



Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions



ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS FOR MARS MISSIONS

ISSUES AND CONCERNS FOR PLANETARY PROTECTION

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March 25, 2015



Outline

◆ **Outline**

◆ **Introduction**

- Human Life Support Consumables & Wastes
- ISS ECLSS: The State of the Art & Starting Point for Exploration Systems

◆ **Forward Contamination**

A partial quantification of the potential contributions by ECLSS including remarks on mitigation and mission phases

- Atmosphere Revitalization Systems
- Cabin Leakage and Contingency Operations
- Water Recovery Systems
- Waste Management Systems
- Bioregenerative Systems

◆ **Backward Contamination**

◆ **Considerations for ECLSS Architecture, Operations and Technology Selection**

◆ **Supplemental Questions & Issues**



Introduction

Selected Principles/Findings/Recommendations from the *Life Support and Habitation and Planetary Protection Workshop, NASA/TM-2006-213485*

- ◆ Human Mars missions will generate materials from both biotic and abiotic sources that could contaminate Mars and/or be classified as indicators of life.
- ◆ No human habitat or EVA system will be fully closed. Missions carrying humans to Mars will inevitably contaminate the planet to some degree.
- ◆ Planetary Protection requirements require definition early in mission development.
 - Definition of “contaminants” is required.
 - *How do you define “biosignature”? Biological and chemical?*
 - Establish forward and back contamination limits.
 - *What releases allowable? Is any contamination acceptable?*
 - Define waste containment and disposal requirements
 - *Can waste be disposed on the surface of Mars? If so, in what state? What would be the containment requirements?*
 - Establish Earth return operations and quarantine requirements
- ◆ Currently, quantitative Planetary Protection guidelines are not available.
- ◆ Define material inventory and characteristics, process products, and release mechanisms.



Human Life Support Consumables & Wastes

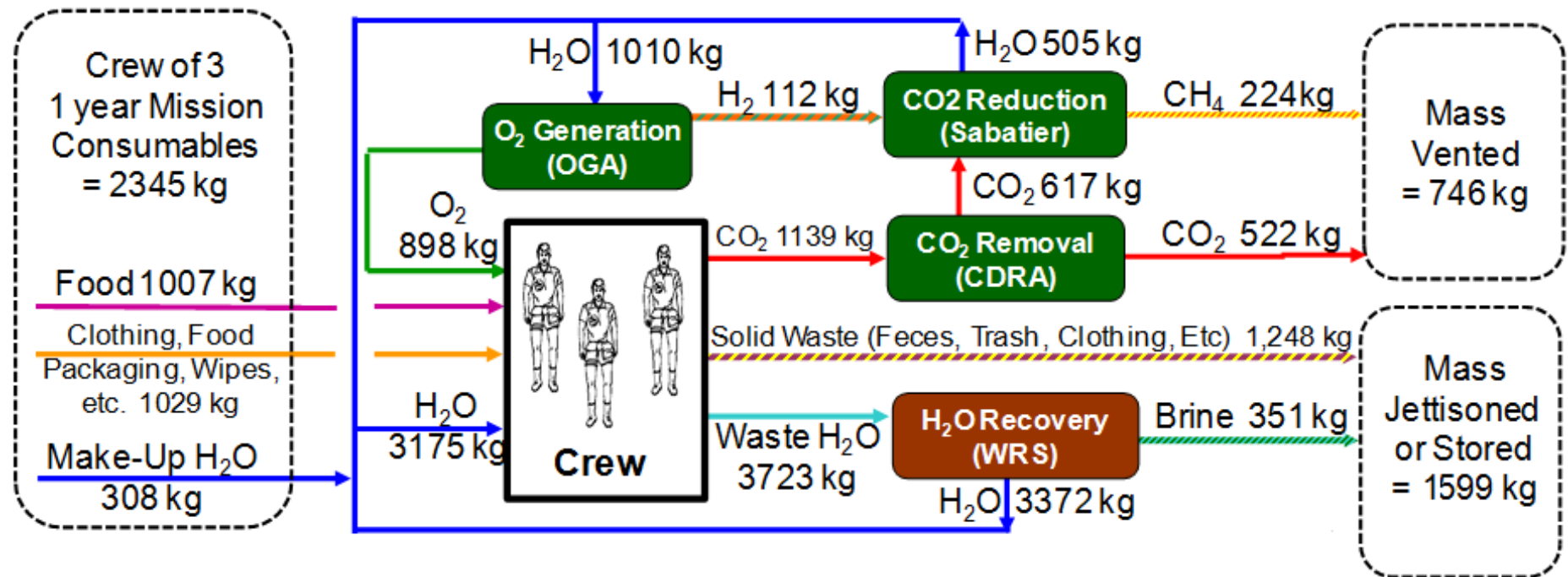
| Consumables | Kilograms per person per day | | Wastes | Kilograms per person per day | |
|------------------------|------------------------------|-------------|--------------------------|------------------------------|-------------|
| Gases | | 0.8 | Gases | | 1.0 |
| Oxygen | 0.84 | | Carbon Dioxide | 1.00 | |
| Water | | 23.4 | Water | | 23.7 |
| Drinking | 1.62 | | Urine | 1.50 | |
| Water content of food | 1.15 | | Perspiration/respiration | 2.28 | |
| Food preparation water | 0.79 | | Fecal water | 0.09 | |
| Shower and hand wash | 6.82 | | Shower and hand wash | 6.51 | |
| Clothes wash | 12.50 | | Clothes wash | 11.90 | |
| Urine flush | 0.50 | | Urine flush | 0.50 | |
| | | | Humidity condensate | 0.95 | |
| Solids | | 0.6 | Solids | | 0.2 |
| Food | 0.62 | | Urine | 0.06 | |
| | | | Feces | 0.03 | |
| | | | Perspiration | 0.02 | |
| | | | Shower & hand wash | 0.01 | |
| | | | Clothes wash | 0.08 | |
| TOTAL | | 24.8 | TOTAL | | 24.9 |

