Advancing ECLSS Reliability Modeling: Integrating ISS Data for Sustainable Long-Duration Mission Planning

ICES-2025-127

Presenter: Cynthia Reuland, *Aerodyne Industries*

NASA JSC EC3 ECLS Subsystem Manager

Authors: Leon Chen, *The Aerospace Corporation*

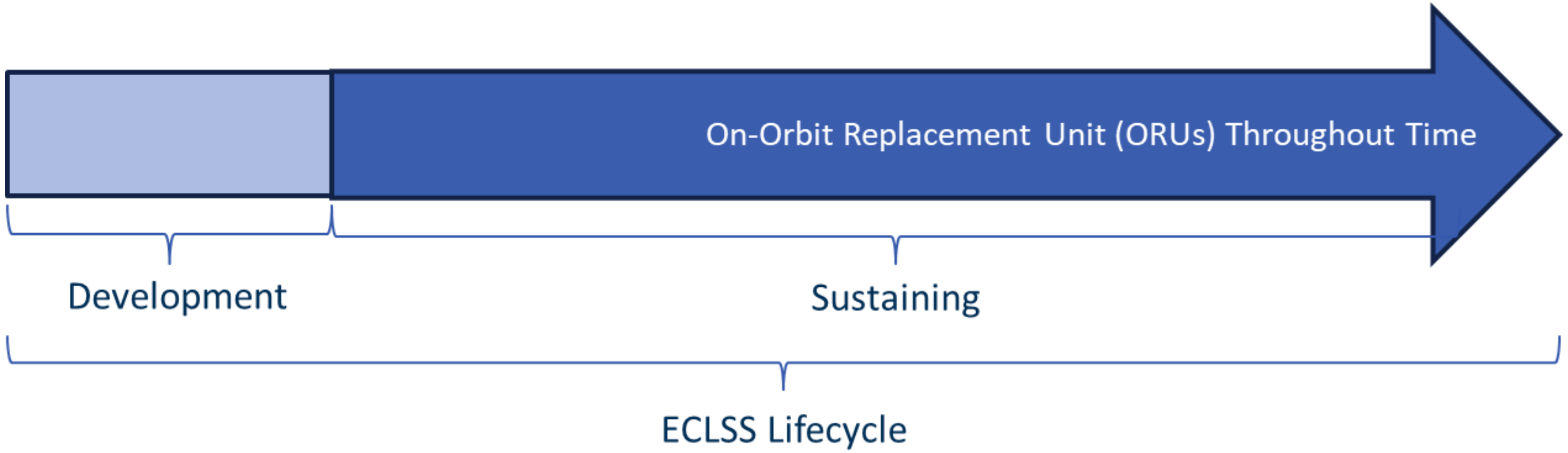
Joseph Rivas, *Amentum*

Alicia Rangel *NASA JSC EC3*

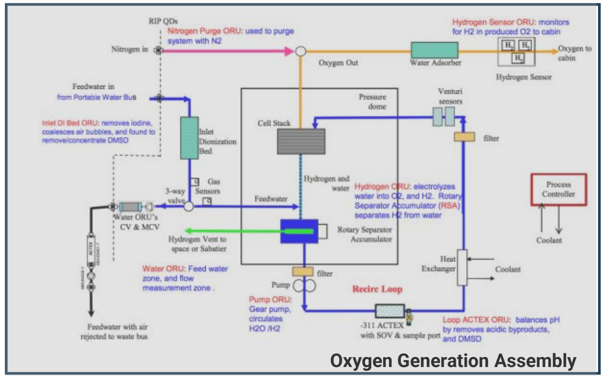
54th International Conference on Environmental Systems (ICES)
13-17 July 2025, Prague, Czech Republic

