This course provides an introduction to the design and development of life support systems to sustain humankind in the harsh environment of space. The life support technologies necessary to provide a respirable atmosphere and clean drinking water are emphasized in the course. A historical perspective, beginning with open loop systems employed aboard the earliest crewed spacecraft through the state-of-the-art life support technology utilized aboard the International Space Station today, will provide a framework for students to consider applications to possible future exploration missions and destinations which may vary greatly in duration and scope. Development of future technologies as well as guiding requirements for designing life support systems for crewed exploration missions beyond low-Earth orbit are also considered in the course.
<table>
<thead>
<tr>
<th>Title</th>
<th>Speaker</th>
<th>Duration</th>
<th>Approx Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welcome/Introduction</td>
<td>Greg Schunk</td>
<td>5 min</td>
<td>1:00</td>
</tr>
<tr>
<td>Agenda/ Speakers</td>
<td></td>
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<tr>
<td>What is Environmental Control and Life Support?</td>
<td></td>
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<tr>
<td>Human Metabolic Needs</td>
<td>Bob Bagdigian</td>
<td>30 min</td>
<td>1:05</td>
</tr>
<tr>
<td>Typical ECLSS Functions</td>
<td>Bob Bagdigian</td>
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</tr>
<tr>
<td>Historical Perspective</td>
<td>Bob Bagdigian</td>
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<tr>
<td>Mercury/Gemini/Apollo/Skylab/Shuttle/ISS</td>
<td>Bob Bagdigian</td>
<td></td>
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<tr>
<td>Guiding Requirements from NASA Standards</td>
<td>Jay Perry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmosphere Revitalization</td>
<td></td>
<td>90 min</td>
<td>1:40</td>
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<tr>
<td>Overview</td>
<td>Jay Perry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 Removal</td>
<td>Jim Knox</td>
<td></td>
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<tr>
<td>O2 Generation</td>
<td>Kevin Takada</td>
<td></td>
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</tr>
<tr>
<td>O2 Recovery/CO2 Reduction</td>
<td>Zach Greenwood</td>
<td></td>
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<tr>
<td>Trace Contaminant Control</td>
<td>Jay Perry</td>
<td></td>
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<tr>
<td>Particulate Control</td>
<td>Jay Perry</td>
<td></td>
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</tr>
<tr>
<td>Water Recovery</td>
<td></td>
<td>45 min</td>
<td>3:15</td>
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<tr>
<td>Overview</td>
<td>Layne Carter</td>
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<td>Water Processing</td>
<td>Layne Carter</td>
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<tr>
<td>Urine Processing</td>
<td>Layne Carter</td>
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<tr>
<td>Challenges for Future Exploration</td>
<td></td>
<td>10 min</td>
<td>4:00</td>
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<tr>
<td>Exploration phases, duration, dormancy, etc.</td>
<td>Jay Perry</td>
<td></td>
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</tr>
<tr>
<td>Question and Answer</td>
<td>All</td>
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</table>

TFAWS 2017 – August 21-25, 2017
Life Support Overview and Historical Perspective

Presented By
Bob Bagdigian
NASA MSFC
Human Exploration Development Chief Engineer’s Office

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
To Keep Humans Alive in Space, We Must…

- Control Cabin Pressure
- Control Cabin Atmosphere Composition & Purity
- Control Temperature, Humidity, & Particulates
- Monitor Cabin Environment
- Detect and Suppress Fires
- Ventilate Cabin
- Supply Oxygen
- Remove Carbon Dioxide
- Supply Water
- Collect, Stabilize, Store, & Dispose of Wastes
- Recycle Water
- Recycle Oxygen
- Produce Food
- Respond to and Recover from Environmental Emergencies
- Recycle Oxygen
ECLSS Functional Integration
• 1-2 astronauts
• 1-14 day missions
• chlorinated potable water & oxygen stored in tanks
• CO₂ removed from atmosphere w/ expendable LiOH
• wastewater vented overboard
Life Support for Apollo

Command Module
- 7-10 day missions
- 3 crew
- Fuel cell by-product water used for drinking, chlorinated manually by crew
- Wastewater vented overboard or used for supplemental evaporative cooling
- $O_2$ stored in tanks
- $CO_2$ scrubbed w/ LiOH
- Rudimentary waste collection

Lunar Module
- 1-3 day missions for 2 crew
- Iodinated potable water stored in tanks
- Wastewater collected in tanks
- $O_2$ Storage
- $CO_2$ scrubbed w/ LiOH
Life Support for Skylab

• 3 missions (28, 59, & 84 days)
• 3 astronauts each mission
• Potable water provided for consumption & hygiene
• Iodinated potable water stored in tanks (10 x 70-gal tanks)
  • Periodic iodine injections by crew
  • Manual colorimetric checks
• Wastewater vented overboard
• Stored O₂
• CO₂ scrubbed w/ molecular sieve and vented overboard
Life Support for Space Shuttle

- 7-16 day missions typical
- 6-7 crew typical
- fuel cell by-product water used for potable water
  - iodine added automatically via flow-thru iodinated resin
- wastewater vented overboard
- stored (cryo) O₂
- CO₂ scrubbed with LiOH
International Space Station Life Support

- Continuously occupied since 10/01
- 90-180 day increments typical
- 3--6 crew typical, more in coming years
- CO₂ removal w/ regenerable zeolite mole sieve
- Trace contaminant control w/ expendable adsorption & catalytic oxidation
- H₂O supplies:
  - cabin humidity condensate processed to potable water (Russian hardware)
  - cabin humidity condensate & urine processed to potable water (U.S. Water Recovery System since 2008)
- O₂ supplies
  - oxygen generation via water electrolysis (US & Russian systems)
  - oxygen recovery via Sabatier CO₂ reduction (US)
  - expendable perchlorate candles (emergency backup)

Waste & Hygiene Compartment
ISS Regenerative ECLSS

Launched July 2006
Activation July 2007

Launched November 2008
Activation March 2009

OXYGEN GENERATION SYSTEM

WATER RECOVERY SYSTEM

HYDROGEN

OXYGEN

POTABLE WATER

URINE

BRINE

HUMIDITY CONDENSATE

PROCESS WATER

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Human Space Exploration Phases from ISS to the Surface of Mars

Today

Phase 0: Exploration Systems Testing on ISS

Phase 1: Cislunar Flight Testing of Exploration Systems
- Ends with testing, research and demos complete*

Phase 2: Cislunar Validation of Exploration Capability

Phase 3: Crewed Missions Beyond Earth-Moon System
- Asteroid Redirect-Crewed Mission Marks Move from Phase 1 to Phase 2
- Ends with one year crewed Mars-class shakedown cruise

Phase 4a: Development and robotic preparatory missions

Phase 4b: Mars Human Landing Missions

Mid-2020s

2030

* There are several other considerations for ISS end-of-life
• Orion Multi-Purpose Crew Vehicle (MPCV)
  • Transport 4 crew to Deep Space Gateway
  • ~21 day mission duration
• Deep Space Gateway (DSG)
  • Support multiple NASA, U.S., commercial, & international partner objectives
  • Supports buildup of Deep Space Transport
  • With Orion, supports 4 crew up to 42 days
• Deep Space Transport (DST)
  • Transport crew between DSG & Mars vicinity
  • 6-9 month 1-way transits
  • Dormant periods while crew is on Mars surface
Guiding Requirements from NASA Standards

Presented By
Jay Perry
NASA MSFC
ECLS Systems Development Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
Introduction

