

Unveiling the System-of-Systems Complexity in Regenerative ECLSS: Insights from ISS

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In regenerative Environmental Control and Life Support Systems (ECLSS), the intricate interconnectivity between subsystems is critical for ensuring sustainable life support in space habitats. This paper aims to provide a comprehensive analysis of ECLS subsystems by highlighting their interactions and dependencies within the larger system. While most studies focus on individual components or subsystems, the true complexity of ECLSS emerges at the system-of-systems level, where the connections between subsystems drive overall functionality and resilience. Due to the inherent complexity of ECLSS and its tightly coupled subsystems, understanding the holistic interdependence remains a challenge. This paper addresses this gap by using the International Space Station (ISS) as a case study, given its advanced regenerative ECLSS architecture. We walk through the major ECLS subsystems, deconstructing each one to examine its interdependencies, resource flows, potential failure modes, and backup mechanisms. For each subsystem, we explore subsystem decomposition: breaking down its components and functions, connections to other subsystems and resource exchanges, impacts of failures on interconnected subsystems, redundancy considerations and backup solutions in case of subsystem failure. An interconnectivity table will also be presented, illustrating the relationships between subsystems and how they contribute to the system-of-systems structure. This analysis provides new insights into the design, operation, and reliability of future regenerative ECLSS, with implications for long-duration missions and space habitat sustainability and exploration.

Acronyms and Nomenclature

AAA	= Avionics Air Assembly	Assembly	
ACS	= Atmosphere Control and Supply	ARS	= Air Revitalization Subsystem
ARFTA	= Advanced Recycle Filter Tank	BPA	= Brine Processor Assembly

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<i>CCAA</i>	= Common Cabin Air Assemblies	<i>ORU</i>	= Orbital Replacement Unit
<i>CDRA</i>	= Carbon Dioxide Removal Assembly	<i>PBA</i>	= Portable Breathing Apparatus
<i>CWC</i>	= Contingency Water Container	<i>PCA</i>	= Pressure Control Assembly
<i>DA</i>	= Distillation Assembly	<i>PCP</i>	= Pressure Control Panel
<i>DI</i>	= Deionization	<i>PCPA</i>	= Pressure Control and Pump Assembly
<i>ECLSS</i>	= Environmental Control and Life Support System	<i>PWD</i>	= Portable Water Dispenser
<i>EVA</i>	= Extravehicular Activities	<i>PSM</i>	= Power Supply Module
<i>FCA</i>	= Firmware Controller Assembly	<i>RPCM</i>	= Remote Power Control Module
<i>FDS</i>	= Fire Detection and Suppression	<i>R&R</i>	= Remove and Replace
<i>FPCA</i>	= Fluids Control and Pump Assembly	<i>RSA</i>	= Rotary Separator Accumulator
<i>GLS</i>	= Gas Liquid Separator	<i>SPA</i>	= Separator Plumbing Assembly
<i>IMV</i>	= Intermodule Ventilation	<i>SM</i>	= Service Module
<i>ISPR</i>	= International Standard Payload Racks	<i>TCCS</i>	= Trace Contaminant Control System
<i>ISS</i>	= International Space Station	<i>UPA</i>	= Urine Processor Assembly
<i>LEO</i>	= Low Earth Orbit	<i>UTS</i>	= Urine Transfer System
<i>LNS</i>	= Liquid Nitrogen System	<i>UWMS</i>	= Universal Waste Management System
<i>MCA</i>	= Major Constituent Analyzer	<i>USOS</i>	= U.S. Orbital Segment
<i>MDM</i>	= Multiplexer/Demultiplexer	<i>VES</i>	= Vacuum Exhaust System
<i>MF</i>	= Multifiltration	<i>VRS</i>	= Vacuum Resource System
<i>MLS</i>	= Mostly Liquid Separator	<i>WHC</i>	= Waste Hygiene Compartment
<i>NORS</i>	= Nitrogen Oxygen Recharge System	<i>WPA</i>	= Water Processor Assembly
<i>QD</i>	= Quick Disconnects	<i>WSTA</i>	= Waste Storage Tank Assembly
<i>THC</i>	= Temperature and Humidity Control	<i>WVA</i>	= Water Vent Assembly
<i>OGA</i>	= Oxygen Generation Assembly	<i>WRM</i>	= Water Recovery and Management
<i>OGS</i>	= Oxygen Generation System	<i>WRS</i>	= Water Recovery System
		<i>WSS</i>	= Water Storage System

I. Introduction

The Environmental Control and Life Support System is a highly complex system of systems, integrating multiple subsystems that work together to ensure crew survival in space. Each subsystem performs essential functions while interacting with others in a tightly coupled framework. However, ECLSS has often not been evaluated as a system of systems, resulting in gaps in comprehensive technology assessment and system-level optimization. This lack of holistic evaluation becomes particularly evident in the development of new technologies, system trade studies, and the establishment of frameworks for long-term sustainability.

One of the primary reasons ECLSS is not usually treated as a system of systems is that each subsystem is often developed, tested, and improved in isolation. For example, advancements in oxygen recovery technologies, such as the Sabatier reactor or Bosch process, are typically evaluated within the atmosphere revitalization domain without fully considering their downstream impacts on water recovery, waste management, or overall system closure rate.

A system-of-systems approach would enable cross-functional evaluation, allowing engineers to understand how changes in one subsystem impact the entire life support architecture. To achieve a comprehensive understanding of system interdependencies, subsystems should be deconstructed and analyzed in the context of their interactions. The ISS serves as an unparalleled testbed for this purpose, leveraging decades of operational experience in system management. The ISS also provides a valuable use case for future space station development, aligning with NASA's efforts to establish new commercial space stations under various Space Act Agreements, ensuring continued human presence in Low Earth Orbit (LEO).^{1,2}

The establishment of reliable ECLSS—through improved system understanding and technological advancements—will be critical to the success of these commercial enterprises. This paper aims to leverage over two decades of ISS operational knowledge to inform the design of future ECLS systems. It focuses on the integration of system management and operational perspectives to develop robust and efficient life support architectures, enabling sustained human presence in space.