Quantities Fixed – Largely Determined by Basic Human Physiological Requirements

Quantities Variable – Largely Determined by Mission Requirements



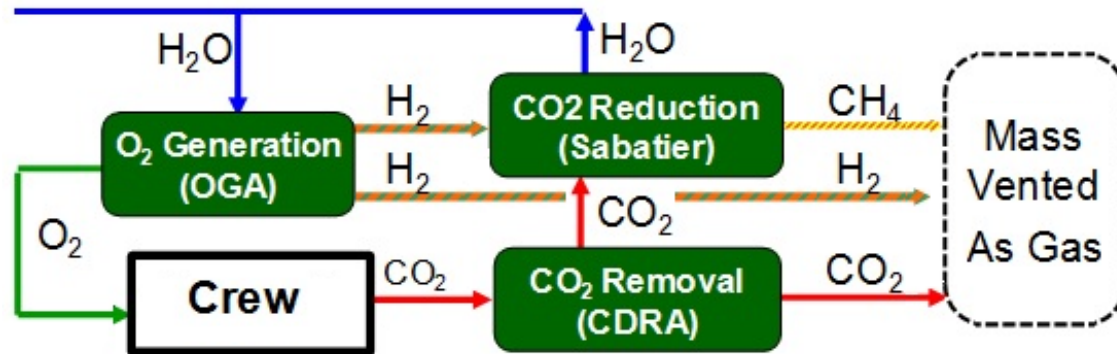
ISS ECLSS: “The State of the Art”



- ◆ Although the state-of-the-art, the ISS ECLSS is only partly closed.
 - *Atmosphere Revitalization: ≈42% oxygen recovery from CO₂*
 - *Water Recovery Systems: 74-85% recovery of water from urine; ≈100% water recovery from humidity condensate; ≈93% total recovery*
 - *Waste Management: no recycling. We collect, store and jettison*
- ◆ Significant amounts of wastes (gas, liquid and solid) are generated during all stages of a human mission to Mars



Atmosphere Revitalization System (ARS) Sources of Forward Contamination



♦ The ISS ARS is designed to vent!

- Gases & amounts will vary depending on the real time operation of ARS hardware.

Possible venting during 540 Day Surface Mission

| Vented Gas | Production Rate [†] (kg/CM/day) | Quantity Vented (kg) | | | |
|-----------------|---|----------------------|--------|------------------------|--------|
| | | Sabatier Operating | | Sabatier Not Operating | |
| | | Crew 4 | Crew 6 | Crew 4 | Crew 6 |
| Methane | 0.21 vs 0 | 454 | 680 | 0 | 0 |
| Carbon Dioxide* | 0.48 vs 1.04 | 1,037 | 1,555 | 2,246 | 3,370 |
| Hydrogen | 0 vs 0.10 | 0 | 0 | 216 | 324 |

[†]Two rates are given: the first is if CO₂ reduction hardware is available; the second is if not.

*Carbon dioxide from CDRA may contain 0.04 ppm trace organics. Integrated over 540 days for the 6 crew w/o Sabatier case equates to approximately 141 mg. The presence of micro-organisms is not known.



Atmosphere Revitalization Systems

Forward Contamination Mitigation Options

- Several alternative technologies have the potential to greatly improve closure of atmosphere revitalization systems over the state of the art.
- Most involve improved recycling of hydrogen
- Potential solutions provide additive capability to existing ARS architecture or substitutional capability disruptive to existing architecture
- 3 examples are noted below.

Carbon Formation Reactors (CFR)

- Potential for 100% recovery of oxygen
- Depending on technology, convert methane or syngas to solid carbon and hydrogen or water depending on technology
- Can be used post Sabatier in existing architecture or post SOE
- Challenges: catalyst poisoning; high temperatures; gas separation including purity of gaseous products.

