Enhancing Future Commercial Space Stations: Applying ISS Insights to Environmental Control and Life Support Systems (ECLSS) Development

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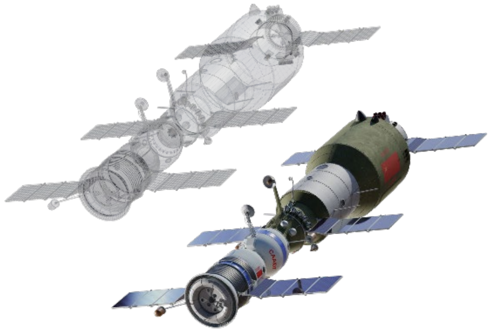
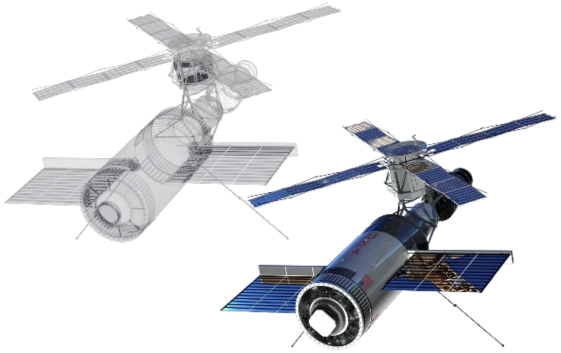
Importance of ECLSS to Human Spaceflight

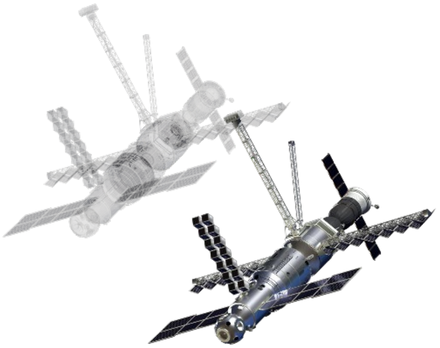
- Humans have a long history of spaceflight aboard various spacecraft and one of the key systems keep astronauts alive is the ECLS system
- Environment Control and life support system (ECLSS) plays an essential role in accomplishing the goal of sustaining human presence as its absence would render human space exploration impossible and severely restricted
- Life support systems are also essential for enabling long-duration space missions, such as those that involve crewed missions to the Moon, Mars, or beyond
  - These missions require systems that can generate and recycle resources, such as air, water, and food, as resupply missions may not be possible or feasible



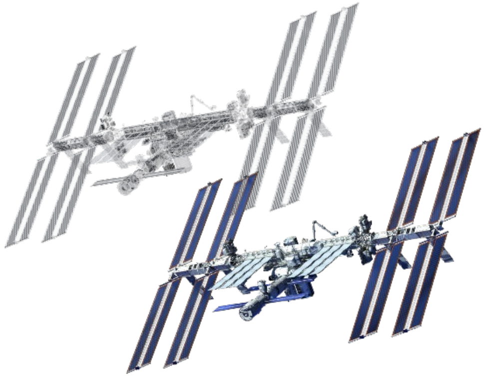
Salyut-1
April 1971 – October 1971



Skylab
May 1973 – February 1974



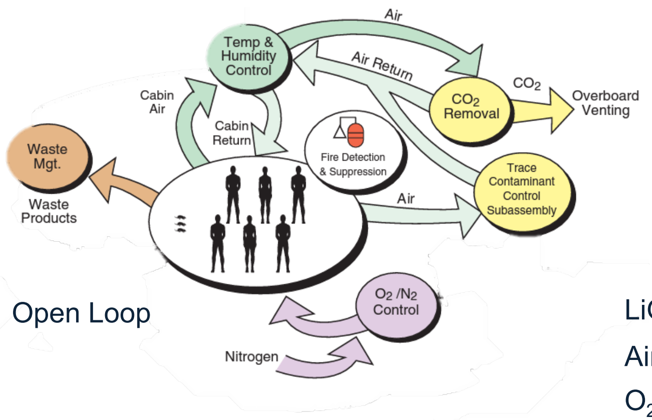
Mir
February 1986 – March 2001



ISS
Nov 1998 - Current

ISS ECLSS Development

- ISS serves as a prime example with its long-standing and evolving ECLS systems
- The evolving ECLSS consistently enhances the loop closure rate, reducing resupply logistics
- With around 25 years of continued evolvement, ISS is still not yet self-sustainable with operations and resupply costs at about $1.1 billion per year from FY 2016 through 2020 [2]



Early ISS ECLSS Systems

Trace Contaminant Control System
Major Constituent Analyzer
Carbon Dioxide Removal Assembly
Atmosphere Revitalization rack

