Introduction to Life Support Systems

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

Course Description

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.

Agenda

Title	Speaker	Duration	Approx Time
Welcome/Introduction	Greg Schunk	5 min	1:00
Agenda/Speakers			
What is Environmental Control and Life Support?		30 min	1:05
Human Metabolic Needs	Bob Bagdigian		
Typical ECLSS Functions	Bob Bagdigian		
Historical Perspective	Bob Bagdigian		
Mercury/Gemini/Apollo/Skylab/Shuttle/ISS			
Guiding Requirements from NASA Standards	Jay Perry		
Atmosphere Revitalization		90 min	1:40
Overview	Jay Perry		
CO2 Removal	Jim Knox		
O2 Generation	Kevin Takada		
O2 Recovery/CO2 Reduction	Zach Greenwood		
Trace Contaminant Control	Jay Perry		
Particulate Control	Jay Perry		
Water Recovery		45 min	3:15
Overview	Layne Carter		
Water Processing	Layne Carter		
Urine Processing	Layne Carter		
Challenges for Future Exploration	Jay Perry	10 min	4:00
Exploration phases, duration, dormancy, etc.			
Question and Answer	All		

Life Support Overview and Historical Perspective

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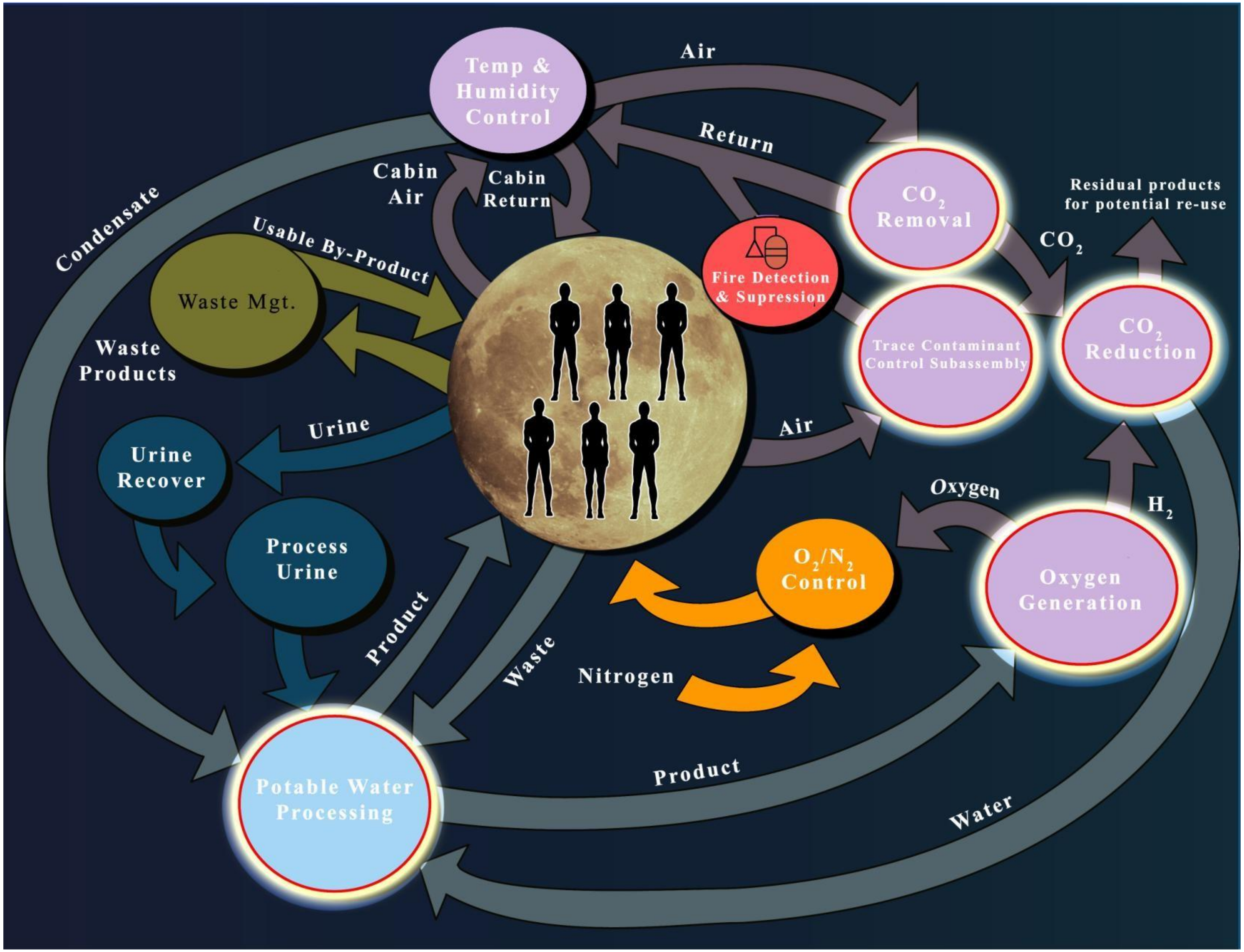
To Keep Humans Alive in Space, We Must…

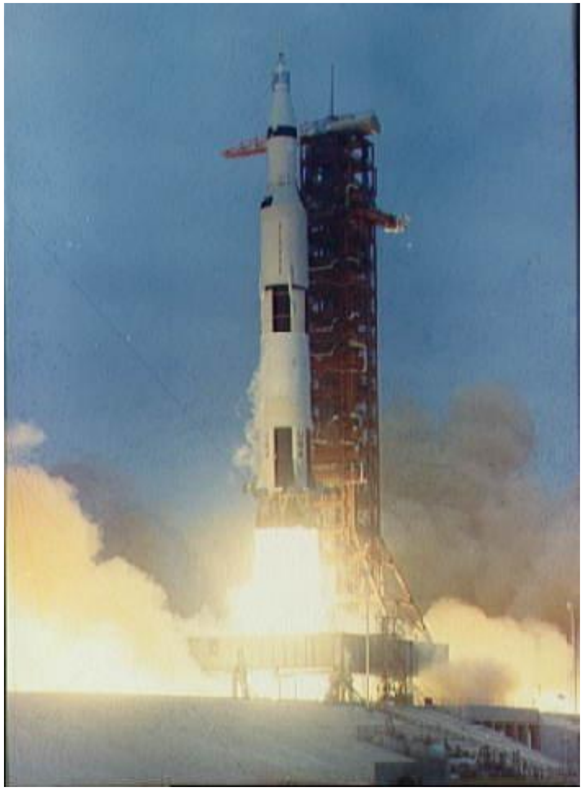
ECLSS Functional Integration

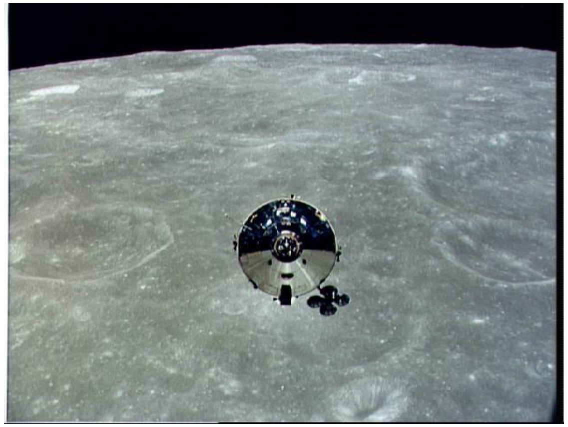


Life Support for Mercury & Gemini

- 1-2 astronauts
- 1-14 day missions
- chlorinated potable water & oxygen stored in tanks
- CO_2 removed from atmosphere w/ expendable LiOH
- wastewater vented overboard

Life Support for Apollo





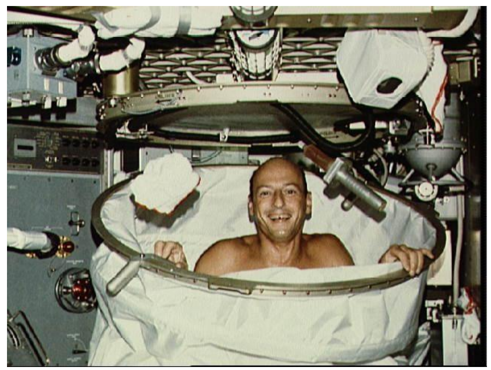
Command Module

- 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 O_2
- CO_2 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) O_2

CO_2 scrubbed with LiOH

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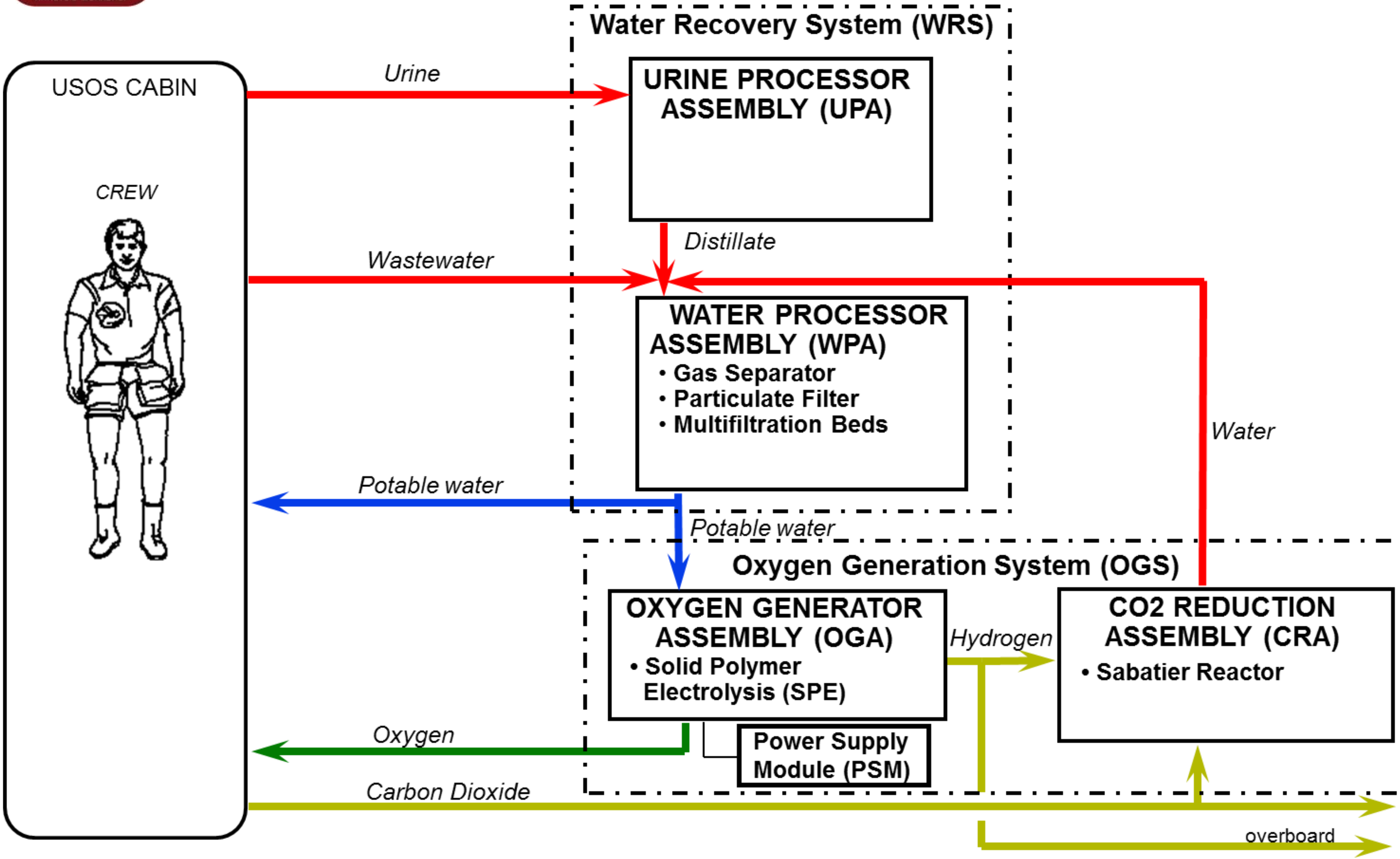
International Space Station Life Support

- Continuously occupied since 10/01
- 90-180 day increments typical
- 3--6 crew typical, more in coming years
- CO_2 removal w/ regenerable zeolite mole sieve
- Trace contaminant control w/ expendable adsorption & catalytic oxidation
- H_2O 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)
- O_2 supplies
  - oxygen generation via water electrolysis (US & Russian systems)
  - oxygen recovery via Sabatier CO2 reduction (US)

  expendable perchlorate candles (emergency backup)

Waste & Hygiene Compartment

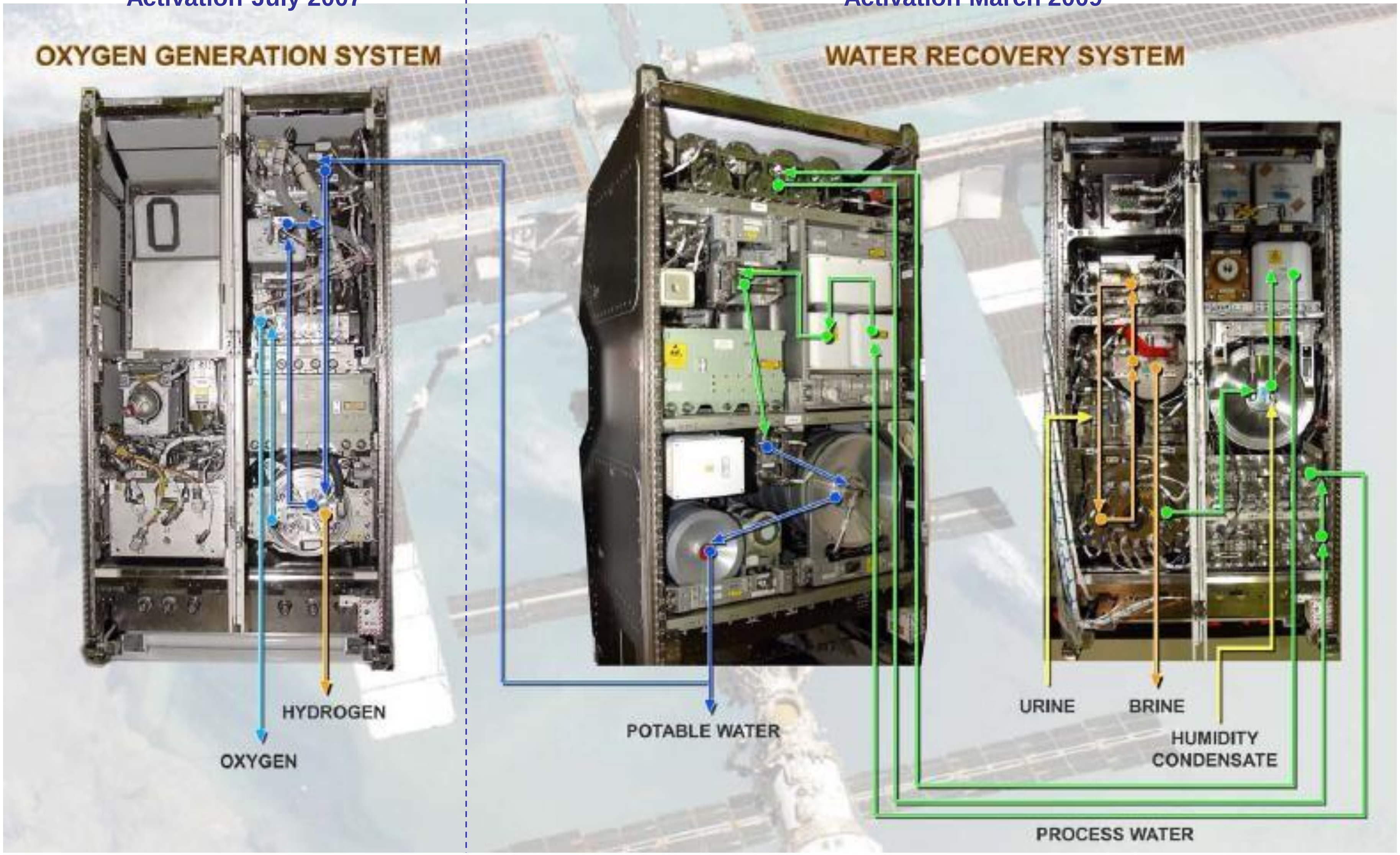
International Space Station ECLSS



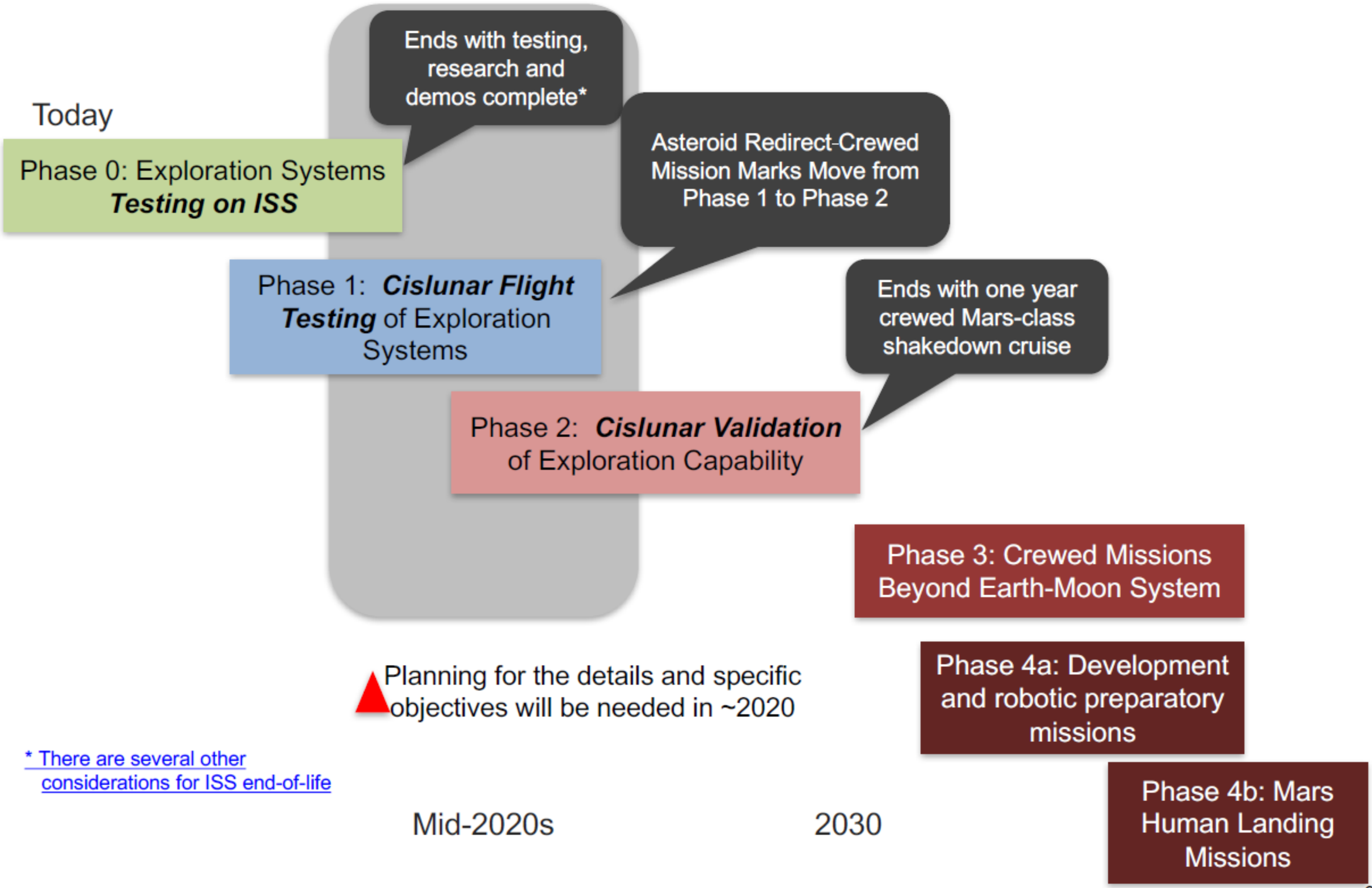
ISS Regenerative ECLSS

Launched July 2006
Activation July 2007

Launched November 2008
Activation March 2009

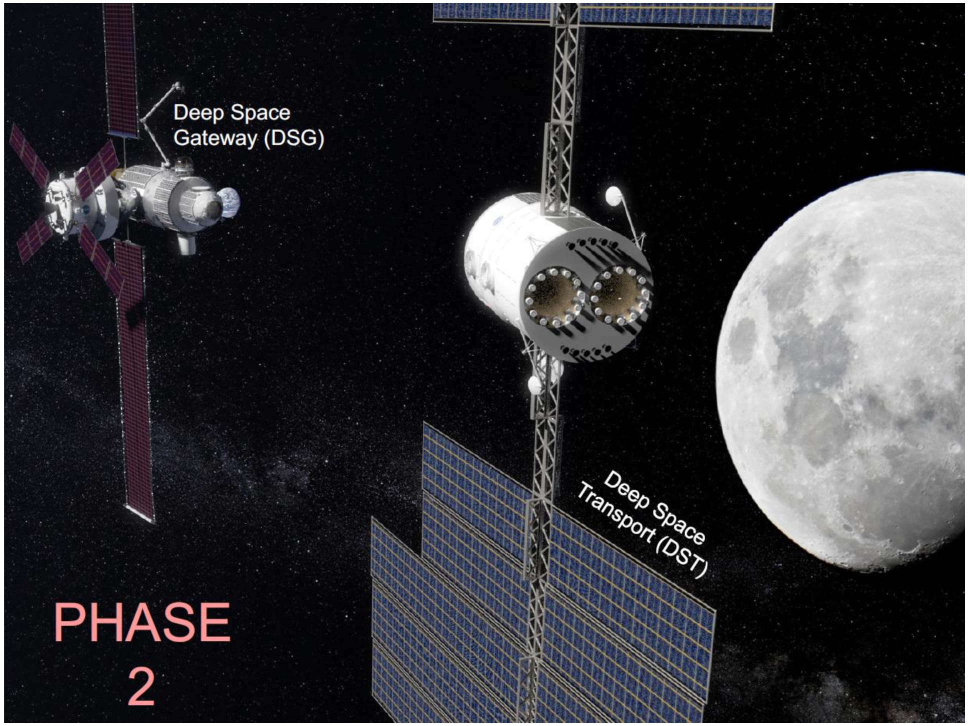


Human Space Exploration Phases from ISS to the Surface of Mars



Exploration Elements Life Support

- 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

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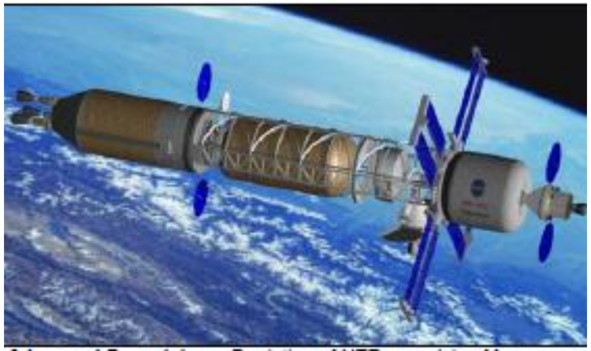
- The Global Exploration Strategy
  - International Space Exploration Coordination Group
  - 14 member agencies
  - 5 themes
  - Path to Mars exploration
- U.S. 2010 Space Exploration Policy
  - Goals similar to the GES themes
  - Missions beyond the moon by 2025
  - Missions to Mars by mid-2030s



Advanced Propulsion – Depiction of NTR propulsion Mars transfer vehicle in LEO prior to departure. Glenn Research Center 2007.

Commuter – An artist's concept depicting a potential Mars exploration outpost. Rawlings 2007

NASA-SP-2009-566, pp. 2, 21

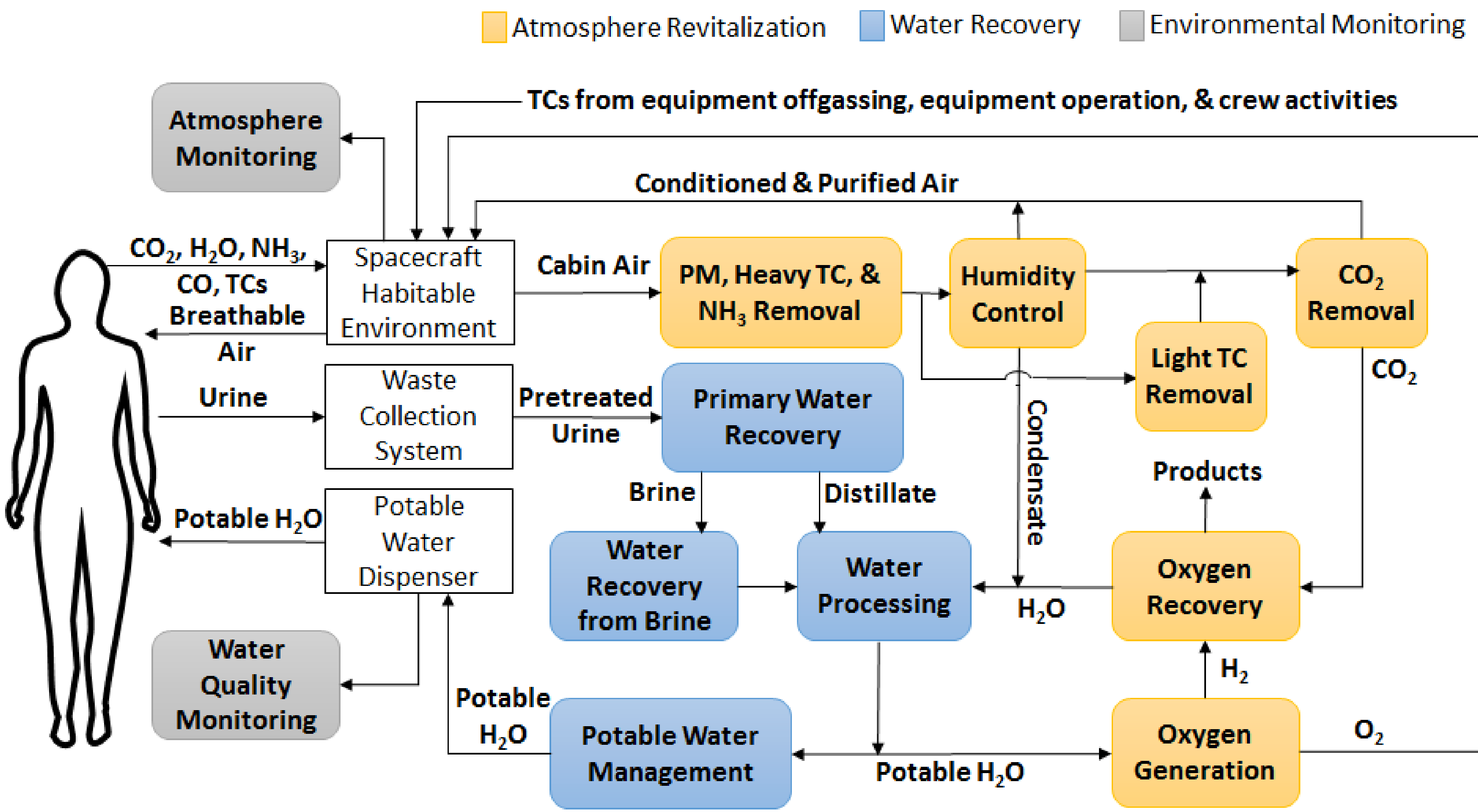
Preparing for the Challenge

- 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 Guidance from Mars DRA5

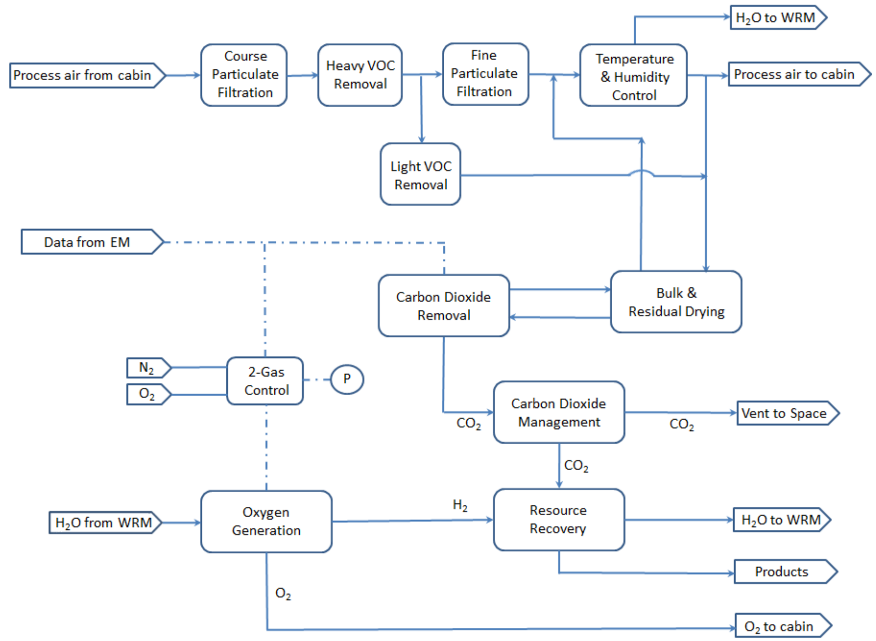
- Mission duration
  - Opposition class: 400-650 days transit; 30-90 days surface; 500-630 days total
  - Conjunction class: 360-420 days transit; 475-540 days surface; 830-960 days total
  - Enable high end: 650 days transit, 540 days surface, total 1190 days
- Crew size
  - 4 crewmembers operationally sufficient
  - 6 crewmembers may reduce mission risk
- Habitat size
  - 280 m^3 pressurized volume; 24 m^3 habitable volume per crewmember
  - Larger pressurized volumes up to 660 m^3 studied
- EVA
  - Up to 16 individual EVA events per week for 71-week surface mission

