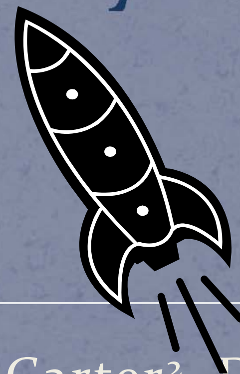
"WateReuse: To Infinity and Beyond"



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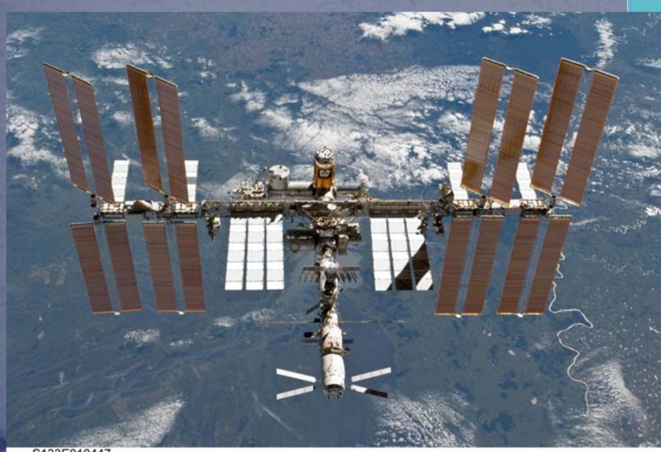
[1]NASA, Johnson Space Center

[2]NASA, Marshall Space Flight Center

[3]Wyle Laboratories, Johnson Space Center

Order of Discussion

- Introduction to Water Reuse in Space
- Background/History on NASA Water Recovery System Engineering and Design
- On-orbit Experiences and Lessons Learned



Armstrong Flight Research Center

Goddard Space Flight Center

Kennedy Space Center

Jet Propulsion Laboratory

Langley Research Center

Glenn Research Center

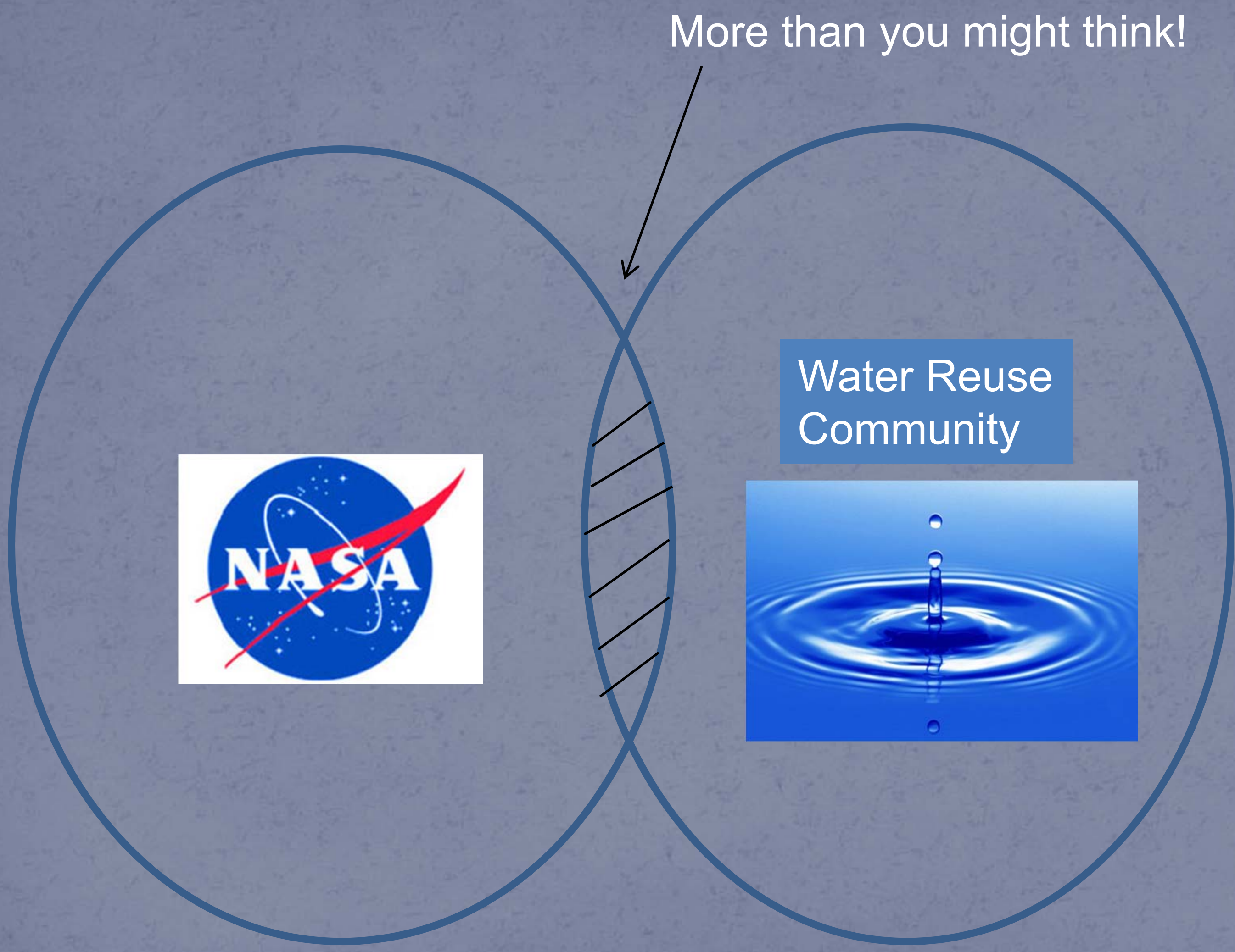
Ames Research Center

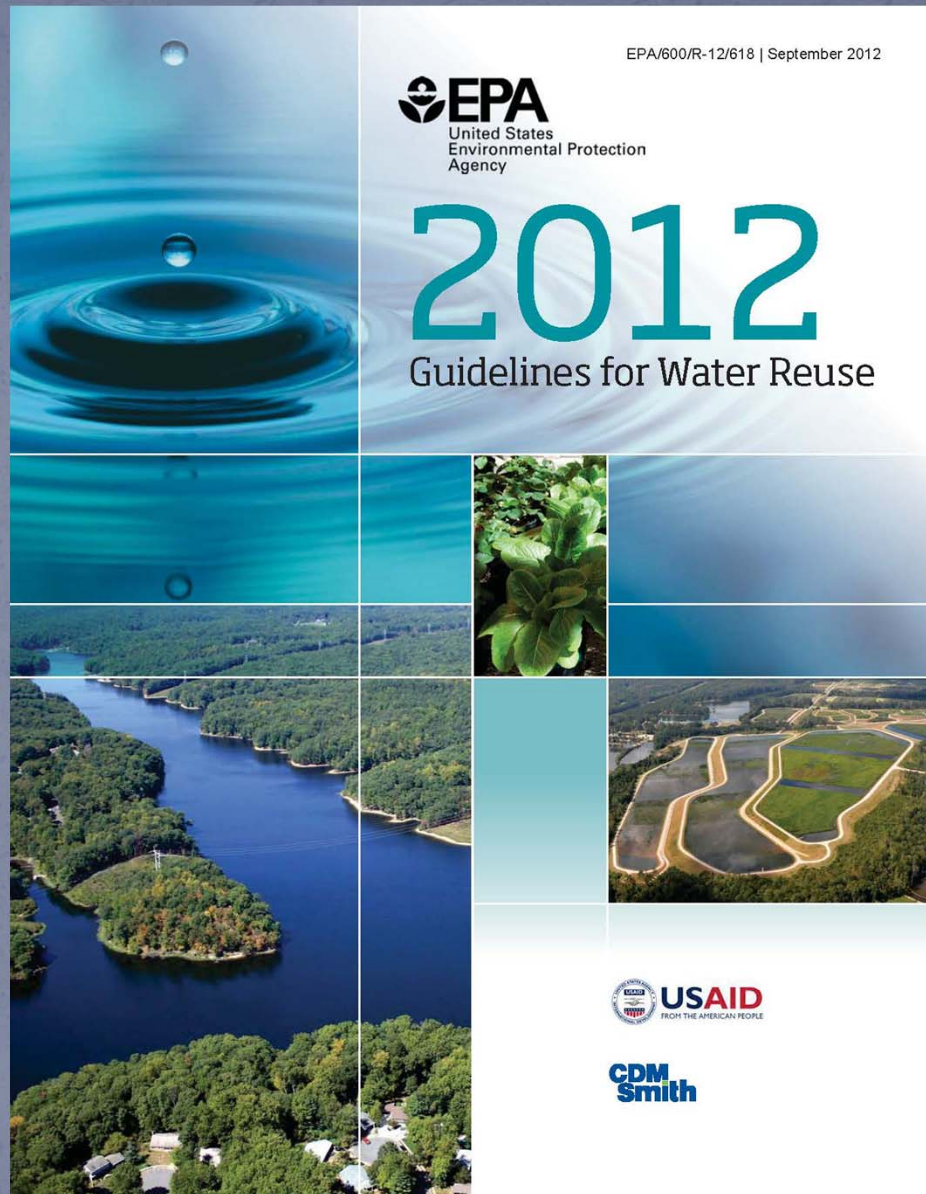
Water Reuse

Johnson Space Center

Marshall Space Flight Center

Stennis Space Center


More than you might think!
Water Reuse Community
NASA

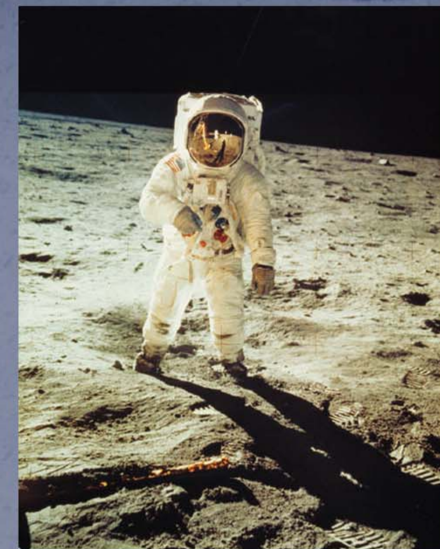

EPA/600/R-12/618 | September 2012

EPA
United States
Environmental Protection
Agency

2012
Guidelines for Water Reuse

USAID
FROM THE AMERICAN PEOPLE

CDM Smith



WATER REUSE COMMON GROUND

- Water is Essential for Living: Ignore it at your own peril!

"Water has always been and will always be a driver in Exploration."

- Population Trends/Future Planning

"Movement from water-rich to water-poor areas. Space is no exception"

- Although undervalued as a resource, true costs are becoming apparent

"Good Water Ain't Cheap: Especially 200+ miles above the earth ~$50,000/Liter to launch"

•Opportunity to Lead and to Tackle Tomorrow's Challenges

"We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win"

John F. Kennedy, 1962 Speech at Rice University

1981-2011

Under Construction 1998-2011

- ✓U.S
- ✓Russia
- ✓Europe
- ✓Japan
- ✓Canada

International Space Station (ISS)

National Laboratory , Operational until at least 2024

Shuttle-supplied water bags

Russian resupply tanks

50%

Russian Recycled
Humidity Condensate
50%

ISS Water Timeline

3 Crew on ISS

1998

2008

- 2008 Launch and Checkout of U.S. Water Recovery System
- With Shuttle retirement, resulted in 100% U.S. reliance on recycled condensate & urine distillate
- Key addition to allow for an expanding ISS crew size and Shuttle retirement! More crew= more research & ISS utilization

~100%

ISS Water Timeline

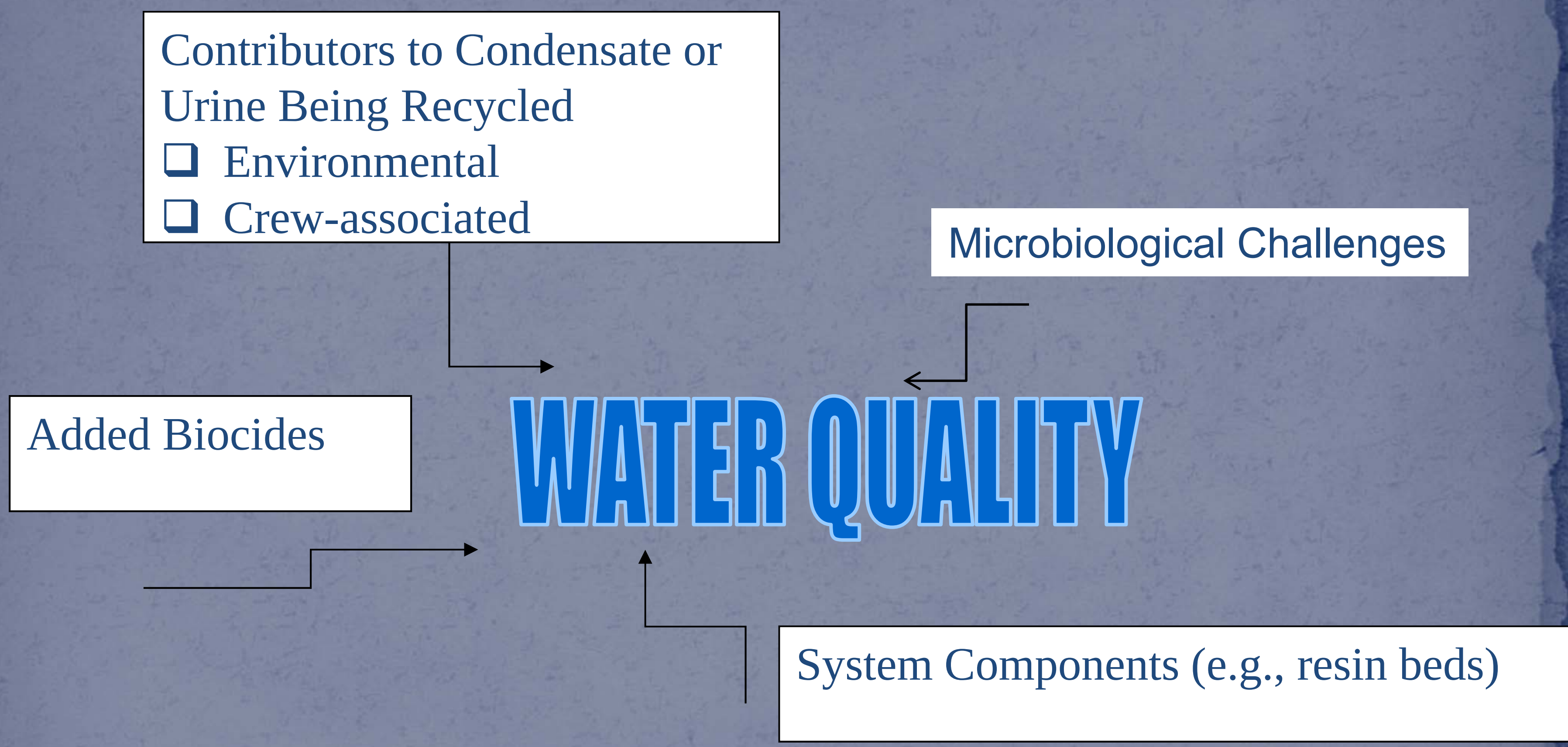
3 Crew on ISS

6 Crew on ISS

1998

2008

Simplified Overview of Stressors in Recycled Spacecraft Water Quality



Decision Making on US Water Recovery System (WRS) Water Quality

Total Organic Carbon Analyzer (TOCA)

