

Shuttle/ISS EMU Failure History and the Impact on Advanced EMU Portable Life Support System (PLSS) Design

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As the Shuttle/ISS EMU Program exceeds 35 years in duration and is still supporting the needs of the International Space Station (ISS), a critical benefit of such a long running program with thorough documentation of system and component failures is the ability to study and learn from those failures when considering the design of the next generation space suit. Study of the subject failure history leads to changes in the Advanced EMU Portable Life Support System (PLSS) schematic, selected component technologies, as well as the planned manner of ground testing. This paper reviews the Shuttle/ISS EMU failure history and discusses the implications to the AEMU PLSS.

Nomenclature

ABO:	Aviator's Breathing Oxygen
ACC:	Auto Cooling Control
AEA:	Assured EMU Availability
AEMU:	Advanced EMU
AES:	Advanced Exploration Systems
AIT:	Autogenous Ignition Temperature
AISI:	American Iron and Steel Institute
ALCLR:	AirLock Coolant Loop Remediation
ALPS:	AirLock Power Supply
BLDC:	BrushLess Direct Current
BMS:	Battery Management System
BTU:	British Thermal Unit
BTU/hr:	BTU/hr
CCC:	Contamination Control Cartridge
CEI:	Contract End Item
CHX:	Condensing Heat Exchanger
CID:	Current Interrupt Device
CO ₂ :	carbon dioxide
CON:	controller
COPV:	Composite Overwrap Pressure Vessel
COTS:	Commercial Off-The-Shelf
CPV:	Combination Purge Valve
CWS:	Caution and Warning System
DCM:	Display and Control Module
DCU:	Display and Control Unit
DCS:	DeCompression Sickness
DI:	DeIonized
DP:	Differential Pressure
DRM:	Design Reference Mission
EC:	Engineering Change
ECWS:	Enhanced Caution and Warning System

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EMI:	Electro-Magnetic Interference
EMU:	Extravehicular Mobility Unit
ESA:	European Space Agency
ETDP:	EVA Technology Development Program
EV:	ExtraVehicular
EVA:	ExtraVehicular Activity
FPGA:	Field Programmable Gate Array
F/P/S or FPS:	Fan-Pump-Separator
FMEA:	Failure Modes and Effects Analysis
FN:	Fan
FOD:	Foreign Object Debris
FSA:	Feedwater Supply Assembly
H2O:	water
HC:	HydroCarbon
HED:	Hall Effect Device
HUT:	Hard Upper Torso
HVAC:	Heat Ventilation Air Conditioning
HX:	Heat eXchanger
ICB:	Increased Capacity Battery
IFM:	In Flight Maintenance
ISS:	International Space Station
IV:	Intra-Vehicular
IVA:	Intra-Vehicular Activity
JSC:	Johnson Space Center
KOH:	Potassium hydroxide
krpm:	thousand revolutions per minute
LCVG:	Liquid Cooling and Ventilation Garment
LIB:	Li-Ion Battery
LLB:	Long Life Battery
LiOH:	lithium hydroxide
LLIL:	Limited Life Items List
LVDS:	Low Voltage Differential Signaling
MEOP:	Maximum Expected Operating Pressure
MLI:	Multi-Layer Insulation
MSPV:	Multi-Position Suit Purge Valve
NC:	normally closed
NDE:	Non-Destructive Evaluation
NESC:	NASA Engineering and Safety Center
NPRV:	Negative Pressure Relief Valve
NVR:	Non-Volatile Residue
O ₂ :	oxygen
OCA:	Oxygen Compatibility Assessment
OEM:	Original Equipment Manufacturer
ORU:	On-orbit Replacement Unit or On-orbit Replaceable Unit
PDA:	Pre Delivery Acceptance
PIA:	Pre Installation Acceptance
PMS:	Power Mode Switch
PLSS:	Portable Life Support System
POR:	Primary Oxygen Regulator
POV:	Primary Oxygen Vessel
pph:	pounds per hour
PPRV:	Positive Pressure Relief Valve
PRA:	Probabilistic Risk Assessment
PRACA:	Problem Reporting And Corrective Action
PT:	Pressure Transducer
PTFE:	Polytetrafluoroethylene

QD:	quick disconnect
RCA:	Rapid Cycle Amine
RCCA:	Root Cause/Corrective Action
RTD:	Resistance Temperature Detector
RV:	Relief Valve
SCU:	Service and Cooling Umbilical
SEM:	Scanning Electron Microscope
SEMU:	Short EMU
SOP:	Secondary Oxygen Pack
SOV:	Secondary Oxygen Vessel
STS:	Space Transportation System
SWME:	Spacesuit Water Membrane Evaporator
TCC:	Trace Contaminant Control
TCV:	Thermal Control Valve
TDL:	Tunable Diode LASER
TMG:	Thermal Micrometeoroid Garment
TMR:	Triple Modular Redundancy
UTRC:	United Technologies Research Center
VFR:	Vent Flow Ring
VOR:	Variable Oxygen Regulator
W:	Watts
WMS:	Wavelength Modulation Spectroscopy
WSTF:	White Sands Test Facility

I. Introduction

In the 35+ years since the Shuttle Extravehicular Mobility Unit (EMU) began operations, it has been used to deploy and service satellites such as Intelsat VI and the Hubble Space Telescope, perform detailed test objectives to gain engineering data on suit performance, and many other tasks from the Shuttle Orbiter internal and then external airlocks as an Extra-Vehicular Activity (EVA) platform. It was then migrated to become the International Space Station (ISS) US EVA spacesuit undergoing a number of upgrades but not significant redesign. The underlying premise that NASA management employed in the management of the early EMU program was that of Root Cause Corrective Action (RCCA). When failures occurred with the system, they were thoroughly investigated and if there was a hardware solution to mitigate that failure on future suit configurations and missions, then frequently within the balance of cost, schedule, and risk the hardware solution was implemented. Over time, this approach matures the system as long as the redesigns or corrective actions are evolutionary in nature (i.e. addressing the outage while minimizing the addition of new “features” that cause future failure conditions). These failures along with their corrective actions were documented in the NASA Problem Reporting and Corrective Action (PRACA) system such that they are available and searchable today making for a great lessons learned repository assuming the careful use of filtering and context. As the Shuttle EMU Program approached the end of its initial life of 15 years and 100 missions, a project within the EMU Program referred to as the Assured EMU Availability (AEA) project was initiated for the purpose of life extending the EMU by studying and ranking the components relative to risk and then implementing replacement or refurbishment plans for each based on the results of analysis, test, and “fleet leader” evaluations. In each of the reports generated for each of the fleet leader components selected for evaluation, a wealth of lesson learned data is documented and available. Each component selected for fleet leader evaluation was initially established by the principal investigator as the fleet leader using application specific criteria which could be operating time, operating life, cycle count, etc. Once the fleet leader was identified and rotated out of operation back to the Original Equipment Manufacturer (OEM) where the component underwent “as-received” testing against its component specification followed by progressively detailed inspections and tests looking at wear, corrosion, contamination, elastomeric set, etc. After the thorough review of the entire sum of inspection and test data the fleet leader report would make recommendations related to replacement or refurbishment of the component; if the component was to be refurbished, the report would detail what parts were to be replaced, cleaned, etc to achieve an extension in the life of the part which was also variable based on the processes at play within the part and the supporting data. The AEA fleet leader reports convey all of the data discussed above with the addition of the Engineering Change (EC) history, failure history, and

historical summary of configuration of the related components across the fleet. Hence, the AEA fleet leader reports are a tremendous resource to study the manner in which a particular design progressed through its operational life as well as to investigate details of that design that could be evolved in the next component design.

For the Advanced EMU (AEMU) development that began at the component level under the Exploration Technology Development Program (ETDP) in 2008 as a risk mitigation for future Constellation Program objectives, has continued into system level development under the Advanced Exploration Systems (AES) Program. As part of that development, establishing system and component level derived requirements based on a range of Design Reference Missions (DRM) and hosting vehicles was paralleled with pneumo-hydraulic schematic development which carefully examined the system designs used for the Apollo EMU as well as the Shuttle EMU and detailed in [1]. The common requirements related to human interfaces and similar to or evolved requirements related to vehicle interfaces and functional capabilities make quite relevant the study of the EMU operational history as it relates directly to the AEMU design space as well. Hence, the systematic review of the successes and lessons learned as documented in the PRACA database, the reports from the AEA project, and the summaries within the EMU Requirements Evolution [2] have been key in areas to focus for reliability improvement.

As a cautionary note regarding the blind use of the PRACA database, over the course of the EMU Program there have been many generations of personnel that have interpreted the rules for what is reportable and what is not and how to go about doing that. The shear counting of failures can be misleading as there are some cases in which the same failure was duplicated across several separate reportable failure entries as each serial number was affected and in other cases all of the affected serial numbers may have been grouped under a single failure entry. Distinctions like these require one to review the failure description for each entry and not necessarily rely on the total quantity as a single indicator.

Before proceeding with a detailed discussion related to specific failure history of the Shuttle/ISS EMU and how it relates to choices or details within the design of the AEMU, a brief overview of context is needed to define each system.

Shuttle/ISS EMU and AEMU PLSS 2.5 Overview

The content contained herein is focused on the EMU failure history and how it can be and is being applied to the AEMU design as lessons learned go forward. In order to contextualize the component references and functions, the relevant schematics (Figure 1, Figure 2) are included but further reading of the following references is suggested if more insight is required. At a high level, a schematics comparison between the EMU and AEMU yields a number of similarities with notable simplifications from the EMU to the AEMU due to the addition of key technologies such as the motor-settable mechanical regulator, the Rapid Cycle Amine (RCA) swing-bed, and the Spacesuit Water Membrane Evaporator (SWME). There are obviously many more differences and new technologies included but this short list has provided the most significant impact on the schematic and design of the AEMU. Many of these changes will be addressed in the relevant sections below.

