

# Abstract

## Post-Shuttle EVA Operations on ISS

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The expected retirement of the NASA Space Transportation System (also known as the “Space Shuttle”) by 2011 will pose a significant challenge to Extra-Vehicular Activities (EVA) on-board the International Space Station (ISS). The EVA hardware currently used to assemble and maintain the ISS was designed assuming that it would be returned to Earth on the Space Shuttle for refurbishment, or if necessary for failure investigation. With the retirement of the Space Shuttle, a new concept of operations was developed to enable EVA hardware (Extra-vehicular Mobility Unit (EMU), Airlock Systems, EVA tools, and associated support hardware and consumables) to perform ISS EVAs until 2015, and possibly beyond to 2020. Shortly after the decision to retire the Space Shuttle was announced, the EVA 2010 Project was jointly initiated by NASA and the One EVA contractor team. The challenges addressed were to extend the operating life and certification of EVA hardware, to secure the capability to launch EVA hardware safely on alternate launch vehicles, to protect for EMU hardware operability on-orbit, and to determine the source of high water purity to support recharge of PLSSs (no longer available via Shuttle). EVA 2010 Project includes the following tasks: the development of a launch fixture that would allow the EMU Portable Life Support System (PLSS) to be launched on-board alternate vehicles; extension of the EMU hardware maintenance interval from 3 years (current certification) to a minimum of 6 years (to extend to 2015); testing of recycled ISS Water Processor Assembly (WPA) water for use in the EMU cooling system in lieu of water resupplied by International Partner (IP) vehicles; development of techniques to remove & replace critical components in the PLSS on-orbit (not routine); extension of on-orbit certification of EVA tools; and development of an EVA hardware logistical plan to support the ISS without the Space Shuttle. Assumptions for the EVA 2010 Project included no more than 8 EVAs per year for ISS EVA operations in the Post-Shuttle environment and limited availability of cargo upmass on IP launch vehicles. From 2010 forward, EVA operations on-board the ISS without the Space Shuttle will be a paradigm shift in safely operating EVA hardware on orbit and the EVA 2010 effort was initiated to accommodate this significant change in EVA evolutionary history.

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# **EVA 2010: Preparing for International Space Station EVA Operations Post-Space Shuttle Retirement**

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The expected retirement of the NASA Space Transportation System (also known as the “Space Shuttle”) by 2011 will pose a significant challenge to Extra-Vehicular Activities (EVA) on-board the International Space Station (ISS). The EVA hardware currently used to assemble and maintain the ISS was designed assuming that it would be returned to Earth on the Space Shuttle for ground processing, refurbishment, or if necessary for failure investigation. With the retirement of the Space Shuttle, a new concept of operations was developed to enable EVA hardware (Extra-vehicular Mobility Unit (EMU), Airlock Systems, EVA tools, and associated support equipment and consumables) to perform ISS EVAs until 2016, and possibly beyond to 2020. Shortly after the decision to retire the Space Shuttle was announced, the EVA 2010 Project was jointly initiated by NASA and the One EVA contractor team. The charter of the EVA 2010 project team was to develop a strategy to maintain EMU EVA capability on ISS post shuttle retirement. Challenges addressed were to extend the operating life and certification of EVA hardware, to secure the capability to launch EVA hardware safely on alternate launch vehicles, and to protect for long duration EMU hardware operability on-orbit. This paper describes the process used in the strategy development and the current results of tactical implementation of some of the projects to maintain EMU EVA capability on ISS. This paper by no means encompasses all work that has occurred, is ongoing, or still needs to be accomplished before the EVA community considers the EVA 2010 project’s efforts fully integrated into the nominal way of doing business that is called EVA. However, it does provide a glimpse of From 2010 forward, EVA operations on-board the ISS without the Space Shuttle will be a paradigm shift in operating EVA hardware on orbit; and the EVA 2010 effort, as initiated, is successfully accomplishing this significant change in EVA evolutionary history.