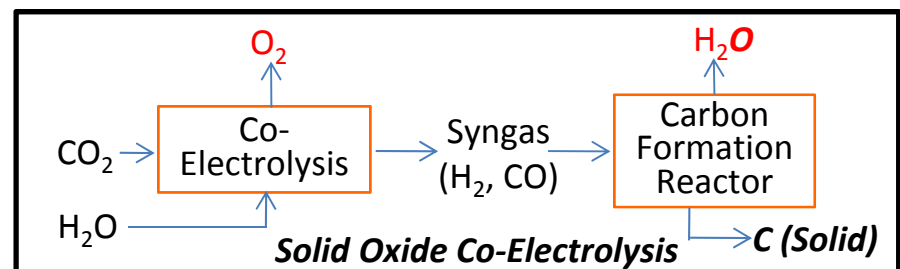
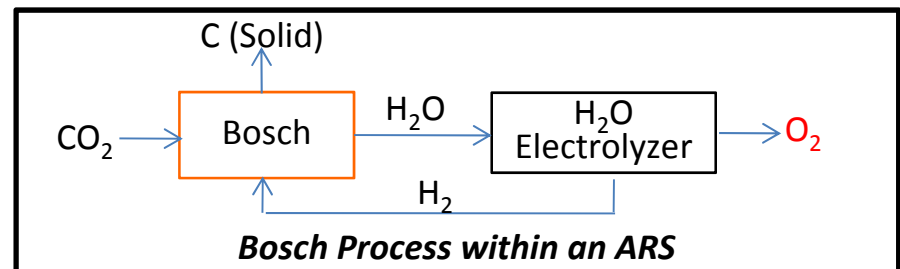
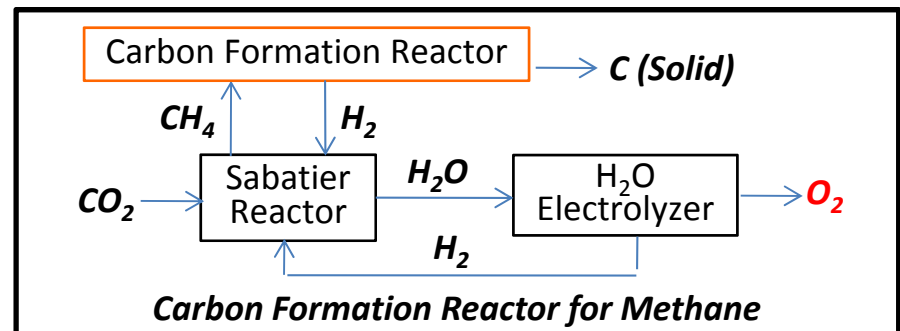
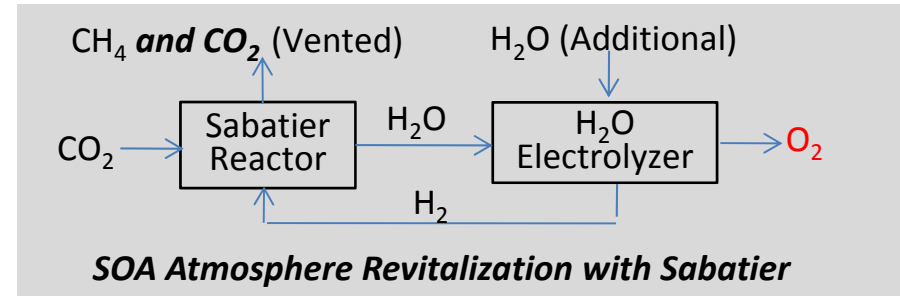
Bosch

- Potential for 100% recovery of oxygen
- Results in solid carbon byproduct rather than methane.
- Would replace Sabatier in existing architecture
- Challenges: catalyst poisoning; high temperatures; gas separation

Solid Oxide Co-Electrolysis (SOE)

- CO₂ reduction and water electrolysis in same process, with direct production of O₂ from CO₂
- SOE with embedded Sabatier may potentially yield 70-80% recovery of O₂ and can approach 100% if followed by a CFR
- Challenges: High temperatures, thermal cycling, electrode life and gas separation

- Others include CH₄ pyrolysis & photosynthesis





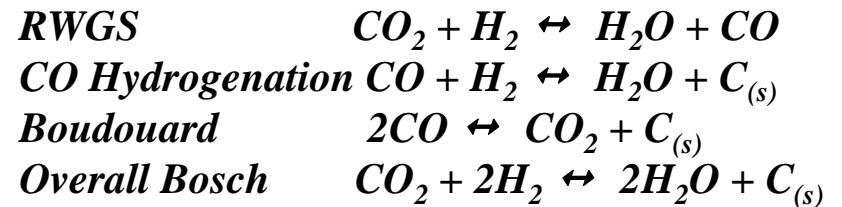
Atmosphere Revitalization Systems

Forward Contamination Mitigation Options

Series Bosch:

- Series-Bosch technology can close the atmosphere revitalization loop for complete recovery of oxygen from CO₂.
- It is a two reactor system, Reverse Water Gas Shift (RWGS) followed by a Carbon Formation Reactor.
- From a planetary protection perspective, we trade the venting of methane for solid carbon, which will accumulate as a solid waste within spacecraft at a rate of ≈ 0.27 kg/CM/day
- We have investigated incorporating Bosch carbon into heat melt compactor discs, and also combining the carbon with concreting materials to make “bricks” for as a planetary construction material.
- There is a mass penalty for catalyst
- We have found that Mars simulated regolith can be used as a catalyst for the carbon formation reactor.