ECLSS Sustaining

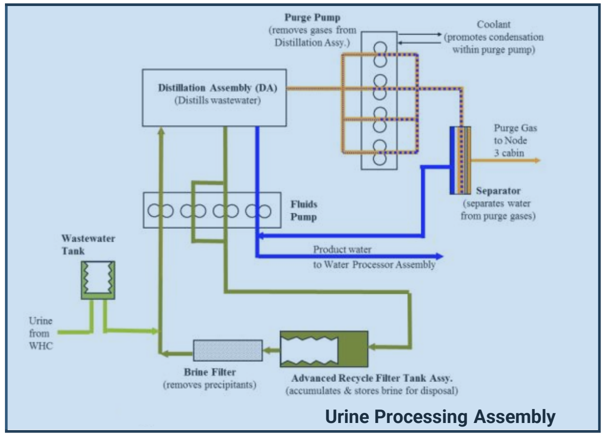
- In evaluating ECLSS loop closure rate and system architecture, the development model plays an essential role
- Another key component of ECLSS design, what completes the picture, is the consideration of the sustaining phase
- Increasing mission durations in human spaceflight necessitates designing ECLSS systems for resilience
- Achieving resilience involves balancing additional redundancy, spares, and consumable margins against their costs and impacts on system reliability



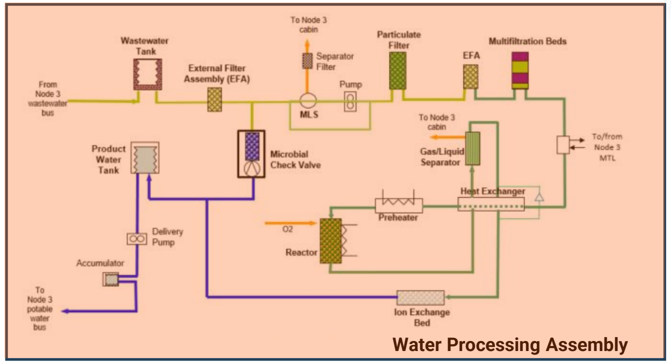
ECLSS Sustaining



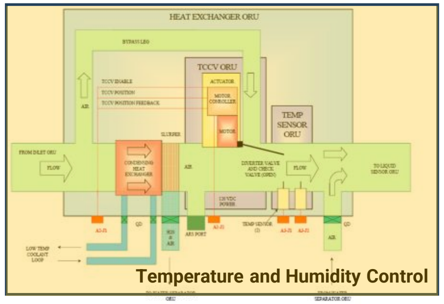
Oxygen Generation Assembly



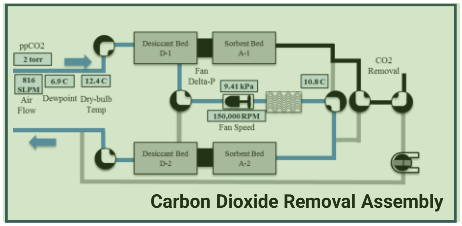
Urine Processing Assembly



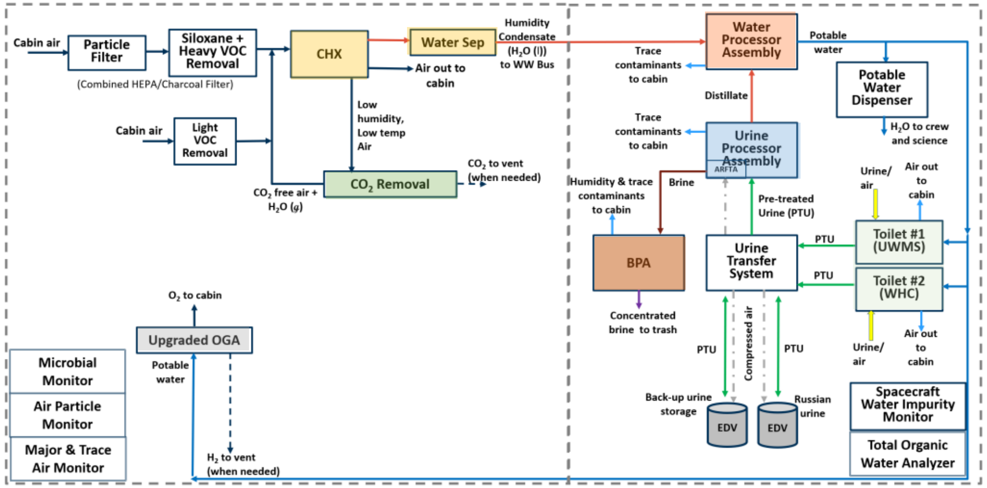
Water Processing Assembly

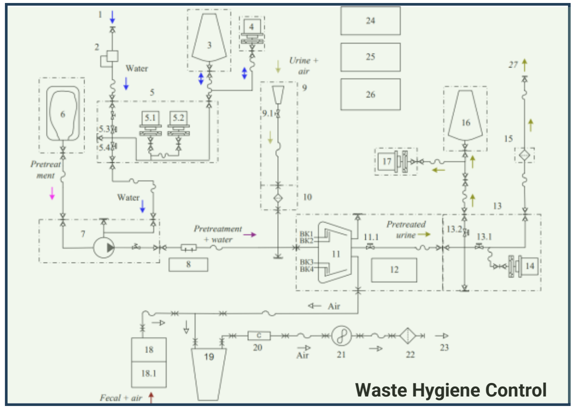


Temperature and Humidity Control

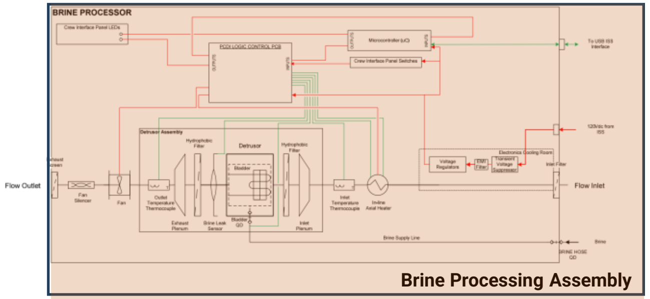


Carbon Dioxide Removal Assembly





Waste Hygiene Control



Brine Processing Assembly

Introduction & Motivation

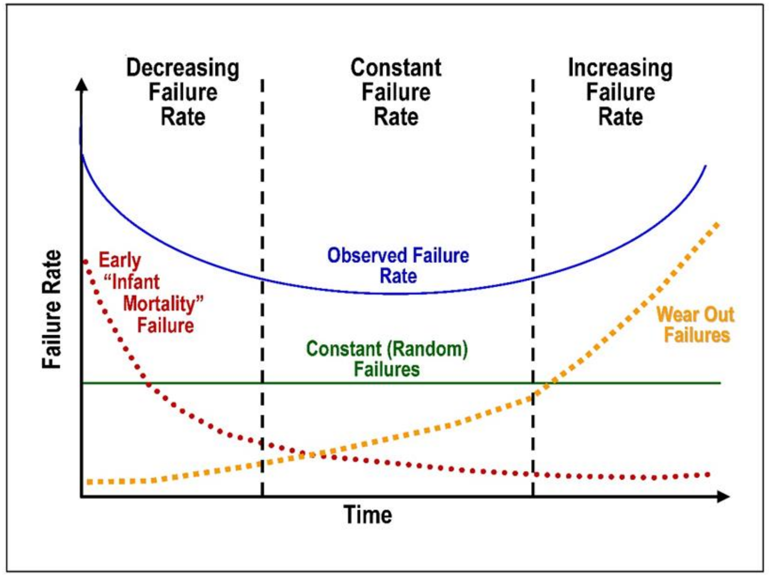
- The Environmental Control and Life Support System (ECLSS) is critically indispensable for the sustenance of human spaceflight, particularly in the context of protracted mission durations
- Identified Deficiencies:
  - Sustainability, as an intrinsic characteristic of ECLSS design, has frequently been accorded insufficient consideration
  - The most recent dissemination of reliability data occurred in 2004, thereby constituting a considerable lacuna in contemporary understanding
  - The absence of updated data impedes the advancement of systems possessing inherent sustainability and resilience
- Mission Imperative:
  - The establishment of robust and reliable ECLSS is of paramount importance for prospective low Earth orbit (LEO) commercial stations, as well as lunar and Martian exploratory endeavors
- Objective of the Present Work:
  - The fundamental aim of this paper is to significantly advance the domain of reliability modeling through the systematic incorporation of recent ISS operational data, specifically pertaining to component replacement rates, shelf life parameters, and throughput limitations

