International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: 2017-2018

Gregory J. Gentry[1]
The Boeing Company, Houston, Texas

Steven F. Balistreri Jr.[2]
The Boeing Company, Houston, Texas

November 2, 2017 marked the completion of the 17th year of continuous human presence in space on board the International Space Station (ISS). After 54 expedition crews, over 115 assembly & utilization flights, over 180 combined Shuttle/Station, US & Russian Extra-Vehicular Activities (EVAs), the post-Assembly Complete ISS continues to fly and the engineering teams continue to learn from operating its systems, particularly the life support equipment. Major events and challenges for each U.S. ECLS subsystem occurring during the last year are summarily discussed in this paper, along with look aheads for what might be coming in the future for each U.S. ECLS subsystem.

Nomenclature

AC	=	Assembly Complete	*O/A*	=	Orbital Alliance
ACS	=	Atmosphere Control & Supply	*OGA*	=	Oxygen Generation Assembly
AIK	=	Airlock Installation Kit	*OGS*	=	Oxygen Generation System
AR	=	Atmosphere Revitalization	*ORU*	=	Orbital Replaceable Unit
ASV	=	Air Selector Valve	*PDMS*	=	polydimethylsiloxane
ATP	=	Acceptance Test Procedure	*PFE*	=	Portable Fire Extinguisher
BEAM	=	Bigelo Expandable Activities Module	*PFMC*	=	Pump Fan Motor Controller
CHEPA	=	Charcoal High Efficiency Particulate Air	*PM*	=	Preventative Maintenance PPA
CCAA	=	Common Cabin Air Assembly	*RTA*	=	Resupply Tank Assembly RPC
CWC	=	Contingency Water Collection	*R&R*	=	Remove & Replace
CDRA	=	Carbon Dioxide Removal Assembly	*SDS*	=	Sample Delivery System
CHX	=	Condensing Heat Exchanger	*SpX*	=	SpaceX
COTS	=	Commercial Off-The-Shelf	*STS*	=	Space Transportation System
DAB	=	Desiccant Adsorbent Bed	*TCS*	=	Thermal Control System
DMPCS	=	Decamethylcyclopentasiloxane	*THC*	=	Temperature & Humidity Control
DTO	=	Developmental Test Objective	*T/S*	=	Troubleshoot
ECLS	=	Environmental Control and Life Support	*TT&E*	=	Test, Teardown & Evaluation
FI	=	Failure Investigation	*UPA*	=	Urine Processor Assembly
FDS	=	Fire Detection and Suppression	*USOS*	=	United States On-orbit Segment
FW	=	Firmware	*W&HC*	=	Waste & Hygiene Compartment
HEPA	=	High Efficiency Particle Air	*WM*	=	Waste Management
HPGT	=	High Pressure Gas Tank	*WPA*	=	Water Processor Assembly
HOPA	=	Hydrogen Oxygen Purge Assembly	*WRS*	=	Water Recovery Subsystem
HTV	=	H2 Transfer Vehicle	*WRM*	=	Water Recovery & Management
IMV	=	Inter-Module Ventilation	*WSS*	=	Water Storage System
ISS	=	International Space Station	*VES*	=	Vacuum Exhaust System
KSC	=	Kennedy Space Center	*VRS*	=	Vacuum Resource System
MCA	=	Major Constituent Analyzer	*VS*	=	Vacuum System
NORS	=	Nitrogen/Oxygen Resupply System			

[1] Associate Technical Fellow & ISS ECLS Technical Lead, Boeing 3700 Bay Area Boulevard, Houston TX 77058
[2] ISS ECLS Atmosphere Revitalization Technical Lead, Boeing 3700 Bay Area Boulevard, Houston TX 77058

1. Introduction

The International Space Station (ISS) program achieved "Assembly Complete" (AC) in 2010, with the Environmental Control and Life Support (ECLS) system supporting ISS crews and visiting Shuttle and Soyuz crews since assembly began in 1998.