REACTIONS OF THE BOSCH PROCESS



| Quantity Carbon Accumulated (kg) | | | |
|----------------------------------|--------|-----------------|--------|
| 180-day Transit | | 540-day Surface | |
| Crew 4 | Crew 6 | Crew 4 | Crew 6 |
| 204 | 307 | 613 | 920 |



Estimates of Gas Loss from Leakage & Airlock Use for Mars Habitat Lander

- ◆ **Estimates of gas loss from the habitat lander based on airlock use and cabin leakage calculations**
 - NASA-SP-2009-566-ADD2 (2014) calls for "up to three 6.5-hour EVAs each week for habitat maintenance, trash ops, local exploration, etc." from the habitat lander.
 - Depending on the level of airlock atmosphere recovery, and habitat pressure, 3 EVAs/week would result in an average air loss of 0.18-0.53 kg/day or 95-286 kg for a 540 day surface mission.
 - Given that habitat leakage can be estimated at approximately 0.1 kg/day, the total air loss would be 0.28-0.63 kg/day or 149-340 kg for a 540-day surface mission.
- ◆ **Estimates of gas loss from the habitat lander based on DRM 5.0 makeup gas requirements**
 - NASA-SP-2009-566-ADD (2009) estimates N₂/Ar needs from leakage and EVAs to be 133 kg, which is equivalent to an air loss of 196 kg at 32% O₂.
- ◆ **200 kg total air loss** from the surface habitat to the Mars environment per mission is a reasonable estimate for evaluating planetary protection impacts.



Estimates of Contaminant Release to Mars Surface from 200 kg Gas Loss

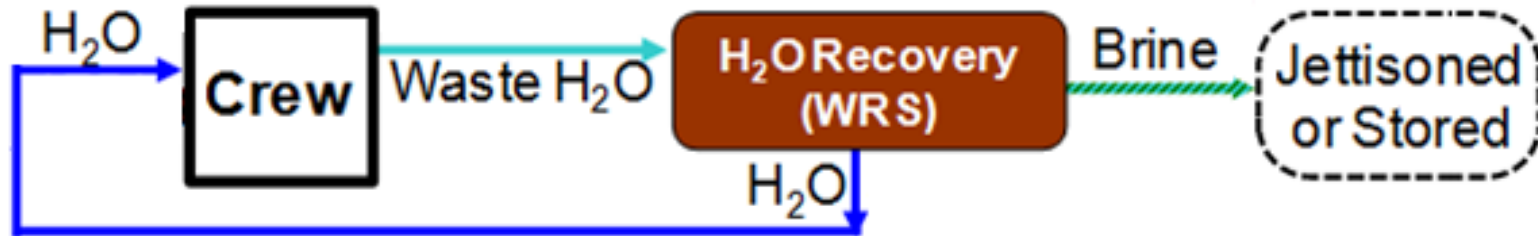
| Approximate Cabin Atmosphere Contaminant Levels Based on ISS Experience | | |
|--|--------------|--------------------|
| <i>Contaminant</i> | <i>Value</i> | <i>Units</i> |
| Airborne Bacteria | 50 | CFU/m ³ |
| Airborne Fungi | 10 | CFU/m ³ |
| Methane | 6 | mg/m ³ |
| Alcohols + Acetone | 6 | mg/m ³ |
| Octafluoropropane | 9 | mg/m ³ |
| Formaldehyde | 0.03 | mg/m ³ |
| Other VOCs | 4 | mg/m ³ |

| Estimate Released | | |
|-----------------------|-----------------|--------------|
| <i>Cabin Pressure</i> | | <i>Units</i> |
| <i>8 psi</i> | <i>10.2 psi</i> | |
| 15,486 | 12,159 | CFU |
| 3,097 | 2,432 | CFU |
| 1,858 | 1,459 | mg |
| 1,858 | 1,459 | mg |
| 2,787 | 2,189 | mg |
| 9 | 7 | mg |
| 1,239 | 973 | mg |

- ♦ Potential releases from habitat leakage represent about ¼ of the total and would be hard to mitigate. We are assuming primary leakage is from seals and bulkheads (unfiltered) rather than wall of hull.
- ♦ Potential releases due to airlock use could be mitigated by suit port
- ♦ Unplanned or contingency depresses (in the case of fire or toxic chemical release) could result in the entire cabin volume vented.



Water Recovery System (WRS) Sources of Forward Contamination – ISS SOA



| | Production Rate (kg/CM-day) | Mass Fraction H ₂ O | Aprx. Mass Fraction Organics* | Aprx. Mass Fraction Inorganics |
|------------------|--------------------------------|-----------------------------------|----------------------------------|-----------------------------------|
| Daily Production | 0.31 | 0.900 | 0.072 | 0.028 |

| Mission Segment & # of Crew | Total Produced (kg) | H ₂ O Content (kg) | Approx. Organic Content (kg) | Approx. Inorganic Content (kg) |
|-----------------------------|------------------------|----------------------------------|---------------------------------|-----------------------------------|
| 180-day Transit, 4 Crew | 222 | 200 | 16 | 6 |
| 180-day Transit, 6 Crew | 333 | 299 | 24 | 9 |
| 540-day Surface, 4 Crew | 665 | 599 | 48 | 19 |
| 540-day Surface, 6 Crew | 998 | 898 | 72 | 28 |