2001

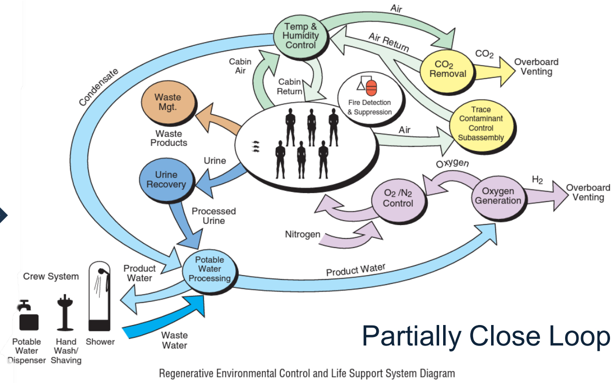
LiOH Can
Air Bags
O_2 and N_2 Air Tanks

2007

Oxygen Generation System Rack
Oxygen Generation Assembly

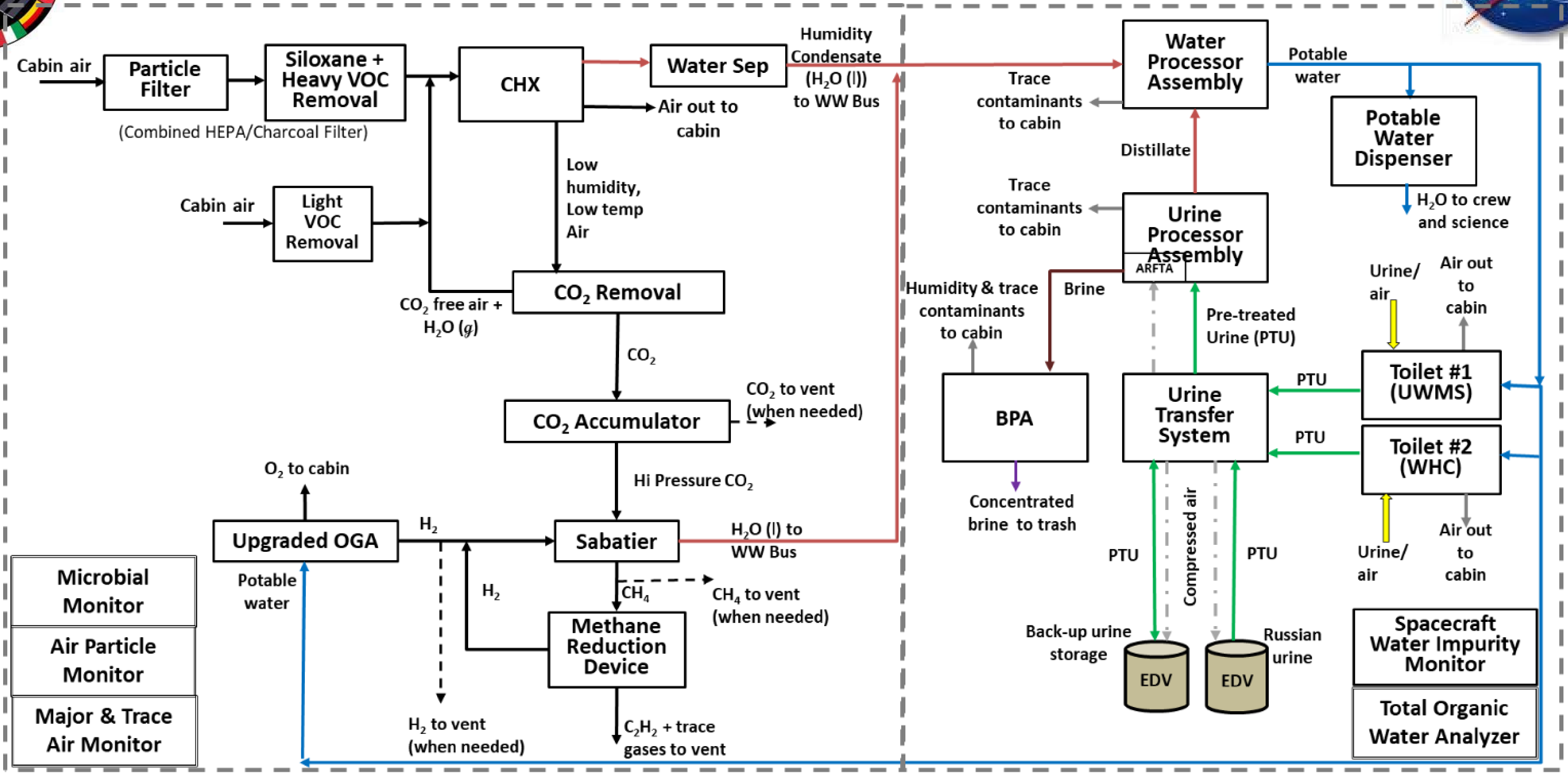
Urine Processing Assembly
Water Processing Assembly
Water Recovery System Racks

