Spacecraft Water Quality and Monitoring Needs for Long Duration Human Missions

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NSI Webinar: "Water Sustainability through Nanotechnology: Enabling Next-Generation Water Monitoring Systems"

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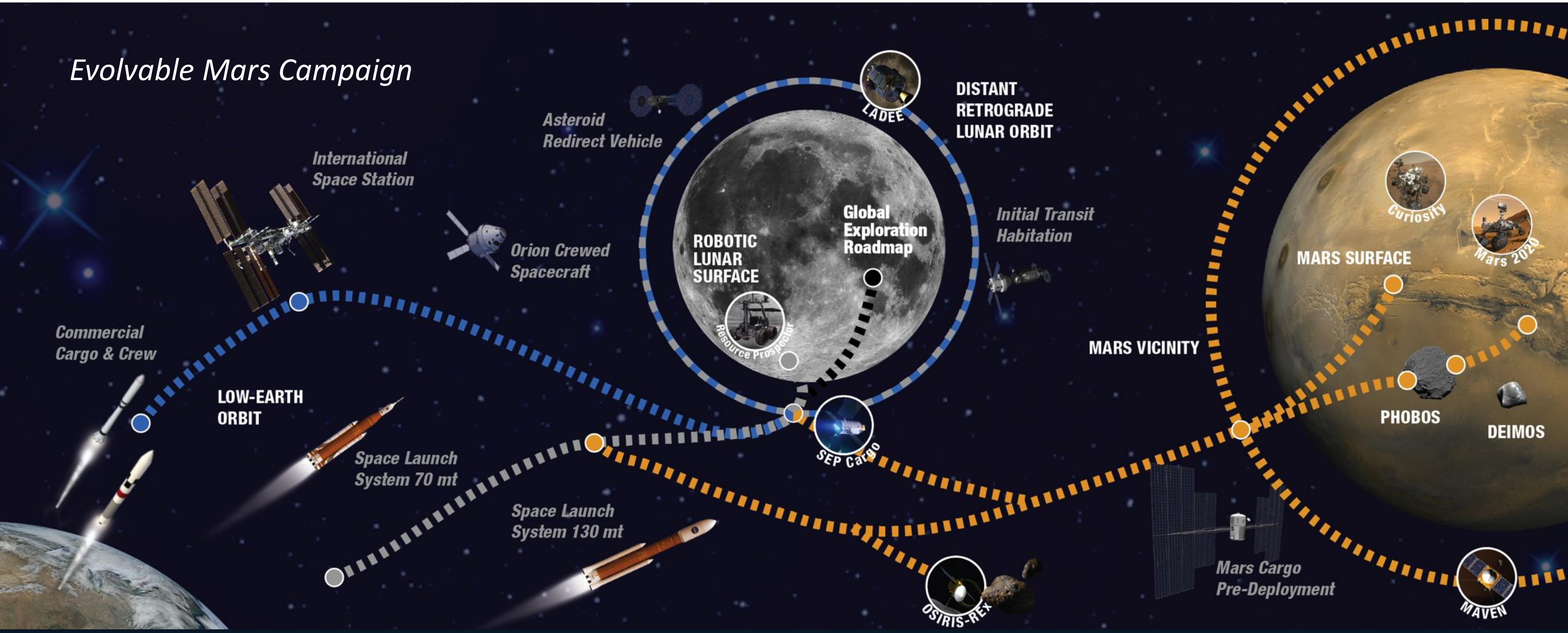
Journey to Mars: Pioneering Next Steps in Human Space Exploration



Earth Reliant
ISS Through at Least 2024
Missions: 6 to 12 months
Return: Hours
Resupply: frequent shipments
Sample return is common

Proving Ground
Missions Beyond LEO Through 2020s
Missions: 1 to 12 months
Return: Days
Resupply: costly and difficult
Sample return is difficult

Earth Independent
Missions to Mars & Vicinity 2030s
Missions: 2 to 3 years
Return: Months
Resupply: not possible
In-flight sample analysis required

Possible Types of Water on Spacecraft

International Space Station

Ground Launched Water
- U.S. – Iodine residual disinfectant
- Russian – Silver residual disinfectant