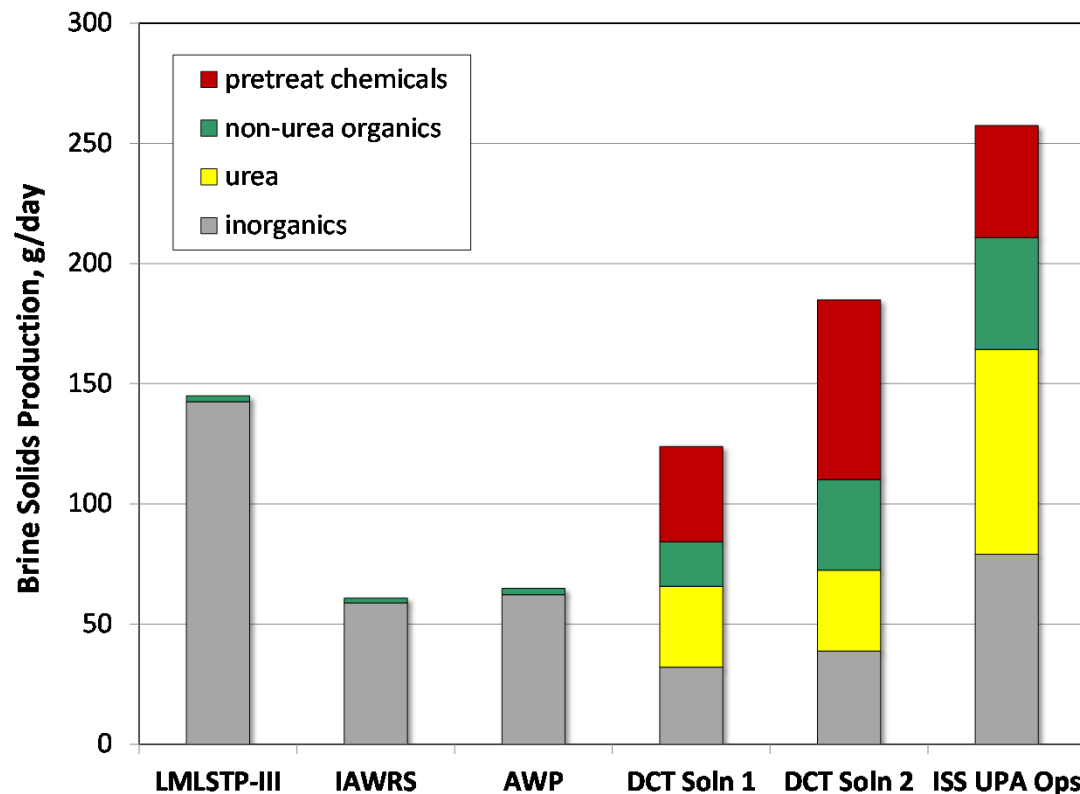
- ♦ Wastewater brines contain significant organic and nitrogen compounds



Water Recovery Systems

Forward Contamination & Mitigation Options

- ♦ Most water recycling technology options generate brines.
- ♦ The organic content of brines are dependent on initial wastewater composition and water processing technology
- ♦ Dried brine residuals become solid waste



LMLSTP: Lunar-Mars Life Support Test Project

IAWRS: Integrated Advanced Water Recovery System

AWP: Alternative Water Processor

DCT: Distillation Comparison Test

UPA: Urine Processor Assembly

Technology Development Focus is on H₂O Recovery

Aerosol Dryers

Spray Drying

Ultrasonic Nebulization

Wick Evaporation

Air Evaporation System

Air Evap. with Reusable Wicks

Membrane Systems

Brine Evaporation Bag (BEB)

Ionomer-Membrane Water Processor System

Bulk or Surface Drying

Brine Residual In-Containment

Enhanced Brine Dewatering

Lyophilization



Waste Management Systems (WRS) Sources of Forward Contamination

- ♦ The SOA for solid waste management is collection, storage and jettison.

| | Production Rate (kg/CM-day) | Mass Fraction H ₂ O | Mass Fraction Organics* | Mass Fraction Inorganics* |
|------------------------|-----------------------------|--------------------------------|-------------------------|---------------------------|
| Crew Consumables Trash | 0.91 | 0.184 | 0.720 | 0.096 |
| Feces | 0.12 | 0.732 | 0.268 | 0.000 |

| Mission Segment, # of Crew | Total (kg) | H ₂ O Content (kg) | Organic Content (kg) | Inorganic Content (kg) |
|--------------------------------|------------|-------------------------------|----------------------|------------------------|
| Feces, 180-day Transit, 4 Crew | 89 | 65 | 24 | 0 |
| Feces, 180-day Transit, 6 Crew | 133 | 97 | 36 | 0 |
| Trash, 180-day Transit, 4 Crew | 654 | 120 | 471 | 63 |
| Trash, 180-day Transit, 6 Crew | 982 | 180 | 707 | 95 |
| Feces, 540-day Surface, 4 Crew | 266 | 194 | 71 | 0 |
| Feces, 540-day Surface, 6 Crew | 399 | 292 | 107 | 0 |
| Trash, 540-day Surface, 4 Crew | 1,963 | 360 | 1,414 | 189 |
| Trash, 540-day Surface, 6 Crew | 2,945 | 541 | 2,120 | 284 |

- ♦ Feces & trash have high organic content (includes paper & plastics)



Waste Management Systems (WRS)

Sources of Forward Contamination

◆ Trash can be highly biologically active!