2008



Matured ISS ECLSS Systems

Current State-of-the-art ECLSS onboard ISS



Simplified SOTA ISS ECLSS [1]

Commercial Development

- International Space Station (ISS) provides tremendous contributions to human space flight by being in orbit for over 22 years [3]
- There is a shift from government-led endeavors to a new competitive era driven by private companies and innovative forces
- Joining the ISS, NASA initiated the Space Act Agreement (SAA) to support the development of commercial space station
- Blue Origin, Nanorack, and Northrop Grumman* were selected in 2021 for funded SAA-1 [4]
- Additional new companies, such as Sierra Space, SpaceX, Vast Space were selected in 2023 for unfunded SAA-Collaborations for Commercial Space Capabilities-2 initiative (CCSC-2) [5]

ISS: 1998 - Present

Low Earth Orbit (LEO)

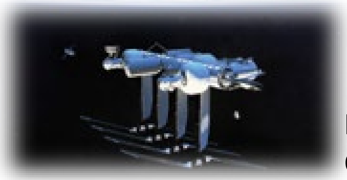


Image Credit: Orbital Reef

Image Credit: Starlab

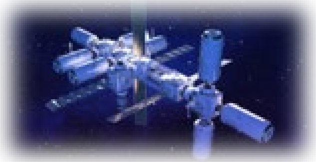
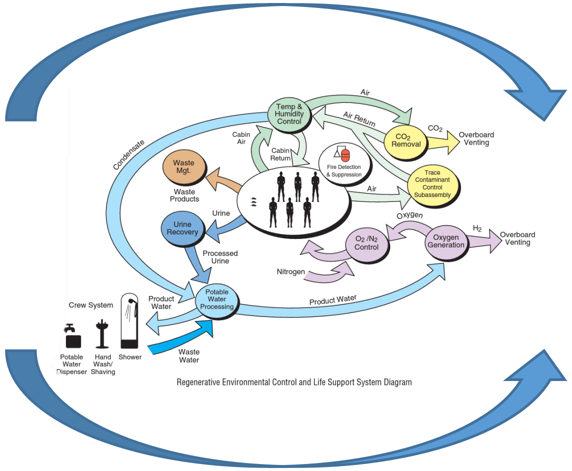


Image Credit: Northrop Grumman

***NG dropped the plan on space station [6]**

ECLSS Knowledge Transfer

- To assist the development of commercial space stations, it is crucial to harness over two decades of ISS operational knowledge to inform and improve the design of future space stations
- Development of future free flyers may benefit from these ISS learning curve
- The development should be considered in two levels:
  - System Level
  - Subsystem Level



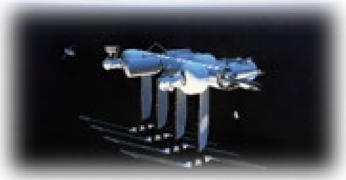


Image Credit: Orbital Reef

Image Credit: Starlab

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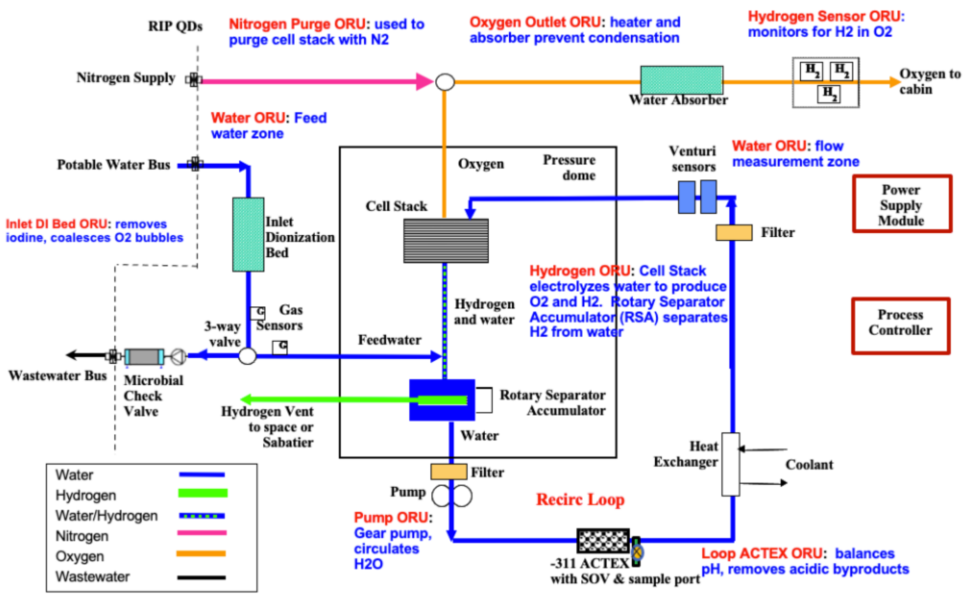
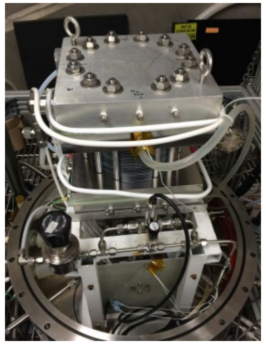
ECLSS Knowledge Transfer