LSS for Exploration Missions



Atmosphere Revitalization Guidance

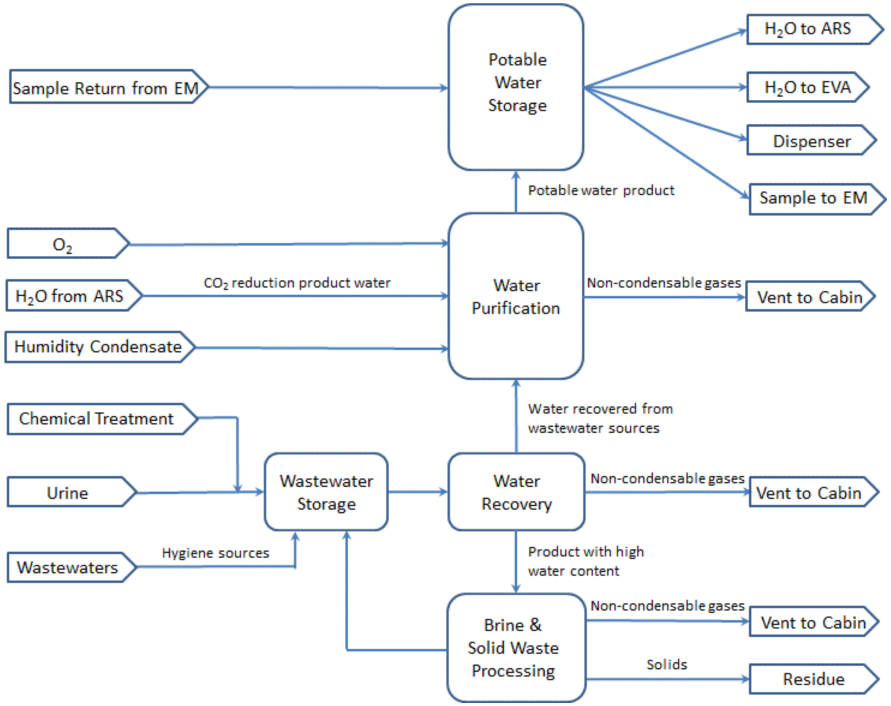
- Accommodate metabolic loads and demands
- CO_2 and trace contaminant control
  - CO_2 to 1000-day SMAC max; 2 mm Hg target
  - Trace contaminants <1000-day SMAC
- Particulate matter control
  - <3 mg/m^3 for >10 µm and <100 µm
  - <1 mg/m^3 for >0.5 µm and <10 µm
- Oxygen supply
  - Supply to pressure 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 O_2 from CO_2
  - Mission: >90% of O_2 from CO_2
- Venting losses <10%



COMPOUND	ACTIVITY	RATE (kg/CM-h)
H_2O	Sleep	0.0378
	Normal	0.0706
	Exercise	0.629
	Post Exercise	0.281
CO_2	Sleep	0.027
	Normal/Post Ex.	0.047
	Exercise	0.3
O_2	Sleep	0.022
	Normal/Post Ex.	0.038
	Exercise	0.24

Water Recovery and Management Guidance

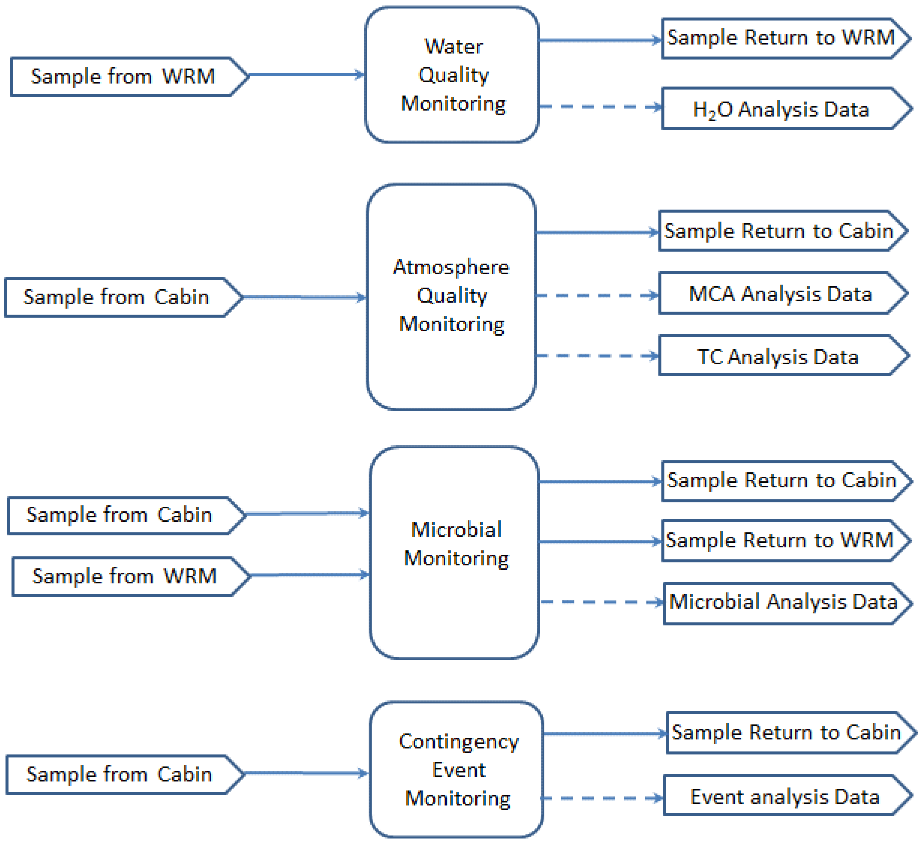
- Achieve >98% overall water recovery
  - >85% water from urine
  - >95% water from brine
- Survive 500-day dormancy
- Enable water recovery from trash, human waste, and process byproducts
- Maintain potable water quality
- Maintain potable water aesthetics
- Provide minimum water quantity



WATER USE	QUANTITY
Drinking	2 kg/CM-day
Food hydration	0.5 kg/CM-day
Personal hygiene	0.4 kg/CM-day
Medical support	5 kg + 0.5 kg/CM
EVA support	0.24 kg/h of EVA
Earth entry fluid loading	1 kg/CM
Post-landing support	4.5 kg/CM

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



Interfaces and Resource Allocation

- 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

Additional Sources

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- Spacecraft Water Exposure Guidelines. JSC-63414, https://www.nasa.gov/centers/johnson/pdf/485931main_SWEGsGuidelines.pdf
- Parker, J.F. and West, V.R. (1973) Bioastronautics Data Book, 2nd Edition. NASA SP-3006. http://ntrs.nasa.gov/search.jsp
- Exploration Systems Development Medical Operations Requirements Document, ESD 10024, NASA, October 2015.
- Human Systems Integration Practitioner's Guide, NASA/SP-2015-3709, November 2015.

Atmosphere Revitalization Overview

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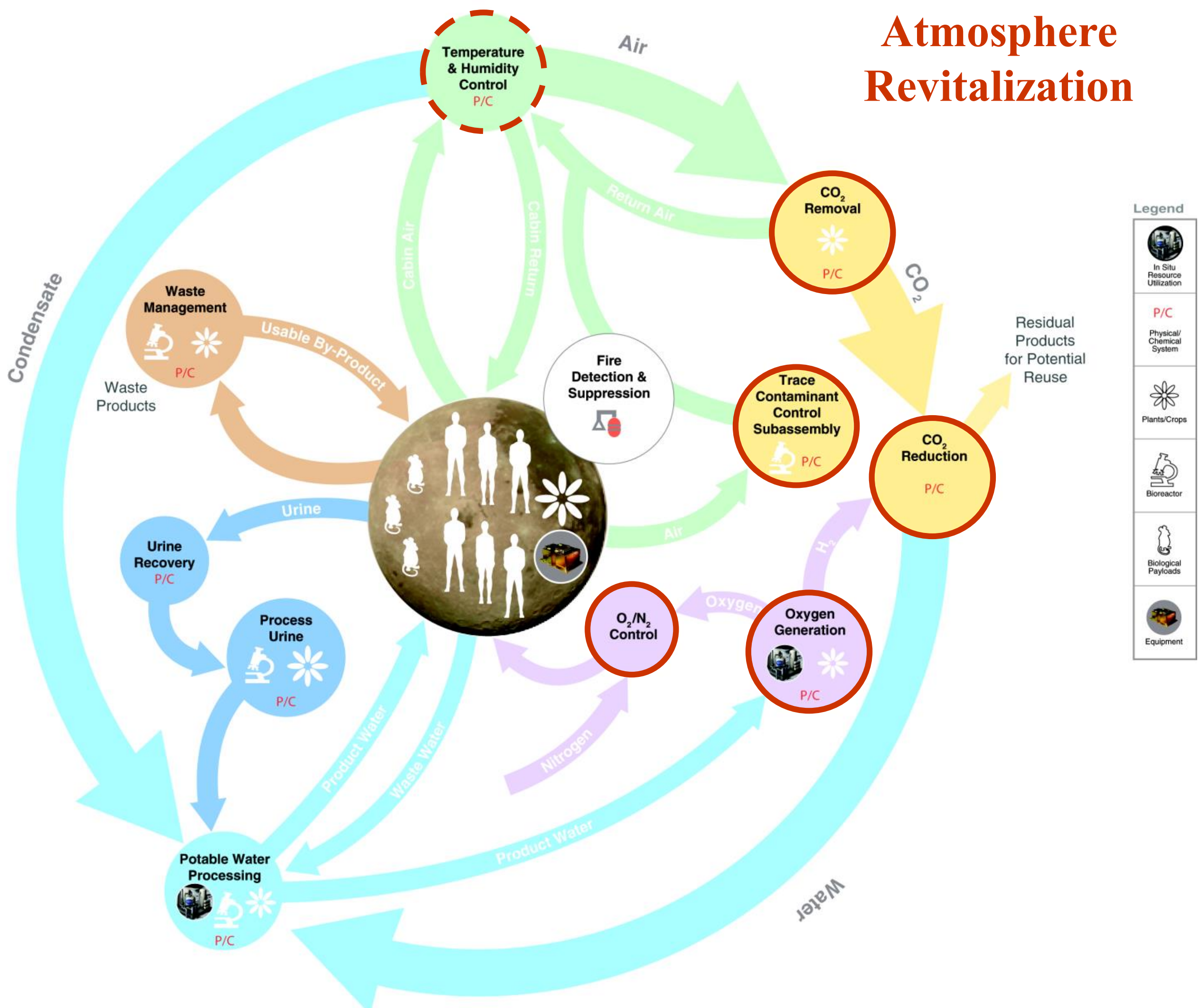
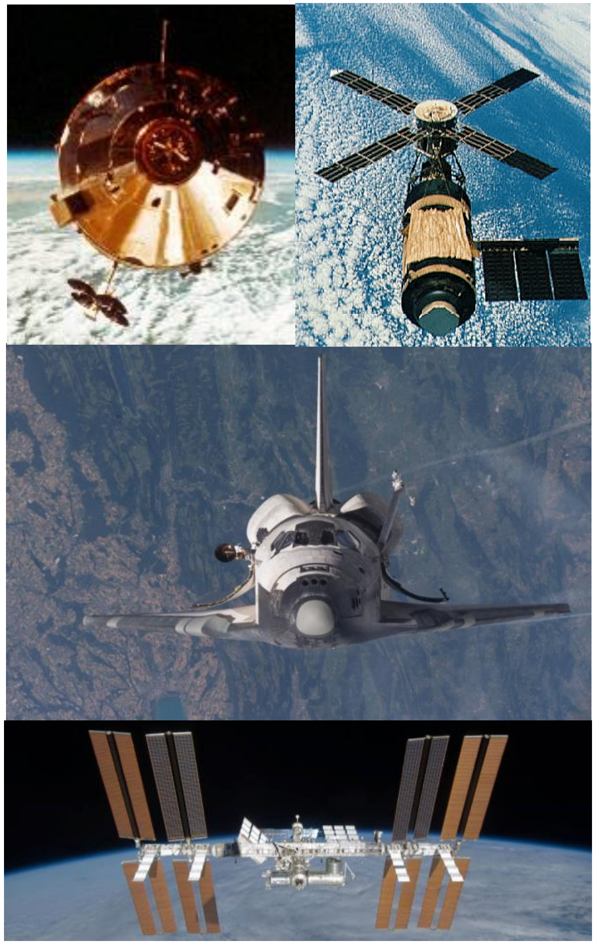
What is Atmosphere Revitalization?



Life Support System Functions

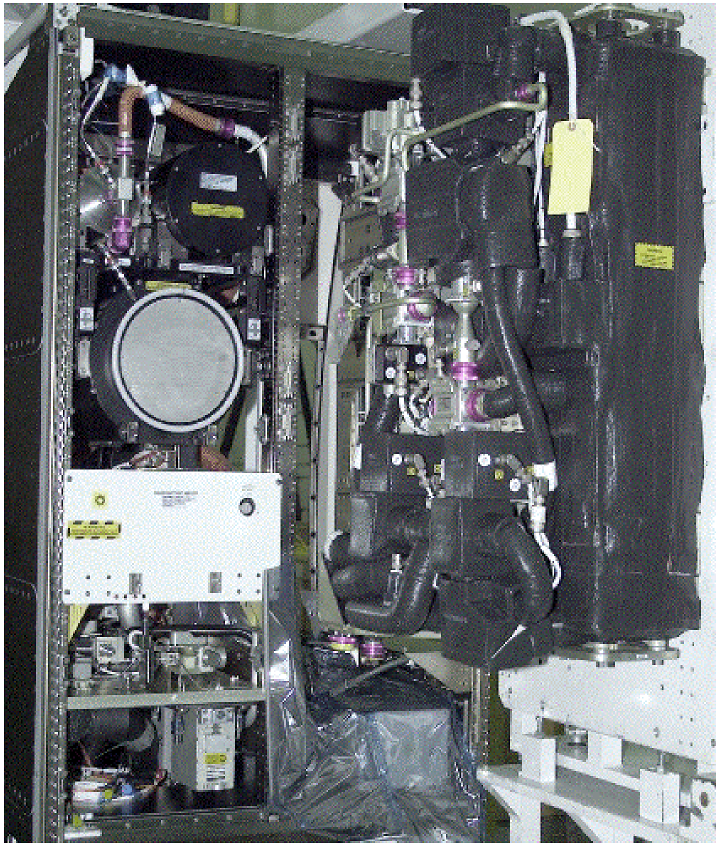
Control Atmosphere Pressure	Condition Atmosphere	Respond to Emergency Conditions	Control Internal CO_2 & Contaminants	Provide Water	Prepare for EVA Operations
• O_2/N_2 Pressure Control Assemblies (USO/RS) • Positive & Negative Pressure Relief (USOS-Transport) • O_2/N_2 Storage (USOS, RS, Pro-gress) • O_2 Generation Assembly, O_2 Solid Chemicals (RS) • Major Constituent Analyzer (USOS) (Share) • Gas Analyzer (RS) (Shared)	• Cabin Air Temperature & Humidity Control Assemblies (All) • Ventilation Fans (USOS, RS, MPLM) • Air Particulate Filters (All) • Intermodule Ventilation Fans & Valves (All) • Ducting (All)	• Smoke Detectors (All) • Portable Fire Extinguishers (All) • Fire Indicators and Fire Suppression Ports (All) • Portable Breathing Apparatus and Masks (All) • O_2/N_2 Pressure Control Assemblies (USOS) (Shared)	• CO_2 Removal Assembly (USOS/RS) • CO_2 Vent (USOS/RS) • Trace Contaminant Control Assembly (USOS/RS) • Major Constituent Analyzer (USOS) • CO_2 Reduction Assembly (RS) • CO_2 LIOH Removal (RS) • Manual Sampling Equipment (USOS) • Gas Analyzer (RS)	• 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)	• O_2/N_2 Pressure Control Assemblies (USOS) • O_2/N_2 Distribution (USOS) • O_2/N_2 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



PROJECT	MISSION DURATION	CABIN VOLUME (m^3)	CREW SIZE	TECHNOLOGICAL APPROACH
Mercury	34 hours	1.56	1	**Atmosphere:** 100% O_2 at 34.5 kPa. **Atmosphere supply:** Gas at 51.7 MPa. **CO_2 removal:** LiOH. **Trace contaminants:** Activated carbon.
Gemini	14 days	2.26	2	**Atmosphere:** 100% O_2 at 34.5 kPa. **Atmosphere supply:** Supercritical storage at 5.86 MPa. **CO_2 removal:** LiOH. **Trace contaminants:** Activated carbon.
Apollo	14 days	5.9	3	**Atmosphere:** 100% O_2 at 34.5 kPa. **Atmosphere supply:** Supercritical storage at 6.2 MPa. **CO_2 removal:** LiOH. **Trace contaminants:** Activated carbon.
Skylab	84 days	361	3	**Atmosphere:** 72% O_2/28% N_2 at 34.5 kPa. **Atmosphere supply:** Gas at 20.7 MPa. **CO_2 removal:** Type 13X and 5A molecular sieves regenerated by vacuum swing. **Trace contaminants:** Activated carbon.
Space Shuttle	14 days	74	7	**Atmosphere:** 21.7% O_2/78.3% N_2 at 101 kPa **Atmosphere supply:** Gas at 22.8 MPa **CO_2 removal:** LiOH **Trace contaminants:** Activated carbon and ambient temperature CO oxidation
International Space Station	180 days	Up to 600	3 to 6	**Atmosphere:** 21.7% O_2/78.3% N_2 at 101 kPa **Atmosphere supply:** Gas at 20.7 MPa/water electrolysis **CO_2 removal:** Silica gel with type 13X and 5A molecular sieves regenerated by vacuum/temperature swing **CO_2 reduction:** Sabatier reactor (scar for future addition) **Trace contaminants:** Activated carbon and thermal catalytic oxidation

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



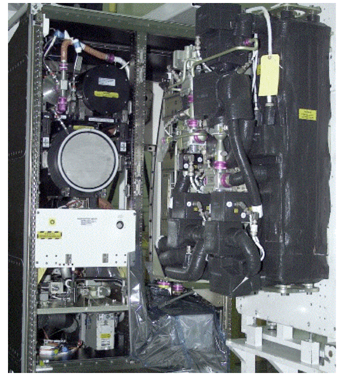
Basic Requirements

PARAMETER	STANDARD	DESIGN POINTS
Total Pressure	97.9-102.7 kPa	<0.23 kg/d leakage
Carbon Dioxide Partial Pressure	0.7-1 kPa	0.52-1.5 kg/p-d; 1 kg/p-d average
Oxygen Partial Pressure	19.5-23.1 kPa	0.49-1.25 kg/p-d; 0.84 kg/p-d average
Water Vapor	4.4-15.5°C dewpoint	0.87-4.3 kg/p-d; 1.82 kg/p-d average
Trace Chemical Contaminants	<SMACs in JSC 20584	SAE 2009-01-2592
Particulates	<0.5 mg/m^3 average; <1 mg/m^3 peak for 0.5 to 100-micron size	10^9 particles/p-d
Microbes	500 CFU bacteria/m^3 100 CFU fungi/m^3	3,000 CFU/person-minute

kg/p-d = kilogram/person-day

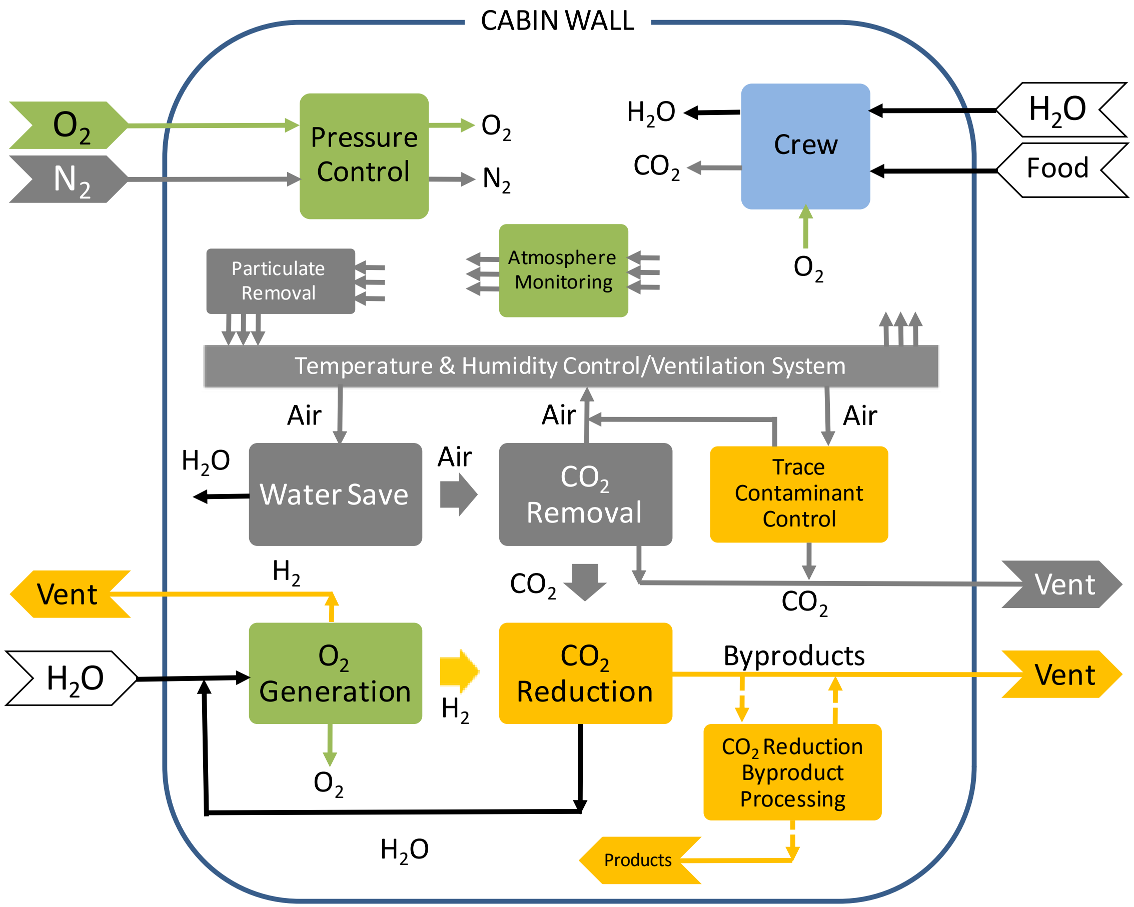
Process Types & Unit Operations

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

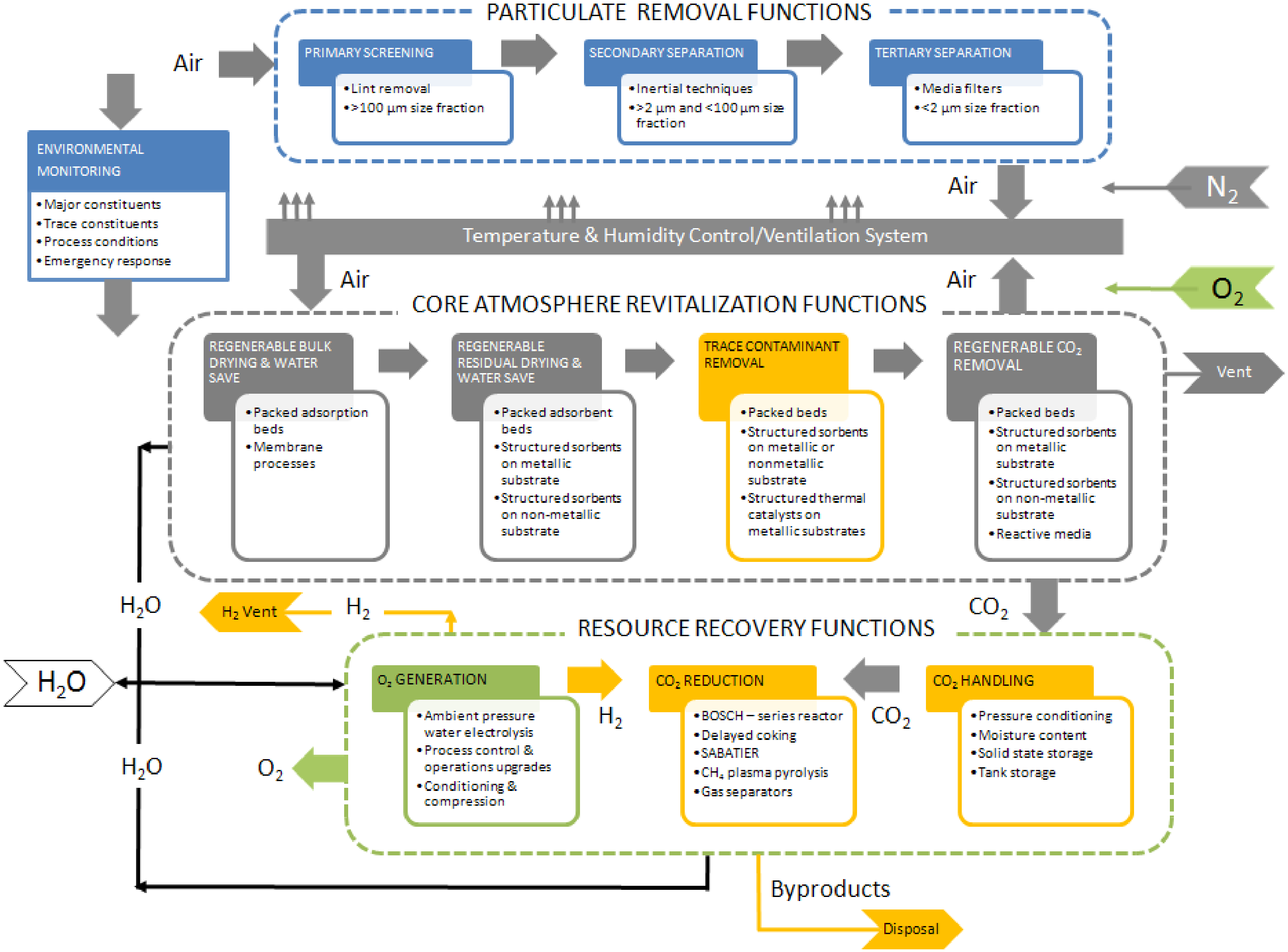


- Process gas drying
- Process gas purification
  - CO_2 removal
  - Trace contaminant removal
  - Particulate matter removal
- Atmospheric gas handling
  - Storage
  - Conditioning
- Atmospheric gas production
  - High pressure capability
  - In-situ resource recovery and use

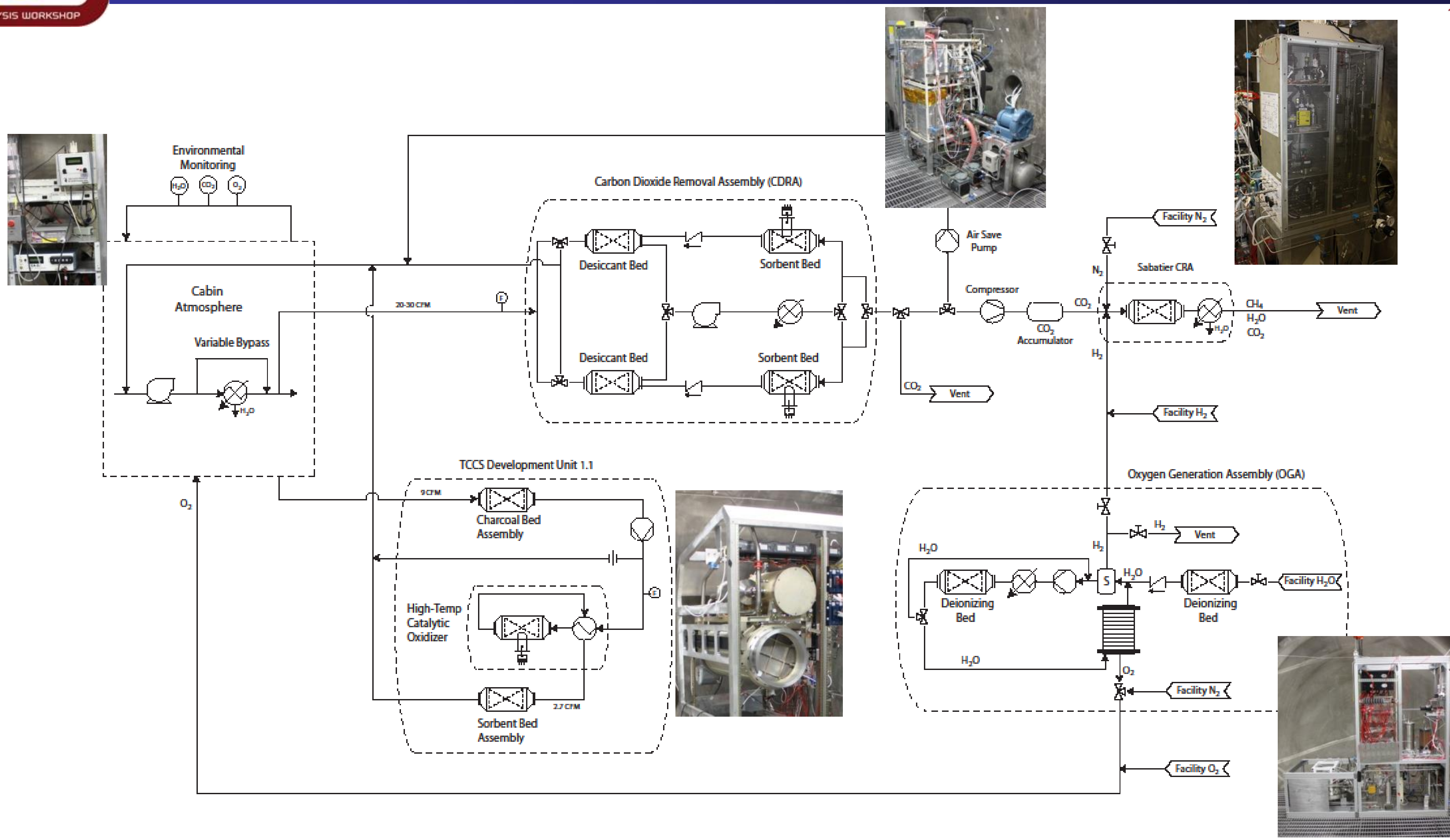
- Core processes
  - Filtration
  - Dehumidification
  - CO_2 removal
  - Trace contaminant control
- Loop closure
  - CO_2 reduction
  - O_2 generation



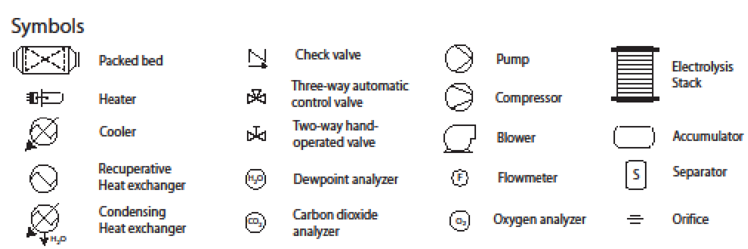
AR Subsystem Functional Trade Spaces



ISS AR Process Architecture



ISS Performance Basis
Hardware Schematic
Draft 4
5-15-2012



Room for Improvement

- 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

Helpful Sources

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Carbon Dioxide Removal: From the Moon to Mars

Presented By
James Knox/MSFC

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Average Human Metabolic Balance (lb/person-day)

- **Oxygen** 1.84
- **Water** 7.77
  - Drink 3.56
  - In food 2.54
  - Food Prep 1.67
- **Food Solids** 1.36
  - Oxygen 0.44
  - Hydrogen 0.08
  - Carbon 0.60
  - Other 0.24
- **Total In** 10.97

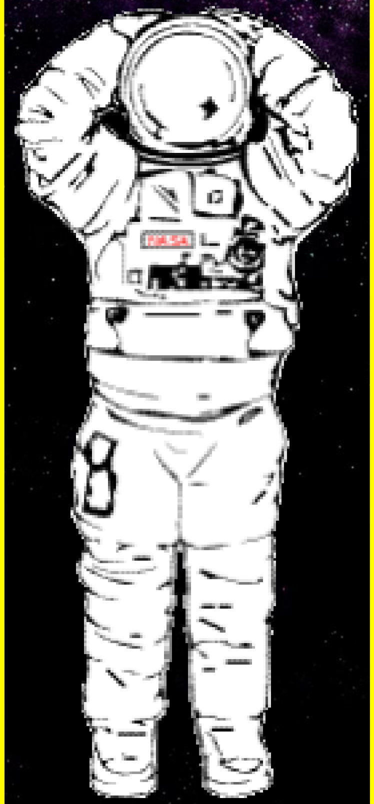
- **Carbon Dioxide** 2.20
- **Water** 8.53
  - Urine 3.31
  - Sweat & respiration 5.02
  - Feces 0.20
- **Solids** 0.24
  - In urine 0.13
  - In sweat 0.04
  - In feces 0.07
- **Total Out** 10.97

Sustaining people in space requires managing all of their "ins and outs"

Daily Metabolic Requirements for Life Support

Needs

- Oxygen = 0.84 kg (1.84 lb)
- Food Solids = 0.62 kg (1.36 lb)
- Water in Food = 1.15 kg (2.54 lb)
- Food Prep Water = 0.76 kg (1.67 lb)
- Drink = 1.62 kg (3.56 lb)
- Metabolized Water = 0.35 kg (0.76 lb)
- Hand/Face Wash Water = 4.09 kg (9.00 lb)
- Shower Water = 2.73 kg (6.00 lb)
- Urinal Flush = 0.49 kg (1.09 lb)
- Clothes Wash Water = 12.50 kg (27.50 lb)
- Dish Wash Water = 5.45 kg (12.00 lb)
- Total = 30.60 kg (67.32 lb)



Effluents

- Carbon Dioxide = 1.00 kg (2.20 lb)
- Respiration & Perspiration Water = 2.28 kg (5.02 lb)
- Food Preparation, Latent Water = 0.036 kg (0.08 lb)
- Urine = 1.50 kg (3.31 lb)
- Urine Flush Water = 0.50 kg (1.09 lb)
- Feces Water = 0.091 kg (0.20 lb)
- Sweat Solids = 0.018 kg (0.04 lb)
- Urine Solids = 0.059 kg (0.13 lb)
- Feces Solids = 0.032 kg (0.07 lb)
- Hygiene Water = 12.58 kg (27.68 lb)
- Clothes Wash Water
  - Liquid = 11.90 kg (26.17 lb)
  - Latent = 0.60 kg (1.33 lb)
- Total = 30.60 kg (67.32 lb)

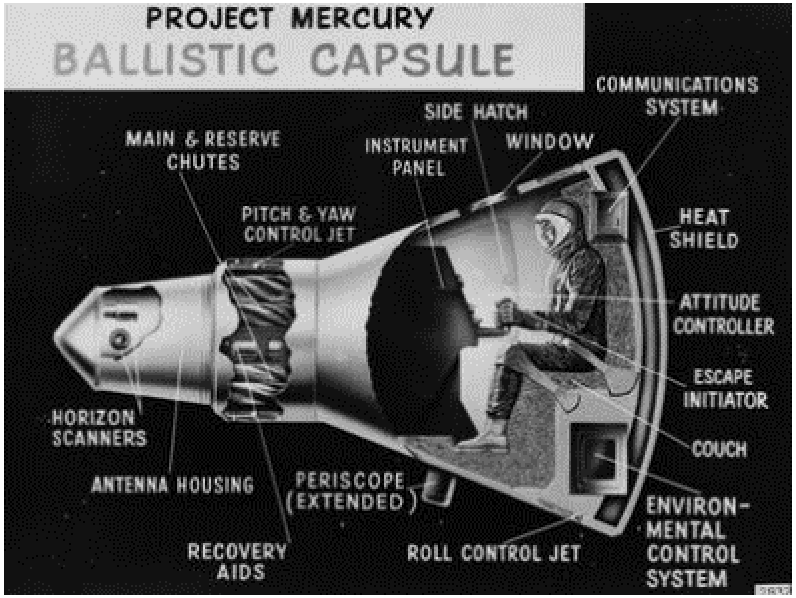
Note: These values are based on an average metabolic rate of 136.7 W/person (11,200 BTU/person/day) and a respiration quotient of 0.87. The values will be higher when activity levels are greater and for larger than average people. The respiration quotient is the molar ratio of CO_2 generated to O_2 consumed.