AIAA 2012-3565: "Characterization of Volume F trash the three FY11 STS missions: Trash weights and categorization and microbial characterization"



| | Fungal Isolates from STS 129-131 | Bacterial Isolates from STS 129-132 |
|-------------------------------|--|---|
| Personal hygiene waste | Fusarium oxysporum, Candida albicans | Staphylococcus aureus, Bacillus subtilis ss subtilis, Staphylococcus sp, Enterobacter aerogenes, Enterococcus pseudoavium, Staphylococcus aureus, Staphylococcus epidermidis, Bacillus subtilis ss subtilis, Curtobacterium spp, Sphingomonas sanguinis, Enterobacter pyrinus |
| Food | Rhodotorula hylophyla, Rhodotorula spp, Penicillium steckii, Cryptococcus albidus, Rhodotorula mucilaginosa, Candida albicans | Bacillus spp., Enterococcus pseudoavium, Staphylococcus aureus Staphylococcus saprophyticus, Bacillus pumilus Sphingomonas sanguinis |
| Drink pouches | Candida catenulate, Rhodosporidium diobovatum, Candida albicans, Cryptococcus laurentii, Rhodotorula, Aspergillus | Bacillus subtilis ss subtilis, Enterococcus pseudoavium, Burkholderia cepacia, Staphylococcus aureus, Enterobacter pyrinus, Citrobacter spp, Sphingomonas sanguinis, Burkholderia multivorans, Enterobacter pyrinus |
| External surfaces | Cladosporium herbarum, Rhodotorula glutinis, Rhodotorula mucilaginosa, Cryptococcus laurentii, Candida albicans, Aspergillus sydowii | Bacillus amyloliquifaciens, Bacillus pumilus, Microbacterium marytipicum, Bacillus amyloliquifaciens, Paenibacillus pabuli, Bacillus amyloliquifaciens, Burkholderia pyrrocinia |
| Internal surfaces | Candida albicans, Rhodosporidium diobovatum | Bacillus subtilis ss subtilis, Bacillus subtilis ss subtilis, |
| MAGS/elbow contents | Candida albicans, Fusarium spp, Rhodotorula spp. | E. coli, Citrobacter murlinae, Shigella flexneri |



Waste Management Systems (WRS) Processes & Technology Candidates

Volume Reduction (VR)

Storage space for wastes is very limited on space vehicles. Volume reduction or compaction saves valuable space.

Water Removal and Recovery (WR&R)

Many wastes such as concentrated brines and food waste contain substantial quantities of water.

Safening – Stabilization (S-S)

Safening means processing the waste to make it safe for the crew or harmless to planetary surfaces. Once safened, stabilization assures that waste does not change its state.

Containment and Disposal (C&D)

Contained waste is isolated from the crew and the external environment. Disposal can be onboard, overboard, in space, and on planetary surfaces.

Resource Recovery (RR)

Waste can be processed for reuse for the initial function, or it can be converted to new useful materials. Examples include cleaning clothes for reuse, converting waste to minerals for use as food growth nutrients, and trash to gas.

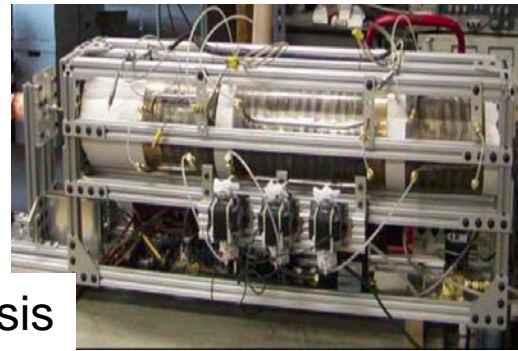
| Technology Candidates | Processes |
|-----------------------------|-------------------|
| Plastic Heat Melt Compactor | VR, WR&R, S-S |
| Lyophilization | WR&R, S-S |
| Air Drying | WR&R, S-S |
| Vacuum Drying | WR&R, S-S |
| Trash to Supply Gas | VR, WR&R, S-S, RR |
| Pyrolysis | VR, WR&R, S-S |
| Incineration | VR, WR&R, S-S, RR |
| Hydrothermal Oxidation | VR, WR&R, S-S, RR |
| Composting | VR, WR&R, S-S, RR |
| Clothes Wash | RR |
| Storage & Jettison | C&D |



Forward Contamination Mitigation Solid Waste Mineralization: Trash to Supply Gas



SCWO



Pyrolysis



Incineration

| General Technology | Technology Subtypes | Technology Process Options | Temp. [°C] | Pressure [atm] | Oxygen Requirement | End Products/ By-products | Challenges |
|-------------------------|---|-----------------------------------|------------|----------------|-------------------------------------|--|---------------------------|
| Thermal Treatment | Pyrolysis (Thermal decomposition) | Fast pyrolysis | 400-650 | ~1 | None | Liquids, tars, char, synthesis gas | tar |
| | Gasification | Direct/ Partial oxidation | 400-800 | ~1 | Substoichiometric | Synthesis gas (CO + H ₂) | waxy residue |
| | Incineration | Incineration mass burn/auger feed | 1000 | ~1 | Excess Oxygen | CO ₂ , H ₂ O, ash | NO _x reduction |
| Chemical Oxidation | Ozone Oxidation | Wet ozonation | <250 | ~1 | Ozone (O ₃) | CO ₂ , H ₂ O, ash | TBD |
| | Steam Reforming | Steam Reforming | 400-600 | ~220 | Steam with substoichiometric oxygen | H ₂ , CO, CO ₂ | TBD |
| Catalytic Decomposition | Low Temperature Catalytic Decomposition | Photocatalytic oxidation | <100 | ~1 | Stoichiometric | CO ₂ , H ₂ O, ash | TBD |
| | | Wet air oxidation | 150-325 | 20-200 | Saturated O ₂ | H ₂ , CO, CO ₂ , CH ₄ | TBD |



