ECLSS Evolution Overview

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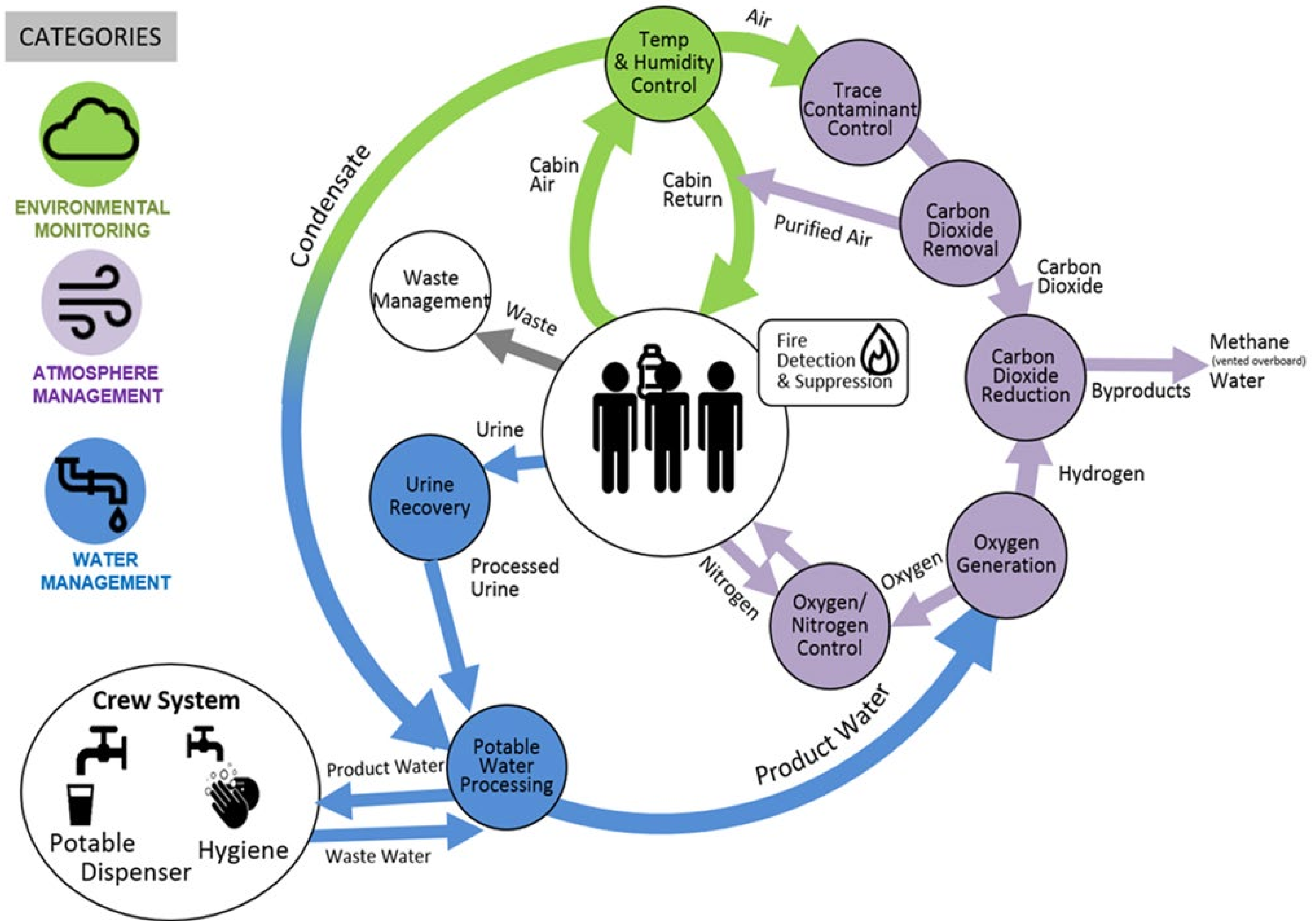
Intro to ECLSS

- **Environmental Control and Life Support System (ECLSS) – everything it takes to keep crew members alive on the International Space Station (ISS)**
- **Atmosphere Control – making sure the cabin air has the right mixture of oxygen & nitrogen, without too much carbon dioxide or other trace contaminants**
  - Pressure control
  - Temperature and humidity control
  - Carbon dioxide (CO_2) removal
  - Oxygen (O_2) production
  - Trace contaminant control
  - Air monitoring
- **Water Recovery – recycling condensation and urine to provide drinking water for crew and water for O_2 generation**
  - Condensate collection from cabin humidity
  - Waste collection
  - Urine processing
  - Condensate/distillate processing
  - Brine processing
  - Potable water dispensing