## **Nomenclature**

<i>ATV</i>	=	Automated Transfer Vehicle
<i>BTA</i>	=	Bends Treatment Adaptor
<i>DCM</i>	=	Display and Control Module
<i>EMU</i>	=	Extravehicular Mobility Unit
<i>ESA</i>	=	European Space Agency
<i>ETCA</i>	=	EVA Tools & Crew Aids
<i>EVA</i>	=	Extravehicular Activity
<i>EVVA</i>	=	Extravehicular Visor Assembly
<i>FIARS</i>	=	Failure Investigation Anomaly Reports
<i>FOD</i>	=	Foreign-Objects & Debris
<i>FY</i>	=	Fiscal Year

<i>HSF</i>	= Human Space Flight
<i>HTV</i>	= H-II Transfer Vehicle
<i>ISS</i>	= International Space Station
<i>JAXA</i>	= Japanese Aerospace Exploration Agency
<i>LSS</i>	= Life Support System
<i>MMU</i>	= Manned Maneuvering Unit
<i>NASA</i>	= National Aeronautics and Space Administration
<i>ORU</i>	= Orbital Replacement Units
<i>PLSS</i>	= Portable Life Support System
<i>RRU</i>	= Removable Replaceable Units
<i>SCOF</i>	= SOP Checkout Fixture
<i>SOP</i>	= Secondary Oxygen Supply
<i>SSA</i>	= Soft Goods Assembly
<i>USOS</i>	= United States Operating Segment
<i>TIM</i>	= Technical Interchange Meeting
<i>WPA</i>	= Water Processor Assembly

## I. Introduction

After the decision to retire the Space Shuttle was announced, it was evident that the capability to return EMUs from ISS back to Earth would be lost. Shortly thereafter, an effort to develop a plan for continued EVA support of ISS in the post-Shuttle environment was initiated. This effort became known as the EVA 2010 Project. The strategy for this project was developed jointly by a focus team with the support of subteams over a course of several months during U.S. Government fiscal year (GFY) 2006. The focus team consisted of representatives from the NASA EVA Customer (XA\EVA Projects Office), the NASA EMU Subsystem Manager (EC5\Space Suit and Crew Survival Branch), and the One EVA Program (Team of contractors that designed and currently maintains, operates, and processes the EVA hardware for flight operation). During this focused team effort, it was determined that the EMU could be able to achieve EVAs after the Space Shuttle retires based upon the ISS continuing until 2016, but not preclude supporting operations, if ISS was to extend to 2020. It was determined that an on-orbit maintenance interval extension would be required beyond the then current 2 years. A 6-year maintenance interval was determined to be attainable; however an 8-year interval was conceivable at the time. The ultimate extension would result in a designation of the EMUs as “MEGA EMUs”. It was also determined that there would be logistical issues to overcome, which were deemed to be manageable. Overall, the existing refurbishment plan would be impacted and there would be a need for new hardware procurement and to have a proactive approach of component swapping during the processing of the hardware. A roadmap was developed (see Figure 1.0) strategies were depicted, and information was provided that revealed how the chosen strategy was going to change the existing way business was being performed. Finally, the decision authorization began in FY2007.<sup>1</sup>

## II. ISS EVA Systems

EVA systems on-board the ISS are categorized as the EMU, EVA tools and crew aids, and A/L systems. Operation of all three systems are required in order to ensure that EVA tasks may be completed successfully completed by the EVA crewmembers.

## **A. Extra-Vehicular Mobility Unit**

The EMU is an independent anthropomorphic system that provides environmental protection, mobility, life support, and communications for the crewmember to perform Extravehicular Activity (EVA) in Earth orbit. The EMU is designed to accommodate EVAs from both on-board the ISS and Space Shuttle Orbiter airlocks for a planned EVA duration of 6.5 hrs, although the EMU can support EVAs longer if necessary. The EMU consists of the spacesuit assembly and the Portable Life-Support System (LSS).<sup>14</sup>

The spacesuit consists of a Hard-Upper Torso (HUT), Lower Torso Assembly (LTA), gloves, Helmet/Visor Assembly, the Liquid Cooling and Ventilation Garment (LCVG), and the Communication Cap Assembly (CCA). The HUT is the portion of the pressure suit above the waist, excluding the gloves and helmet. The HUT comes in three sizes: medium, large, and extra-large. The LTA is the portion of the pressure suit below the waist, including the boots which are integrated into the LTA. The LCVG is a garment worn under the pressure suit and sewn-in tubes to provide circulation of cooling water for the crewmember. The CCA is a cap worn under the helmet and hold the earphones and microphones for the communication system.