Bacterial Enumeration and Coliform Testing

- **Provides "TOTAL" values only**
- **No characterization possible**
- **No inorganics (metals, etc.)**

In-Flight

Decision Making on Water Quality

Archive

Detailed Chemical/Microbial Analysis of archive samples returned to ground (350+ analytes)

- **Profiles what made up the "total" values from on orbit hardware**
- **Provides inorganic content (metals, etc.)**

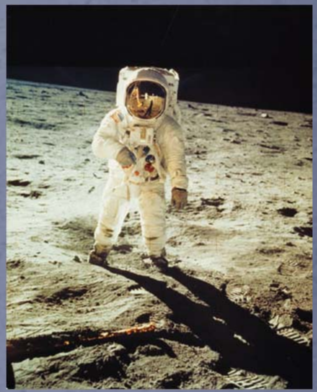
Microbial characterization of returned capture devices

Frequency: In-flight weekly- monthly. Archives returned quarterly

Stakeholders in Water Reuse Decisions in Spaceflight

International Partners

Environmental Chemists/Toxicologists



Program Stakeholders
($$$)

Flight Surgeons
Safety Community

Environmental Control and Life Support System
Engineers and System Specialists

Setting Water Exposure Guidelines

- Spacecraft Water Exposure Guidelines (SWEGs)
  - Volumes 1, 2, 3, & Guidelines Document
  - Describe chemical-specific environmental challenges

    Monitored levels, toxicological background
  - Health-based water quality limits for 27 chemicals/compounds that are of particular significance to spaceflight

Water Quality Requirements: Compare and Contrast

USEPA Maximum Contaminant Levels (MCLs)

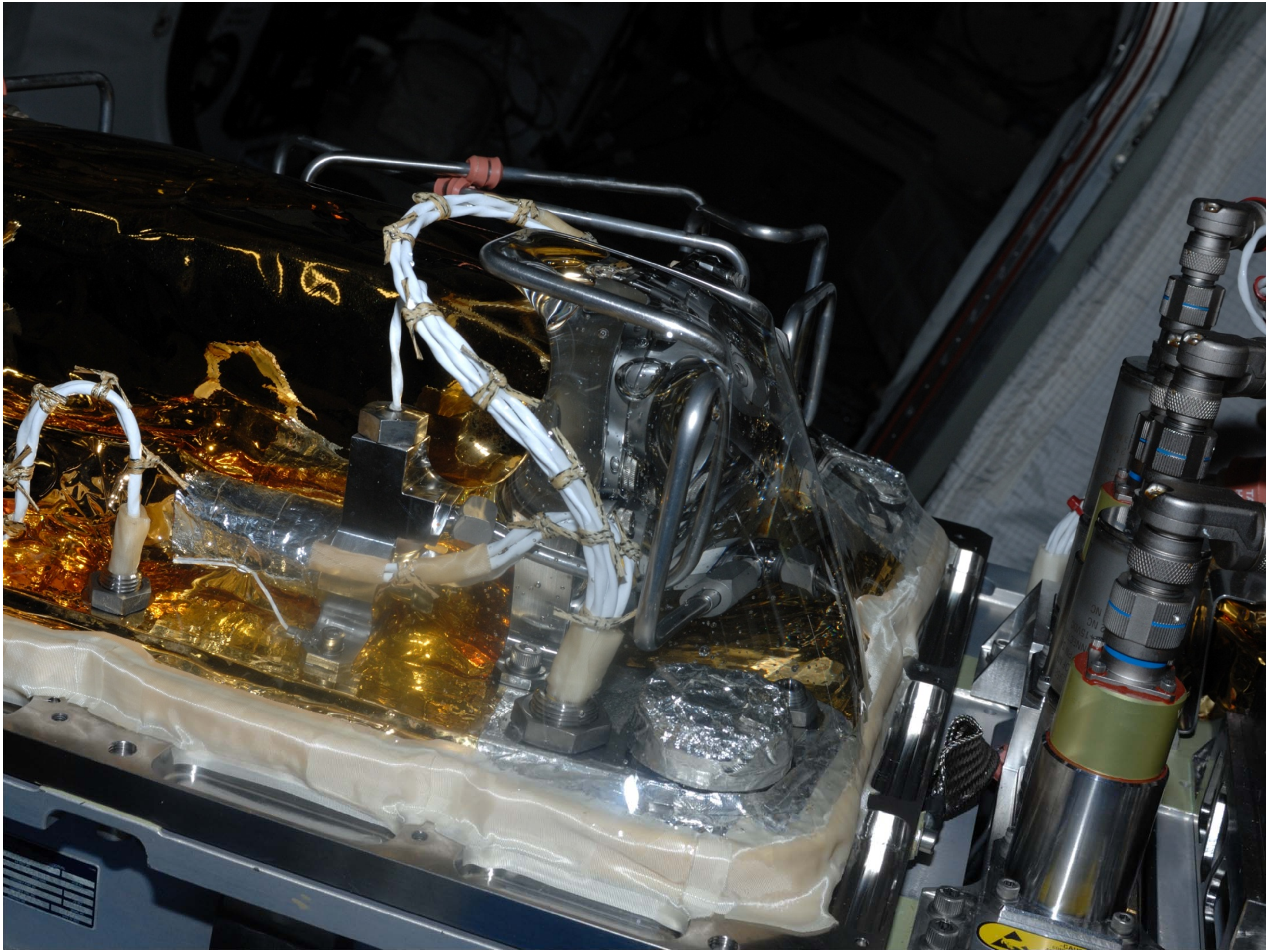
- ✓ Designed to protect a wide variety of consumers
- ✓ Address chemicals of most relevance to public water systems
- ✓ Consider lifetime exposures
- ✓ 2 Liters of drinking water consumption
- ✓ Often incorporate margin to account for other routes of exposure

NASA Spacecraft Water Exposure Guidelines (SWEGs)

- ✓ Consider strengths/susceptibilities of spaceflight crews
- ✓ Address chemicals relevant to spaceflight
- ✓ Consider exposure durations critical for spaceflight
- ✓ Account for higher spaceflight drinking water consumption (2.8 L/day)

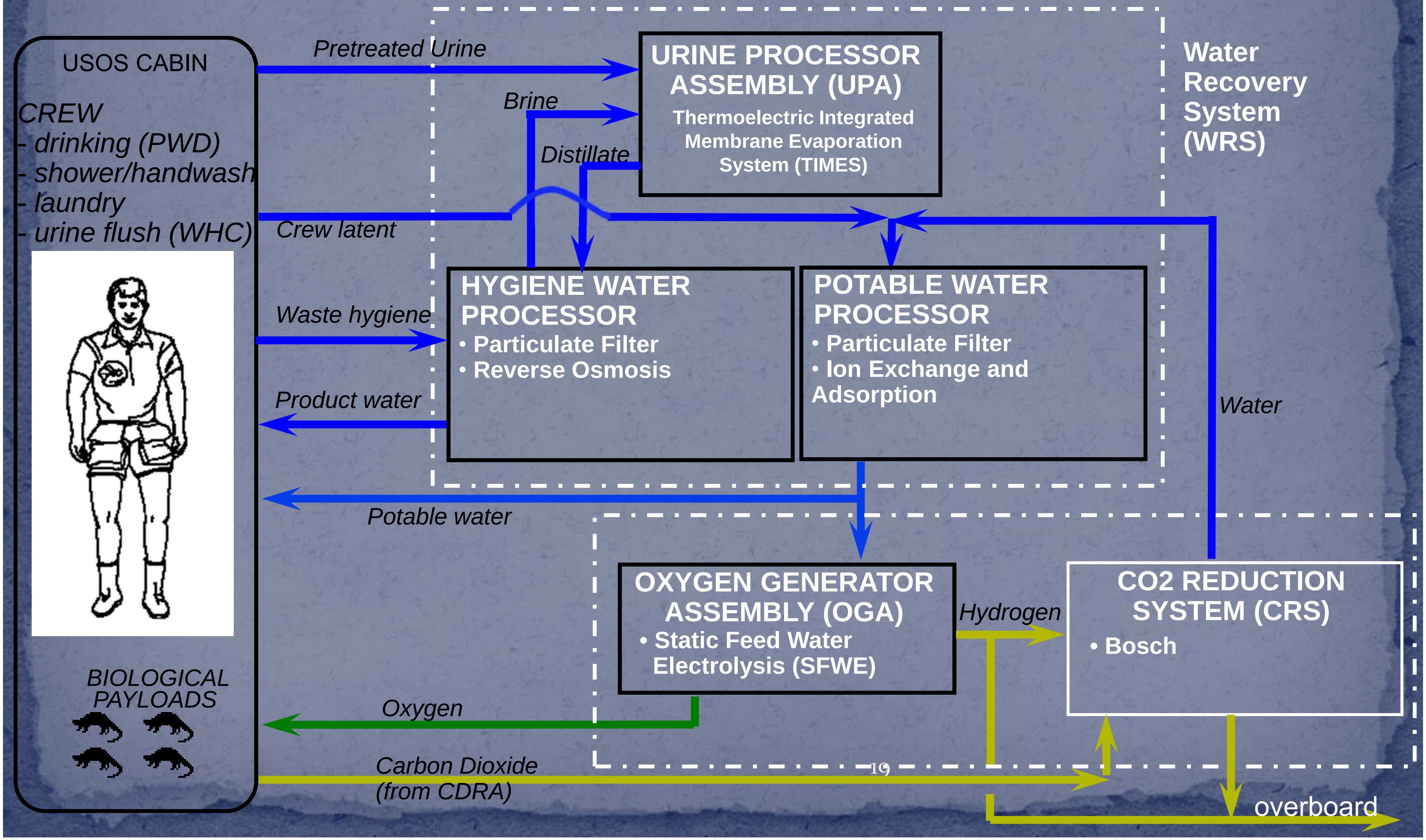
Of 27 SWEGs, only 9 have corresponding MCLs

VOLUME 1 (2004)	VOLUME 2 (2007)	VOLUME 3 (2008)
Chloroform	Acetone	Benzene
Dichloromethane	Ammonia	Propylene glycol
Di-nb-phthalate	Barium	2-Butanone
Di-eh-phthalate	Alkylamines	Antimony
2-mercaptobenzothiazole	Cadmium, Zinc	Ethylene glycol
Nickel	Caprolactam	
Phenol	Formaldehyde, Formate	
N-ph. Naphtylamine	Manganese	
Silver	Total Organic Carbon	



- The ISS Water Recovery System (WRS) architecture evolved over 20 years
  - Technology development
  - Direction of ISS Program
- The original architecture was to produce potable water from a combination of crew urine, waste hygiene, waste laundry, humidity condensate, and Sabatier product water