Exploration ECLSS Overall Schematic – Everything is Connected Through the Crew



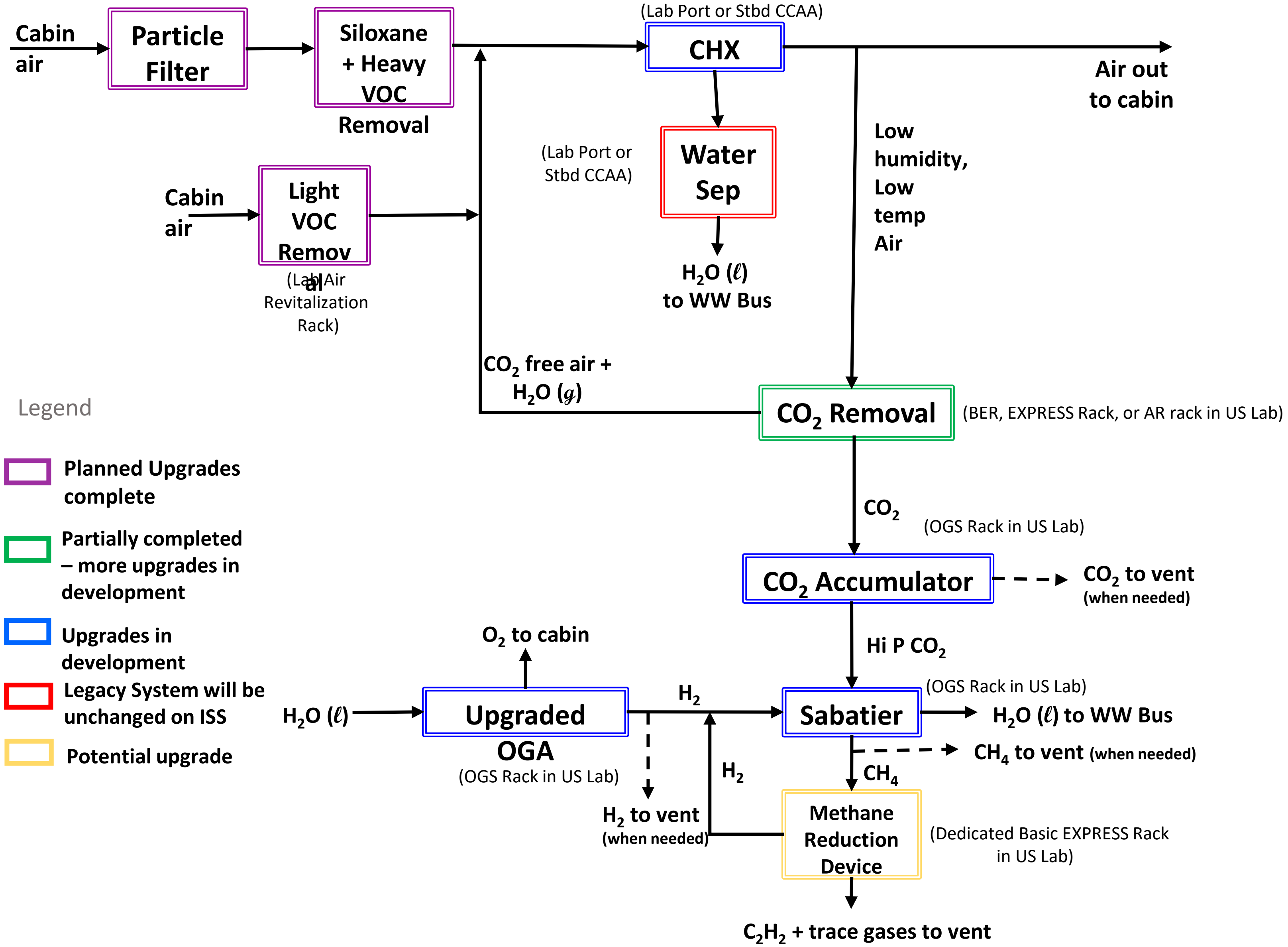
History of ECLSS on ISS

- **Early ECLSS consisted of consumable systems**
  - LiOH cans removed CO_2
  - O_2 and Nitrogen flown in Airlock tanks, replenished via transfer from space shuttle
  - Water flown in bags, replenished via space shuttle fuel cell generation
  - Hand-held sensors
- **More regenerable systems arrived over the course of multiple ISS assembly missions**
  - Atmosphere Revitalization (AR) rack – brought Carbon Dioxide Removal Assembly (CDRA), Major Constituent Analyzer (MCA), Trace Contaminant Control System (TCCS) – 2001
  - Oxygen Generation System (OGS) Rack - 2007
  - Water Recovery System (WRS) Racks – Urine Processor Assembly (UPA) and Water Processor Assembly (WPA) – 2008
- **Systems were improved-upon and redesigned as necessary when issues were identified**
- **In 2015 – Exploration Capabilities, now under Mars Capability Office (MCO), initiated effort to demonstrate Exploration-Class ECLSS via primarily the upgrade of existing, core systems**
  - MCO funds the ISS Program Vehicle Office/OB to initiate and integrate these technology demonstrations (tech demos)
  - Parallel efforts for technology development also funded by MCO – fly as payloads

ISS Demonstration Approach

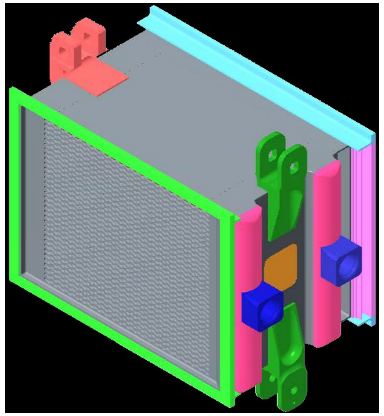
- **Develop a testbed that mimics exploration spacecraft ECLSS as much as possible**
  - ISS architecture presents limitations such as rack layout, 120VDC power, MIL-STD-1553 command and data handling systems, varying crew size
    - Arcturus Data System developed and in operation to provide alternative for data connectivity
  - Internal cooling – limited capacity for large new users, especially given Commercial Element work
  - Objective is to mature performance and reliability predictions of the core system components (e.g. Urine Processor Assembly (UPA) Distillation Assembly or Oxygen Generation Assembly (OGA) Cell Stack) and enable repackaging/layout of the systems when actual mission profiles and spacecraft designs are established
  - Close key technology gaps
- **For ease of integration into ISS, overall system is divided into two strings:**
  - Air String
  - Water String
- **Environmental Monitors are installed as their functions dictate, such as water monitoring devices inline with the WPA**