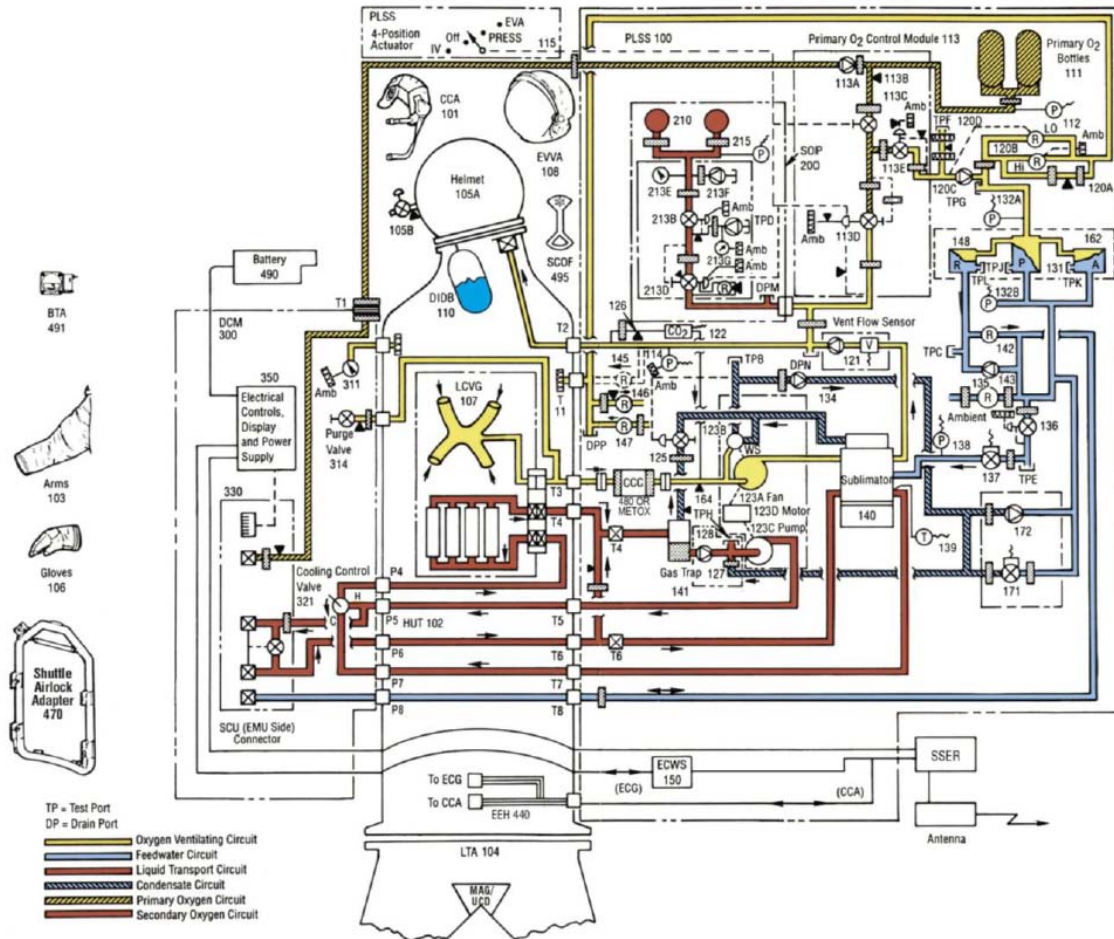


Figure 1 - ISS EMU Pneumo-hydraulic Schematic

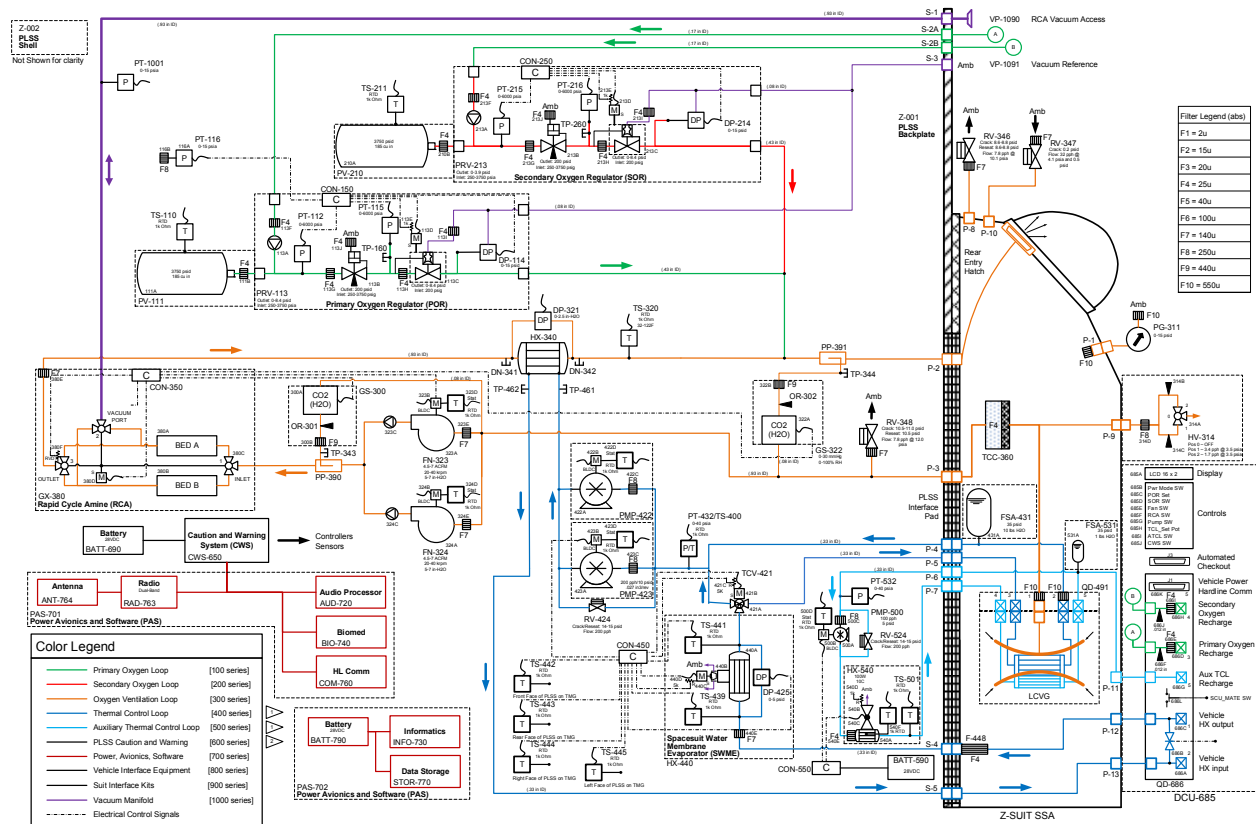


Figure 2 - AEMU PLSS 2.5 Pneumo-hydraulic Schematic

Shuttle/ISS EMU Failure History with AEMU in mind

As has been discussed previously, the AEMU development has been progressing and influenced by corporate knowledge with discrete investigations of selected components to achieve a base design iteration (PLSS 2.5) progressing in maturity towards the final flight design. This review of the Shuttle/ISS EMU failure history will then be grouped based on existing choices such that they are: components with similar design, components removed between ISS EMU and AEMU, and components that have been redesigned. The overall approach that has governed those choices has been to “fix what is broken” but carry on mature designs that work well. Those will be discussed in detail in the following paragraphs. In order to structure the review, the components have been listed by their ISS EMU Program Contract End Item (CEI) numbers with comparison to the AEMU PLSS 2.5 Item Designations. For the purposes of nomenclature throughout this document, EMU will be used to refer to the Shuttle/ISS EMU and AEMU will be used to refer to the Advanced Exploration Systems (AES) Advanced EMU.

A. Components with similar design between ISS EMU and AEMU

In reality, given improvements in technology over the past few decades fewer than 20% of the components were carried through using the same technology or design.

Shuttle/ISS EMU CEI	Description	AEMU Item	Description
111	Primary Oxygen Tank	PV-111	Primary Oxygen Vessel
123A	Fan/Pump/Separator - Fan	FN-323 FN-324	Ventilation Loop Fan
126	Filter and orifice (for IRCO ₂ sensor)	OR-324 OR-301	Orifice for multi-gas sensors
147	Negative Pressure Relief Valve (NPRV)	RV-347	Negative Pressure Relief Valve (NPRV)
161	PLSS/SOP TMG	Z-007	PLSS TMG
213	Secondary Oxygen Pressure Control Module	PRV-213	Secondary Oxygen Regulator
215	Secondary Oxygen Bottle Pressure	PT-215	Secondary Oxygen Vessel Pressure

Table 1 - Components with Similar Design

Primary Oxygen Tank (Item 111)

For the AEMU, this design is shared between both the Primary Oxygen Vessel (POV) and also the Secondary Oxygen Vessel (SOV) as they are identical designs for commonality and cost reduction. This was possible due to the selection of a single operating pressure for the tankage of 3000 psi rather than the divergent pressure schedules used in the ISS EMU which were 900 psi in the primary and 6000 psi in the secondary. The Item 111 on the ISS EMU Program is a cryo-formed AISI 301 tank which was actually a lesson learned early in the Shuttle EMU Program. The cryo-formed tankage was originally used as the primary tankage in the Apollo EMU and the Shuttle EMU was looking to use newer technologies that could offer a lower cost and a small mass savings so they performed a trade and selected an aluminum lined fiberglass overwrap tank design. Significant issues were observed in production along with the issues that plague the composite tank designs such as designing a critical pressure vessel as “leak before burst”, being able to properly model the vessel, being able to properly inspect the vessel given its composite nature to ensure that the load bearing filament, or the accumulation of Discrepancy Reports (DR) from rigorous and repeated quality inspections during flight processing due to minor imperfections in the outer wrap. The early Shuttle EMU tankage was demonstrated as “leak before burst” via test but the supplier had difficulty producing them reliably so the program reverted to the Apollo EMU tankage design which had worked well previously, made a few process updates to enhance the yield and lower the scrap rate, then implemented the design. As of 2004, the tankage had been life extended to 32 years by the AEA project given inspections [3]. A review of the PRACA failure history covering the Item 111 yielded no hardware failures attributed to the tankage.

At the beginning of the ETDP, an initial market survey and trade study was performed which evaluated available approaches for the tankage. For the AEMU trade study, the cost of custom tankage runs using COPV or cryo-formed 301 were similar. Likewise, there was minimal potential mass savings (~ 1.6 lbm/tank) as well, leading to the consideration of reliability and safety (leak before burst design) as the driving factor. That consideration favored the use of the cryo-formed AISI 301, a monolithic material that can be analyzed, designed as leak-before-burst, and directly inspected. These factors coupled with the extended successful usage on both the Apollo and Shuttle/ISS EMU Programs led to the use of the same approach for the AEMU.

Centrifugal Fan (Item 123A)

For the EMU, the Item 123 Fan/Pump/Separator is one of the most complex devices within the PLSS as it combines a centrifugal fan, a pitot separator, and magnetically coupled centrifugal water pump all on a single shaft connected to a BLDC motor with on-board controller. As noted in [2], the choice was made to combine all of these functions together onto a single motor in order to save 10W of power over the Apollo PLSS which had a separate fan and pump. A review of the PRACA failure history reveals a total 96 failures attributed to the F/P/S as a component over the life of the program to date including three significant in flight failures (Figure 3), each attributed to the fan, pump, and water separator, respectively. The first in-flight failure occurred early in the Shuttle/EMU Program on STS-5 due to corrosion of one of the Hall Effect Devices (HED) exposed to the moist ventilation loop [4]. The fan was redesigned

in two steps yielding a “canned motor” which physically isolated the stator from the armature (and ventilation loop) using a metal can with redundant elastomeric seals. The bearings remained in the ventilation loop with added features (drain holes, slinger, change to Mobil 28 bearing grease, etc) to improve tolerance of condensate from the ventilation loop. The design then functioned well in operation with the balance of the failure reports over the next ~18 years mostly limited to non-functional or test configuration issues. The second major flight failure occurred with the loss of the water pump function during ISS Increment 7 on two different suits at the same time, SEMU 3005 and SEMU 3013. The coupled, tightly tolerance centrifugal water pump that had worked well in Shuttle-based EVAs over the previous two decades was not performing well a few years into the mission in the ISS Airlock as the thermal loop contaminants increased. In the end, the two failed units suffered from rotor growth from internal corrosion of the permanent magnet potting within the rotor; the water quality in the thermal loop was addressed by increased on-orbit maintenance both scrubbing the loop via resin beds and increased biocide dosing with Iodine using the Airlock Coolant Loop Remediation (ALCLR) system. A sharp, well experienced mentor and former EMU Program Manager used to say that “every design change to fix one problem causes two more...” [5]. The statement seemed a bit cynical but in this case it could be seen as prophetic. As the use of ALCLR followed on during the ISS Program as a remediation to the initial failure of the pump, the third major in flight failure occurred with the “water intrusion” failure of the integrated pitot style water separator in SEMU 3011 during ISS EVA 23 [6]. The failure of the pitot separator was attributed to the accumulation of silica from contaminated ALCLR beds in the small holes around the outer part of the drum on the separator preventing it from feeding condensate to the pitot and forcing it back to the feedwater bladders. This produced overflow from a portion of the ~1 lpph slurry fed from the gas trap which drifted into the fan volute as well as excessive sublimator carryover (condensed ventilation loop moisture not picked up by the sublimator slurper which migrates beyond the sublimator in the ventilation loop). The two sources contributed to an excess of free water in the ventilation loop which was then migrated downstream into the helmet area where an estimated 1 to 1.5 liters accumulated by the end of the EVA termination. The most recent failure occurred when a FPS would not spin up during an ALCLR maintenance activity. The investigation is on-going but appears to be attributable to fan motor bearing corrosion with the cause theorized to be increased FPS on/off cycles driven by ALCLR usage in which the pitot separator drum is filling on startup and dumping ~10cc water on shutdown into the fan volute allowing the free water to work its way back to the fan bearings.

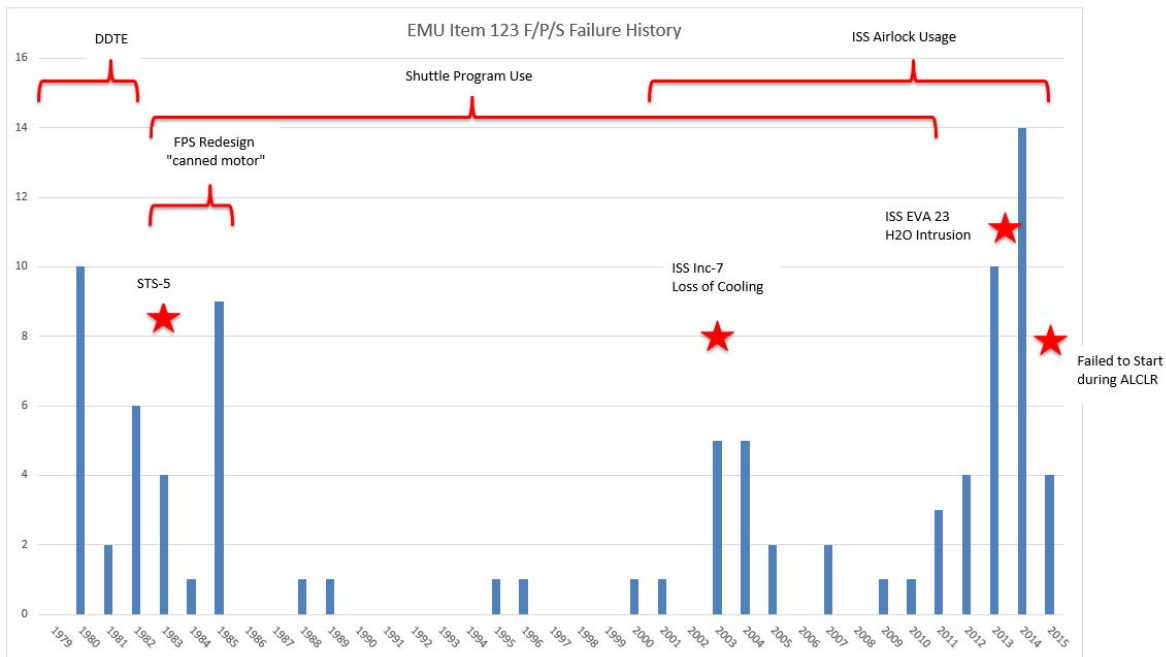


Figure 3 - EMU Item 123 F/P/S Failure History

When evaluating the operational and failure history of the FPS in consideration with the design implementation of similar functions in the AEMU, the following takeaways come to mind:

1. After its initial design, the canned motor concept and design has an excellent usage history on both ground and on-orbit over a period of 30 years. The chief contributor to failures both before the motor canning and recently on ISS, has been the presence of free water in the ventilation loop. The use of an amine swing-bed for CO₂ and H₂O removal from the ventilation loop in the AEMU precludes the need for a condensing heat exchanger and allows the ventilation loop to operate with significantly more thermal excursion margin with respect to the dew point (similar to the concept of superheat in a vapor compression cycle HVAC system); hence, no real risk of making free water in the AEMU ventilation loop with the relative humidity typically running <25% (dew points typically near 20-30F) and a sensible heat exchanger operating on the thermal loop inputs at 50F. Use of the canned motor design, but with a ceramic can is advantageous at this point, not because of the need for free water/humidity tolerance but because of the oxygen compatibility or isolation of wetted oxygen from the higher current carrying drive circuits in the motor stator [7].
2. The use of a tightly tolerance or shaft coupled centrifugal water pump should be excluded from consideration. This is the case and will be discussed at length throughout this paper. The desire to decouple the fluid loops, tolerate water contamination, save power, lower pump speed, enable self-priming, tolerate entrained gas, lower the cavitation pressure point, and add redundancy all drive the selections towards a positive displacement pump like the gerotor style presently used in the AEMU.
3. The use of a condensing heat exchanger and pitot water separator is not necessary as discussed earlier but also not advisable for additional reasons such as the need to tolerate contaminated thermal loop fluid, the very cause for one of the on-orbit failures of the EMU FPS.
4. For long term missions such as ISS and exploration missions yet to be defined, the water quality will more than likely be more challenging than DI water so future systems such as the AEMU will be designed and tested with contaminants realized from the ISS EMU Program and from theorized contaminants based on materials of construction. This also assumes the switching of the biocide selection from Iodine which the EMU had for compatibility reasons with the Shuttle to silver which ISS, the Russian Orlan, and all future ECLSS systems have been using or are planning. A tightly toleranced, low torque pump would not be expected to fare well with silver plating, a side effect of using silver as a biocide albeit that the spacesuit/PLSS have a pretty high surface area to volume ratio with the majority of it as non-metallics such as Ethylene-Vinyl Acetate (EVA) tubing used in the Liquid Cooling and Ventilation Garment (LCVG).
5. A few failures were carried at the system level (EMU, SEMU, PLSS) but were considered to be an interaction between the FPS motor/controller, the Air-lock Power Supply (ALPS), and radio such that communications were interrupted when certain serial numbers were combined. This was managed logistically and screened directly during V1103.02, the Orbiter to EMU preflight verification performed about 10 days before every Shuttle launch. Improved motor control and noise isolation on the power lines will be an objective for the AEMU fan implementation and the subject of many integrated electrical tests as the AEMU design matures as a reference.