Initial WRS Architecture

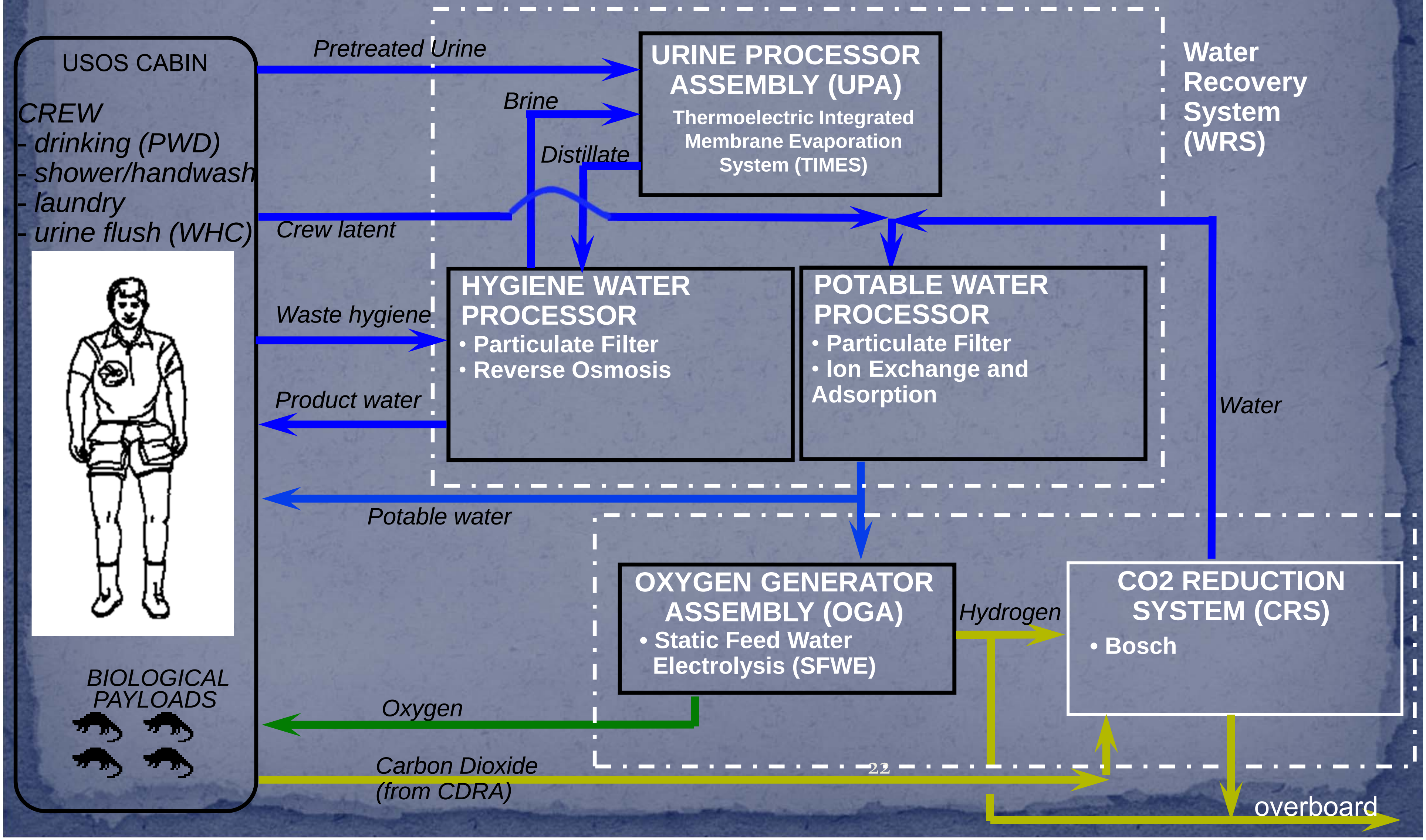


Technology Selection

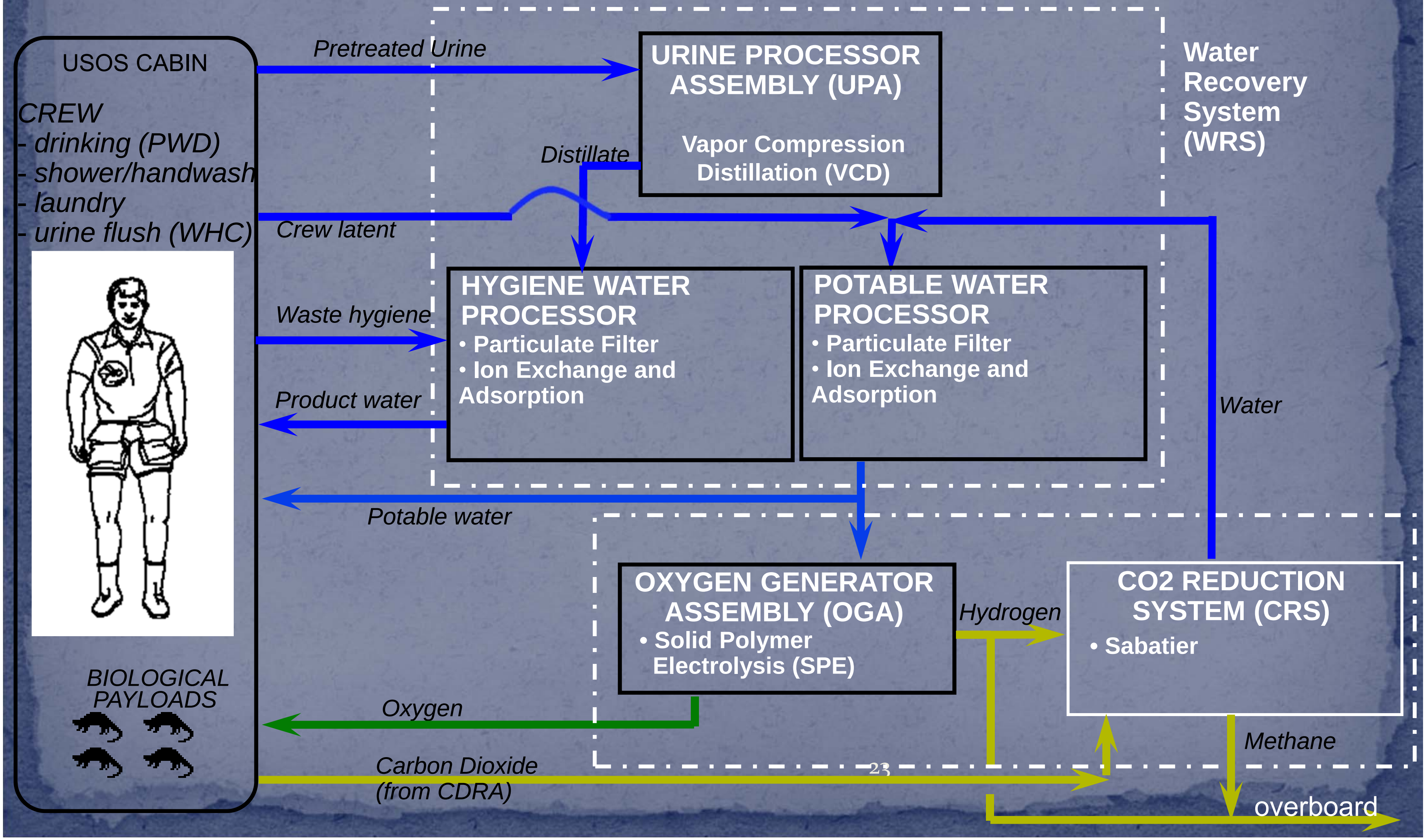
- In the late 1980's, viable technologies for each subsystem function were evaluated based on mass/volume for launch and resupply, power consumption, technical maturity, safety, maintainability, reliability, acoustics, microgravity sensitivity, and performance

Resource	Potable		Hygiene		Urine	
	Ion Exchange and Adsorption	Reverse Osmosis	Ion Exchange and Adsorption	Reverse Osmosis	TIMES	VCD
Launch Mass (kg)	1147	1211	1896	1900	481	598
Power (W)	364	496	364	918	334	177
90-day Resupply (kg)	51	80	96	108	19	33
Major Strength	Reliability		Reliability			Power
Major Weakness	Volatiles	Volatiles	Surfactant	Surfactant	Reliability	
	Winner		Winner			Winner