The Life Support System consists of a Portable Life-Support System (PLSS), a Secondary Oxygen Pack (SOP), EMU battery, a CO<sub>2</sub> removal cartridge, radio & telemetry system, a Caution & Warning System (CWS), and the Display and Control Module (DCM).<sup>14</sup>

The PLSS provides the EVA crewmember with oxygen for breathing, ventilation, and pressurization as well as water for the LCVG. The SOP assembly provides oxygen for breathing, ventilation, pressurization, and cooling in the event of a malfunction of the primary O<sub>2</sub> tanks or a suit leak. The SOP is contained within the EMU backpack and is attached to the bottom of the PLSS. The CO<sub>2</sub> removal cartridge is a crew-replaceable module used in the PLSS to remove CO<sub>2</sub>, odors, particulates, and other contaminants from the ventilation circuit. And the DCM allows the crewmember interface with the PLSS as well as the C&W system and is mounted on the front of the upper torso. The DCM contains displays and controls associated with the operation of the EMU.

## **B. EVA Tools & Crew Aids**

The number and variety of EVA tools and crew aids are too numerous to describe in this paper with over 350 different tool designs available for use by the EVA crewmember, depending on the task. In general EVA tools are categorized as large tools, small tools, with the Pistol Grip Tool (PGT) considered separate from the small-tools given its complexity.

The types and variety of small EVA tools vary, but in general a small EVA tool is one that is carried by the crewmember to the ISS external worksite. Typically the tool is tethered to the crewmember or secured to a Body-Restraint Tether (BRT). Additionally the crewmember has a Modular-Mini Workstation (MMWS) located below the DCM on the HUT. The MMWS allows the crewmember to tether tools and other hardware in an easily accessible location. Safety tether and equipment tethers are also considered as small EVA tools and are used by the EVA crewmembers in ensuring the hardware does not detach and float away, later posing a risk of re-contact with the ISS. During a typical EVA, the

crewmember may have up to a dozen small tools attached to their MMWS or other tether points on the EMU and another dozen in a crew lock bag.

The PGT is a battery operated, programmable, tool used to tighten and loosen various nuts, bolts & fasteners. Speed, torque & revolution settings are programmable.<sup>13</sup> Additionally there are several small-tools that may be used with the PGT to enhance its capability, the Torque Multiplier and the Right-Angled Drive. The battery used by the PGT is a Rechargeable Nickel Metal Hydride (NiMH) battery. The current on-orbit life of the PGT is less than 2 years before it is returned to the ground for calibration.

### **C. EVA Airlock Systems**

The ISS Airlock (A/L) module for the EMUs is located on the starboard side of Node 1 and is comprised of two sections, the Equipment Lock and the Crew Lock. The primary purpose of the A/L module is to allow ISS crews, in EMUs, access to the exterior of the station to perform assembly & maintenance tasks. It was launched early in the ISS assembly sequence on STS-104/7A in July 2001. Initially the A/L was to have the capability to support both EMUs and Orlans, but outfitting for the Orlan capability was never completed. The airlock for the Orlan resides on the Russian Segment. Systems for the Orlan were not addressed as part of the EVA 2010 project.

The A/L provides the capability to service, maintain, don, doff, and store the EMUs as well as EVA tools and other EVA ancillary equipment. The A/L systems that provide EMU servicing and recharge are known as the Service, Performance, and Checkout Equipment (SPCE) and is comprised of the Power Supply Assembly (PSA), Battery Charger Assembly (BCA), Battery Stowage Assembly (BSA), the Umbilical Interface Assembly (UIA), and the EMU Don/Doff Assembly (EDDA). Other critical equipment related to the EMU includes the Metox regenerator and stowage locations for EVA hardware.<sup>15</sup>

### **III. ISS Ops Concept Post-Shuttle**

The EMU, as well as associated EVA Tools and Crew aids, were designed starting in the late 1970's to support short-duration Space Shuttle missions. The hardware was designed to fly on a shuttle mission, perform 1-3 EVAs, then return to earth for refurbishment and checkout by ground personnel before being re-flown. This concept of operations was significantly different than that employed on previous NASA missions such as Apollo and Skylab. In pre-Shuttle NASA HSF missions, due to the nature of the mission and limited cargo return capability, much of the EVA hardware, including the PLSS, was discarded either on the lunar surface or left on-board Skylab. The Space Shuttle afforded the capability to return EVA hardware for refurbishment and repair and mission designers took advantage of this capability in designing the EMU and associated hardware.

Prior to the start of ISS assembly in November 1998, 41 EMU EVAs were conducted out of the Space Shuttle airlock in support of a variety of missions and tasks. These included EVAs to retrieve and service commercial and civilian satellites (i.e. STS-41C and the repair of the Solar Max satellite and STS-61 and the first Hubble Space Telescope servicing mission), test the Manned Maneuvering Unit, and conduct tests related assembly techniques for the ISS.