Air String Schematic



Air String Upgrades

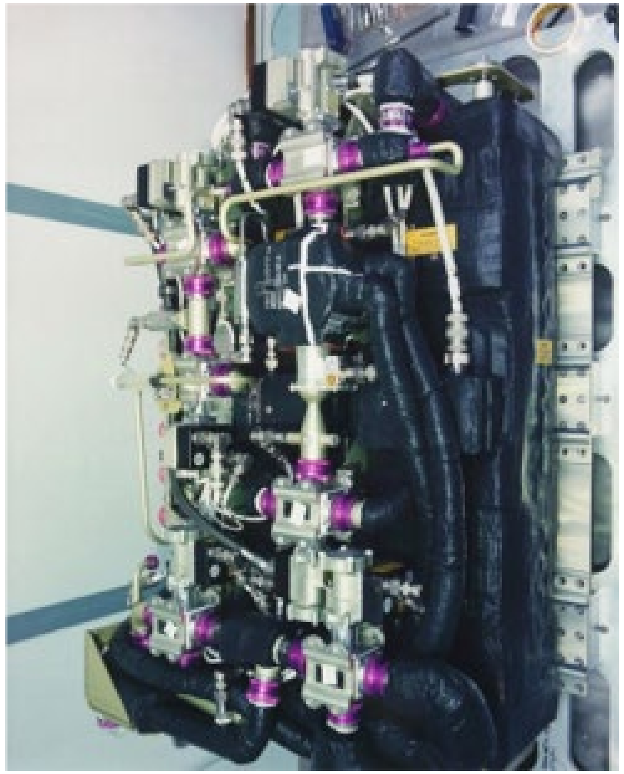
- **Condensing Heat Exchanger (CHX)**
  - Part of the Common Cabin Air Assembly (CCAA) – which performs cabin air temp and humidity control, collecting condensate for processing
  - ISS Legacy CHX will be upgraded to incorporate a modified hydrophilic coating with improved properties for microbial control, siloxane resistance, and overall lifetime
    - Current coating starts to degrade after 2-4 years – weldment rejuvenation has been accomplished but it is suspected that particulate liberates and contributes to Liquid Check Valve clogging – most common cause of Water Separator ORU failure
    - It took ~10 years of integrated ISS ops to identify that siloxanes in the cabin atmosphere react to form dimethylsilanediol (DMSD) which impacts WPA Cat Reactor life. One mechanism of DMSD production is specifically via condensation on the existing CHX coating.[1,2]
  - Goal to enable longer periods between CHX dryouts or eliminate need altogether (CHX dry-out drives temperature changes on ISS to collect condensate elsewhere – not feasible in a small spacecraft)
  - Build will make use of additive manufacturing – reduces time, complexity, and cost of future builds
  - Project: NASA direct contract to Collins for CHX, Boeing contract for integration into CCAA with delivery in 2025



- **Water Separator – sends condensate collected by the CHX into the wastewater bus for processing**
  - Technology will remain with current state-of-the-art (SOA) rotary separator that pairs well with hydrophilic CHX.
- **Trace Contaminant Control System (TCCS) – legacy system is considered SOA**
  - Additional filtering (charcoal) added to the inlet of the CHX to remove volatile siloxanes from cabin atmosphere
    - Performance is still being evaluated – condensate sample return did confirm overall reduction in atmospheric and condensate-based siloxane levels
    - Appear to be at a steady-state DMSD level now which has been manageable
  - Some ground testing planned for catalyst obsolescence – future system would likely be integrated into cabin airflow differently (in-line with CCAA vs. independent)

Air String Upgrades

- **Carbon Dioxide Removal (CO_2) System – Carbon Dioxide Removal Assembly (CDRA)**
- **Historical Problems**
  - Bed containment issues that resulted in Zeolite dusting from Adsorption/Desorption Beds, caused clogging of Air Selector Valves and Check Valves, and drove the need for frequent changeouts
  - Temp sensor failures
  - Heater sheet shorting after years of ops
  - Honeywell blower obsolete
  - CO_2 moisture introduction into Sabatier compressor which led to compressor/accumulator failure
  - CDRA concentrated ISS trace contaminants which poisoned Sabatier reactor catalyst
- **New technology/system required for robust, reliable CO_2 removal sized for 4-crew at 2mmHg inlet ppCO_2 with similar or less mass, power, volume compared to CDRA (close technology gap)**