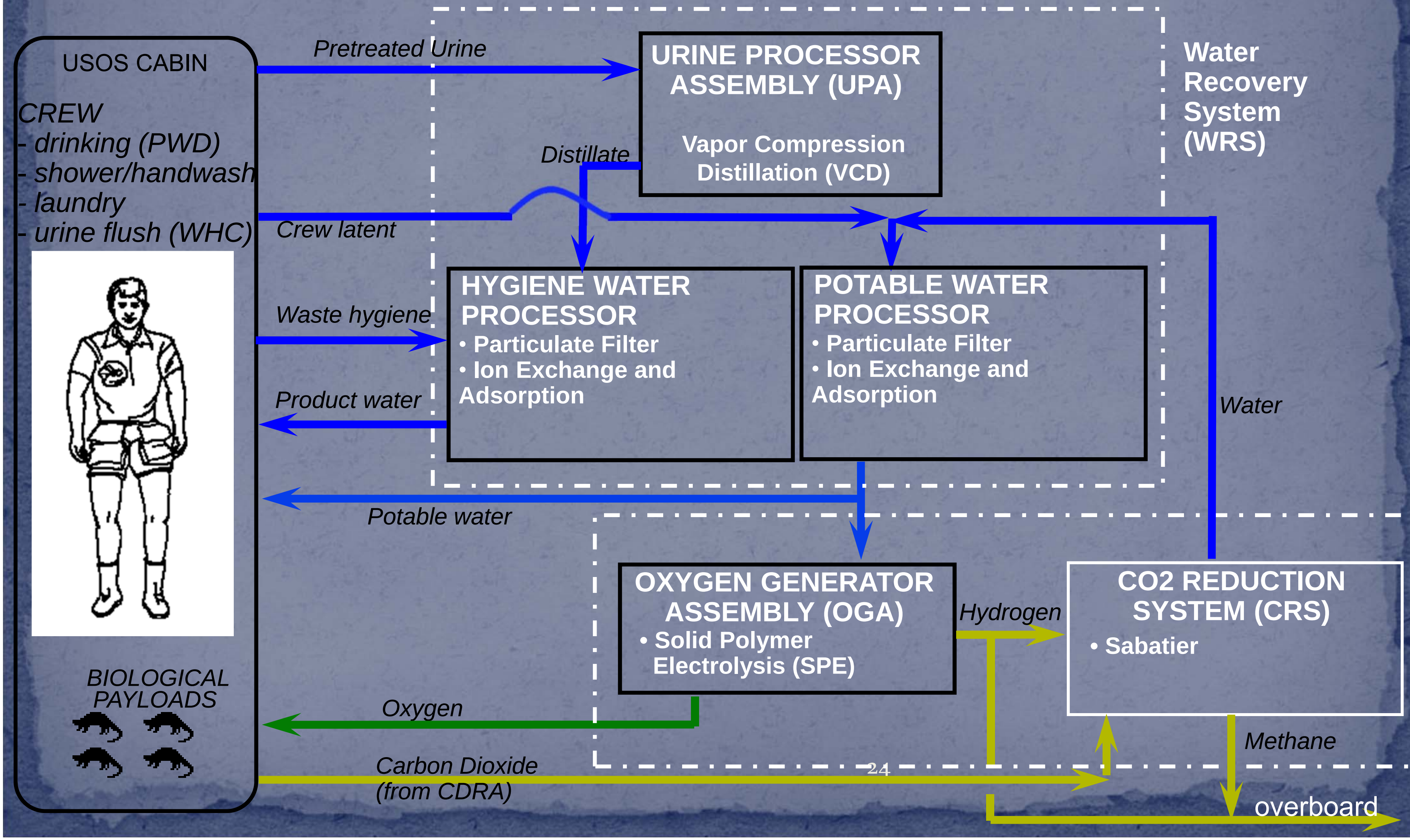
WRS Architecture 1989



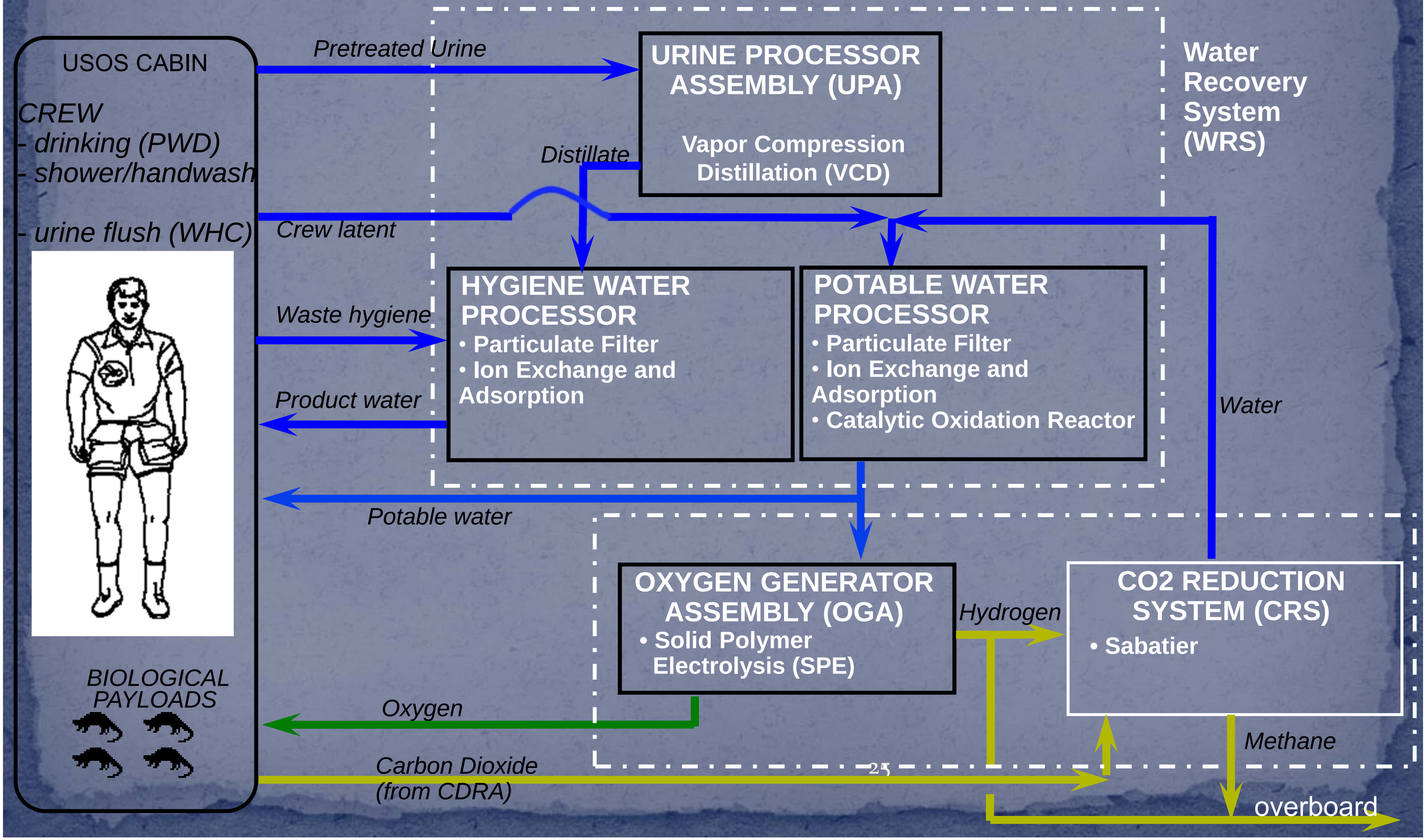
WRS Architecture 1991



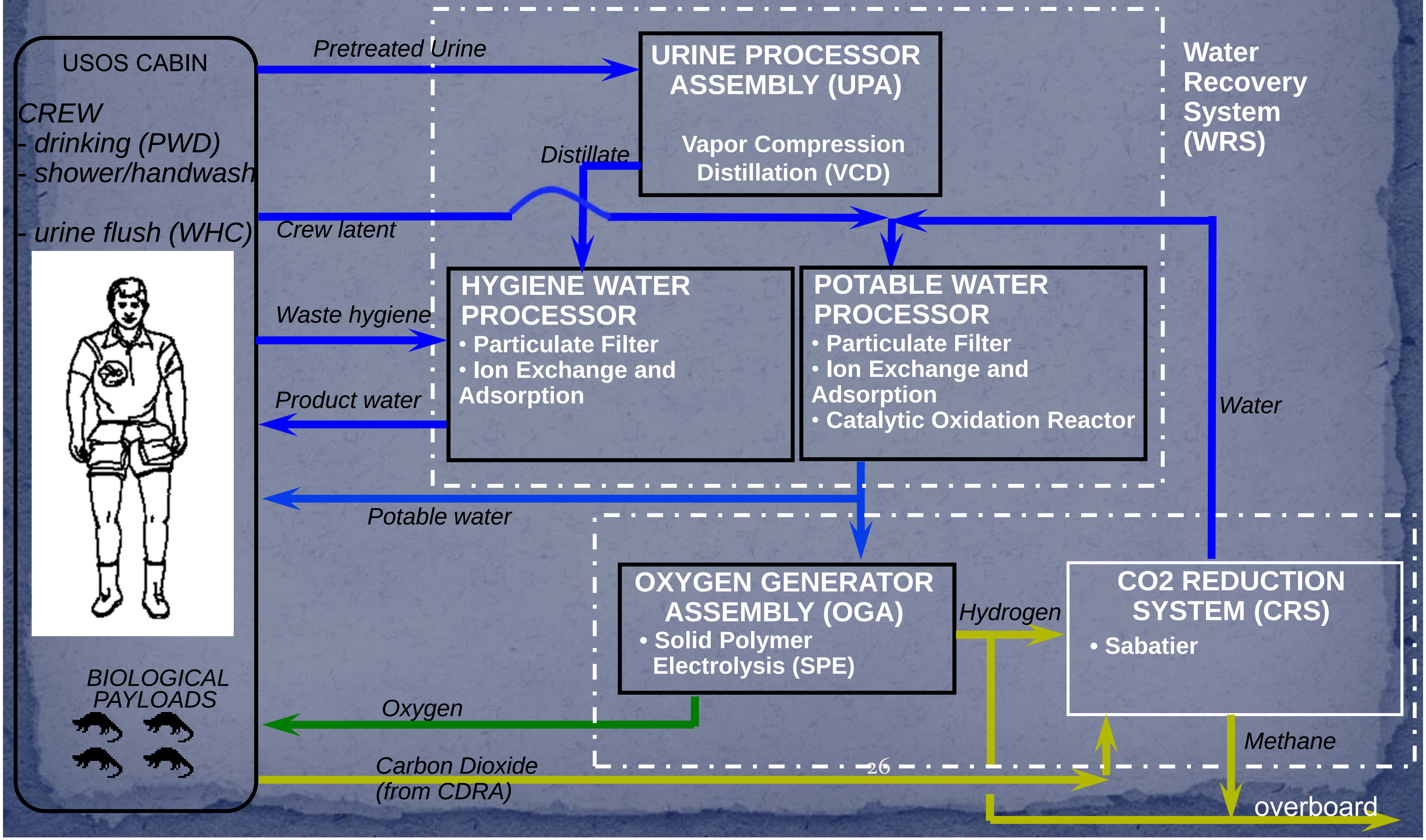
WRS Architecture 1992



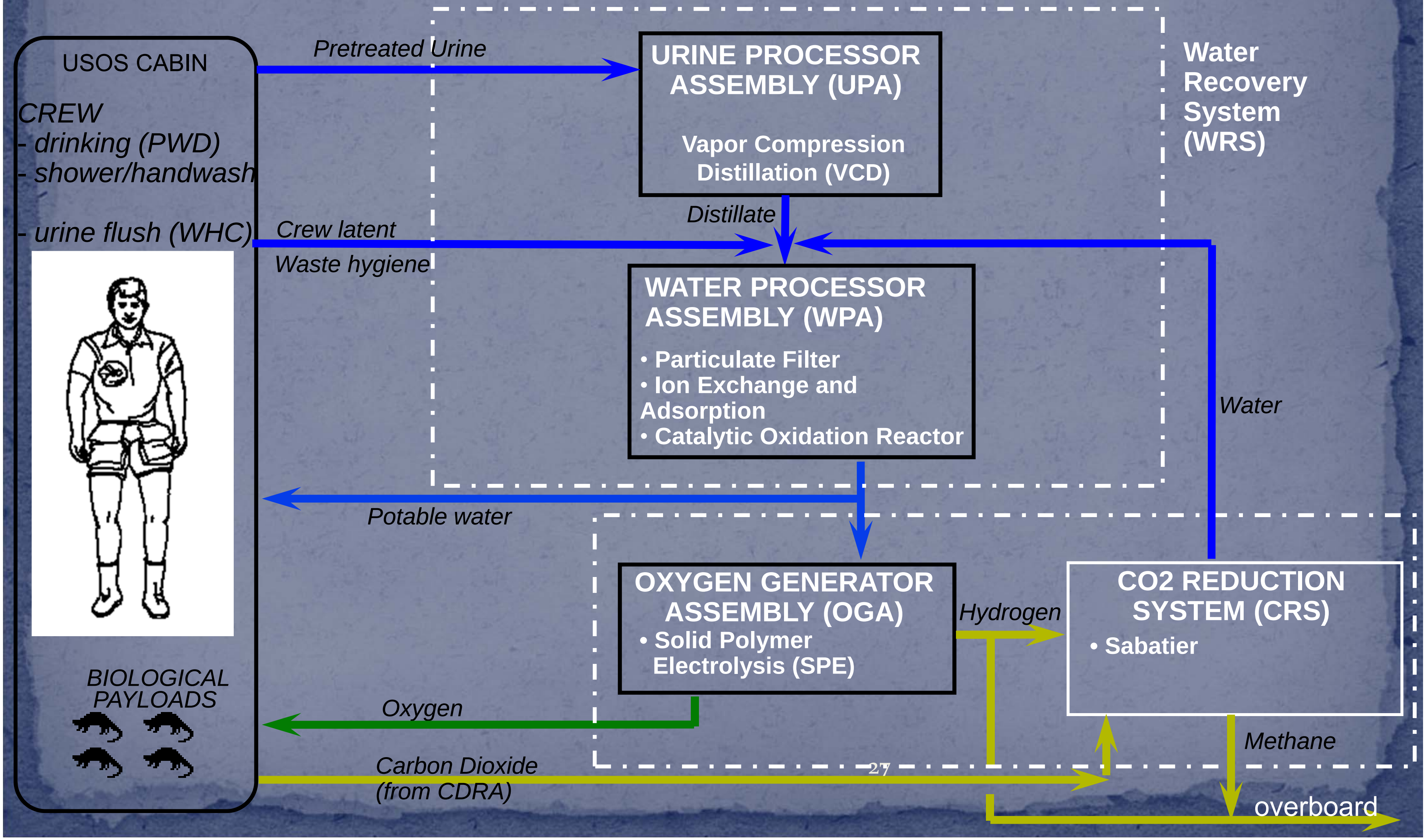
WRS Architecture 1992



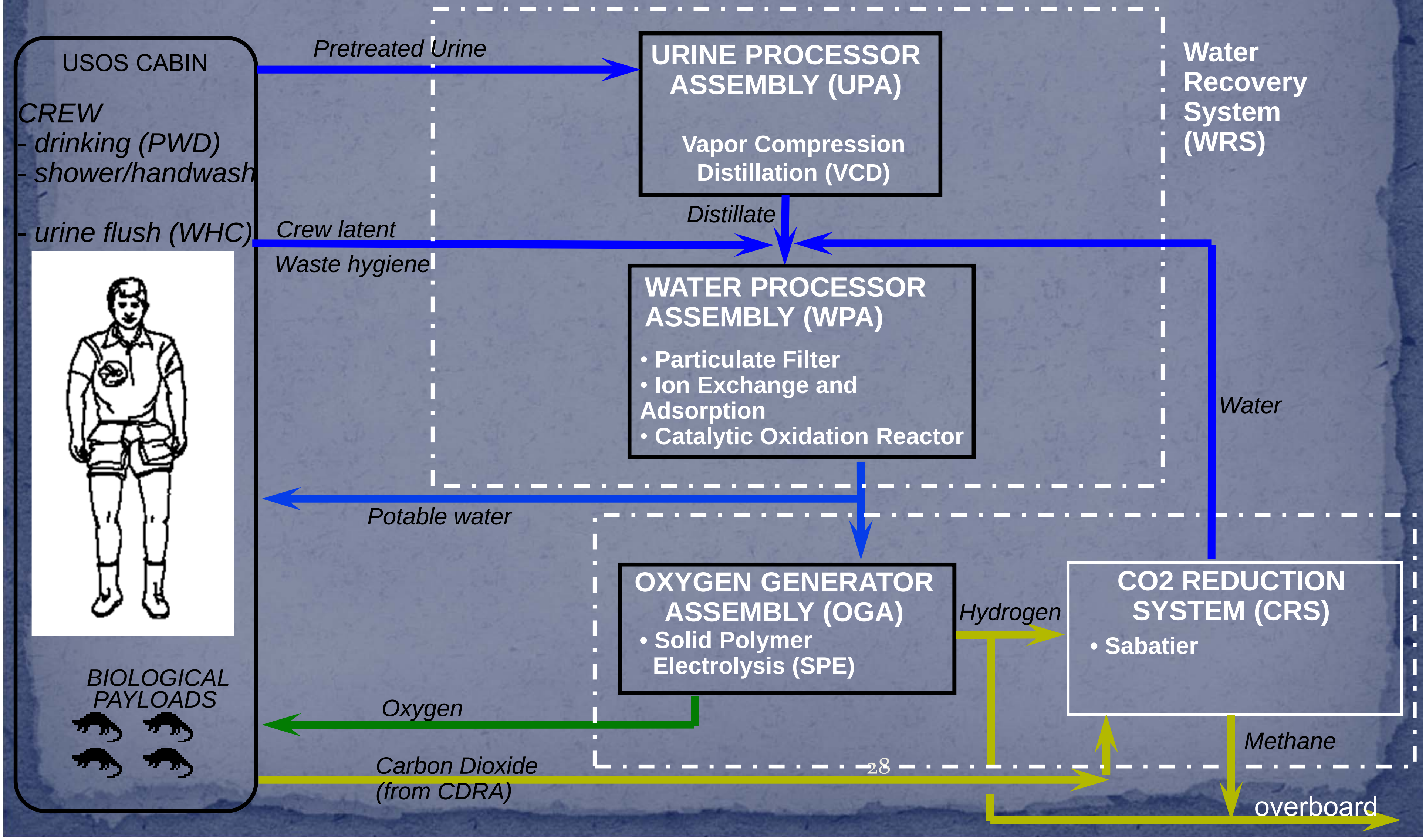
WRS Architecture 1995



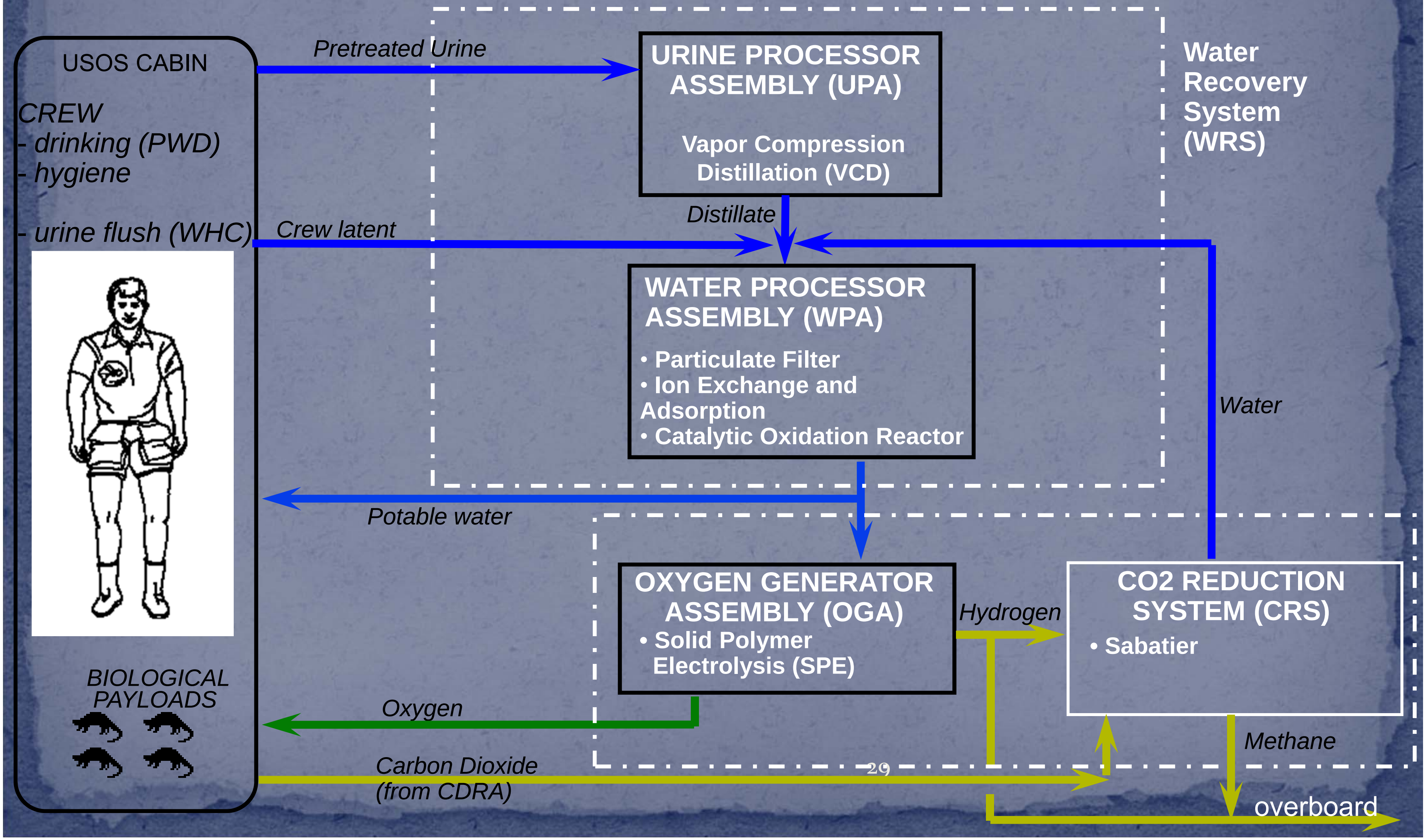
WRS Architecture 1995



WRS Architecture 2000



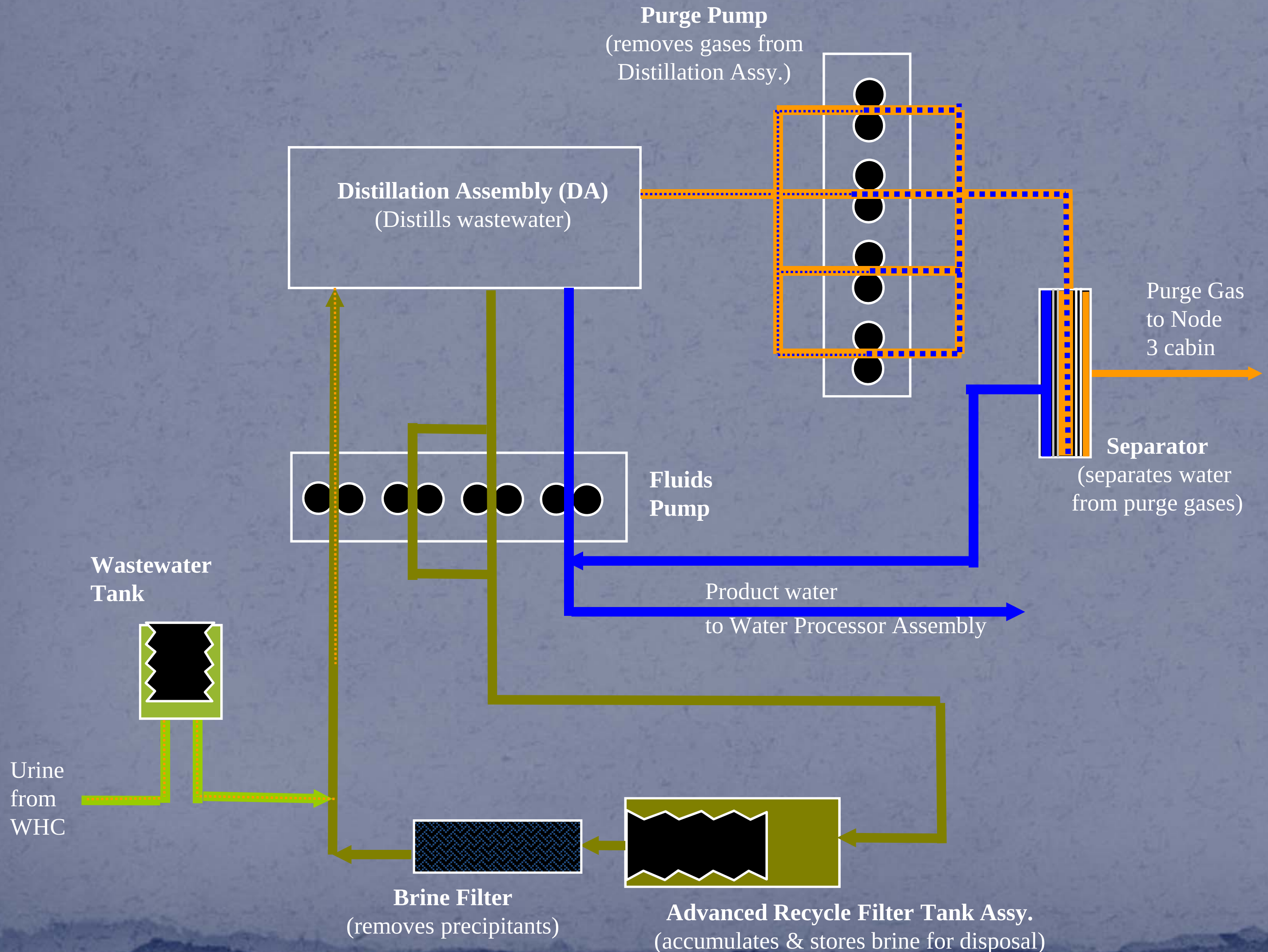
WRS Architecture (final)



