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)
Driving Requirement: High Pressure Oxygen for EVA Recharge

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\textsubscript{2} bottle capacities are:

- Primary O\textsubscript{2}, 850 psia 1.2 lb
- Secondary O\textsubscript{2}, 6000 psia 2.6 lb

High pressure oxygen users in Lunar Outpost

- O\textsubscript{2} for EVA\textsuperscript{3}
  - Primary O\textsubscript{2} bottle, 3000 psia 1.6 lb/CM\textsuperscript{1}-EVA
  - Secondary O\textsubscript{2} bottle, 3000 psia 2.6 lb/CM-EVA
  - (infrequent)
  - Suit purge, <20 psia 1.0 lb/CM-EVA

High pressure (3000 psia) O\textsubscript{2} resupply (primary tank only) 1.6 lb/CM-EVA

Low pressure metabolic O\textsubscript{2} consumption 1.94 lb/day

Number of Outpost EVA Sorties

- Nominal EVA-CM hours\textsuperscript{2} (8 hours/CM-EVA) 2400 hours
- 300 CM-EVA’s in 180-day Outpost mission

Total O\textsubscript{2} requirements (high and low pressures) 1745 lb

Total high pressure O\textsubscript{2} required (180 days) 480 lb

- Mission average delivery rate 2.7 lb/day
- Design O\textsubscript{2} daily delivery rate (consecutive day EVAs) 3.2 lb/day

\textsuperscript{1} CM: crew member
\textsuperscript{3} Conger, B., Falconi E., Greg Leavitt, and Chullen C.,” PLSS Baseline Schematics and Internal Interfaces”, Rev. A, JSC-65563/CTSD-CX-5117
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

Power

H₂

O₂

Moisture dryer

Multi-stage Compressor

70 °F 500 psia GOX

Low Pressure Tank

70 °F 3100 - 3600 psia GOX

High Pressure Tank

V5 Relief Valve

EMU O₂ Bottle 3000 psia

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

180-day mission: LOX scavenged 273 kg
LOX brought up 520 kg

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\textsubscript{2} Generation Options (Open architecture) - Lunar Lander 7-day Sortie Mission

**Total Mass and ESM of HP-O\textsubscript{2} Generation Technologies**

Mission: Lander with 2-CM EVA  
Technology: High Pressure Storage + Compressor Combination

- **ESM, kg**
- **Total mass, kg**

### Mass, ESM, kg

- **(8)5000 psia tanks + (3)5000 psia LP tanks**
- **(3)Cryo Tanks + (2)HP evap + (3)pumps with Scav. LOX**
- **(3)Cryo Tanks + (2)HP evap + (3)pumps with launched LOX**
- **(2)LP OGA + (dryer) + 3(compressors)**
Mass and ESM of O₂ Generation Options (Open architecture) – 180-day Mission

Mass and ESM of Technologies for Generating High Pressure O₂
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

Total mass, kg
ESM, kg
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


## Mass, Volume, Power & ESM for O\textsubscript{2} Provision (Sortie Mission) – 7-d Sortie Mission

<table>
<thead>
<tr>
<th></th>
<th>Oxygen/Water, kg</th>
<th>Mass\textsuperscript{1}, kg</th>
<th>Volume, m\textsuperscript{3}</th>
<th>Power, W</th>
<th>Cooling, W</th>
<th>ESM, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOX Tanks (5000 psia)</td>
<td>34</td>
<td>132</td>
<td>0.106</td>
<td>0</td>
<td>0</td>
<td>136</td>
</tr>
<tr>
<td>Cryo Tanks + Evaporizers + Scavenged LOX</td>
<td>0</td>
<td>102</td>
<td>0.190</td>
<td>42</td>
<td>4</td>
<td>116</td>
</tr>
<tr>
<td>Cryo Tanks + Evaporizers + Launched LOX</td>
<td>32</td>
<td>134</td>
<td>0.190</td>
<td>42</td>
<td>4</td>
<td>149</td>
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<tr>
<td>LP OGA + Compressors</td>
<td>40</td>
<td>721</td>
<td>0.457</td>
<td>1,610</td>
<td>889</td>
<td>1,121</td>
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</tbody>
</table>

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>
</tr>
</thead>
<tbody>
<tr>
<td>GOX Tank (5000 psia)</td>
<td>891¹</td>
<td>337</td>
<td>2.314</td>
<td>0</td>
<td>0</td>
<td>1,228</td>
<td>1,288</td>
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<tr>
<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>
<td>1,155</td>
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<tr>
<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>
<td>HP OGA + Compressor</td>
<td>894⁴</td>
<td>832</td>
<td>1.596</td>
<td>1,999</td>
<td>1,006</td>
<td>1,726</td>
<td>1,985</td>
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<tr>
<td>ECLSS/Power Sharing HP OGA</td>
<td>894⁴</td>
<td>243</td>
<td>0.947</td>
<td>2,012</td>
<td>1,019</td>
<td>1,137</td>
<td>1,368</td>
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</tbody>
</table>

**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.
<table>
<thead>
<tr>
<th>Technologies</th>
<th>Initial Mass&lt;sup&gt;1&lt;/sup&gt;, kg</th>
<th>Initial Volume, m&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Power, W</th>
<th>Cooling, W</th>
<th>Resupply Mass, kg</th>
<th>Resupply Volume, M&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Total Mass&lt;sup&gt;1&lt;/sup&gt;, kg</th>
<th>ESM, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>GOX Tanks</td>
<td>1,227</td>
<td>2.314</td>
<td>0</td>
<td>0</td>
<td>23,319</td>
<td>43.966</td>
<td>24,546</td>
<td>25,740</td>
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<tr>
<td>LOX Tanks + Vaporizer</td>
<td>784</td>
<td>1.715</td>
<td>19</td>
<td>7</td>
<td>11,025</td>
<td>29.054</td>
<td>11,809</td>
<td>12,605</td>
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<tr>
<td>LOX Tank + Sorption Compressor</td>
<td>1,052</td>
<td>1.715</td>
<td>444</td>
<td>432</td>
<td>17,994</td>
<td>17.299</td>
<td>19,047</td>
<td>19,573</td>
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<td>LP OGA + Compressor&lt;sup&gt;2&lt;/sup&gt;</td>
<td>459</td>
<td>0.464</td>
<td>1,703</td>
<td>982</td>
<td>1,232</td>
<td>1.151</td>
<td>1,691</td>
<td>2,088</td>
</tr>
<tr>
<td>HP OGA + Compressor&lt;sup&gt;2&lt;/sup&gt;</td>
<td>733</td>
<td>0.775</td>
<td>2,003</td>
<td>1,010</td>
<td>1,482</td>
<td>1.482</td>
<td>2,080</td>
<td>2,516</td>
</tr>
<tr>
<td>ECLSS/Power Sharing HP OGA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>137</td>
<td>0.126</td>
<td>2,012</td>
<td>1,019</td>
<td>1,347</td>
<td>1.482</td>
<td>1,484</td>
<td>1,905</td>
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<tr>
<td>ECLSS/ISRU Sharing HP OGA&lt;sup&gt;2&lt;/sup&gt;</td>
<td>161</td>
<td>0.396</td>
<td>2,074</td>
<td>1,081</td>
<td>1,346</td>
<td>1.482</td>
<td>1,507</td>
<td>1,943</td>
</tr>
</tbody>
</table>

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 $O_2$ from a LOX and GOX mixture in an Isochoric Process