• The Global Exploration Strategy
  – International Space Exploration Coordination Group
  – 14 member agencies
  – 5 themes
  – Path to Mars exploration

• U.S. 2010 Space Exploration Policy
  – Goals similar to the GES themes
  – Missions beyond the moon by 2025
  – Missions to Mars by mid-2030s
Preparing for the Challenge

- Design reference mission architecture studies
  - Mars DRA 5.0 in 2009, updated in 2014

- Technical needs assessments
  - Reliable, maintainable life support system

- Technical area roadmaps
  - Human health, life support, and habitation systems

- Learning from the ISS experience
  - Valuable insight on design, development, testing, flight operations, and international collaboration

- Requirements from NASA standards and supporting documents
  - NASA-STD-3001; NASA/SP-2010-3407
Mission duration
- Opposition class: 400-650 days transit; 30-90 days surface; 500-630 days total
- Conjunction class: 360-420 days transit; 475-540 days surface; 830-960 days total
- Enable high end: 650 days transit, 540 days surface, total 1190 days

Crew size
- 4 crewmembers operationally sufficient
- 6 crewmembers may reduce mission risk

Habitat size
- 280 m³ pressurized volume; 24 m³ habitable volume per crewmember
- Larger pressurized volumes up to 660 m³ studied

EVA
- Up to 16 individual EVA events per week for 71-week surface mission
Atmosphere Revitalization Guidance

- Accommodate metabolic loads and demands
  - CO₂ to 1000-day SMAC max; 2 mm Hg target
  - Trace contaminants <1000-day SMAC
- Particulate matter control
  - <3 mg/m³ for >10 µm and <100 µm
  - <1 mg/m³ for >0.5 µm and <10 µm
- Oxygen supply
  - Supply to pressure up to 24.8 MPa
- Cabin pressure and composition
  - 20.7 kPa – 103 kPa with inert diluent
- Cabin temperature and humidity
  - 18° C - 27° C; 25% - 75%
- Resource recovery
  - Transit: >75% of O₂ from CO₂
  - Mission: >90% of O₂ from CO₂
- Venting losses <10%

<table>
<thead>
<tr>
<th>COMPOUND</th>
<th>ACTIVITY</th>
<th>RATE (kg/CM-h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>Sleep</td>
<td>0.0378</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0.0706</td>
</tr>
<tr>
<td></td>
<td>Exercise</td>
<td>0.629</td>
</tr>
<tr>
<td></td>
<td>Post Exercise</td>
<td>0.281</td>
</tr>
<tr>
<td>CO₂</td>
<td>Sleep</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td>Normal/Post Ex.</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>Exercise</td>
<td>0.3</td>
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<tr>
<td>O₂</td>
<td>Sleep</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td>Normal/Post Ex.</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>Exercise</td>
<td>0.24</td>
</tr>
</tbody>
</table>

*Single CM.*
Water Recovery and Management Guidance

- Achieve >98% overall water recovery
  - >85% water from urine
  - >95% water from brine
- Survive 500-day dormancy
- Enable water recovery from trash, human waste, and process byproducts
- Maintain potable water quality
- Maintain potable water aesthetics
- Provide minimum water quantity

**WATER USE QUANTITY**

<table>
<thead>
<tr>
<th>USE</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drinking</td>
<td>2 kg/CM-day</td>
</tr>
<tr>
<td>Food hydration</td>
<td>0.5 kg/CM-day</td>
</tr>
<tr>
<td>Personal hygiene</td>
<td>0.4 kg/CM-day</td>
</tr>
<tr>
<td>Medical support</td>
<td>5 kg + 0.5 kg/CM</td>
</tr>
<tr>
<td>EVA support</td>
<td>0.24 kg/h of EVA</td>
</tr>
<tr>
<td>Earth entry fluid</td>
<td>1 kg/CM</td>
</tr>
<tr>
<td>Post-landing support</td>
<td>4.5 kg/CM</td>
</tr>
</tbody>
</table>

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Environmental Monitoring Guidance

- Provide multiple functions
  - Atmospheric monitoring
  - Water quality monitoring
  - Microbial monitoring
  - Contingency events

- Minimize monitoring needs by
  - Selecting chemicals with low toxic hazard
  - Selecting chemicals with minimal LSS and cabin impact

- Monitoring data
  - Temporal trend analysis
  - Near real-time display
• Pre-Phase A/Early Phase A
  – Allocations mass, power, and volume undefined
• Electrical power
  – 120 VDC; undefined allocation of DRA5 22 kW
• Structural
  – Must enable open physical layout for maintainability
• Must address exploration figures of merit
  – Maintainability, robustness, and scalability
Conclusions

- Exploration vision builds toward Mars missions
  - Global Exploration Strategy
  - U.S. 2010 Space Exploration Policy
- Reference architectures, exploration goals, and technology needs guide development
  - Mars DRA5 as the guide
  - Updated as knowledge base grows
- Guiding requirements are readily available
  - NASA-STD-3001
  - NASA/SP-2010-3407


Atmosphere Revitalization Overview

Presented By
Jay Perry
NASA MSFC
ECLS Systems Development Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
What is Atmosphere Revitalization?
# Life Support System Functions

## Control Atmosphere Pressure
- O₂/N₂ Pressure Control Assemblies (USOS/RS)
- Positive & Negative Pressure Relief (USOS-Transport)
- O₂/N₂ Storage (USOS, RS, Progress)
- O₂ Generation Assembly, O₂ Solid Chemicals (RS)
- Major Constituent Analyzer (USOS) (Share)
- Gas Analyzer (RS) (Shared)

## Condition Atmosphere
- Cabin Air Temperature & Humidity Control Assemblies (All)
- Ventilation Fans (USOS, RS, MPLM)
- Air Particulate Filters (All)
- Intermodule Ventilation Fans & Valves (All)
- Ducting (All)

## Respond to Emergency Conditions
- Smoke Detectors (All)
- Portable Fire Extinguishers (All)
- Fire Indicators and Fire Suppression Ports (All)
- Portable Breathing Apparatus and Masks (All)
- O₂/N₂ Pressure Control Assemblies (USOS) (Shared)

## Control Internal CO₂ & Contaminants
- CO₂ Removal Assembly (USOS/RS)
- CO₂ Vent (USOS/RS)
- Trace Contaminant Control Assembly (USOS/RS)
- Major Constituent Analyzer (USOS)
- CO₂ Reduction Assembly (RS)
- CO₂ LOH Removal (RS)
- Manual Sampling Equipment (USOS)
- Gas Analyzer (RS)

## Provide Water
- Potable Water Processor (USOS/RS)
- Urine Processor (USOS/RS)
- Process Control Water Quality Monitor (USOS)
- Condensate Storage (USOS/RS)
- Fuel Cell Water Storage (USOS)
- Waste Water Distribution (USOS)
- Hygiene Water Processor (RS)

## Prepare for EVA Operations
- O₂/N₂ Pressure Control Assemblies (USOS)
- O₂/N₂ Distribution (USOS)
- O₂/N₂ Storage (USOS)
- Major Constituent Analyzer (USOS) (Shared)