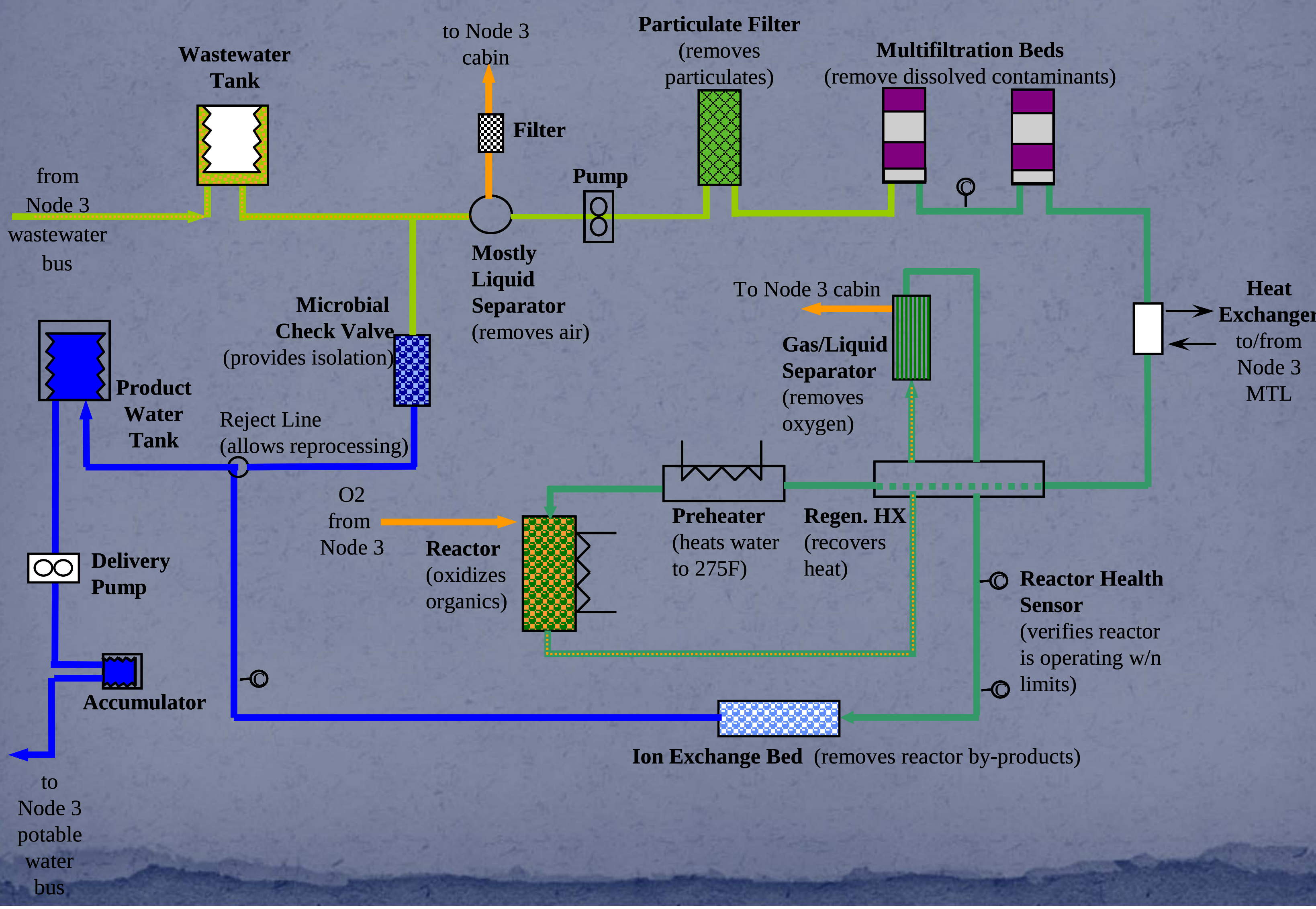
ISS Requirements

- The critical requirements that drove the design of the water recovery system:
  - Process 11.6 L of pretreated urine, 7.9 L of condensate, 0.6 L of Sabatier water each day (summarized in a waste water model)
  - Produce water meeting stringent water quality requirements (TOC <0.5 mg/L, microbial content of <1 CFU/100 ml)
  - Micro-gravity operation
  - Survive launch loads
  - Limited volume, resupply mass
  - Packaging for maintenance of Orbital Replacement Unit (ORU)
  - Autonomous operation
  - Safety (fluid containment, electrical hazards, pressure control)

UPA Simplified Schematic



WPA Simplified Schematic



Flight Experiment

- Multiple experiments performed on the NASA micro-gravity plane
  - evaluate two-phase flow through a packed bed
  - gas occlusion in conductivity sensors
  - Fluid dynamics in VCD Distillation Assembly
  - Identified several engineers prone to motion sickness

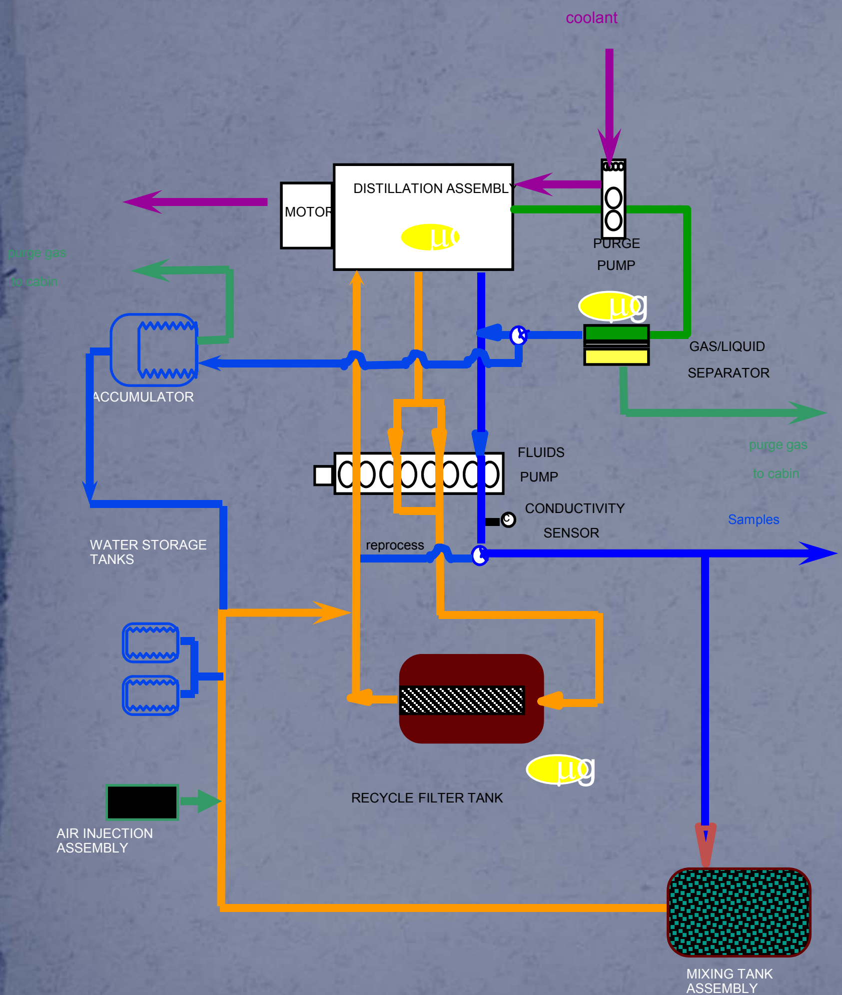
VRA Flight Experiment

- Catalytic Reactor Flight Experiment was performed to verify reactor performance in micro-gravity

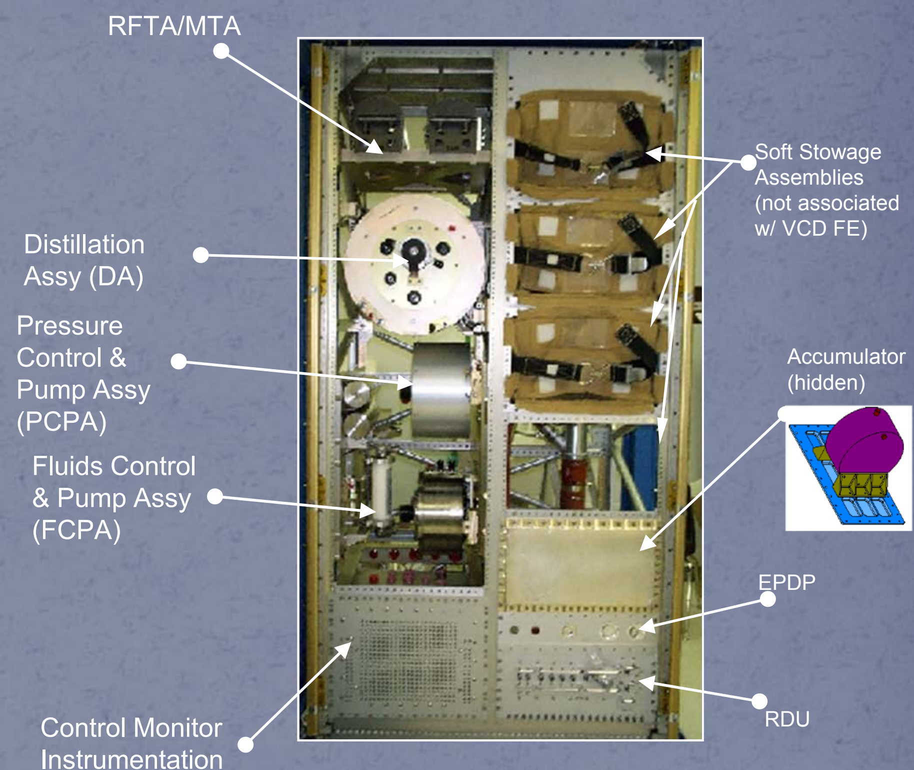
- 1st Mission: verified catalyst fines will cause a pressure regulator to fail open
- 2nd Mission: verified adequate oxygen distribution to meet reactor requirements

VCD Flight Experiment

VCD FE Schematic

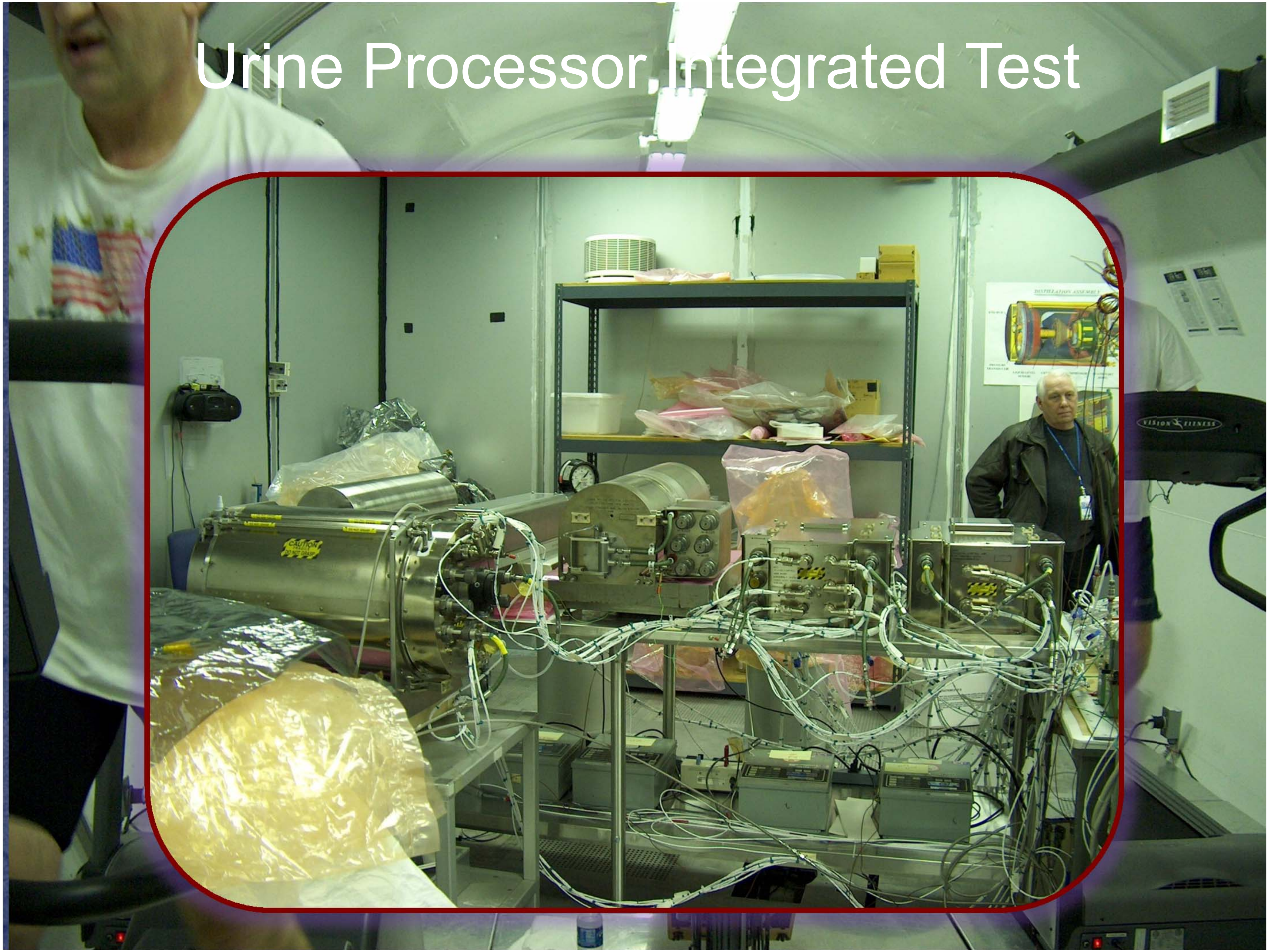


Flight Experiment in Spacehab Rack (prior to acoustic treatment)