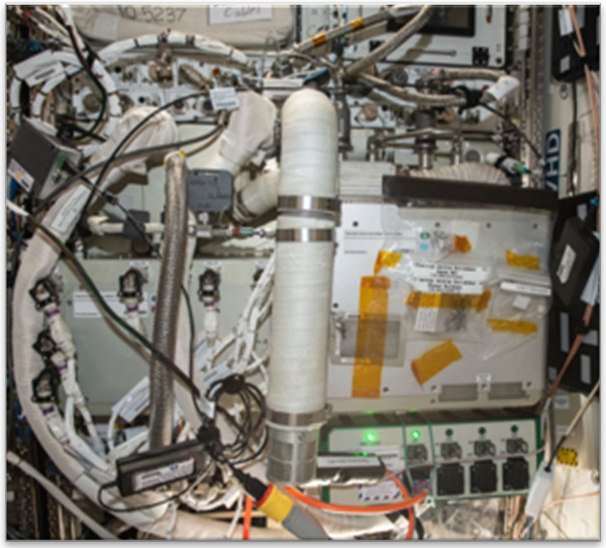


Air String Upgrades

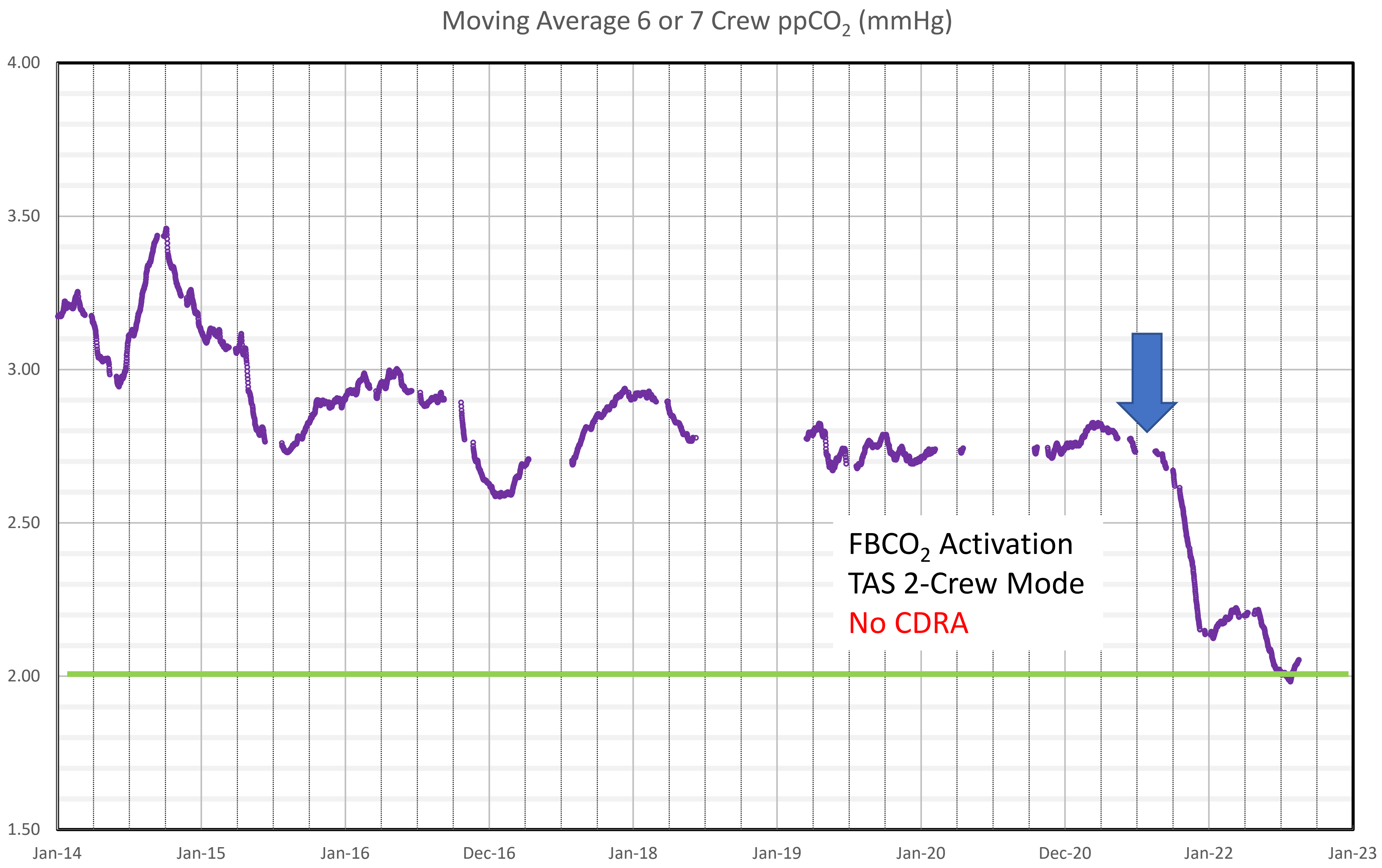
- **Carbon Dioxide Removal (CO_2) System – Four Bed CO_2 ($FBCO_2$) Scrubber**
  - Logical evolution of CDRA
    - Upgraded beds
    - More robust air valves
    - Improved heater design
    - Calnetix Blower installed 2/13 – replaces Honeywell blower and sized to improve performance to objective 4-crew removal at 2mmHg inlet $ppCO_2$
  - Developed by MSFC ECLSS - began operating Sep 2021 – 13 months cumulative on-orbit runtime
  - Failure History
    - UA Honeywell Blower/Commercial Off the Shelf (COTS) Celeroton Blower Controller comm. issues cause intermittent blower speed faults and $FBCO_2$ shutdown. Nuisance for flight control team
    - Non op periods
      - Shared Vacuum Exhaust System with other payloads that needed access
      - Basic Express Rack firmware controller issues
      - $FBCO_2$ Arcturus comm system issues
- Calnetix blower installation occurred 2/13 with activation 2/15
  - Acoustics blanket brought levels to within acceptable limit
  - Performance assessment pending resolution of software issues
- New fluid/electrical jumpers and software required to integrate with air string in Lab (i.e. connect to other systems)

Air String Upgrades

- **Carbon Dioxide Removal (CO_2) System – Thermal Amine Scrubber (TAS)**
  - Technology based on thermally regenerated solid amine with passive water save (similar to systems used on Shuttle and Amine Swingbed tech demo)
  - Began May 2019 – 22 months cumulative on-orbit runtime
  - System was limited based on constraints imposed in order to speed up development and for ease of integration onto ISS
    - 300W heater power based on Express Rack location (CDRA and $FBCO_2$ both need ~800W)
    - Humidity requirement did not meet Sabatier 2.0 integration needs
  - Integration into air string would require rebuild for Sabatier 2.0 compatibility and move to Lab AR rack (which frees up ER for other payloads)
  - Blower, Desiccant Wheel, Bulk Water Save Valve were all replaced due to various issues
  - Currently controller is failed and on the ground for repair – plan to fly again in fall for system recovery



ISS $ppCO_2$



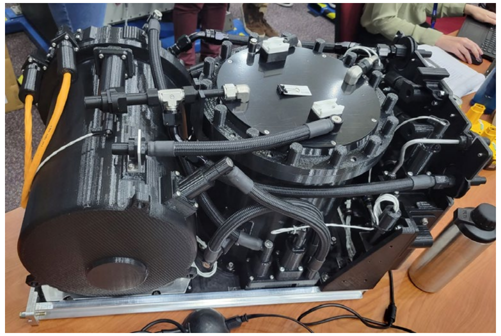
Moving Average 6 or 7 Crew $ppCO_2$ (mmHg)
4.00
3.50
3.00
2.50
2.00
1.50
Jan-14
Jan-15
Jan-16
Dec-16
Jan-18
Jan-19
Jan-20
Dec-20
Jan-22
Jan-23
$FBCO_2$ Activation
TAS 2-Crew Mode
No CDRA

Air String Updates (cont'd)

- **CO_2 Reduction System**
  - Sabatier operated on ISS until Oct 2017 (~2 years runtime), was returned following reactor failure for upgrade and demonstration
    - Root cause determined to be catalyst poisoning from contaminants that were concentrated from ISS atmosphere in CDRA and the Oxygen Generation Assembly
    - Liquid water also passed through to CO_2 accumulators and caused corrosion (condensation in compressor)
  - Sabatier 2.0 will provide better protection for the reactor and allow for its maintenance, and will interface with new CO_2 accumulator tanks
    - Addition of a getter which removes poisons from mixed CO_2 /H_2 input stream to Sabatier reactor
    - Reactor position within system is relocated for on-orbit replacement
    - Addition of humidity sensors to detect moisture and safe Sabatier
  - Sabatier 2.0 Preliminary Design Review (PDR) occurred 11/1, delivery 2025
  - ISS can be ready to support additional CO_2 Reduction technologies if they mature sufficiently in time for flight demonstration
    - Methane Reduction takes Sabatier waste product methane and recovers additional H_2 which can be fed back into Sabatier to improve efficiency (waste product is carbon)
    - Technologies currently in development need both footprint and relatively high levels of power and heat rejection