Through AC a total of 16 pressurized elements have been added to the ISS. Since then ECLS activity has focused mainly on maintaining the ISS systems currently onboard while acquiring on-orbit operational knowledge in microgravity. Additional changes to the "AC" ISS configuration continue to occur, including preparations for the first Commercial Crew vehicle arrvials and support for exploration ECLSS techology testing.

A. ISS ECLS OVERVIEW

The ISS on-orbit ECLS system is comprised of 6 subsystems, including Atmosphere Control and Supply (ACS), Temperature and Humidity Control (THC), Fire Detection and Suppression (FDS), Atmosphere Revitalization (AR), Water Recovery and Management (WRM), and Vacuum System (VS). The following sections briefly summarize each subsystem and its function within the ISS pressurized elements.

1. Atmosphere Control and Supply (ACS)

The ACS subsystem provides cabin atmosphere pressure control, overpressure relief, pressure equalization, rapid depressurization detection and response, nitrogen and oxygen distribution, and nitrogen and oxygen high pressure tank recharge from NORS tanks delivered on unmanned logistics vehicles.

2. Temperature and Humidity Control (THC)

The THC subsystem provides airborne heat removal, air temperature control and monitoring, intra-module and inter-module ventilation, humidity removal, and airborne particulate/bacteria removal.

3. Fire Detection and Suppression (FDS)

The FDS subsystem includes smoke detection, fire isolation, fire extinguishment, and fire recovery.

4. Atmosphere Revitalization (AR)

The AR subsystem revitalizes the habitable atmosphere by removing carbon dioxide, potentially hazardous volatile trace contaminants generated by inadvertent spills, crew metabolic processes, and equipment off-gassing such that cabin contaminants levels are maintained within limits. Additionally, the ISS habitable environment is monitored for atmosphere major constituents O_2, N_2, and CO_2, as well as H_2, CH_4, and H_2O. In the United States On-orbit Segment (USOS), the Sample Distribution System (SDS) carries sample cabin air through lines from the various modules to the Major Constituent Analyzer mass spectrometer.

5. Water Recovery and Management (WRM)

The WRM subsystem supplies potable water, hygiene water, and water for payloads, as well as collects humidity condensate. The WRM also provides excess wastewater venting; condensate storage; and potable, waste, and fuel cell water distribution. The WRM subsystem was expanded significantly prior to Shuttle retirement with the addition of the Regenerative ECLS Racks known as Water Recovery System (WRS) 1 & 2 & Oxygern Generation System (OGS), which include the Urine Processor Assembly (UPA), the Water Processor Assembly (WPA) and the Oxygen Generator Assembly (OGA). WRM includes Waste Management (WM) which, for ISS, is the Waste & Hygiene Compartment (W&HC), a U.S. On-orbit Segment (USOS) bathroom that collects solid waste and collects, treats and transports liquid waste to the Urine Processor Assembly (UPA) for water recovery.

6. Vacuum System (VS)

The VS supplies the U.S. Lab module payload rack locations with access to space vacuum. The VS consists of two separate subsystems: the Vacuum Exhaust System (VES) and the Vacuum Resource System (VRS). Connected to all thirteen payload rack locations, the VES can vent payload gases overboard. The VRS provides high-quality vacuum to nine of the thirteen payload rack locations for user access.

2. SUMMARY DISCUSSION OF MAJOR SUBSYSTEM EVENTS IN UNITED STATES ON-ORBIT SEGMENT BY FUNCTION

A. Atmosphere Control and Supply

1. Internal Sampling Adapter (ISA) Pressure Probe Noisy Readings

The ISA pressure probe uses a Crystal Engineering Multi-Cal pressure module. MultiCal modules don't display pressure, since they only have an electrical output. Instead, the modules convert pressure to millivolts. Modules are used with devices capable of measuring DC millivolts, such as a digital multimeters or oscilloscopes. MultiCals are calibrated to convert pressure units (for this model, millimeters of mercury or PSIA) to 1 millivolt per pressure unit.

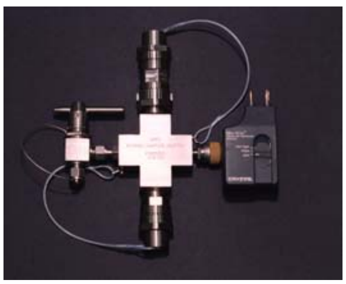

Figure 1 ISA Pressure Probe

Because the mmHg/PSIA model measures absolute pressure, output is always positive.

