Providing Oxygen for the Crew of a Lunar Outpost

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Overview

Part of a Lunar Surface Integrated Fluid Systems Analysis, which is a collaborative effort between the following Exploration Technology Development Projects:

- Exploration Life Support (ELS, a.k.a ECLSS), Extravehicular activity (EVA), In-situ resource utilization (ISRU), Propulsion and cryogenic advanced development (PCAD), Cryogenic fluid management (CFM)
- Goal: Starting with non-integrated fluid systems as a baseline, develop an optimized integrated concept and identify technology needs

This study evaluates technologies for provision of oxygen (O₂) to the crew of a Lunar Outpost

- Especially high-pressure O₂ for EVA life support system recharge
- By calculating equivalent system mass (ESM) of the options

3 Cases are presented:

- 7 day Lunar Lander sortie mission
- 180 Lunar Outpost
- 10 years of successive 180 missions to the Outpost
- (Updates are included from previously reported studies)
Lunar exploration plan is to fill primary & secondary oxygen bottles with one pressure at 3000 psia

Concepts for providing high pressure EVA O₂ refill include:

- Store GOX in 5000 psia tanks and transfer via pressure equalization
- Low pressure electrolysis followed by mechanical compression
- Store LOX in space suit to provide for breathing, CO₂ washout & thermal control (results shown in previous paper)
- Convert LOX into high pressure oxygen by:
  - direct heating and expansion for EVA and ECLSS applications (a.k.a. “vaporizer”)
  - Or by using a Temperature Swing Adsorption Compressor (TSAC)
  - Use left over LOX in propellant tanks if available; otherwise, bring it along
- High pressure electrolysis
  - May be able to share the electrolyzer of the regenerative fuel cell at an Outpost
- Compress and store GOX from ISRU

4 person crew

- 2 crew per EVA (if 4 crew per EVA is required, double these results)
Crew Requirements for Oxygen (180 day case)

Current Shuttle/ISS EMU O$_2$ bottle capacities are:
- Primary O$_2$, 850 psia 1.2 lb
- Secondary O$_2$, 6000 psia 2.6 lb

High pressure oxygen users in Lunar Outpost
- O$_2$ for EVA$^3$
  - Primary O$_2$ bottle, 3000 psia 1.6 lb/CM$^1$-EVA
  - Secondary O$_2$ bottle, 3000 psia 2.6 lb/CM-EVA
  - (infrequent)
  - Suit purge, <20 psia 1.0 lb/CM-EVA

High pressure (3000 psia) O$_2$ resupply (primary tank only) 1.6 lb/CM-EVA

Low pressure metabolic O$_2$ consumption 1.94 lb/day

Number of Outpost EVA Sorties
- Nominal EVA-CM hours$^2$ (8 hours/CM-EVA) 2400 hours
- 300 CM-EVA’s in 180-day Outpost mission

Total O$_2$ requirements (high and low pressures) 1745 lb

Total high pressure O$_2$ required (180 days) 480 lb
- Mission average delivery rate 2.7 lb/day
- Design O$_2$ daily delivery rate (consecutive day EVAs) 3.2 lb/day

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1. CM: crew member
Baseline Technology – High Pressure Oxygen Tanks

Simple and reliable
Tanks made of Inconel® liner over-wrapped with carbon-fiber are relatively light weight.
For oxygen gas storage, 5000 psia is a reasonable limit.

– Material compatibility and safety issues increase with higher pressures

While 3100 – 3600 psia is the range for charging EVA oxygen bottles, left-over oxygen is enough for medium/low pressure applications, such as:

Crew breathing
EMU purging
Other ECLSS use
Low Pressure Water Electrolyzer, Dryers and Multi-Stage Piston Compressor

ELS Technology

CO₂ Reduction System

DI Water

LP Water Electrolyzer

H₂

Power

O₂

Moisture dryer

Multi-stage Compressor

Low Pressure Tank

High Pressure Tank

EMU O₂ Bottle 3000 psia

70 °F

3100 - 3600 psia GOX

V5 Relief valve

PI PC

70 °F

500 psia GOX

ISS Technology
Deliver LOX to HP Tank and Vaporize to High Pressure (Supply from Dedicated Tanks or Propellant Scavenging)

Thermal energy on lunar surface is used to generate high pressure GOX, heater is for back-up.
The TSAC is solid-state technology; its operation life should be longer than a mechanical compressor; but lower TRL
Solid Polymer Electrolysis (SPE®) water electrolysis technology has been used in UK and US submarines for approximately 20 years.

- Hamilton Sundstrand has accumulated 50,000+ hours in testing a single cell water electrolysis unit operated at 1850 psia.

Lunar Surface Power System and ECLSS could share the high pressure water electrolyzer.

Two options for generating O₂ at 3600 psia:

- Use an electrolyzer operating at 3600 psia
- Use a mechanical compressor to boost O₂ pressure from 1850 psia to 3600 psia (assumed here)
Import Moderate Pressure O2 from ISRU and Compress to Desired EVA O₂ Pressure

A Concept of Generating And Delivering O₂ on a Surface Vehicle
Mass and ESM of $O_2$ Generation Options (Open architecture) – 180-day Mission

Mass and ESM of Technologies for Generating High Pressure $O_2$
180-day Mission, Open ECLSS Architecture

- GOX Tank
- LOX Tank + Vaporizer (LOX from Earth, Prop. Scavenge)
- LOX tank + Sorption Compressor (LOX from Earth)
- LPOGA + Compressor
- HPOGA + compressor
- ECLSS/Power Sharing HPOGA

Legend:
- Total mass, kg
- ESM with Fluid, kg
Mass and ESM of $O_2$ Generation Options (Closed architecture) - 10-year Outpost Mission