Air String Updates (cont'd)

- **O_2 Generation System: Advanced Oxygen Generation Assembly (AOGA)**
  - **Failure history:**
    - Pump lock-ups due to material incompatibility (one bearing issue corrected, another being addressed currently with Niflor coating in Quick Disconnect connectors)
    - Cell Stack failure due to fluoride generation reducing pH in recirculation loop – addition of activated carbon filter in recirculation loop addressed this
    - Back Pressure Regulator (BPR) failure over time – component within H_2 Orbital Replacement Unit (ORU)
    - Cell stack failure due to material thinning/shorts
  - **AOGA Objectives:**
    - Utilize current industry standard cell stack design features: chemically stabilized Nafion membranes with cerium doping for reduced material loss through electrolysis, sintered plate membrane supports (rather than fine mesh screens that allow material creep over time which causes shorts)
    - Redesign for maintainability
      - Change from a single sealed dome that houses the cell stack and Rotary Separator Accumulator to two, maintainable domes
      - Crew ability to replace components inside domes will be demonstrated – key improvement for mass/volume reduction
      - Dome seal design is being finalized after much technical discussion and additional requirement

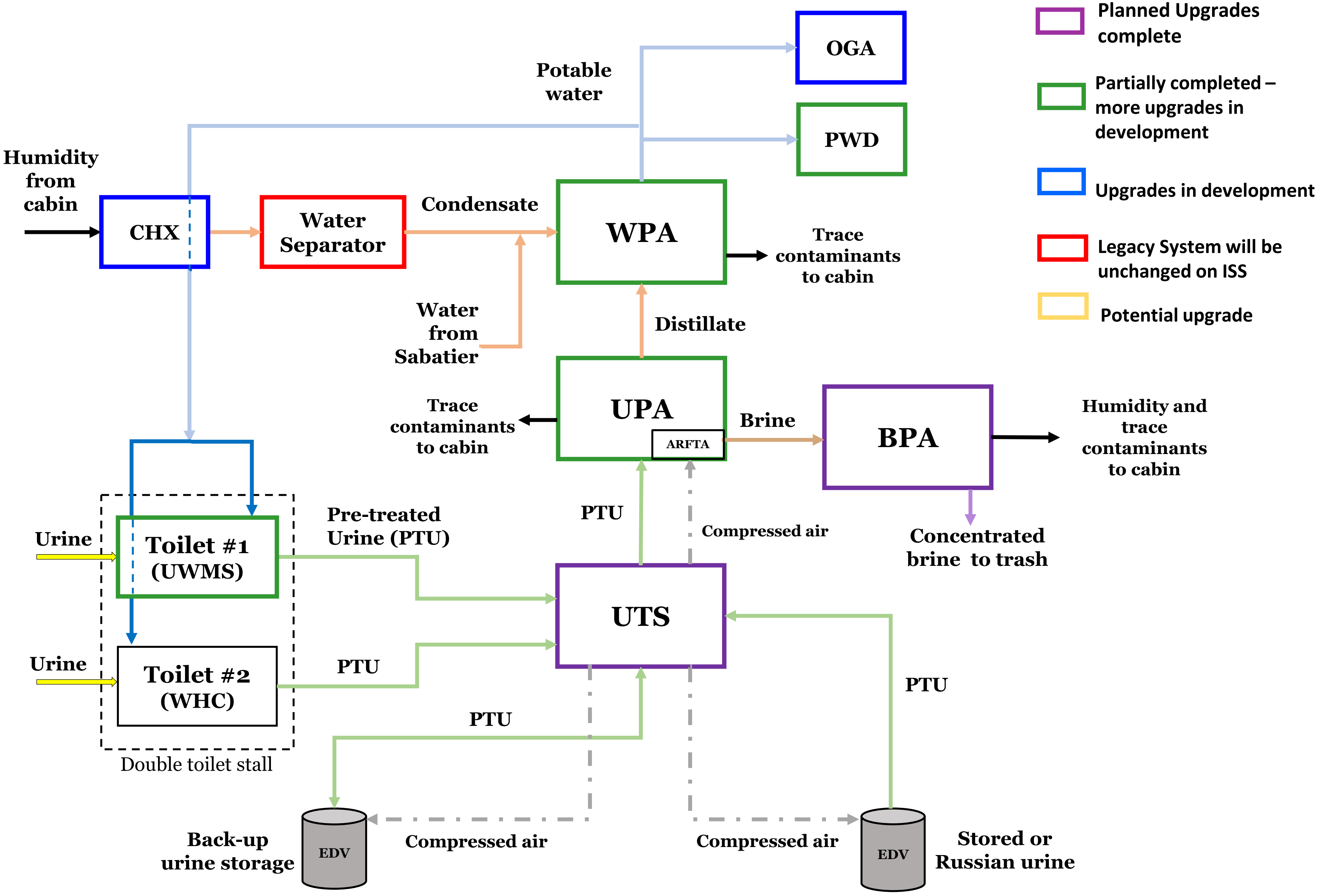

AOGA Mockup for Procedure Evaluation


H2ST installed on LSR in Lab

Air String Updates (cont'd)