The ISA is used to monitor pressure of an isolated vestibule during depressurization prior to un-berth of an attached visiting vehicle.

Figure 2 REALM COTS IMS Antennas

During OA-8 undock on December 5, 2017 the ISA was noted to have erratic readings that were impeding the ability to adequately monitor the depress acvtivity. An astute flight control operator noticed concurrent use of the Commercial-Off-The-Shelf (COTS) Inventory Management System (IMS) tool, known as the RFID-Enabled Autonomous Logistics Management (REALM), may be interfereing with the ISA electronics. Some quick trounbleshooting (on board crew switching REALM antennas on and off while monitoring ISA pressure reading) correlated the ISA noisy behavior to times when the REALM antennas were on! Figure 1 depicts the ISS MPEV ISA Pressure Probe. Figure 2 shows two of the NASA COTS REALM IMS antennas in the U.S. Lab module. Electromagnetic interference (EMI) issues have always been a concern with COTS hardware. Forward work is to insure the REALM system is turned off prior to use of the ISA for vestibule depresses.

2. Oxygen Generator Assembly (OGA) Status & OGA H2 ORU F/I status

Figure 3 OGS Rack

The OGS rack was launched on STS-121/ULF1.1 in July 2006 and initially installed in the U.S. Lab module for operation. After Node 3 arrived on STS-130/20A in 2010, the OGS rack (along with WRS 1 & 2 racks) was relocated to Node 3. The OGA has accumulated 62,134 hours of operational run time through January 30, 2018 with an ***average*** production rate of 2.41 kg /day (5.3 lbs./day) oxygen providing a total of 6235 kg (13,716 lbs.) of O_2 and 779 kg (1714 lbs.) of H_2. Figure 3 depicts the OGS rack pre-launch.

As reported in ICES-2017-59 OGA H2 ORU SN 002 suffered a failure resulting in its removal and replacement. The investigation is still in process, however results to date are pointing to an extremely small piece of metallic FOD trapped in cell #1 during manufacturing coupled with compressed membrane cold flow over several years that resulted in an electrical shunt path that caused the anomalous cell #1 electrical signature. Figure 4 shows the FOD discovered on cell #1's MEA. A dedicated paper summarizing this topic is planned for next year's ICES conference.

Hydrogen ORU SN 003, installed and activated on November 10, 2016 after failure of ORU S/N 002 has continued to operate flawlessly despite having a suspect wiring harness.


Figure 4 Cell #1 Metallic FOD

Hydrogen ORU SN 004 (w/rebuilt harness) is the current on-board Hydrogen ORU spare.

Hydrogen ORU SN 005 has been built-up from a kit to an ORU to be the ground ready-to-launch spare.

3. Depress Pump Anomalous Current Draw

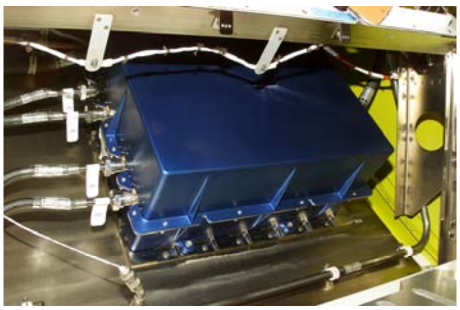
Figure 5 Airlock Depress Pump

The Airlock Depress pump is a two-stage rotary gear-type design built by Rocket Space Corporation Energia. It has accumulated about 160 hours of run time over about 16 years of ISS EVA operations. The expected pump life is 1200 hours.

During Airlock depress activities supporting EVA 44 on October 5, 2017 the observed depress pump current was higher than typical for the initial ~11 minutes of the depress ops. Current draw reached a peak of ~14.5 amps vs. typical levels of ~13 amps. Several EVA airlock depresses have occurred since then with no recurrence of the anomaly. Figure 5 shows the Russian built depress pump in the U.S. Airlock Quest.