Initially the predecessor to the ISS, Space Station Freedom, was to have had its own spacesuit, designed and built specifically to space station requirements. However budgetary constraints and a re-focus of the space station program from that of Space Station Freedom to the International Space Station resulted in the decision to continue using the Shuttle EMUs as the primary spacesuit for the United States Operating Segment of the ISS (the Russian Orlan spacesuit is the primary spacesuit for the ISS Russian Segment and is not covered in this paper). As such the EVA concept of operations had to be changed from that of early-Shuttle based EVAs.

Since the ISS was to have an independent U.S. Airlock for EVA operations, with EMUs being left on-board the ISS for longer periods of time than the original on-orbit certification allowed, a re-certification effort was initiated to extend the period between maintenance cycles from 1-3 EVAs on a short duration Shuttle mission to 3 months and 25 EVAs. Later this certification was extended to 2 years, after which the EMUs would be returned to the ground for servicing and refurbishment, with replacement EMUs being delivered by the Space Shuttle.

Additionally, the requirements to build the ISS drove the design and development of a large number of new EVA tools. As with the EMU, early Shuttle tools were designed and certified for short-duration Shuttle missions. However for the ISS, many of these tools would have to be left on the ISS to support contingency EVAs, that is EVAs required to replace external ORUs on the ISS that have failed. As with the EMU, the on-orbit certification life of these tools allowed them to be left on the ISS for an extended period of time, which varied depending on the tool, then later returned on the Shuttle for refurbishment and later returned to the ISS on subsequent Shuttle missions.

Shortly after the decision to retire the Space Shuttle was made in 2004, it was realized that the entire EVA concept of operations related to providing EMU EVA on ISS would have to significantly change. Without a vehicle to provide return capability, EVA hardware would have to become disposable. Additionally the on-orbit life of EVA hardware would have to be extended as much as possible to minimize upmass requirements, and procedures would have to be developed that allowed the ISS crew to service and repair EVA hardware, including the EMU PLSS. EVA hardware, originally certified to be delivered to the ISS by the Space Shuttle would now have to be certified for delivery on expendable International Partner vehicles such as the Japanese HTV or the European ATV. And since each EVA crewmember requires specific suit sizing components, from custom built EMU gloves to three different sizes of the Hard Upper Torso, the concept of a component sizing “pantry” had to be developed that would allow the maximum number of crewmembers to have specific crew-sizing components while minimizing EVA hardware upmass requirements.

This change in the philosophy of EVA concept of operations was deemed so dramatic that the formation of the EVA 2010 Project was crucial to successful transition into the post-Shuttle era. By identifying the differences between ISS EVA operations pre-Shuttle and post-Shuttle the EVA 2010 team was able to set in motion the appropriate project plans with complete community support.

#### **IV. EVA 2010 Strategy Development**

The EVA 2010 strategy was cultivated by a focus team chartered to develop a methodology for changing current ways of doing business to ensure EVA capability on the ISS post Shuttle retirement. The team knew it had to look at EVA, as it is done today, and see how much was dependent on the shuttle model, then take those issues and develop projects to resolve them to support an ISS model. The focus team

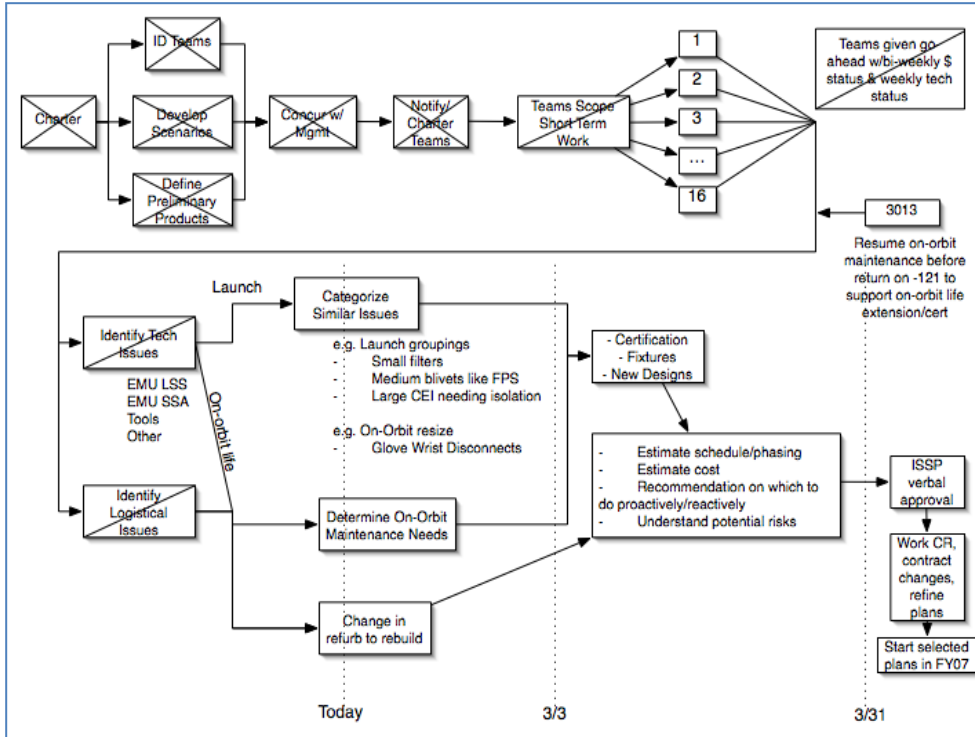
began by identifying all the stakeholders in the EVA community and grouped them into subteams (Table 1.0). Representatives of these subteams met with the focus team to explain what concerns they each had with shuttle retirement. The focus team took the subteams' inputs and developed the roadmap in Figure 1.0.