- From a holistic perspective, ECLSS can be enhanced in the following areas:
  - **Lower Level of Component Replacement**
    - ISS implements many ORU hardware systems that require replacement of an entire assembly given a single component failure
      - Example: the OGA cell stack includes the electrolyzing membranes among other components, is housed within a sealed dome that is not designed to be opened during flight
      - Consequently, if any component within this dome fails, the entire assembly must be replaced
    - The development of the Advanced Oxygen Generation Assembly (AOGA) is designed to allow for the replacement of individual components within the dome, enhancing maintenance efficiency
    - Overall, it could simplify on board repairs, return to function more quickly, and require less crew time



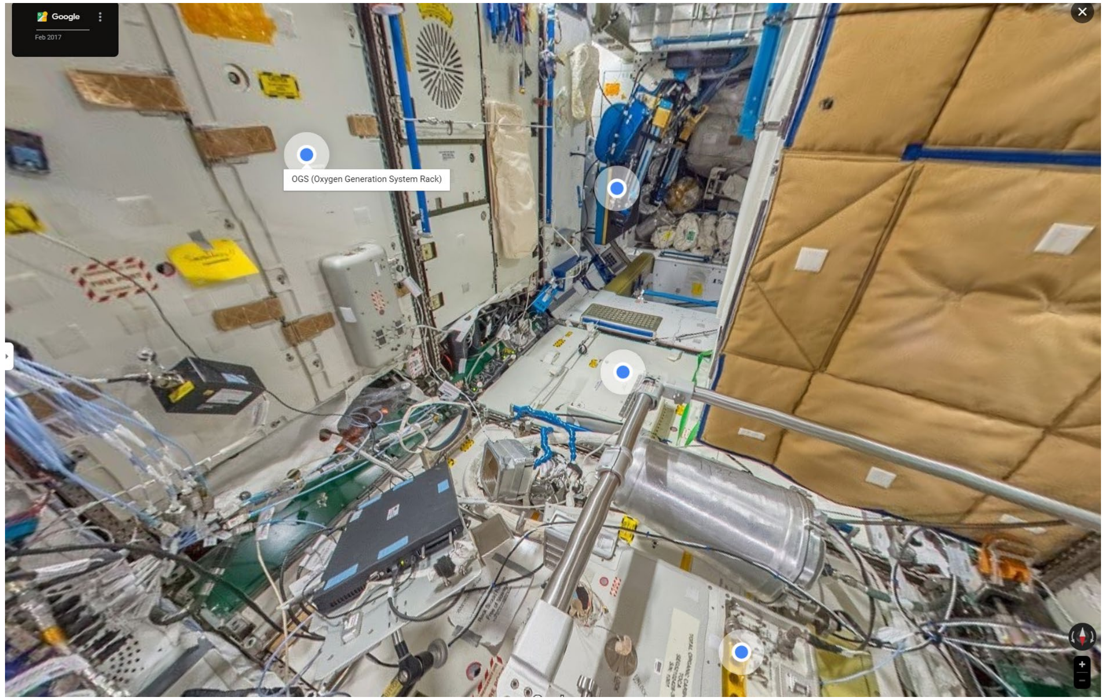
ISS OGA Simplified Schematic [7]



Giner 28 Cell Stack [8]

ECLSS Knowledge Transfer

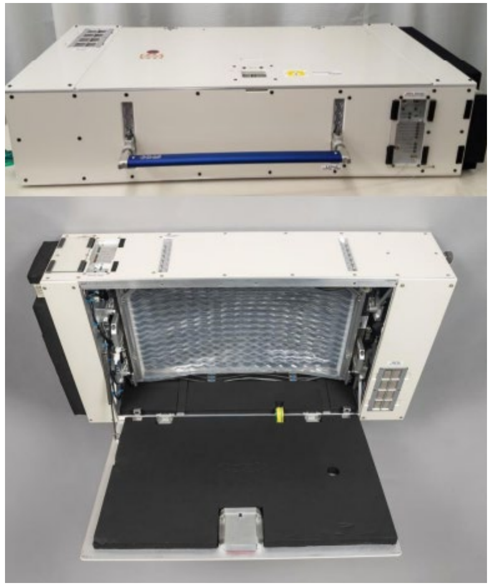
- From a holistic perspective, ECLSS can improve in the following areas:
  - Lower Level of Component Replacement
  - **<u>Anticipating and planning the design space in advance</u>**
    - During the initial design phase, accurately forecasting and anticipating the free volume presents a significant challenge
    - The ISS ECLSS, especially within Node 3, encompasses an extensive array of air subsystems and hardware
    - Node 3 faces a notable limitation of sufficient rack space to accommodate the addition of the CO2 Reduction System. To resolve this spatial challenge, it has been proposed that the Oxygen Generation System rack be relocated to the US Laboratory module



