Air Revitalization

- Fundamentals of Air Revitalization
- Gas Supplies
- CO$_2$ Collection
- CO$_2$ Reduction
- H$_2$O Electrolysis
- Trace Contaminant Control
Life Support System Design

• Have to supply air, water, food, and waste management for crew

• Typical objective function: minimize system mass
  – Consumables (units: kg/crew-day)
  – Installed mass (units: kg/crew)

• But there is also a mass impact from utilities required by life support components
  – Additional power generation and energy storage
  – Additional thermal management capability
  – Additional pressurized volume

• Approach: Equivalent Systems Mass (ESM)
Orbiter Air Revitalization System

Cabin Temp 18.3 - 26.7 °C (65-80°F)
Dew Pt 3.9 - 16.1 °C (39-61°F)
pCO₂ 7.6 mm Hg

Duct
Temp Sensor

Exhaust Ducting

Atmosphere Bypass Duct

Condensing Heat Exchanger

Atmosphere

Water Separators

Condensate

LiOH & Charcoal Canisters

Cabin Fans Debris Trap

Intake Ducting

Cabin Temp Controller

Cabin Temp Selector

Temp Control Valve

Avionics

UNIVERSITY OF MARYLAND

Air Revitalization

ENAE 697 - Space Human Factors and Life Support
Equivalent Systems Mass

• Compress multiple decision criteria (mass, power, volume, thermal control) into one (mass)
• ESM relates consumables to marginal mass required to supply them
• ISS ESM values:
  – Volume: 67 kg/m³
  – Power: 77 kg/kW
  – Thermal: 164 kg/kW
• Does not include resupply mass or return mass
## ESM Conversion Factors by Mission

<table>
<thead>
<tr>
<th>Mission/Segment</th>
<th>Volume kg/m³</th>
<th>Power kg/kW</th>
<th>Thermal kg/kW</th>
<th>Crew Time kg/crew-hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS</td>
<td>67</td>
<td>476 (cont)</td>
<td>164</td>
<td>1.6</td>
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<tr>
<td></td>
<td></td>
<td>77 (day)</td>
<td></td>
<td></td>
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<tr>
<td>Mars transit</td>
<td>16</td>
<td>83</td>
<td>21</td>
<td>1.1</td>
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<tr>
<td>Mars surface</td>
<td>2.1</td>
<td>175</td>
<td>67</td>
<td>1.1</td>
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<tr>
<td>Minimal Lunar</td>
<td>51</td>
<td>300 (cont)</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 (day)</td>
<td></td>
<td></td>
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</table>
## ISS Consumables Budget

<table>
<thead>
<tr>
<th>Consumable</th>
<th>Design Load (kg/person-day)</th>
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<tbody>
<tr>
<td>Oxygen</td>
<td>0.85</td>
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<tr>
<td>Water (drinking)</td>
<td>1.6</td>
</tr>
<tr>
<td>Water (in food)</td>
<td>1.15</td>
</tr>
<tr>
<td>Water (clothes and dishes)</td>
<td>17.9</td>
</tr>
<tr>
<td>Water (sanitary)</td>
<td>7.3</td>
</tr>
<tr>
<td>Water (food prep)</td>
<td>0.75</td>
</tr>
<tr>
<td>Food solids</td>
<td>0.62</td>
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</tbody>
</table>
Nitrogen Makeup

- Nitrogen lost to airlock purges, leakage (can be >1% / day)
- Need to replenish N₂ to maintain total atmospheric pressure
- Choices:
  - High pressure (4500 psi) N₂ gas bottles
  - Cryogenic liquid nitrogen
  - Storable nitrogen-bearing compounds (NH₃, N₂O, N₂H₄)
Nitrogen from Hydrazine (N2H4)

Air Component Storage

- **Cryogenic Liquids**
  - $O_2$: 1140 kg/m$^3$, $T_{\text{boil}}$= -183°C=84K (= -308°F)
  - $N_2$: 808 kg/m$^3$, $T_{\text{boil}}$= -196°C=77K (= -320°F)
  - $H_2$: 70 kg/m$^3$, $T_{\text{boil}}$= -253°C=20K (= -433°F)