II. System Decomposition

This inherent complexity of ISS ECLSS makes a deep understanding of system integration not just important, but essential. Each subsystem plays a critical role in regulating atmospheric conditions, recovering water, processing

waste, and supporting other essential life-sustaining functions, ensuring both crew safety and mission sustainability in space. To gain a deeper understanding of resource flow and system interconnectivity, the system and its operations are decomposed and analyzed at the individual subsystem level, enabling a comprehensive assessment of their interactions and dependencies.

A. Water Recovery and Management

The ISS Water Recovery and Management (WRM) System’s primary functions are to store, distribute, collect, and dispose of water within the U.S. Element which ensures the availability of potable water for crew drinking, hygiene, oxygen generation, urinal flush water, and payloads as needed. The system collects wastewater in the form of crew urine, humidity condensate, and Sabatier product water, which is then processed by the Water Recovery System (WRS) into potable water. This potable water is supplied to the potable bus for various uses and can be stored in water bags for future supplementation.³

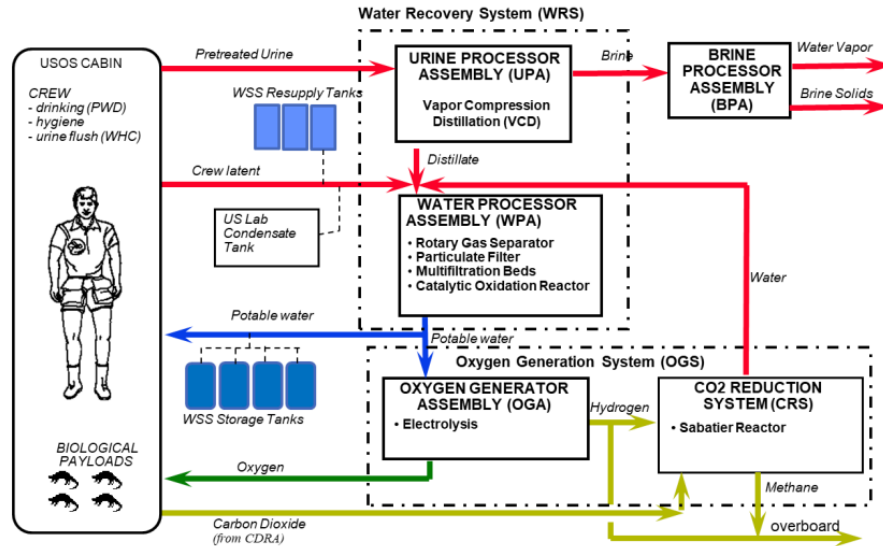


Figure 1. Water Recovery and Management Architecture for the ISS US Segment ³

One of the primary components of the U.S. Element WRM subsystem is the condensate and wastewater distribution network. This network is a sophisticated plumbing system comprising pipes, flexible lines, joints, quick disconnects (QDs), Gamma fittings, valves, and a storage tank. Its primary function is to transport condensate and wastewater from their sources to the Condensate Storage Tank and the Water Vent Assembly (WVA), with system pressure maintained by the Condensate Storage Tank.

The Condensate Storage Tank is a positive-expulsion bellows tank designed with an Inconel bellows to store condensate water collected from the Temperature and Humidity Control (THC) Common Cabin Air Assemblies (CCAA). This water travels through the Condensate/Wastewater Distribution Bus before being stored in the tank. Typically, the tank’s contents are offloaded into a Contingency Water Container (CWC), a large, flexible bag used aboard the ISS or shuttle for water storage and transport. The CWC connects to the condensate tee in the U.S. laboratory module for offloading and can also be directly attached to the CCAA to collect condensate during maintenance activities or other off-nominal scenarios. It is filled using water-line pressure and manually emptied by pumping out the water.

In situations where water venting is necessary, the Water Vent System provides a contingency method for disposing of excess condensate and wastewater. However, this system is not typically used during standard operations.

The regenerative part of the WRM is the WRS. The WRS is comprised of the Urine Processor Assembly (UPA) and Water Processor Assembly (WPA), which are located in two International Standard Payload Racks (ISPR).

The UPA is responsible for recovering water from pretreated urine, which is delivered either directly from the U.S. Orbital Segment (USOS) Waste Hygiene Compartment (WHC) or via manual transfer from the Russian Segment’s EDB containers. Pretreated urine consists of crew urine, flush water, and a pretreatment formula containing chromium trioxide and an inorganic acid to inhibit microbial growth and prevent the conversion of urea to ammonia. While sulfuric acid is used in the Russian Segment, the USOS uses phosphoric acid to address calcium sulfate precipitation

issues. The pretreated urine is pumped into the Waste Storage Tank Assembly (WSTA) and subsequently into the UPA recycle loop by the Fluids Control and Pump Assembly (FCPA). In the recycle loop, the pretreated urine is processed using a Vapor Compression Distillation (VCD) process within the Distillation Assembly (DA). This process operates at low pressure, where wastewater is rotated within the DA to create a thin fluid film on the inner drum surface, enabling evaporation without the need for added heat. The vapor is then condensed on the outer surface of the same drum, recovering the latent heat of condensation to improve efficiency. The recovered water, called urine distillate, is filtered and pumped to the Wastewater Tank of the WPA for further treatment. The DA includes a rotary centrifuge for waste evaporation and compression, driven by a rotary lobe compressor. Non-condensable gases and water vapor are removed from the DA by the Pressure Control and Pump Assembly (PCPA), a peristaltic pump system that condenses water through liquid cooling and transfers it to the Separator Plumbing Assembly (SPA). The SPA recovers and redirects condensed water from the purge gases back into the product distillate stream, maximizing water recovery. The waste brine remaining after distillation is stored in the Advanced Recycle Filter Tank Assembly (ARFTA), a bellows tank designed for filling and draining aboard the ISS. Once the brine is concentrated to the required limit, it is emptied into EDB containers, which are transferred to the Russian Rodnik tank aboard the Progress vehicle for disposal. The ARFTA is then refilled with pretreated urine to initiate a new processing cycle. A Firmware Controller Assembly (FCA) provides command control, monitoring, and data downlink for the UPA's sensors and components.³ While the UPA efficiently recovers water from urine, it does not produce potable water directly. Instead, it outputs two products: distillate and waste brine, which is either stored or further processed by Brine Processor Assembly (BPA) to recover additional water. And to accommodate the expansion of water management, Urine Transfer System (UTS) added to the water system to establish its connection to toilet and others.