## Atmosphere Control & Supply (ACS) & AR

## Temperature Humidity Control

## Fire Detection & Suppression & ACS

## Atmosphere Revitalization (AR)

## Water Recovery & Mgmt/Waste Mgmt

## ACS & AR
## Atmosphere Revitalization History

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>MISSION DURATION</th>
<th>CABIN VOLUME (m³)</th>
<th>CREW SIZE</th>
<th>TECHNOLOGICAL APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>34 hours</td>
<td>1.56</td>
<td>1</td>
<td><strong>Atmosphere:</strong> 100% O₂ at 34.5 kPa. <strong>Atmosphere supply:</strong> Gas at 51.7 MPa. <strong>CO₂ removal:</strong> LiOH. <strong>Trace contaminants:</strong> Activated carbon.</td>
</tr>
<tr>
<td>Gemini</td>
<td>14 days</td>
<td>2.26</td>
<td>2</td>
<td><strong>Atmosphere:</strong> 100% O₂ at 34.5 kPa. <strong>Atmosphere supply:</strong> Supercritical storage at 5.86 MPa. <strong>CO₂ removal:</strong> LiOH. <strong>Trace contaminants:</strong> Activated carbon.</td>
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<tr>
<td>Apollo</td>
<td>14 days</td>
<td>5.9</td>
<td>3</td>
<td><strong>Atmosphere:</strong> 100% O₂ at 34.5 kPa. <strong>Atmosphere supply:</strong> Supercritical storage at 6.2 MPa. <strong>CO₂ removal:</strong> LiOH. <strong>Trace contaminants:</strong> Activated carbon.</td>
</tr>
<tr>
<td>Skylab</td>
<td>84 days</td>
<td>361</td>
<td>3</td>
<td><strong>Atmosphere:</strong> 72% O₂/28% N₂ at 34.5 kPa. <strong>Atmosphere supply:</strong> Gas at 20.7 MPa. <strong>CO₂ removal:</strong> Type 13X and 5A molecular sieves regenerated by vacuum swing. <strong>Trace contaminants:</strong> Activated carbon.</td>
</tr>
<tr>
<td>Space Shuttle</td>
<td>14 days</td>
<td>74</td>
<td>7</td>
<td><strong>Atmosphere:</strong> 21.7% O₂/78.3% N₂ at 101 kPa. <strong>Atmosphere supply:</strong> Gas at 22.8 MPa. <strong>CO₂ removal:</strong> LiOH. <strong>Trace contaminants:</strong> Activated carbon and ambient temperature CO oxidation</td>
</tr>
<tr>
<td><strong>International Space Station</strong></td>
<td>180 days</td>
<td>Up to 600</td>
<td>3 to 6</td>
<td><strong>Atmosphere:</strong> 21.7% O₂/78.3% N₂ at 101 kPa. <strong>Atmosphere supply:</strong> Gas at 20.7 MPa/water electrolysis <strong>CO₂ removal:</strong> Silica gel with type 13X and 5A molecular sieves regenerated by vacuum/temperature swing. <strong>CO₂ reduction:</strong> Sabatier reactor (scar for future addition) <strong>Trace contaminants:</strong> Activated carbon and thermal catalytic oxidation</td>
</tr>
</tbody>
</table>
ISS ECLSS – The Exploration “Launch Platform”

- Reduce resupply
- Reduce expendable resources
- Increase operational robustness
- Reduce complexity
- Improve life cycle economics
- Improve loop closure
## Basic Requirements

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>STANDARD</th>
<th>DESIGN POINTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Pressure</td>
<td>97.9-102.7 kPa</td>
<td>&lt;0.23 kg/d leakage</td>
</tr>
<tr>
<td>Carbon Dioxide Partial Pressure</td>
<td>0.7-1 kPa</td>
<td>0.52-1.5 kg/p-d; 1 kg/p-d average</td>
</tr>
<tr>
<td>Oxygen Partial Pressure</td>
<td>19.5-23.1 kPa</td>
<td>0.49-1.25 kg/p-d; 0.84 kg/p-d average</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>4.4-15.5°C dewpoint</td>
<td>0.87-4.3 kg/p-d; 1.82 kg/p-d average</td>
</tr>
<tr>
<td>Trace Chemical Contaminants</td>
<td>&lt;SMACs in JSC 20584</td>
<td>SAE 2009-01-2592</td>
</tr>
<tr>
<td>Particulates</td>
<td>&lt;0.5 mg/m³ average; &lt;1 mg/m³ peak for 0.5 to 100-micron size</td>
<td>10⁹ particles/p-d</td>
</tr>
<tr>
<td>Microbes</td>
<td>500 CFU bacteria/m³ 100 CFU fungi/m³</td>
<td>3,000 CFU/person-minute</td>
</tr>
</tbody>
</table>

kg/p-d = kilogram/person-day
Process Types & Unit Operations

- Separations
  - Physical adsorption
  - Absorption
  - Filtration
- Reactions
  - Chemical adsorption
  - Oxidation
  - Reduction
  - Electrochemical

- Process gas drying
- Process gas purification
  - CO$_2$ removal
  - Trace contaminant removal
  - Particulate matter removal
- Atmospheric gas handling
  - Storage
  - Conditioning
- Atmospheric gas production
  - High pressure capability
  - In-situ resource recovery and use
A Typical AR Subsystem Architecture

- **Core processes**
  - Filtration
  - Dehumidification
  - CO₂ removal
  - Trace contaminant control

- **Loop closure**
  - CO₂ reduction
  - O₂ generation
Realize improvements through a functional, unit operation-driven approach

- Focus on ISS ECLSS strengths and weaknesses
- Employ robust design principles to achieve stage-wise optimization

Leverage core process technologies from heritage systems as appropriate

Attention to design modularity to address commonality across mission and vehicle architectures


Carbon Dioxide Removal: From the Moon to Mars

Presented By
James Knox/MSFC

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
### Average Human Metabolic Balance (lb/person-day)

<table>
<thead>
<tr>
<th>Category</th>
<th>Total Out</th>
<th>Total In</th>
<th>Water</th>
<th>Solids</th>
<th>Oxygen</th>
<th>Hydrogen</th>
<th>Carbon</th>
<th>Other</th>
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<tbody>
<tr>
<td>Water Drink</td>
<td>3.56</td>
<td>3.56</td>
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<tr>
<td>Water In food</td>
<td>2.54</td>
<td>2.54</td>
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<td></td>
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<tr>
<td>Food Prep</td>
<td>1.67</td>
<td>1.67</td>
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<td>Carbon Dioxide</td>
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<tr>
<td>Water Urine</td>
<td>3.31</td>
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<td></td>
<td></td>
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<tr>
<td>Sweat &amp; respiration</td>
<td>5.02</td>
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<td>Feces</td>
<td>0.20</td>
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<tr>
<td>Solids Oxygen</td>
<td>0.44</td>
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<tr>
<td>Solids Hydrogen</td>
<td>0.08</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Solids Carbon</td>
<td>0.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids Other</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>10.97</td>
<td>10.97</td>
<td>8.53</td>
<td>0.24</td>
<td>1.84</td>
<td>7.77</td>
<td>1.36</td>
<td>1.67</td>
</tr>
</tbody>
</table>

Sustaining people in space requires managing all of their “ins and outs”
Daily Metabolic Requirements for Life Support