CO₂ Control Orifice (Item 126)

The EMU Item 126, a simple .022in dia orifice that throttles the flow into the Item 122 IRCO₂ sensor has no failures attributed to it. An orifice design is a simple one that is easily modeled and verified and one that is being applied in a similar manner to control the flow through the multi-gas sensors GS-322/GS-300 on the AEMU.

Negative Pressure Relief Valve (Item 147)

The NPRV is a valve that protects for the rare condition in which the airlock is rapidly repressed from vacuum to ambient pressure at a rate of 1 psi/sec. It has been a relatively reliable design over the duration of the Shuttle/ISS EMU Programs with four failures identified in a PRACA review (Figure 4), only two of which in the last 35 years were believed to be contamination.

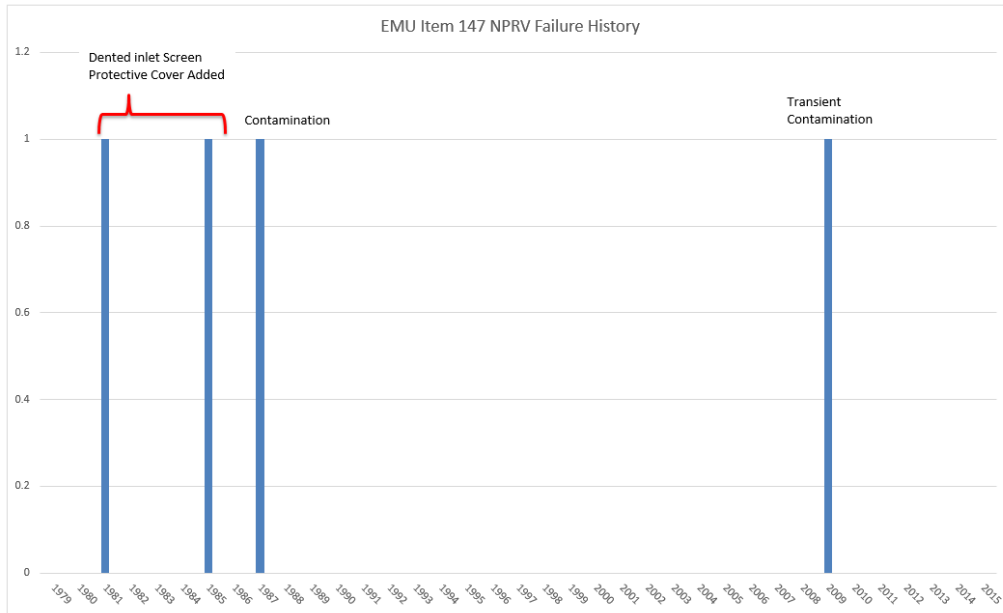


Figure 4 - Item 147 PRACA History Plot

The presence of potential contamination with this valve exposure to ambient on the exterior and, on the interior to a ventilation loop with a crewmember wearing textiles and multiphase fluids with corrosion products, is not that surprising as there will always be a balance between protecting the valve with filters that impede its desired function. The filtration requirements will be reassessed with respect to exploration usage going forward. Aside from a potential increase in flow capability (~60 pph) to cover suit free volumes of 3ft³ and a change in the mounting associated with direct mounting on the Hard Upper Torso (HUT), the valve design will be similar. The key difference between the EMU and AEMU is in the first 2 failures, both due to inadvertent contact with the exterior screen (Figure 5) which then deformed inward causing the valve to stroke open. For EMU, this valve is located within the PLSS and protected by a fiberglass “impact shield” underneath the PLSS TMG; the two failures occurred during processing where the impact shield and TMG were not present leading to the implementation of a protective cover that is removed at the time of final assembly of the impact shield and TMG onto the PLSS. For the AEMU, whether this valve is placed on the exterior of the HUT or within the PLSS and subject to In Flight Maintenance (IFM), the valve needs to incorporate some level of impact protection that serves the same function as the tool that was developed on the EMU Program.

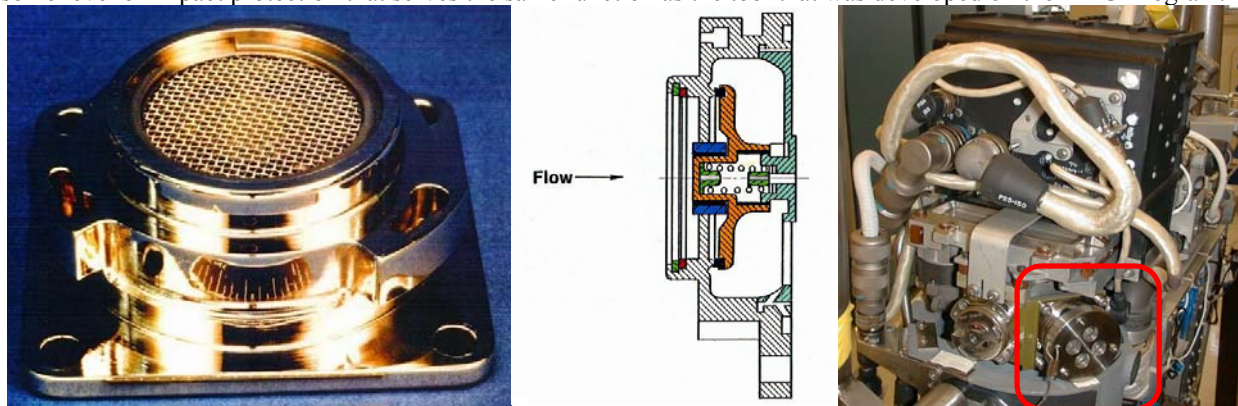


Figure 5 - EMU Item 147 NPRV Photo/Diagram

PLSS Thermal Micrometeoroid Garment (Item 161)

Due to the simplicity and the fact that the materials of construction remain state of the art, the basic TMG design will be similar for the AEMU. Ortho-fabric which is well documented and possesses advantageous emissivity/absorptivity will be used for the external layer. The chief differences will likely be the number of Multi-Layer Insulation (MLI) layers based on the required thermal performance on static surfaces such as the PLSS outer shell (vs surfaces on the suit where mobility is inhibited reducing the MLI to a minimum) and careful selection and implementation of closure

devices such as zippers, Velcro, snaps, etc. As is indicated in Figure 6, a review of the PRACA system reveals a total of 6 failures written against the PLSS TMG over the life of the EMU Program, all occurring with the original Shuttle laced-closure style TMG and none with the ORU TMG introduced in 1998. Five of the six failures were related to the breakage of zipper closures which appear to have been mitigated in the design of the ORU TMG potentially due to both improvements in the zipper design but also perhaps the fact that the ORU TMG uses Velcro and snap closures rather than lacing cord making for a looser fit and reduced side load on the zippers used for the Metox/Battery consumables access flap.

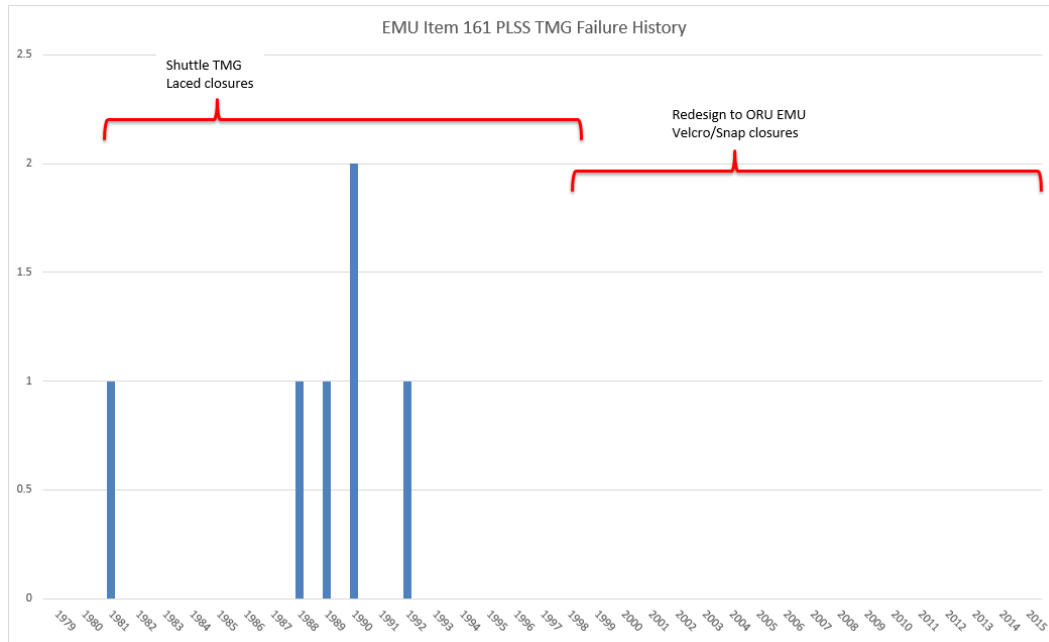


Figure 6 - Item 161 PLSS TMG Failure History

Secondary Oxygen Regulator (Item 213)

The SOP regulator was the cause of the worst suit-related failure in history. In 1980, in B7 at JSC, PLSS S/N 1002 was undergoing a checkout and its first oxygen wetting in the lab. When the technician proceeded to take the O2 actuator to EVA and engage the SOP regulator, an oxygen fire occurred injuring the technician and destroying the PLSS, including SOP (Figure 7). There are multiple potential causes for this event, among them are adiabatic compression heating of the Silastic 675 o-seals [8], particle impact ignition of a dead-end aluminum passage [9], adiabatic compression heating of kindling chain contaminants in the dead end passage or compression heating or rupture of a thin aluminum section in the dead-ended passage. Many of the procedures and processes and supporting data that is taken as a standard today came from the study and corrective action from this event. The SOP regulator was completely redesigned:

- dead-end passages were removed
- the body was changed from aluminum to monel (non-flammable under these operating pressures)
- the fast acting upstream shut-off valve was removed
 - shut-off accomplished via 2nd stage regulator lock-up
- many other more subtle changes were made

Several NASA processes were changed including the requirement to perform the initial oxygen wetting (minimum of 10 impacts of pure O2) at an appropriate facility like the White Sands Test Facility (WSTF).

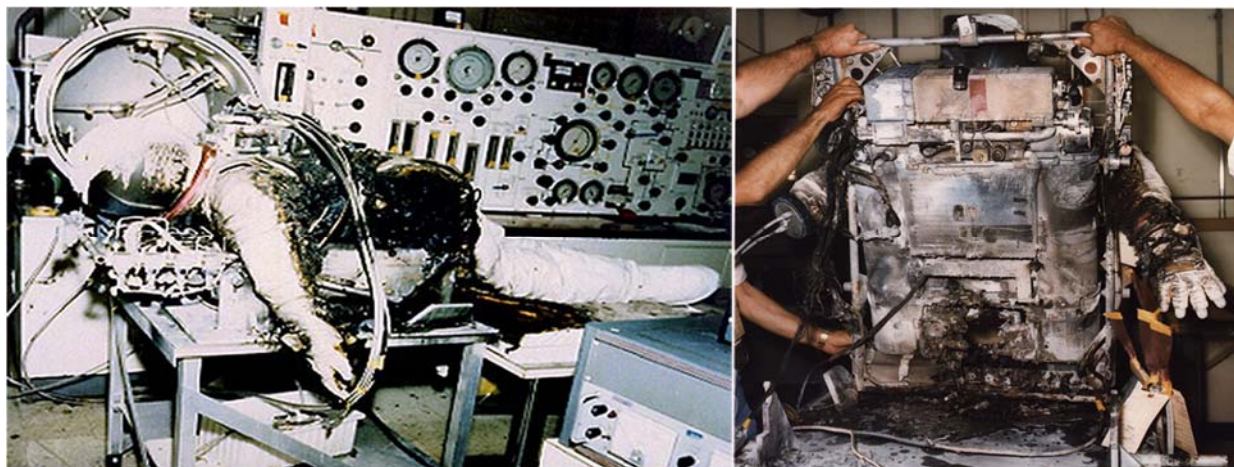


Figure 7 - SOP Fire Photos (1980)

After the redesign, the regulator design was stable until the late 1980's when failures were experienced with the 1st stage diaphragm due to corrosion from residual soldering flux. The process was corrected to address cleaning of the diaphragm and the problem did not recur. As is annotated in Figure 8, another significant event occurred in the year 2000, in which the entire EMU fleet was found to be contaminated with hydrocarbon Non-Volatile Residue (NVR). Nearly all Oxygen Compatibility Assessments (OCA) generated by WSTF, consider a "clean" system with an "A" rating per JPR5322.1 ($< 1 \text{ mg/ft}^2$) or equivalent and a maximum allowable NVR level of $< 2 \text{ mg/ft}^2$. This unlikely systematic contamination event yielded $> 100 \text{ mg/ft}^2$ of C10-C34 NVR near/on the seat of the regulator [10]. Three different improbable mechanisms were found to have contributed to contamination of the entire fleet of SOP regulators

1. Direct contamination of the interfacing test rigs with Sebacate hydrocarbon oil via improperly connected/faulty dead weight testers which was then transported to the regulator
 - a. Found in 4 of 12 regulators sampled [11]
2. Secondary contamination of the interfacing test rigs from Fomblin oil leaking through failed diaphragms on compressors and subsequent transport of background hydrocarbon contamination to the regulator
3. Direct contamination of the regulator from trace quantities of hydrocarbons permitted in Aviator's Breathing Oxygen (ABO) or nitrogen manifested due to Joule-Thompson cooling of the regulator during high flow acceptance testing during the Pre Delivery Acceptance (PDA) testing

The regulator fleet was cleaned and refurbished and cryogenic coldtraps were developed and placed in front of the regulators during testing with gas supplies at the OEM and the field laboratories. A Limited Life Items List (LLIL) requirement was levied on the SOP regulator such that it had to be refurbished after 2.5 mg/ft^2 HC NVR was accumulated based on a relation of worst case allowable contaminants of ABO and an established empirical efficiency of the coldtraps protecting the regulators during test.