The WPA processes wastewater to produce potable water for the ISS potable water bus. The feedwater for the WPA includes distillate from the UPA, humidity condensate from the Wastewater Bus, and Sabatier product water when available. This feedwater is first stored in the Waste Water (WW) Tank before undergoing processing. The process begins with the Mostly Liquid Separator (MLS), which removes free gases from the water before it enters the main pump. The water is then pumped through a 300-micron External Filter Assembly (EFA) to capture biofilm and debris from the Wastewater Tank. Next, it flows through a 0.5-micron particulate filter, which protects the downstream components, including the Multifiltration (MF) Bed. The MF Bed contains adsorbent and ion exchange media to remove non-volatile organic and inorganic impurities from the water. Prior to 2019, the WPA used two MF Beds in series; however, this was streamlined to a single MF Bed in July 2019. Volatile organics that are not effectively removed by the MF Bed are oxidized in the Catalytic Reactor, which operates at elevated temperatures. The reactor also eliminates microbial contamination. Excess oxygen and gaseous by-products generated during oxidation are removed in the Gas Liquid Separator (GLS). The water then flows through a regenerative heat exchanger for cooling before entering the Ion Exchange Bed. This bed removes any dissolved and soluble by-products from the catalytic reactor and adds iodine to the water as a biocide to ensure microbial control. The processed water is stored in the Water Storage System (WSS), where it is made available for use in the ISS potable water bus. The WPA provides a highly efficient system for treating wastewater streams and ensuring a reliable supply of potable water for the crew and systems onboard.³

The BPA operates aboard the ISS as a technology demonstration for NASA's exploration missions, enhancing water recovery by processing brine generated by the UPA. This system achieves approximately 98% water recovery by utilizing a specially designed membrane-based bladder. The bladder enables water vapor to pass through via a process called membrane distillation, which is supported by heated forced convection. The reclaimed water vapor is then captured and processed by the established humidity control systems aboard the ISS, completing the final stage of water reclamation.^{5,6}

As shown in Figure 2, the WRM integrates several subsystems and components to ensure efficient water recovery and management. The system interfaces with the Universal Waste Management System (UWMS) and the WHC, which deliver pretreated urine to the UTS. The UTS transfers urine to be processed within the WRS and produce potable water. This potable water is distributed via the Water Storage System (WSS) to downstream users, including the potable water dispenser (PWD) and eXploration potable water dispenser, oxygen generation system (OGS), and toilets. By integrating these systems, the WRS achieves a high water recovery rate, supporting the partial closed-loop environmental control and life support needs of the ISS.

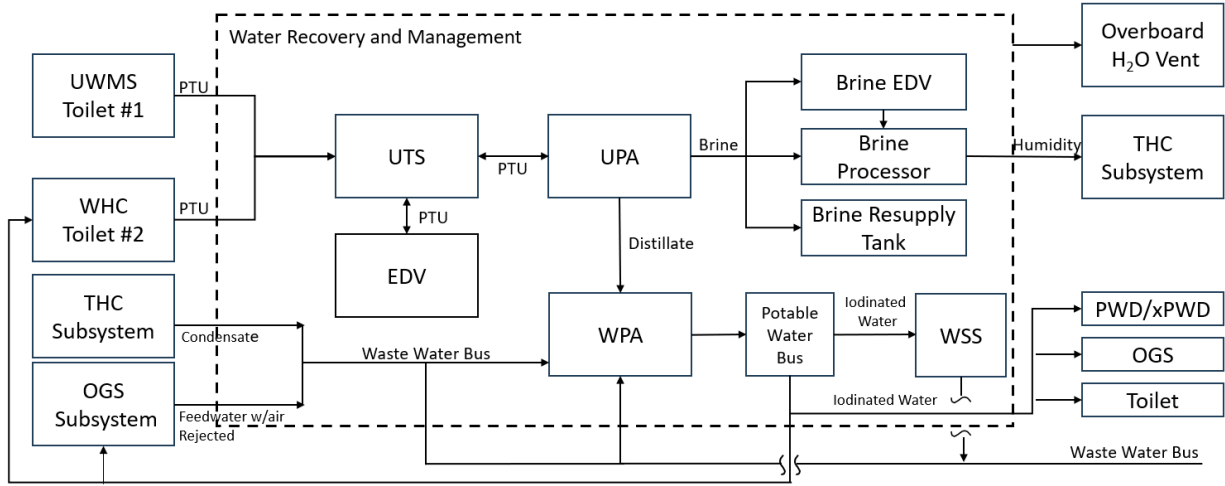


Figure 2. WRM Interface

B. Waste Management

Waste management aboard the ISS ensures the collection and disposal of human waste, a critical function for maintaining crew health and system operations. The station is equipped with three toilets: the ACY located in the Service Module (SM), the WHC, and the Universal Waste Management System (UWMS) in the USOS. Currently, the UWMS is in a stand-down configuration due to unresolved technical issues.