Verified fluid dynamics in Distillation Assembly during start/stop transitions

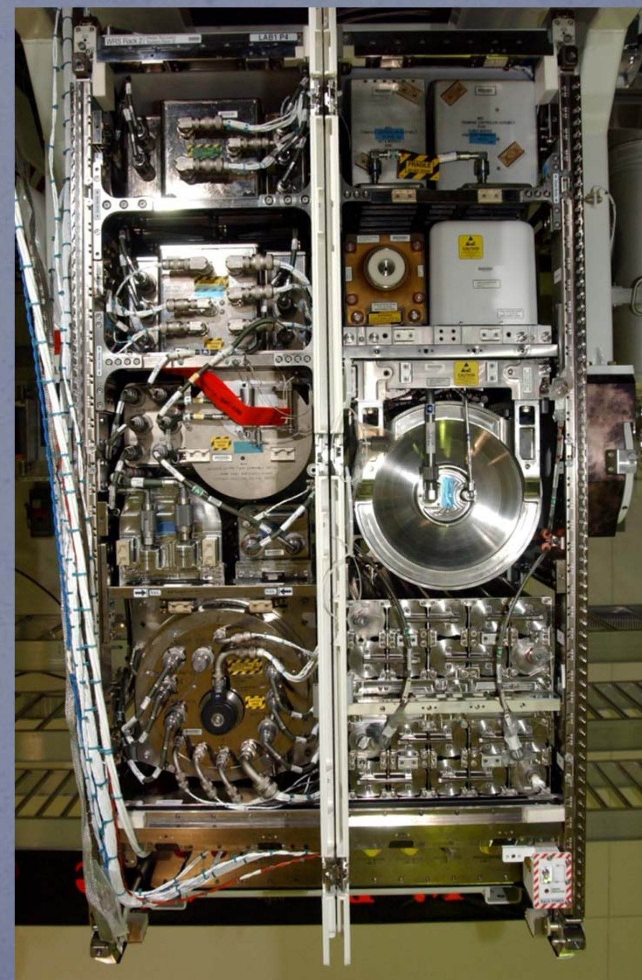
Urine Processor Integrated Test

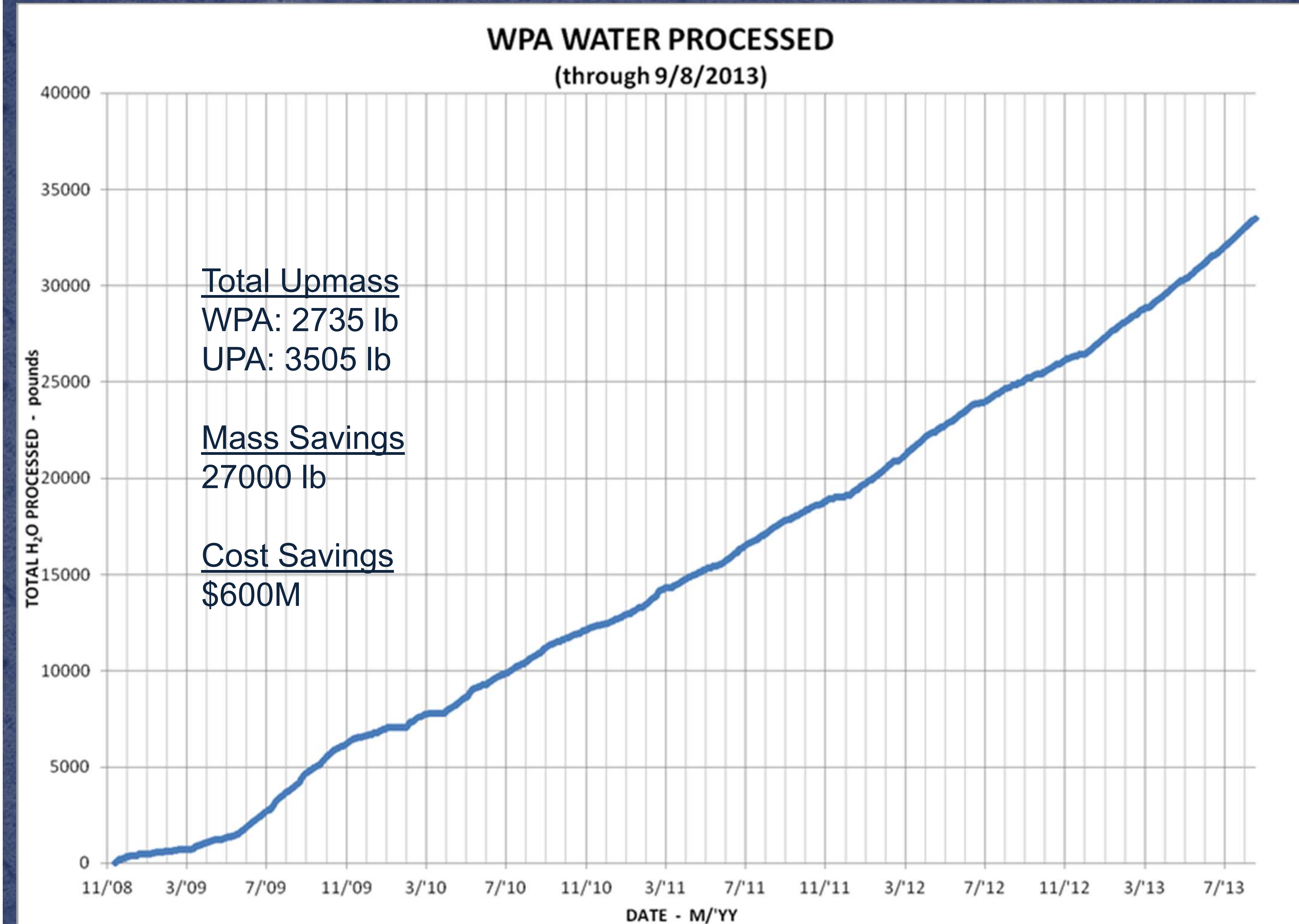


Water Recovery System (WRS)

Water Recovery System Rack #1

Water Recovery System Rack #2




WPA WATER PROCESSED
(through 9/8/2013)
TOTAL H_2O PROCESSED - pounds
DATE - M/'YY
40000
35000
30000
25000
20000
15000
10000
5000
0
11/'08
3/'09
7/'09
11/'09
3/'10
7/'10
11/'10
3/'11
7/'11
11/'11
3/'12
7/'12
11/'12
3/'13
7/'13
Total Upmass
WPA: 2735 lb
UPA: 3505 lb
Mass Savings
27000 lb
Cost Savings
$600M


To JEM
To COL
TODAY'S
COFFEE
YESTERDAY'S
COFFEE

Findings

Known Challenges

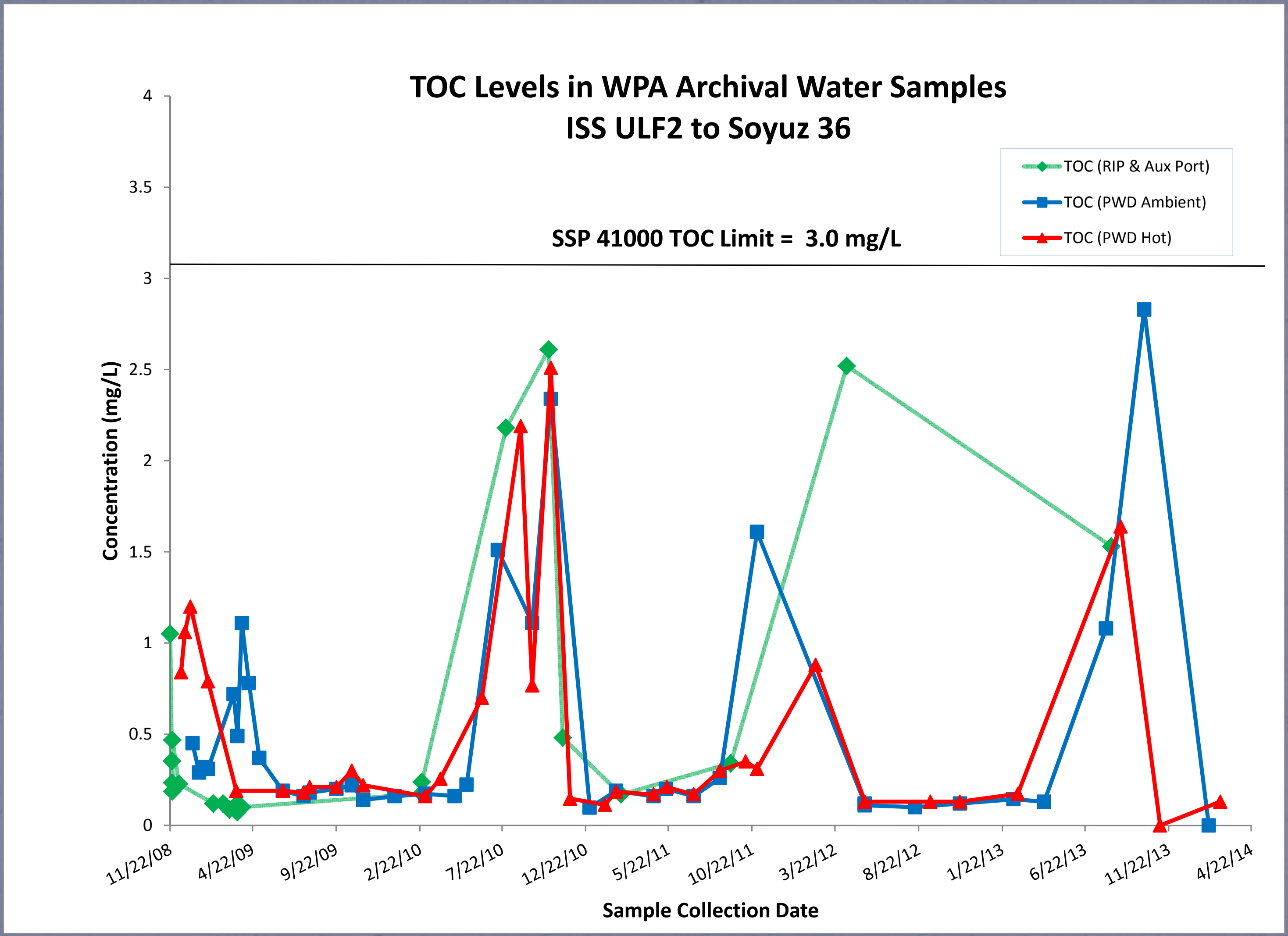
Humidity Condensate

- Alcohols
- Metabolic byproducts
  - Organic acids
  - Acetone
- Personal Care Products
- Off-gassing
  - Formaldehyde
- Metals
  - Nickel
  - Zinc
- Microorganisms

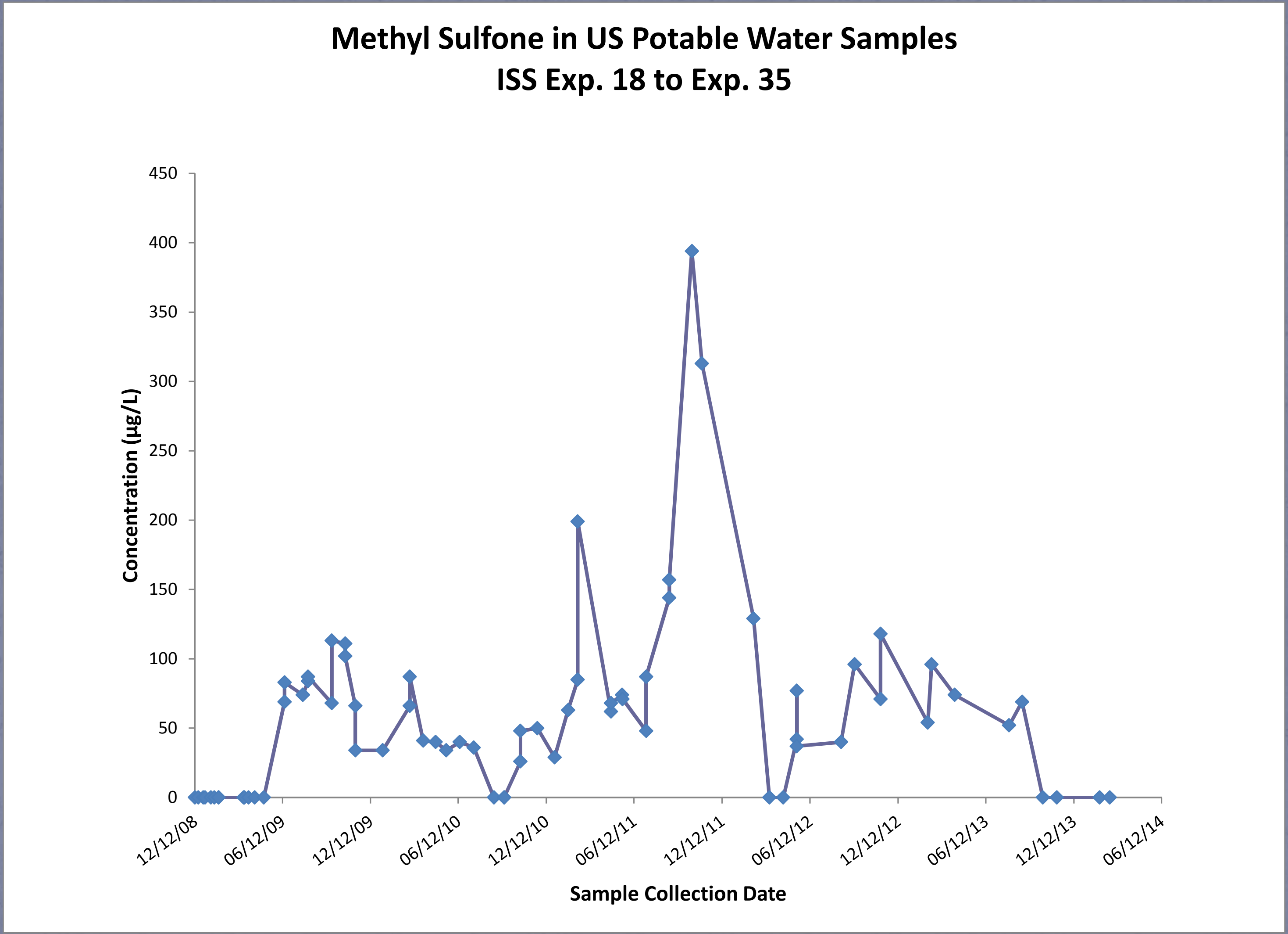
Urine

- Preservative
  - Sulfuric acid
  - Chromic acid
- Standard urine components
  - Organics
  - Minerals
- Pharmaceuticals
  - Hormones
  - Metabolic products
  - Oxidation by-products