Health effects of respiratory exposure to carbon dioxide

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

1. James, J. T.; Meyers, V. E.; Sipes, W.; Scully, R. R.; Matty, C. M., Crew health and performance improvements with reduced carbon dioxide levels and the resource impact to accomplish those reductions. In 41st International Conference on Environmental Systems, Portland, Oregon, 2011.
2. Baxter, P.J., 2000. Gases. In: P.J. Baxter, P.H. Adams, T.-C. Aw, A. Cockcroft and J.M. Harrington (Editors), Hunter's Diseases of Occupations. Arnold, London, pp. 123-178.
3. Faive-Pierret, R. and Le Guern, F., 1983. Health risks linked with inhalation of volcanic gases and aerosols. In: H. Tazieff and J.C. Sabroux (Editors), Forecasting Volcanic Events. Elsevier Science Publishers B.V., Amsterdam, pp. 69-81.
4. National Institute for Occupational Safety and Health (NIOSH), 1981. Occupational Health Guidelines for Chemical Hazards, DHHS (NIOSH) Publication No. 81-123. http://www.cdc.gov/niosh/81-123.html.

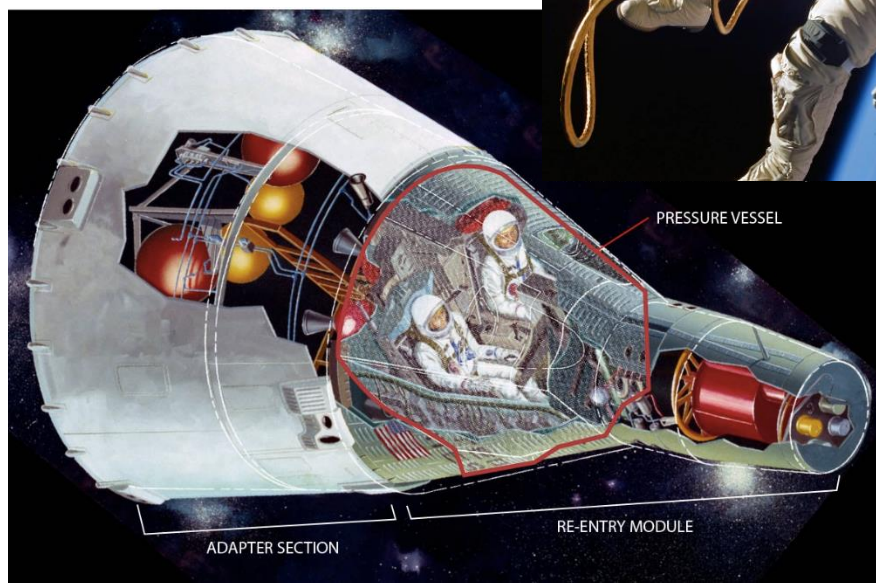
Project Mercury: First U.S. Manned Spaceflight

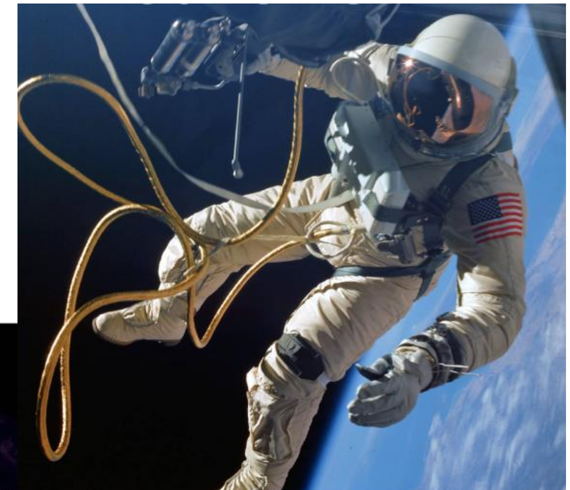


Objectives:
- To orbit a manned spacecraft around Earth
- To investigate man's ability to function in space
- To recover both man and spacecraft safely

Misson Specifics:
- 1 astronaut
- Up to 34 hour missions
- CO_2 removed from atmosphere with expendable LiOH

Project Gemini: Bridge to the Moon





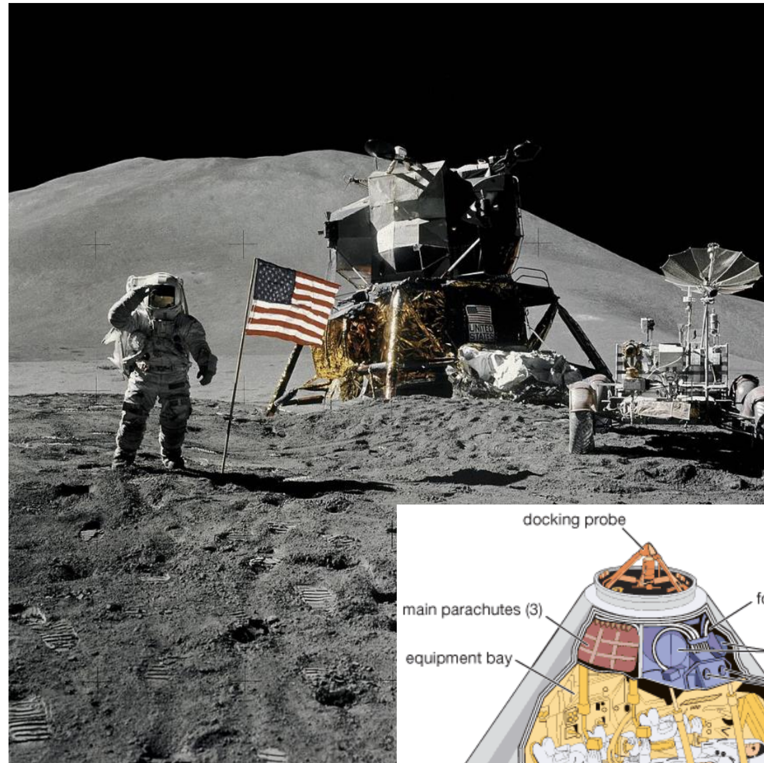
Objectives:

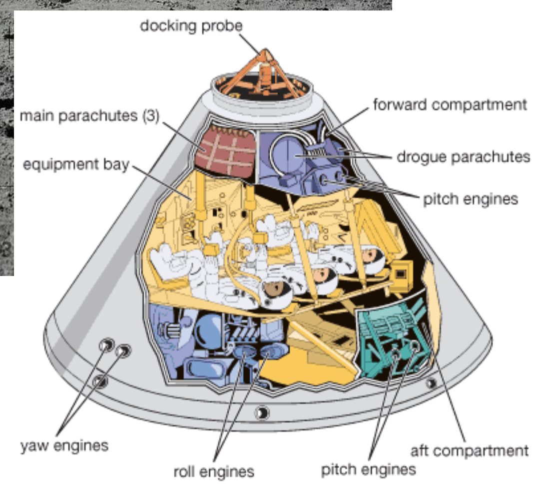
- To test an astronaut's ability to fly long-duration missions
- To understand how spacecraft could rendezvous and dock in orbit around the Earth and the moon
- To perfect re-entry and landing methods

Misson Specifics:

- 2 astronauts
- Up to 14 day missions
- CO_2 removed from atmosphere with expendable LiOH

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
- CO_2 removed from atmosphere with expendable LiOH

Expendable CO_2 Removal via Lithium Hydroxide

Lithium hydroxide crystals

$$2LiOH(s) + CO_2(g) \rightarrow Li_2CO_3(s) + H_2O(g)$$

One gram of anhydrous lithium hydroxide can remove 450 cm^3 of carbon dioxide gas, or about 90% by mass.

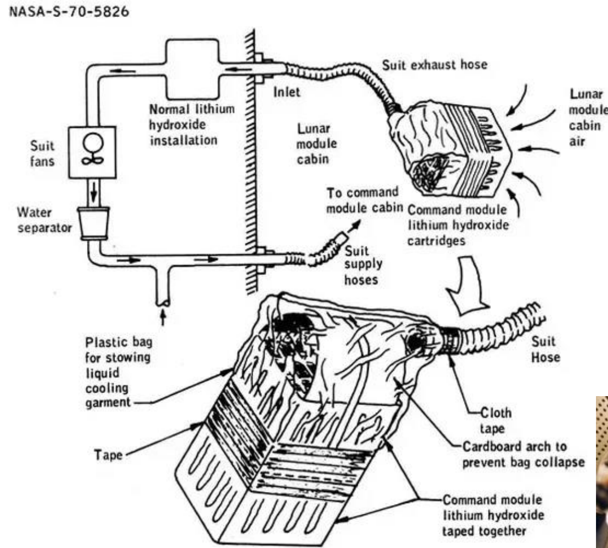
Apollo Lunar Module (LM) LiOH Canister (left)

Apollo Command Module (CM) LiOH Canister (right)

https://en.wikipedia.org/wiki/Lithium_hydroxide

Apollo 13: Disaster Averted

Alan Bean, Apollo 13...Houston, We Have a Problem, 1995, Acrylic on Aircraft Plywood



(a) Configuration schematic.

Figure 6.7-1.- Supplemental carbon dioxide removal system.

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 CO2 concentration rose to ~13 torr

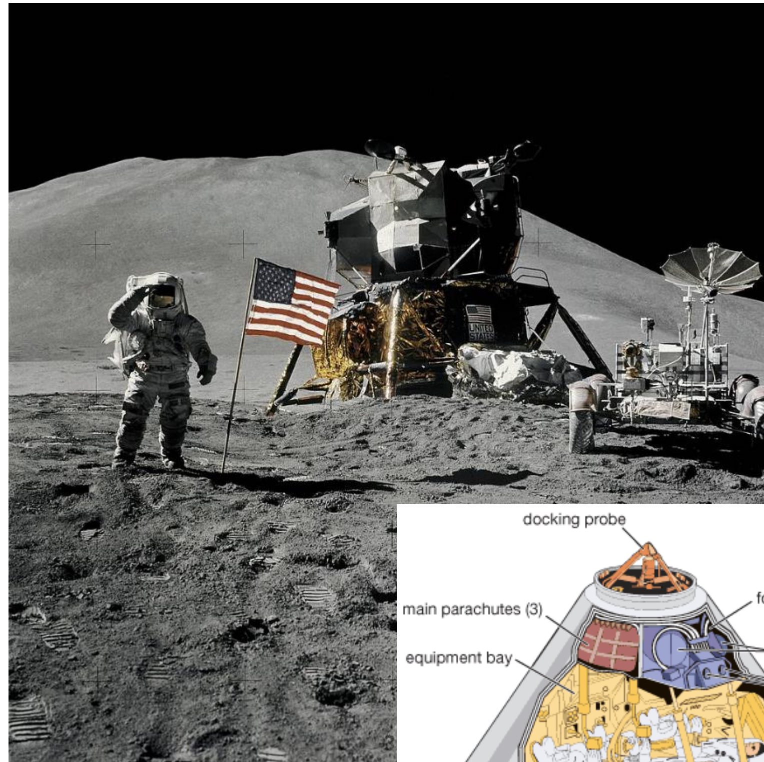
Challenge:

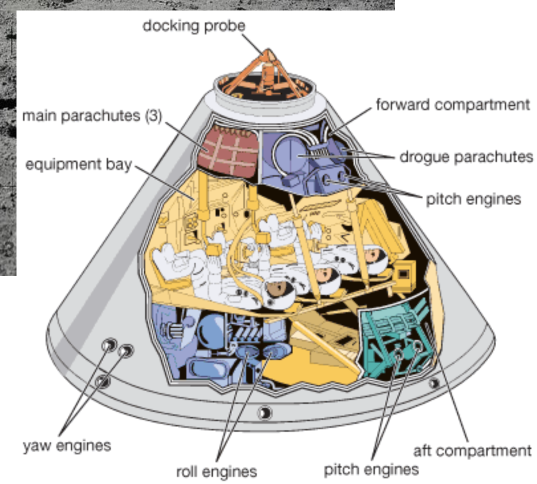
- Integrate active environmental control system in LM with CM LiOH canisters

Solution:

- Combine cardboard from EVA cue card, plastic bag from liquid cooling garment, suit hose, and duct tape

Project Apollo: Landing on the Moon





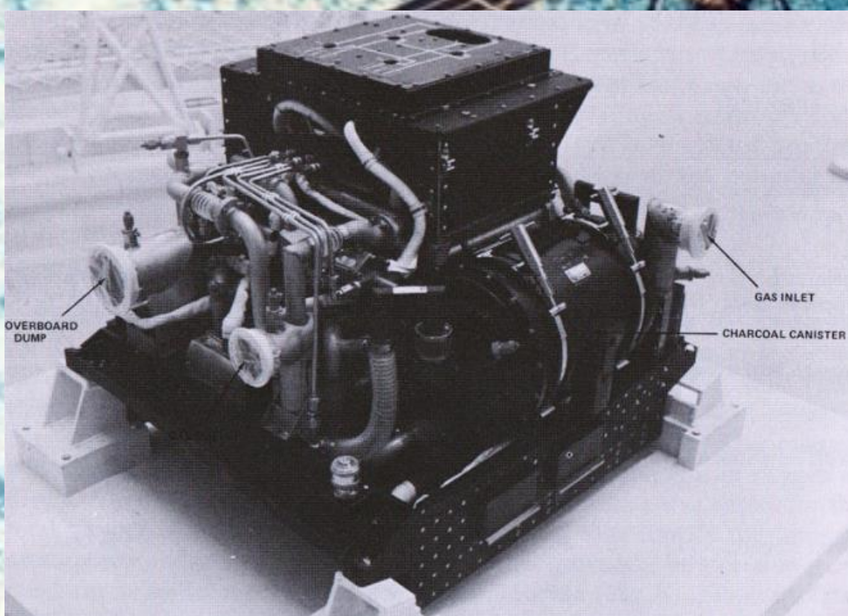
Objectives:
- Landing Americans on the moon and returning them safely to Earth.
- Establishing the technology to meet other national interests in space.
- Achieving preeminence in space for the United States.
- Carrying out a program of scientific exploration of the Moon.
- Developing man's capability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

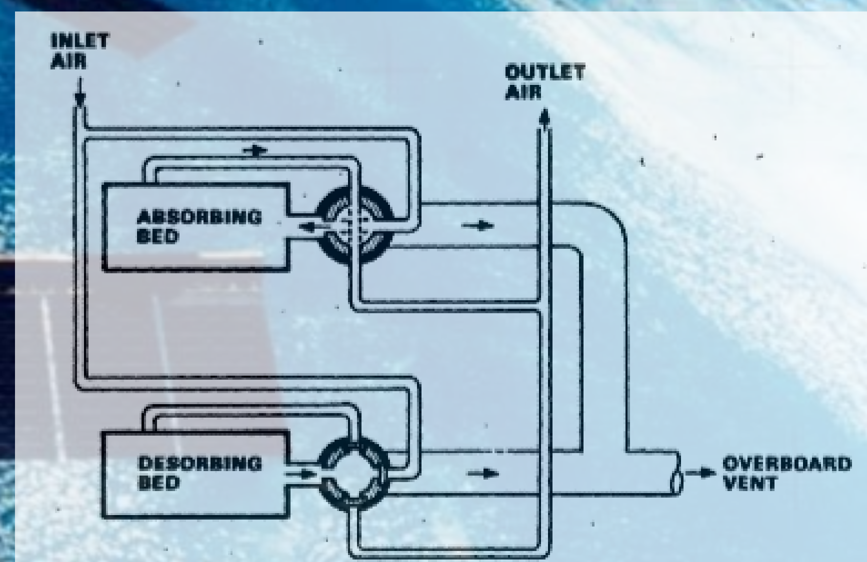
Misson Specifics:
- 3 astronauts
- Up to 12.5 day missions
- CO_2 removed from atmosphere with expendable LiOH

SKYLAB IN ORBIT AT END OF MISSION

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 CO_2 and H_2O removal on Skylab for 171 days without hardware anomaly.
- 70% of metabolic water and 100% of metabolic CO_2 for 3 crew was removed via a regenerable vacuum swing adsorption process.
- Three 2BMS units would provide sufficient removal for 6 non-exercising crew.





MSFC-74-SL4 7200-405

Space Shuttle: A Reusable Launch Vehicle

Extended Duration Orbiter (EDO) Regenerable CO2 Removal System (RCRS)

- First spacecraft use of solid amine (liquid amine bound to a resin or pellet)
- Need for space vacuum for regeneration required LiOH supplement for launch and landing

Objectives:

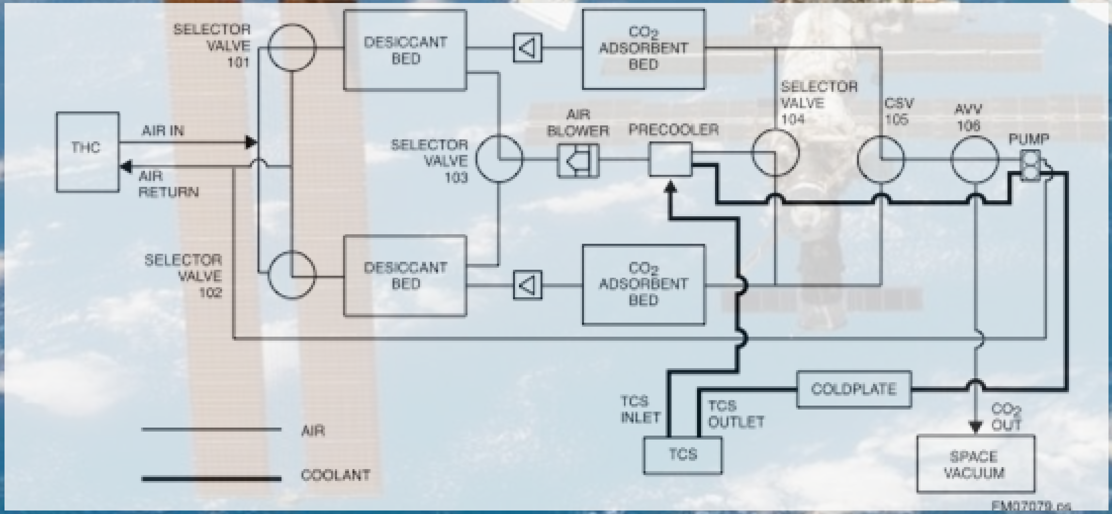
- Reusable launch system and orbital spacecraft
- Launched satellites, interplanetary probes, Hubble Telescope
- Conducted numerous science experiments
- Launched all U.S International Space Station modules

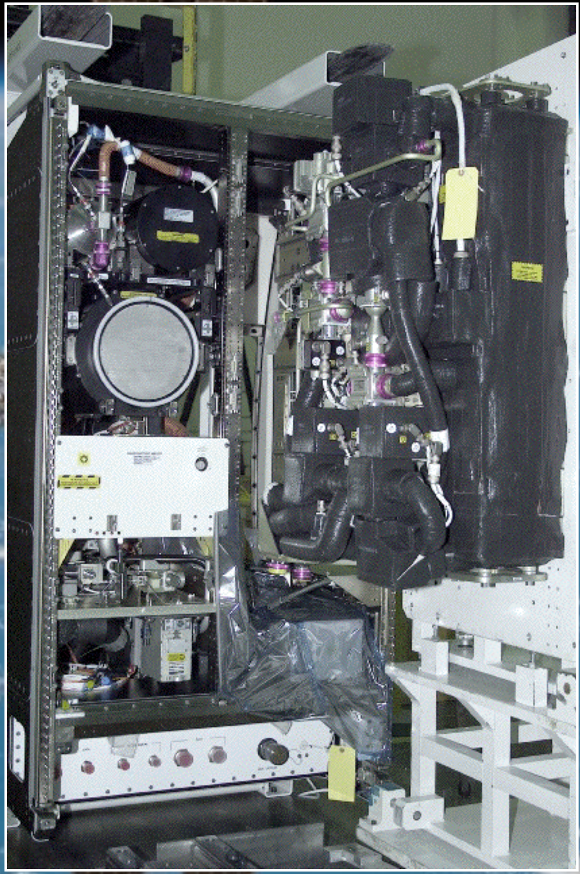
Misson Specifics:

- 135 missions with 5 orbiters (2 destroyed in accidents)
- Up to 10-day missions, or 16-day missions with EDO
- CO_2 removed from atmosphere with expendable LiOH
- Supplemental removal with RCRS on extended missions

Current Spacecraft Carbon Dioxide and Humidity Removal Systems

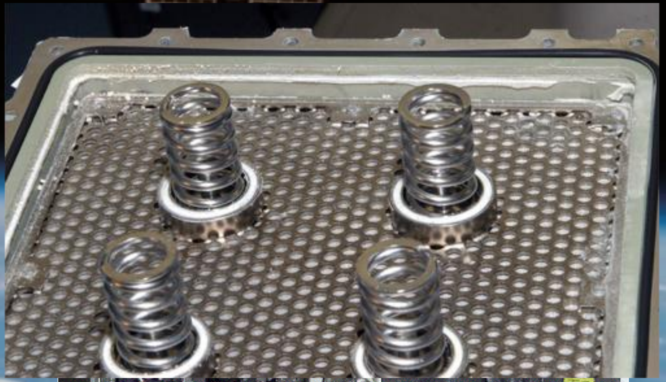
- The International Space Station uses a 4 Bed Molecular Sieve to remove CO_2 from the ISS.
- Anomalies due to flaws in the containment design have highlighted the need for a more robust sorbent configuration ***(such as structured sorbents)***
- The 4BMS design returns water to the cabin and can either vent CO_2 or store it in an accumulator for subsequent reduction reaction and water recovery

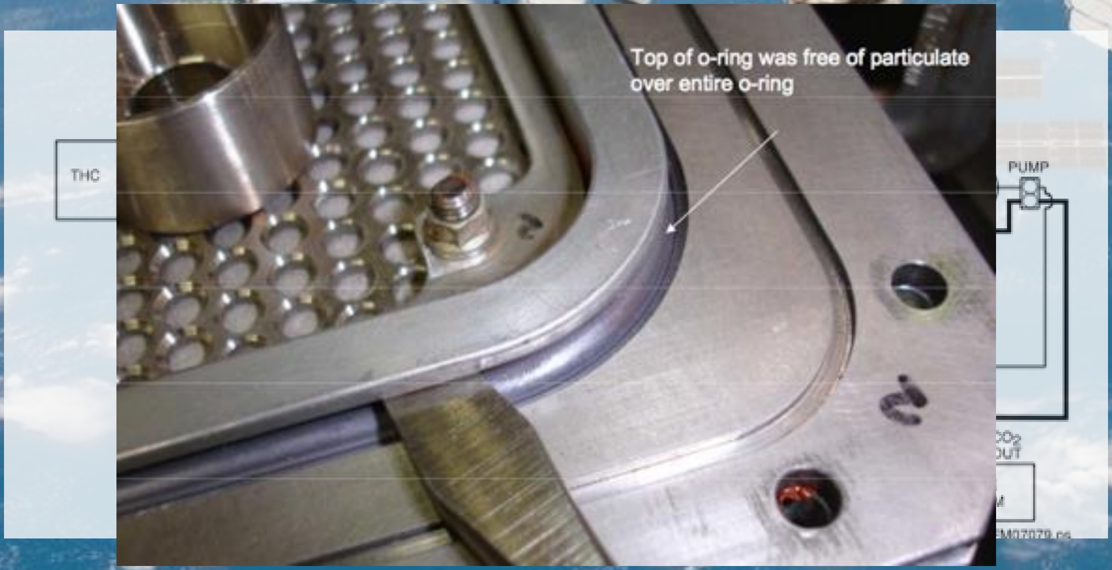


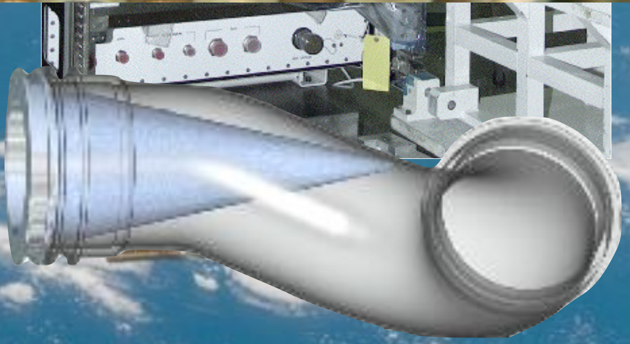


Current Spacecraft Carbon Dioxide Removal Systems

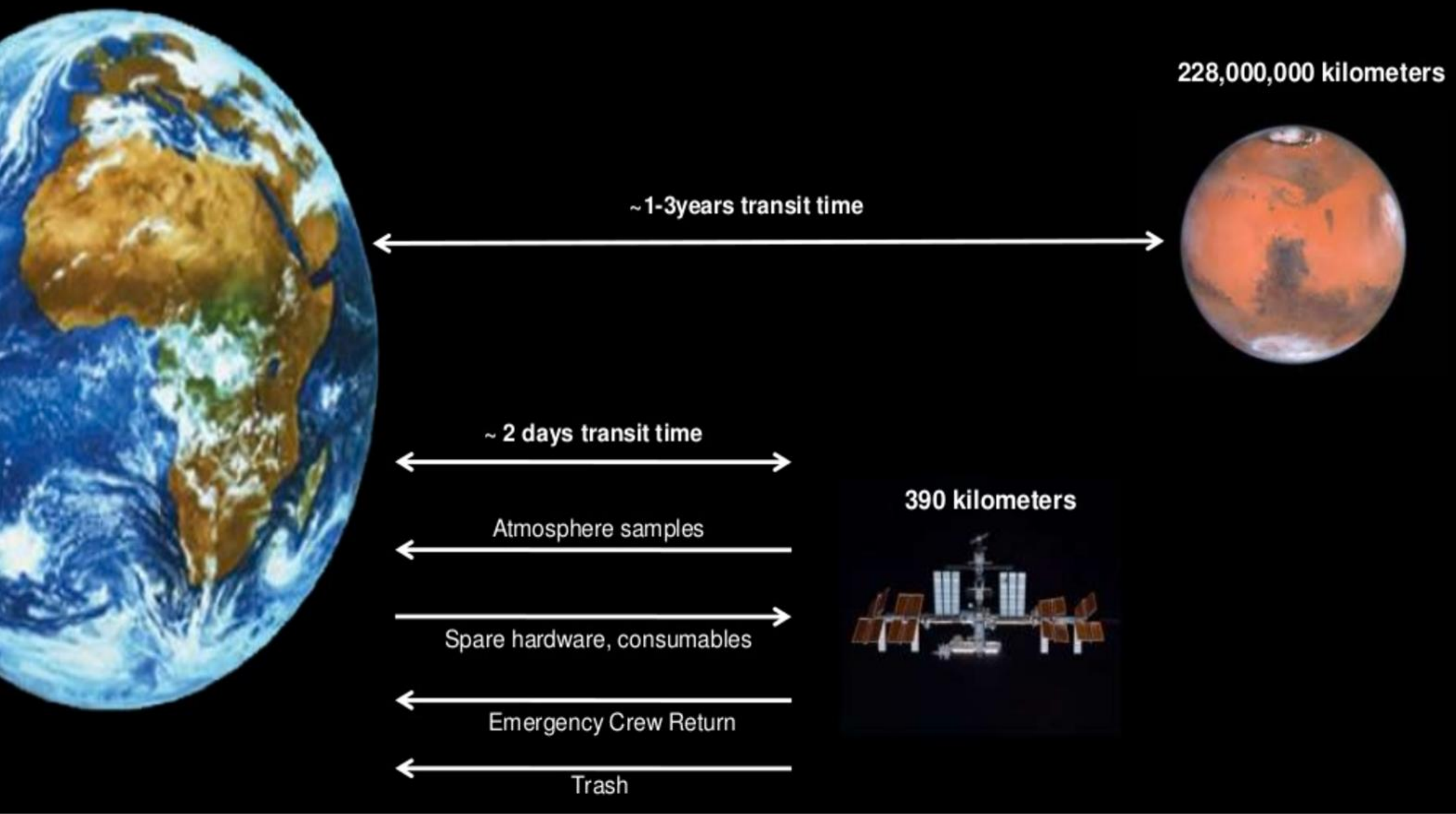
- The International Space Station uses a “4 Bed Molecular Sieve” (4BMS) to remove CO_2 from the ISS.
- The 4BMS desiccates with silica gel and zeolite 13X, and removes CO_2 with zeolite 5A. CO_2 is vented presently, though will be reclaimed in the near future
- **Anomalies due to flaws in the containment design have highlighted the need for a more robust sorbent configuration *(such as structured sorbents)***