4. OGA Hydrogen Sensor ORU sensor #1 Off-Scale High

H_2 Sensor ORUs have three sensor dies to redundantly monitor hydrogen in the oxygen outlet stream. ORU S/N 1005 was put in service (second time around) and shortly thereafter sensor die #1 spiked briefly then came back to normal, while the other two diodes did not register any change. A day later sensor #1 spiked off scale high and railed and has been there ever since. The sensor has been inihibited and the ORU is running on the two remaining sensors. The ORU has a 201 day service life and is scheduled for removal on June 18, 2018. While a fault tree has been developed and electrical circuits and power supplies common to all three sensor dies have been exonerated, determination of root cause will have to wait for the ORU to be returned to the original equipment manufacturer (OEM).

Figure 6 OGA Hydrogen Sensor ORU

Figure 6 depicts the OGA H_2 Sensor ORU.

B. Temperature and Humidity Control (THC)

Figure 9 Final Assembly of New Charcoal Filters at KSC

1. Common Cabin Air Assembly (CCAA) Condensing Heat Exchangers (CHXs) Weldment Repair

Figure 8 CCAA CHX weldment

CCAA CHXs have launched in the U.S. Laboratory *Destiny* module (2), the *Quest* Airlock (1), Node 2 *Harmony* (1) and Node 3 *Tranquility* (1) modules. See Figure 7 for a picture of an ISS CCAA CHX.

During rejuvenation of the returned hydrophobic CCAA CHX's from ISS, one of the weldments sprung a leak. This was one of four available for assembly so it was put on the shelf. The program now needs this weldment on-orbit, so it's leak must be repaired. The repair is in work. Figure 8 shows a CCAA CHX weldment.

2. Polydimethysiloxane (PDMS) Scrubbers update, Node 1 fungus problem and combination charcoal/HEPA status

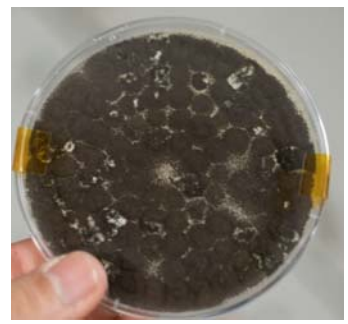

Figure 10 Node 1 Fungus Test Result

While the source of the PDMS contaminants on ISS CCAA CHXs cannot be eliminated, a method of controlling the problem has been developed. A "temporary near term" solution was implemented and flown on SpX-6 in April 2015, as reported in 2015 (Reference: ICES-2015-155). See Figure 9 for a picture of a charcoal filter being assembled at KSC.

Because the modified Charcoal filters are considered an interim step that doesn't directly protect the five installed CCAA CHXs, a long term goal is to scrub the USOS atmosphere to eliminate or reduce CCAA CHX exposure to the PDMS contaminants by installing combined charcoal/HEPA filters, called the Integrated Charcoal HEPA (CHEPA) Filter Assembly, directly ahead of each installed CCAA CHX, located in the U.S. Lab, Airlock, Node 2 & Node 3.

On November 30, 2017 the ISS crew reported a problem with the atmosphere in Node 1. Subsequent sampling and incubation of samples on board ISS showed significant fungal growth as seen in Figure 10. As a result the crew did a "deep clean" of Node 1 including removal of the first set of charcoal filters in Node 1, despite no sign of chemical breakthrough, and installed HEPA filters to reduce fungal contaminants from the atmosphere. Two of the used charcoal filters were brought down on SpX-13 on January 13, 2018 for evaluation to see if fungus was growing on/in the filters. Result is no fungus detected. Source seems to have been a near by trash bag.

C. Atmosphere Revitalization

1. CDRA Desiccant-Adsorbent Bed (DAB) status

Figure 11 "-5" DABs

As of February 2017 the -5 DABs in Node 3 CDRA have accumulated approx. 33 months of run time with the ΔP signature relatively flat, thus curtailing the need for frequent crew maintenance. This has indicated the -5 DAB ORU configuration is performing better than expected (it was estimated that DAB internal screen cleaning would be needed every 3 years).