- **Gases**
  - $O_2$: 1.43 kg/m$^3$ @ STP (292 kg/m$^3$ @ 3000 psi)
  - $N_2$: 1.25 kg/m$^3$ @ STP (255 kg/m$^3$ @ 3000 psi)
  - $H_2$: 0.09 kg/m$^3$ @ STP (18.4 kg/m$^3$ @ 3000 psi)
Cryogenic Tankage

- **Volume-based relation**
  \[ m \ < \ kg \ > = 68.38 \ [ V \ < \ m^3 \ ]^{0.75} \]

- **Specific mass-based relations**
  \[ m_{tank} \ < \ kg \ > = 0.3485 \ [ M_{LOX} \ < \ kg \ ]^{0.75} \]
  \[ m_{tank} \ < \ kg \ > = 0.4512 \ [ M_{LN_2} \ < \ kg \ ]^{0.75} \]
  \[ m_{tank} \ < \ kg \ > = 2.826 \ [ M_{LH_2} \ < \ kg \ ]^{0.75} \]

- **Generic mass-based nondimensional relation**
  \[ \frac{m_{tank}}{m_{contents}} = 68.38 \ \left( \frac{\rho_{contents}}{m_{contents}} \right)^{0.25} \]
High Pressure Gas Tanks

• Typical pressures 200 atm (mass optimized) to 500-700 atm (volume optimized)
• GN2 tanks 0.56-1.7 x mass of contained gas
• GOx tank 0.36 x mass of contained gas
CO2 Removal Options

- 4BMS (Four Bed Molecular Sieves)
- 2BMS (Two Bed Molecular Sieves)
- EDC (Electrochemical Depolarized Concentrator)
- APC (Air Polarized Concentrator)
- SAWD (Solid Amine Water Desorption)
- LiOH (Lithium Hydroxide Canisters)
- METOX (Metal Oxide Adsorption)
Air Revitalization

4BMS Schematic

2BMS Schematic

**CO₂ Regenerable Scrubbing Systems**

- CO₂ production ~1 kg/person-day
- 4-Bed Molecular Sieves (4BMS)
  - Dual paths (one scrubbing, one regenerating)
  - Desiccant bed for moisture removal, 5 A zeolite sieve for CO₂
  - Heat to 350°-400°C to regenerate
  - 30 kg; 0.11 m³; 170 W (all per kg-day of CO₂ removal); TRL 9
- 2-Bed Molecular Sieves (2BMS)
  - Carbon molecular sieve for CO₂
  - 16 kg; 0.09 m³; 77 W (per kg/day CO₂); TRL 3
\[ \text{CO}_2 + \text{OH} \rightarrow \text{CO}_3 + \text{HCO}_3 \]

CO₂ Regenerable Scrubbing Systems

- Electrochemical Depolarization Concentration (EDC)
  - Uses fuel-cell type reaction to concentrate CO₂ at the anode
  - \( CO₂ + \frac{1}{2}O₂ + H₂ \rightarrow CO₂ + H₂O + \text{electricity} + \text{heat} \)
  - CO₂ and H₂ are collected at anode and directed to CO₂ recycling system (combustible mixture!)
  - 11 kg; 0.02 m³; 60 W (all per kg-day of CO₂ removal); does not include reactants for power output
  - TRL 6
APC Schematic

SAWD Schematic

CO₂ Regenerable Scrubbing Systems

- Solid Amine Water Desorption (SAWD)
  - Amine resin absorbs H₂O and CO₂; steam heat regenerates
    - Amine + H₂O --> Amine-H₂O (hydrated amine)
    - Amine-H₂O + CO₂ --> Amine-H₂CO₃ (bicarbonate)
    - Amine-H₂CO₃ + steam --> Amine + H₂O + CO₂
  - 17 kg; 0.07 m³; 150 W (all per kg-day of CO₂ removal)
  - TRL 6
LiOH Schematic

\[
LiOH + H_2O \rightarrow (LiOH - H_2O)
\]

\[
2(LiOH - H_2O) + CO_2 \rightarrow Li_2CO_3 + 3H_2O
\]

LiOH Mass Estimating Factor

- Space Shuttle LiOH system uses 7 kg cartridge, good for 4 crew-days $= 1.75$ kg/crew/day
- $0.003 \text{ m}^3$/canister
- TRL 9
CO2 Membrane Removal Systems