Waste Management Systems (WRS)

Technology Candidates – Heat Melt Compaction



Heat Melt Compactor

- *Reduces volume, removes & recovers water, encapsulates organics and renders trash a biologically stable and safe product.*
- *Plastic content - potential for radiation shielding*
- *Microbial studies demonstrated efficacy*



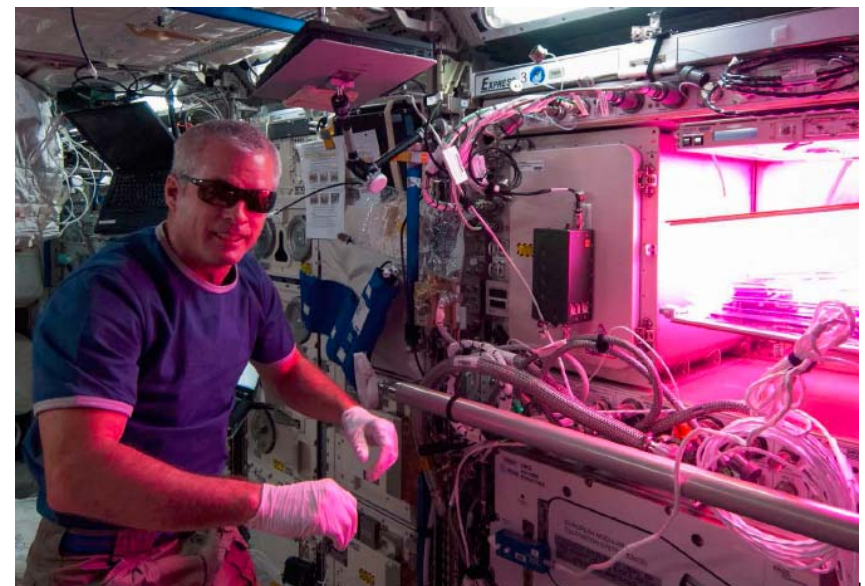
Heat Melt Compactor discs were evaluated with spore test strips (*Bacillus atrophaeus* & *Geobacillus stearothermophilus*)



Bioregenerative Life Support Systems

♦ **Biological systems, including food production, represent the potential “ultimate” in closed life support.**

- Bioreactors and composters could be used to biologically degrade liquid and solid wastes.
- Plants produce food but also photosynthetically convert CO₂ into oxygen and can utilize nutrients in wastewater.
- These systems will include very unique biological burdens
- These could be benefactors for recycling mineralized or composted solid wastes.
- But likely, on a first human mission to Mars, plants may be used only for food system augmentation – for fresh vegetables.

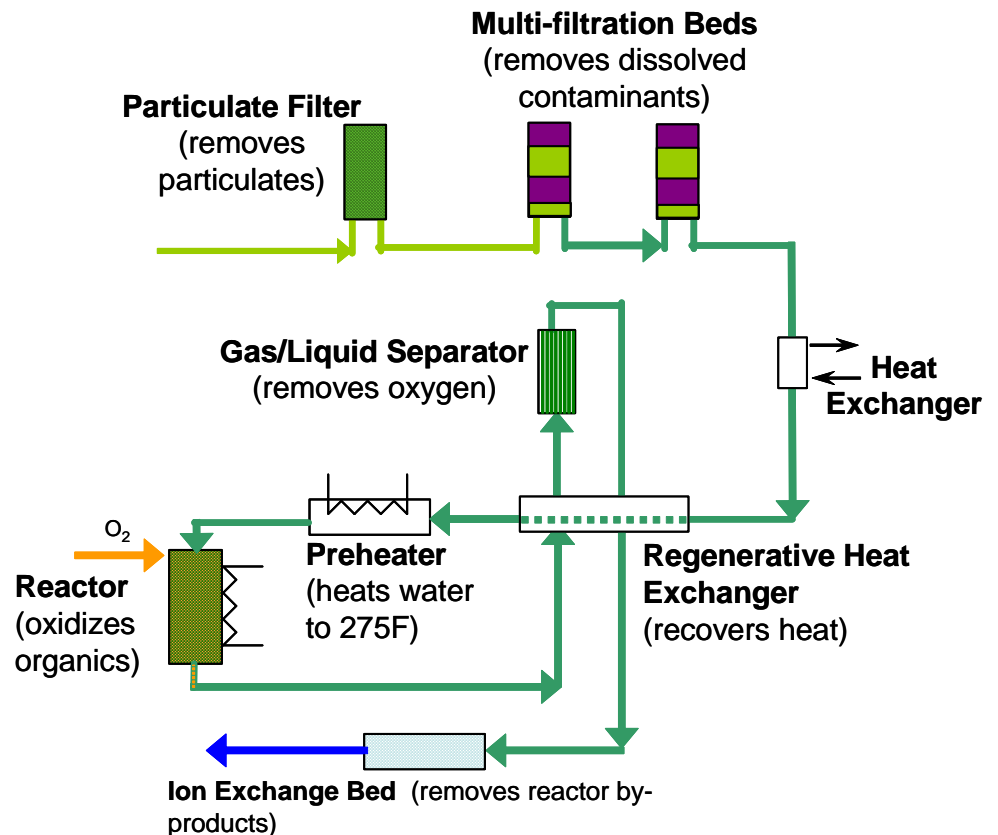




Backward Contamination Considerations

- ◆ Dust mitigation will be a consideration for protection from hazards of Mars regolith, including hexavalent chromium and perchlorates.
- ◆ Human quarantine capability – dual ECLSS systems, compartmented cabin?
- ◆ Continuing the chain – if people have been exposed to Mars materials, what does that say about the return transit vehicle?