The second set of -5 DABs, shown in Figure 11, were completed, delivered and launched on HTV-6 December 9, 2016. They were installed in the Lab CDRA on March 2, 2017, bringing both CDRAs on orbit up to the -5 DAB configuration while leaving the -3 bed ORUs on ISS as temporary spares until a third set of -5 DABs are delivered on orbit. These -5 DABs are currently being manufactured for delivery on 11/14/2018.

2. CDRA Blower 149 KRPM Test

Figure 12 CDRA Blower

During the course of 2017, an effort has been made to gain some extra performance from the CDRA Blower in order to help support future 7 crew operations. The goal is to support CO2 removal for larger crew compliments using a single operating CDRA. Stress and containment analysis was completed to demonstrate that the blower could be safely operated up to 150kRPM (110kRPM is the maximum spec speed). On-orbit tests were conducted using both the Node 3 and Lab CDRAs. While the blower itself is capable of operating at the higher speed, the tests proved that additional operational & control hurdles exist to achieve the desired 150kRPM. The US Lab CDRA blower successfully ran up to maximum speed of 139kRPM on HC1 and 142kRPM on HC2, while the Node 3 CDRA reached 133.4kRPM on HC1 and 141kRPM on HC2. The year, 2017, ended with on-going ground testing at MSFC using a development Pump Fan Motor Controller (PFMC) to determine if the controller or software is limiting further speed increases.

3. Node 3 CDRA Heater Controller fault(s)

Figure 13 CDRA Heater Controller

The Node 3 CDRA Heater Controller faulted on 10/19/17. Data analysis showed that the primary heater strings were still operating, however the secondary string was not operational. This fault only occurred on the front bed. After re-starting the CDRA, the secondary string was recovered. Over the last few months of 2017, the controller faulted out several more times. The time between failures decreased with each subsequent failure. Fault tree analysis has yet to determine where the fault exists (i.e., controller, bed, or elsewhere). Opening the Remote Power Controller (RPC) to the secondary string allows the CDRA to remain in continuous operation without faulting. Running on just the primary string is the current operational for the Node 3 CDRA while troubleshooting and fault tree analysis continue.

4. MCA ORU02 F0001 Z-Axis Deflection Issue

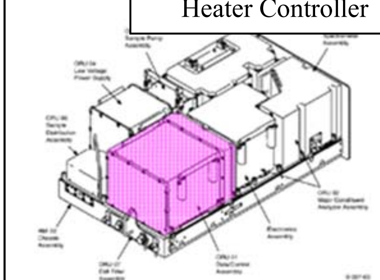

Figure 14 MCA

During calibration, an issue with Z-axis deflection tolerance was noted with ORU02 F0001 while operating with the new firmware version 4.25. (See Figure 14.) During calibrations, the ion beam is deflected away from the electrometer cups to obtain the background signal. Under the previous firmware, version 4.18, the deflection was compared to the deflection from the previous calibration. It depended on the signal deflection to be < .25, roughly within 5-7% of the typical 4-5 V undeflected signal. Under the currently installed firmware version 4.25, only the current deflection is mesasured. For a successful calibration, the deflected signal needs to be < 2% of the undeflected signal. Unfortunately, the issue was not detected on the ground because ORUs are tested with firmware version 4.18. To correct for the deflection issue with F0001, corrective values have to be uploaded via a Range Limit 46 command every time a calibration is perfomed. Future ORUs will be ground tested using the new firmware, version 4.25, to avoid issues with Z-Axis deflection.

5. MCA ORU 02 F0001 & F0006 ppO2 discrepancy

During early 2017, MCA operations were performed using both the US Lab and Node 3 MCAs. Improved accuracy for ppO2 is considered +/- .61 mmHg. The variation between the MCAs was recorded as 2.0 mmHg. The readings were not considered an anomaly as both MCAs were giving readings within their specification accuracy. During the investigation, it was discovered that default values for the Verification Gas Assembly (VGA) were used in Node 3, rather than measured readings. No record to date has been noted for the actual Node 3 VGA calibration gas input. It is expected that in 2018 the VGA in Node 3 will be returned to the ground, where data can be gathered to rectify the discrepancy between the two MCAs.