The integration of the WHC into the ECLSS aboard the ISS is a vital aspect of maintaining a sustainable and habitable environment for astronauts. The WHC is responsible for the collection, containment, and initial processing of human waste, which directly ties into the broader goals of the ECLSS to recycle resources and minimize waste. Urine collected in the WHC is transferred to the UPA within the WRS, where water is extracted through distillation and purification processes. This reclaimed water is then reused for drinking, hygiene, and oxygen generation via the Oxygen Generation Assembly (OGA), creating a closed-loop system that drastically reduces the need for resupply missions.⁷

Additionally, the WHC's solid waste management system collects fecal matter and packages it for safe storage and eventual disposal in cargo vehicles, such as Cygnus, which burn up upon reentry into Earth's atmosphere. Proper containment of solid waste is essential to prevent contamination of the cabin air and surrounding equipment. To achieve this, the WHC is integrated with the Air Revitalization Subsystem (ARS) to manage airflow and prevent odors and humidity from spreading throughout the ISS. Ventilation fans and air filters within the WHC ensure that waste-related gases, such as ammonia and methane, are captured and treated to maintain air quality.

The WHC's integration affects other systems as well, as demonstrated in Figure 3. For instance, the high water content in urine requires the thermal control system to dissipate the heat generated during the distillation process in the UPA. Any failure or inefficiency in the WHC, such as blockages in waste flow or ventilation issues, can have cascading effects on other ECLSS subsystems, disrupting water recovery, air quality, and thermal balance. As a result, careful monitoring, regular maintenance, and redundancy in the WHC's design are critical to ensure reliability and minimize the impact on other components. The interdependence of the WHC with the WRS, ARS, and thermal systems highlights the complexity of the ECLSS, where each subsystem must function harmoniously to sustain life in the unique environment of space.

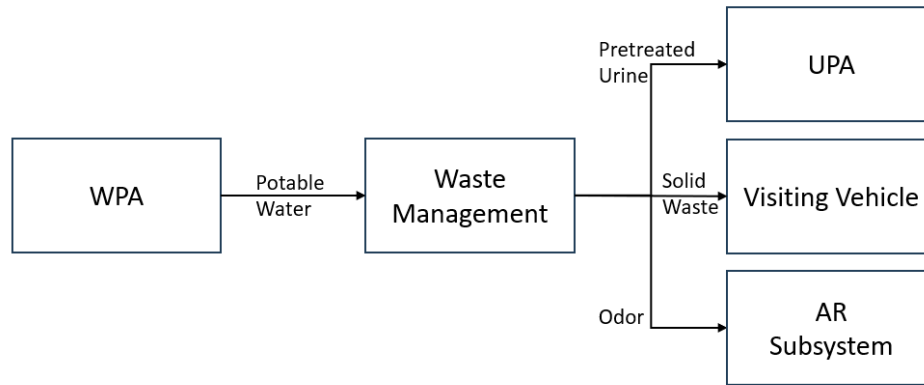


Figure 3. Waste Management Interface

C. Atmosphere Control and Supply

The Atmosphere Control and Supply (ACS) subsystem ensures a safe and breathable atmosphere for the ISS crew in a fully pressurized working environment, simulating Earth-like conditions. This eliminates the need for crew members to wear space suits for extended periods, enhancing comfort and practicality during long-duration missions. It maintains the ISS atmospheric pressure between 724 mmHg (14.0 psia) and 770 mmHg (14.9 psia) and monitors atmospheric composition, providing oxygen (O₂) and nitrogen (N₂) as needed. It utilizes various sources, including Progress, ATV, Elektron, OGA, and U.S. High-Pressure Gas Tanks (HPGTs), and will incorporate the Nitrogen Oxygen Recharge System (NORS) for future refills. Additionally, ACS supports nominal operations, spacewalks (EVA), and pressure equalization between modules.⁸

ACS provides N₂ and O₂ for other ISS systems, payloads, and experiments, utilizing the Liquid Nitrogen System (LNS) for nitrogen supply and the Vacuum Resource System for vacuum-dependent payloads. By maintaining Earth-like conditions and supporting various operations, ACS plays a critical role in ensuring crew safety, comfort, and mission success.

Within the ACS subsystem, the Pressure Control Assembly (PCA) plays a vital role in maintaining the ISS atmosphere. The PCA, which includes the Pressure Control Panel (PCP) and the Vent and Relief Assembly (VRA), performs five key functions: monitoring total atmospheric pressure, detecting and annunciating rapid depressurization, controlling atmospheric composition through the introduction of oxygen (O₂) and nitrogen (N₂), providing vacuum access, and protecting against overpressurization with positive pressure relief.

The ACS subsystem interfaces with two other ECLSS subsystems, as shown in Figure 4. Oxygen is supplied at designated locations for the Fire Detection and Suppression (FDS) Portable Breathing Apparatus (PBA) during emergencies. Additionally, the PCA provides total pressure measurements to the Major Constituent Analyzer (MCA), part of the AR system. The MCA combines this data with its own measurements to determine the partial pressures of atmospheric constituents. It then sends the partial pressure of oxygen (ppO₂) reading to the Integrated System Multiplexer/Demultiplexer (INT SYS MDM), which it can command the PCA to introduce O₂ as needed to maintain proper atmospheric composition.