• Osmotic membranes
  – Poor gas selectivity
  – Returns CO2 to cabin air

• Electroactive carriers
  – Electroactive molecules act as CO2 “pump”
  – Very early in development

• Metal Oxides
  – AgO2 absorbs CO2 (0.12 kg O2/kg AgO2)
  – Regenerate at 140°C for 8 hrs (1 kW) - 50-60 cycles
  – Replacing LiOH in EMUs for ISS
METOX (Metal Oxide Adsorption)

- Rechargeable cartridge system
- Direct replacement for LiOH cannisters in EMU PLSS
- 14.5 kg/8 person-hr cartridge
- 14 hr recharge in oven
- 55 cycles in operating lifetime
- Regenerator module is 17.7”w x 19”h x 30”d, 105 lbs (holds 2 canisters for recharge) - power is 1000 W steady state
CO2 Reduction Options

- Bosch reactor
- Sabatier reactor
- ACRS (Advanced Carbon Reactor System)
- CO2EL/BD (CO2 Electrolysis/Boudouard)
Sabatier Reactor Schematic

Bosch Reactor Schematic

CO₂ Reduction

• Sabatier reaction
  – CO₂ + 4H₂ → CH₄ + 2H₂O
  – Lowest temperature (250°-300°C) with Ni catalyst
  – Electrolyze H₂O to get H₂, find use for CH₄
  – 91 kg; 3 m³; 260 W (all per kg-day of CO₂ removal)

• Bosch reaction
  – CO₂ + 2H₂ → C + 2H₂O
  – 1030°C with Fe catalyst
  – C residue hard to deal with (contaminates catalyst)
  – 700 kg; 3.9 m³; 1650 W (all per kg-day of CO₂ removal)
ACRS Schematic


Air Revitalization
CO2EL/BD Schematic

Oxygen Generation Options

- SFWE (Static Feed Water Electrolysis System)
- WVE (Water Vapor Electrolysis)
- SPE (Solid Polymer Electrolyte)
- Perchlorate candles
SFWE Schematic

WVE Schematic

SPE Schematic

## Nonregenerable O2 Production

<table>
<thead>
<tr>
<th>Material</th>
<th>kg(material)/kg(O2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O2</td>
<td>2.1</td>
</tr>
<tr>
<td>LiO2</td>
<td>1.62</td>
</tr>
<tr>
<td>K2O2</td>
<td>2.96</td>
</tr>
<tr>
<td>MgO4</td>
<td>1.84</td>
</tr>
<tr>
<td>CaO4</td>
<td>2.08</td>
</tr>
<tr>
<td>LiClO4</td>
<td>2.8</td>
</tr>
<tr>
<td>KClO4</td>
<td>2.16</td>
</tr>
<tr>
<td>Mg(ClO4)2</td>
<td>1.74</td>
</tr>
</tbody>
</table>

- Allocate an additional 10 kg/kg O2 for packaging, in addition to combustion receptacle (mass TBD)
Superoxides and Ozonides

• O2 generation
  – KO₂ + 2H₂O --> 4KOH + 3O₂
  – KO₃ + 2H₂O --> 4KOH + 5O₂

• CO2 reduction
  – 4KOH + 2CO₂ --> 2K₂CO₃ + 2H₂O
  – 2K₂CO₃ + 2H₂O + 2CO₂ --> 4KHCO₃

• KO₂ removes 0.31 kg CO₂/kg and generates 0.38 kg O₂/kg
Trace Contaminant Control

• Particulate Filters (dusts and aerosols)
• Activated Charcoal (high molecular weight contaminants)
• Chemisorbant Beds (nitrogen and sulphur compounds, halogens and metal hybrids)
• Catalytic Burners (oxidize contaminants that can’t be absorbed)
• 100 kg; 0.3 m³; 150 W (all per person)
Trace Contaminant Control Schematic

CO2 Collection System Trade

- System Mass (kg) vs. Duration (days)
- Blue line: CO2/LiOH
- Red line: CO2/2BMS
O2 Recovery System Trade

**Graph:**
- **Y-axis:** System Mass (kg)
- **X-axis:** Duration (days)
- Two lines:
  - **Blue line:** O2/Open Loop
  - **Red line:** O2/Sabatier

**Legend:**
- O2/Open Loop
- O2/Sabatier
ISS Air Revitalization System Rack

References