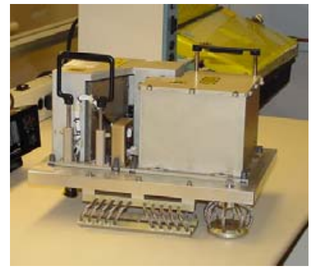

Figure 15 MCA ORU 02

D. <u>Water Recovery Management</u>

As of January 30, 2018 the USOS Water Processor Assembly (WPA) has processed 33,424 kg (73,533 lbs.) of water on ISS. The UPA has provided 15,255 kg (33,561 lbs.) of distillate, and the rest (18,177 kg (39,991 lbs.)) has been combined condensate + Contingency Water Collection (CWC) bag transfers, and includes approximately 1,064 kg (2,342 lbs.) of Sabatier product water.
To date the WPA has processed almost 10 times its hardware weight in water proving that the investment in regenerative water processing systems for ISS has been worthwhile. Accumulated water production through January 2018 is shown in Figure 17.

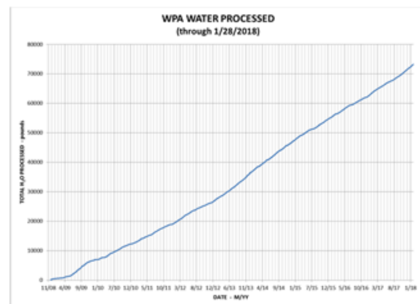

Figure 17 WPA Water Production

1. Reactor Health Sensor (RHS) ORU SN 0003 Suspect QD Missing O-ring

Due to a pressing need on-orbit for a spare RHS ORU a ground unit was quickly processed and delivered for launch on SpaceX-12 on 8/14/2017. After the ORU was launched to ISS it was noted at the hardware supplier that an interfacing QD had an extra O-ring lodged in its interior cavity. After an investigation it was concluded that the most likely location the O-ring may have come from the flight ORU mating QD. While QDs have redundant seals (primary & backup) this would leave the on-orbit ORU with only one seal. While this might work if needed the program is considering returning the ORU to fix the QD, while in parallel prepping another spare ORU for flight. Figure 18 depicts an RHS ORU.

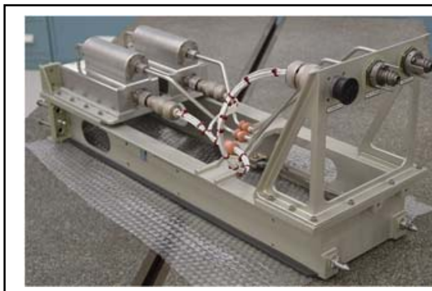

Figure 18 WPA Reactor Health Sensor

2. Water Storage System (WSS) Update

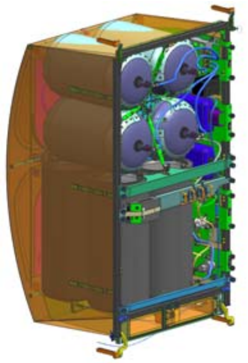

Figure 19 WSS Layout

WSS flight hardware delivery is beginning, with possible launch to ISS in the fall of 2018. Figure 19 shows the WSS installed in a Zero-g Storage Rack (ZSR). Operationally this will help the flight control team and on-board crew to manage the ebb and flow of potable and waste water. When the WPA is down for maintenance or repairs, the WSS will be able to take over the potable bus management duties by providing uninterrupted water feed to crew, OGA and payloads, while also providing a significantly increased waste water storage capability.

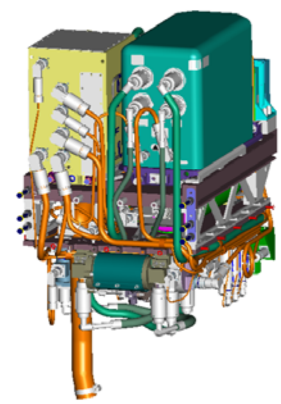

Figure 20 Sabatier Reactor

Sabatier: The Sabatier was removed from the OGS rack and returned to earth on SpX-13 on January 13, 2018. It has been returned to the OEM for disassembly and assessment of its condition. It will be refurbished and re-launched to ISS within the next 2 years. Figure 20 depicts the Sabatier Assembly.