<table>
<thead>
<tr>
<th>Needs</th>
<th>Effluents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen = 0.84 kg (1.84 lb)</td>
<td>Carbon Dioxide = 1.00 kg (2.20 lb)</td>
</tr>
<tr>
<td>Food Solids = 0.62 kg (1.36 lb)</td>
<td></td>
</tr>
<tr>
<td>Water in Food = 1.15 kg (2.54 lb)</td>
<td></td>
</tr>
<tr>
<td>Food Prep Water = 0.76 kg (1.67 lb)</td>
<td></td>
</tr>
<tr>
<td>Drink = 1.62 kg (3.56 lb)</td>
<td>Respiration &amp; Perspiration Water = 2.28 kg (5.02 lb)</td>
</tr>
<tr>
<td>Metabolized Water = 0.35 kg (0.76 lb)</td>
<td></td>
</tr>
<tr>
<td>Hand/Face Wash Water = 4.09 kg (9.00 lb)</td>
<td>Food Preparation, Latent Water = 0.036 kg (0.08 lb)</td>
</tr>
<tr>
<td>Shower Water = 2.73 kg (6.00 lb)</td>
<td>Urine = 1.50 kg (3.31 lb)</td>
</tr>
<tr>
<td>Urinal Flush = 0.49 kg (1.09 lb)</td>
<td>Urine Flush Water = 0.50 kg (1.09 lb)</td>
</tr>
<tr>
<td>Clothes Wash Water = 12.50 kg (27.50 lb)</td>
<td>Feces Water = 0.091 kg (0.20 lb)</td>
</tr>
<tr>
<td>Dish Wash Water = 5.45 kg (12.00 lb)</td>
<td>Sweat Solids = 0.018 kg (0.04 lb)</td>
</tr>
<tr>
<td>Total = 30.60 kg (67.32 lb)</td>
<td>Urine Solids = 0.059 kg (0.13 lb)</td>
</tr>
<tr>
<td></td>
<td>Feces Solids = 0.032 kg (0.07 lb)</td>
</tr>
<tr>
<td></td>
<td>Hygiene Water = 12.58 kg (27.68 lb)</td>
</tr>
<tr>
<td></td>
<td>Clothes Wash Water Liquid = 11.90 kg (26.17 lb)</td>
</tr>
<tr>
<td></td>
<td>Latent = 0.60 kg (1.33 lb)</td>
</tr>
<tr>
<td></td>
<td>Total = 30.60 kg (67.32 lb)</td>
</tr>
</tbody>
</table>

Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 BTU/person/day) and a respiration quotient of 0.87. The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO₂ generated to O₂ consumed.
# Health effects of respiratory exposure to carbon dioxide

<table>
<thead>
<tr>
<th>Exposure Limits, percent in air (partial pressure, torr)</th>
<th>Health Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 - 0.65 (3 - 5)</td>
<td>Headaches, visual disturbances, behavioral changes noted in conjunction with microgravity-induced increases in inter-cranial pressure on the International Space Station</td>
</tr>
<tr>
<td>2 - 3 (15.2 - 22.8)</td>
<td>Unnoticed at rest, but on exertion there may be marked shortness of breath</td>
</tr>
<tr>
<td>3 (22.8)</td>
<td>Breathing becomes noticeably deeper and more frequent at rest</td>
</tr>
<tr>
<td>3 - 5 (22.8 - 38)</td>
<td>Breathing rhythm accelerates. Repeated exposure provokes headaches</td>
</tr>
<tr>
<td>5 (38)</td>
<td>Breathing becomes extremely laboured, headaches, sweating and bounding pulse</td>
</tr>
<tr>
<td>7.5 (57)</td>
<td>Rapid breathing, increased heart rate, headaches, sweating, dizziness, shortness of breath, muscular weakness, loss of mental abilities, drowsiness, and ringing in the ears</td>
</tr>
<tr>
<td>8 - 15 (60.8 - 114)</td>
<td>Headache, vertigo, vomiting, loss of consciousness and possibly death if the patient is not immediately given oxygen</td>
</tr>
<tr>
<td>10 (76)</td>
<td>Respiratory distress develops rapidly with loss of consciousness in 10-15 minutes</td>
</tr>
<tr>
<td>15 (114)</td>
<td>Lethal concentration, exposure to levels above this are intolerable</td>
</tr>
<tr>
<td>25+ (190+)</td>
<td>Convulsions occur and rapid loss of consciousness ensues after a few breaths. Death will occur if level is maintained.</td>
</tr>
</tbody>
</table>

Objectives:
• To orbit a manned spacecraft around Earth
• To investigate man’s ability to function in space
• To recover both man and spacecraft safely

Mission Specifics:
• 1 astronaut
• Up to 34 hour missions
• CO₂ removed from atmosphere with expendable LiOH
Objectives:
- To test an astronaut's ability to fly long-duration missions
- To understand how spacecraft could rendezvous and dock in orbit around the Earth and the moon

Mission Specifics:
- 2 astronauts
- Up to 14 day missions
- CO₂ removed from atmosphere with expendable LiOH
- To perfect re-entry and landing methods
Objectives:
- Landing Americans on the moon and returning them safely to Earth.
- Establishing the technology to meet other national interests in space.
- Achieving preeminence in space for the United States.
- Carrying out a program of scientific exploration of the Moon.
- Developing man's capability to work in the lunar environment.

Misson Specifics:
- 3 astronauts
- Up to 12.5 day missions
- CO$_2$ removed from atmosphere with expendable LiOH
Expendable CO₂ Removal via Lithium Hydroxide

Lithium hydroxide crystals

Apollo Lunar Module (LM) LiOH Canister (left)

Apollo Command Module (CM) LiOH Canister (right)

2LiOH(s) + CO₂(g) → Li₂CO₃(s) + H₂O(g)

One gram of anhydrous lithium hydroxide can remove 450 cm³ of carbon dioxide gas, or about 90% by mass.

https://en.wikipedia.org/wiki/Lithium_hydroxide
By Mondalor - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=7159838
Apollo 13: Disaster Averted

Issue:
- After loss of oxygen tanks and power in CM, crew used LM as lifeboat
- LiOH in LM sized for 2 crew for 2 days (2 canisters), vs. 3 crew for 3.6 days
- Estimated CO$_2$ concentration without taking action: 50%
- Actual CO$_2$ concentration rose to ~13 torr

Challenge:
- Integrate active environmental control system in LM with CM LiOH canisters

Solution:
- Combine cardboard from EVA cue card, plastic bag from liquid cooling garment, suit hose, and duct tape
Project Apollo: Landing on the Moon

Objectives:
- Landing Americans on the moon and returning them safely to Earth.
- Establishing the technology to meet other national interests in space.
- Achieving preeminence in space for the United States.
- Carrying out a program of scientific exploration of the Moon.
- Developing man's capability to work in the lunar environment.

Misson Specifics:
- 3 astronauts
- Up to 12.5 day missions
- CO₂ removed from atmosphere with expendable LiOH
Skylab: America’s First Space Station

- Three Skylab missions with a total of 171 days in the early 1970’s.
- Molecular Sieves 13X and 5A were successfully used for CO₂ and H₂O removal on Skylab for 171 days without hardware anomaly.
- 70% of metabolic water and 100% of metabolic CO₂ for 3 crew was removed via a regenerable vacuum swing adsorption process.
- Three 2BMS units would provide sufficient removal for 6 non-exercising crew.
Objectives:
- Reusable launch system and orbital spacecraft
- Launched satellites, interplanetary probes, Hubble Telescope
- Conducted numerous science experiments
- Launched all U.S International Space Station modules

Mission Specifics:
- 135 missions with 5 orbiters (2 destroyed in accidents)
- Up to 10-day missions, or 16-day missions with EDO
- CO₂ removed from atmosphere with expendable LiOH
- Supplemental removal with RCRS on extended missions
Current Spacecraft Carbon Dioxide and Humidity Removal Systems