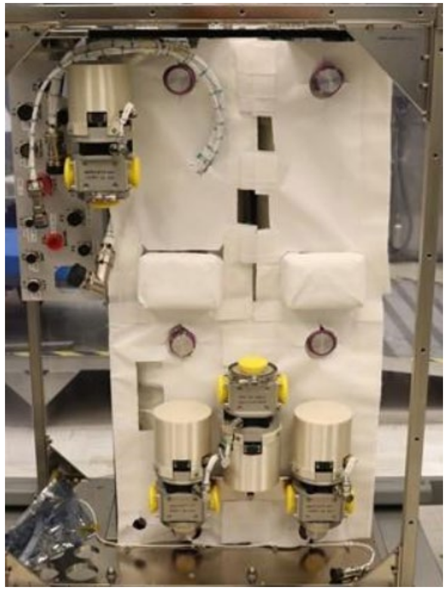
ISS Node 3
Image Credit: Google Map

ECLSS Knowledge Transfer

- From a holistic perspective, ECLSS can improve in the following areas:
  - Lower Level of Component Replacement
  - Anticipating and planning the design space in advance
  - **Considerations on Future Power Availability**
    - Power demands constantly increasing
    - ECLSS is an evolving system with the aim to closing the loop as much as possible
      - Increasing loop closure rate demands a higher power availability
      - Incorporation of additional exploration technologies
      - Example:
        - Exploration Tech Demo – Brine Processor Assembly and 4BCO2 Assembly



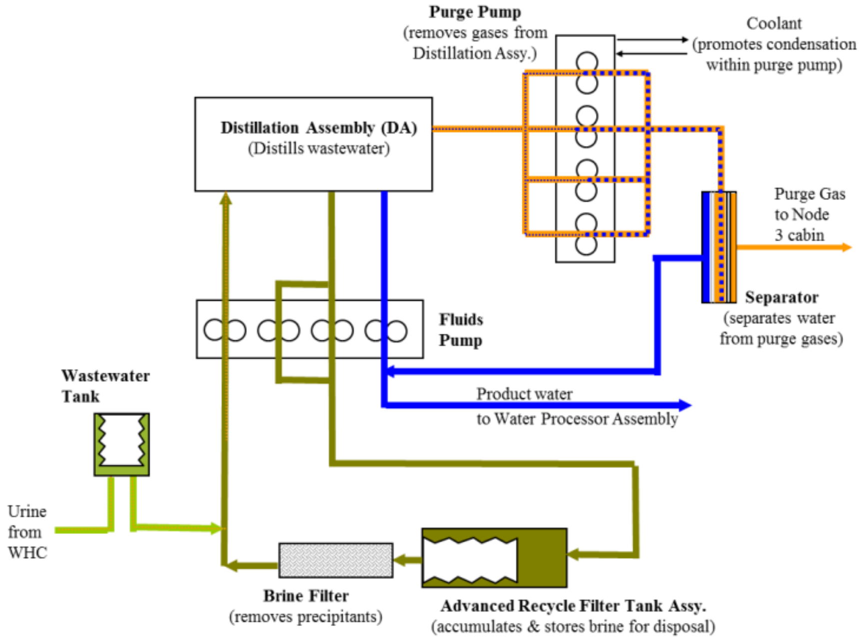
Brine Processor Assembly [9]



4BCO2 Assembly [10]

ECLSS Knowledge Transfer

- From a holistic perspective, ECLSS can improve in the following areas:
  - Lower Level of Component Replacement
  - Anticipating and planning the design space in advance
  - Considerations on Future Power Availability
  - **Maintainability and Crew time concern**
    - Reducing the frequency and complexity of maintenance tasks can lead to substantial cost saving by:
      - The implementation of automated systems and smart sensors
        - Incorporating a conductivity sensor in the brine loop and a quantity sensor on the ARFTA could provide valuable insights on urine/brine characteristics for processing downstream
        - Incorporating IMV fan dp sensors can avoid the need of crew time to perform inspection



Urine Processor Assembly Schematic [11]

ECLSS Knowledge Transfer

- From a holistic perspective, ECLSS can improve in the following areas:
  - Lower Level of Component Replacement
  - Anticipating and planning the design space in advance
  - Considerations on Future Power Availability
  - Maintainability and Crew time concern
  - **Universal Hose/Connector Design**
    - The implementation of a universal hose and connector design can significantly streamline operations
    - Allows for flexibility in use
    - However, there are concerns of inadvertent improper connections
      - It could be mitigated with special keying for important hose and connector application