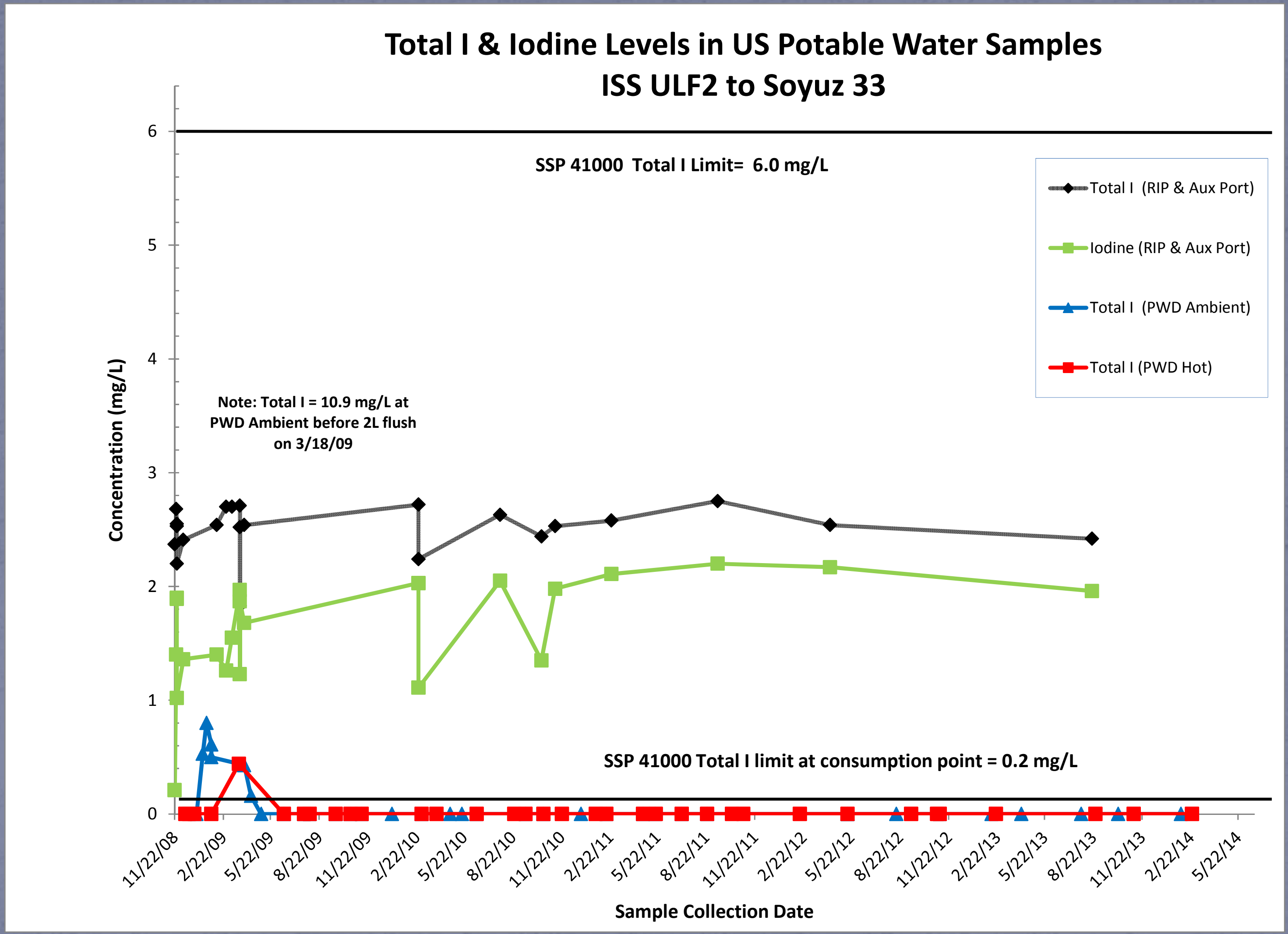
Total Organic Carbon (TOC)



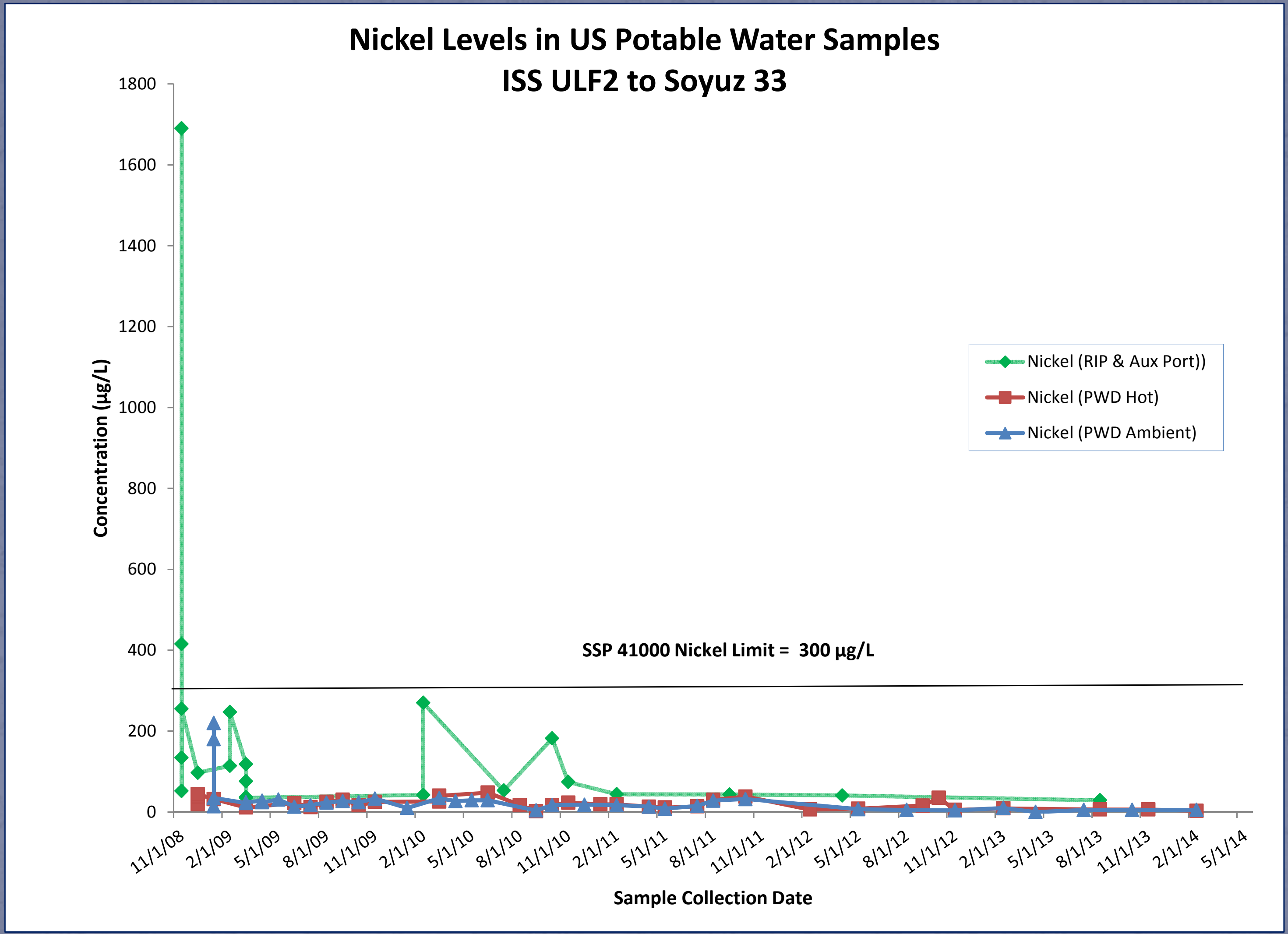
Methyl Sulfone



Iodine and Total Iodine



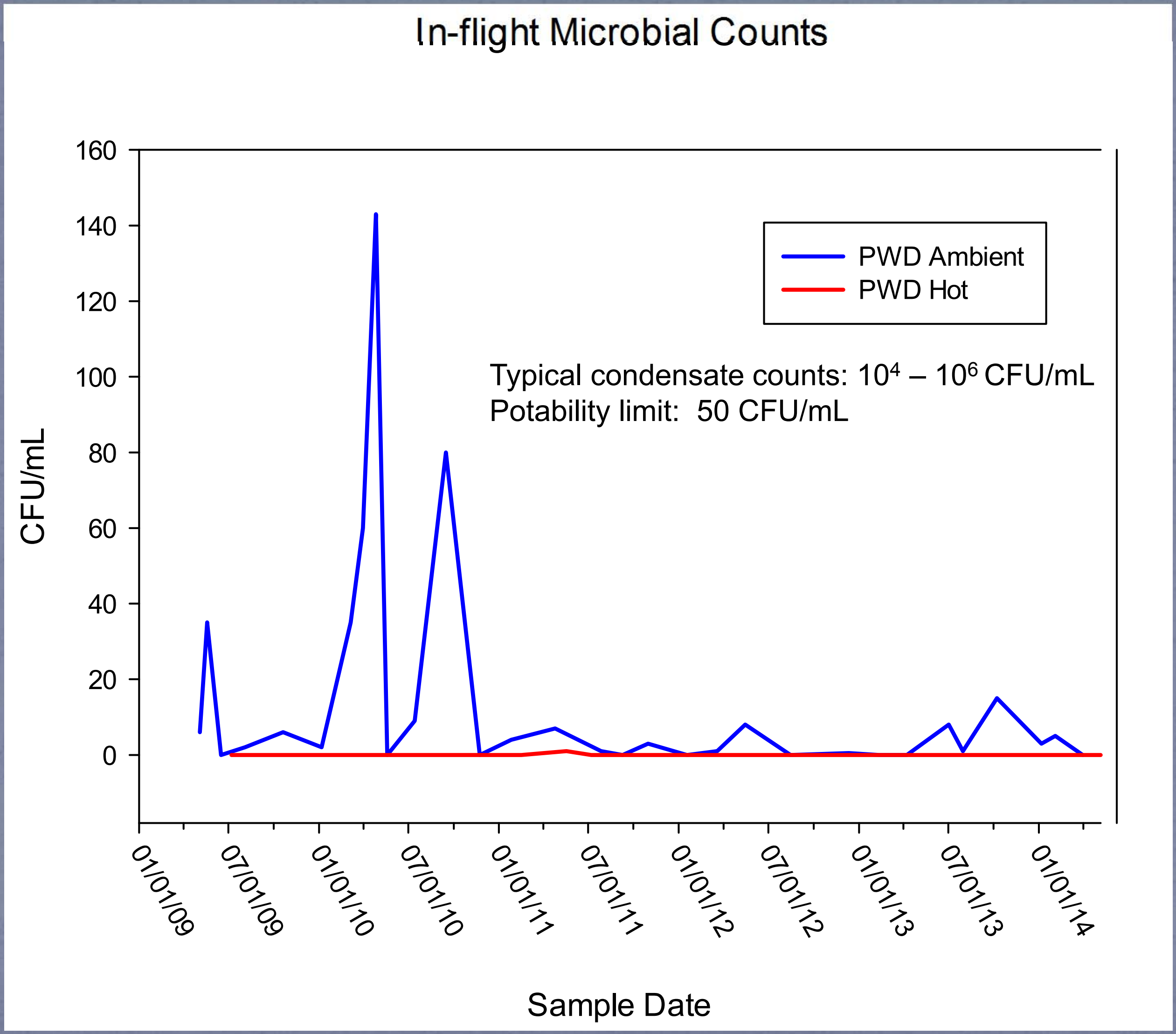
Nickel


Nickel Levels in US Potable Water Samples
ISS ULF2 to Soyuz 33
Concentration (µg/L)
1800
1600
1400
1200
1000
800
600
400
200
0
SSP 41000 Nickel Limit = 300 µg/L
Nickel (RIP & Aux Port))
Nickel (PWD Hot)
Nickel (PWD Ambient)
11/1/08
2/1/09
5/1/09
8/1/09
11/1/09
2/1/10
5/1/10
8/1/10
11/1/10
2/1/11
5/1/11
8/1/11
11/1/11
2/1/12
5/1/12
8/1/12
11/1/12
2/1/13
5/1/13
8/1/13
11/1/13
2/1/14
5/1/14
Sample Collection Date

Chemical Findings (2008- present)

- Extremely efficient removal of organics, metals, and other inorganics.
  - TOC in Feedwater to System: 75-100 mg/L
  - TOC in Product Water: ~0.2 mg/L (500x reduction)
- No individual organics detected at levels of concern.
  - Combination of multi-filtration and catalytic oxidation is very effective.
- Occasionally detect leachates from wetted materials.
  - Typically in samples from stagnant lines.
- One recurring anomaly associated with organo-silicon compounds.
  - No potability impacts, but does impact resupply.

In-Flight Bacterial Enumeration



Microbial Findings (2008-present)

- Combination of high temperature oxidation and residual biocide provides effective microbial control.
  - 2-4 Log reduction in microbial counts
  - Most samples contain less than 50 colony forming units/mL
- Bacterial isolated include *Ralstonia pickettii*, *Burkholderia multivorans*, and *Caulobacter vibrioides*
  - These are gram-negative bacteria commonly found in water
  - *Ralstonia* & *Burkholderia* are opportunistic pathogens
- Stagnancy can lead to growth of organisms during down times.
- No coliform bacteria have been detected in US product water.

Surprises!