Since the SOP began flying to ISS, it has been tracked as a consumable given that it cannot be recharged on-orbit; the lock-up leakage performance that is nominally achieved by the second stage regulator seat design (sapphire ball/vespel seat) enables the charging and flying of SOP's for 2+ years until they drop below no-go threshold $\sim 5400 \text{ psia}$.

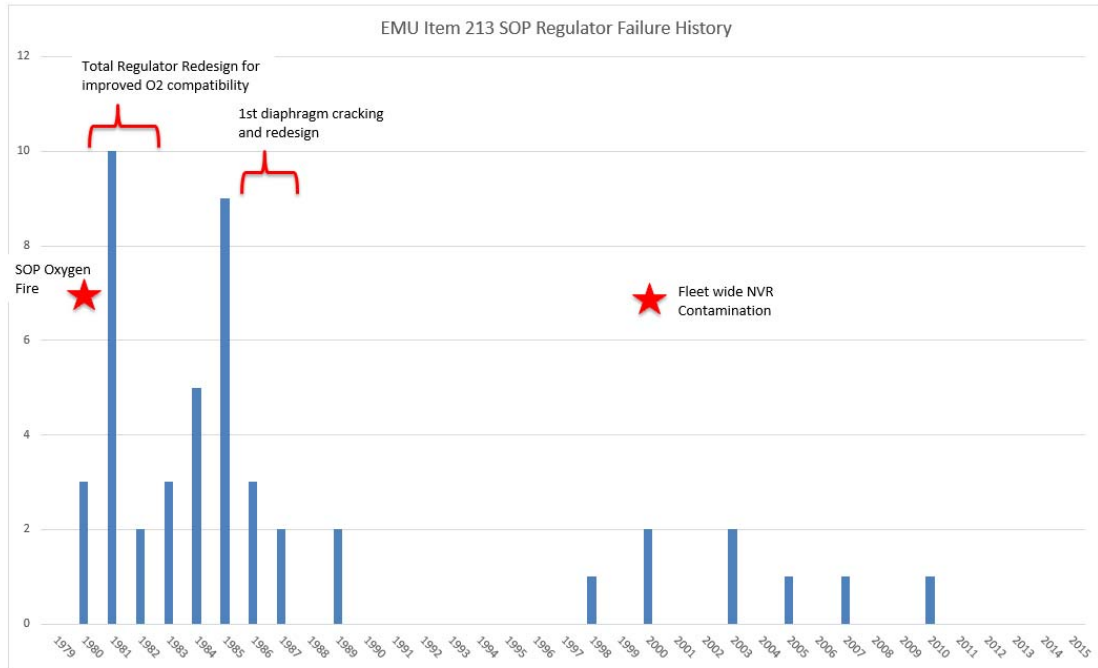


Figure 8 - Item 213 SOP Regulator Failure History

Key takeaways from this operational history:

1. The regulator design has been reliable since its redesign in the early 1980's.
2. The assumption that a high pressure oxygen system will remain clean indefinitely with procedural controls is suspect. Not one, not two, but three different mechanisms were found as contributors to the contamination of the system.
3. The second stage regulator seat has incredible lock-up leakage performance

These lessons learned from the ISS EMU have been applied to the Variable Oxygen Regulator (VOR) design and development under ETDP and now AES. For the VOR, which is implemented in both the Primary Oxygen Regulator (POR) and Secondary Oxygen Regulator (SOR) for commonality, the design leverages much of the second stage design but simplifies the first stage regulator to a piston sense design to remove the diaphragm that was the subject of a failure in late 1989. With the lowered operating pressure (3000 psi nominal, 3750 MEOP), the Nickel 200 mesh filters are considered non-flammable and serve to protect the seats from particle impact as well as to protect from combustion propagation. Several of the elastomeric seals have been removed and replaced by copper crush seals. Other seals have been protected metal annuluses with high L/D to reduce adiabatic compression heating of the seals. The VOR 2.0 regulator was tested at WSTF in 2013 initially with 60 dry impacts of ABO at 3750 psia and elevated temperature and then 10 impacts (2 sets of 5 with added HC each time) with >100 mg/ft² of dodecane at elevated temperatures [12]. The regulator operated nominally through-out the test and appeared clean to the naked eye during post-test teardown. After closure inspection with magnification (Figure 9) and later SEM, evidence was present that the dodecane had combusted within the interstage but the design precluded the propagation.

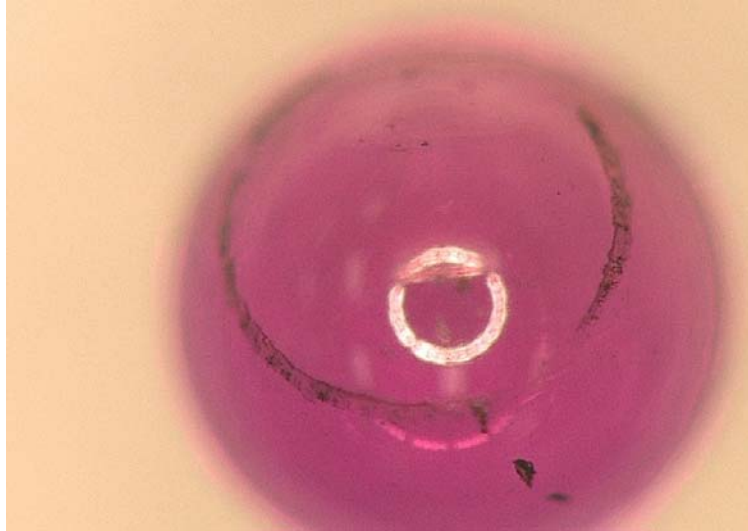


Figure 9 - Sapphire Ball from 1st Stage Regulator

Secondary Oxygen Vessel Pressure (Item 215)

The EMU Item 215 is unique from many of the other pressure transducers in the EMU as it was redesigned in 2000 and does not rely on a bourdon tube-pot/wiper assembly, rather it utilizes a diaphragm/strain gauge based design more common to most modern pressure transducers.

The PRACA history for this component (Figure 10) indicates that 16 failures have been attributed to this component over the course of the EMU Program with one in flight failure which was eventually attributed to EMI as the sensor became known as the “EMI sensor” providing occasional false high readings when the radios were turned on in the airlock. After initial failures associated with solving EMI shielding/termination on the new design followed by some supplier manufacturing process issues, the sensor has been free of failures in the past 9 years.

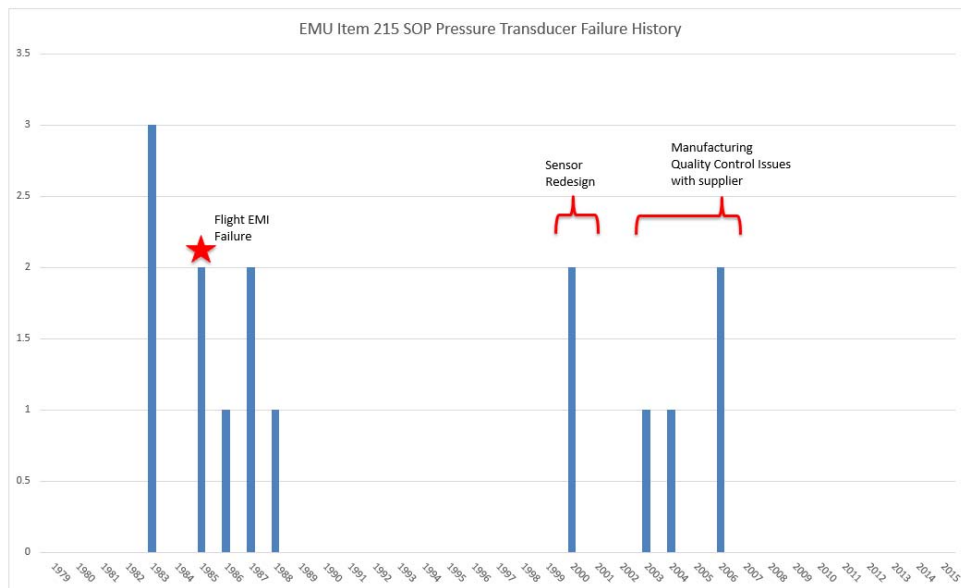


Figure 10 - EMU Item 215 SOP Pressure Transducer Failure History

The bulk of the sensors included in the AEMU utilize the strain gauge/diaphragm approach with recent improvements in isolation within the sensor electronics. Extensive testing will be performed to determine effectiveness of the evolved design.

B. Components removed from ISS EMU to AEMU

Throughout the AEMU development, schematic simplification has been a goal as permitted by available technologies that have been developed in the time since the design of the EMU:

- Spacesuit Water Membrane Evaporator (SWME)
- Rapid Cycle Amine (RCA) swing bed
- High Efficiency BLDC motor with ceramic canned motor
- Gerotor style positive displacement pumps

AEMU Thermal loop simplifications

The combination of the SWME input pressure tolerance and implementation of a separated positive displacement thermal loop pump (Gerotor) led to the removal of the following components from the EMU schematic:

- Item 113E – Primary Pressure Control Module, Feedwater Pressure Regulator
The feedwater pressure regulator is a component within the Item 113, Primary Pressure Control Module which is responsible for regulating the inlet pressure from the primary oxygen tanks at ~900 psia to a nominal pressure of 14.6-15.7 psid [13] which is fed to the backside of the feedwater bladders in the watertank structure. For the AEMU, this regulator was removed as a result of at the breakout of Fan/Pump/Separator (F/P/S) into two discrete components, a centrifugal fan and gerotor style positive displacement pump. The EMU F/P/S runs at a nominal 19.7krpm when in speed control with a centrifugal fan, pitot style water separator, and centrifugal pump all combined onto a single BLDC motor. For the pump, testing early in the EMU Program demonstrated a need for a supply pressure above suit pressure and ~15 psia under EVA conditions was selected as the range. For the AEMU, with the use of the gerotor style pump which operates without cavitation down to pressures as low as 2.7 psia, the input pressure is being driven by the suit ventilation loop pressure between 3.5 – 8.4 psia under EVA conditions. Hence, the function is satisfied by either the PRV-113 or PRV-213 allowing for a simpler and yet redundant thermal loop pressure source capable of allowing nominal thermal loop operation even when on secondary oxygen supply; something that the EMU cannot accommodate. This has the effect of converting a several 1R failure modes to 2R failure modes. A review of the PRACA system indicates that 18 failures of the 59 attributed to the Item 113.
- Item 120 – Dual Mode Relief Valve
With deletion of the Item 113E, a separate dual mode relief valve and orifice was no longer needed as the relief protection for the thermal loop gas side pressure is the same as the ventilation loop, RV-346 PPRV. The Item 120A orifice which was used to keep the Item 113E from going into lock-up and overshooting the pressure set-point given the exceedingly low demand needed to feed the bladder volume change was again simplified when combined with the ventilation loop as the demand applied to the PRV-113/PRV-213 regulators consisting of suit leakage makeup and metabolic consumption is adequate to preclude the need for a separate bleed or demand. A review of the PRACA system indicates that 42 failures have been attributed to the Item 120 Dual Mode Relief Valve.
- Item 128 – Pump Inlet Check Valve (a pump inlet filter similar but more course than the Item 127 still exists to protect the gerotor style pump)
The use of the gerotor style positive displacement pump removed the need for the Item 128 check valve which was used to assist with priming the centrifugal pump in the Item 123, F/P/S. A review of the PRACA system indicates that 5 failures have been attributed to the Item 128 Pump Inlet Check Valve all related to leakage.
- Item 132A - Feedwater supply pressure sensor, gas side
With removal of the separate gas supply via the Item 113E, the pressure transducers monitoring the suit ventilation loop pressure perform the equivalent function. In the case of the AEMU, DP-114 and DP-214 perform this function with added redundancy over the EMU and logic included as part of the CWS to enable exclusion of a faulty sensor without the need of a third voting sensor as would be used for Triple Modular Redundancy (TMR) approaches. A review of the PRACA system indicates that 17 failures have been attributed to the Item 132.
- Item 135 – Feedwater Relief Valve
Movement of the feedwater bladders from the three Fluorel bladders housed within a rigid aluminum watertank structure, to bladders with more compliant integrated fabric restraints retained in the hatch of the rear entry Hard Upper Torso (HUT) removed the need for the Item 135 which was present to prevent a hard-charged bladder from over-pressuring the rigid feedwater tank structure due to thermal expansion

of the trapped fluid. A review of the PRACA system indicates that 16 failures have been attributed to the Item 135.

- **Item 136 - Feedwater pressure regulator**
The Item 136 serves to reduce the feedwater pressure sourced from Item 113E at ~15 psid to 2.05-4.15 psid [13] such that the Item 140 sublimator porous plate does not experience “break-through” resulting in the dumping of feedwater into space. The SWME input water pressure range has been tested in development up to 21 psid during AEMU PLSS 1.0 Bread-board testing [14] with fiber weeping near 40 psid making it acceptable to pressurize the thermal loop via the ventilation loop pressure 3.5 – 8.4 psid. The final pressure schedule for the SWME is presently under revision based on the needed support operations such as vacuum water recharge vs the available vehicle interfaces. A review of the PRACA system indicates that 30 failures have been attributed to the Item 136.
- **Item 137 – Feedwater Shut-off Valve**
The Item 137 serves to isolate the feedwater source from the sublimator when not at vacuum conditions below the triple point of water which would facilitate the formation of the ice layer within the porous plate. If the valve were not present or were thrown open prior without vacuum available, the feedwater fills in the small gap under the porous plate and flows out through the porous plate quickly extinguishing the feedwater supply. If the system is then taken to vacuum after this situation has occurred the expansion of the feedwater in the gap under the porous plate results in permanent warping of the plate and an underperforming sublimator. A review of the PRACA system indicates that 17 failures have been attributed to the Item 137.
- **Item 142 – Feedwater Relief Valve**
The Item 142 is a relief valve that is positioned between the reserve feedwater bladder and the two main feedwater bladders which cracks at 4-5 psid [13] enabling the transition from primary feedwater supply to reserve supply via a difference between the Item 132A and Item 132B feedwater pressure transducers. The ECWS uses a limit of 2.1 psid as the empirically resolved trigger to determine when the system is using reserve water. For the AEMU, there is no separate primary and reserve bladder, rather just a single primary bladder that has variable compliance such that the reduction in the pump inlet pressure as read by PT-432 can be used to determine when 1-1.5 lbm of feedwater remains in the bladder. This particular method is the alternate method to determine critical water levels in the event of an external leak given that the primary method for determination of water quantity remaining is offered by the direct calculation of heat rejection from the SWME which was found to have a 95-99% utilization rate in AEMU PLSS 1.0 testing [14]. A review of the PRACA system indicates that 4 failures have been attributed to the Item 142.
- **Item 143 – Feedwater Check Valve**
The Item 143 is a check valve that enables the feedwater recharge filling the two main water bladders to also fill the reserve bladder on the same umbilical recharge line. The valve has a maximum cracking pressure of 1.0 psid [13]. The removal of a separate reserve bladder resulted in the removal of the Item 142 as well as the Item 143. A review of the PRACA system indicates that 1 failure has been attributed to the Item 143.