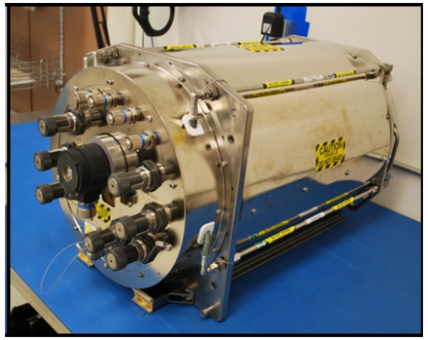
- **AOGA Objectives (cont'd):**
  - Redesign some components to address lessons learned form on orbit operational issues (in addition to the cell stack: check valves, back pressure, pressure sensors, relief valves)
    - BPR failure investigation findings will be implemented in AOGA version (mainly rigid adherence to surface finish requirements, tolerances and quality/testing)
  - Add recirculation loop flush to protect downstream systems (like Sabatier) and enable dormancy
  - Resin cartridge being resized for Exploration mission duration and to reduce dP in the recirculation loop – new version called ARMADILLO
  - AOGA will deliver early 2025
    - Critical Design Review (CDR) 11/15-11/16, delta CDR 7/24/2023
  - Separate tech demo to evaluate alternative H_2 sensor technology flew in Feb 2022 and was activated April 2022
    - Monitors O_2 product from OGA/AOGA for H_2 downstream of existing integrated sensors
    - Existing sensors drift and are extremely sensitive to moisture: 210-day lifetime
    - Installed on OGS rack following relocation to Lab

Water String Schematic with Status

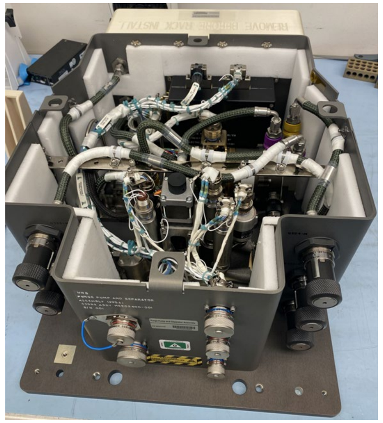


Water String Upgrades

- **Urine Processing System**
  - **Urine Processor Assembly (UPA) is being upgraded to correct design weaknesses and improve maintainability**
  - **Improvements have been incremental throughout operational life**
    - Upgraded bearing material in Distillation Assembly (DA)
    - Changed from a disposable brine tank, Recycle Tank Filter Assembly (RFTA) to a reusable, advanced version (ARFTA) with fill/drain valve external to the system for ease of crew use
    - Recovery from precipitation event caused by excessive sulfates in the brine loop and DA resulted in the change from legacy sulfuric acid pretreat to phosphoric/chromic acid ‘alternate’ pretreat
      - UPA operations on ISS advanced NASA’s understanding of metabolic changes in crew (i.e. significantly higher levels of calcium and sulfates in urine) as well as contributed to a focus on better hydration
    - Accepted % recovery of pre-treated urine (PTU) was increased slowly over time in order to minimize risk of precipitation (involved continuous analysis of returned brine filters)
    - Fluids pump and purge pump were both modified to changed to a planetary gear design to improve design life
    - Purge pump modified to reduce squeeze on the tubing
  - **Upgraded DA installed on ISS in 2020 – system runtime has surpassed all other DA units (7234 hrs as of 6/13 which is 165% DA life)**
    - DA eliminated several failure modes including belt slippage via use of a toothed gear belt and fluid leak path through bearings



Upgraded Distillation Assembly



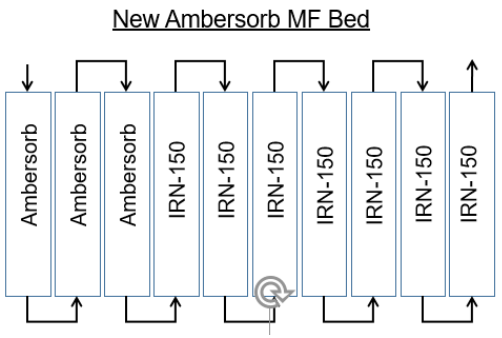
PPSA

Water String Upgrades

- **Urine Processing System (cont'd)**
  - **Purge Pump and Separator Assembly (PPSA) - smaller, more efficient, maintainable at a lower level and potentially more reliable**
    - Installation on-orbit planned for end of June
    - PPSA combines legacy purge pump and separator filter ORUs into footprint of purge pump
  - **ARFTA Quantity Insight – crew inspection require to ensure adequate fill/drain of ARFTA at start and end of concentration cycles**
    - Sensor reduces crew time and enables automated concentration cycle
    - Ground demonstration in development
  - **Fluids Pump – legacy design is a 3-channel pump used to move different fluids through UPA and driven by a single motor**
    - New design separates channels into independent pumps
    - More efficient design, independent control (advantageous for dormancy) and replaceable/repairable (reduces mass/volume of spares)
    - Ground prototype funded with flight demo unfunded to date
  - **Joint team: MSFC, JSC and ARC established to implement recommendations from a study identifying areas that would benefit from additional failure insight – initial goal is ground demonstration of automation capabilities for exploration (late 2023)**

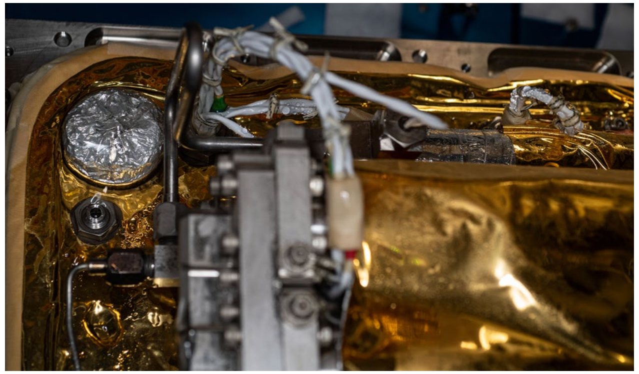
Water String Upgrades

- **Water Processing System**
  - **Water Processing Assembly (WPA) on ISS upgraded to address key reliability issues and optimize based on lessons learned**
    - Prevalence of siloxanes, their conversion to DMSD, and subsequent impact on Cat Reactor life was unknown prior to extended operations on ISS
    - Addition of charcoal beds upstream of CHX reduced siloxanes in the condensate and reduced Cat Reactor life
    - Biofilm growth in the Wastewater Tank clogged a valve downstream – led to an operational control for biofilm growth in the tank via regular cycling of the full bellows travel, and installation of a filter downstream (External Filter Assembly originally intended just for new Cat Reactor flushing)
  - **Multifiltration Bed (MF Bed) config reduced from two beds to one**
    - Improves system ability to withstand siloxanes in condensate – how contaminants collect and are pushed off beds was something learned over time ("breakthrough cycles")
    - Better posture for dormancy (less hardware to replace post-dormancy)
  - **MF Bed redesigned for improved sorbent material (performance) and extend operational life – first installed Oct 2020**