Wastewater
- Humidity condensate
- Urine, urine flush, pretreatment
- Water processor distillate and brine

Recycled water
- Humidity condensate
- Urine, urine flush, pretreatment
- Water processor distillates and brines

Other sources
- Medical water
- Flight experiments & science samples

Possible Additions - Future Missions

Wastewater
- Hygiene, laundry, dishwasher
- Water recovered from solid wastes
- Biological life support (nutrient solution)

Extraterrestrial water
- Water from In Situ Resource Utilization (ISRU)
- Science - planetary sources, asteroids & comets

Nominal Wastewater Generation by Mission

Parameter	**ISS**	**Transit Vehicle**	**Early Planetary Base**	**Mature Planetary Base**
	Kg per Crew Member per Day			
Urine	1.20	1.50	1.50	1.50
Urine Flush	0.30	0.30	0.50	0.50
Subtotal	**1.50**	**1.80**	**2.00**	**2.00**
Oral Hygiene	-	-	0.37	0.37
Hand Wash	-	-	4.08	4.08
Shower	-	-	2.72	2.72
Laundry	-	-	-	11.87
Dish Wash	-	-	-	5.87
Food Prep.	-	-	-	TBD
Subtotal	**0.00**	**0.00**	**7.17**	**24.45+**
Condensate	2.27	2.27	2.27+	2.90+
Total	**3.77**	**4.07**	**11.44+**	**29.35+**

Data derived from "Life Support Baseline Values and Assumptions Document" NASA/TP-2015–218570

Considerations for Long Duration Deep Space Missions

Water Recycling is Enabling for Long Duration Human Exploration Missions

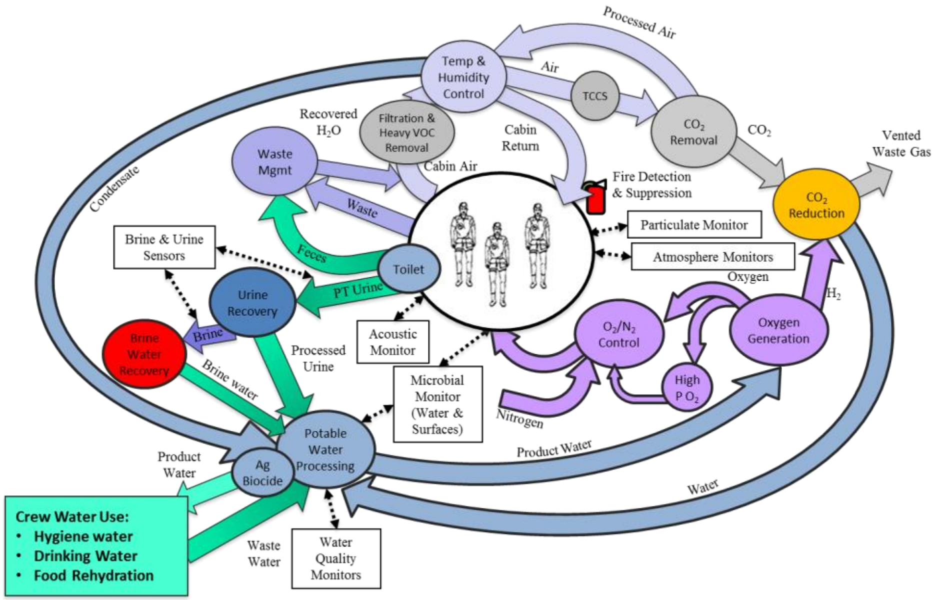
- A mission duration of 12 months for a crew of 4 will require about 3 metric tons of potable water for drinking and hygiene.
- To save mission and launch costs, recycling water will be essential to reduce launch mass.
- New potable water will be generated on board the spacecraft and systems/processes need to be in place to guarantee its quality.