AEMU Ventilation Loop Simplifications

The combination of the RCA which removes CO₂ and H₂O from the ventilation loop along with the SWME which removes gas from the thermal loop allowed the removal of the condensate loop and the condensing heat exchanger function that the EMU Item 140 Sublimator performed. The water separator is implemented via a small pitot style probe that sits fixed on the F/P/S and extends into a rotating drum that is coupled to the BLDC motor shaft spinning at ~19.7krpm. The spinning drum is fed a slurry of gas bubbles and water through small port holes extending to the outer part of the drum. The water is slung using centrifugal force to the outside of the drum whereas the gas is freed and drifts toward the center which is open to the fan intake. The water slurry is sourced from either the Item 140 Sublimator slurpers picking up condensate from the ventilation loop or from the gas trap picking up a bubble slurry in the thermal loop. Since the RCA removes CO₂ and H₂O simultaneously from the ventilation loop, the slurper function is not required. Also, since the SWME removes gas bubbles from the thermal loop directly by venting them across the membrane walls to vacuum, the gas trap which feeds the majority of the slurry (~ 11pph) to the separator is not required either and the separator itself is not required. The deletion of the condensate loop results in a decoupling of the thermal and ventilation loops significantly reducing the opportunity for failure modes that result in free water in the ventilation loop, a direct hazard for the crew and a significant contributor to subsequent component failures due to the affects from free water (corrosion of fan bearings, latch-up of the CO₂ sensor, corrosion of ventilation loop flow

passages, etc). The removal of the condensate loop and water separator led specifically to the removal of the following components:

- **Item 123B – Fan/Pump/Separator – Water Separator**
As noted previously, the function is satisfied by a combination of the RCA and SWME. A review of the PRACA database indicates that at least 8 of the 96 F/P/S failures were attributed to the Item 123B pitot separator including the prominent in-flight failure on ISS EVA 23 already discussed earlier but also one just prior to STS-98 related to the potential loss of weld plugs from the pitot posing an ignition risk were they to drift back into the aluminum fan impeller running at 19.7krpm. This particular failure was not just a functional loss for removing condensate from the ventilation loop and the inability to degas the thermal loop, it also posed a catastrophic oxygen fire hazard to the crew.
- **Item 141 – Gas Trap**
The gas trap is a ~20 micron absolute pleated filter screen configured in a cylindrical shape with an orifice tube positioned at the internal center axis to scavenge gas bubbles trapped in the screen as the thermal loop flow passes through [2]. This is the finest filter in the loop under nominal operating conditions and is responsible for protecting the tight tolerances between the pump impeller and housing. A review of the PRACA database indicates that 18 failures have been attributed to the gas trap over the course of the EMU Program, the majority of which have been caused by contamination of the filter mesh. This is one of the reasons that the AEMU design includes the thermal loop filter, F-448 that includes considerably more surface area and is located within the rear entry hatch for easy access to allow replacement as a maintenance item.
- **Item 140 – Sublimator (CHX slurper)**
The sublimator slurper which performs the condensing heat exchanger function is composed of a ventilation loop passage coated in a hydrophilic coating thermally tied to the core with small holes on the edges connected to the inlet of the Item 123B water separator. A review of the PRACA database indicates that 3 failures of the 35 generated against the Item 140 sublimator, have been attributed to the slurper hydrophilic coating. That last failure of the three occurred more than 26 years ago indicating that the corrective actions for the contamination thought to have caused the noted failures were successful.
- **Item 125 - Pitot Actuated Valve**
This valve ensures that flow from the gas trap to the water separator is isolated if the water separator cannot generate needed head-rise. The valve allows a manual over-ride actuation in order to prime the water separator should it not self-prime from residual water in the drum. Removal of the water separator removes the need for this valve. A review of the PRACA database indicates that 5 failures total have been attributed to the Item 125 over the life of the program with 4 of them related to contamination and subsequent leakage.
- **Item 134 – Condensate Water Relief Valve**
This check valve prevents back-flow of water from the feedwater tanks/thermal loop if the water separator is not spinning or generating pressure head. Removal of the water separator removes the need for this valve. Review of the PRACA database indicates that 17 failures have been attributed to the Item 134 over the course of the program.
- **Item 171/172 – Coolant Loop Isolation Valve**
This solenoid valve is actuated via the Fan switch and is intended to preclude the pressurization of the thermal loop prior to operation of the F/P/S, specifically the separator. Removal of the separator and associated condensate loop removes the need for this valve. Review of the PRACA database indicates that there have been 13 failures attributed to the Item 171/172 over the course of the program.

Oxygen System Simplification

For the packaging method utilized by the ISS EMU, the main structural parts consist of the aluminum watertank structure topped by a stainless steel valve module and a shearplate assembly that attaches the primary oxygen tanks and regulator to the bottom side of the watertank structure. For the AEMU, the selection of a common operating pressure of 3000 psia between both the primary and secondary oxygen assemblies coupled with the implementation of a two stage motor settable mechanical regulator design allows for commonality between the primary and secondary oxygen supplies (Figure 13). The pressure allows for recharge of both supplies via the SCU removing the need for an ORU-able Secondary Oxygen Pack (SOP) package necessitated by the fact that the EMU SOP pressure is ~6000 psi and not rechargeable on-orbit. The conversion to a motor-settable mechanical regulator which utilizes a stepper

actuator to compress the main load-spring a total stroke of ~.5in in 8000 steps eliminates the need for the sliding mechanical cable and micro-switches that drive a complex, tightly toleranced sliding cam in order to change the set-point on the Item 113 and engage the Item 213, SOP regulator (Figure 12). Hence, the following EMU items were removed along with the failure modes associated with them:

- Item 115 – Shearplate Assembly

The reference to the Item 115 here is not to include the removal of tankage (Item 111) as that is addressed separately, but moreover to address the removal of the structural and actuator linkage components of the shearplate assembly. Review of the PRACA database indicates that 31 failures have been attributed to the Item 115, Shearplate assembly with 14 of those failures attributed to the actuator mechanism itself with most of those due to binding or exceeding the actuation force allocation. The removal of the slide actuator also removes the micro switches and interface that is brought all the way around to the front of the DCM. This slide actuator interface is where the crew interfaces with gloved hands to the regulator assemblies for the purpose of choosing the regulator set-point configurations. This assembly has been subject to contamination as a cause for the binding but has also suffered from binding due to bending of the delicate slide shown in the anterior portion of Figure 11. For the AEMU, removal of this interface and replacement with a less sensitive electrical switch interface to a controlled stepper motor driver may prove to be an adequate answer to these observed failures.



Figure 11 - EMU Shearplate Photo

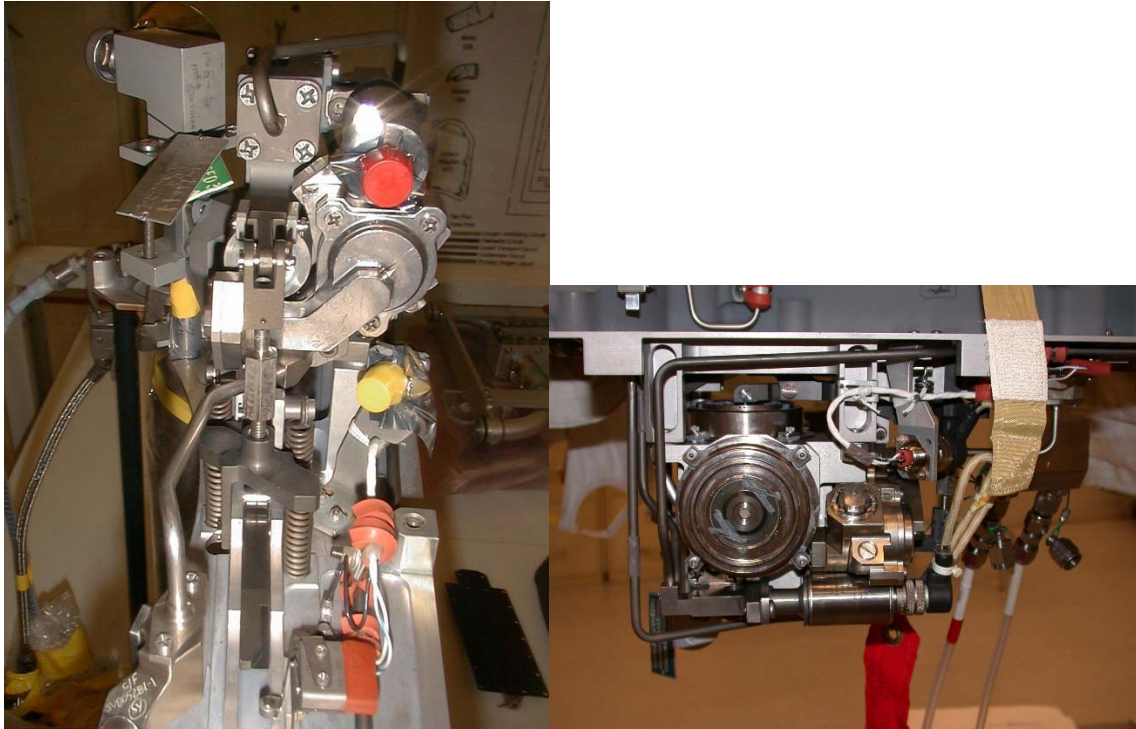


Figure 12 - EMU Shearplate Detail Photo

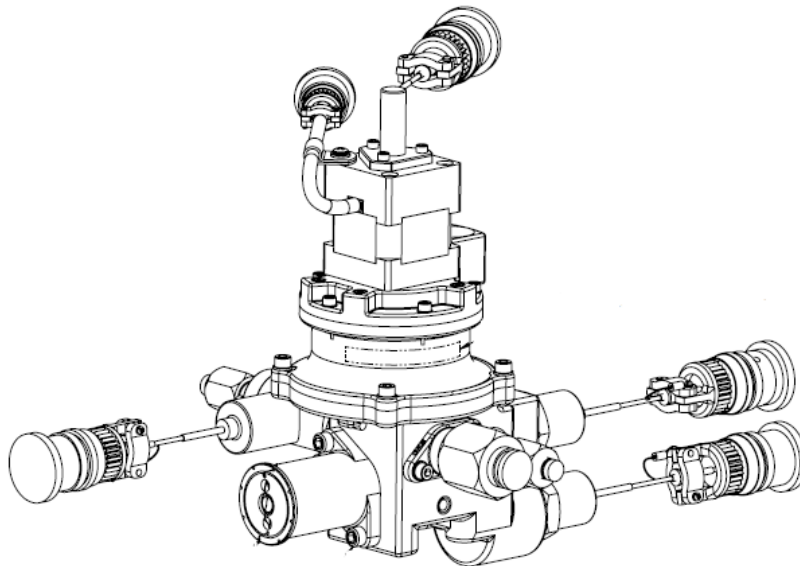


Figure 13 - Primary Oxygen Regulator with Stepper Linear Actuator

- Item 116 – EVA mode micro-switch
This is a single micro-switch that is actually a component within the Item 115 but is tracked separately. The PRACA database indicates that 2 failures have been attributed to the Item 116 micro-switch. Both were assembly/production based issues addressed by changes to assembly procedures.
- Item 200 – Secondary Oxygen Pack (as a separable assembly)
As with the shearplate, the tankage is not considered in this section as it is covered elsewhere, rather the structure that enables the SOP to be a separable item due to its logistical limitations (cannot charge 6000 psi on-orbit) is the topic being addressed herein. A review of the PRACA database indicates that 18 failures have been attributed to the SOP (excluding Item 213, 215, 210 specific failures).

Summary

It is impossible to state with certainty that the AEMU and its associated simplifications vs the EMU will lead to improved reliability as the new hardware such as the RCA, SWME, regulators, gerotor pumps are unproven operationally; a risk that the AES component level and system level development testing [16] is attempting to mitigate as the design moves towards a flight reference design. That said, the removal of components with extensive failure histories, reduction in component count, deletion of the condensate loop, and associated reduction in the likelihood of free water in the ventilation loop all point in the right direction with the summation of failures for all of the removed components totaling 248 failures on the EMU Program. Extensive testing and tools such as the Failure Modes and Effects Analysis (FMEA) and Probabilistic Risk Assessment (PRA) will inform future decisions as the new AEMU components mature towards the flight application.

C. Components that have been redesigned

With the plan to upgrade or redesign hardware based on technological improvements that provide extended functionality or to mitigate undesirable failure mechanisms observed in the operational use of the product, there have been many components which are being redesigned. Table 2 provides the listing of the EMU components that have been redesigned in comparison to the AEMU application along with their designation cross-references. The subsequent paragraphs provide a brief description of the function of the component in the EMU, similar or added functionality in the AEMU, the details of the failure history with the EMU operational use, as well as a brief description of the design changes being implemented for the AEMU.