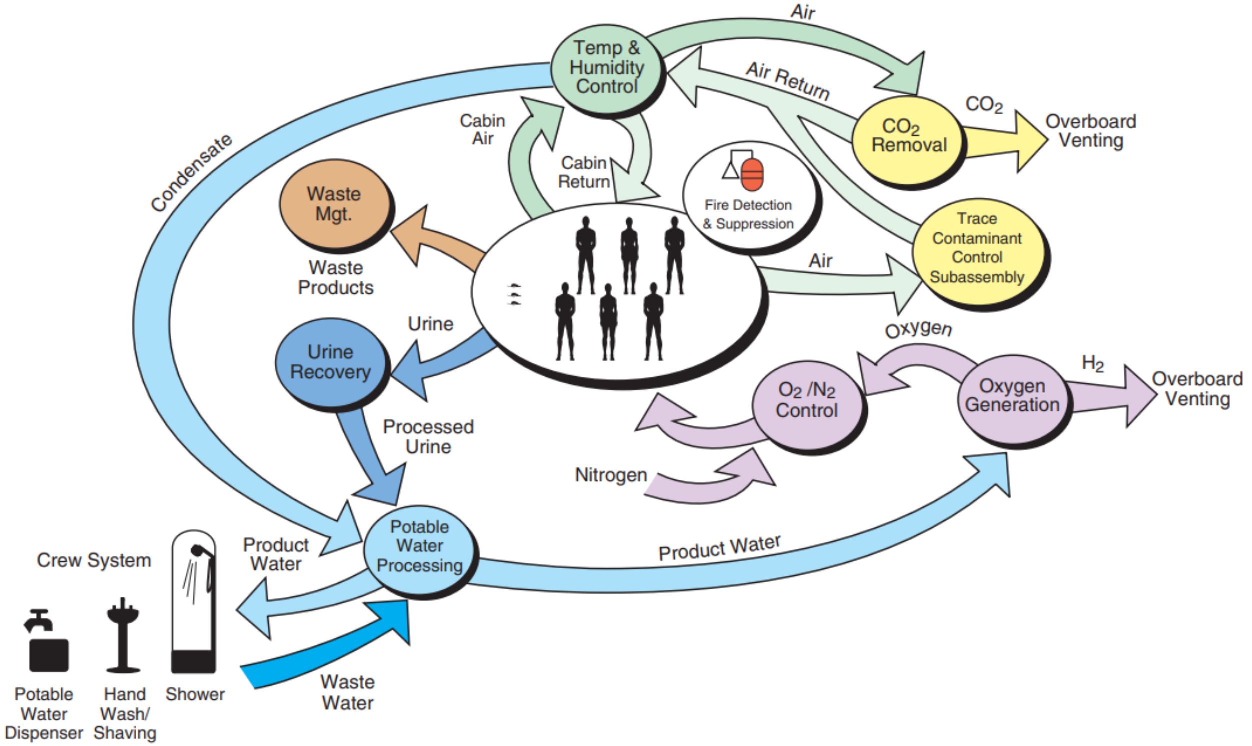
Universal Hose and Connector Illustration

ECLSS Knowledge Transfer

- From a holistic perspective, ECLSS can improve in the following areas:
    - Lower Level of Component Replacement
    - Anticipating and planning the design space in advance
    - Considerations on Future Power Availability
    - Maintainability and Crew time concern
    - Universal hose/connector design
    - **System Integration and Testing**
        - During the integration of the ISS ECLSS, it was observed that compatibility issues often arose between the upstream and downstream hardware
            - Key challenges included size discrepancies in the piping and mismatches in flowrate acceptance capabilities
        - Ground-based system integration and testing enable engineers to ensure that all components work seamlessly together, reducing the risk of costly and time-consuming corrections in space
        - Multiple components built by different groups may not work together as expected
            - Testing full integrated system and ensuring compatibility before launch to avoid issues on orbit

ISS ECLSS Subsystems

- Beyond system level considerations, it is also important to evaluate the subsystem level of ECLSS
- ISS ECLSS consists of the following major subsystems:
  - Atmosphere Control and Supply (ACS)
  - Temperature and Humidity Control (THC)
  - Water Recovery and Management (WRM)
  - Atmosphere Revitalization (AR)
  - Vacuum System (VS)
  - Oxygen Generation System (OGS)



Regenerative Environmental Control and Life Support System Diagram

Atmosphere Control and Supply (ACS)