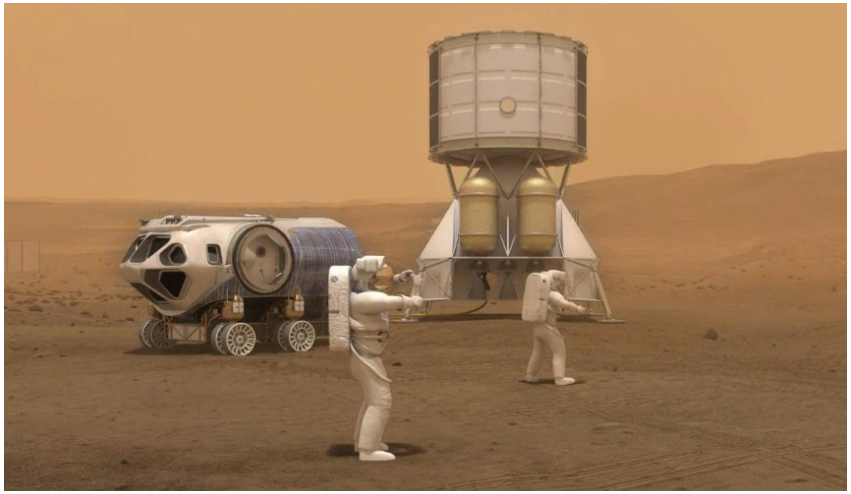
Long Distances from Earth

- A spacecraft will require a higher level of self sufficiency when distances prohibit resupply.
- Sample analysis will be limited to capability within the vehicle.
- This may drive the need for greater analytical monitoring capability on board the spacecraft.

Planetary Protection

- In-flight microbial sampling as part of controls and processes to prevent forward contamination of planetary bodies and backward contamination of Earth may be required





Spacecraft Water Exposure Guidelines (SWEGs) for Potable Water

Considerations

- Protection of Crew Health
- Strengths & susceptibilities of astronauts
- Spaceflight relevant chemicals
- Consider exposure durations critical for spaceflight
- Account for higher drinking water consumption rates
- These drive design goals for water recycling, but are purposefully not so stringent to cause over-design

Two Exposure Groups

- Acute Exposure – for contingencies
- Prolonged Consumption - drives requirements for water processor design

Selected Chemicals (list is not complete)	Concentration (mg/L)			
	1 day	10 days	100 days	1000 days
Acetone	3500	3500	150	15
Alkylamines (di)	0.3	0.3	0.3	0.3
Ammonia	5	1	1	1
Antimony (soluble salts)	4	4	4	4
Barium (salts), soluble	21	21	10	10
Benzene	21	2	0.07	0.07
Cadmium (salts), soluble	1.6	0.7	0.6	0.022
Caprolactam	200	100	100	100
Chloroform	60	60	18	6.5
Di-n-butyl phthalate	1200	175	80	40
Dichloromethane	40	40	40	15
Ethylene glycol	270	140	20	4
Formaldehyde	20	20	12	12
Formate	10,000	2500	2500	2500
Manganese (salts), soluble	14	5.4	1.8	0.3
Mercaptobenzothiazole	200	30	30	30
Methanol	40	40	40	40
Methyl Ethyl Ketone	540	54	54	54
Nickel	1.7	1.7	1.7	0.3
Phenol	80	8	4	4
Silver	5	5	0.6	0.4
Zinc soluble compounds	11	11	2	2