Shuttle/ISS EMU CEI	Description	AEMU Item	Description
100	Primary Life Support System (PLSS)	Z-000	Portable Life Support System (PLSS)
112	Primary Oxygen Supply Pressure	PT-112	Primary Oxygen Vessel Pressure
113D	Primary Pressure Control Module, Suit Regulator	PRV-113	Primary Oxygen Regulator
114	Ventilation Loop Pressure	DP-114 DP-214	Ventilation Loop Pressure
121	Ventilation flow sensor and check valve	DP-321 FM-323C FM-324C	Ventilation flow sensor Check Valve on Primary Fan Outlet Check Valve on Secondary Fan Outlet
122	IRCO2 sensor	GS-322 GS-300	Multi-gas sensor (CO2/H2O)
123C	Fan/Pump/Separator - Pump	PMP-423 PMP-422	Thermal Loop Pump
131/148/162	Feedwater tanks	FSA-431 FSA-531	Feedwater Supply Assembly
132B	Feedwater supply pressure sensor, water side	PT-432	Feedwater supply pressure (pump inlet)
138	Feedwater pressure sensor (also used for airlock pressure)	PT-116 PT-1001	Vacuum and ambient reference pressure transducers
139	Sublimator temperature sensor	TS-439	SWME outlet temperature
140	Sublimator	HX-440 HX-340	Spacesuit Water Membrane Evaporator (SWME) Ventilation Loop Heat Exchanger
146	Positive Pressure Relief Valve (PPRV)	RV-346 RV-348	Positive Pressure Relief Valve (PPRV)
150	Caution and Warning System	CWS-650 CON-150 CON-250 CON-350 CON-450 CON-550	Caution and Warning System
210	Secondary Oxygen Bottle	PV-210	Secondary Oxygen Vessel

Shuttle/ISS EMU CEI	Description	AEMU Item	Description
300	Display and Control Module (DCM)	DCU-685	Display and Control Unit (DCU)
350	DCM electronics assembly	DCU-685	Display and Control Unit (DCU)
385	Oxygen and water manifold	DCU-685	Display and Control Unit (DCU)
311	Suit Pressure Gauge	PG-311	Suit Pressure Gauge
314	DCM Purge Valve	HV-314	Multi-position Suit Purge Valve (MSPV)
321	Thermal Control Valve (TCV)	TCV-421	Thermal Control Valve (TCV)
330	Multiple Connector	QD-686	Common Multiple Connector
480	Contamination Control Cartridge (CCC)	TCC-360	Trace Contaminant Control
490	Battery Assembly	BATT-690	PLSS Primary Battery Assembly

Table 2 - Component/Functions Redesigned

Pressure Transducers (Item 112/114/132/138)

All of the listed pressure transducers utilize either a bourdon tube (Item 112) or bellows (Items 114/132/138) connected to a potentiometer/wiper assembly. This approach offers the lowest power solution while providing a 0-5 VDC output signal. However, the technology is not well supported or widely used in industry and has several drawbacks due to the moving contact of the wiper on the potentiometer. A review of the PRACA database revealed the following:

Item 112 – 3 failures since 1979; none related to actual sensor performance (GSE test errors, installation problems)

Item 114 – 12 failures including 4 in the last 5 years

Item 132 – 17 failures nearly all due to improper output

Item 138 – 7 failures; none in the last 12 years

The design for the Item 114/132/138 is essentially the same with slightly different scaling and ambient referencing. The AEMU pressure transducer designs will utilize a more common media isolated strain gauge approach to reduce sensitivity to solder balls, FOD, and wear. For the AEMU DP-114/DP-214 wet-wet differential pressure transducer application in the ventilation loop, the sensor design will include the use of Fomblin Y06 fluorocarbon oil as the hydraulic fluid, much like what was done with the Item 112; in this way, should the stainless diaphragm rupture, a small amount of Fomblin (AIT of >427C in 100% O₂ at 1500 psia, [17]) rather than silicone (silicone grease Oxygen Index = 26+/-1, [17]) will be introduced into the ventilation loop.

Primary Pressure Control Module, Suit Regulator (Item 113D)

The dual mode regulator (113D) enables remote setting of the regulator output to different set-points via the use of a dual spring approach on top of the Belleville spring. Both springs are used to provide the EVA pressure of 4.2-4.4 psid and one spring is pulled up with a clevis attachment to a sliding cam mechanism to provide the IVA pressure 0.4-1.4 psid. In order to meet the added functionality required for the AEMU, a two set-point design could not be used and the design evolved into a stepper actuated mechanical regulator with ~8000 possible set points that can be defined by the program using the suit. These multiple set-points meet all of the same operational capabilities that the previous dual mode regulator could achieve but then offer the ability to perform in-suit Decompression Sickness (DCS) treatment, zero prebreathe protocols (and a number in between), and the ability to have the flexibility to mate with vehicles having differing pressure schedules such as suitport with a rover or other vehicle. A review of the PRACA database with respect to the Item 113D in particular indicates that a total of 64 failures were attributed to the Item 113 over the course of the program with 22 of them related to the Item 113D. All but 4 of the 22 failures occurred before 1985 in the early phase of the program. However, the 113D dual mode regulator cannot be easily divorced from the 115 shearplate assembly where the sliding cam actuator and micro-switches reside as they are critical to the implementation of the dual mode approach. As mentioned previously, there were an additional 14 failures attributed to the actuator itself. This would be expected to worsen if the suit were operated in a dusty environment such as the lunar surface. This was another consideration in the decision to convert the actuation mechanism into a stepper linear actuator which could be electrically controlled and sealed to the environment.

Ventilation flow sensor and check valve (Item 121)

The Item 121 utilizes a flapper style check valve tied to sealed micro-switch assembly that is set to trip when the valve closes enough that the volumetric flowrate through the valve is below 3.7 acfm. A review of the PRACA database indicates that 21 failures have been attributed to the Item 121. As is shown in Figure 14, most of the early program failures centered on check valve performance with a stable period of performance into the mid-1990's where failures of the micro-switch and sensor portion became more prevalent.

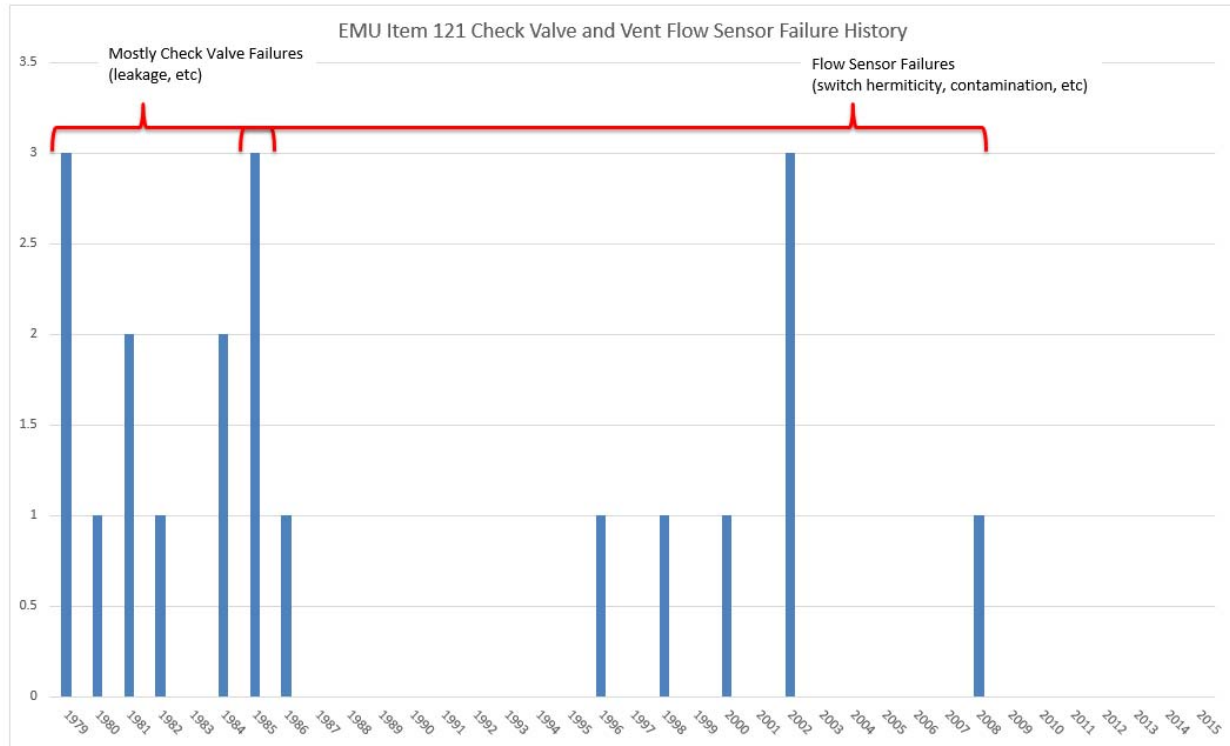


Figure 14 - Item 121 Failure History

For the AEMU, the original intention was to utilize an analog flow sensor such as flowmeter to enable the use of variable trip points in order to make the PLSS more easily adaptable between various spacesuit assemblies with varying ventilation flow requirements. However, as a further simplification in the recent AEMU design work, the sensor has been removed and the flow sensing is now accomplished by measuring the pressure drop across the HX-340 ventilation loop heat exchanger (a component that is already present for the purpose of controlling the helmet inlet gas temperature) with DP-321, a simple differential sensor that is similar in design to that of DP-114/DP-214.

IRCO2 sensor (Item 122)

The Item 122 uses an incandescent source and photo detector with filtering in the 4.3um wavelength range to detect and quantify the presence of CO2 in a flow through sense cell using a Beer-Lambert Law relation. The current sensor design has been in use since the early 1990s after it was the answer to the challenges that the electro-chem sensor posed: frequent calibrations and slow response times. The sensor itself has been quite reliable and even with most of the fleet now in the ~20 year old range, these sensors are functioning with only calibration checks not calibrations (alter the sensor output to align with a standard). The problem for this sensor arises with the excessive moisture present in the EMU ventilation loop both from sublimator slurper carryover but also from high dew point gas entering the sense head which has an excellent view to space through the sublimator vent hole in the PLSS Impact Shield/TMG. Early issues with free water in the ventilation loop were dealt with via design changes such: implementation of the Zytex sleeve intended to tolerate direct free water exposure in the head and implementation of the Vent Flow Ring (VFR) which precludes the water released from the separator drum on shutdown from running down into the sensor head. For a Beer-Lambert sensor, the free water absorbs across a large range that encompasses the particular CO2 absorption peak of choice resulting in a false high CO2 reading which the sensor is capable of detecting and latching the output at full scale (30 mmHg). In the case of the Item 122, this sensor is responsible for a high number of in-flight failures (Figure 15).

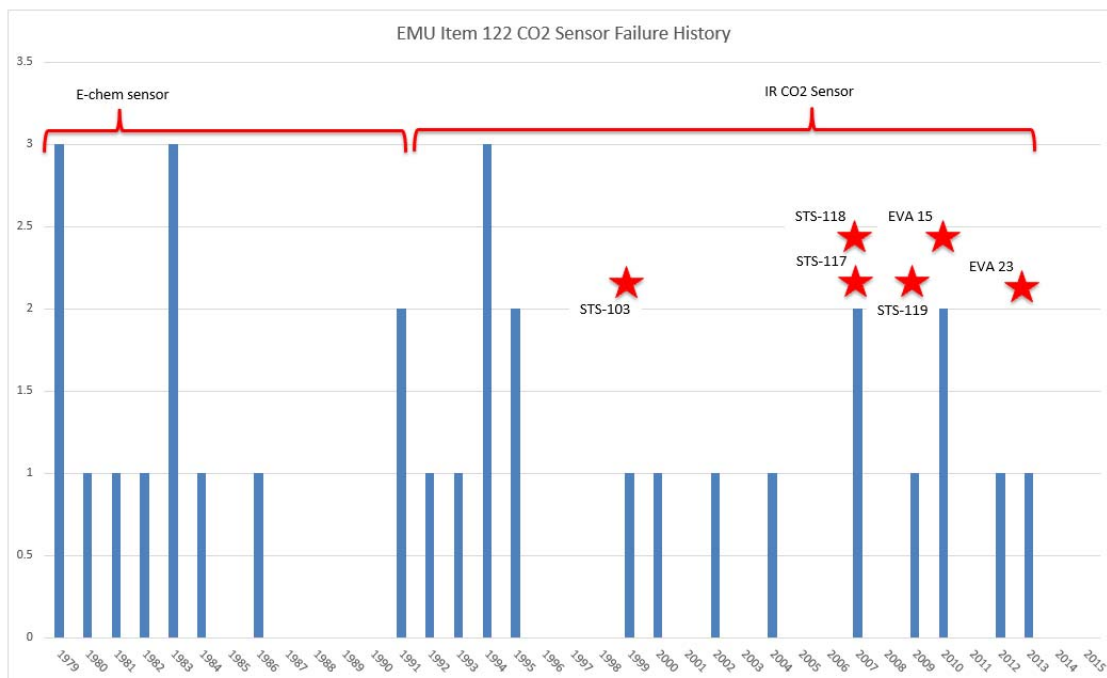


Figure 15 - Item 122 CO2 Sensor Failure History

This is undoubtedly due to multiple causes:

- As experienced, the sensor failure is criticality 3 as flight rules allow for derating of the remaining time on LiOH or Metox and the use of the crew to detect their own hypercapnia symptoms, then the EVA is continued. Hence, there is less of a driver to correct this failure than one that forces EVA termination albeit that it is not trivial and results in a loss of system margin as there is no suit level detection of the scrubber health during the EVA.
- There are no easy answers to provide a guaranteed fix to the problem, although there have been a few simple things that could be implemented with expectation of yielding no worse a result than the current failure rate [18].
 - Place a thermal “sock” over the sense head to reduce the thermal IR lost through the view to space (Figure 16) from the exposed stainless steel sense head; this was recommended as a result of the STS-103 flight failure investigation.
 - Install a “pitot style” insert into the Item 122 pickup tube to raise its input to the gas stream centerline instead of the outer most wall pick-up which easily picks up free water from slurper carryover.

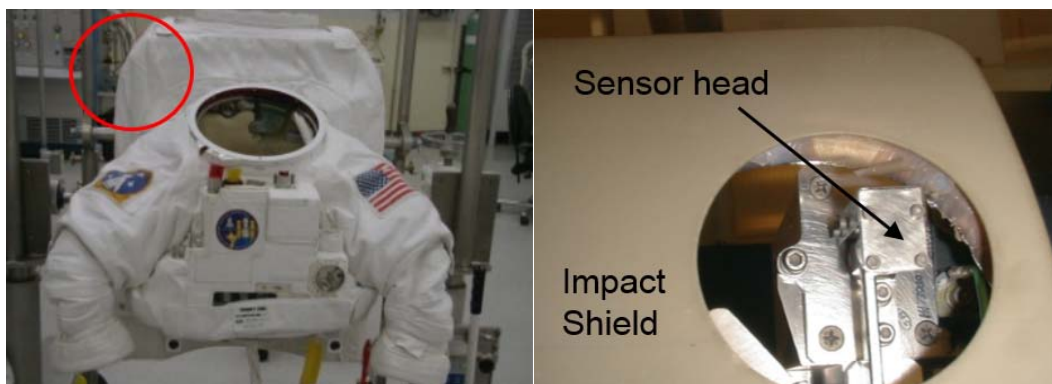


Figure 16 - IRCO2 Sensor Head View to Space

For the AEMU, key technological advances like the RCA and SWME enable the removal of the sublimator slurper function and the use of gas that has a much lower dew point providing more margin in the ventilation loop to prevent

inadvertent formation of free water where it is not desirable. In this environment, the Item 122 would work well and as a result, it is a backup plan to mitigate the risk of some of the newer technologies being pursued. The primary plan for the AEMU gas sensor is the use of a Tunable Diode Laser (TDL) which enables the measurement of both CO₂ and H₂O content to greater accuracy in the ventilation loop using a single instrument while offering a potentially lower power consumption as well. The TDL also referred to as Wavelength Modulation Spectroscopy (WMS), is also a Beer-Lambert Law device that would not work well in the EMU but will work well in the lower dew point ventilation loop of the AEMU.