- The ACS subsystem is pivotal in managing the cabin atmosphere aboard the ISS, ensuring optimal living conditions for the crew
- While the ACS has demonstrated reliability and effectiveness in maintaining a conducive environment, there is room for improvement, particularly in the conceptual design phase:
  - **Operational Considerations**:
    - Nitrogen and oxygen quick disconnects with unique keying prevent incorrect connections, enhancing safety
      - However, specific keying may hinder rapid configuration changes during emergencies
    - Portable device for pressurizing and depressurizing small volumes can conserve gas consumables and optimize air management
  - **Noise Mitigation**:
    - ACS gas supply line is a significant noise source due to turbulence, cavitation, valve operations, and resonance
    - Design improvements: minimize sharp bends, ensure smooth valve operations, maintain optimal gas flow speed and pressure
    - Aim to reduce noise without needing extensive acoustic attenuation
  - **Design with Gas Type in Mind**:
    - Different gases require tailored resupply strategies based on specific applications and needs
    - High-pressure oxygen needs complex refilling procedures for EVA support
    - Simpler air resupply systems for compensating ambient air loss from cabin leakage

Temperature and Humidity Control (THC)

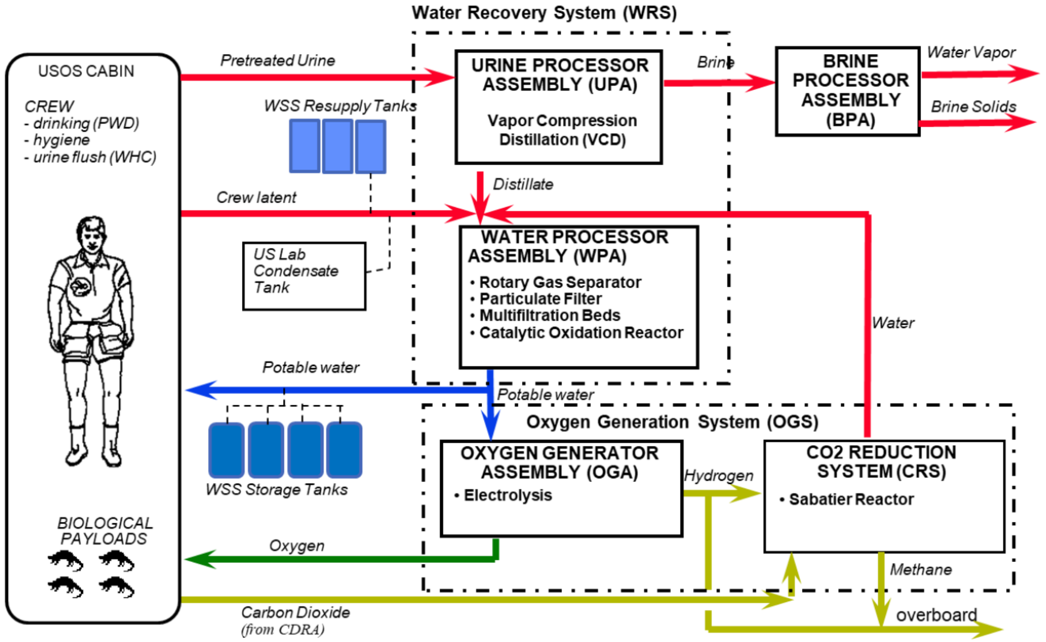
- ISS THC Subsystem provides cabin air heat removal, air mixing, and ventilation within and between modules
- The THC subsystem has faced many challenges during operations:
  - **Operational Considerations**:
    - Managing microbial and fungal growth within the condensing heat exchangers on the ISS involves using HEPA filters and performing heat exchanger dryouts
      - Maintenance intervals have been extended from 33 to 90 days, improving operational flexibility and reducing the frequency of dryouts
    - Redundant systems allow for continuous functionality during maintenance activities such as heat exchanger
    - Standardizing hardware with universal hoses and using predictive models for spares can optimize maintenance and spare part management
    - Portable fans enhance crew comfort and airflow in unventilated areas
    - Remotely operated valves improve safety and operational efficiency, and flexibility to reconfigure ventilation with temporary ducting is useful for unexpected situations
    - Noise mitigation requires careful design considerations and regular acoustic surveys

Temperature and Humidity Control (THC)

- **Foreign Object Debris (FOD):**
  - FOD accumulation on fans has led to diminished airflow, affecting ventilation efficiency
  - Preventative measures include incorporating screens and filters to protect fans and ease cleaning and testing commercial airflow sensors to monitor airflow
  - Delta pressure sensors can provide early warnings of airflow disruptions caused by FOD accumulation
- **Stowage Blocking Ventilation:**
  - Effective air circulation within a module must accommodate variations in stowage, equipment placement, and crew movement
  - Biannual video surveys identify and address obstructions in ventilation paths
    - The utilization of machine learning can help reduce ground engineering support time by identifying potential obstructions
  - Designing module layouts with integrated stowage spaces can prevent blockage of air diffusers and returns, reducing reliance on manual surveys
- **Modeling Capability:**
  - Computational Fluid Dynamics (CFD) models and accurate heat load modeling predict changes in atmospheric conditions and ensure adaptability
  - These tools assist in decision-making processes and evaluate the feasibility of configuration changes
  - Ensuring specific environmental requirements for scientific experiments can optimize research outcomes and maintain habitat well-being