Spacecraft Water Exposure Guidelines (SWEGs), JSC-63414, 2008

International Space Station Water Monitoring Capability

Inorganics

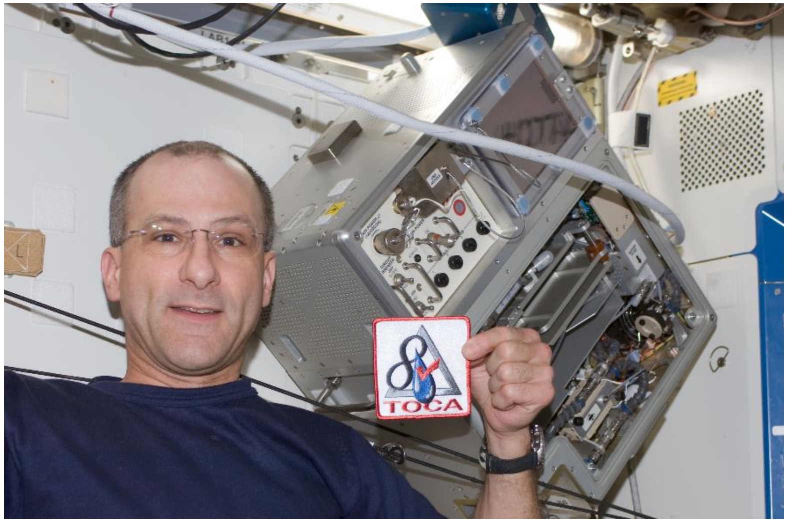
- Process water from Water Recovery System is monitored for electrical conductivity
- No capability exists for determination of constituent ion concentrations
    - Samples must be returned to Earth.
- Exception – Iodine as a residual disinfectant.
    - Colorimetric Solid Phase Extraction (CSPE) Water Biocide Monitor

Organics

- Water Recovery System process water is monitored for Total Organic Carbon
- No capability exists to determine levels of specific organic compounds
    - Samples must be returned to Earth.

Microbial Monitoring

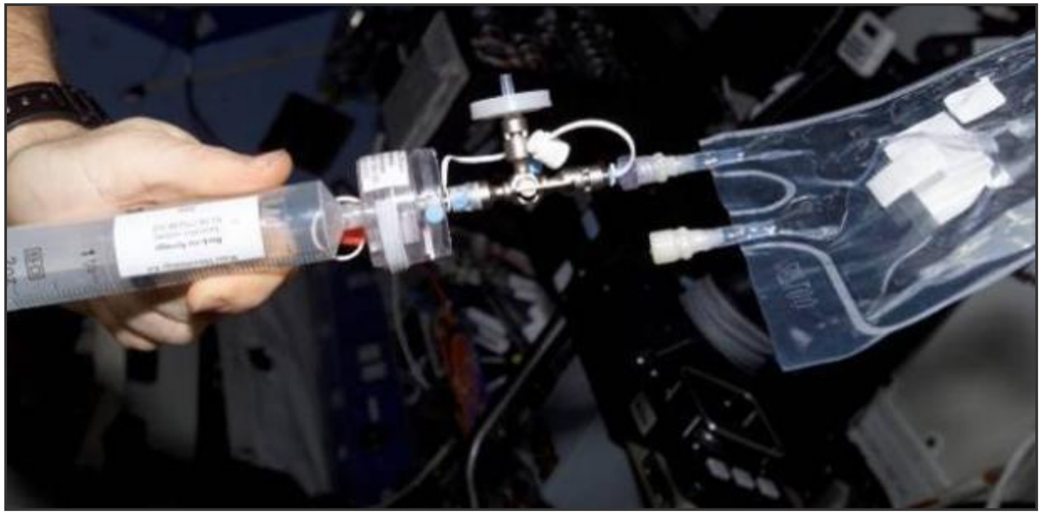
- Total heterotrophic plate counts
- Total Coliform
- For identification & enumeration of specific organisms, samples are returned to Earth



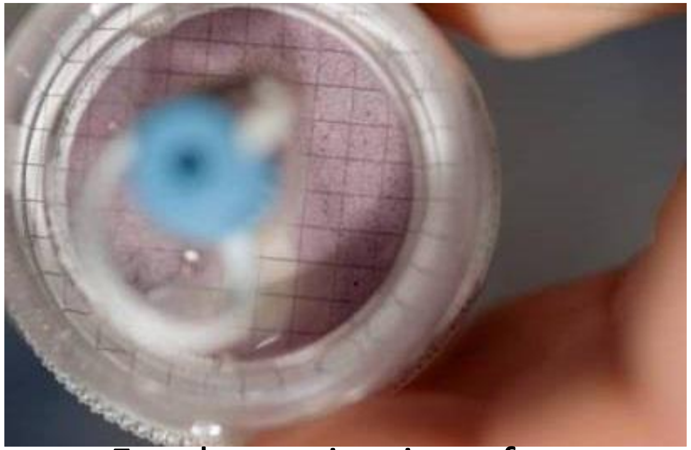
Total Organic Carbon Analyzer (TOCA) on the ISS with Astronaut Don Pettit.