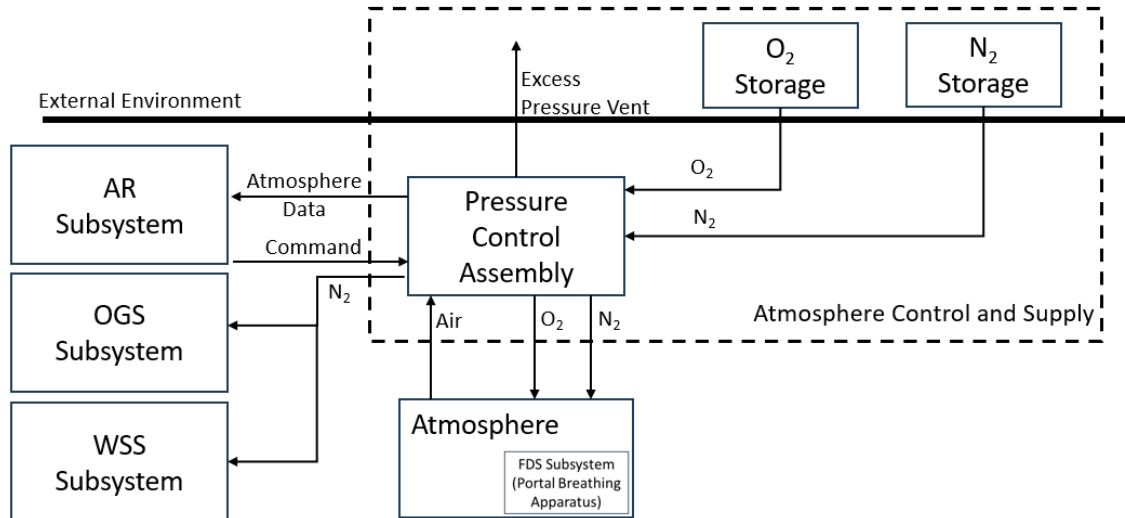


Figure 4. ACS Interface

D. Oxygen Generation System ⁹⁻¹¹

The Oxygen Generation System (OGS) is a vital component of the ISS, designed to provide oxygen for the crew through the electrolysis of water. The system consists of a rack structure housing the OGA, Power Supply Module (PSM), smoke detector, Avionics Air Assembly (AAA), Remote Power Control Module (RPCM), and flexible hoses. At the core of the OGS, the OGA electrolyzes water, producing oxygen and hydrogen.

The OGA is composed of nine Orbital Replacement Units (ORUs) that ensure efficient and reliable operation. The Water ORU manages the flow of feed water, which enters the assembly through feed water valves and sensors and passes through the Inlet Deionization (DI) Bed. The DI Bed removes iodine and other contaminants, coalesces air bubbles, and prevents any oxygen present in the feed water from mixing with hydrogen by rejecting bubble-contaminated water back to the wastewater bus. The Hydrogen Dome ORU contains the electrolysis cell stack, where water is split into oxygen and hydrogen. The oxygen generated is routed through the Oxygen Outlet ORU, which monitors pressure and temperature, removes liquid moisture via a water absorber, and protects downstream hydrogen sensors. The Hydrogen Sensor ORU continuously monitors the oxygen for hydrogen contamination, signaling the Process Controller ORU to shut down the system if any hydrogen is detected. Meanwhile, hydrogen is separated from water in the Rotary Separator Accumulator (RSA) and recirculated by the Pump ORU through a controlled loop known as the recirculation loop. The Nitrogen Purge ORU purges the hydrogen dome and other system lines with nitrogen during shutdowns, ensuring system safety. The Process Controller ORU oversees all OGS commands, operations, and communication with the HCZ Multiplexer/Demultiplexer (MDM). Together, these components allow the OGS to provide a steady and reliable oxygen supply to support crew operations aboard the ISS.

The OGS interfaces with multiple subsystems to support life support and resource recycling as shown in Figure 5. The system receives potable water from the WRS as feedwater for the electrolysis process. Any feedwater containing air bubbles is rejected back to the WRS for further processing, ensuring high-quality input for efficient oxygen generation. The oxygen (O₂) produced by the OGS is delivered directly to the ISS atmosphere, maintaining a breathable environment for the crew. The hydrogen (H₂) generated as a byproduct of electrolysis is sent to the Sabatier System (if present), where it reacts with carbon dioxide (CO₂) to produce water and methane, thereby contributing to the ISS's closed-loop resource recycling. When Sabatier system is not present, or if there is any excess hydrogen, it will be safely vented into space through the Vent System.

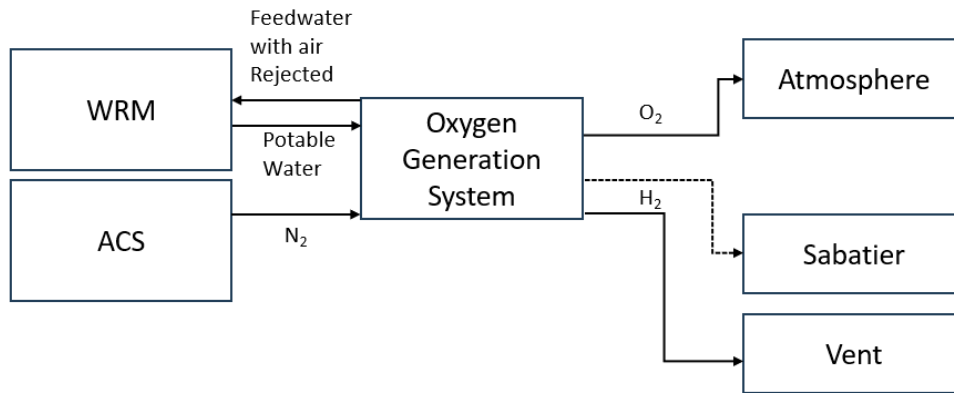


Figure 5. OGS Interface

E. Temperature and Humidity Control¹²⁻¹⁵

The ISS Condition Atmosphere function is implemented by the THC Subsystem whose purpose is to thermally condition and circulate cabin air. Condition Atmosphere functions are shown in Figure 6 along with the hardware implementation, the functions it supports and the redundancy.