Prevalent Reliability Analysis Methodologies and Associated Limitations

- **Conventional** Approaches (NASA and Industry Standards):
  - A **"lessons learned" paradigm**, deriving insights from historical data and expert consensus, has been traditionally employed
  - The **ISS Risk Management Application** (IRMA) provides a two-dimensional framework for risk assessment
  - **Probabilistic Risk Assessment (PRA)** was developed for implementation within the Space Shuttle program
  - Industry-standard methodologies encompass **Failure Modes and Effects Analysis (FMEA**), **Fault Tree Analysis (FTA),** and **Hazard and Operability (HAZOP)** studies
- ECLSS-Specific Modeling Frameworks:
  - The **Exploration Maintainability Analysis Tool** (EMAT) facilitates the simulation of daily operations, with a primary focus on component reliability
  - **Semi-Markov Process** (SMP)-based algorithms, as developed by Owen, have enhanced spare parts prediction capabilities; however, their scalability has been observed to be constrained
  - **ELISSA/RELISSA**, originating from the University of Stuttgart, permits the simulation of failures and the evaluation of mass, volume, power, and heat attributes
  - **Monte Carlo simulations**, whilst capable of yielding profound insights, are characterized by significant computational demands, and their outcomes are contingent upon the quantity of simulations executed

Methodology - Data Integration Strategies

- Categorization of Failure Modes:
  - Preventive Maintenance
  - Infant Mortality
  - Characteristic Life (inclusive of Wearout or Limited Life phenomena)
  - Random Failures (quantified by MTBF)
  - External Influences (e.g., human error, environmental damage, improper maintenance), tracked through K-Factors
- Constant Failure Rate (CFR) has been commonly utilized with its well-known memoryless characteristic
- Addressing the **Data Deficiency**:
  - Each ECLSS subsystem undergoes a detailed disaggregation into its constituent major components.
  - The performance of these components is meticulously monitored across three primary categories:
    - Mean Time Between Failures (MTBF)
    - Throughput Capacity
    - Shelf Life (where applicable)