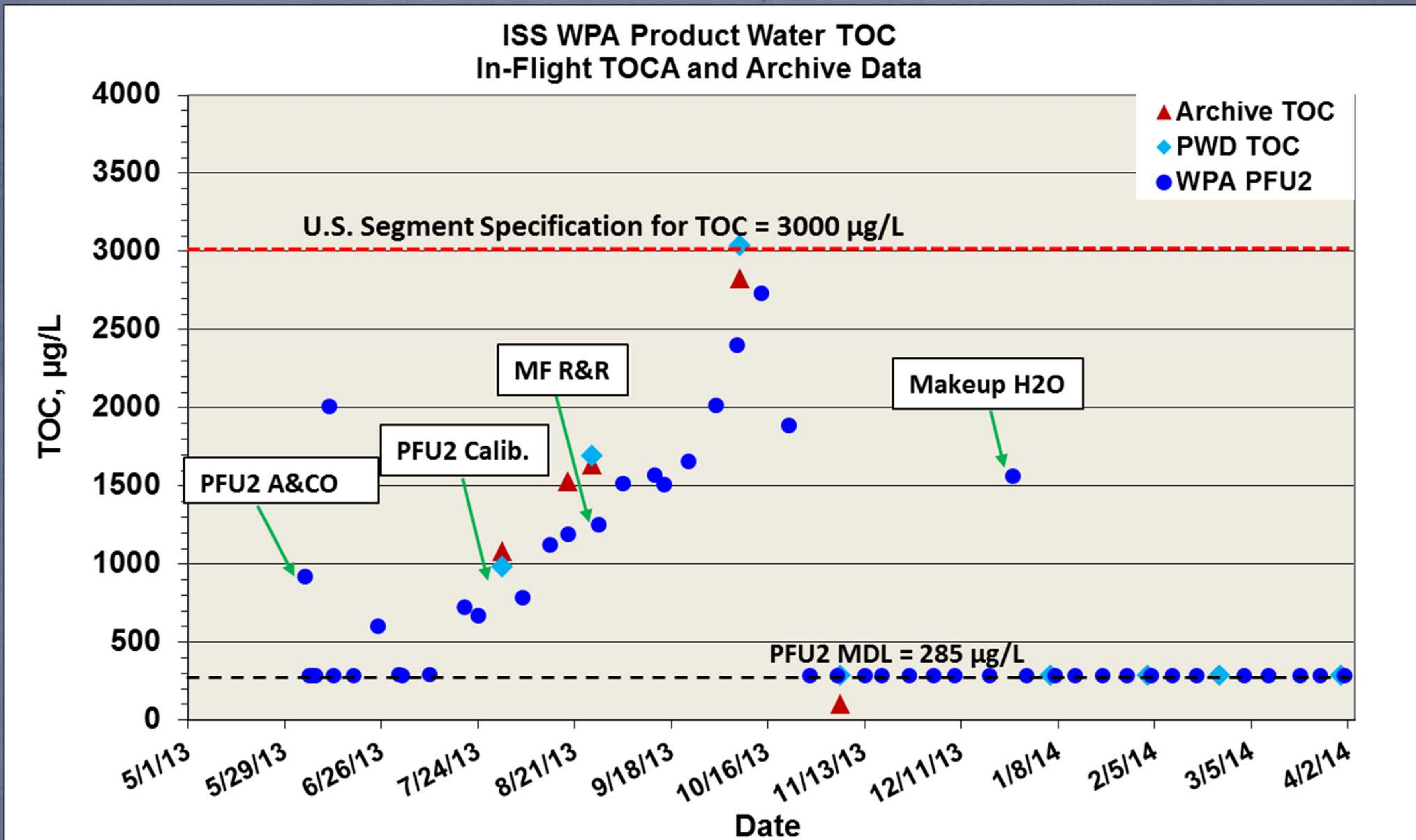
Humidity Condensate

- Personal Care Products
  - Siloxane compounds
- Microorganisms
  - Biofilms
    - Clogs/obstructions

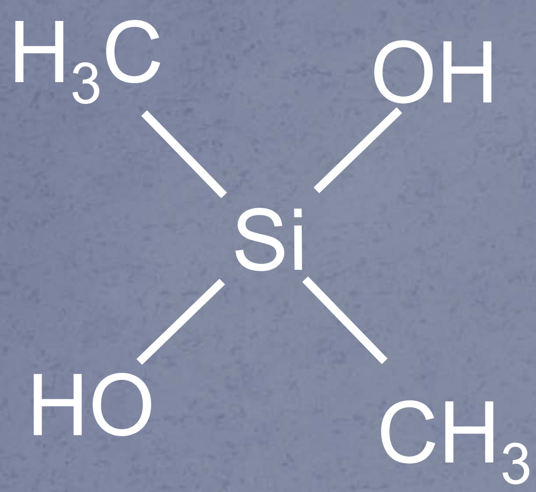
Urine

- Microgravity effects
  - Elevated calcium
  - Reduced urine volume
- Pharmaceuticals
  - Stability in preservative

In-flight TOC



Dimethylsilanediol (DMSD)



- Present in condensate
- Very water soluble
- Low vapor pressure

- Degradation product of larger polydimethylsiloxanes (PDMSs)
  - Potentially formed on surface of condensing heat exchangers
  - Wet/dry cycling may play role in formation

Biofilms

- Pre and post processing
- Stagnation
- Orifices, valves, areas with tight tolerances
- Corrugated lines
- Corners/turns in tubing

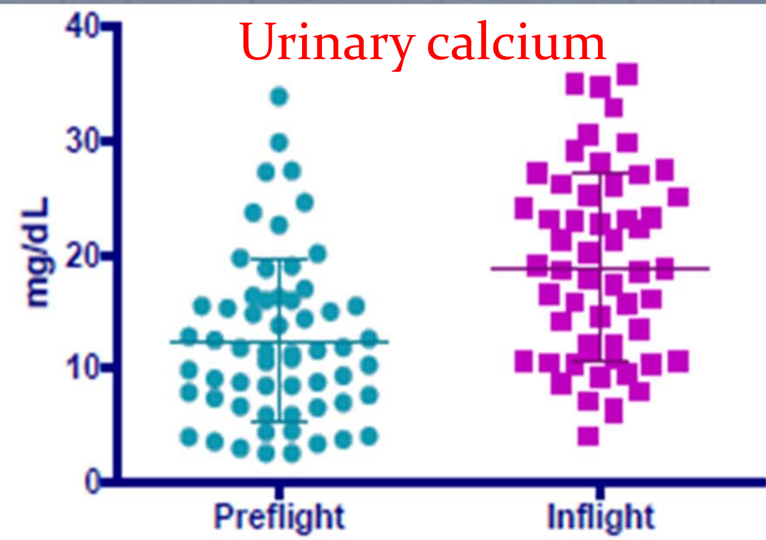
Precipitation in the UPA

"...Houston, we have a problem"

Microgravity Effects

Physiological changes result from extended exposure to microgravity

- Decreased bone density
- Excrete excess minerals
    - Elevated urinary calcium
- Reduced water intake

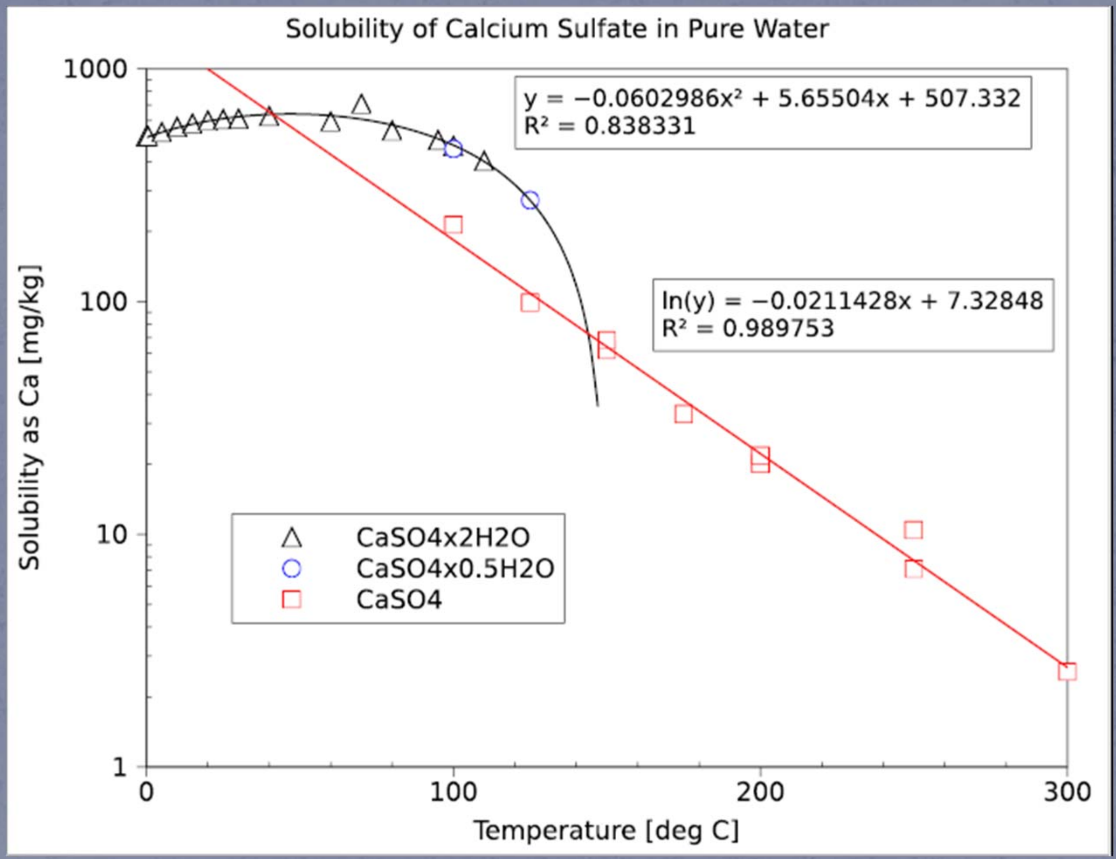


	Preflight	Inflight
Mean	12.46	18.91
Std. Deviation	7.239	8.290

+49%

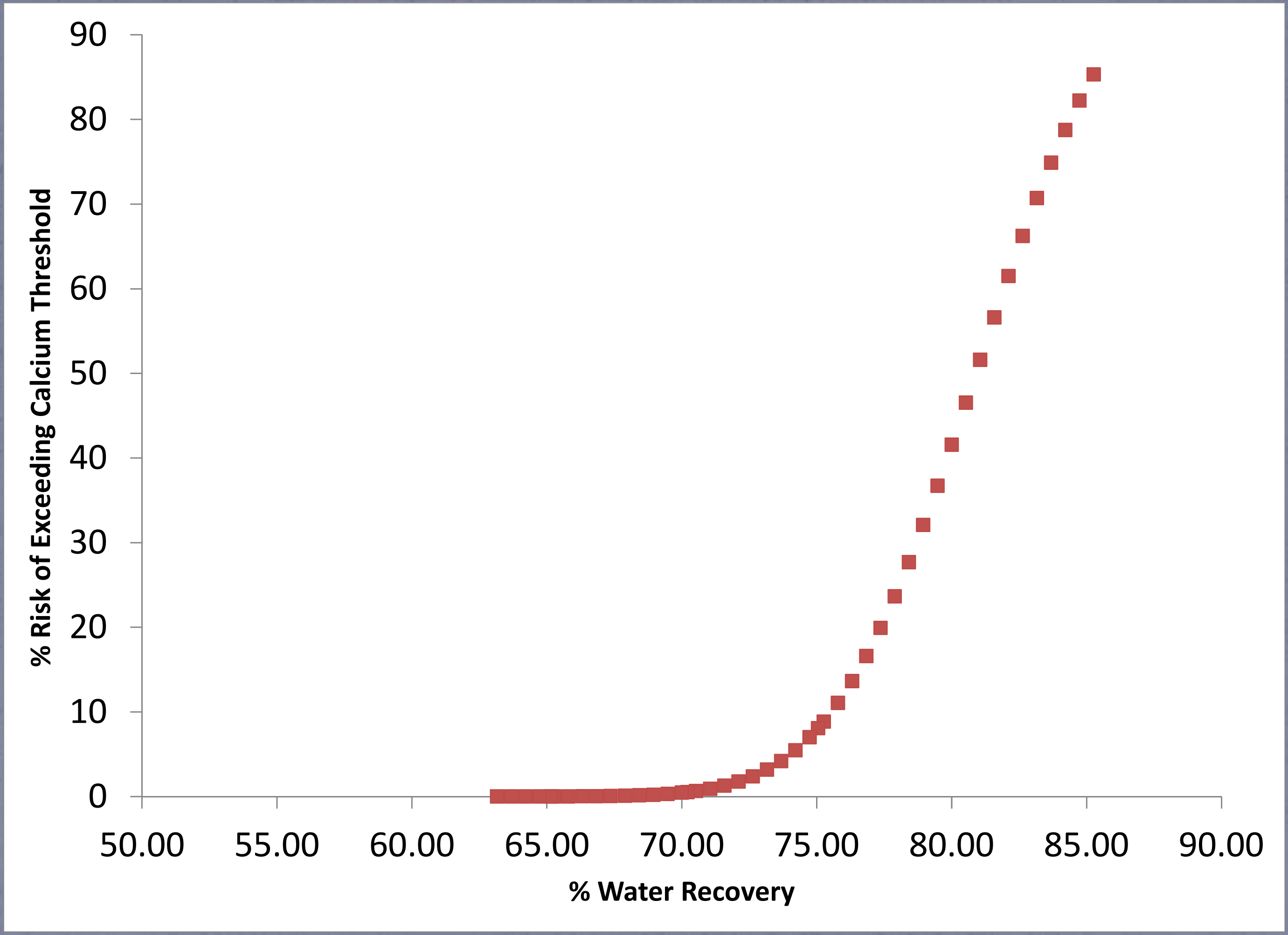
Solubility of Calcium Sulfate

$Ca^{2+} + SO_4^{2-} \longrightarrow CaSO_4 \cdot 2H_2O$



$K_{sp} = \gamma_{Ca}[Ca^{2+}]\gamma_{SO4}[SO_4^{2-}]$

Precipitation Risk



Pharmaceuticals and Personal Care Products

- TOC levels in potable water is very low (typically <200 ppb).
  - WPA effectively removes these compounds from condensate and wastewater.
- Focus upstream fluids
  - Condensate: atmospheric moisture collected on condensing heat exchangers.
  - Wastewater: mixture of condensate and urine distillate. Feed stream for WPA.
  - Preserved urine: crew urine collected in the Waste and Hygiene Compartment (WHC) and preserved prior to being processed in the UPA.
- 136 target analytes
  - 17 steroids and hormones
  - 119 PPCPs
- Standards exposed to urine preservative to assess degradation and identify degradation byproducts.

Results

- Condensate
  - No target hormone detected in the wastewater.
  - Trace levels of several steroids present in blank.
  - Six target PPCPs detected in wastewater sample.
- Wastewater
  - One target hormone detected in the wastewater.
  - Trace levels of several steroids present in blank.
  - Six target PPCPs detected in wastewater sample.
- Preserved Urine
  - Three target hormones detected in the preserve urine.
  - Trace levels of several steroids present in blank.
  - Fourteen target PPCPs detected in preserved urine.

- Of the 136 target analytes, 93 remained quantifiable following exposure to the urine preservative!

Lessons Learned

- Test thoroughly
  - Expect surprises
- Stagnation is bad
  - Leaching
  - Biofilm formation
- Account for unique circumstances and environment
- Adapt and improve
  - Methods to reduce/remove siloxanes from WPA feed
  - Alternative urine preservative
- Use of ISS to develop technologies for future missions