Capability	Function	Components	Redundancy	Provide function to	Impacts of loss of function
Condition Atmosphere	Cabin air cooling	CCAA heat exchanger	USL is redundant ISS level redundancy R&R	ARS CO2 removal ARS TCCS	USL 1 FT to ARS other modules ARS wait for R&R
	Cabin air humidity removal	CCAA heat exchanger and water separator	USL is redundant ISS level redundancy R&R	WRS WPA	ISS level 2 FT to WRS WPA receives waste water from any one CCAA WS across ISS
	Intramodule ventilation	CCAA fan	USL is redundant ISS level redundancy R&R	Cabin Smoke detection	USL has redundant fans Remaining modules wait for R&R
	Particulate filtering	HEPA filters	R&R		Wait for R&R
	Reduce load to water processing	Charcoal filters	R&R	WRS WPA	Reduces life of WPA until R&R
	Circulate atmosphere between modules	IMV fan	Some interfaces have supply and return fans R&R	Indirectly for ARS functions	Time to R&R depends on location
	Isolate modules	IMV valve	Automatic Manual operation		Manually open/close valve R&R

Figure 6. Condition Atmosphere

Not shown in the table is the THC function of airflow for smoke detection. The THC subsystem primary components are CCAA including fan, heat exchanger and water separator; Intermodule (IMV) air fans and valves; and AAA including heat exchanger and fan.

ISS was designed to have centralized Regenerative ECLS Systems that are 2 failures tolerant to a catastrophic hazard. The primary regenerative ECLS subsystems (WRM and ARS) are located in Node 3 and USL with the third capability to Remove and Replace (R&R) ORU. The THC subsystem enables the centralized functions by providing intermodule (IMV) circulation throughout ISS to circulate air to the centralized ARS and WRM functions at an ISS ECLS level see Figure 7. Having a centralized ECLS ARS and WRS allows for fewer components contained in every module. ISS is comprised of major modules USL, Node 2, Node 3, Airlock, Node 1, BEAM, International partner

modules Columbus and JEM and smaller volumes are PMA 1,2,3, and Cupola which rely on IMV. Every major module has a CCAA or similar cabin air fan for intramodule ventilation and IMV fans for intermodule ventilation. USL, Node 2, Node 3, and Airlock have full CCAAs and the international partners modules Columbus and JEM provide similar functions. Node 1 has a CCAA cabin fan and relies on other modules for cabin air cooling.

Temperature And Humidity Control (THC)

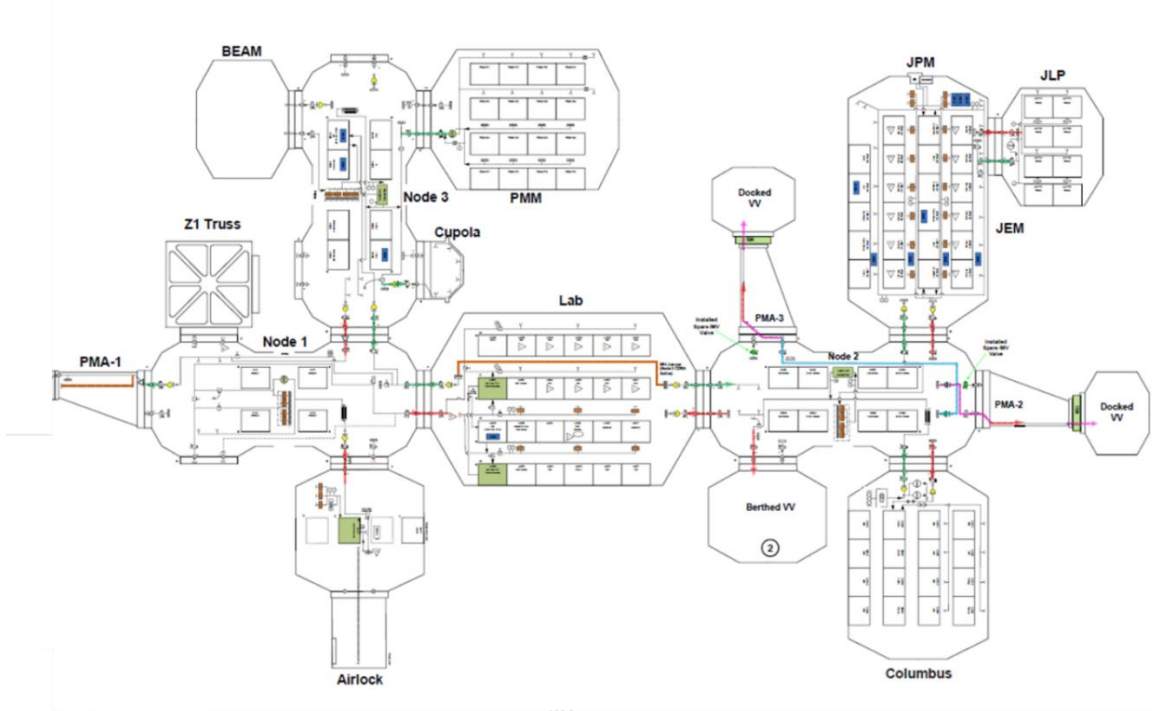


Figure 7. IMV to support Centralized Regenerative ECLS¹⁵

The THC subsystem provides conditioned air to the ARS subsystem to provide less humid air to ARS carbon dioxide removal and ARS trace contaminant control. The THC subsystem removes the humidity from the air through the condensing heat exchanger and separates the air from the water in the CCAA water separator. The water is sent to the waste water bus which goes into tanks for WRS water processing. Figure 8 shows the interfaces of the THC subsystem with ARS and WRS.