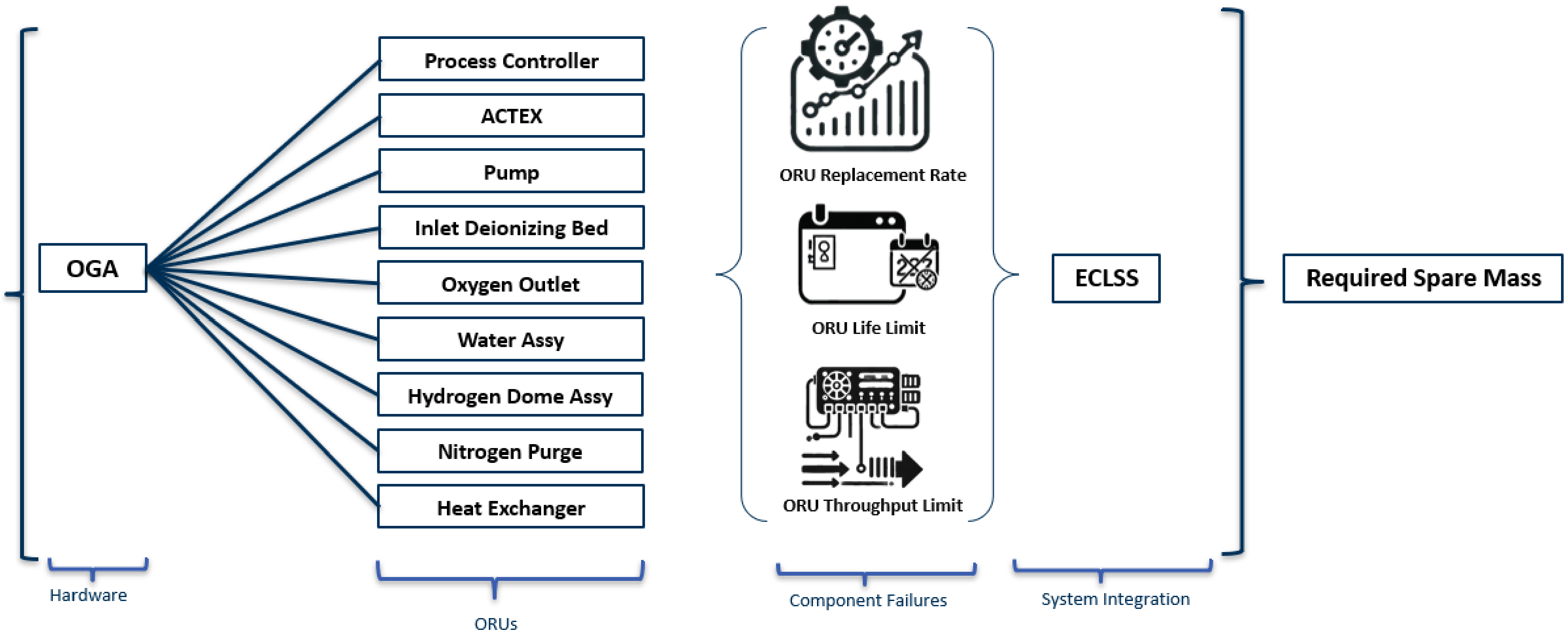
Simplified Bathtub Curve

$$\lambda(t) = \begin{cases} c_0 - c_1 t + \lambda & \text{for } 0 \le t \le \frac{c_0}{c_1} \\ \lambda & \text{for } \frac{c_0}{c_1} < t \le t_0 \\ c_2(t - t_0) + \lambda & \text{for } t_0 < t \end{cases}$$

Simplified Bathtub Curve and Failure Rate Function

Methodology - Data Integration Strategies

- Addressing the Data Deficiency:
  - Each ECLSS subsystem undergoes a detailed disaggregation into its constituent major components.
  - The performance of these components is meticulously monitored across primary categories



Data Extraction and Practical Application

- **Primary Data Repository**: The ISS Maintenance & Analysis Data Set (MADS) constitutes the principal repository for data acquisition
- **Comprehensive ECLSS Reliability Dataset Inclusions**: The dataset encompasses, but is not limited to, the following critical parameters to enable users the flexibility to analyze sparing mass:
  - Orbital Replacement Unit (ORU) mass
  - Operational K-factor
  - Mean Time Between Failures (MTBF)
  - Operational Mean Time to Repair (MTTR)
  - Mean Time Between Preventative Maintenance Remove and Replace (MTBPMRR)
  - Mean Time to Preventative Maintenance Remove and Replace (MTTPMRR)
  - Operational Limited Life
  - Throughput Limited Life
- The complete dataset provides a great opportunity for not only theoretical sparing calculation, but also integration into a comprehensive simulation framework, the details of which will be presented in a forthcoming ICES paper
- The analytical outcomes serve to inform critical decision-making processes pertaining to sparing requirements, maintenance scheduling, and operational readiness