Water Recovery and Management (WRM)

- WRM is an invaluable part of ECLSS system as it ensures a consistent supply of potable water for drinking, hygiene, oxygen generation, urinal flushing, and various payload requirements
- WRM's design shall consider the following:
  - **Water Balance Considerations:**
    - Align water supply capabilities with anticipated demand to ensure efficiency
    - Manage flow rates to avoid bottlenecks in the water cycle
    - Consider hardware constraints and storage capacities, especially for contingency situations
    - Develop contingency plans and account for the limited shelf life of stored water.
  - **Maintenance and Sparing:**
    - Select water filters carefully to balance operational efficiency and safety
    - Ensure availability of spare water hoses and other components for troubleshooting and maintenance
    - Coordinate design with medical sciences and human factors to accommodate biological changes and diverse crew needs



Water Recovery and Management Architecture for the ISS US Segment [11]

Water Recovery and Management (WRM)

- **Design coordination/Integration with Medical Sciences, Human factors:**
  - Early medical consultation can prevent failures, such as the issue with calcium sulfate in the UPA system
  - Adapt designs to cater to diverse crew members and consider variations in waste collection devices
- **Simplicity of Design:**
  - Design water and toilet systems to be simple and intuitive, minimizing training and operational errors
  - Avoid overly complicated operations that can lead to hardware errors, as seen in the Space Shuttle STS-123 mission
- **Separate Hygiene from Waste Collection:**
  - Separate hygiene areas from waste management to ensure cleanliness and availability
  - Provide designated spaces for body cleaning, hair washing, and tooth brushing away from toilet areas
- **Waste Collection and Maintenance:**
  - Ensure toilets are available for frequent use by coordinating maintenance with crew schedules
  - Assess waste collection system quantities based on crew needs and expected maintenance downtime
  - Plan for alternate units during maintenance to support multiple crew members

Air Revitalization (AR) and Vacuum System (VS)

- Air revitalization within the ECLSS is essential for creating a safe, livable atmosphere in space, primarily by removing CO_2, managing trace contaminants, and replenishing oxygen levels. Due to the complex nature of this system
- **<u>Operational Considerations</u>**
    - Having the capability to start/stop hardware mid-cycle if needed, specifically the CO_2 scrubber
    - ISS hardware can typically take 1.5 hours to 12 hours, depending on the hardware so make sure time is allocated for the operational impact for this phase.
    - Consider modularity of components to adapt to changing requirements would be advantageous
        - For example, ISS $ppCO_2$ desired control ranges have changed since the original CDRA development work.
    - Having the ability to activate additional contingencies for scrubbing beyond the baseline design can be useful
        - ISS has had multiple instances of visiting vehicles bringing strange odors or elevated-off gassing of volatiles that has required activating redundant hardware or even cobbling together an additional situational scrubber using IMV ducting and spare filters.

Oxygen Generation System (OGS)

- ISS OGS has been a pivotal subsystem of the ECLSS to produce breathable oxygen for the crew through the electrolysis of water, aiming to establish a closed-loop system
- Following challenge and insight can be beneficial during the early design phase:
  - **Design Challenges & Operational Considerations**:
    - Achieving high electrolysis efficiency in microgravity is challenging
    - Robust and dependable components are essential for extended missions
    - Common failures in sensors can be catastrophic without proper contingencies
    - Modular and replaceable ORU components simplify maintenance in space
    - Real-time diagnostics can enhance system reliability and safety
  - **Improved Sustainability**
    - On-site oxygen generation reduces the need for heavy oxygen tanks from Earth
      - Reducing payload weight allows for more efficient spacecraft designs
    - Cost-effective launch services improve the economic viability of space missions
  - **Contingency Planning**
    - Redundant components and failsafe mechanisms ensure crew safety
    - Emergency response procedures and crew training enhance system resilience
    - Rapid response to malfunctions is critical for uninterrupted oxygen supply

Conclusion

- The ISS has been a key platform for scientific research and technological development over the past 25 years
- Designing an ECLSS involves multiple subsystems and disciplines, with early ISS insights helping to mitigate current issues
- Collaborate early with safety, maintenance, and health teams to ensure safe and low-level maintenance tasks
- Minimize connector types to simplify crew training and avoid fluid line cross-connections
- Address high calcium levels in urine and challenging acoustic levels in modules with team assistance
- Develop a well-thought-out spares strategy, balancing on-orbit storage and launch needs
- Conduct thorough ground testing to minimize early failures and redesign hardware as necessary
- Ensure adequate filters upstream of ventilation fans for easy cleaning and maintenance by crew members

Reference

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