Parameter	Acceptability Limit or Range
Total Organic Carbon	3 mg/L
Iodine, potable water	0.2 mg/L
Iodine, biocidal	1 – 4 mg/L
Silver, potable, biocidal	.05 – 0.4 mg/L
Heterotrophic plate count	50 CFU/ml
Total coliform bacteria	0 CFU 100 ml

Microbiological Monitoring of Water



Astronaut Ken Bowersox draws a water sample onto a plate for enumeration of microbes



For determination of heterotrophic plate counts

Coliform Detection Bag

International Space Station Design Considerations

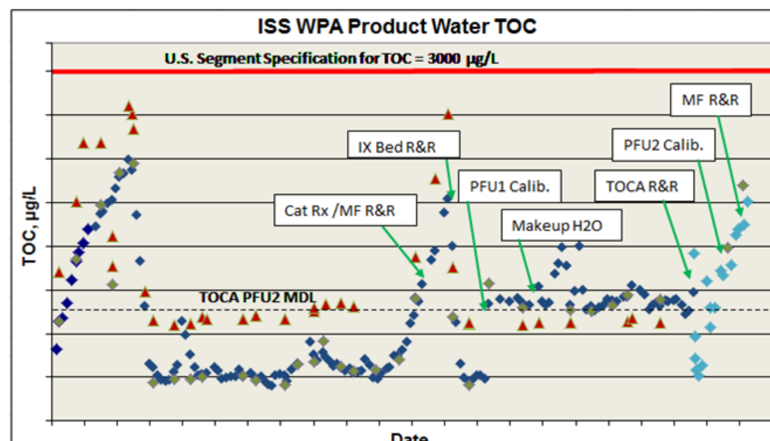
A Spacecraft is a Controlled Environment

- We have configuration management for materials and process hardware.
- These are known systems where contaminants and failure modes are largely known.
- Operations and potential anomalies are well understood given sufficient pre-flight testing.