F/P/S Water Pump (Item 123C)

The EMU F/P/S water pump, as described earlier, is implemented via a centrifugal pump that rotates at 19.7krpm magnetically coupled the common motor shaft. The F/P/S failure history was discussed as part of the earlier section covering the reuse of the centrifugal fan design. Detailed review of the PRACA database with respect to the water pump, Item 123C, indicates that 33 failures of the 96 total have been attributed to the pump itself. The desire to decouple the fluid loops, tolerate water contamination, save power, lower pump speed, enable self-priming, tolerate entrained gas, lower the cavitation pressure point, and add redundancy all drive the selections towards a positive displacement pump like the gerotor style presently used in the AEMU.

Temperature Sensor (Item 139)

The sublimator outlet temperature on the thermal loop, referred to as the Item 139, is implemented via a thermistor that is bonded in-place. Review of the PRACA database indicates that, as one would expect, there are only 5 failures over the course of the program and they were either errors in configuration, production, or integration but not really of the sensor itself. In one case, the sensor was located .75in from the outlet flow and was not effectively reading the fluid temperature so an engineering change (EC) was incorporated to locate the sensor closer to the flow. For the AEMU, the current approach is to use 1k Ohm RTDs with immersion style integration as a mitigation towards that lesson learned. The 1k RTD was chosen given its accuracy and linear response.

Sublimator (Item 140)

The sublimator is a complex counter flow condensing heat exchanger that uses a porous plate and vacuum reference to sublimate feedwater to vacuum in order to reject the heat. The sublimator is an engineering marvel as there is only a slight difference between an effect unit and one that makes “snow cones” without effective use of feedwater. Review of the PRACA database indicates that 35 failures have been attributed to the Item 140 with the most frequent failure being the contamination of the porous plates due to various compounds in the feedwater; this was attributed to 9 failures. The contamination of slurper holes and the hydrophilic coating was considered the cause for 4 failures. The AEMU is planning to make a significant change due to technology advancement in this area. To that end, the AEMU will be using the Spacesuit Water Membrane Evaporator (SWME) which uses a hydrophobic polypropylene to directly evaporate a portion of the thermal loop stream to reject heat. The SWME has already been and continues to be tested to demonstrate its tolerance to contaminants in the water. There were also a number of failures due to handling sensitivity of the sublimator both due to bending or altering dimensions of the soft aluminum flange during installation/removal but also due to the tight gap tolerance for the porous plate shimming. These do not exactly fit the SWME application but consideration of handling requirements will be important in the packaging.

Positive Pressure Relief Valve (Item 146)

The PPRV is a relatively simple poppet style relief valve which has a very tight crack/reseat pressure of 4.7 psid with full open flow requirements satisfied by 5.5 psid. The valve has had reliability issues throughout the course of the program which is reflected in the PRACA database as there are 52 failures attributed to the PPRV. Of those failures, the valve has shown sensitivity to contamination as there were 16 failures attributed to contamination. There were also three failures related to high cracking pressure attributed to stiction. The PPRV has long been on the Limited Life Items List requiring yearly cycling to limit the risk of stiction. There were also 5 failures attributed to chattering when operating at elevated ambient pressures. For the AEMU, the PPRV has been redesigned to improve contamination tolerance, reduce the chance of stiction, and increase stability when operating at elevated ambient pressures.

Caution and Warning System (Item 150)

The CWS was redesigned in the early 2000s and renamed the Enhanced Caution and Warning System (ECWS). The development was cleaner and the deployment was also cleaner than the original CWS development based on the number and type of failure generated (Figure 17). In both cases, the Item 150 is implemented as a monitoring system

which monitors system analog and digital data, computes the system state, limiting consumables, and issues messages to the crew based on detected faults, limiting consumables, or suit configuration changes. The recent failure history is not a driver for the change in the CWS as implemented in the AEMU, rather it is the change in technology available and the functional requirements being implemented. One of the key lessons learned from the difference seen between the two developments is that the ECWS development included the source code for the system wrapped in a Windows desktop simulator that enabled the operations community to simulate and thoroughly debug the code before implementation. This is something that needs to be repeated as part of the AEMU development as well.

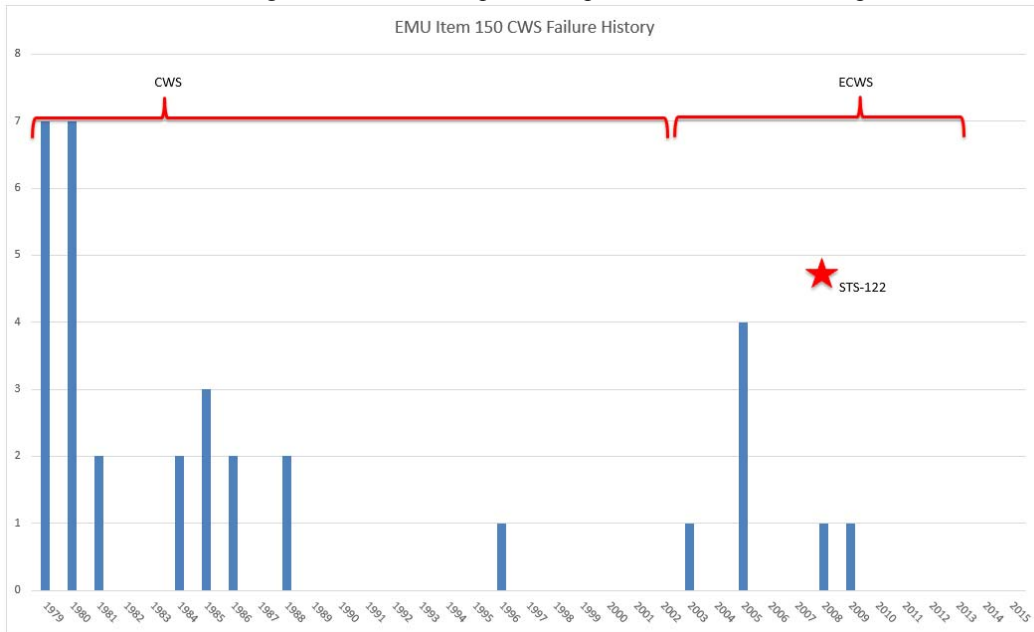


Figure 17 - EMU Item 150 CWS Failure History

The ECWS uses a UTRC 196 16-bit microprocessor while the AEMU CWS is planning to use a SPARC Leon 3 32-bit microprocessor which has been developed and supported by ESA and has newer versions readily available with modern software development toolchains. The AEMU CWS is being asked to do more computationally as there are a few more sensors present and more calculations to be performed. That said, the approach between the two has many similarities including the use as a monitoring system not a control system. The recent versions of the AEMU have pushed the control functionality back into directly commanded controls from the crew via the Display and Control Unit (DCU) to FPGA-based controllers that are modular and lower level. Since the AEMU uses more electro-mechanical actuators, the control functionality has been pushed into low level, simple, modular controllers that possess a serial link via LVDS back to the CWS with control lines from the DCU [19].

Display and Control Module (Item 300/350/385)

The DCM began as a single unit (referred to as the 1000 series for the serial numbers) and, due to manufacturing issues, was later split into two halves, an electrical half referred to as the Item 350, DCM Electronics Assembly and a pneumo-hydraulic half referred to as the Item 385, DCM Oxygen and Water Manifold Assembly. The new assembly has also been referred to as the 2000 series DCM. A review of the PRACA database indicates that the DCM, due to its complexity and significant crew/vehicle interfaces, has had the most in-flight failures of any other component (Figure 18). The combination of the Item 300, Item 350, and Item 385 has 132 failures attributed to the combination; this does not account for the details that are tracked separately such as the potentiometers, etc.

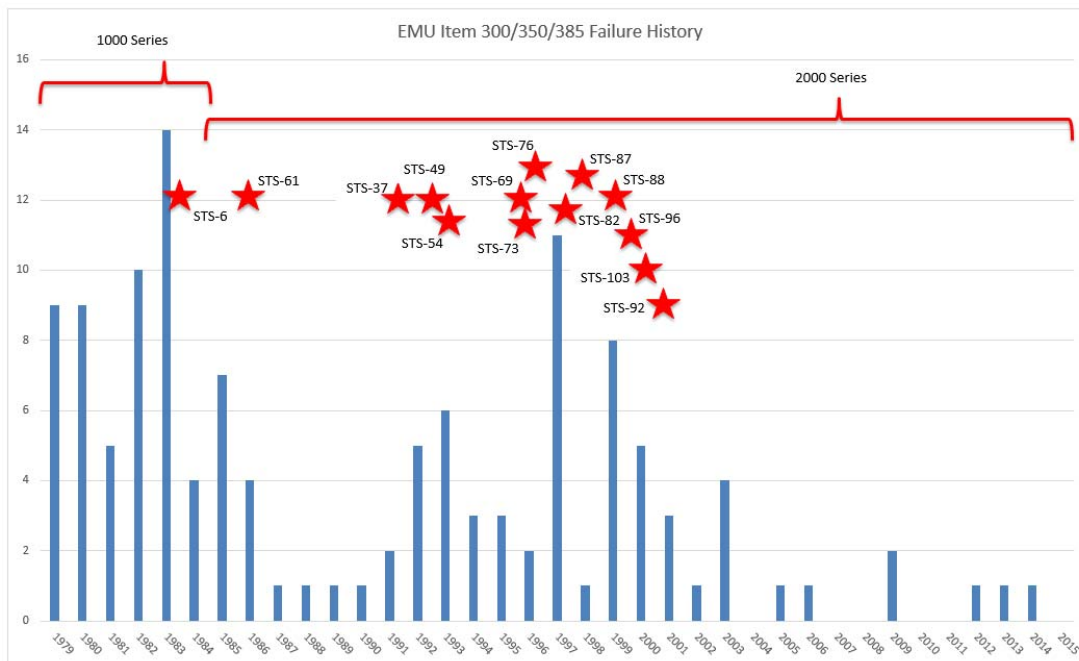


Figure 18 - Item 300/350/385 Failure History

Takeaways relevant to the AEMU design include:

- Thermal loop pressure drop
 - Prior to the design of the 2000 series DCM, there were multiple failures related to the pressure drop of the thermal loop lines. This was largely mitigated in the redesign. Pressure drop in the thermal loop will be sensitive from a power point of view in the AEMU but not as sensitive as the EMU due to the very limited head rise available from the small centrifugal pump.
- Micro-switches
 - There were several failures due to micro-switches failing to read the O2 actuator position. The micro-switch assembly was combined with the shearplate in a modular fashion as part of the ORU EMU conversion in 1997. The complexities and issues related to the micro-switches are discussed in the Item 115, shearplate section.
- Power reset circuit
 - The simplicity of the Power Mode Switch (PMS) does not permit a mate before break on the power transfer resulting in a potential brown out condition during power transfer. This is addressed by the use of reset circuits on the affected controllers in the Item 350, DCM Electronics assembly and the Item 150, CWS. However, the reset circuit in the CWS was redesigned to correct the problem in the ECWS. The DCM reset circuit has not been redesigned to correct the issue, so it continues to manifest itself as an occasional DCM display lockup during power transfer. The AEMU will use a low power diode OR approach to enable a mate before break on the power transfer between vehicle and battery power.

Thermal Control Valve (Item 321)

The TCV as implemented on EMU, is a spool type mixing valve that the crew directly operates with gloved hands and limited access to set the effective water temperature and in limited cases flowrate fed to the LCVG for metabolic heat removal. A review of the PRACA database indicates that there have been 10 failures over the course of the program that have been attributed to the Item 321. A total of 8 of the 10 failures noted were due to excessive torque for valve operation. For the AEMU, the valve function has been changed to that of a diverter valve which alters the mass flow rate to alter the removed heat, still supporting LCVG bypass functionality required for colder environments. The operation of the valve is performed remotely by the thermal loop controller (CON-450) driving the linear stepper actuator to position the valve back in the PLSS. This approach has the following benefits over the directly actuated Item 321:

- Crew interface with gloved hands can be adjusted to avoid challenging the capabilities of reach and applied force of gloved hands
- The exact valve position will be known by virtue of the stepper actuator with the added benefit of a linear potentiometer as a redundant position reading
- Future capabilities such as Auto-Cooling Control (ACC) may be used as the valve directly supports it
- Simplification of the thermal loop by conversion to a diverter valve approach

Battery (Item 490)

The battery has undergone significant change over the course of the program. The original battery used on the program was a single string of 11 series Ag-Zn cells forming a battery rated for just over the required 26.6Ah and referred to as the 1000 series battery. It was later upgraded to another battery composed of a single string of 11 series Ag-Zn cells offering a capacity increase with >32Ah nominally and the promise of a longer wet-life/higher cycle-life referred to as the “Increased Capacity Battery” or ICB or 2000 series battery. The first two changed suppliers but the technology was evolutionary. The significant change occurred when the Lithium Ion Battery (LIB) a single string of 5 series prismatic Li-Ion cells was chosen as the next EMU battery. The LIB encountered a number of challenges and could not be realized as a flight product. It was completely redesigned and named the Long Life Battery (LLB). The LLB used carefully screened high volume COTS cylindrical 18650 cells arranged in a 5 series of 16 parallel cells.