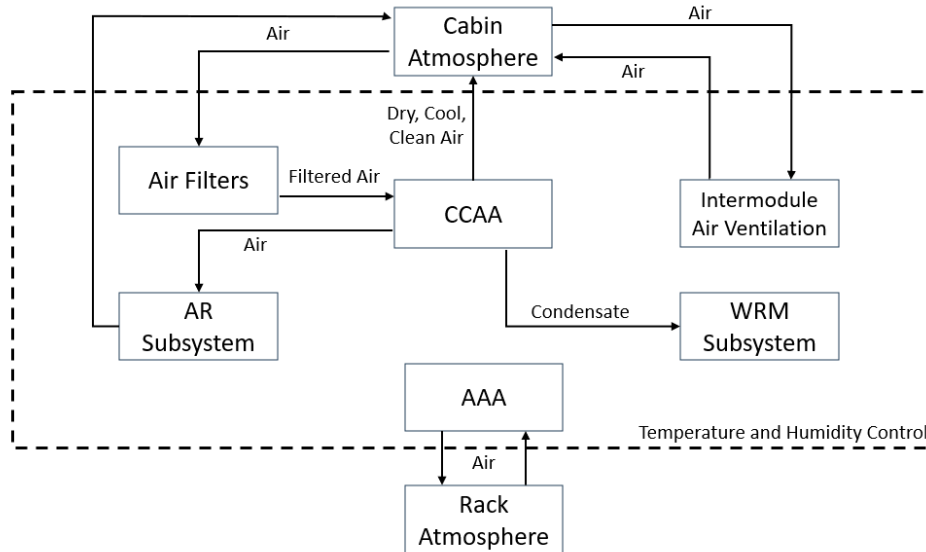


Figure 8. THC Interface

For THC functions that support ARS and WRS functions, the main redundancy method is to R&R components at the ORU level. Having THC functions in multiple modules, allows for short term loss of function while awaiting crew time to perform the R&R. Also, the use of portable fans can be deployed for short term ventilation.

Two redundancy scenarios exist for THC functions supporting ARS. The first scenario is the USL has redundant CCAAs. If one CCAA goes down, then the redundant CCAA can provide air directly to the ARS by changing an air valve position. The second scenario is for Node 3, if the CCAA goes down, then the ARS also has to be powered down since there is not a secondary direct source of airflow. If both ARS subsystems are needed for high crew numbers, then the R&R to fix the failed unit would need to occur sooner to maintain levels. If there is a major unrepairable loss, it is possible to use LIOH beds with a portable fan assembly for short term CO₂ removal.

WRS is connected to a waste water bus and to waste water tanks. Any one of the 5 CCAAs with a water separator can provide waste water to the bus and to the waste water tanks for water processing. Therefore, there is multiple redundancy for THC supporting WRS.

For CCAA R&Rs, there is one spare CCAA fan and one spare water separator maintained On-Orbit to accommodate a failure. A spare CCAA heat exchanger is not maintained On-Orbit due to its large size. In addition, heat exchangers fail over long periods of time and can be observed by data for performance degradation. A spare heat exchanger can be launched in time for the needed R&R. In a worst-case scenario, one of the redundant USL CCAA heat exchangers could be removed and used in another module. Degradation of the heat exchanger is shown in the telemetry by a wet indications from water bypassing the heat exchanger and splattering into the ducting where the sensor detects it. When heat exchangers begin to degrade wet indications become more frequent and are longer durations. The ARS CO₂ removal has a desiccant bed and if too much water passes to the ARS, then it can impact the life of the beds. CCAA heat exchanger degradation can also be seen in the temperature data. The cabin temperature setpoints may not be maintained. The crew can select the temperatures in modules based on crew comfort. If the heat exchanger performance is degrading, then the crew may become uncomfortable. Typically, the frequent long wet indications have driven the need for heat exchanger R&Rs.

Water separator life can also be observed with On-Orbit data for the water separator pressure and also the wet indications. When the water separator, builds up Foreign Object Debris from contaminants over time, the volume of water it can hold decreases. This results in water separator wet indications. Also, the pressure can build and when it reaches a certain pressure, then it needs to be replaced. This data provides insight into the health of the water separators but is not a linear progression. Therefore, an On-Orbit spare is maintained. In addition, the redundant USL CCAA water separator could be used in another location if multiple water separators failed.

IMV supports centralized WRS and ARS functions by circulating air throughout the modules and to the USL and Node 3 for cleaning and processing. IMV contains an IMV fan and valve to perform ventilation and isolation respectively. If an IMV fan fails, it will be removed and replaced. There is one IMV fan On-Orbit as a spare. The USL also has 2 IMV fans at the USL to Node 2 interface which are essentially redundant. Only the port fan is used

predominantly unless more airflow is needed and both starboard and port fans are turned on. If multiple IMV fans fail, then the USL IMV fan can be used.

THC also has AAA fans and heat exchangers that are used for system rack and payload rack cooling and ventilation. The AAAs have temperature indications and speed to observe changes over time. Typically, the fans build up FOD from pulling into the fans and heat exchanger from the rack face cabin air.¹⁵ The AAAs can be cleaned and returned to normal function. Upon a fan failure, there are 2 spare AAAs On-Orbit since there are 35 locations. The AAAs can be R&R to restore system or payload ventilation and cooling.

F. Atmosphere Revitalization (AR)¹⁶

The ACS subsystem introduces oxygen (O_2) and nitrogen (N_2) into the ISS atmosphere to maintain appropriate partial pressures for a breathable environment. Meanwhile, carbon dioxide (CO_2) produced by crew respiration must be removed to ensure crew safety. Trace atmospheric contaminants from equipment off gassing and metabolic processes also require removal, a task performed by the AR subsystem. This subsystem comprises equipment designed to monitor atmospheric constituents and regulate contaminant levels.

The AR subsystem performs CO_2 removal, trace contaminant control, and monitoring of major atmospheric components. The Carbon Dioxide Removal Assembly (CDRA) collects CO_2 from crew respiration and vents it to space or sends it to the Sabatier, if present. The Trace Contaminant Control System (TCCS) removes a variety of contaminants introduced through off-gassing, crew metabolism, leaks, and spills. The MCA monitors and reports on the levels of key atmospheric components. While MCA data can be used by the ACS subsystem to control O_2 injection into the ISS atmosphere, this function is typically managed by ground control. The MCA also provides atmospheric data to crewmembers and flight controllers, helping to track constituent levels and alerting them to off-nominal conditions via Internal Systems software.