Water Quality and Safety is Designed into Process Hardware

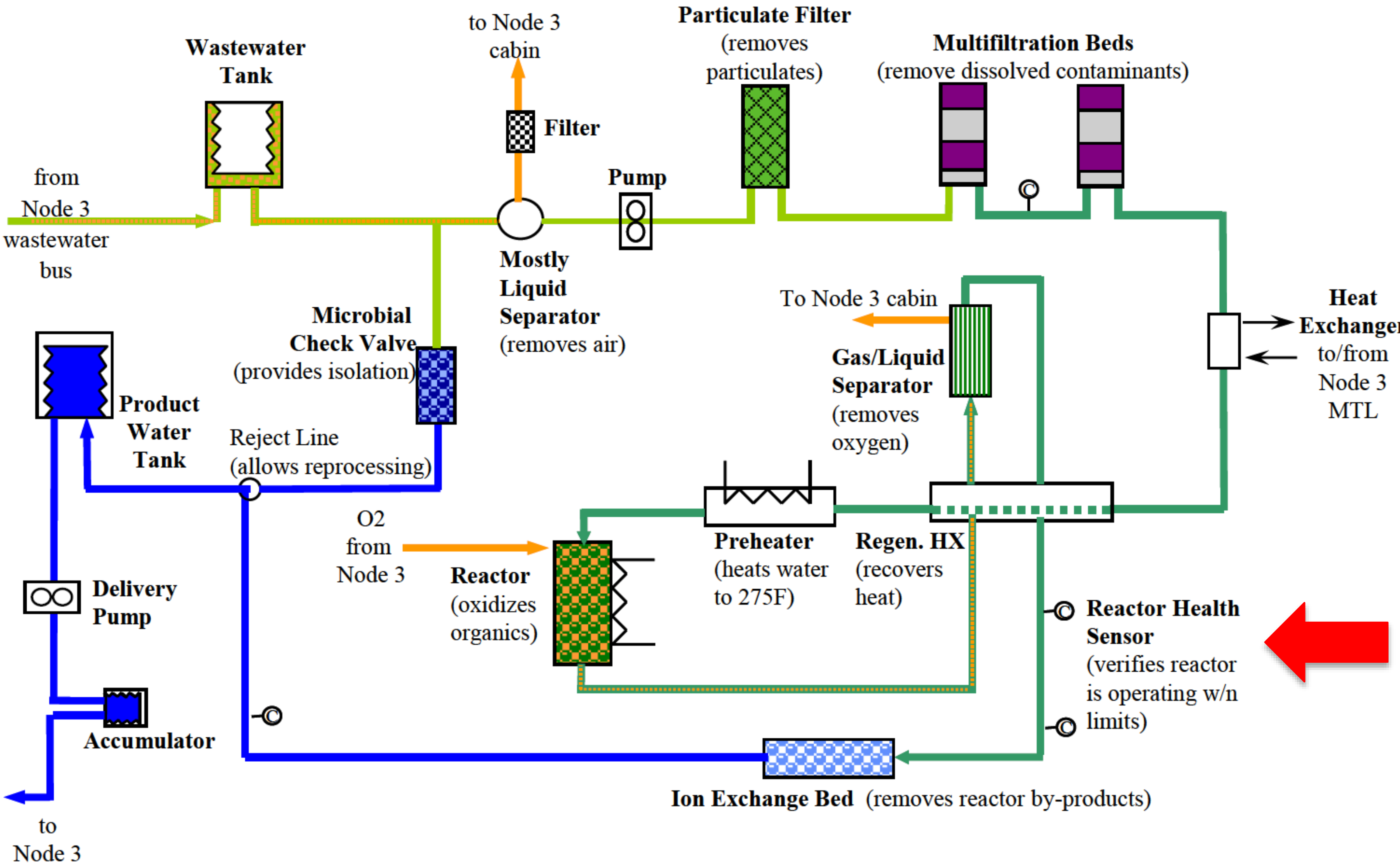
- If hardware is operating as designed within performance limits, the quality of the processed fluids are predictable.
- The key is keeping process hardware operating nominally.
- Monitoring is focused at confirming that process hardware is operating within normal performance ranges.
- Degree of monitoring is commensurate with risk.
- Fewer sensors to calibrate, fewer to fail!


ISS Water Recovery System Racks



TOC as Measure of Hardware Health

Water Processor Assembly Simplified Schematic



In-line electrical conductivity sensors measure system health (red arrow).

International Space Station Lessons Learned

Background

- The Urine Processor Assembly includes a rotary vapor compression distillation system for recovery of water from urine.
- Urine is treated with a strong acid (sulfuric) and oxidant (hexavalent chromium) to prevent microbial growth and keeping ammonia from breaking down into ammonia.
- The unit was designed to recover 85% of water from urine, with the remainder as a concentrated brine that is discarded.

What Happened

- In flight urine had a higher calcium concentration than expected.
- In 2009, precipitation of calcium sulfate salts caused the UPA to fail.
- The Distillation Assembly was replaced, but had to be operated at 70-75% recovery to prevent further issues.
- Could in-flight monitoring of calcium have prevented this?

Calcium sulfate precipitation in the Urine Processor Assembly (UPA)

What We Are Doing About It

- The pre-treatment was re-formulated with phosphoric acid.
- We are seeking in-flight process control sensors for calcium, conductivity and pH to more effectively control recovery rate.