The Challenges of Going Beyond the ISS for ECLSS



Oxygen Generation

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

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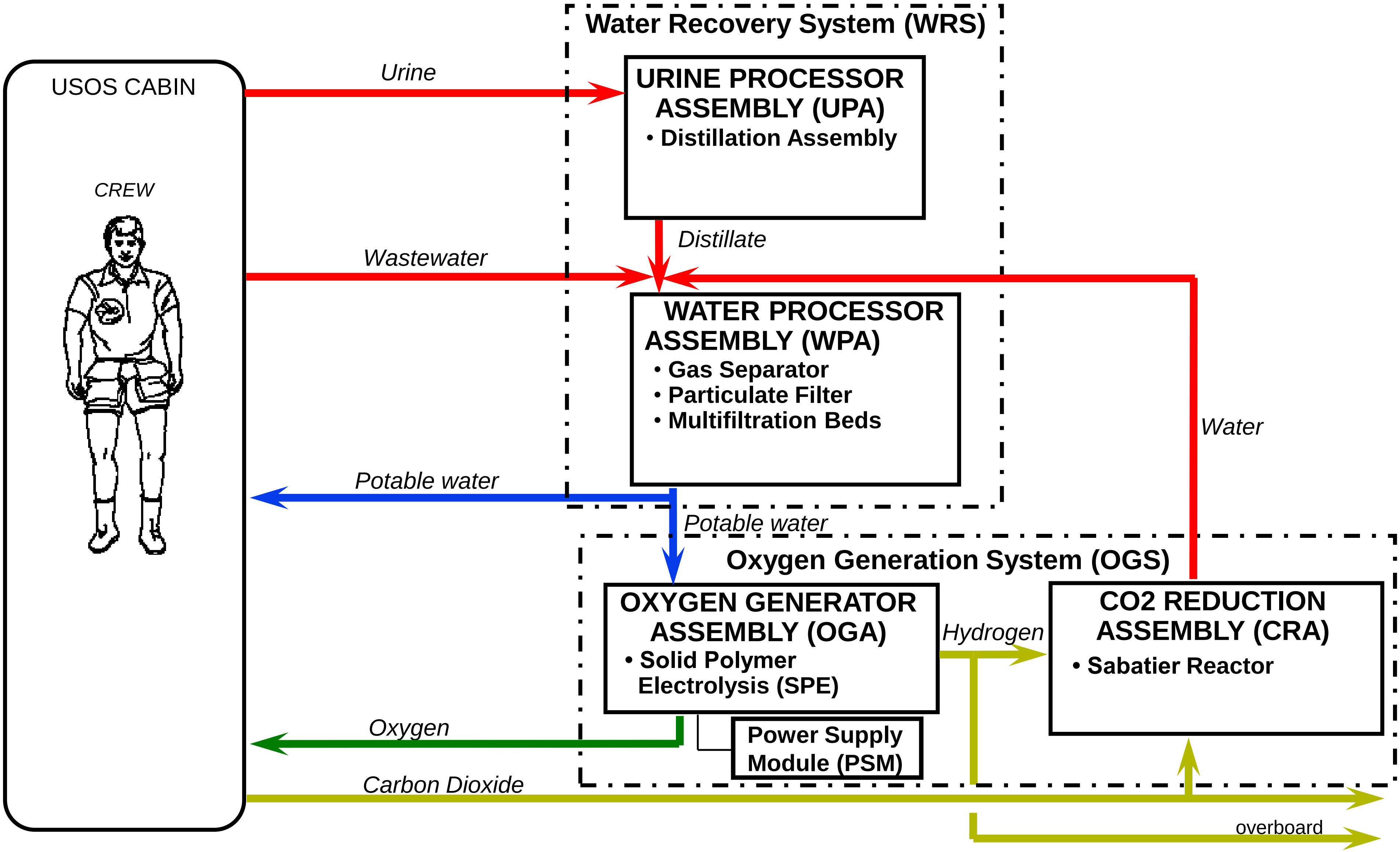
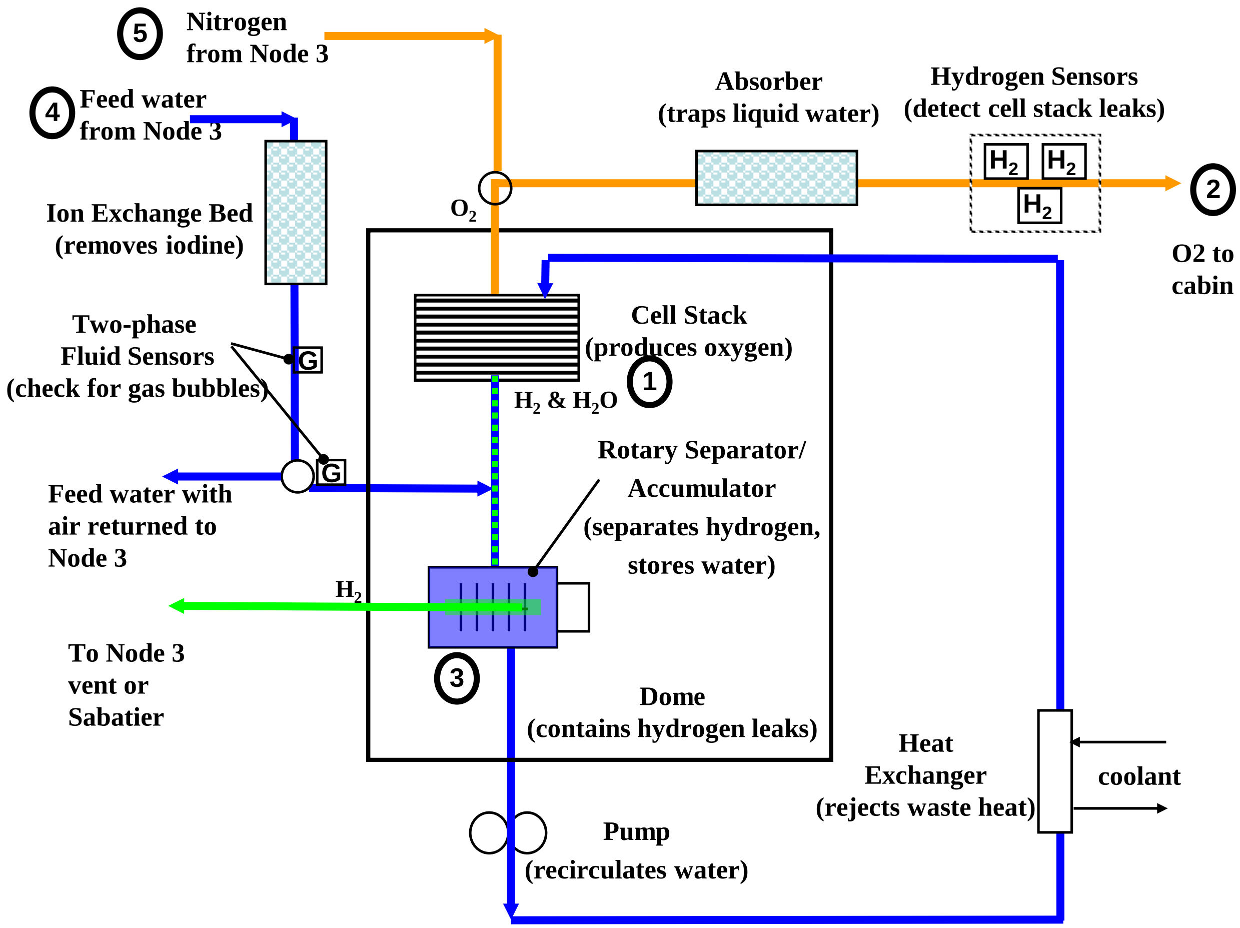
ISS Regenerative ECLSS Architecture



ISS OGA Simplified Schematic

Integrated Process

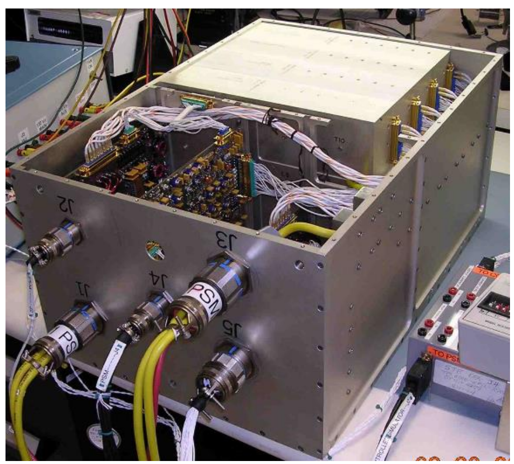
1. Oxygen & hydrogen produced in 28-cell stack
2. O_2 delivered to cabin
3. H_2 mixed with excess re-circulated water, separated dynamically, and vented overboard or to Sabatier
4. Makeup water periodically added and stored within rotary separator
5. Oxygen lines purged with nitrogen for safety after shutdowns



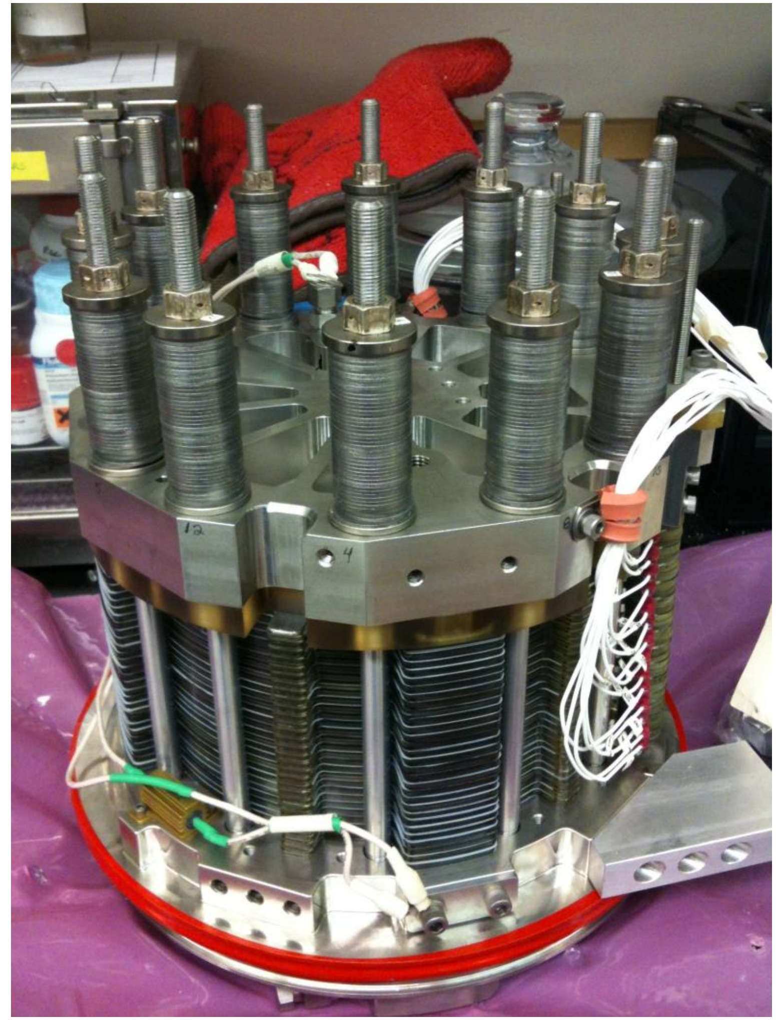
ISS OGS Key Components

Rotary Separator Accumulator

Hydrogen Sensor

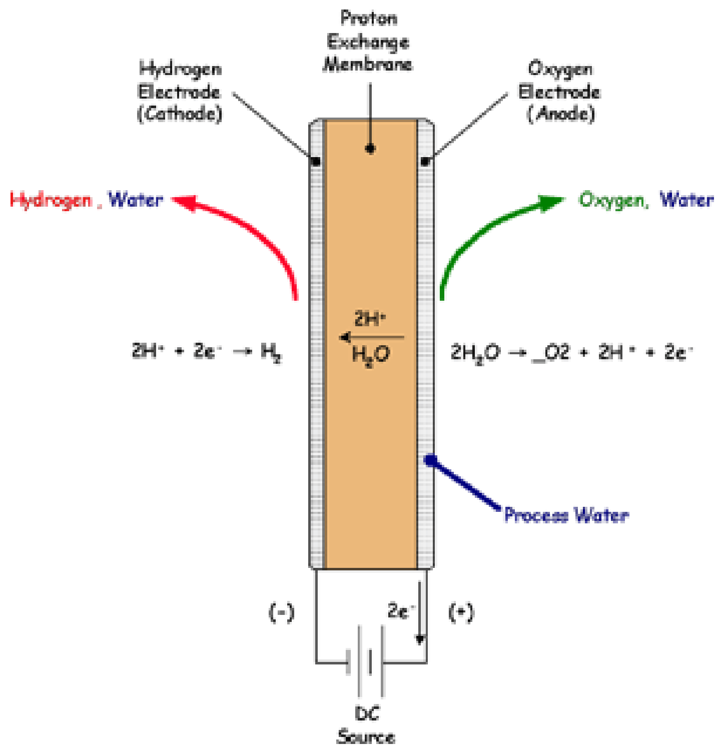


Cell Stack Power Supply Module (PSM)



Cell stack (28 cells)

Cathode Feed Cell Membrane (Nafion)



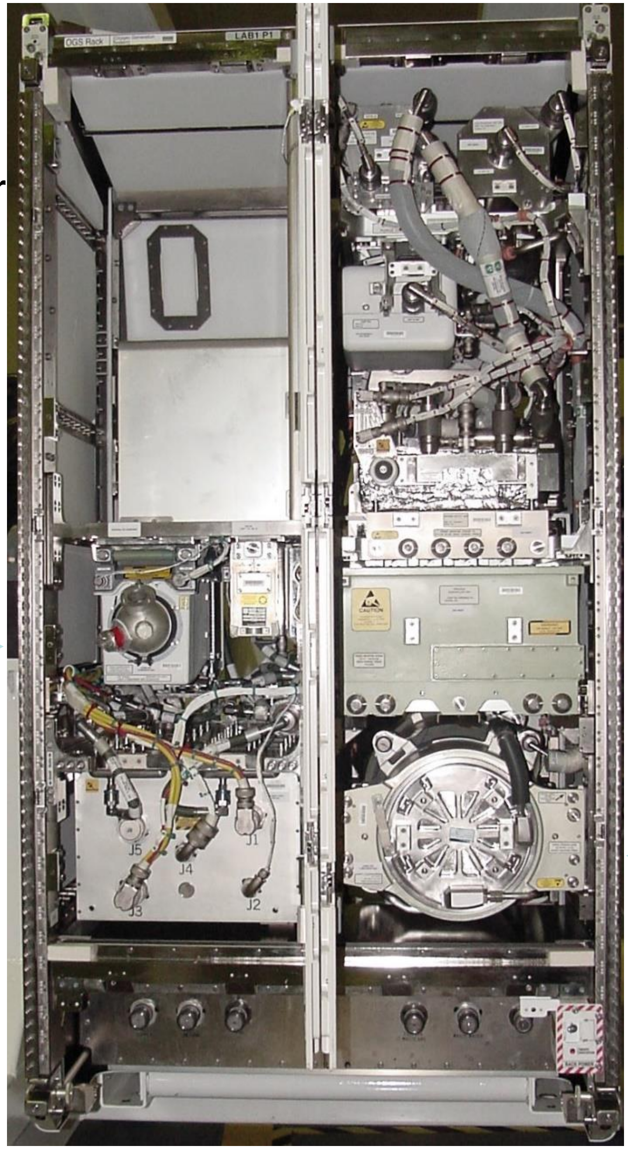
ISS OGS Rack at MSFC

Sabatier (not shown)

AAA

RPCM

PSM



DI Bed

Nitrogen Purge

Pump, Heat Exchanger

Oxygen Outlet

Hydrogen Sensor

Controller

Cell Stack

Rotary Separator Accumulator

Interfaces

(nitrogen, coolant, vacuum,

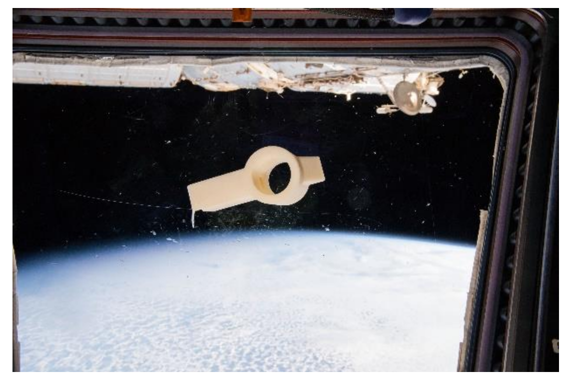
feedwater, wastewater, power, 1553)

At MSFC in 2005

OGA on ISS

ISS020E031453

ISS020E038784



ISS OGS Key Parameters

Parameter	Value
Max crew size supported	11
Typical crew size supported	3
Oxygen Production	20.4 lb/day (max)
Hydrogen Production	2.6 lb/day (max)
Water Consumption	23 lb/day (max)
Oxygen consumption per crew member	1.8 lb/day
OGS Launch Weight	1774 lb
OGS Power Consumption	3955 W (max)
OGS Volume	1 ISPR Rack

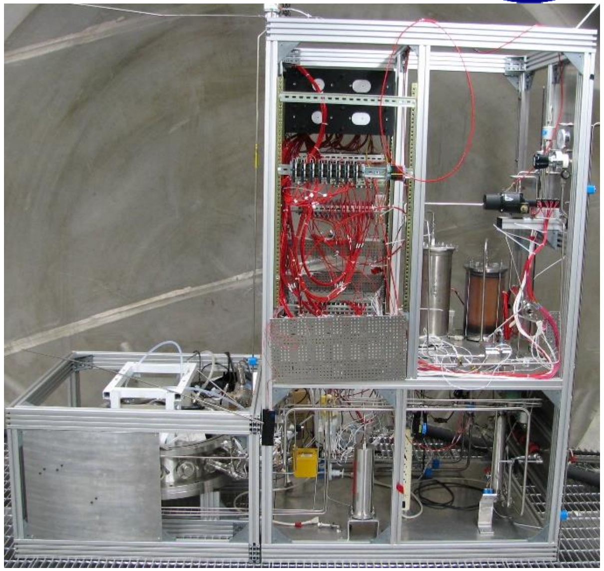
ISS OGS Status

- 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

OGS Rack on ISS

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



OGA Testbed
In E-Chamber

Oxygen Recovery and CO_2 Reduction Overview

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

1960's Technology ID'd

- Carboxy (CO_2 Electrolysis)
  - $2CO_2 \leftrightarrow CO + O_2$
- Methoxy (Sabatier)
  - $CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$
- Bosch Process
  - $CO_2 + H_2 \leftrightarrow CO + H_2O$
  - $2CO \leftrightarrow CO_2 + C(s)$
  - $CO + H_2 \leftrightarrow H_2O + C(s)$

1980-90's Tech Development

Sabatier Development Unit developed by Hamilton Sundstrand

Competed for ISS

ped by

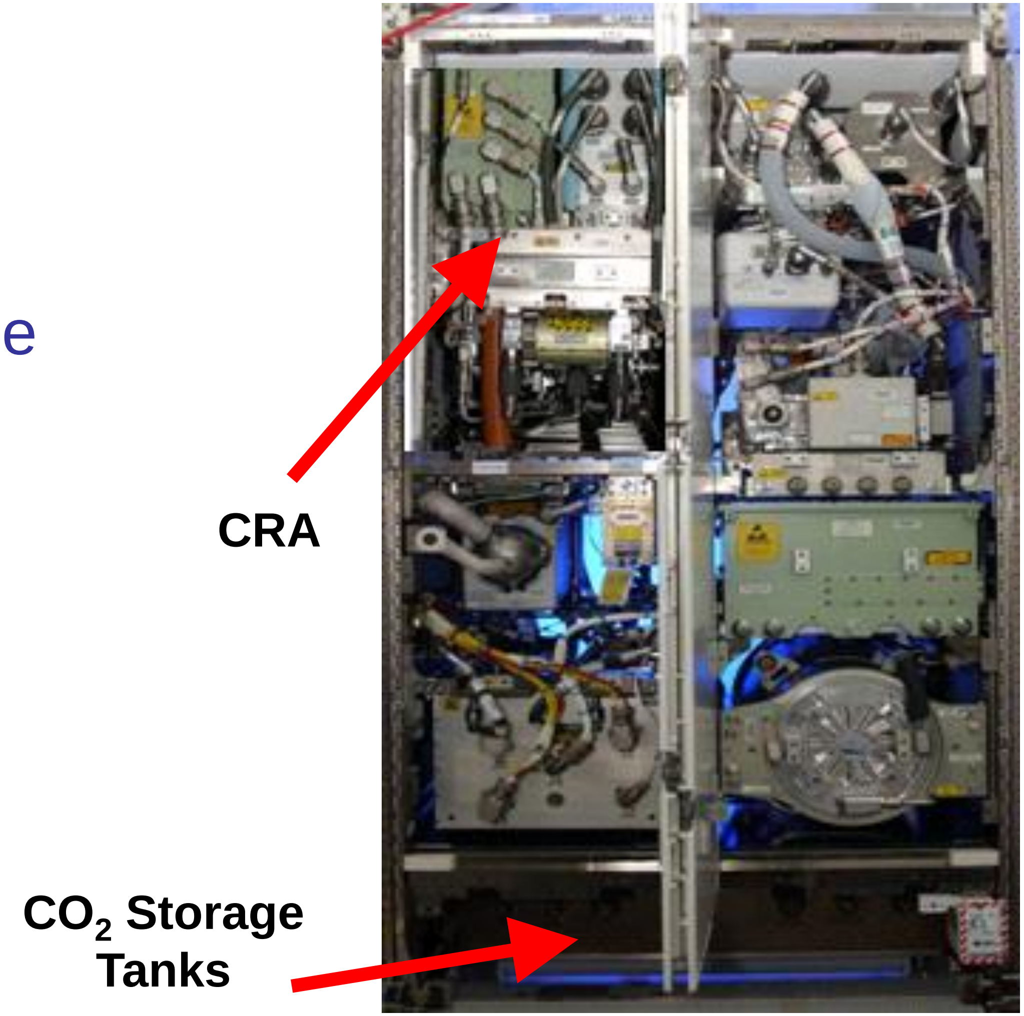
ms

Sabatier won because:

- Lower power
- Smaller system
- No consumables
- Clean process
- Sufficient for low earth orbit

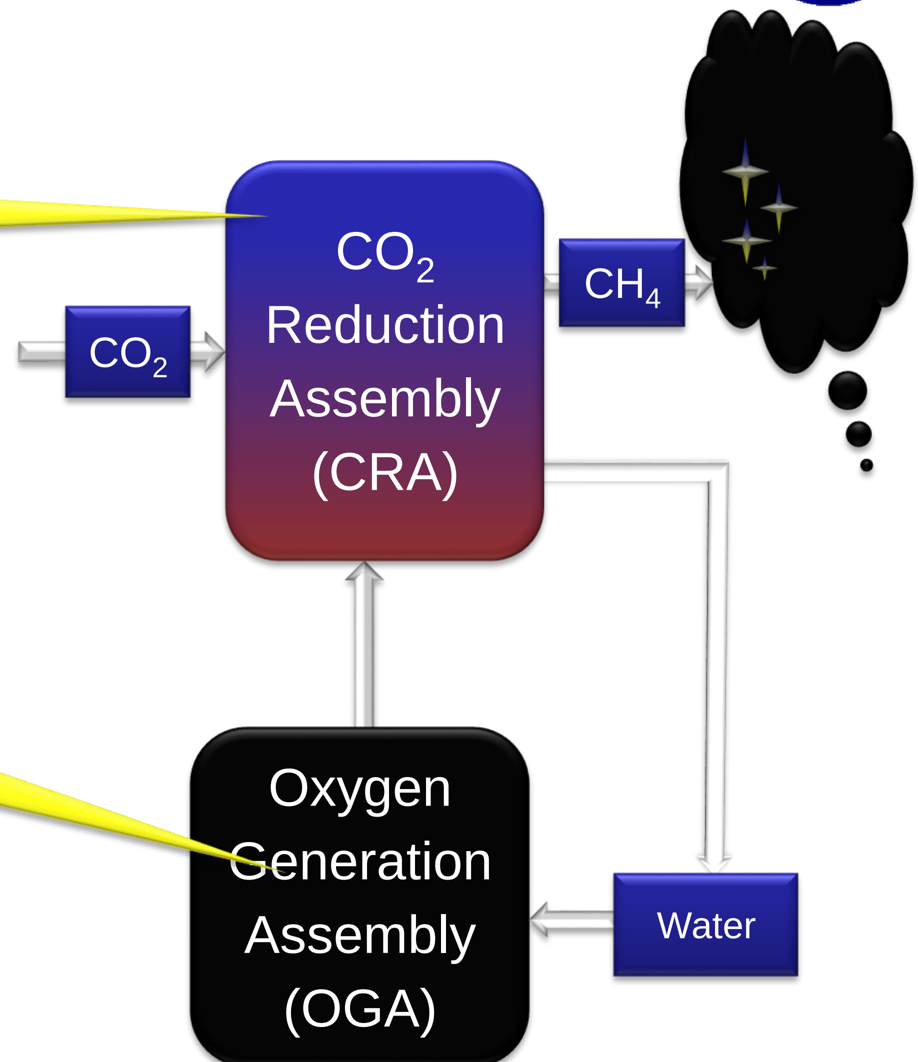
CO_2 Reduction Assembly

- Sabatier Reactor
  - $CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$
- CO_2 Management System provides compressed storage of CO_2 until needed
- OGA provides H_2
- O_2 recovery ~47%



Oxygen Recovery

Net loss of hydrogen must be resupplied as water from Earth



Launch Costs

1lb Water ~ $31,000

1 gallon Water = 8.3 lbs

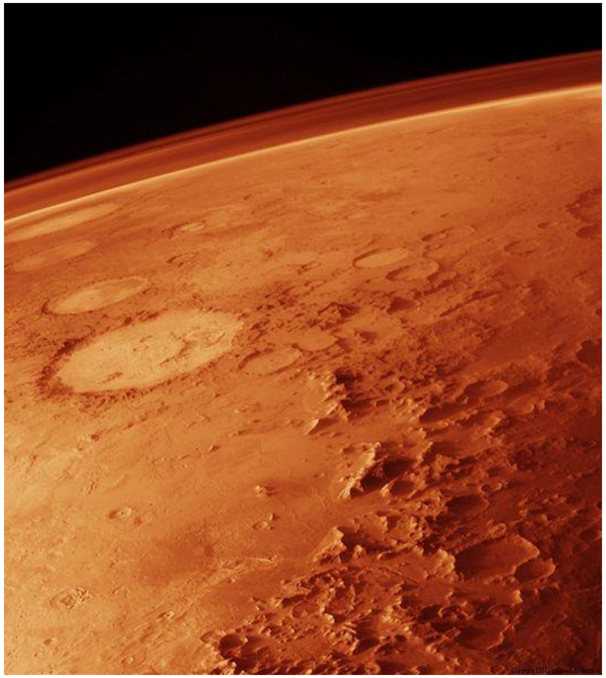
1 gal Water ~ $257,300

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 O_2 Recovery and Recycling with a highly reliable and robust system



Today

- Carboxy (CO_2 Electrolysis)
  - $2CO_2 \leftrightarrow CO + O_2$
- Methoxy (Sabatier)
  - $CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$
- Bosch Process
  - $CO_2 + H_2 \leftrightarrow CO + H_2O$
  - $2CO \leftrightarrow CO_2 + C(s)$
  - $CO + H_2 \leftrightarrow H_2O + C(s)$
- Others

Explored by small businesses and NASA, Significant challenges with materials and separating dissolved CO_2 from liquid

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

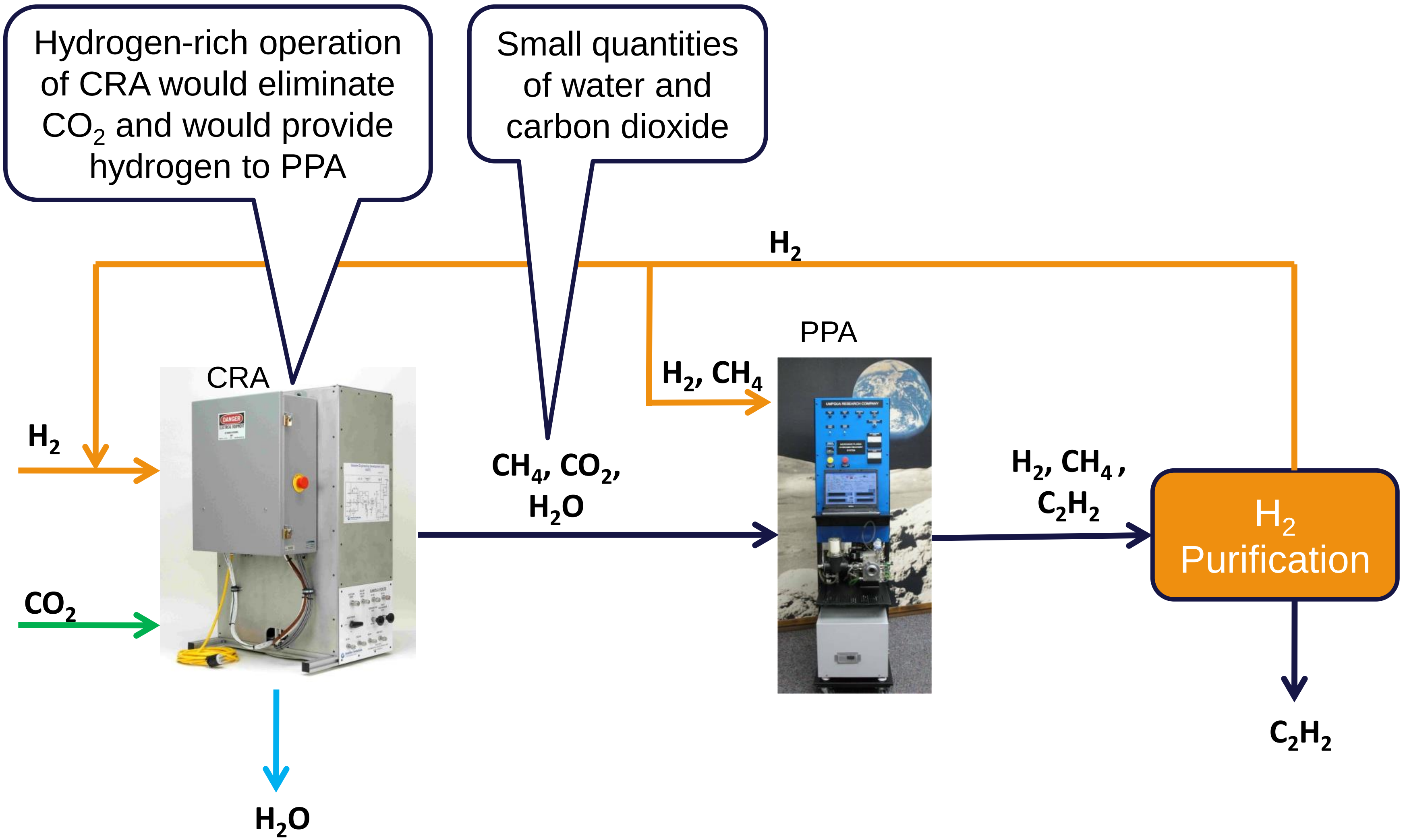
New approach: Series-Bosch. First reactor = CO formation. Second reactor = C formation