- The International Space Station uses a 4 Bed Molecular Sieve to remove CO$_2$ from the ISS.
- Anomalies due to flaws in the containment design have highlighted the need for a more robust sorbent configuration *(such as structured sorbents)*
- The 4BMS design returns water to the cabin and can either vent CO$_2$ or store it in an accumulator for subsequent reduction reaction and water recovery.
Current Spacecraft Carbon Dioxide Removal Systems

• The International Space Station uses a “4 Bed Molecular Sieve” (4BMS) to remove CO$_2$ from the ISS.
• The 4BMS desiccates with silica gel and zeolite 13X, and removes CO$_2$ with zeolite 5A. CO$_2$ is vented presently, though will be reclaimed in the near future.
• Anomalies due to flaws in the containment design have highlighted the need for a more robust sorbent configuration (such as structured sorbents)
The Challenges of Going Beyond the ISS for ECLSS

- ~2 days transit time
  - Atmosphere samples
  - Spare hardware, consumables
  - Emergency Crew Return
  - Trash

- ~1-3 years transit time
  - 228,000,000 kilometers
  - 390 kilometers
Oxygen Generation

Presented By
Kevin Takada
NASA MSFC
ECLS Systems Development Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
ISS Regenerative ECLSS Architecture

Water Recovery System (WRS)

URINE PROCESSOR ASSEMBLY (UPA)
• Distillation Assembly

WATER PROCESSOR ASSEMBLY (WPA)
• Gas Separator
• Particulate Filter
• Multifiltration Beds

USOS CABIN
CREW

Urine
Wastewater
Distillate

Potable water

Oxygen Generation System (OGS)

OXYGEN GENERATOR ASSEMBLY (OGA)
• Solid Polymer Electrolysis (SPE)

Power Supply Module (PSM)

CO2 REDUCTION ASSEMBLY (CRA)
• Sabatier Reactor

Water

Urine
Wastewater
Distillate

Potable water

Oxygen
Carbon Dioxide

Hydrogen

overboard

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Integrated Process

1. Oxygen & hydrogen produced in 28-cell stack
2. O\textsubscript{2} delivered to cabin
3. H\textsubscript{2} mixed with excess re-circulated water, separated dynamically, and vented overboard or to Sabatier
4. Makeup water periodically added and stored within rotary separator
5. Oxygen lines purged with nitrogen for safety after shutdowns
ISS OGS Key Components

Rotary Separator Accumulator

Hydrogen Sensor

Cell Stack Power Supply Module (PSM)

Cell stack (28 cells)

TFAWS 2017 – August 21-25, 2017
Cathode Feed Cell Membrane (Nafion)
## ISS OGS Key Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max crew size supported</td>
<td>11</td>
</tr>
<tr>
<td>Typical crew size supported</td>
<td>3</td>
</tr>
<tr>
<td>Oxygen Production</td>
<td>20.4 lb/day (max)</td>
</tr>
<tr>
<td>Hydrogen Production</td>
<td>2.6 lb/day (max)</td>
</tr>
<tr>
<td>Water Consumption</td>
<td>23 lb/day (max)</td>
</tr>
<tr>
<td>Oxygen consumption per crew member</td>
<td>1.8 lb/day</td>
</tr>
<tr>
<td>OGS Launch Weight</td>
<td>1774 lb</td>
</tr>
<tr>
<td>OGS Power Consumption</td>
<td>3955 W (max)</td>
</tr>
<tr>
<td>OGS Volume</td>
<td>1 ISPR Rack</td>
</tr>
</tbody>
</table>
• OGS operational on ISS, so far producing a total of ~12,000 lb of oxygen and ~1,500 lb of hydrogen
• OGS developed by MSFC and United Technologies Aerospace Systems (UTAS) in Windsor Locks, CT
• Launched in 2006 on Space Shuttle Discovery
• First activated in 2007 in the US Lab
• Relocated to Node 3
• May be relocated back to the US Lab
• Several other oxygen sources available to the crew:
  – Russian Elektron oxygen generator
  – Progress oxygen tanks
  – New oxygen and hydrogen flow meters
  – Airlock High Pressure Gas Tanks (HPGT) for EVAs
OGA Testbed in the E-Chamber

• Functionally equivalent to ISS OGA
  – Use development cell stack, RSA, pump, and PSM
  – Use commercial sensors, valves, etc.

• Demonstrated integrated operation with Sabatier
  – Supply H2 to Sabatier

• Support troubleshooting of on-orbit ISS operations

• Demonstrate incremental improvements that will be incorporated into ISS OGA and an Exploration OGA
  – New smaller cell stack design with chemically stabilized Nafion
  – New hydrogen sensor technologies
  – Delete hydrogen dome and wastewater interface
Oxygen Recovery and CO2 Reduction Overview

Presented By
Zach Greenwood
NASA MSFC
ECLS Systems Development Branch
1960’s Technology ID’d

• Carboxy (CO₂ Electrolysis)
  – 2CO₂ ↔ CO + O₂

• Methoxy (Sabatier)
  – CO₂ + 4H₂ ↔ CH₄ + 2H₂O

• Bosch Process
  – CO₂ + H₂ ↔ CO + H₂O
  – 2CO ↔ CO₂ + C(s)
  – CO + H₂ ↔ H₂O + C(s)
Sabatier Development
Unit developed by Hamilton Sundstrand

Sabatier won because:
- Lower power
- Smaller system
- No consumables
- Clean process
- Sufficient for low earth orbit

Competed for ISS
**CO₂ Reduction Assembly**

- **Sabatier Reactor**
  - \( \text{CO}_2 + 4\text{H}_2 \rightarrow 2\text{H}_2\text{O} + \text{CH}_4 \)

- **CO₂ Management System** provides compressed storage of CO₂ until needed

- **OGA provides H₂**

- **O₂ recovery ~47%**
Oxygen Recovery

Net loss of hydrogen must be resupplied as water from Earth

Launch Costs
1 lb Water ~ $31,000
1 gallon Water = 8.3 lbs
1 gal Water ~ $257,300

Need to recover and recycle more for long-duration missions
Ongoing Technology Development

• **Long Duration Missions**
  – Lunar or Mars Surface
  – Mars Transit

• **All Systems – Increase Reliability and Robustness**
  – Improve on ISS?
    or
  – New Technology?

• **Increase O₂ Recovery and Recycling with a highly reliable and robust system**
Today

• Carboxy (CO₂ Electrolysis)
  – 2CO₂ ↔ CO + O₂

• Methoxy (Sabatier)
  – CO₂ + 4H₂ ↔ CH₄ + 2H₂O

• Bosch Process
  – CO₂ + H₂ ↔ CO + H₂O
  – 2CO ↔ CO₂ + C(s)
  – CO + H₂ ↔ H₂O + C(s)

• Others

Explored by small businesses and NASA, significant challenges with materials and separating dissolved CO₂ from liquid.

Carbon Dioxide Reduction Assembly in operation on ISS. Post-processors now of interest (Plasma Pyrolysis Assembly).