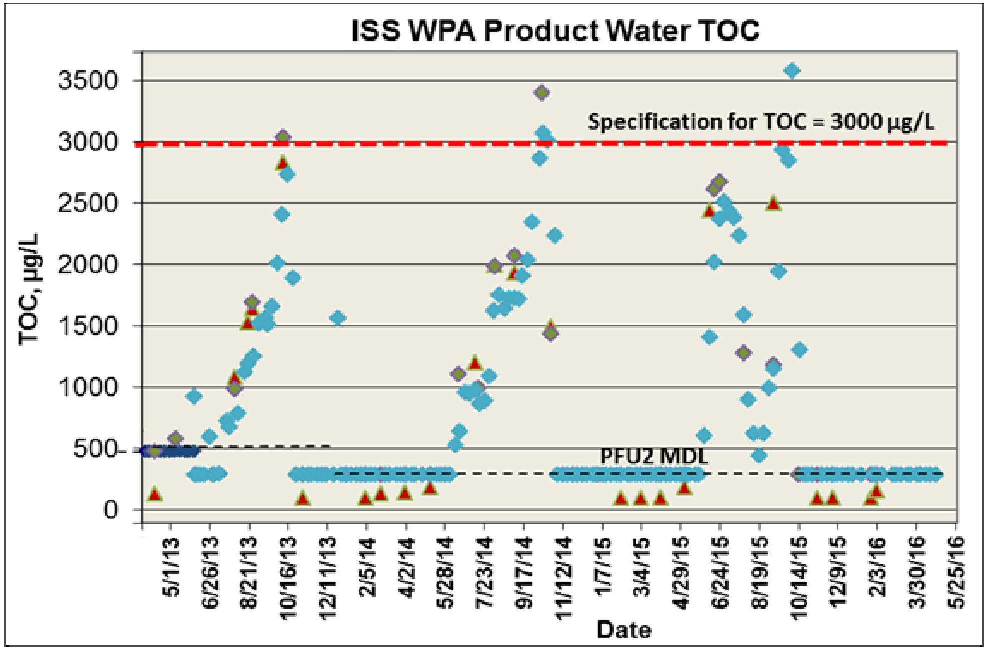
International Space Station Lessons Learned

Background

- The Water Processor Assembly (WPA) treats condensate and UPA distillate.
- Organic carbon and inorganic compounds are removed by multi-filtration (MF) beds (ion exchange and activated carbon adsorption) and by catalytic oxidation.
- System operation is confirmed by electrical conductivity and TOC analysis.

What Happened

- Product water TOC increased after approximately 15 months of operation.
- Ground analysis indicated the culprit was dimethylsilanediol (DMSD) and monomethysilanetriol (MMST), from humidity condensate, originating from decomposition of atmospheric siloxanes.
- DMSD is not readily removed by the WPA and can mask TOC from more toxic compounds.
- Ground-based analysis was required. What if we were heading to Mars?



Breakthrough of ISS Multi-Filtration Beds as measured by TOC and attributed to DMSD

What Next?

- Investigating removal of siloxanes from atmosphere and their sources of origin.
- Investigating use of Reverse Osmosis to remove DSMD & extend the life of MF beds.
- We are looking for a simple analysis method for in-flight measurement of silicates in water

Water Monitoring Needs and Current Investments

Function	Capability Gaps	Transit Habitat	Planetary Surface
Water monitoring	In-flight identification & quantification of species in water (organic and inorganic)	X	X
Microbial monitoring	Non-culture based in-flight monitor with species identification & quantification	X	X

Work at NASA Field Centers

"Organic Water Monitor (OWM)", expands existing gas GC/MS capabilities to address water analysis. To identify and quantify organic species in water samples using gas chromatography mated to a miniaturized thermal conductivity detector.

"Microbial Monitoring", investigations of commercial Polymerase Chain Reaction (PCR) systems and Biomolecular DNA Sequencing for flight use.

SBIR Investments

2017 Solicitation (closes January 20) includes requests for "In-Line Silver Monitoring Technologies" and "Sample Processing Module for the ISS Microbial Monitors".

2016 Phase I Award: "Compact Chemical Monitor for Spacecraft Water Recovery Systems", Intelligent Optical Systems, Inc., 16-1-H3.01-7755

2016 Phase I Award: "Miniaturized Sensor Array Platform for Monitoring Calcium, Conductivity, and pH in Urine Brine", Polestar Technologies, Inc., 16-1-H3.01-7659

2015 Phase II Award: "Microchip Capillary Electrophoresis for In-Situ Water Analysis", Leiden Measurement Technology, LLC, 15-2-H3.01-8900

2015 Phase I Award: "Rapid Concentration for Improved Detection of Microbes in ISS Potable Water", InnovaPrep, LLC, 15-2-H3.01-9921

Summary and Closing Remarks

Future Water Quality Analysis Needs – Notional*

- In-flight identification and quantification of groups or species of trace organics
- In-flight identification and quantification of groups or species of inorganics
- In-flight identification and quantification of groups or species of microbes
- Sample types: potable, wastewater, medical, science, planetary origin
- A compact in-flight fully functional analytical laboratory would be useful.