E.g. Ionic Liquids

Sabatier Reactor (SOA)

- Sabatier Reaction: $CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$
- 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



Methane Post-Processing

- Plasma Pyrolysis Assembly
  - Plasma generated by microwaves
  - $2CH_4 \rightarrow 3H_2 + C_2H_2$
  - 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

Bosch Technology

- Chemistry

RWGS:

$$CO_2 + H_2 \rightarrow H_2O + CO$$

Carbon Formation:

$$\begin{cases} 2CO \rightarrow CO_2 + C(s) \\ CO + H_2 \rightarrow H_2O + C(s) \end{cases}$$

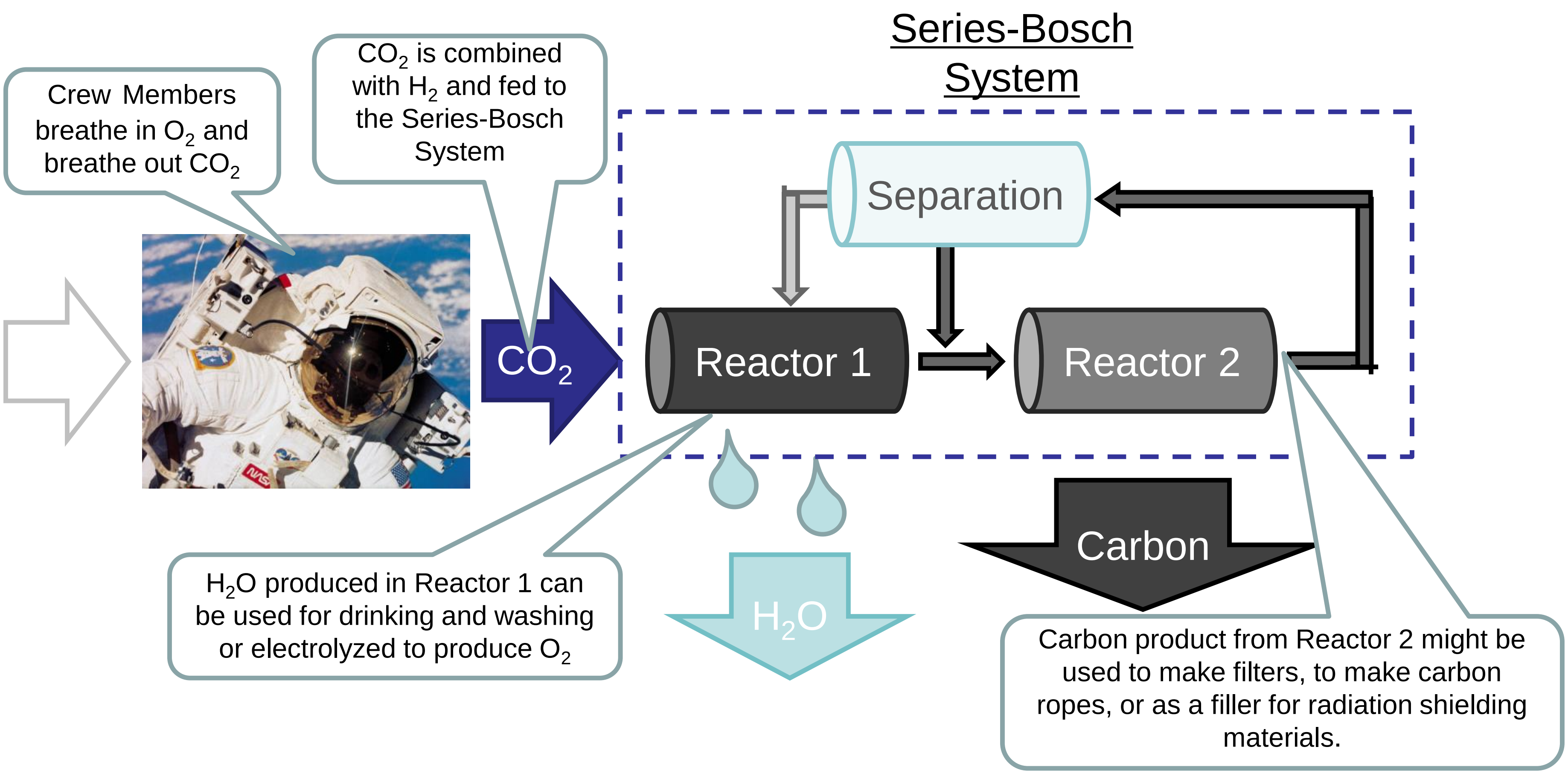
$$CO_2 + 2H_2 \rightarrow 2H_2O + C(s)$$

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

1980's Bosch System

Bosch Technology

- Bosch Process



Questions?

Trace Contaminant Control

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

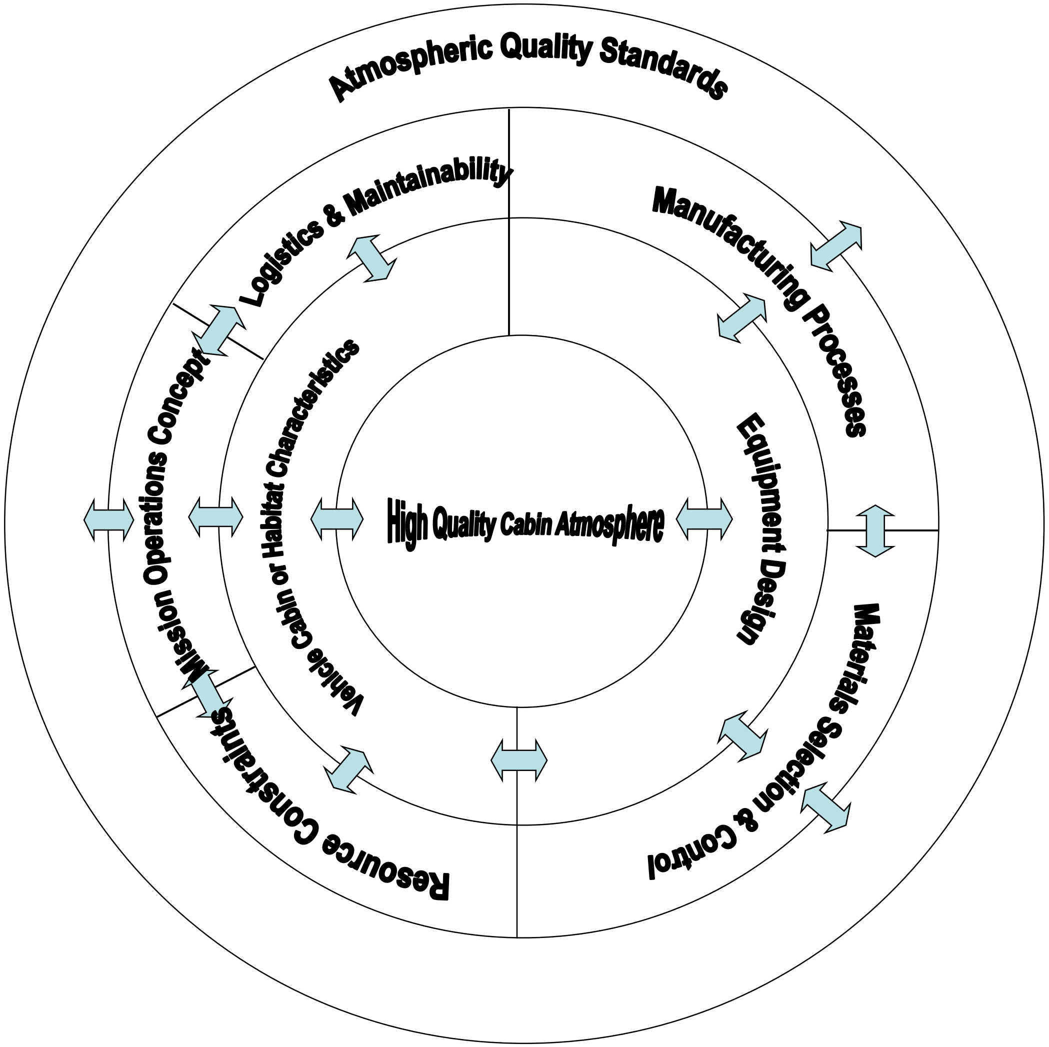
Background

- 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



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

Spacecraft Cabin Atmospheric Quality

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 m^3 Air/Day/Person

Combined Loads & Control Processes

- **Crew Transfer and Cargo Vehicle Docking**
- **Adsorption/Desorption from Surfaces**

Trace Contaminant Control Design Point

- 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

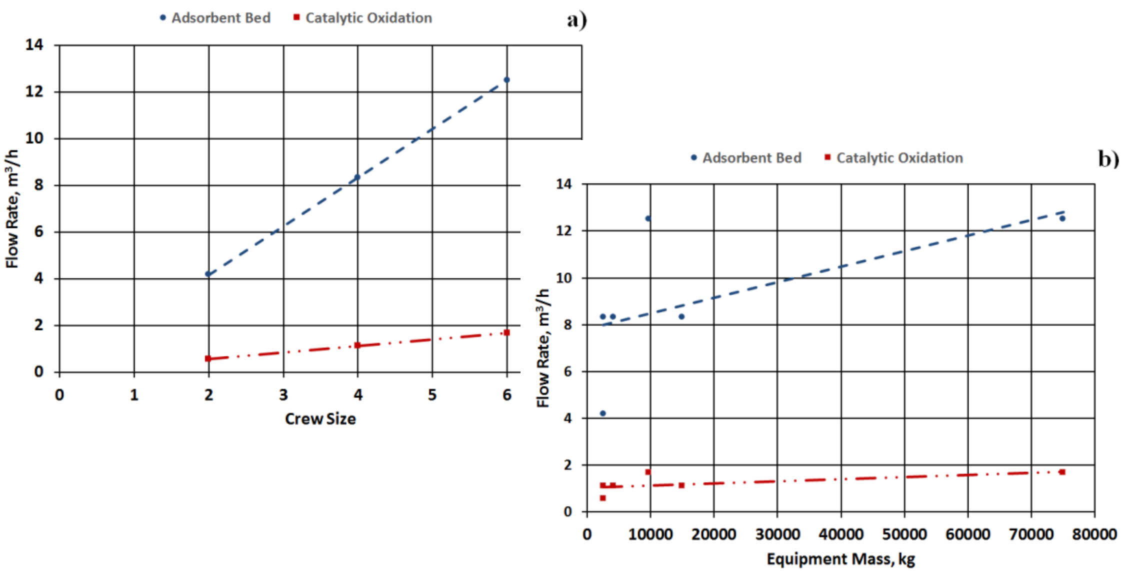
CONTAMINANT NAME		GENERATION RATE[b]	
IUPAC	COMMON	OFFGASSING (mg/day-kg)[a]	METABOLIC (mg/day-person)
Methanol	Methyl alcohol	1.3×10^{-3}	0.9
Ethanol	Ethyl alcohol	7.8×10^{-3}	4.3
n-butanol	Butyl alcohol	4.7×10^{-3}	0.5
Methanal	Formaldehyde	4.4×10^{-6}	0.4
Ethanal	Acetaldehyde	1.1×10^{-4}	0.6
Benzene	Benzol	2.5×10^{-5}	2.2
Methylbenzene	Toluene	2×10^{-3}	0.6
Dimethylbenzenes	Xylenes	3.7×10^{-3}	0.2
Furan	Divinylene oxide	1.8×10^{-6}	0.3
Dichloromethane	Methylene chloride	2.2×10^{-3}	0.09
2-propanone	Acetone	3.6×10^{-3}	19
Trimethylsilanol	Trimethyhydroxysilane	1.7×10^{-4}	0
Hexamethylcyclotrisiloxane	D3 siloxane	1.7×10^{-4}	0
Azane	Ammonia	8.5×10^{-5}	50
Carbon monoxide	Carbonous oxide	2×10^{-3}	18
Hydrogen	Dihydrogen	5.9×10^{-6}	42
Methane	Carbane	6.4×10^{-4}	329

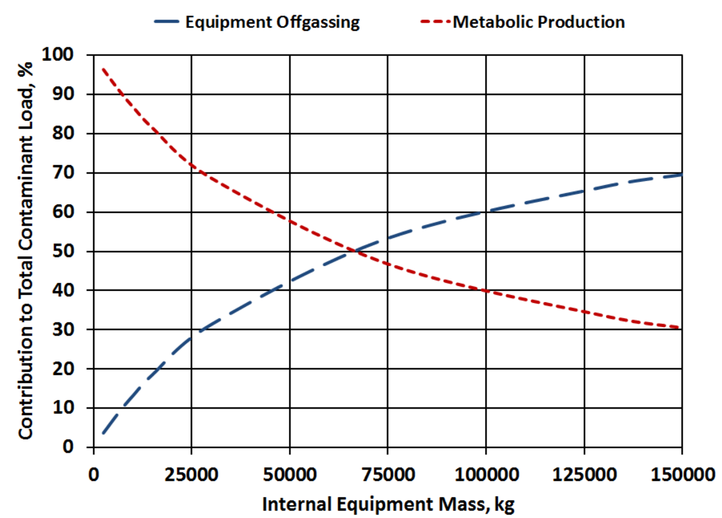
a. Offgassing rate is for the mass of internal, non-structural equipment.
b. Offgassing and metabolic sources may be supplemented by system sources as they are identified.

Perry, J.L., "A Design Basis for Spacecraft Cabin Trace Contaminant Control, SAE 2009-01-2592, *SAE 39th International Conference on Environmental Systems*, Savannah, Georgia, 2009.

Crew and Vehicle Size Considerations

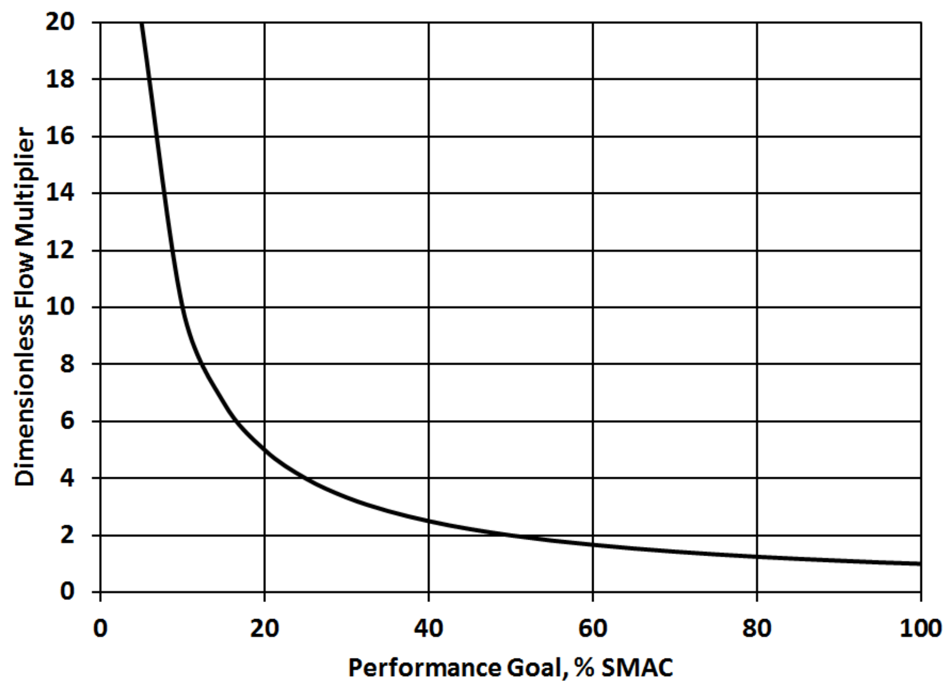
- TCC design-driving compounds are primarily from crew metabolic sources
  - Four compounds account for 94% of the crew metabolic load
  - Ammonia is the most significant design driver
  - Formaldehyde is a secondary design driver
  - Methane, carbon monoxide, and dichloromethane are tertiary design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



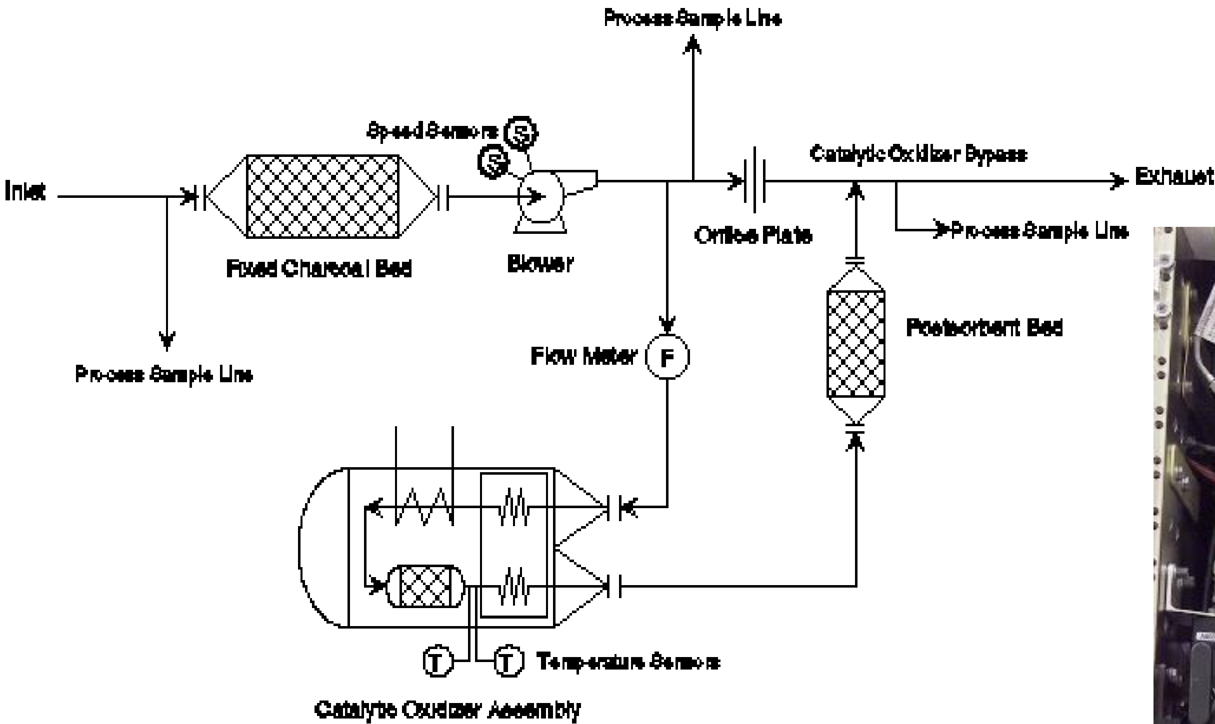


TCC Equipment Performance Goal

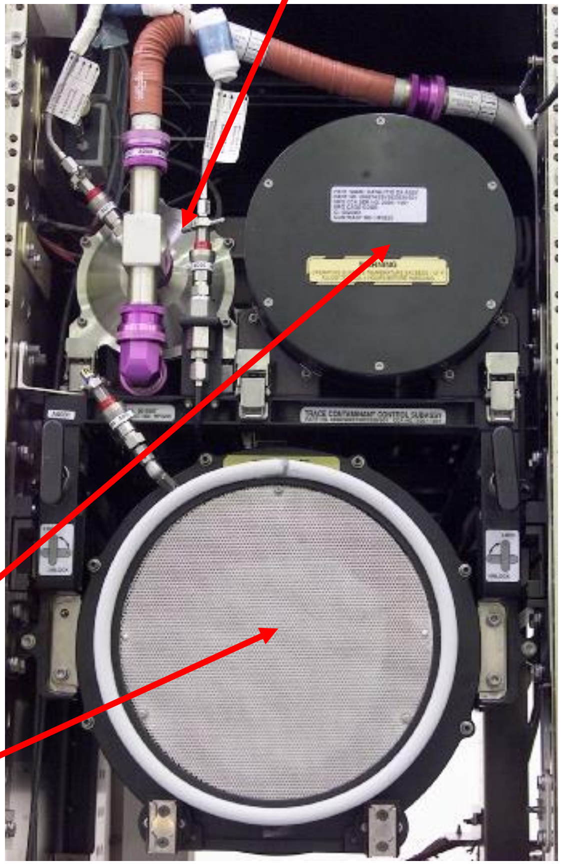
- Performance goal is the percentage of the individual compound SMAC
  - Usually 50% SMAC with 10% to 20% functional margin
  - Achieves <40% SMAC
- Performance goal impacts on TCC equipment design
  - Flow rate impacts
  - Component mass and volume impacts
  - Pressure drop and power impacts
- Performance 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

Predicting Cabin Air Quality

- 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

$$dC_i/dt = r_i/V - (C_i/V)\sum \eta_j \nu_j$$

  - Calculate toxic hazard index

$$T = \sum C_i/C_{s,i}$$

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.

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Particulate Matter Design Considerations

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

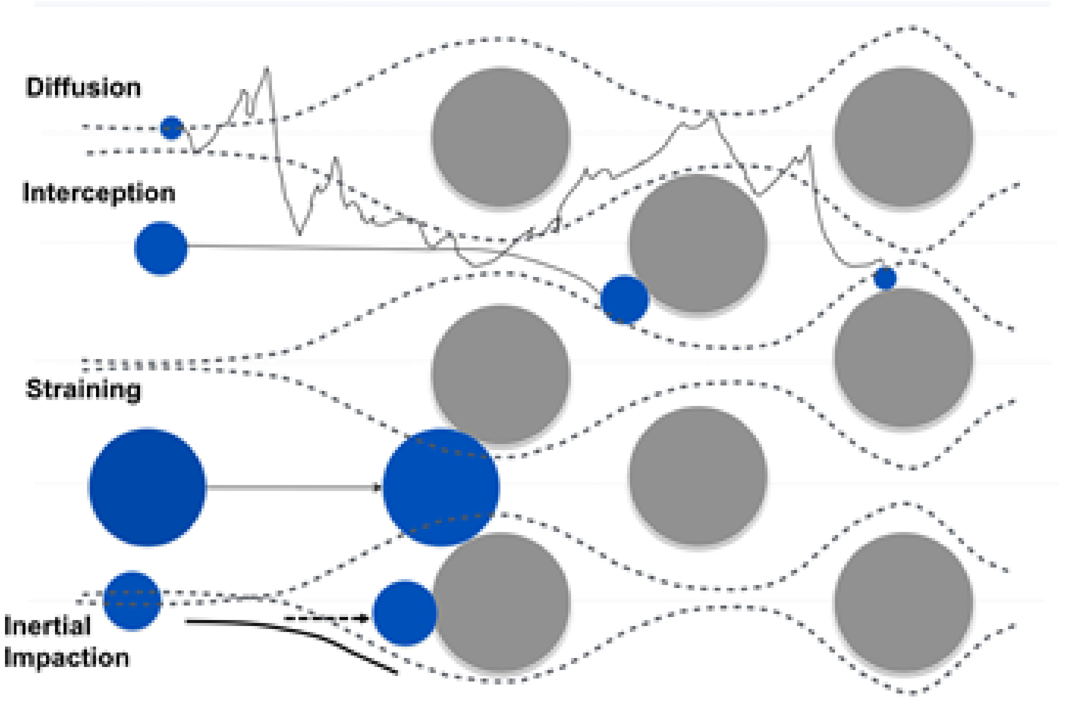
The Particulate Matter Challenge

- Many sources
  - Fabrics - lint
  - Crew – skin & hair
  - Food debris
  - Activities – paper, plastic, miscellaneous debris
  - Surface dust intrusion
- Standards
  - 3 mg/m^3 for <100 µm
  - 0.3 mg/m^3 for <10 µm

Defining the Load for Design

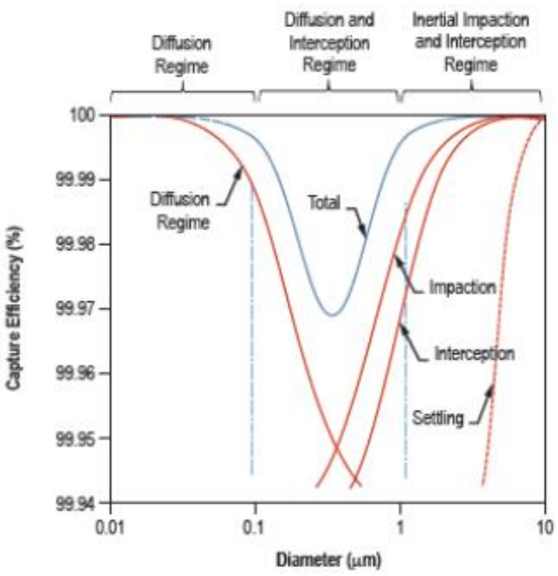
- Basic load
  - 95 wt% >500 µm
  - Fraction <500 µm
    - 2 wt% <100 µm
    - 0.6 – 1.6 mg/CM-minute
- Surface dust load
  - 227 grams dust/CM-EVA
  - Fraction <10 µm remains suspended (7 wt% of total)
  - 15.9 grams/CM-EVA or 7X the basic daily load
- Dust intrusion barriers need to be >99% effective

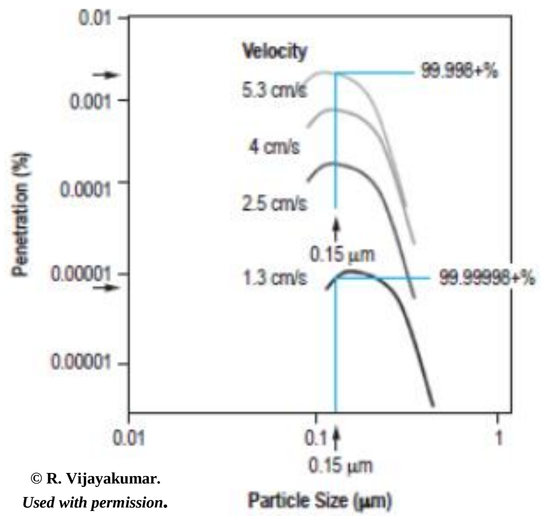
- Particle capturing mechanisms
  - Diffusion
  - Interception
  - Straining
  - Inertial impaction



$$E_T = 1-(1-E_I)(1-E_D)(1-E_R)(1-E_{DR})(1-E_G)$$

- 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





Filtration Design Considerations 3

- 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

TECHNOLOGY	BENEFITS	DISADVANTAGES
Media Filtration	• Low to very high efficiency • Very broad size range from nanometers to 10's of microns	• Challenges under high dust loading conditions requiring pre-filtration and filter logistics management to provide good capacity • Regeneration possible but complicated
Cyclone separation	• Size range limited to particles larger than a few microns • Large holding capacity • Can handle large particle concentrations • Regenerable	• Large pressure drop • Requires flow cessation for regeneration • Emptying the particulate collection receiver
Inertial Impaction	• Large holding capacity • Can handle large particle concentrations • Particulate capture in scroll reduces handling by crew during maintenance • Regenerable	• Large pressure drop for small particle size • Requires flow cessation for regeneration • Scroll mechanism introduces complexity
Electrostatic Precipitation	• Effective for capturing small particles • Regenerable	• Complexity • Power consumption • Ozone generation
Hybrid media and packed bed filtration	• Primarily for gaseous contaminant removal • Can offer some particle pre-filtration	• Complexity and compatibility • Requires particulate matter pre-filters

Conclusion

- 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

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Introduction to the ISS Water Recovery