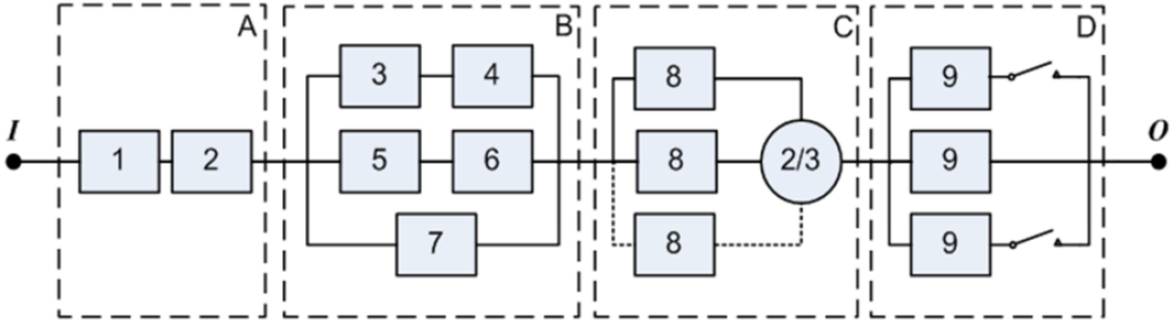
Sample Data

Urine Processor Assembly Reliability Data

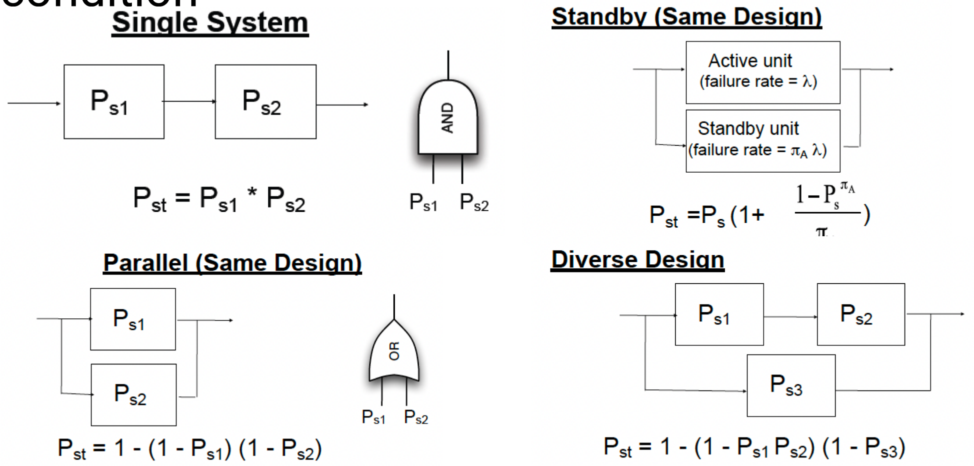
Component	Mass (kg)	MTBF (hr)	MTTR(hr)	Kfactor (-)
Distillation Assembly	75.57	41,376	7	1.84
Firmware Controller Assembly	-	13,453	1.54	1.02
Fluids Control and Pump Assembly	45.59	22,759	1.93	1.19
Pressure Control and Pump Assembly	44.77	59,221	1.19	1.28
Advanced Recycle Filter Tank Assembly	52.62	1,321,000	1	1.38
Separator Plumbing Assembly	172.72	88,993	1.04	2.63
Wastewater Storage Tank Assembly	47.76	82,200	1.48	1.11
	Mass (kg)	**MTBPMRR (d)**		**MTRPMRR (hr)**
Brine Filter	5.35	60		0.17
Purge Filter	1.61	545		0.17
Distillate Filter	1.61	545		0.17

Methodology - Reliability Block Diagrams (RBDs)

- Reliability Block Diagrams (RBDs) serve as a foundational method for representing component interactions within a system through a network of interconnected blocks
- Configurations
  - Series System (Configuration A): The failure of any single component within this configuration precipitates system failure.
  - Parallel System (Configuration B): The system remains operational provided at least one component continues to function.
  - k-out-of-n System (Configuration C): System functionality is maintained if a minimum of 'k' components are operational.
  - Passive Redundancy (Configuration D): Backup components are activated solely upon the failure of primary components.
- While the majority of ECLSS subsystems exhibit characteristics of a series system, the overarching system-of-systems architecture may judiciously incorporate other configurations to enhance overall reliability and assure operational continuity under diverse condition