NASA Unique Considerations

- Miniaturized, multi-functional, and small mass, volume, power & consumables
- Cabin atmosphere may be reduced and oxygen elevated compared to Earth
- Long working life (more than 3 years), stable calibration, reliable
- Operation in micro- or partial- gravity: buoyancy, multi-phase behavior, heat transfer and convection, boundary layers, mixing & settling, etc., are affected.
- Number of manufactured units is very small compared to Earth applications.
- For process control and operations, we try to limit our dependency on sensors.
- Monitoring requirements will be driven by needs for troubleshooting, anomaly resolution, biomedicine & science, and absence of access to Earth based labs.

**Requirements for missions beyond ISS are not fully established. What we implement will be determined by resource availability and mission priorities.*

Citations & Acknowledgements

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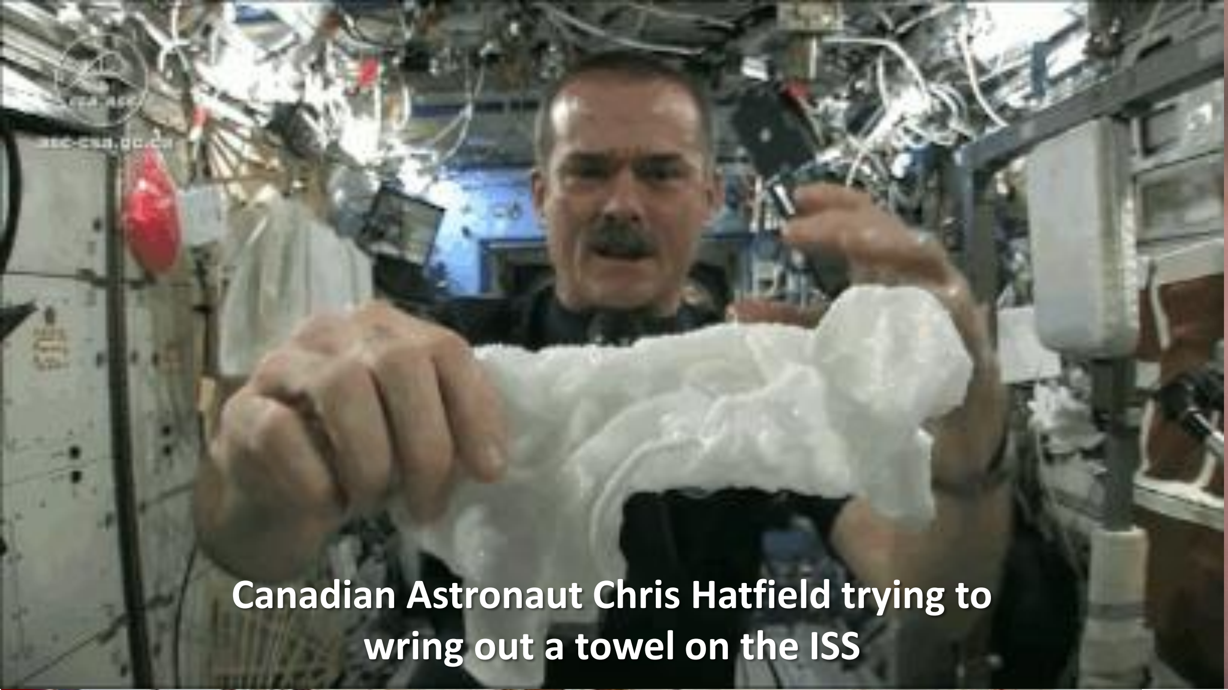
Canadian Astronaut Chris Hatfield trying to wring out a towel on the ISS


ESA Astronaut Andre Kuipers' image refracted and reflected in water


Astronaut Susan J. Helms in front of Contingency Water Containers (CWCs) on the ISS


Astronaut Scott Kelly, ping pong with water