- ◆ **Use of ISRU derived life support consumables (water, O₂)**
 - The ISS Water Recovery System's Multi-filtration Beds and/or Vapor Compression Distillation assembly would need to be evaluated for removal of chromium and perchlorates
 - The Volatiles Removal Assembly (VRA) heats process water to 275F in a catalytic oxidizer. Would this be sufficient to sterilize Mars surface water?





Planetary Protection Considerations for ECLSS Technology Development

- ◆ Planetary protection represents an additional set of requirements that technology developers need to consider early in development programs.
- ◆ Planetary protection will affect technology development by constraining how technologies can operate and what technologies may be considered:
 - Limiting or prohibiting certain kinds of operations or processes (e.g. venting)
 - Necessitating that other kinds of operations be performed (e.g. sterilization)
 - Prohibiting what can be brought on a mission (e.g. extremophiles)
 - Creating needs for new capabilities/technologies (e.g. containment)
 - This may result in certain types of technologies being prohibited (vacuum desorption of beds?) or modifying their use (filtering vent lines)
- ◆ Backward Contamination has impacts (use of ISRU consumables; dispositioning contaminated materials; needs for quarantine capability)
- ◆ A “fully closed” ECLSS may ultimately be ideal for planetary protection, but to achieve this closure, launch mass and complexity may be extremely high – the law of diminishing returns.
- ◆ Ultimately, there will be effects on mission costs, development costs, and the mission trade space. Will a PP compliant ECLSS fit into the mission allocation?



Supplemental Questions & Issues

- ◆ ECLSS engineers hunger quantitative requirements!
- ◆ What constitutes a biomarker?
- ◆ What discharges are acceptable?
- ◆ How can unacceptable discharges be made acceptable?
- ◆ For storage of wastes on the surface, what is the requirement for the life of the containment vessel?
- ◆ How can we certify the quality of ISRU produced consumables before use if we don't know the threat?
- ◆ How much can we learn from precursor robotic missions?
- ◆ Will a conservative approach to planetary protection prohibit using bioregenerative systems?
- ◆ Prioritization of Planetary Protection against other mission requirements, including mass and complexity
- ◆ An ECLSS trade study driven by Planetary Protection requirements needs to be performed.
- ◆ We need to start re-investing in critical low TRL technologies, including waste management



Summary

- ◆ Planetary protection guidelines will affect many operations, processes, and functions that have been utilized in spacecraft life support systems in the past or are under consideration for future missions
 - Venting and discharge of liquids and solids
 - Ejection of wastes
 - Use of ISRU
 - Requirements for cabin atmospheric trace contaminant concentrations and cabin leakage
 - What materials, organisms, & technologies that can be brought on missions
- ◆ Planetary protection represents an additional set of requirements that must be considered during the technology development phase.
- ◆ Planetary protection requirements will have a major impact on technology selection for future missions.
- ◆ Planetary protection requirements need to be considered early in technology development programs.



The Questions

- ♦ **What planetary protection (PP) related research activities or technical developments do you feel are critical for inclusion in your study area?**
 - Properties of regolith & dust to design filtration and removal systems
 - Medical research to set allowable exposure limits
 - Science inputs on how much of what type can be vented. (Zero is not a good answer.)
 - Science inputs on how long wastes (or whole habitats) left on the surface must remain stable and sealed. (Forever is not a useful answer.)
- ♦ **What work/research is already underway?**
 - Life support teams are investing minimal work in planetary focused technologies. Stabilizing or destroying solid wastes is not minimally funded. Regolith focused particulate work is not funded.
 - MEDA on Mars 2020 will do more to characterize regolith (in one location...)
 - Any climate models from Mars 2020 may help science community specify release requirements.



The Questions

- ◆ **Is special information or technology needed to plan for nominal vs. non-nominal situations?**
 - If crewmembers need to be quarantined from each other (and a recycling life support system) then different technology is needed
 - Abort cases could drop significant portions of a spacecraft on a surface and ruin any containment.
- ◆ **Are existing human mission mitigation options and approaches adaptable for PP needs on the martian surface?**
 - Filtration can be applied to known outputs (leakage always happens...), but often at a performance cost
- ◆ **Are there any significant stumbling blocks ahead that are evident? (Including coordination across PP, science exploration, engineering, operation and medical communities.)**
 - Engineers require numbers to drive design and make decisions. “ALARA” requirements are very difficult to use to create good results.



The Questions

- ◆ **In your opinion, what still needs to be accomplished?**
 - Work to set storage time limits for known wastes
 - Identify criticality of impact inevitable leakage to science objectives
 - At minimum, formulate requirements with TBD quantitative levels for human environment conditions soon so we can at least start to address functions
 - Perform a systems analysis and mission trade study for Mars mission ECLSS with focus on Planetary Protection constraints and flush out costs/penalties to mass, power, volume and technology selection.