Water String Upgrades

- **Water Processing System (cont'd)**
  - **Catalytic Reactor (Cat Reactor) – Demo Catalytic Reactor ORU will address 3 primary improvements**
    - **New Catalyst:** a new catalyst developed under NASA funding. Ground tests at MSFC showed this catalyst will improve oxidation efficiency, and specifically improve oxidation of DMSD
    - **Metal Seals:** new metal seals will replace the existing soft seals that lead to failure
      - Every Catalytic Reactor ORU has failed due to external leakage from degraded seals
    - **O_2 Flow Rate Adjustment:** testing has shown increased O2 flow will improve oxidation efficiency
    - Additionally, the O2 Filter ORU will be modified to remove the filter element, not needed and eliminates a consumable
  - **Microbial Check Valve (MCV) - study completing to develop new check valve design, as well as upgrade microbial resin**
    - Resin Dormancy (1 year) testing in process to determine barrier breakthrough
    - Exploration solution likely a solenoid valve (dP is too low for a check valve to function adequately)

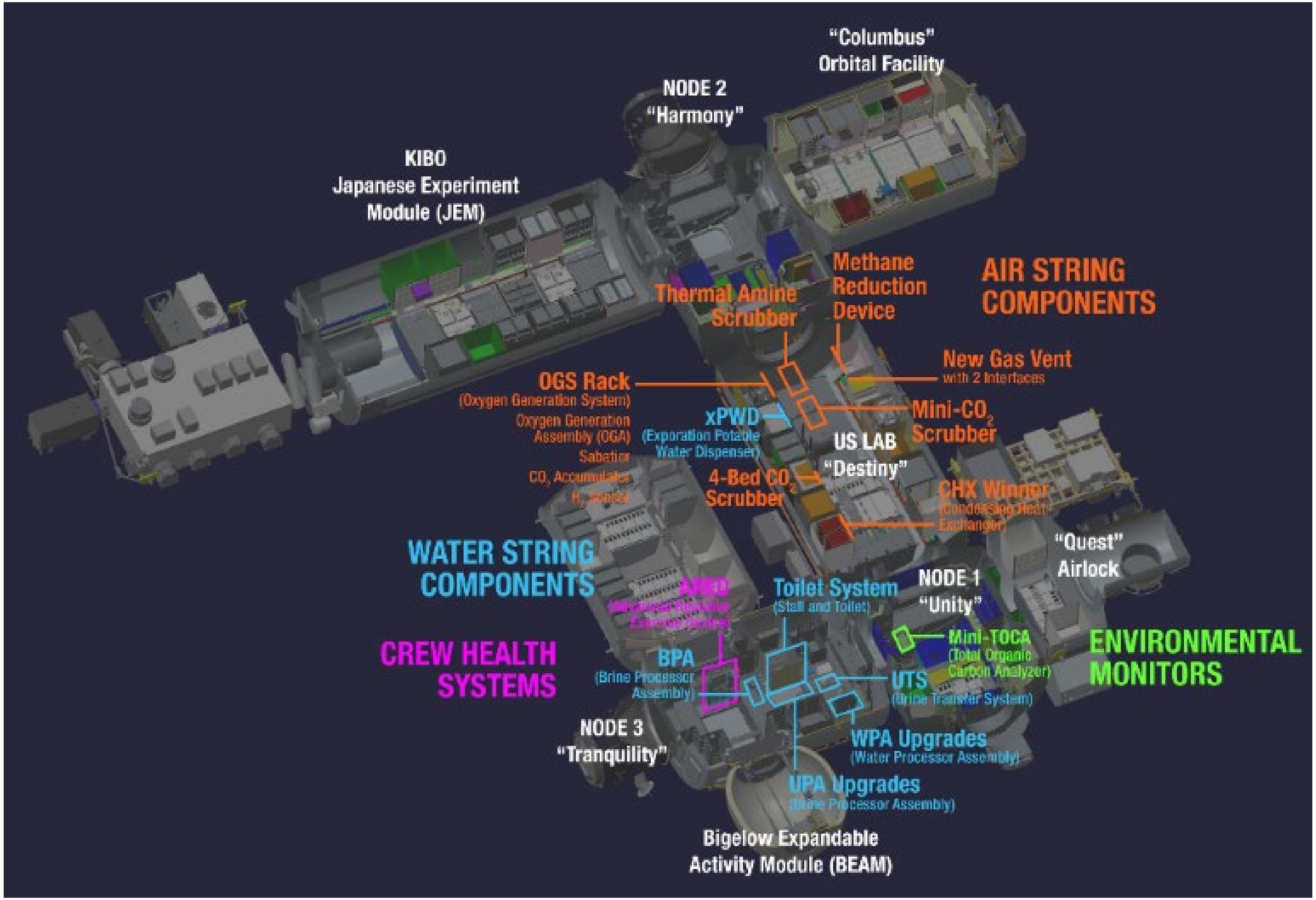


DTO Cat Reactor leak on-orbit

Water String Upgrades

- **Potable Water Dispensing System**
  - **Upgraded Exploration Potable Water Dispenser (xPWD)**
    - Addresses concerns with microbial control during dormancy through removal of stagnant portions of system
    - Demonstrate flow-through ultraviolet (UV) disinfection technology at point-of-use – intent to reduce consumable filter usage
    - Launching on NG-19 fall 2023

xPWD Flight Unit


"Columbus"
Orbital Facility
NODE 2
"Harmony"
KIBO
Japanese Experiment
Module (JEM)
Thermal Amine
Scrubber
Methane
Reduction
Device
AIR STRING
COMPONENTS
New Gas Vent
with 2 Interfaces
OGS Rack
(Oxygen Generation System)
Oxygen Generation
Assembly (OGA)
xPWD
(Exporation Potable
Water Dispenser)
Mini-CO_2
Scrubber
US LAB
"Destiny"
4-Bed CO_2
Scrubber
"Quest"
Airlock
WATER STRING
COMPONENTS
Toilet System
(Stall and Toilet)
NODE 1
"Unity"
CREW HEALTH
SYSTEMS
BPA
(Brine Processor
Assembly)
Mini-TOCA
(Total Organic
Carbon Analyzer)
UTS
(Urine Transfer System)
ENVIRONMENTAL
MONITORS
NODE 3
"Tranquility"
WPA Upgrades
(Water Processor Assembly)
UPA Upgrades
Bigelow Expandable
Activity Module (BEAM)