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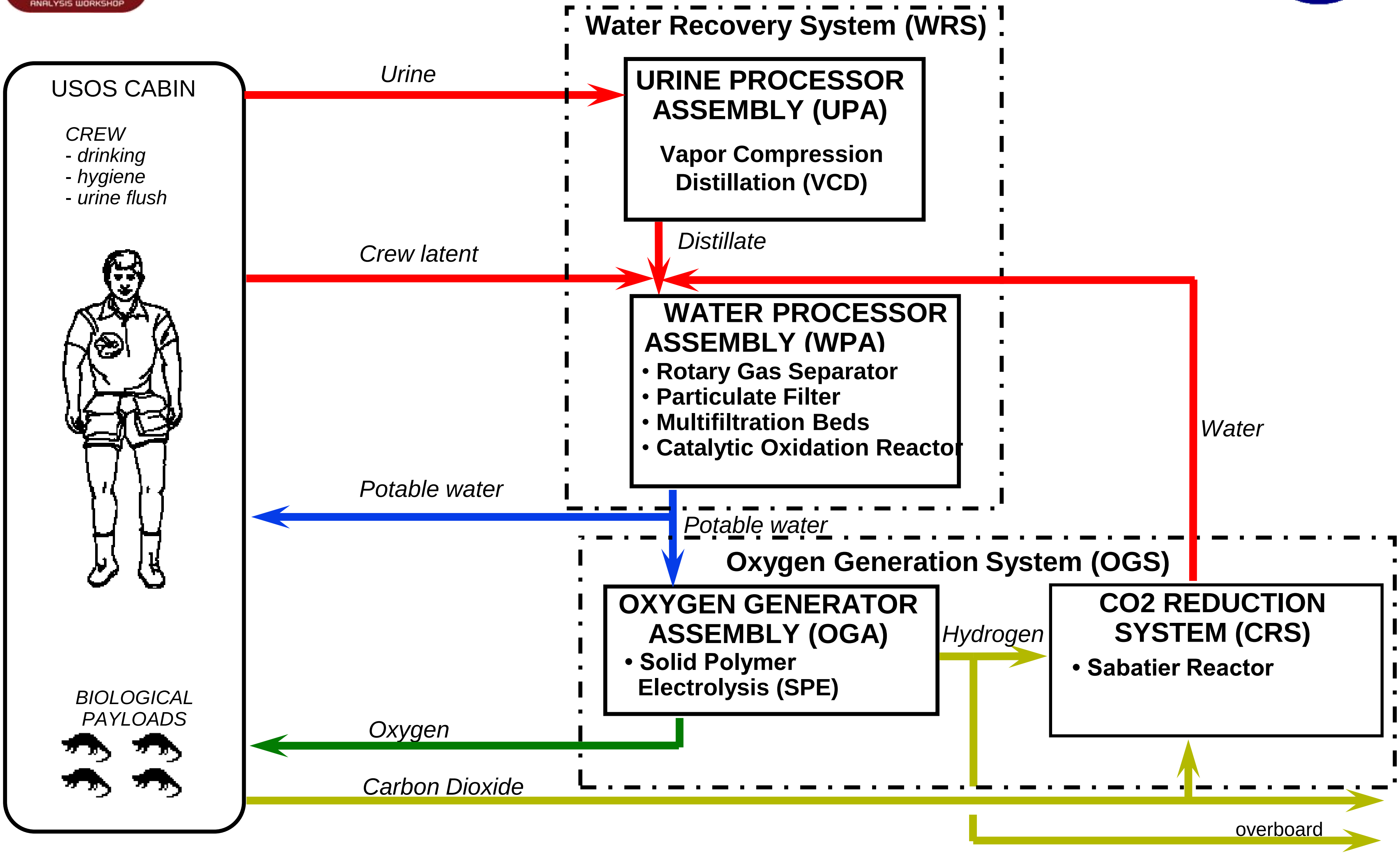
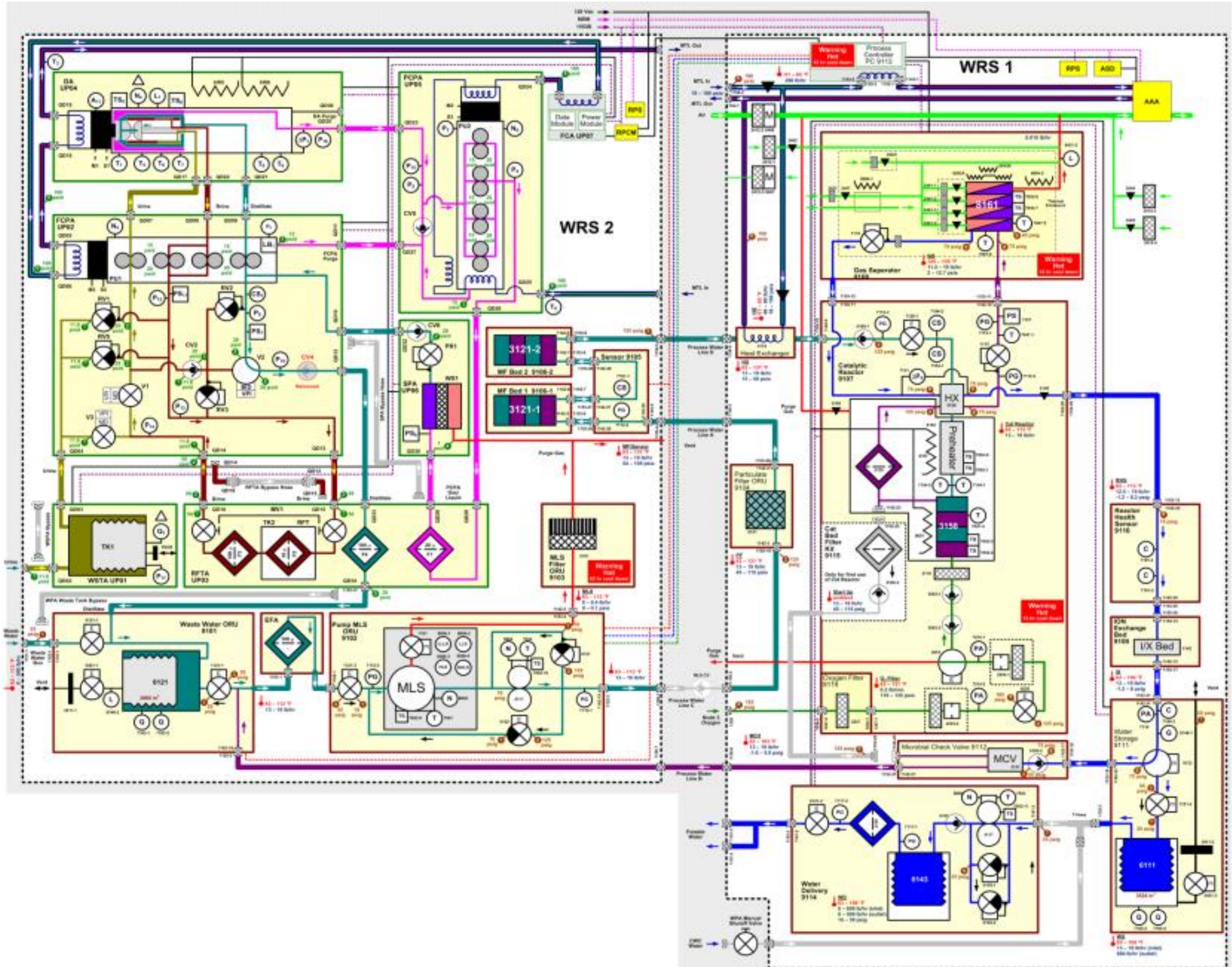
WRS & OGS Architecture Overview

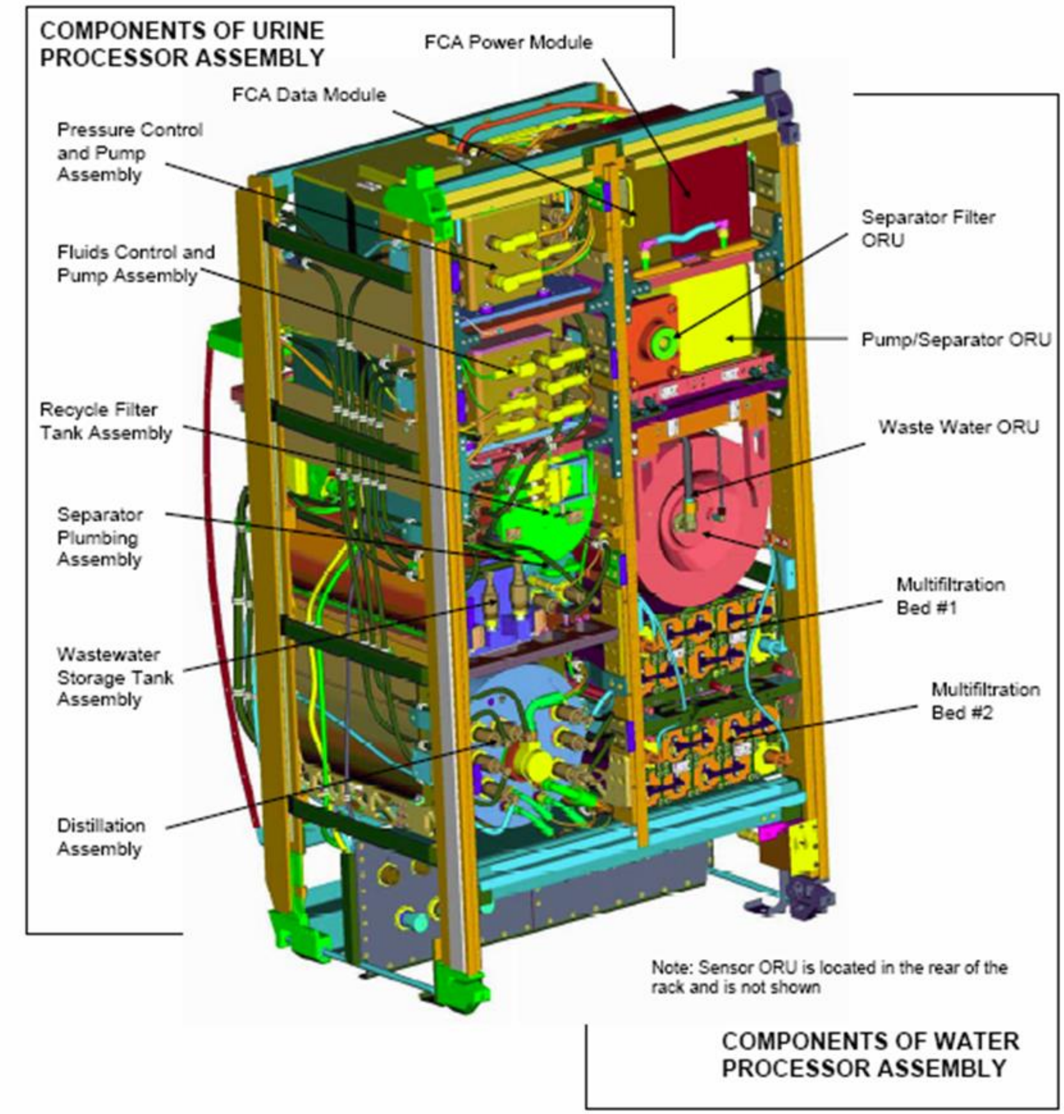


WRS Schematic



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

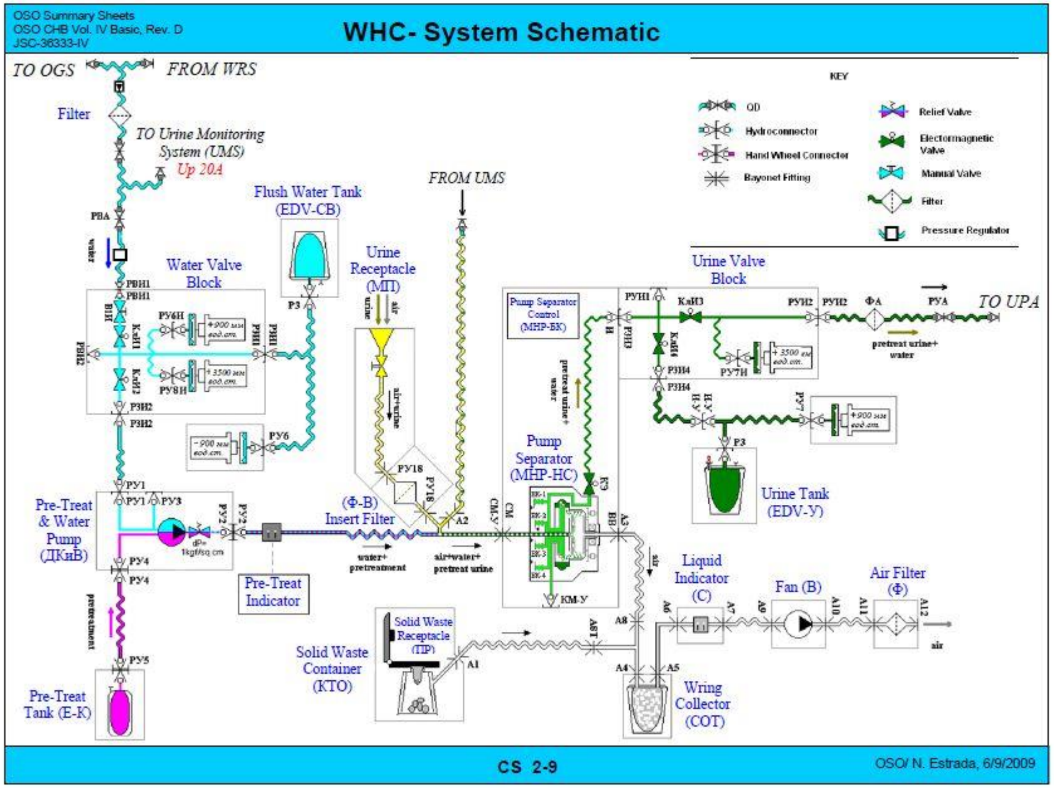
$68,255,000

If UPA returns to 6 crew and 85% per year

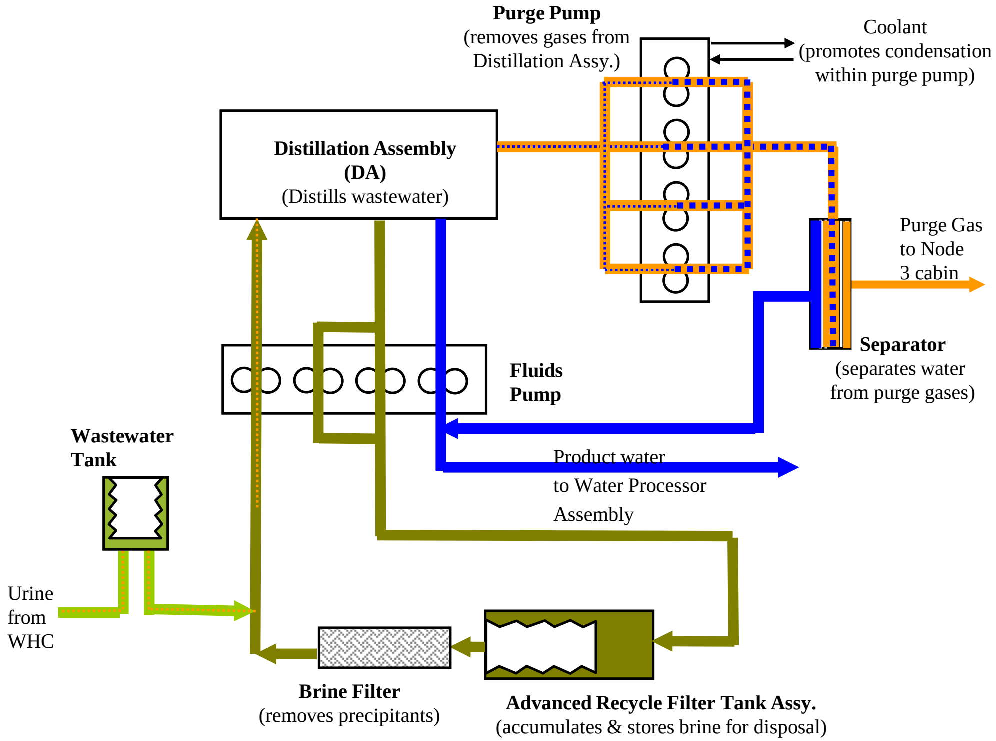
$154,798,000

Disclaimer: Old data, but gives an idea of impact

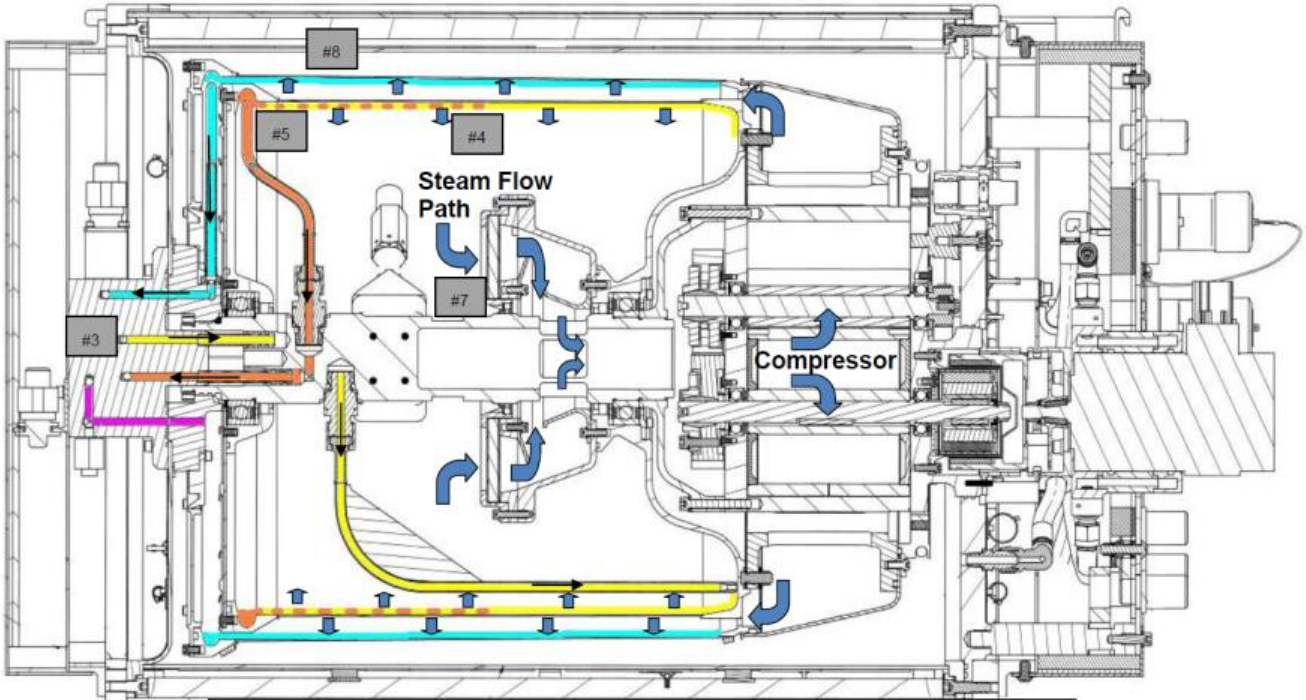
Waste and Hygiene Compartment (Space Potty)



Urine Processor Assembly Simplified Schematic

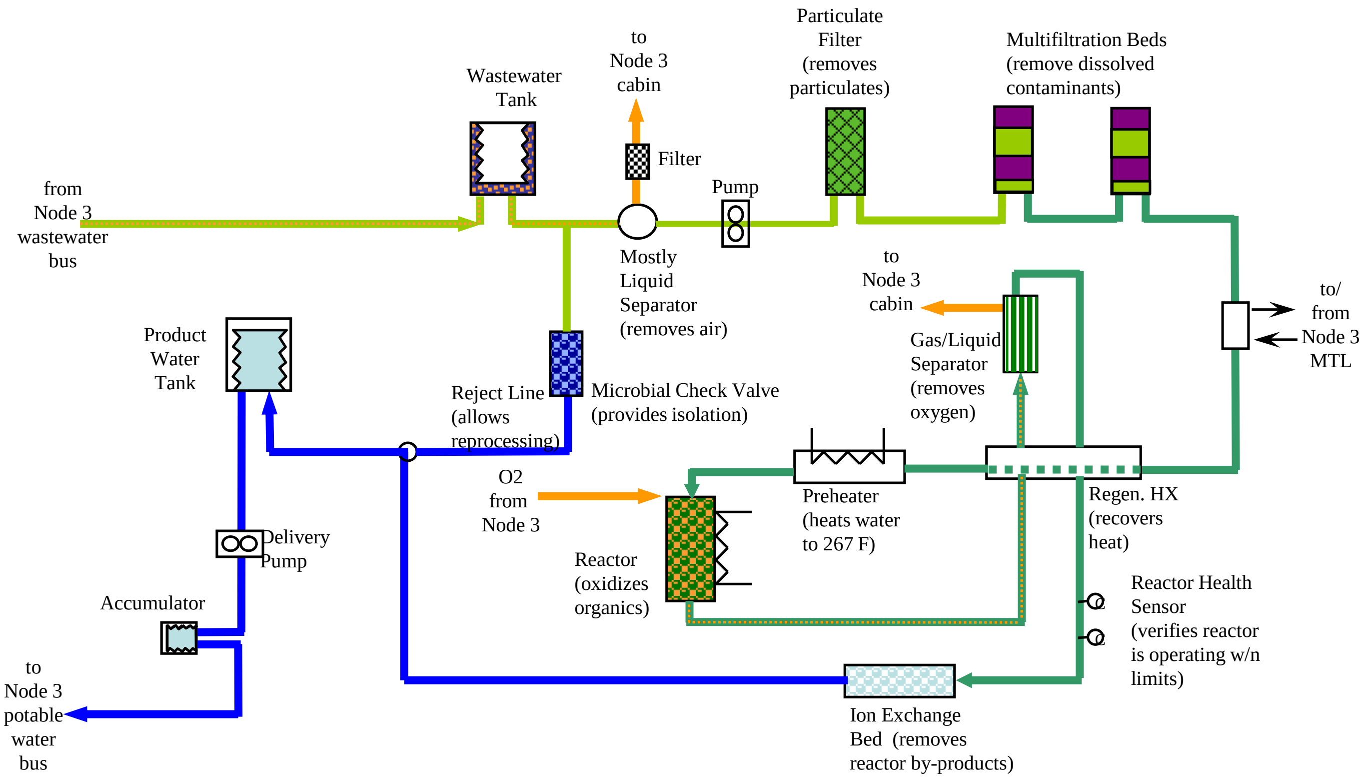


Detail View of Distillation Assembly



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

Water Processor Simplified Schematic



Introduction to the ISS Urine Processor

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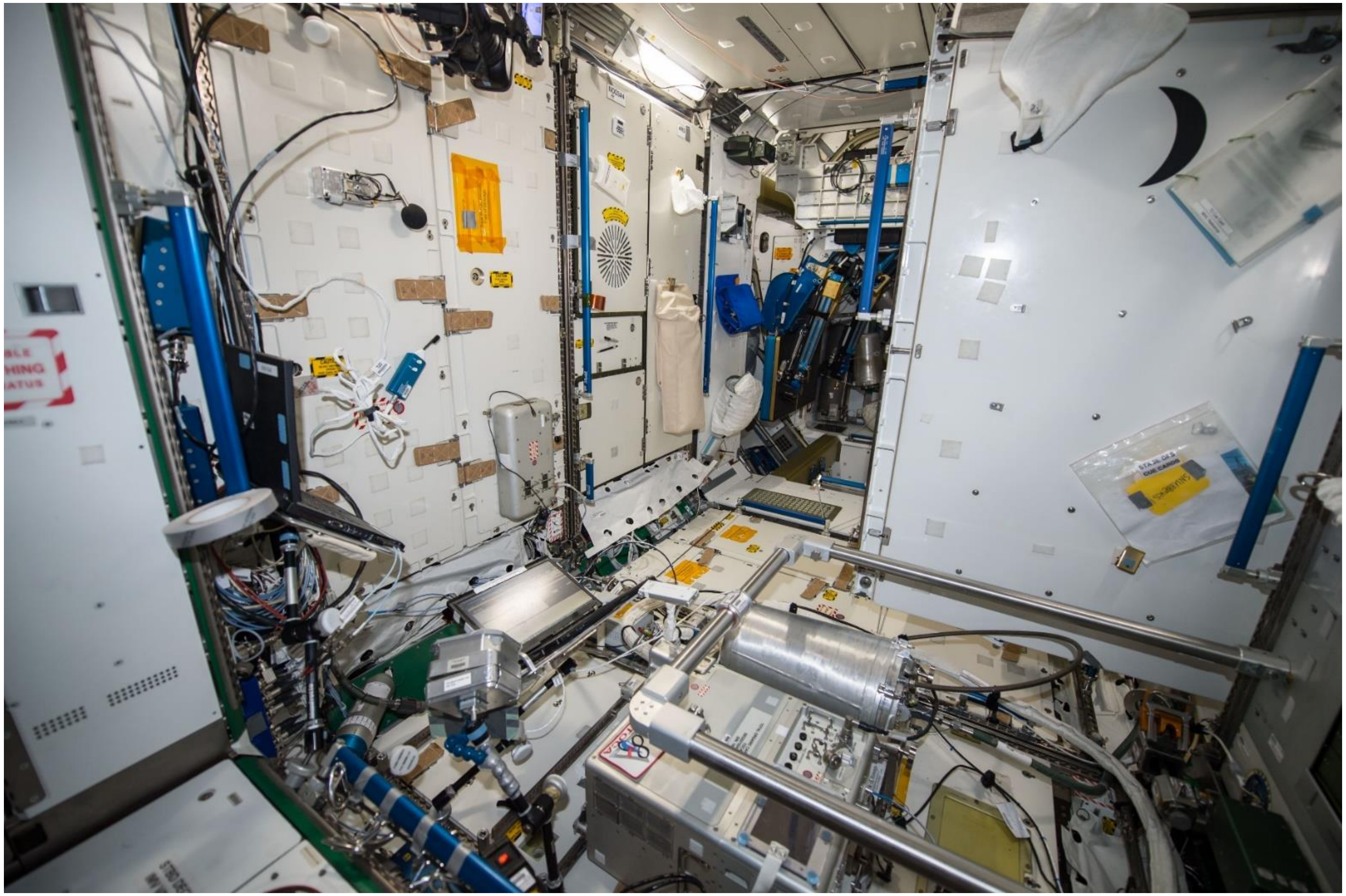
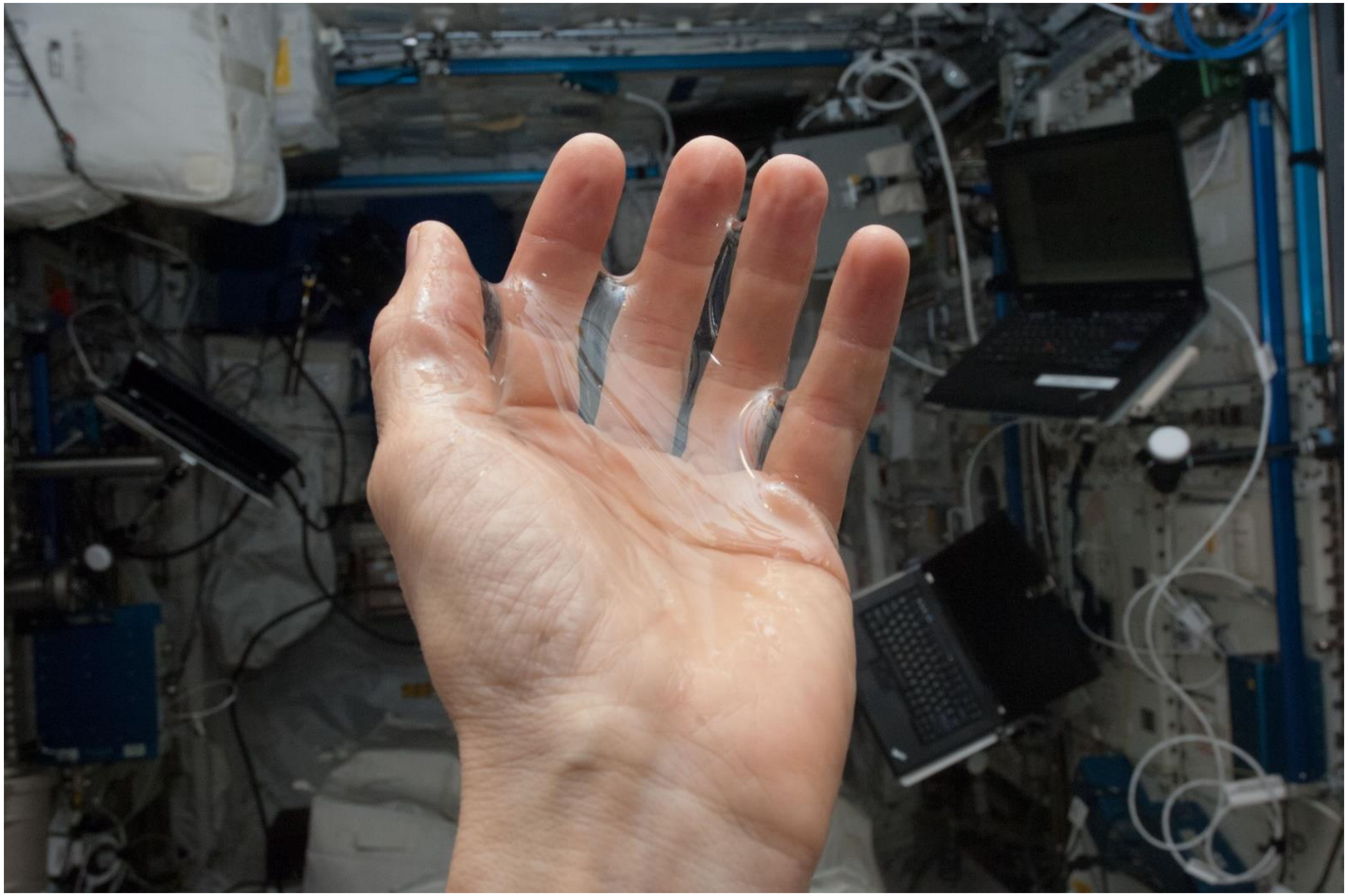
EDV STORAGE