As shown in Figure 9, the AR subsystem interfaces directly with three other ECLSS subsystems: the THC, ACS, and Regenerative ECLSS. The CDRA relies on cool air provided by THC CCAA for CO_2 removal, while warm air with reduced CO_2 and trace contaminants from the CDRA and TCCS is returned to THC CCAA. Additionally, THC AAA provides cooling for AR rack equipment.

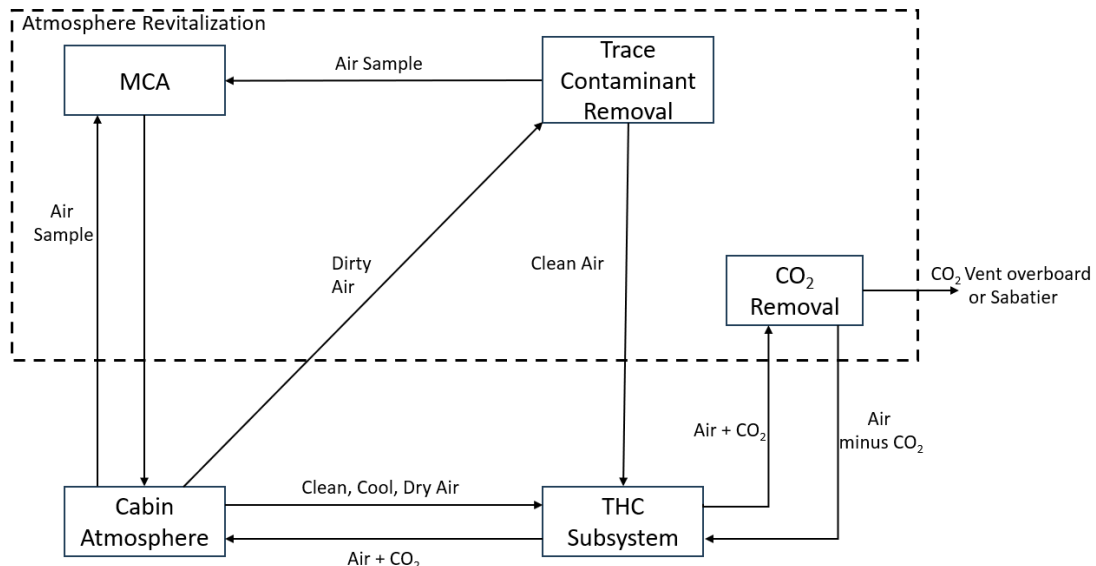


Figure 9. ARS Interface

The MCA receives cabin pressure data from the ACS subsystem and provides atmospheric constituent data back to ACS, which uses this information to determine the need for adding oxygen to the cabin atmosphere. This data exchange between AR and ACS occurs via the Internal Systems MDM. A smoke detector installed in the AR rack ensures fire detection capabilities. Furthermore, AR interfaces with the Regenerative ECLSS by sending CO_2 collected by the Node 3 CDRA to the Sabatier Reactor System for further processing, where it can be converted into water and methane.

G. Complete Interconnectivity for ISS ECLSS

A complete interconnectivity table is illustrated in Table 1. It presents the ECLSS subsystem interconnectivity matrix, illustrating the functional and resource linkages among key components of the ISS regenerative life support architecture. Each yellow-marked cell represents a direct operational dependency or shared resource flow between the corresponding subsystems. The upper triangular format highlights asymmetric relationships, such as how the OGA relies on water from the WPA, while the WPA does not reciprocate that dependency. This matrix serves as a visual summary of the system-of-systems nature of ECLSS, reinforcing the critical importance of integration-aware design and coordinated subsystem management in sustaining a closed-loop habitat.

Table 1. ISS ECLSS Interconnectivity Table

	PCA	CAA	AAA	OGA	O2 Tank	N2 Tank	WPA	WSS	UPA	BPA	Toilet	CDRA/4BCO2	Smoke Detector	CA/Atm Monitor	TCCS/CHiPs	VES/VRS/Vacuum
PCA					X	X								X		
CAA								X		X		X	X		X	
AAA				X			X					X	X			
OGA						X	X	X					X	X		
O2 Tank														X		
N2 Tank								X						X		
WPA								X	X		X		X		X	
WSS									X	X	X				X	
UPA										X	X		X			
BPA																
Toilet																
CDRA/4BCO2													X		X	X
Smoke Detector														X	X	
MCA/Atm Monitoring															X	
TCCS/CHiPs																
VES/VRS/Vacuum																

III. Conclusion

A comprehensive understanding of ECLSS interconnectivity is essential for evaluating new technologies and designing optimized life support systems. Treating ECLSS as a system of systems ensures that subsystems and technologies are not developed in isolation but rather as integrated components working toward a common mission objective. This system-level perspective allows for better compatibility, efficiency, and overall performance, ultimately enhancing mission sustainability and crew safety.

This paper has decomposed and analyzed key ECLSS subsystems, highlighting their interdependencies and resource flows to provide a clear visualization of the system’s complexity. By leveraging insights from the ISS testbed, the analysis reinforces the importance of holistic system evaluation, which is critical for future commercial space station development and deep-space habitats.

Through subsystem-level breakdowns and operational mappings, this study further illustrates how interconnected components collectively ensure the ISS’s closed-loop life support functionality. The cascading effects of individual subsystem failures and the strategies for operational redundancy underscore the critical importance of integration-aware design.

As the space industry advances toward long-duration missions and sustainable human presence beyond LEO, a system-of-systems approach will be pivotal in shaping next-generation ECLSS architectures. This framework will facilitate the seamless integration of emerging technologies, ensuring that future life support systems are not only reliable but also scalable and resilient to meet evolving exploration demands. Grounded in decades of ISS experience, these insights offer a foundation for designing life support systems capable of supporting the next era of human space exploration.

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