E.g. Ionic Liquids
Sabatier Reactor (SOA)

- Sabatier Reaction: \( \text{CO}_2 + 4\text{H}_2 \rightarrow 2\text{H}_2\text{O} + \text{CH}_4 \)

- **Pros**
  - Minimal-fouling catalytic reaction (Ruthenium cat.)
  - High single pass conversion (>90%)
  - Significant testing and analysis
  - High TRL level
  - Flight information prior to extended duration missions

- **Cons**
  - What to do with the methane?
  - Loss of hydrogen resulting in incomplete oxygen recovery
Methane Post-Processing

Hydrogen-rich operation of CRA would eliminate CO₂ and would provide hydrogen to PPA

Small quantities of water and carbon dioxide

H₂, CH₄, CH₂O, CO₂, H₂O

Purification

H₂, CH₄, C₂H₂

H₂, CO₂

H₂O
Methane Post-Processing

• **Plasma Pyrolysis Assembly**
  – Plasma generated by microwaves
  – \( 2\text{CH}_4 \rightarrow 3\text{H}_2 + \text{C}_2\text{H}_2 \)
  – **Pros**
    • Recover some of the hydrogen from methane
    • Limited solid carbon to clean
  – **Cons**
    • What to do with acetylene?
    • Still lose some hydrogen

• **Hydrogen Purification**
  – Electrochemical cell stack

Plasma observed in viewport

3rd Generation Plasma Pyrolysis Assembly
• Chemistry

- RWGS

\[
\begin{align*}
\text{CO}_2 + \text{H}_2 & \rightarrow \text{H}_2\text{O} + \text{CO} \\
2\text{CO} & \rightarrow \text{CO}_2 + \text{C(s)} \\
\text{CO} + \text{H}_2 & \rightarrow \text{H}_2\text{O} + \text{C(s)} \\
\text{CO}_2 + 2\text{H}_2 & \rightarrow 2\text{H}_2\text{O} + \text{C(s)}
\end{align*}
\]

- Carbon Formation

• Challenges for Space Application
  - Power Consumption
    - High Temperature Reactions
  - Catalyst Resupply
  - Volume/Mass

1980’s Bosch System
Bosch Technology

• Bosch Process

Crew Members breathe in \( \text{O}_2 \) and breathe out \( \text{CO}_2 \)

\( \text{CO}_2 \) is combined with \( \text{H}_2 \) and fed to the Series-Bosch System

\( \text{H}_2 \text{O} \) produced in Reactor 1 can be used for drinking and washing or electrolyzed to produce \( \text{O}_2 \)

Carbon product from Reactor 2 might be used to make filters, to make carbon ropes, or as a filler for radiation shielding materials.
Questions?
Trace Contaminant Control

Presented By
Jay Perry
NASA MSFC
ECLS Systems Development Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
Background

- Spacecraft viewed as a tight building
  - Atmosphere recycled
  - Minimal leakage

- Design to avoid sick building syndrome symptoms
  - Nasal and eye irritation
  - Dry mucous membranes
  - Fever
  - Joint and muscle pain
  - Lethargy
  - Nosebleeds
  - Dry skin or skin rash
  - Headache
Approach to Air Quality Design

- Set air quality standards based on crew health
- Evaluate contamination sources
  - Minimize generation sources via material selection
  - Specify active control systems
- Collect data to validate the approach
  - Material and equipment offgassing data
  - Human metabolic data
  - Contamination control system performance
  - Mission timeline
- Predict cabin air quality
- Validate approach by collecting in-flight samples
  - Compare measured air quality to predictions
Approach to Air Quality Design

High Quality Cabin Atmosphere

- Logistics & Maintainability
- Manufacturing Processes
- Equipment Design
- Materials Selection & Control
- Resource Constraints
- Mission Operations Concept
- Vehicle Cabin or Habitat Characteristics

Atmospheric Quality Standards
Cabin Air Quality Factors

Cabin Air Loads

- Crew Metabolism & Activities
  - Exercise
  - Sanitary & Hygiene
  - Housekeeping
  - Food Preparation & Consumption
  - Medical Testing

- Payload Facility Operation
  - Venting
  - Accidental Releases

- Microbial Metabolism

- Crew Exchange

- Contingency Events
  - Fire
  - Extravehicular Activity
  - Contamination control system upsets

Control Processes

- Atmosphere Revitalization
  - Trace Contaminant Control
  - Carbon Dioxide Removal

- Temperature and Humidity Control
  - Condensing Heat Exchanger
  - Bacteria & Particulate Filters

- Spacecraft Leakage

- Human Respiration
  - 20 to 30 m³ Air/Day/Person

Combined Loads & Control Processes

- Crew Transfer and Cargo Vehicle Docking
  - Adsorption/Desorption from Surfaces
• Establish a design load model
• Consider the crew size and vehicle size
• Establish active trace contaminant control equipment performance goals
• Evaluate system-generated chemical contamination sources

<table>
<thead>
<tr>
<th>CONTAMINANT NAME</th>
<th>GENERATION RATEb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OFFGASSING</td>
</tr>
<tr>
<td></td>
<td>(mg/day-kg)a</td>
</tr>
<tr>
<td>IUPAC</td>
<td>COMMON</td>
</tr>
<tr>
<td>Methanol</td>
<td>Methyl alcohol</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Ethyl alcohol</td>
</tr>
<tr>
<td>n-butanol</td>
<td>Butyl alcohol</td>
</tr>
<tr>
<td>Methanal</td>
<td>Formaldehyde</td>
</tr>
<tr>
<td>Ethanal</td>
<td>Acetaldehyde</td>
</tr>
<tr>
<td>Benzene</td>
<td>Benzol</td>
</tr>
<tr>
<td>Methylbenzene</td>
<td>Toluene</td>
</tr>
<tr>
<td>Dimethylbenzenes</td>
<td>Xylenes</td>
</tr>
<tr>
<td>Furan</td>
<td>Divinylene oxide</td>
</tr>
<tr>
<td>Dichloromethane</td>
<td>Methylene chloride</td>
</tr>
<tr>
<td>2-propanone</td>
<td>Acetone</td>
</tr>
<tr>
<td>Trimethylsilanol</td>
<td>Trimethyhydroxysilane</td>
</tr>
<tr>
<td>Hexamethylyclosiloxane</td>
<td>D3 siloxane</td>
</tr>
<tr>
<td>Azane</td>
<td>Ammonia</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Carbonous oxide</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Dihydrogen</td>
</tr>
<tr>
<td>Methane</td>
<td>Carbone</td>
</tr>
</tbody>
</table>

a. Offgassing rate is for the mass of internal, non-structural equipment.
b. Offgassing and metabolic sources may be supplemented by system sources as they are identified.

Crew and Vehicle Size Considerations

- TCC design-driving compounds are primarily from crew metabolic sources
  - Four compounds account for 94% of the crew metabolic load
  - Ammonia is the most significant design driver
  - Formaldehyde is a secondary design driver
  - Methane, carbon monoxide, and dichloromethane are tertiary design drivers
- Active TCC equipment flow rate more strongly driven by crew size
  - Equipment offgassing from 65000 kg of equipment equivalent to 4 crewmembers
TCC Equipment Performance Goal

• Performance goal is the percentage of the individual compound SMAC
   • Usually 50% SMAC with 10% to 20% functional margin
   • Achieves <40% SMAC
• Performance goal impacts on TCC equipment design
   • Flow rate impacts
   • Component mass and volume impacts
   • Pressure drop and power impacts
• Performance goal no lower than 30% SMAC is reasonable for active TCC equipment design
ISS Trace Contaminant Control

POSTSORBENT BED

THERMAL CATALYTIC OXIDIZER

ACTIVATED CARBON BED
Lessons Learned from Flight Operations

- **System fluid selection is important**
  - Compatibility with ECLS systems to minimize impacts and provided for easy cleanup in the event of a leak into the cabin
  - Examples include thermal fluids, cleaning solutions, and payload chemicals