Conclusions/Forward Work

This paper documents ECLS system events encountered mostly between January and December 2017. Significant progress has been made in resolving ISS on-orbit problems to achieve full ECLS system operational status. After almost 18 years on-orbit, the ISS ECLS system has established an outstanding continuum of data and operation, working from a level of experience supporting over 54 Expedition crews, as well as providing support to Shuttle and Soyuz taxi crews.

Opportunities exist to begin flying astronauts to ISS in U.S. commercial crew vehicles in 2018 and NASA has been discussing augmenting the existing ISS ECLS with components and technologies anticipated for exploration, utilizing ISS as a flying testbed for those systems.

Universal Waste management System (UWMS)

The UWMS is scheduled to be flown to ISS as a DTO prior to use on Orion. Delivery is anticipated to be in late 2019 and will be installed adjacent to the existing commode in Node 3.

Brine Processor Assembly (BPA)

The BPA is scheduled to be flown to ISS as a DTO. Delivery is anticipated ot be in late 2019 and installation will be in Node 3.

Lunar Orbitign Platform/Gateway

Definition studies of the Gateway are progressing. As ECLSS architecture is defined new technologies to support the DSG are being considered for flight on ISS, including new CO_2 removal systems, new CO_2 reduction systems, advanced OGA & WPA subsystems and a variety of new environmental monitors.

Acknowledgments

The authors wish to acknowledge the excellent work by the Boeing, NASA and Subcontractor ECLS Team, without whom none of the accomplishments, improvements and investigations reported herein would have been possible. This work was accomplished by NASA and Boeing and its subcontractors under the International Space Station contract NAS15-10000.

References

1. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Equipment Failures, Causes, and Solutions, February 2001 - February 2002, Gregory J. Gentry, Richard P. Reysa, John F. Lewis, SAE Paper 2002-01-2495, 32nd International Conference on Environmental Systems, July 15-18, 2002, San Antonio, Texas.

2. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: February 2002 – 2004, Gregory J. Gentry, Richard P. Reysa, Dave E. Williams, SAE Paper 2004-01-2383, 34th International Conference on Environmental Systems, July 19-22, 2004, Colorado Springs, Colorado.

3. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: February 2004 – 2005, Gregory J. Gentry, Richard P. Reysa, David E. Williams, SAE Paper 2005-01-2778, 35th International Conference on Environmental Systems, July 12-15, 2005, Rome, Italy.

4. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: February 2005 – 2006, Gregory J. Gentry, Richard P. Reysa, David E. Williams, SAE Paper 2006-01-2056, 36th International Conference on Environmental Systems, July 16-20, 2006, Norfolk, VA.

5. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: February 2006 – 2007, Gregory J. Gentry, Richard P. Reysa, David E. Williams, SAE Paper 2007-01-3099, 37th International Conference on Environmental Systems, July 9-12, 2007, Chicago, Il.

6. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: February 2007 – 2008, Gregory J. Gentry, Richard P. Reysa, David E. Williams, AIAA Paper 2008-01-2132, 38th International Conference on Environmental Systems, June 30-July 3, 2008, San Francisco, CA.

7. Development of the International Space Station Nitrogen Oxygen Recharge System, Brandon Dick, Paper AIAA 2013-3499, 43rd International Conference on Environmental Systems, July 14 –July 18, 2013, Vail, CO.

8. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: 2010 – 2014, Gregory J. Gentry, John Cover, Paper ICES-2015-155, 45th International Conference on Environmental Systems, July 12-16, 2015, Bellevue, WA.

9. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: 2015–2016, Gregory J. Gentry, Paper ICES-2016-255, 46th International Conference on Environmental Systems, July 10-14, 2016, Vienna, Austria.

10. International Space Station (ISS) Environmental Control and Life Support (ECLS) System Overview of Events: 2016–2017, Gregory J. Gentry, Paper ICES-2017-059, 47th International Conference on Environmental Systems, July 16-20, 2017, Charleston, South Carolina.