Mass and ESM of Technologies for Generating High Pressure $O_2$
10-yr, multi 180-d Mission, Closed ECLSS Architecture

- GOX Tank
- LOX Tank + Vaporizer (LOX from Earth, Prop. Scavenge)
- LOX tank + Sorption Compressor (LOX from Earth)
- LPOGA + Compressor
- HPOGA + Compressor
- ECLSS/Power Shares HPOGA
- ECLSS/MSRU Shares HPOGA

<table>
<thead>
<tr>
<th>Total mass, kg</th>
<th>ESM, kg</th>
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<tbody>
<tr>
<td>GOX Tank</td>
<td></td>
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<tr>
<td>LOX Tank + Vaporizer (LOX from Earth, Prop. Scavenge)</td>
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<tr>
<td>LOX tank + Sorption Compressor (LOX from Earth)</td>
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<tr>
<td>LPOGA + Compressor</td>
<td></td>
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<tr>
<td>HPOGA + Compressor</td>
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<tr>
<td>ECLSS/Power Shares HPOGA</td>
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<td>ECLSS/MSRU Shares HPOGA</td>
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Conclusions and Recommendations

For Sortie missions (open ECLSS architecture)
- Scavenging LOX & vaporizing it to meet high/low pressure O₂ needs has lowest ESM, followed closely by launching 5000 psia GOX tanks

For a 180-day Outpost mission (open ECLSS architecture)
- Scavenging LOX & vaporizing it into high/low pressure GOX has lowest ESM, followed by LOX plus sorption compressor

For 10-yr multi 180-day missions (closed ECLSS architecture)
- Sharing high pressure oxygen generation assembly (HPOGA) between Power and ECLSS has the lowest total mass and ESM
- But the ISRU option & low pressure electrolysis with compressor are within 10% of HPOGA

Development of the following technologies recommended:
- Multi-stage O₂ piston compressor
- Vaporization and compression of a LOX/GOX mixture to 3600 psia
  A thermal compression technology with few rotating components
- High pressure cryogenic O₂ pump
  An essential component in the above LOX vaporizing technology
- HPOGA for generating O₂ up to 3600 psia and H₂ to a moderate pressure.
  A technology shared among Power, ECLSS and ISRU Elements.

Further Study recommended on:
- Risks, including micrometeoroids and high pressure oxygen safety in the various options
- Optimization of exact O₂ tank pressure and geometry
- The propellant scavenging concept, including launching extra O₂ for delivery of LOX or H₂O
- Mission water balance
- Mission scenarios involving pressurized rovers
References


<table>
<thead>
<tr>
<th></th>
<th>Oxygen/Water, kg</th>
<th>Mass¹, kg</th>
<th>Volume, m³</th>
<th>Power, W</th>
<th>Cooling, W</th>
<th>ESM, kg</th>
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<td>GOX Tanks (5000 psia)</td>
<td>34</td>
<td>132</td>
<td>0.106</td>
<td>0</td>
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<td>102</td>
<td>0.190</td>
<td>42</td>
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<td>0.190</td>
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<td>LP OGA + Compressors</td>
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<td>0.457</td>
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<td>889</td>
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Notes:
1. Includes mass of oxygen/water and hardware.
# Mass, Volume, Power & ESM for O₂ Provision (Open Architecture) – 180-d Mission

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Fluid, kg</th>
<th>Hardware Mass, kg</th>
<th>Volume, m³</th>
<th>Power, W</th>
<th>Cooling, W</th>
<th>Total Mass, kg</th>
<th>ESM of Hardware and Fluid, kg</th>
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<tr>
<td>GOX Tank (5000 psia)</td>
<td>891¹</td>
<td>337</td>
<td>2.314</td>
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<td>0</td>
<td>1,228</td>
<td>1,288</td>
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<td>LOX Tank + Vaporizer</td>
<td>520²</td>
<td>264</td>
<td>1.715</td>
<td>19</td>
<td>7</td>
<td>784</td>
<td>830</td>
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<tr>
<td>LOX Tank + Sorption Compressor</td>
<td>804³</td>
<td>373</td>
<td>1.844</td>
<td>444</td>
<td>432</td>
<td>1,052</td>
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<td>LP OGA + Compressor</td>
<td>894⁴</td>
<td>560</td>
<td>1.285</td>
<td>1,703</td>
<td>982</td>
<td>1,454</td>
<td>1,682</td>
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<tr>
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<td>832</td>
<td>1.596</td>
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<td>243</td>
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<td>2,012</td>
<td>1,019</td>
<td>1,137</td>
<td>1,368</td>
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Notes:
1. Includes O₂ left over in the tank.
2. 520 kg LOX launched from Earth. No mass penalty for 273 kg scavenged from Lander propellant.
3. All LOX from Earth.
### Mass, Volume, Power and Resupply Penalties of O₂ Generation Options (Closed Architecture) – 10-yr Outpost Mission

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Initial Mass¹, kg</th>
<th>Initial Volume, m³</th>
<th>Power, W</th>
<th>Cooling, W</th>
<th>Resupply Mass, kg</th>
<th>Resupply Volume, M³</th>
<th>Total Mass¹, kg</th>
<th>ESM, kg</th>
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<td>0</td>
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<td>1.151</td>
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<td>0.775</td>
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<td>1,346</td>
<td>1.482</td>
<td>1,507</td>
<td>1,943</td>
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1. Total mass includes fluid and hardware.
2. Includes 73 kg make-up water for each 180-day mission with a closed ECLSS architecture.
Generating 3600 psia \( \text{O}_2 \) from a LOX and GOX mixture in an Isochoric Process