- **Pervasive chemical contaminant sources can accumulate**
  - Low equipment offgassing sources can become significant
  - Examples include formaldehyde and polydimethylsiloxane (PDMS) sources

- **Chemical and physical properties must be considered**
  - Expendable TCC process technologies that use irreversible chemical reactions can drive maintenance schedules
  - Example is LiOH reaction with HCl to form LiCl which is highly hygroscopic

- **Process technology obsolescence must be considered**
  - Suppliers of adsorbents and catalysts used for TCC equipment respond to market demands that are stronger than space exploration needs
  - Multiple process technology suppliers should be cultivated
• Define trace contaminant load
  – Equipment offgassing data and human metabolic products

• Define assumptions
  – Offgassing rates are constant with time
  – Cabin volume is well mixed
  – Cabin leakage is nearly zero
  – Steady cabin temperature and relative humidity
  – No gas phase reaction between contaminants

• Employ predictive modeling tool
  – Routines for multiple removal technologies
  – Solve basic mass balance equation
    \[ \frac{dC_i}{dt} = \frac{r_i}{V} - \left(\frac{C_i}{V}\right)\sum \eta_j \nu_j \]
  – Calculate toxic hazard index
    \[ T = \sum \frac{C_i}{C_{s,i}} \]
Conclusion

- Active TCC equipment design is a vital component of the life support system.
- Active TCC equipment design precedes detailed knowledge of vehicle characteristics.
  - Challenges associated with selecting design performance goals relative to individual compound SMACs.
  - Challenges associated with incorporating toxic hazard as a design criterion.
  - Designing to 34.5% of SMAC is a reasonable design performance goal.
- The metabolic load component most greatly influences TCC equipment design until the vehicle size approaches that of the ISS.
- A TCC equipment design for exploration missions may benefit from using both high flow, low aspect ratio and low flow, high aspect ratio adsorbent beds.
  - Provide for both crew health and ECLS system equipment health maintenance.
  - Reduce technical risk presented by emerging contaminant compounds of interest.
- Future work includes the following:
  - Conducting periodic market research on core process technologies.
  - Evaluating promising candidates relative to exploration mission figures of merit.
  - Studying arrangement of TCC components in the ECLS system architecture.
  - Refining testing methods, including contaminant injection and gas phase monitoring.
  - Incorporating lessons learned from ISS flight operations into the future design.
Selected Sources

Particulate Matter Design Considerations

Presented By
Jay Perry
NASA MSFC
ECLS Systems Design Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
The Particulate Matter Challenge

• Many sources
  – Fabrics - lint
  – Crew – skin & hair
  – Food debris
  – Activities – paper, plastic, miscellaneous debris
  – Surface dust intrusion

• Standards
  – 3 mg/m³ for <100 µm
  – 0.3 mg/m³ for <10 µm
Defining the Load for Design

• Basic load
  – 95 wt% >500 µm
  – Fraction <500 µm
    • 2 wt% <100 µm
    • 0.6 – 1.6 mg/CM-minute

• Surface dust load
  – 227 grams dust/CM-EVA
  – Fraction <10 µm remains suspended (7 wt% of total)
  – 15.9 grams/CM-EVA or 7X the basic daily load

• Dust intrusion barriers need to be >99% effective
Filtration Design Considerations 1

- Particle capturing mechanisms
  - Diffusion
  - Interception
  - Straining
  - Inertial impaction

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Filtration Design Considerations 2

\[ E_T = 1 - (1 - E_I)(1 - E_D)(1 - E_R)(1 - E_{DR})(1 - E_G) \]

- Media filtration
- Capturing Efficiency
  - Components: impaction, diffusion, interception, combined diffusion/interception, and gravity
- Particle diameter influences most penetrating particle size (MPPS)
- Flow influences pressure drop & penetration

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• Other separation techniques
  – Cyclonic separation
    • Efficiency determined from the 50% particle cut size
    • Design parameters: number of turns, inlet diameter, and velocity
  – Electrostatic separation
    • Efficiency dependent on the particle migration velocity, electrode surface area, & gas flow rate
    • Particle electrical resistivity plays a role – moderate resistivity is best
    • Risk for ozone production
  – Packed beds
    • High aspect ratio beds shown to remove ultrafine (<0.1 µm) and course (>1 µm) particulates
    • Efficiency is order of magnitude lower for HEPA MPPS (0.3 µm)
    • Not suitable alone for particulate filtration
    • May require protection from particulate loading (application dependent)
## Technology Options

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>BENEFITS</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Media Filtration</td>
<td>• Low to very high efficiency</td>
<td>• Challenges under high dust loading conditions requiring pre-filtration and filter logistics management to provide good capacity</td>
</tr>
<tr>
<td></td>
<td>• Very broad size range from nanometers to 10’s of microns</td>
<td>• Regeneration possible but complicated</td>
</tr>
<tr>
<td>Cyclone separation</td>
<td>• Size range limited to particles larger than a few microns</td>
<td>• Large pressure drop</td>
</tr>
<tr>
<td></td>
<td>• Large holding capacity</td>
<td>• Requires flow cessation for regeneration</td>
</tr>
<tr>
<td></td>
<td>• Can handle large particle concentrations</td>
<td>• Emptying the particulate collection receiver</td>
</tr>
<tr>
<td></td>
<td>• Regenerable</td>
<td></td>
</tr>
<tr>
<td>Inertial Impaction</td>
<td>• Large holding capacity</td>
<td>• Large pressure drop for small particle size</td>
</tr>
<tr>
<td></td>
<td>• Can handle large particle concentrations</td>
<td>• Requires flow cessation for regeneration</td>
</tr>
<tr>
<td></td>
<td>• Particulate capture in scroll reduces handling by crew during maintenance</td>
<td>• Scroll mechanism introduces complexity</td>
</tr>
<tr>
<td></td>
<td>• Regenerable</td>
<td></td>
</tr>
<tr>
<td>Electrostatic Precipitation</td>
<td>• Effective for capturing small particles</td>
<td>• Complexity</td>
</tr>
<tr>
<td></td>
<td>• Regenerable</td>
<td>• Power consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Ozone generation</td>
</tr>
<tr>
<td>Hybrid media and packed bed filtration</td>
<td>• Primarily for gaseous contaminant removal</td>
<td>• Complexity and compatibility</td>
</tr>
<tr>
<td></td>
<td>• Can offer some particle pre-filtration</td>
<td>• Requires particulate matter pre-filters</td>
</tr>
</tbody>
</table>
Particulate matter removal is a LSS key function
Consideration must be given to:
  – Airborne particulate level standards
  – Particulate sources and loads
  – Removal techniques and their defining characteristics
  – Factors influencing efficiency and mission economics
A flexible, multi-stage concept shows promise for providing needed performance relating to:
  – Total efficiency
  – Size
  – Power
  – Maintainability
  – Logistics
Selected Sources

Introduction to the ISS Water Recovery

Presented By
Layne Carter
NASA MSFC
ECLS Systems Development Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
WRS & OGS Architecture Overview

USOS CABIN
- CREW
  - drinking
  - hygiene
  - urine flush

BIOLOGICAL PAYLOADS

WRS & OGS Architecture Overview

Water Recovery System (WRS)

URINE PROCESSOR ASSEMBLY (UPA)
- Vapor Compression Distillation (VCD)

WATER PROCESSOR ASSEMBLY (WPA)
- Rotary Gas Separator
- Particulate Filter
- Multifiltration Beds
- Catalytic Oxidation Reactor

OXYGEN GENERATOR ASSEMBLY (OGA)
- Solid Polymer Electrolysis (SPE)

CO2 REDUCTION SYSTEM (CRS)
- Sabatier Reactor

USOS CABIN
- Crew latent

Urine

Water

Potable water

Oxygen

Carbon Dioxide

Hydrogen

overboard

TFAWS 2017 – August 21-25, 2017
UPA in WRS2 Rack
UPA in WRS2 Rack
Why Process Urine?