WHC on ISS -1



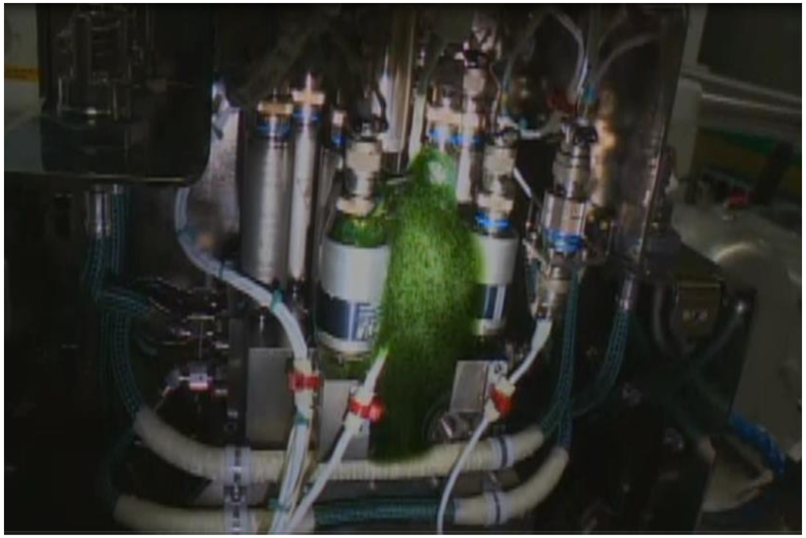
WHC on ISS -2

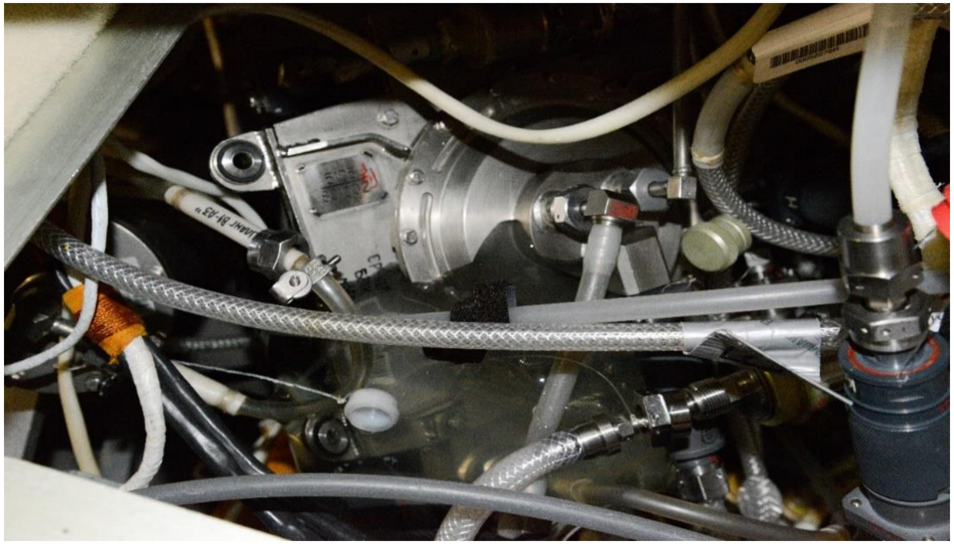
Fluid In μG



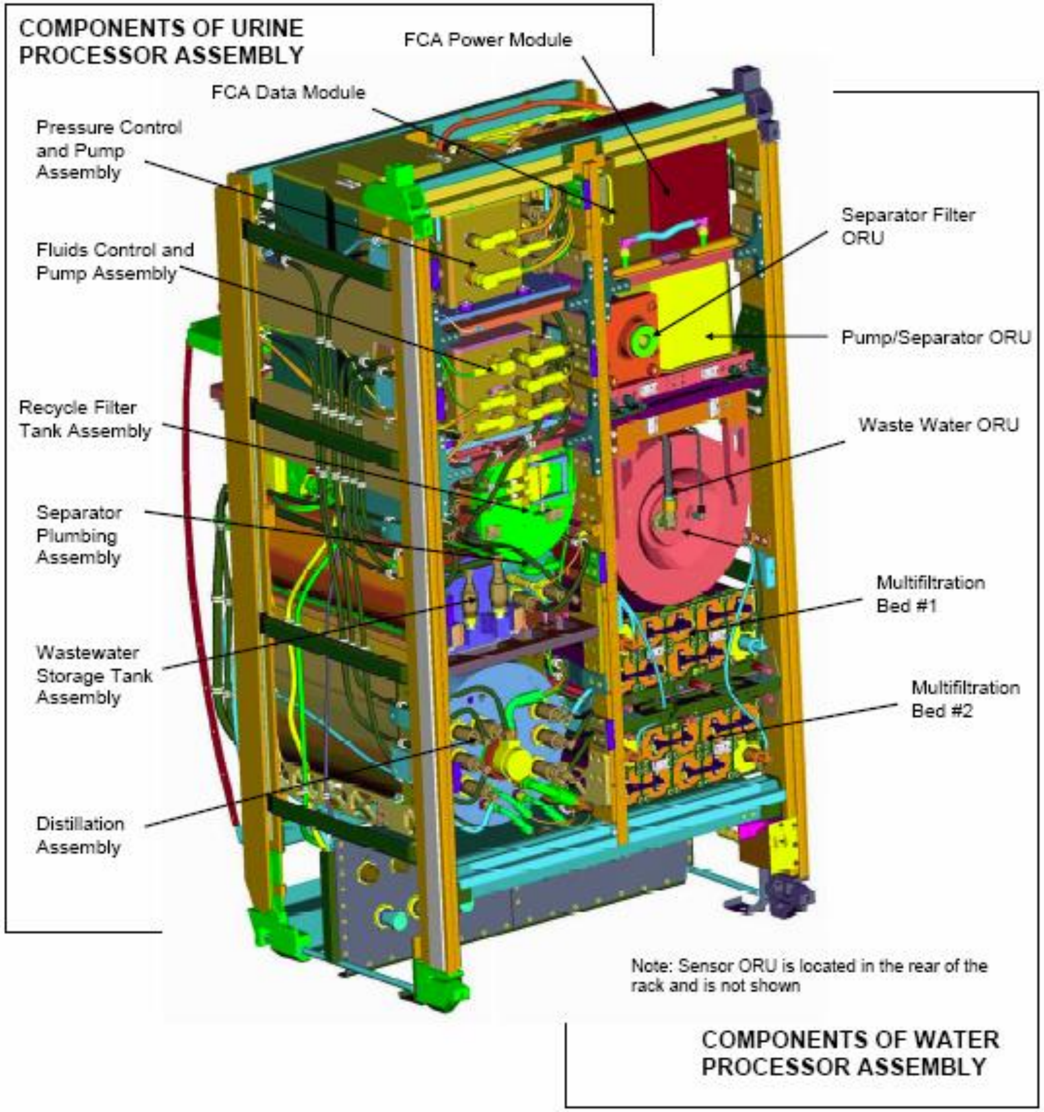
Fluid In μG

Fluid In μG





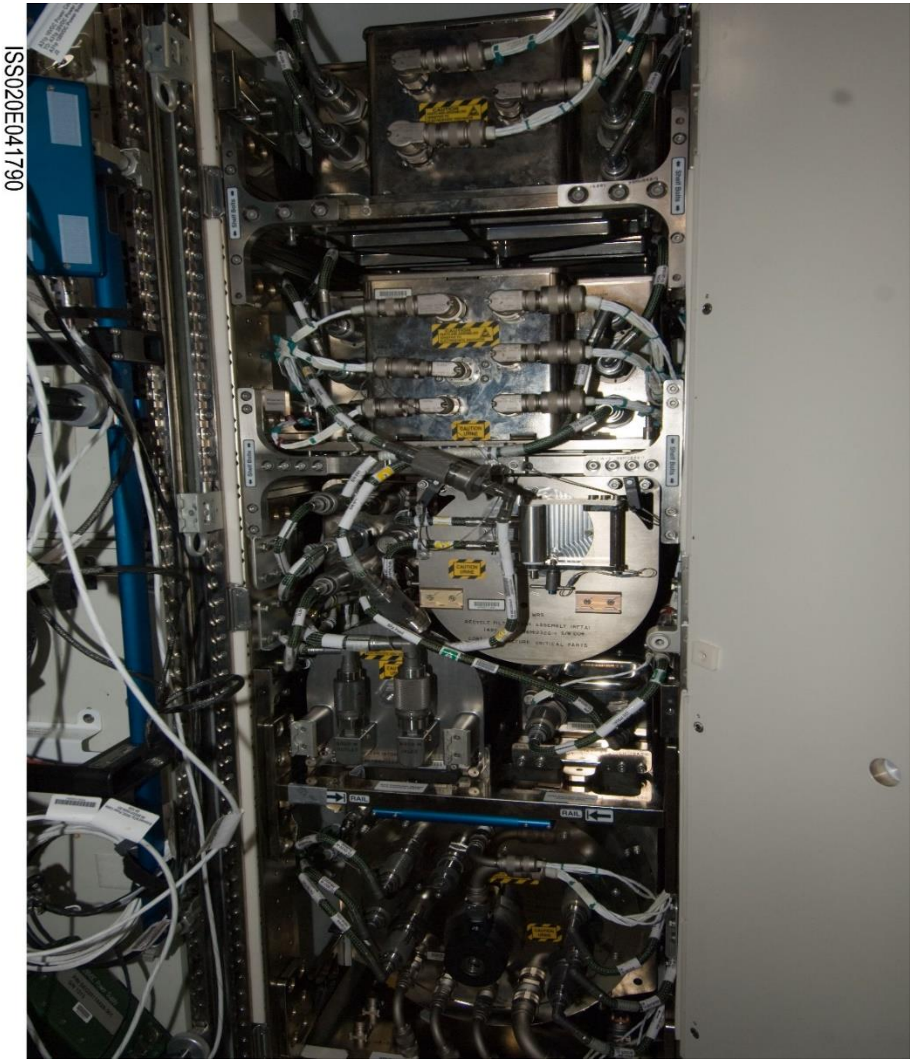
UPA in WRS2 Rack



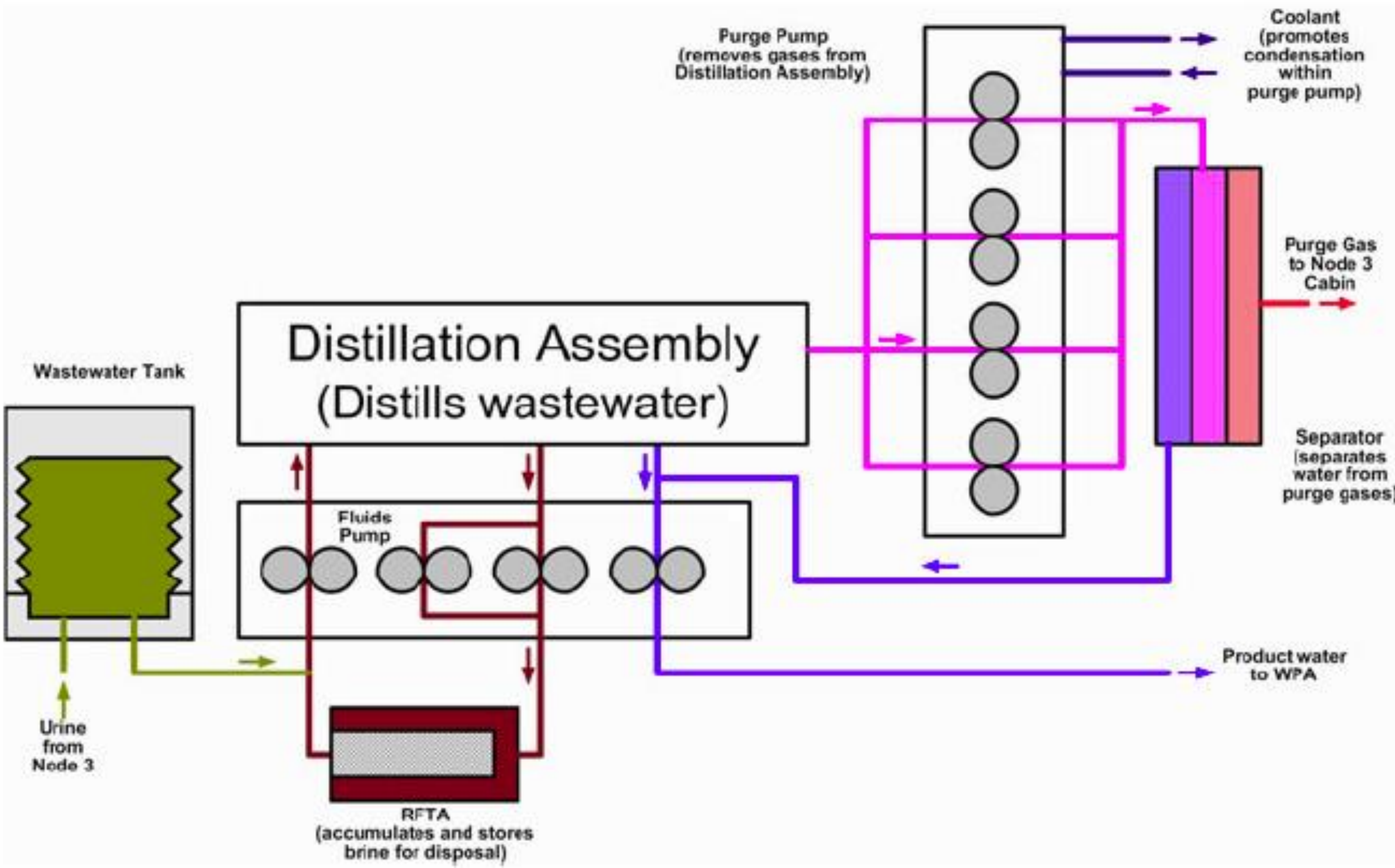
UPA in WRS2 Rack

UPA On-Orbit

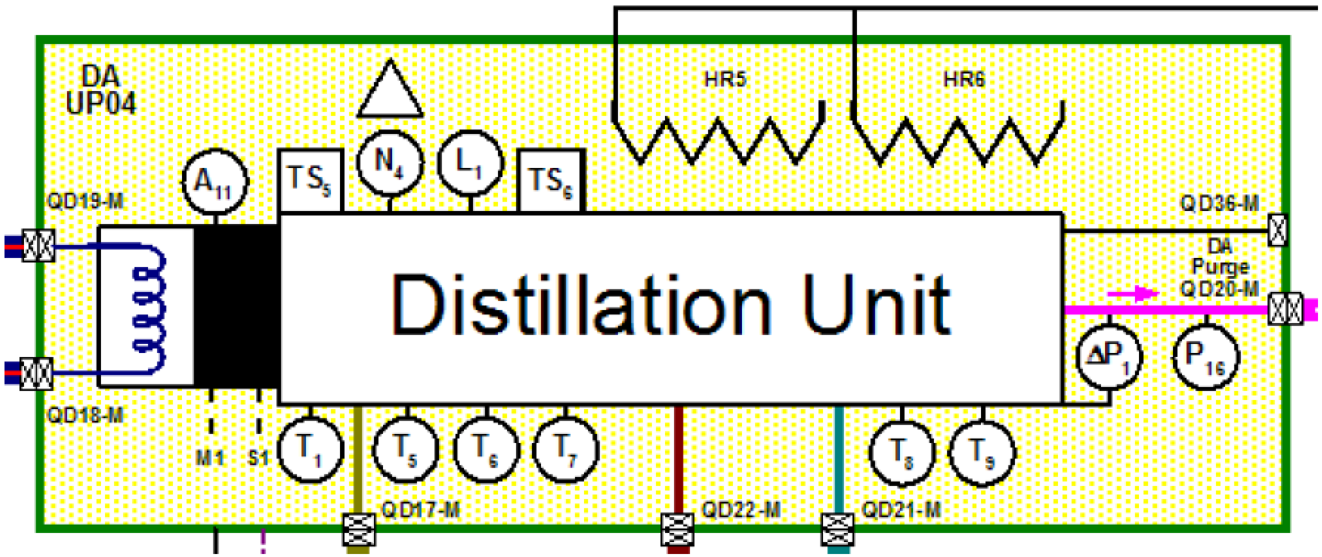
ISS020E041790

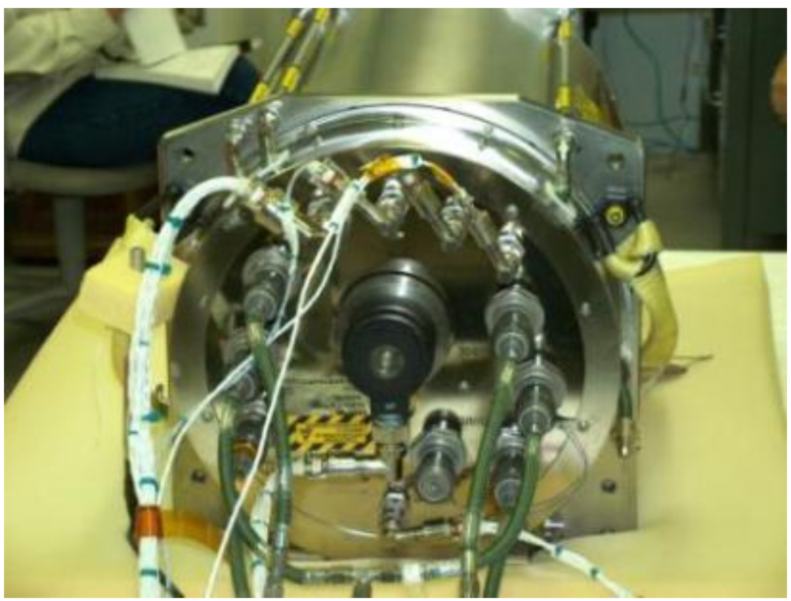


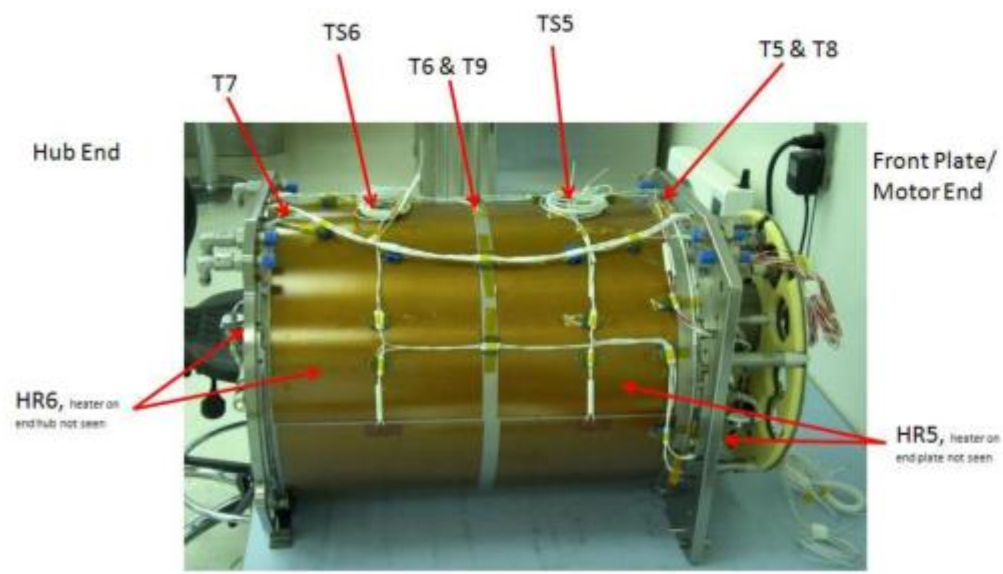
UPA Simplified Schematic



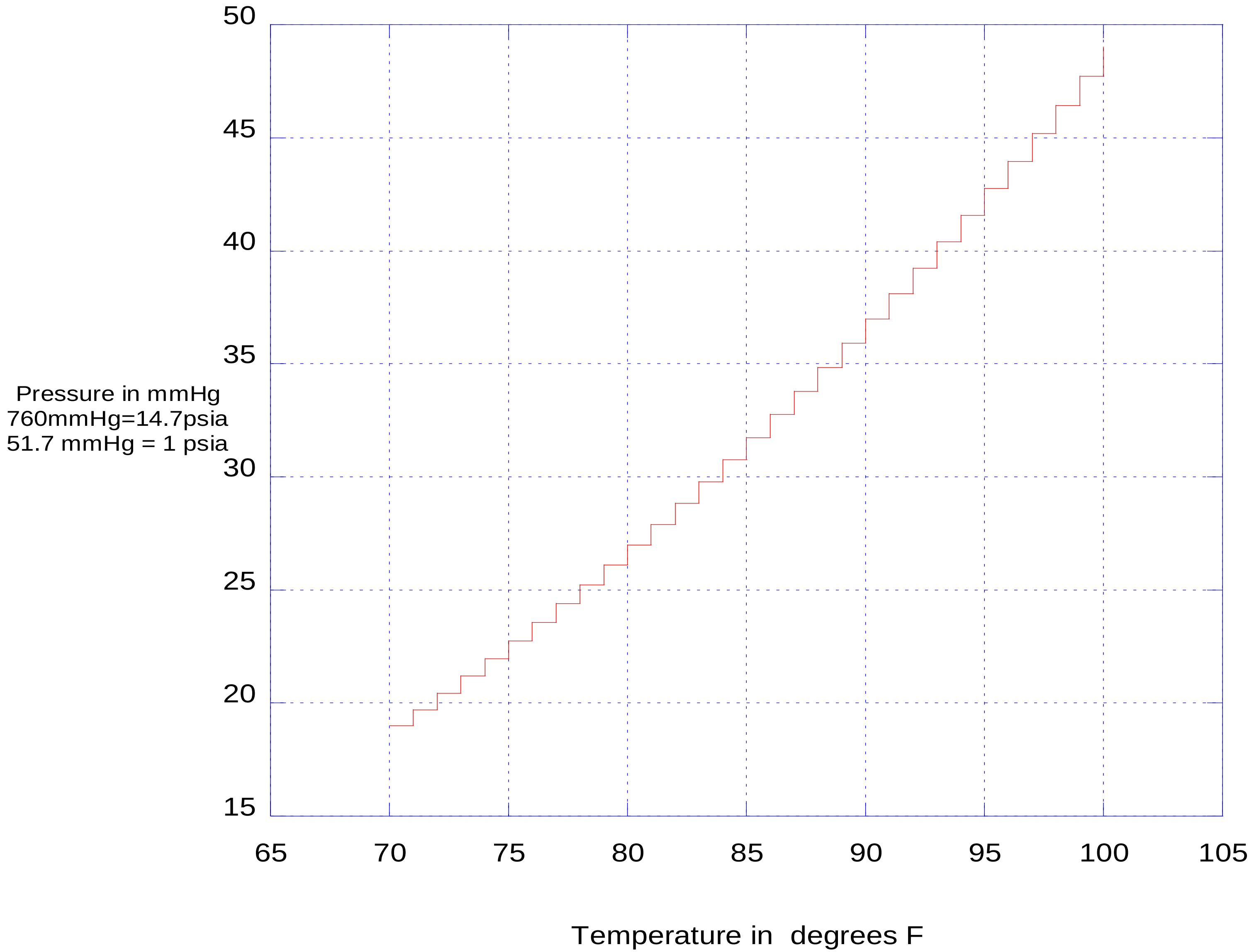
Distillation Assembly



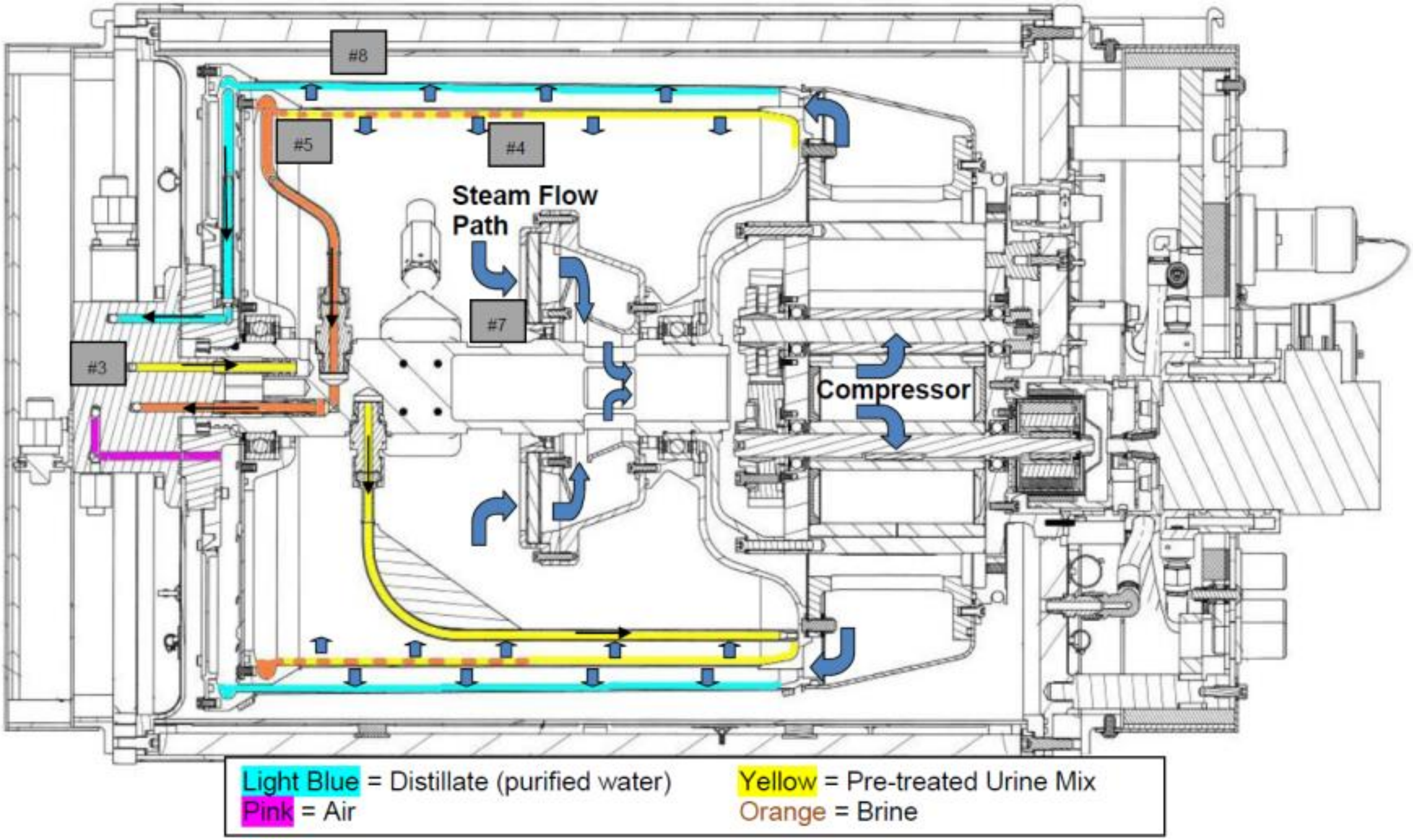




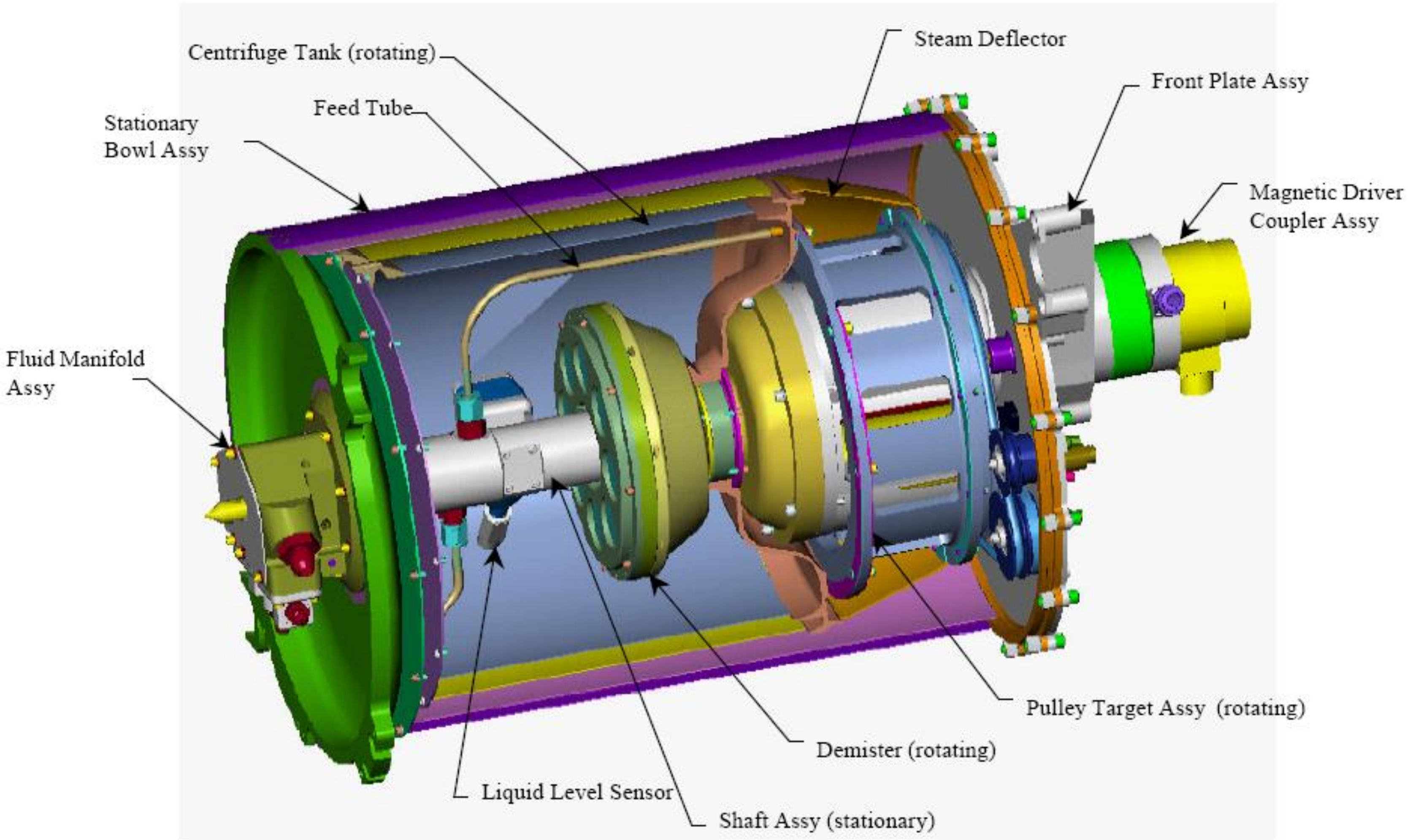
Water Vapor Pressure Curve



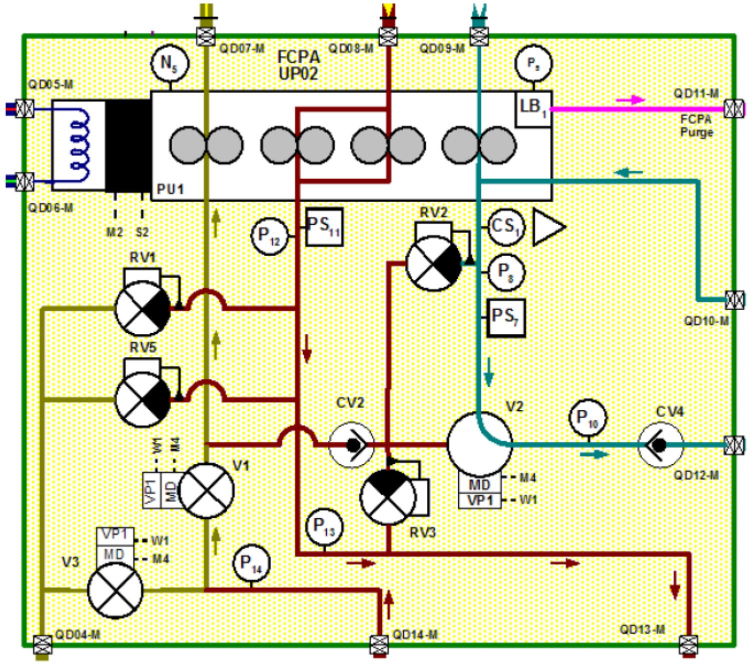
Detail View of Distillation Assembly

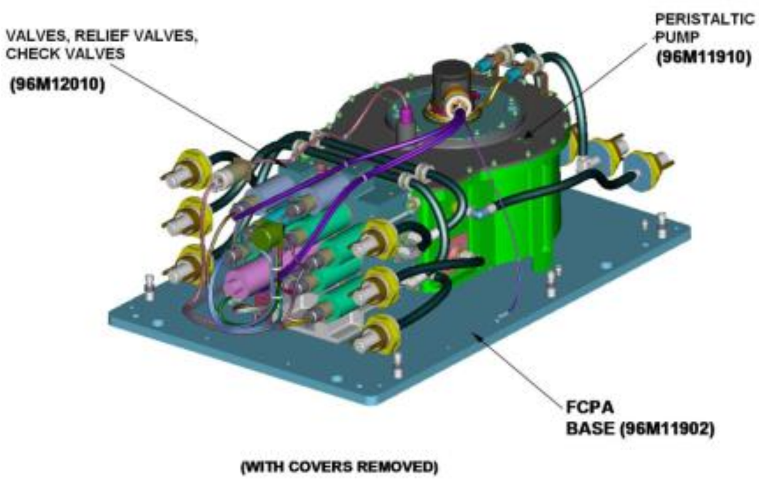


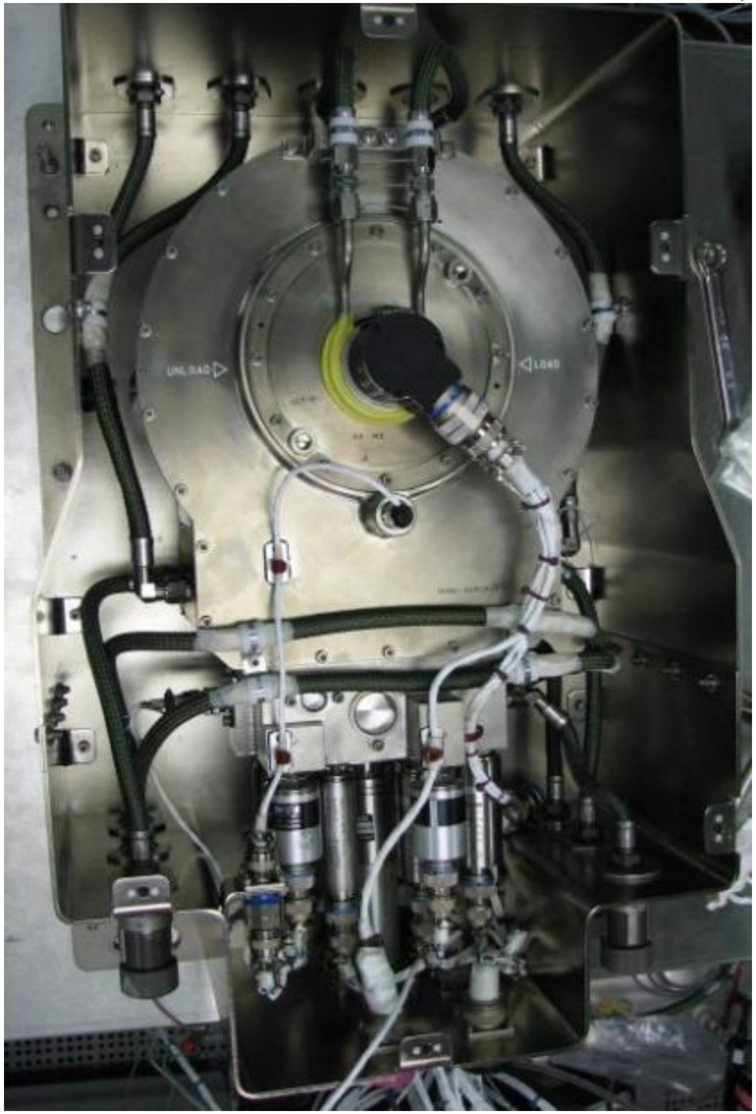
Detail View of Distillation Assembly



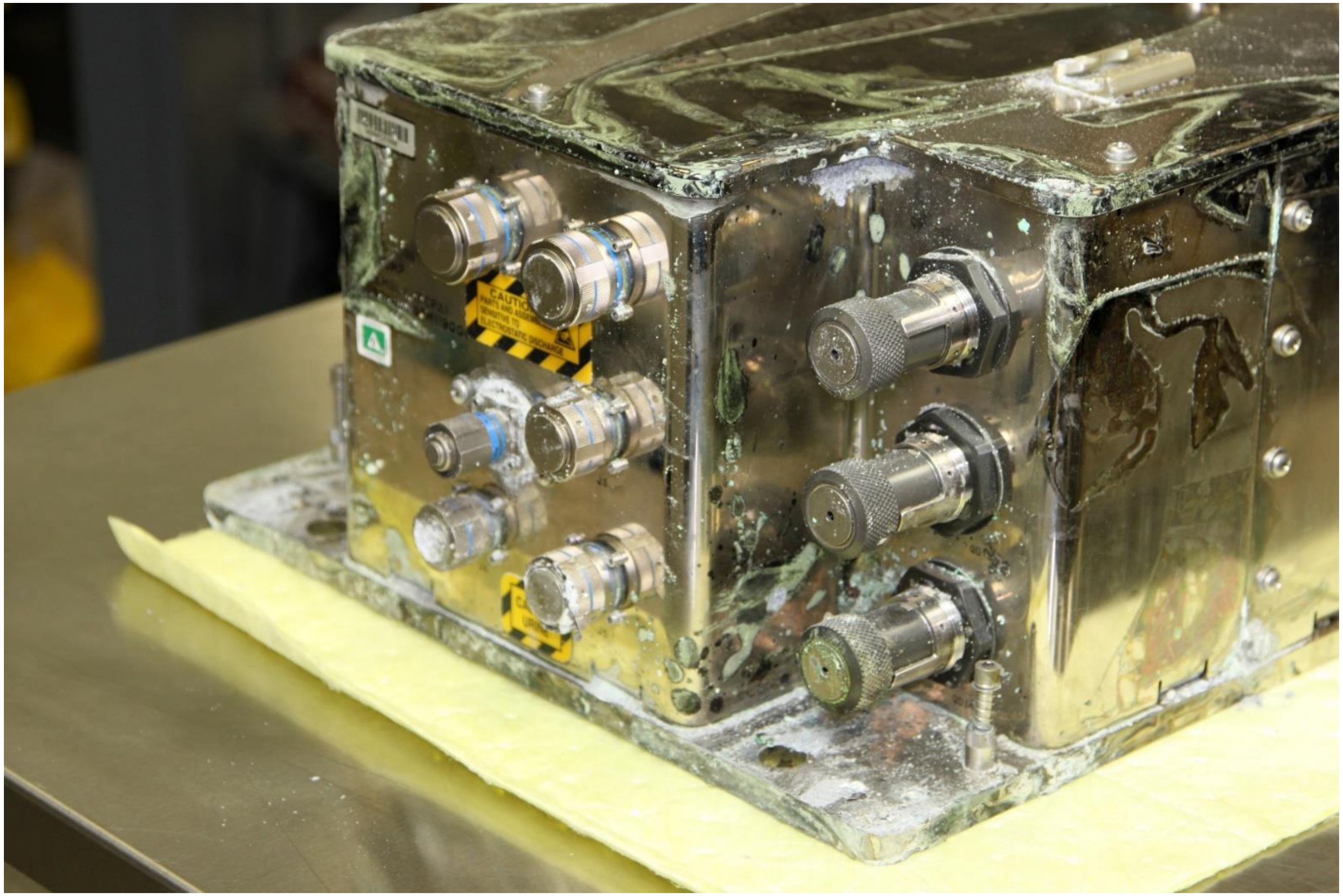
Fluids Control and Pump Assembly



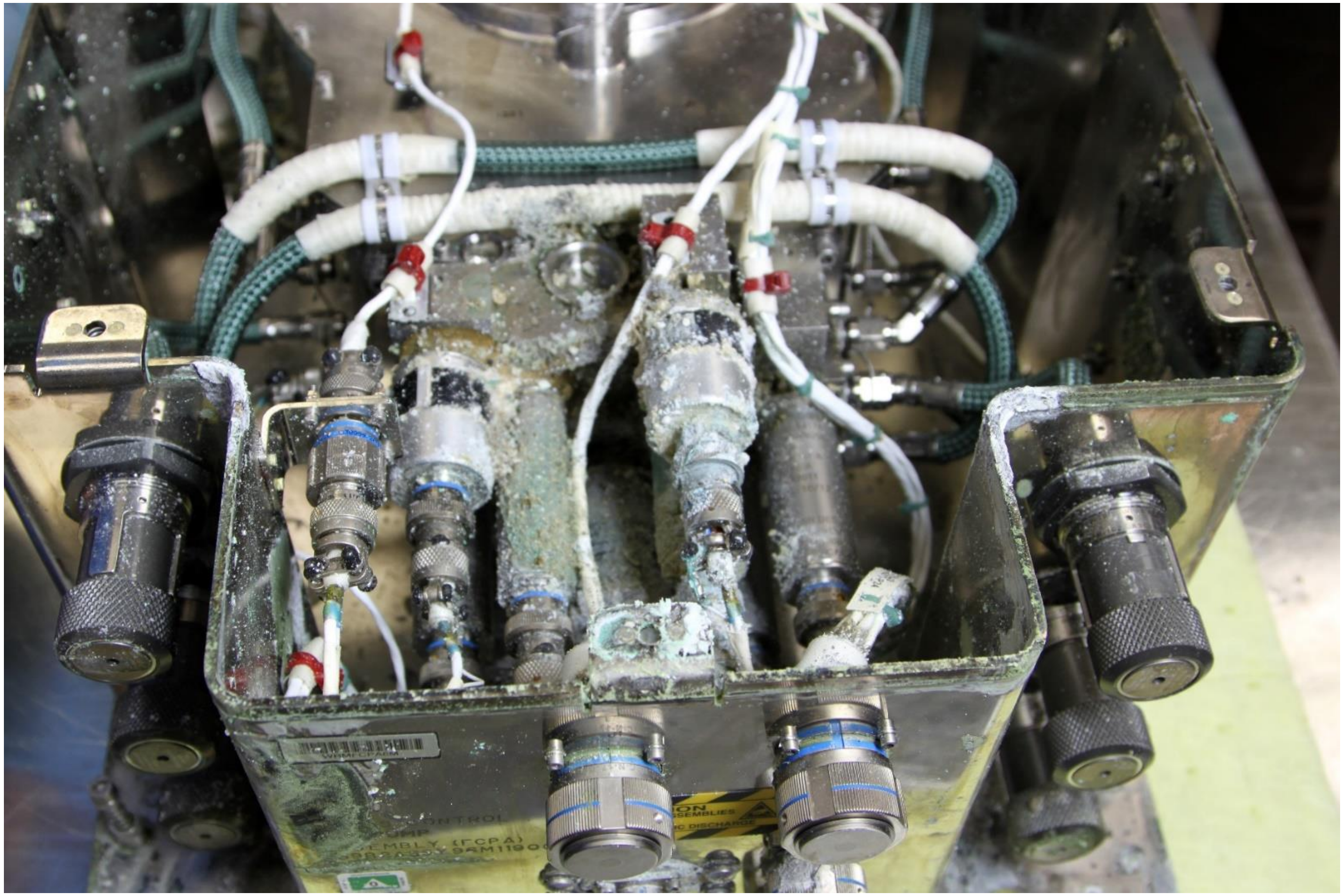




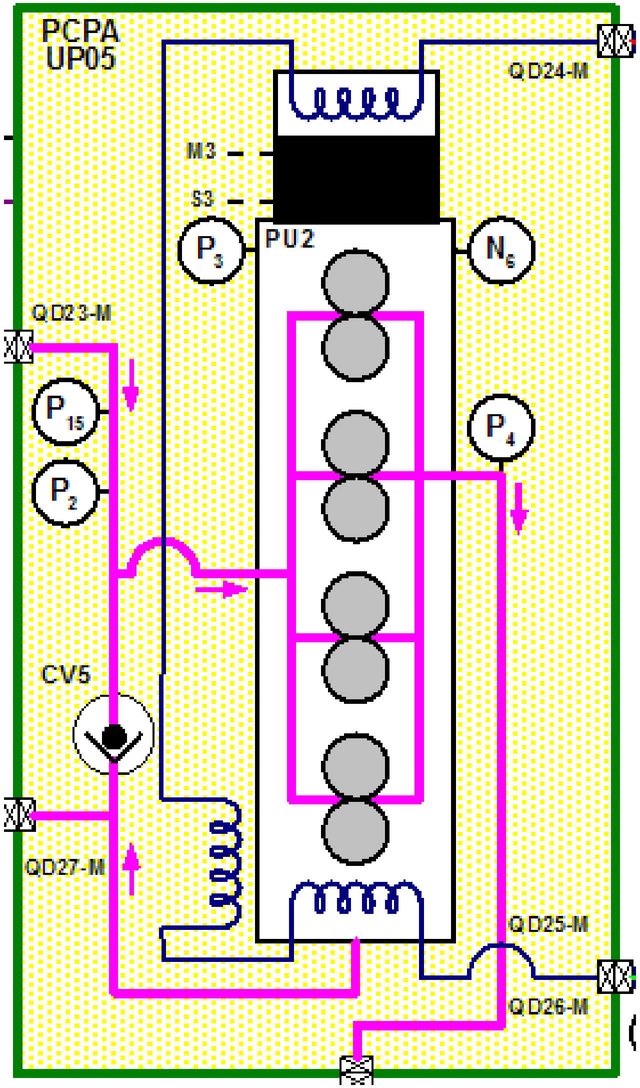
Fluids Pump Leak

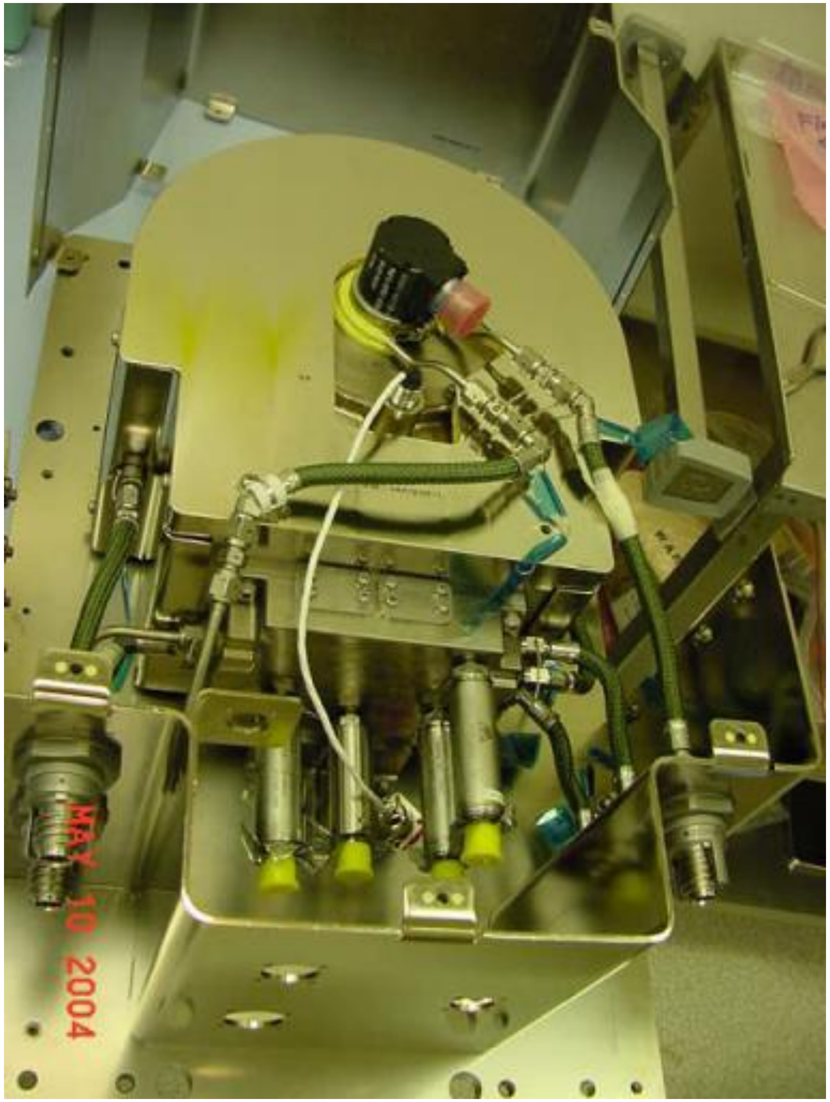


Fluids Pump Leak -2

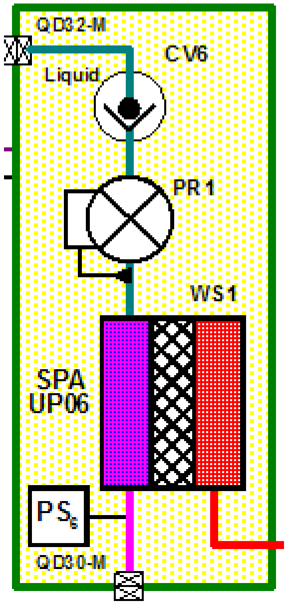


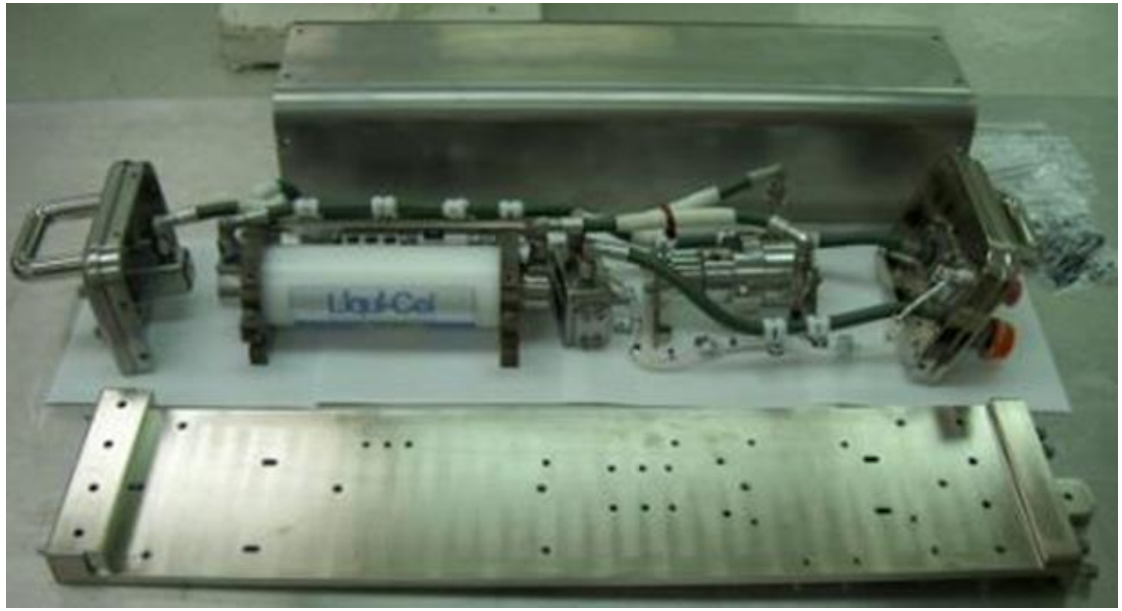
Pressure Control and Pump Assembly

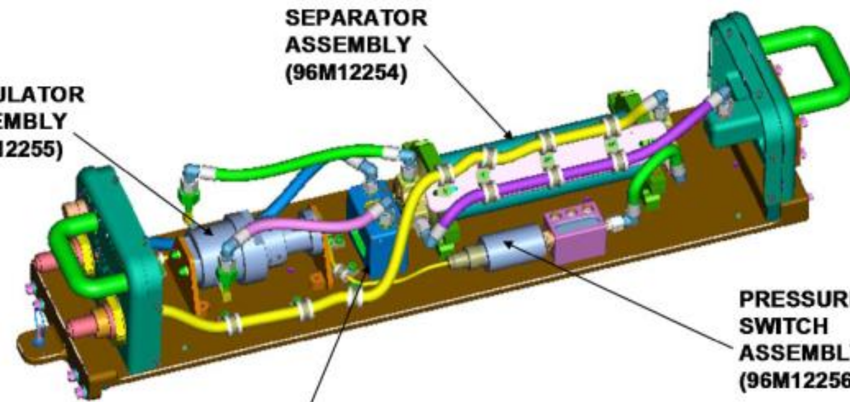




