigation strategies for sub-critical LOX during transport; and (6) understanding payload limitations on the resupply interval.

Appendix

Table 8. Mass, Volume, Power, and Cooling Breakdown for the ESM versus Individual Mission Duration Comparison.

		FSH				Rover				Spares		Consumables		Total
Description	**Individual Mission Duration (days)**	**Mass (kg)**	**Volume (m^3)**	**Power (W)**	**Cooling (W)**	**Mass (kg)**	**Volume (m^3)**	**Power (W)**	**Cooling (W)**	**Mass (kg)**	**Volume (m^3)**	**Oxygen (kg)**	**Water (kg)**	**ESM (kg)**
High Pressure Gas Tank	50	193	0.43	0	0	337	0.75	0	0	25	0.01	261	0	982
	270	866	1.94	0	0	1781	3.98	0	0	80	0.12	1383	0	4957
Electrolysis: AOGA, 100% Recovered	50	526	1.09	2135	1013	48	0.11	0	0	447	1.41	0	294	1877
	270	526	1.09	2096	994	48	0.11	0	0	659	2.30	0	1558	2332
Cryogenic LOX with Cryocooler	50	241	0.64	515	147	171	0.33	235	210	63	0.06	261	0	990
	270	281	1.85	515	147	171	0.33	235	210	86	0.07	1383	0	2328
Cryogenic LOX without Cryocooler	50	239	0.66	435	140	171	0.33	235	210	63	0.06	280	0	1003
	270	285	2.04	435	140	171	0.33	235	210	86	0.07	1569	0	2536

Table 9. Mass, Volume, Power, and Cooling Breakdown for the ESM versus 10-year Mission Comparison.

		FSH				Rover				Spares		Consumables		Total
Description	**Individual Mission Duration (days)**	**Mass (kg)**	**Volume (m^3)**	**Power (W)**	**Cooling (W)**	**Mass (kg)**	**Volume (m^3)**	**Power (W)**	**Cooling (W)**	**Mass (kg)**	**Volume (m^3)**	**Oxygen (kg)**	**Water (kg)**	**ESM (kg)**
High Pressure Gas Tank	20	626	1.40	0	0	1348	3.01	0	0	63	0.12	1026	0	3697
	40	1252	2.80	0	0	2648	5.92	0	0	105	0.14	2045	0	7290
	60	1829	4.09	0	0	3995	8.93	0	0	129	0.15	3066	0	10869
Electrolysis: AOGA, 100% Recovered	20	526	1.09	2099	996	48	0.11	0	0	617	2.24	0	1156	2313
	40	526	1.09	2093	993	48	0.11	0	0	774	2.73	0	2303	2483
	60	526	1.09	2092	992	48	0.11	0	0	900	3.17	0	3453	2766
Electrolysis: AOGA, 100% Resupplied	20	591	2.28	2099	996	48	0.11	0	0	629	2.25	0	1156	3266
	40	648	3.43	2093	993	48	0.11	0	0	799	2.75	0	2303	4849
	60	705	4.59	2092	992	48	0.11	0	0	935	3.20	0	3453	6395
Cryogenic LOX with Cryocooler	20	775	1.77	515	147	171	0.33	235	210	163	0.25	1094	0	2625
	40	817	2.95	515	147	171	0.33	235	210	173	0.26	2115	0	3847
	60	857	4.09	515	147	171	0.33	235	210	205	0.30	3127	0	5079

Acknowledgments

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