Integrated Ground Testbed

- **Per LaRC statistical analysis, will not be able to accomplish amount of testing on ISS to reach Probability of Success (POS) and mass/volume targets for Mars Transit Habitat by 2030**
- **Required mass and volume of spares is critical to mission success – cannot resupply if you run out of a spare part**
- **Effort to "double the data set" underway – establish Exploration-class, integrated ground test bed to mimic baseline architecture at MSFC**
  - Numerous testbeds already existed and are being upgraded (UPA, OGA, Sabatier)
  - WPA, xPWD, CCAA CHX ground testbeds must be built from scratch
  - $FBCO_2$ testbed will be re-built completely in order to make fully flight-like and enable testing in low pressure, high O_2 environment
- **JSC & MSFC working through process of establishing most cost-effective methods of developing/assembling testbeds**
  - Balance 'flight-like' with reduced cost and higher risk acceptance for ground use – may involve initial activation with more COTS parts and evolution to full flight equivalency
  - Consider critically what must match flight config
  - Determine additional objectives for ground testing aside from reliability (challenge testing, demonstration of dormancy) and determine how they affect testbed config
- **Major challenges:**
  - Cost/schedule of components that must be procured from original manufacturer/vendor – contracts work is slow
  - Resource limitations – competition between other projects/programs

Conclusion

- **ISS Vehicle is being fully utilized as platform for demonstrating Exploration ECLSS technology**
  - Continually identifying system failure modes and correcting designs
  - Increasing understanding of system reliability for successful/efficient spares planning
- **Many challenges related to these demonstrations have already been addressed**
- **Largest areas of forward work**
  - Completing Integrated Air String
  - Developing Integrated Ground Test Bed
  - Integrating methane reduction if tech matures sufficiently for ISS flight demo

ECLSS Capability Advancements on ISS continue – we still have much to learn

  - Discussions ongoing to ensure we are utilizing ISS fully and reducing risk for near-term NASA Programs (Orion, Gateway, Commercial Leo Destination Program) in addition to Exploration missions
- **Need to incorporate ECLSS lessons learned to avoid reinventing the wheel**
  - Crew survival means minimizing risks that may be imposed by procurement or partnership strategies
  - Drafting a list of recommended NASA standard interfaces/components for better compatibility across programs and platforms

Backup

Acronyms

- *AOGA* =Advanced Oxygen Generation Assembly
- *AR* = Air Revitalization
- *ARC* = Ames Research Center
- *ARFTA* = Advanced Recycle Filter Tank Assembly
- *BPA* = Brine Processor Assembly
- *BPR* = Back Pressure Regulator
- *CCAA* = Common Cabin Air Assembly
- *CDRA* = Carbon Dioxide Removal Assembly
- CH_4 = Methane
- *CHIPS* = Charcoal HEPA Integrated Particle Scrubbers
- CHP = Crew Health and Performance
- *CHX* = Condensing Heat Exchanger
- CO_2 = Carbon Dioxide
- COTS = Commercial Off the Shelf
- *DA* = Distillation Assembly
- *DMSD* = dimethylsilanediol
- *ECLS* = Environmental Control and Life Support
- *ECLSS* = Environmental Control and Life Support System
- *EDV* = Russian-Built Water Tank
- *EVA* = Extravehicular Activity
- *EXPRESS* = Expedite the Processing of Experiments to ISS
- $FBCO_2$ = Four Bed CO_2 Scrubber
- *(g)* = Gas Phase
- H_2 = Hydrogen
- H_2O = Water
- *HEPA* = High Efficiency Particulate Air
- *IMV* = Intermodule Ventilation
- *ISS* = International Space Station
- *JSC* = Johnson Space Center
- *LaRC* = Langley Research Center
- *LiOH* = Lithium Hydroxide
- *MCA* = Major Constituent Analyzer
- *MCC-H* = Mission Control Center – Houston
- *MCO* = Mars Campaign Office
- *MCV* = Microbial Check Valve
- *MER* = Mission Evaluation Room
- *MF* = Multi Filtration
- *MSFC* = Marshall Space Flight Center
- *NASA* = National Aeronautics and Space Administration
- O_2 = Oxygen
- *OGA* = Oxygen Generation Assembly
- *OGS* = Oxygen Generation System
- *ORU* = Orbital Replacement Unit
- *PDR* = Preliminary Design Review
- *POS* = Probability Of Success
- *PPSA* = Purge Pump and Separator Assembly
- *PTU* = Pre-treated Urine
- *PWD* = Potable Water Dispenser
- *SOA* = State of the Art
- *TAS* = Thermal Amine Scrubber
- *TOCA* = Total Organic Carbon Analyzer
- *TCCS* = Trace Contaminant Control System
- *US Lab* = United States Laboratory Module
- *USOS* = United States On-orbit Segment
- *UWMS* = Universal Waste Management System
- *UPA* = Urine Processor Assembly
- *UTS* = Urine Transfer System
- *UV* = Ultraviolet
- *VOC* = Volatile Organic Compound
- *WHC* = Waste and Hygiene Compartment
- *WPA* = Water Processor Assembly
- *WRS* = Water Recovery System
- *WW* = Waste Water
- *xPWD* = Exploration Potable Water Dispenser

ICES Paper References

- [1] The Incidence and Fate of Volatile Methyl Siloxanes in a Crewed Spacecraft Cabin
- [2] Process Development for Removal of Siloxanes from ISS Atmosphere
- Thermal Amine Scrubber – Space Station Installation and Start-Up
- Oxygen Generation Assembly Design for Exploration Missions
- Status of ISS Water Management and Recovery
- Water Recovery System Architecture and Operational Concepts to Accommodate Dormancy
- Upgrades to the International Space Station Urine Processor Assembly