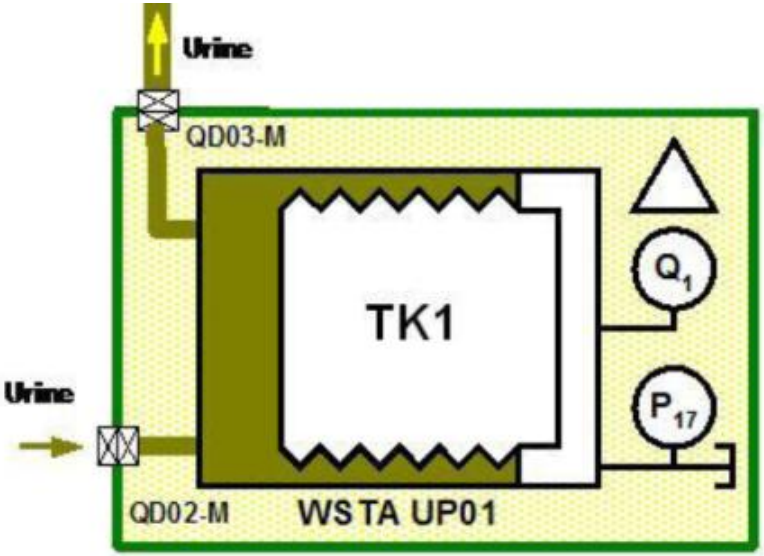
Separator and Plumbing Assembly

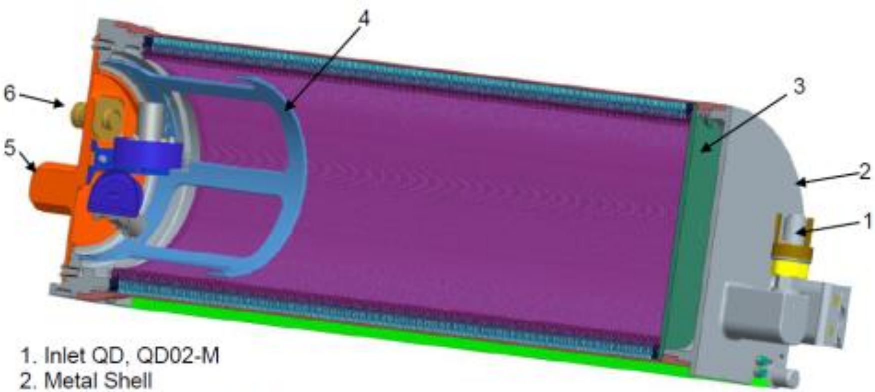




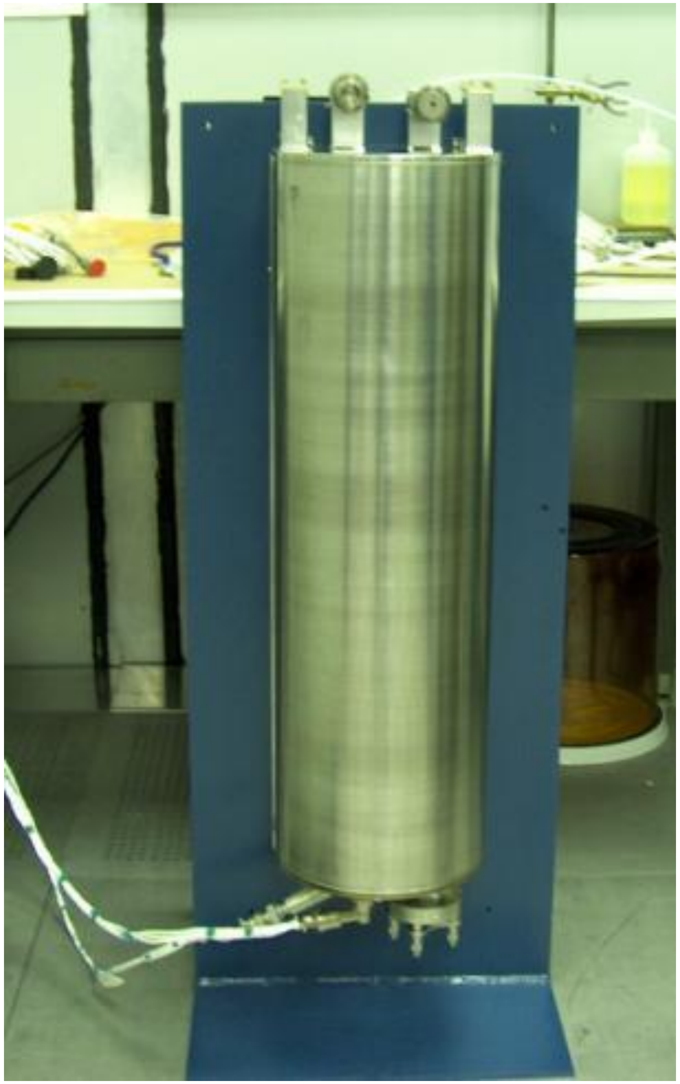


Wastewater Storage Tank Assembly

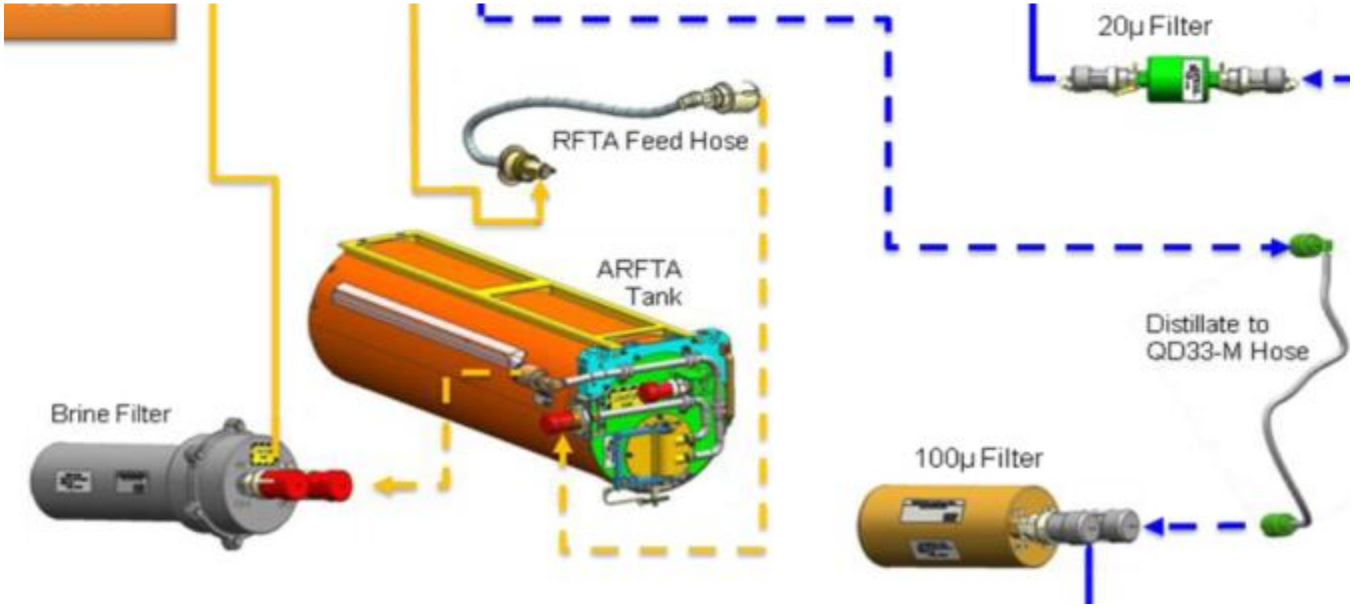




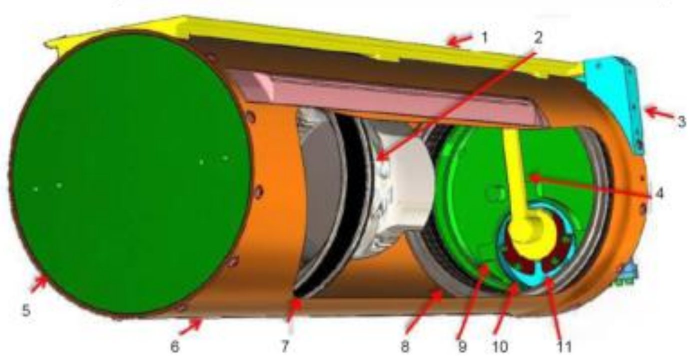
1. Inlet QD, QD02-M
2. Metal Shell
3. End of bellows (sweeper)
4. Stop
5. Quantity Sensors, Q1
6. Pressure Sensor, P17



Advanced Recycle Filter Tank



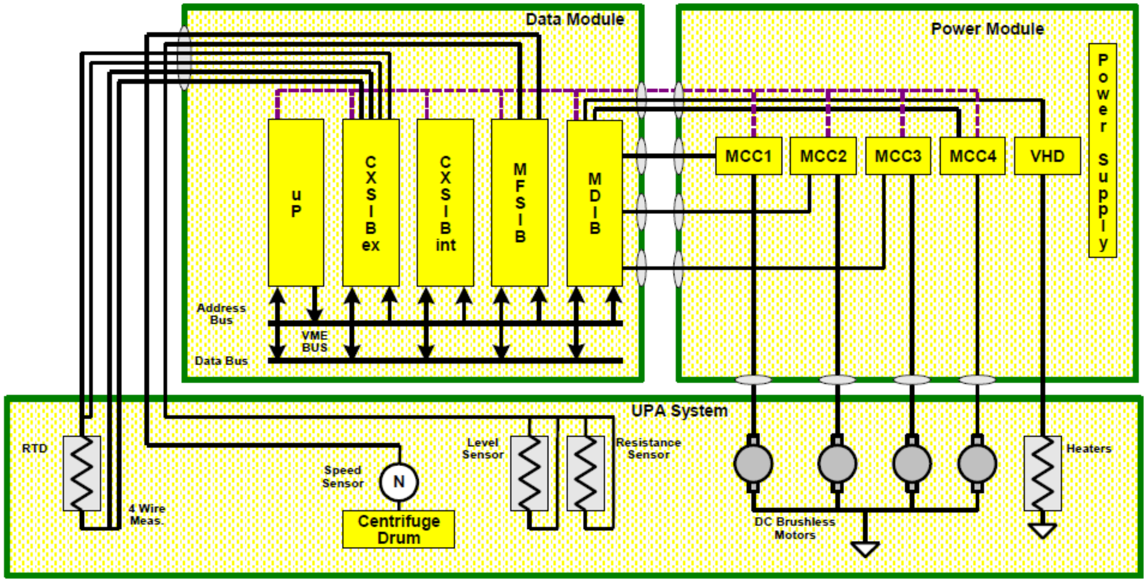
1. Rail (yellow)	8. Bellows (metallic)
2. Sweeper (metallic)	9. Stationary Term/Port Cap (green)
3. Bracket (blue)	10. Iso Valve (blue)
4. Manifold (yellow)	11. Clip (red)
5. End Cap (green)	(majority of bellows removed for clarification)
6. Housing (orange)	
7. Sweeper Guide (black)	

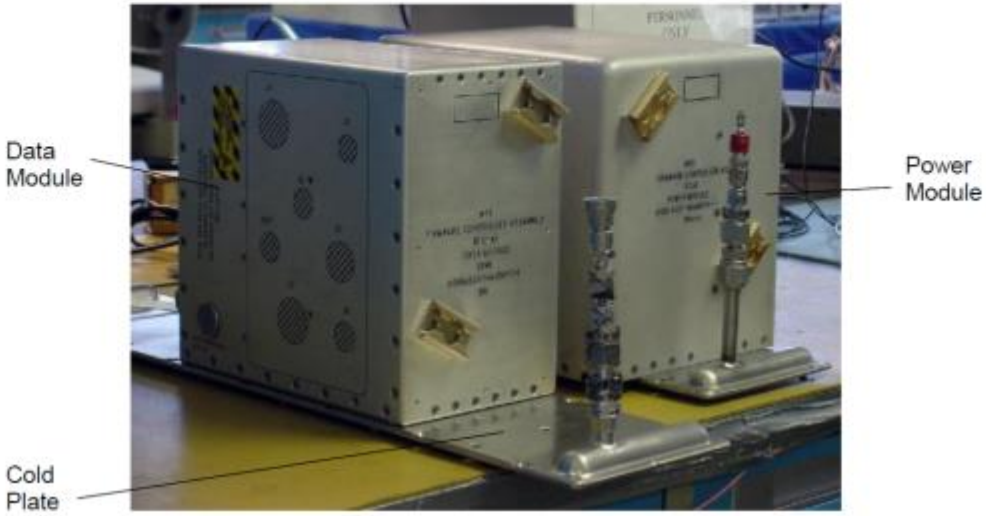


ARFTA

ARFTA DRAIN

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***

Ends with testing, research and demos complete*

Phase 1: ***Cislunar Flight Testing*** of Exploration Systems

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

Phase 2: ***Cislunar Validation*** of Exploration Capability

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

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

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

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.