- Urine processing is not required to keep crew on ISS, you can resupply water from the ground
- For a nominal crew of 6, about 20 pounds of urine produced per day
  - Currently only processing US Crew Urine ~10 pounds/day
- UPA recovers 85% of the water from the urine
- With launch costs currently at $55,000/Kg
- UPA currently makes $187,000 worth of resupplied water per day

**UPA currently recovers per year**

$68,255,000

If UPA returns to 6 crew and 85% per year

$154,798,000

Disclaimer: Old data, but gives an idea of impact
Waste and Hygiene Compartment (Space Potty)
Urine Processor Assembly Simplified Schematic

- Urine from WHC
- Wastewater Tank
- Fluids Pump
- Distillation Assembly (DA) (Distills wastewater)
- Purge Pump (removes gases from Distillation Assy.)
- Coolant (promotes condensation within purge pump)
- Purge Gas to Node 3 cabin
-Separator (separates water from purge gases)
- Brine Filter (removes precipitants)
- Advanced Recycle Filter Tank Assy. (accumulates & stores brine for disposal)
- Product water to Water Processor Assembly
Detail View of Distillation Assembly

- Light Blue = Distillate (purified water)
- Pink = Air
- Yellow = Pre-treated Urine Mix
- Orange = Brine
Water Processor Simplified Schematic

- **Ion Exchange Bed**: Removes reactor by-products.
- **Preheater**: Heats water to 267°F.
- **Regen. HX**: Recovers heat.
- **Gas/Liquid Separator**: Removes oxygen.
- **Particulate Filter**: Removes particulates.
- **Multifiltration Beds**: Remove dissolved contaminants.
- **Mostly Liquid Separator**: Removes air.
- **Microbial Check Valve**: Provides isolation.
- **CC Reactor Health Sensor**: Verifies reactor is operating within limits.

Flow paths:
- **From Node 3 wastewater bus**
- **Product Water Tank**
- **Reject Line** (allows reprocessing)
- **O2 from Node 3**
- **Microbial Check Valve** (provides isolation)
- **Ion Exchange Bed** (removes reactor by-products)
- **Gas/Liquid Separator** (removes oxygen)
- **Regen. HX** (recovers heat)
- **Reactor Health Sensor** (verifies reactor is operating within limits)
- **To Node 3 cabin**
- **Wastewater Tank**
- **Filter**
- **Mostly Liquid Separator** (removes air)
- **Pump**
- **Preheater** (heats water to 267°F)
- **Particulate Filter** (removes particulates)
- **Multifiltration Beds** (remove dissolved contaminants)
- **To Node 3 cabin**

**TFAWS 2017 – August 21-25, 2017**
Introduction to the ISS Urine Processor

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WHC on ISS -2
Fluid In μG
Fluid In $\mu G$
Fluid In μG
UPA in WRS2 Rack

Components of Urine Processor Assembly:
- FCA Power Module
- FCA Data Module
- Pressure Control and Pump Assembly
- Fluids Control and Pump Assembly
- Recycle Filter Tank Assembly
- Separator Plumbing Assembly
- Wastewater Storage Tank Assembly
- Distillation Assembly

Components of Water Processor Assembly:
- Separator Filter ORU
- Pump/Separator ORU
- Waste Water ORU
- Multifiltration Bed #1
- Multifiltration Bed #2

Note: Sensor ORU is located in the rear of the rack and is not shown.
UPA in WRS2 Rack
UPA On-Orbit
Distillation Assembly
Water Vapor Pressure Curve

Pressure in mmHg
760 mmHg = 14.7 psia
51.7 mmHg = 1 psia

Temperature in degrees F
Detail View of Distillation Assembly

Light Blue = Distillate (purified water)  Yellow = Pre-treated Urine Mix
Pink = Air  Orange = Brine
Detail View of Distillation Assembly

- Centrifuge Tank (rotating)
- Feed Tube
- Stationary Bowl Assy
- Fluid Manifold Assy
- Steam Deflector
- Front Plate Assy
- Magnetic Driver Coupler Assy
- Pulley Target Assy (rotating)
- Demister (rotating)
- Liquid Level Sensor
- Shaft Assy (stationary)
Fluids Pump Leak
Fluids Pump Leak -2
Pressure Control and Pump Assembly
Separator and Plumbing Assembly
Wastewater Storage Tank Assembly

1. Inlet QD, QD02-M
2. Metal Shell
3. End of bellows (sweeper)
4. Stop
5. Quantity Sensors, Q1
6. Pressure Sensor, P17
Advanced Recycle Filter Tank

1. Rail (yellow)
2. Sweeper (metallic)
3. Bracket (blue)
4. Manifold (yellow)
5. End Cap (green)
6. Housing (orange)
7. Sweeper Guide (black)
8. Bellows (metallic)
9. Stationary Term/Port Cap (green)
10. Iso Valve (blue)
11. Clip (red)

(majority of bellows removed for clarification)
Firmware Controller Assembly
Challenges for Future Exploration

Presented By
Jay Perry
NASA MSFC
ECLS Systems Development Branch

Thermal & Fluids Analysis Workshop
TFAWS 2017
August 21-25, 2017
NASA Marshall Space Flight Center
Huntsville, AL
Exploration Phases

Today

Phase 0: Exploration Systems *Testing on ISS*

Phase 1: *Cislunar Flight Testing* of Exploration Systems

Phase 2: *Cislunar Validation* of Exploration Capability

Ends with testing, research and demos complete*

Asteroid Redirect-Crewed Mission Marks Move from Phase 1 to Phase 2

Ends with one year crewed Mars-class shakedown cruise

Phase 3: Crewed Missions Beyond Earth-Moon System

Phase 4a: Development and robotic preparatory missions

Phase 4b: Mars Human Landing Missions

* There are several other considerations for ISS end-of-life

Planning for the details and specific objectives will be needed in ~2020

Mid-2020s 2030

Source: J. Free, Architecture Status, March 28, 2017 presentation to the NAC.
The Challenges

- ECLS component sizing and physical layout.
  - Fit and form
  - Accessibility for in-flight maintenance
  - Minimal spare part mass
  - Earth-independent logistics

- Earth-independent logistics
  - Minimal spare part mass
  - Earth-independent logistics

- Accounting for and managing dormant periods.

- Establishing the degree of autonomy needed.
  - Control architecture based on open-source core flight software
  - Autonomous, smart control necessary to accommodate communication lag
  - System and environmental monitoring

- Managing technology obsolescence.
  - Adsorbents, catalysts, membranes, etc.

- Higher degree of ECLS consumable mass closure.
  - The role of in-situ resource utilization

- Airborne Martian dust standard.

- Mission environments and impacts on the LSS.
  - Partial gravity, radiation, planetary protection, etc.

- Accommodating plants in the cabin environment.
Guidance from ISS

- Minor contaminants from pervasive sources can become major challenges.
- Chemical and physical properties are important.
- Atmospheric gas permeation into LSS processes must be considered.
- Develop and integrate software early.
- Near real-time environmental monitoring is essential.
- Design for statistical loads, not average loads.
- Learn the hardware’s language.