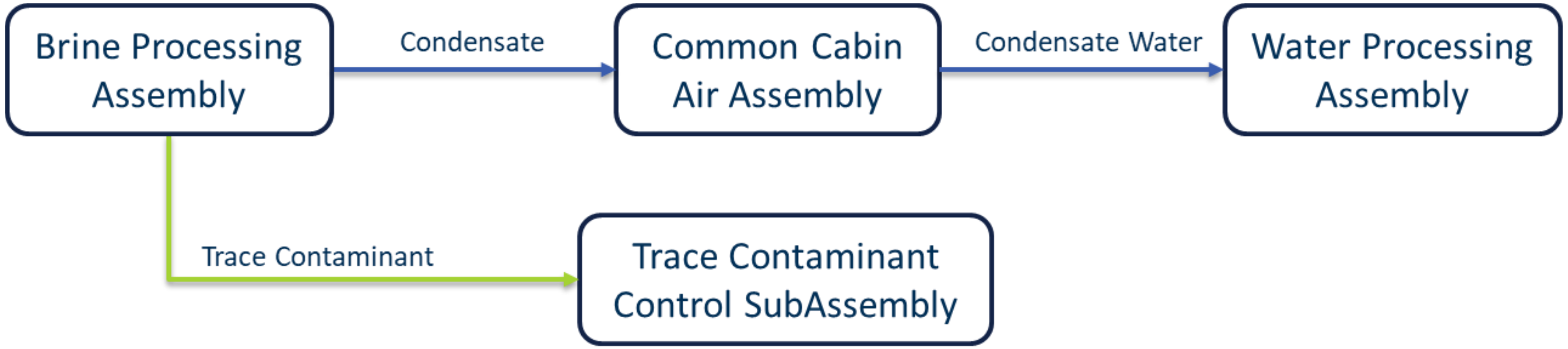


Reliability Block Diagram



Illustrative Example: Brine Processor Assembly (BPA)

- ECLSS, system of systems, serves as a prime example which can be greatly benefited from the mindset of RBD
- Taking Brine Processing Assembly (BPA) as an example:
- **Inter-System Interaction**: The hot, humid exhaust generated by the BPA is processed via the Common Cabin Air Assembly's (CCAA) redundant Condensing Heat Exchanger (CHX) configuration. This subsystem interaction is represented by Blocks A and D within the RBD
- **Holistic System Evaluation**: The comprehensive understanding of ECLSS as a system-of-systems, including the intricate interdependencies among its constituent elements, is emphasized
  - Refer to ICES-2025-125 for insight on ECLSS Integration "Unveiling the System-of-Systems Complexity in Regenerative ECLSS: Insights from ISS"



The Consequential Impact of Crew Time

- **Previously Overlooked Factor:** Numerous prior investigations have posited an instantaneous replacement following component failure, thereby neglecting significant operational and logistical constraints
- **Real-World Operational Constraints:** The availability of crew, conflicts in scheduling, training prerequisites, and overarching operational limitations introduce substantial delays in the restoration of system functionality
- This work presents previously unavailable data pertaining to the crew time required for the removal and replacement (R&R) of major ISS Orbital Replacement Units (ORUs)
- **Key Performance Indicators:**
  - Mean Time to Repair (MTTR)
  - Mean Time to Preventative Maintenance Remove and Replace (MTTPMRR)
- The crew time has the potential to be utilized to evaluate the system downtime. These delays demonstrably influence system performance, overall reliability, and the potential consequences arising from hardware failure events

Concluding Remarks and Future Endeavors

- This work provides the most up to date data for future reliability studies
- This work also establishes a foundational framework for the development of integrated simulation environments, thereby merging reliability analysis with resource planning and logistics management.
- The findings are instrumental in the design of resilient and autonomous ECLSS architectures, requisite for lunar, Martian, and commercial low Earth orbit (LEO) missions, wherein repair windows, spares logistics, and crew resources are stringently constrained
- The fidelity of future simulations will be enhanced through the integration of functional behavior and probabilistic system reliability across mission timelines
- The paramount goal of this research is to facilitate the transition towards sustainable, protracted human exploration beyond the confines of low Earth orbit

Questions?

JSC Crew & Thermal Systems Division

Backup