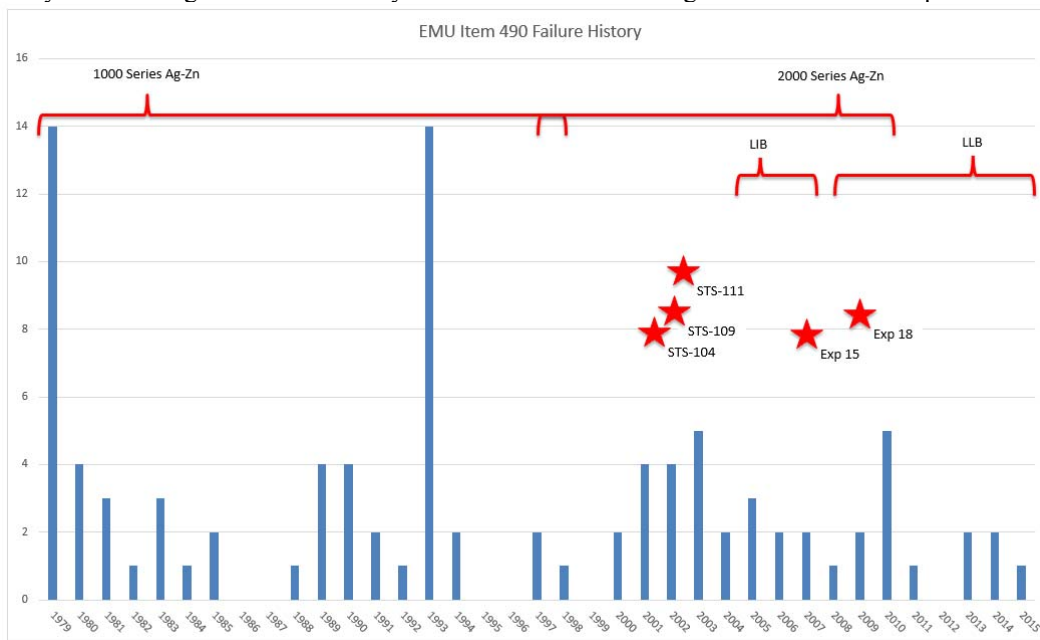


Figure 19 - Item 490 Failure History

A review of the PRACA database indicates that there have been 104 failures attributed to the Item 490 battery over the course of the program (Figure 19). Of those listed failures, the basic break-out of the largest contributors is included in Table 3.

High Level Grouping	Number of Failures	Percentage of Total (%)
Case/cell leakages of custom prismatic cells	15	14.4
Formation procedure failures	6	5.7
RV leakage or other RV failure	18	17.3
Internal shorts (electrolyte bridging, etc)	11	10.5
Manufacturing errors (potting, over-torque, etc)	27	26.0
Testing errors	8	7.7
Usage/handling operational procedures	5	4.8

Table 3 - Item 490 Failure Contributor Break-out

As can be seen in Figure 19, there were a number of failures with the 1000 series Ag-Zn battery, many of which were manufacturing issues and case/cell leakage failures associated with the custom prismatic cells in the battery. The RV

leakage and other RV failures were spread across both of the Ag-Zn battery designs along with the internal shorts from electrolyte bridging. The number of testing/handling errors over the life of the program is not surprising with the extent of manual testing that existed in the 1980's. While the concerns over the addition of the catastrophic thermal runaway and fire failure mode that the Li-Ion presents requires additional work, one should also note that many of the failure causes present on the custom prismatic Ag-Zn cells are much less likely to be present in cylindrical mass produced and screened cells for the following reasons:

- Low volume custom prismatic cell production does not really enable NASA to refine the cell production process while companies like Panasonic, Molitel, Boston Power, and others makes thousands if not millions of the batteries that can be cherry-picked taking advantage of the investment in those companies have made in their processes.
- The cells are “formed” at the time of manufacture so there is no need for battery formation procedures where the improper amount of electrolyte can be added, or other critical steps can be omitted or improperly executed; rather companies with highly automated processes can make these cells over and over more successfully.
- The cells already include their own Current Interrupt Devices (CID) and relief valve integrated into the cells meaning that the overhead of tracking, storing, and performing crack/reseat/leakage for all 11 RVs that below to a single Ag-Zn battery is no longer required.
- The mass produced cells are observed, bought in lots, screened including NDE and destructive evaluation of samples reducing the opportunity for the frequency of internal shorts seen with the venting of KOH into the wicking and the migration associated with some of the Ag-Zn batteries.

In the end, the difficult part of the battery fabrication is left to the companies that do it a lot and are efficient and effective. This can be observed by examining the plot of the failure history (Figure 19) noting that the failure rates have dropped considering the implementation of a new battery, LLB into the fleet. There have been 11 failures since 2010 with 5 of them attributed to the ICB Ag-Zn battery and only 6 of them attributed to the new LLB in its initial implementation; of those 6 failures, infant mortality manufacturing issues have been the causes as would be anticipated in a new product. This validates the current battery development plan for AEMU which is to fabricate modular distributed battery packs using Li-Ion 18650 cells carefully screened from major manufacturers.

One of the most significant takeaways from the LLB experience is one that has, fortunately not manifested as an actual failure on the EMU Program, but is a lesson learned from the Boeing 787 Li-Ion battery failures [20] and has been applied to several NASA Li-Ion batteries with the assistance of the NESC. Recent testing of the LLB for thermal runaway propagation which could occur with an internal short in one of the 18650 cells revealed that the current battery design did not limit or control the propagation as several cells within the test battery ignited. The purpose here is not to try to give third party anecdotal information about the LLB testing prior to the publishing of a formal test report by those responsible in EP/JSC as much as it is to relay that these lessons learned are being applied concurrently to the AEMU battery design. The same organization testing the current batteries is consulting on the design of the AEMU battery to first provide controls for a single cell thermal runaway without propagation followed by further design and debate over the extent of the Battery Management System (BMS) needed within the battery design.

Suit Pressure Gauge (Item 311)/Suit Purge Valve (Item 314)/Multiple Connector (Item 330)

The Item 311 suit pressure gauge included as part of the Item 385 oxygen water manifold is implemented via a simple and classic bourdon tube design. A review of the PRACA database indicates that 21 failures have been attributed to the Item 311 suit pressure gauge. Of the listed failures, 7 failures were attributed to condensation formation from the moist ventilation loop gas followed by subsequent water column offset readings and/or corrosion. The pressure gauge port is connected directly to the suit volume through a small orifice feed-through from the DCM to HUT interface pad. The gauge location for the AEMU is presently anticipated to be on the arm of the Z-suit but assessments are still pending as to whether or not there will be sufficient room on the anterior of the HUT to add the pressure gauge to the DCU. If this is added to the DCU, the protection of the gauge from condensation will be an input into the design of the interface. The second largest contributor to the 21 failures was manufacturing/quality control issues with the chosen supplier; this will be investigated further during the initial gauge prototyping phase of the gauge.

The Item 314 Suit Purge Valve is a simple orificed slide-action valve that has been quite reliable over the course of the EMU Program; it is used at the start of every EVA. A review of the PRACA database indicates that only 4 failures have been attributed to the Item 314 and 3 of them prior to the valve redesign that was implemented in 1982. For the AEMU, this would be a good starting point with exception of the need for a multi-position suit purge valve (MSPV) and the need for dust tolerance.

Item 330 DCM Multiple Connector is a custom pneumo-hydraulic and electrical connector which connects the high pressure oxygen supply, thermal loop inlet/outlet, feedwater recharge, and power/comm from the vehicle supplies. A review of the PRACA database indicates that 23 failures have been attributed to the Item 330 multiple connector. Twelve of the 23 failures occurred before 1985 during the initial development and implementation. For the remaining failures that occurred after that time, there were 5 flight failures occurring after 1991; 4 of them were related to the DB25 electrical connector (1 for a bent pin, 1 for high impedance improper engagement, 2 for damaged environmental o-ring). The bent pin failure occurred on the STS-103 Hubble servicing mission. The result of the failure was the inability to power the suit on umbilical meaning that the crew had to use battery margin to perform the IVA activities; something quite undesirable for long complex EVAs like those of a Hubble mission. The other flight failure occurred on STS-96 when the lubricant washed out of the thermal loop water poppets which were located on one side of the multiple connector; this increased the actuation force to engage the poppets generating a torque about the centerline cam and causing the multiple connector to bind. This particular failure was critical as it took ~30 min for the crew to mate the SCU to the DCM to get vehicle services. The corrective action from this failure was to add a four year limited life to the multiple connector in which every four years, it would be torn down, cleaned, and reassembled with lubricant. This had the effect of putting more Krytox 240AC or Braycote 601 fluorinated grease (thickened with fine PTFE particulate) into the water loop where it would show up in later years clogging filters. While the AEMU will require a new multiple connector design due to the changes in the required vehicle services, these failures and lessons learned are critical to designing an improved multiple connector. The AEMU multiple connector will need to tolerate differential forces from each of the services if poppets are used. There were two leakage failures due to contamination of the poppet seals along with an excessive pressure drop in the thermal loop as a result of a clogged/contaminated filter. The fluid ports need to tolerate contamination if possible and the filtration needs to be serviceable. For the listed failures associated with the electrical connector, the use of a scoop proof, blind mate connector will reduce the chances of having a bent pin and the blind mate features coupled with proper tolerancing should reduce the chance of improper engagement. The use of an o-ring around the connector can be mitigated by using alternate means to isolate the electrical connector from the fluids ports.

Other lessons learned

Aside from the individual lessons learned from the individual components, the sub-assemblies, and assemblies, there are considerable lessons to be learned from system level operational failures and successes. Overall, the ORU EMU Program has been successful in that it made possible the disassembly/reassembly of major assemblies of the ISS EMU such as the DCM, HUT, PLSS, and SOP. Key features employed were captive fasteners with hex-drive screws, face-seals, and novel integrated minimum torque checks from Belleville washers and slide locks that won't engage without proper compression of the washers. The use of common tools was also a focus albeit that a separate ORU toolkit was developed to house the needed tools and the assembly/disassembly aids in order to save crew time. All of these features have worked well and are being carried over in the AEMU. The only problem with the ORU EMU approach is that it wasn't implemented to a lower level because the ground rules at the time of the project did not assume the duration of operation that ISS would later require. Lessons learned from the Loss of Cooling on-orbit failure troubleshooting and others since have demonstrated that component level ORU-ability is a necessity. This is one of the primary drivers in the packaging of the AEMU and its use of a motherboard style backplate with each component independently accessible as an ORU item on the backplate secured with captive fasteners, sealed predominantly with face seals, and electrical connectors which include triple start Acme threads and scoop proof designs. From the Shuttle Program usage model for which the EMU was initially designed, everything was basically a maintenance item fully serviced on the ground during a full tear-down PIA that occurred between flights. As that usage model evolved to the 6 years and 25 EVA model that the ISS EMU is using today, there were limitations as to what could be done short of significant redesign of the EMU. Hence, the finest filter set in the PLSS (Item 141 and Item 127) both are accessed for replacement but require removal of the PLSS TMG and Impact shield to achieve that access. The feedwater bladders (Items 131/148/162) are highly integrated to the machined watertank structure such that it would be impractical (although not impossible) to change them on-orbit. The Item 490 battery and Item 480 CCC (LiOH or Metox) are routinely accessed each EVA to change out consumables. The access is made simple by a dual zipper access of a rear flap on the PLSS TMG and some simple to actuate latches to secure/release them. Considering these areas of improvement as well as successes, the AEMU implements access to all anticipated nominal maintenance items without removing the PLSS TMG or accessing the PLSS at all, rather they are immediately available in the hatch the crew uses to don/doff the suit. The items that the AEMU includes as readily available within the hatch include (Figure 20):

F-448 – Thermal Loop Filter
FSA-431 – Primary Feedwater Supply Assembly
FSA-531 – Auxiliary Feedwater Supply Assembly
TCC-360 – Trace Contaminant Control

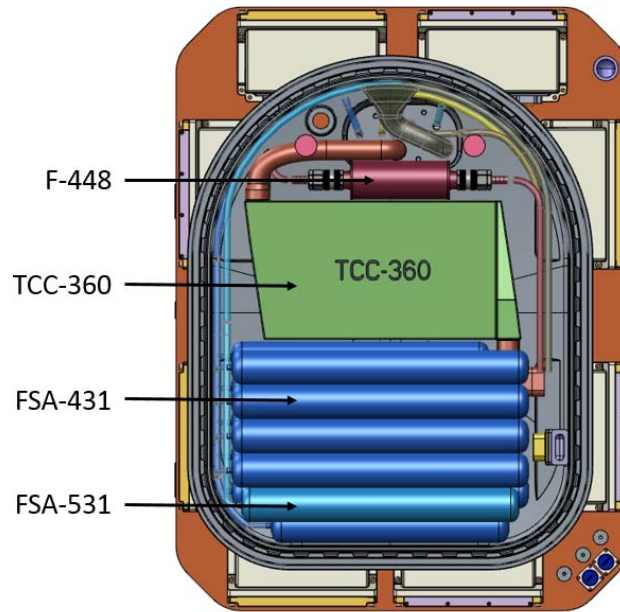


Figure 20 - AEMU Rear Entry Hatch Maintenance Item Access

The modular battery cartridges which are intended to be charged in-situ via umbilical connection from the vehicle charger are also readily accessible by opening the PLSS TMG access flaps around the hatch area. Although there is no intention to need to replace the battery in the PLSS within 100 EVAs, should that need arise due to malfunction, changing the battery will be reasonable.

Summary

As has been discussed throughout the entirety of this paper, the Shuttle/ISS EMU Program has offered an extensive and well documented operational history from which many lessons can be learned and applied to the next suit design. Even for those components or technologies that have been operationally reliable in the EMU and hence are similar between the EMU and AEMU designs, there are lessons to be learned for why certain choices were made in that may have affected that success. In the study of the components/technologies that have been removed between the EMU and the AEMU designs, some might ask why bother? But once again, even this case, there are significant lessons that can be learned and at minimum an appreciation can be garnered for the relative increases in complexity locally (such as the RCA) which enable the simplification of the system as a whole and the associated operational failure history of the components no longer present. For the components/functions that are common from the EMU to the AEMU, but the design approaches and technology are different, some of the most significant lessons can be assessed and considered in the AEMU design. A phrase that has made its way around the internet and popular culture for a number of years is [21] “Those who cannot remember the past are condemned to repeat it.” While there is no guarantee that the successes of the past will be recreated or that failures of the past will be ameliorated, the study of this history provides insight that would otherwise be unknown until the failures were repeated in ignorance. To that end, this paper has given key takeaways and planned actions to demonstrate that the base design approach to the AEMU PLSS packaging, the system level design, the design of every component in the AEMU, and the outline processes are rooted in the knowledge obtained from the review of the failures and successes of the suit system that has successfully served Shuttle and assembled the International Space Station over the past 35+ years.

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