Team 1: Life Support System (LSS)	Team 9: Non-LSS Elect. components
Team 2: Space Suit Assembly (SSA)	Team 10: Suit Servicing/SPCE
Team 3: Water team	Team 11: Shuttle hdwr usable on ISS
Team 4: Logistics	Team 12: KSC
Team 5: Mission Operations	Team 13: Financial
Team 6: Hardware processing	Team 14: Crew
Team 7: EVA Tools	Team 15: Medical
Team 8: Alternate launch vehicles	Team 16: Contracts

**Table 1.0 EVA Stakeholder Teams**

This roadmap gave the focus team a means of tracking the path to a unified technical recommendation on how to maintain EMU EVA on ISS. The focus team provided the sub-teams with same ground rules and constraints. Many of these assumptions have since changed, but the kickoff of the EVA 2010 project used this basic list in some form.

- Post-2010 ISS EVA rate of 4 scheduled plus 2 contingency EVAs per year
- Soyuz, Progress, ATV and HTV are minimally available for hardware delivery
- All EVA hardware is disposable
- Oxygen and water will be provided by ISS
- 3 ISS crewmembers, all trained for EVA
- Maintain stowage volume within existing allocation on ISS
- Crew specific hardware will launch with CM on Soyuz
- ORU capability of EMU will be used
- EMU and EVA Tools will be capable of non-ORU component replacement as needed
- Work within the perimeters of the current EMU system certification (no influx of advanced technology and no major redesign)
- No CEV cargo space available from 2010 until NET 2014
- EMU system has life limitations (using the current configuration plan for future activities) 730 days
- Must maintain existing programmatic safety margins and commitments



**Figure 1.0 EVA 2010 Roadmap**

The focus team’s primary objective was on addressing EMU and its support equipment. EVA Tools and Crew Aids (ETCA) are also vital to successful EVA sorties and were considered; but issues identified for them were believed to be more easily overcome. Thus, the ETCA efforts were pushed to the future. See more details on ETCA in the EVA 2010 Project Implementation section.

The focus team worked with all subteams, but was primarily interested in determining what major issues existed for the EMU Life Support System (LSS) being able to support ISS without returning to the ground. The thought process in varying levels of detail worked the same for all subteams that actively participated in the development of the EVA 2010 plans. For brevity and because it was the largest amount of work, the authors will focus on just the LSS exchange of ideas.

The major area the LSS subteam felt needed to be addressed were life extension, on-orbit maintenance, and resupply of the EMU on alternate launch vehicles. As for all teams, the starting point for their efforts was to review failure history of critical hardware. The LSS team developed a weighted matrix that included how difficult it was to replace the hardware, criticality of hardware failure, whether the failure was detectable on-orbit, and did failures drive previous life extension efforts. After all LSS components were reviewed and weighted, the output was a listing of the most vulnerable components and those most susceptible to issues later on-orbit. It is on this list of components, that the LSS team decided to focus future EVA 2010 projects.

This list was then more specifically reviewed by different groups, one concentrating on the on-orbit maintenance capability and one concentrating on the logistics required to ensure hardware inventories would meet the future demands. Yet another group started looking at the details of extending the



maintenance interval to meet the then end date of ISS- 2016. This life extension team raised concerns of corrosion and material degradation, which historically had been a significant driver in LSS anomalies.

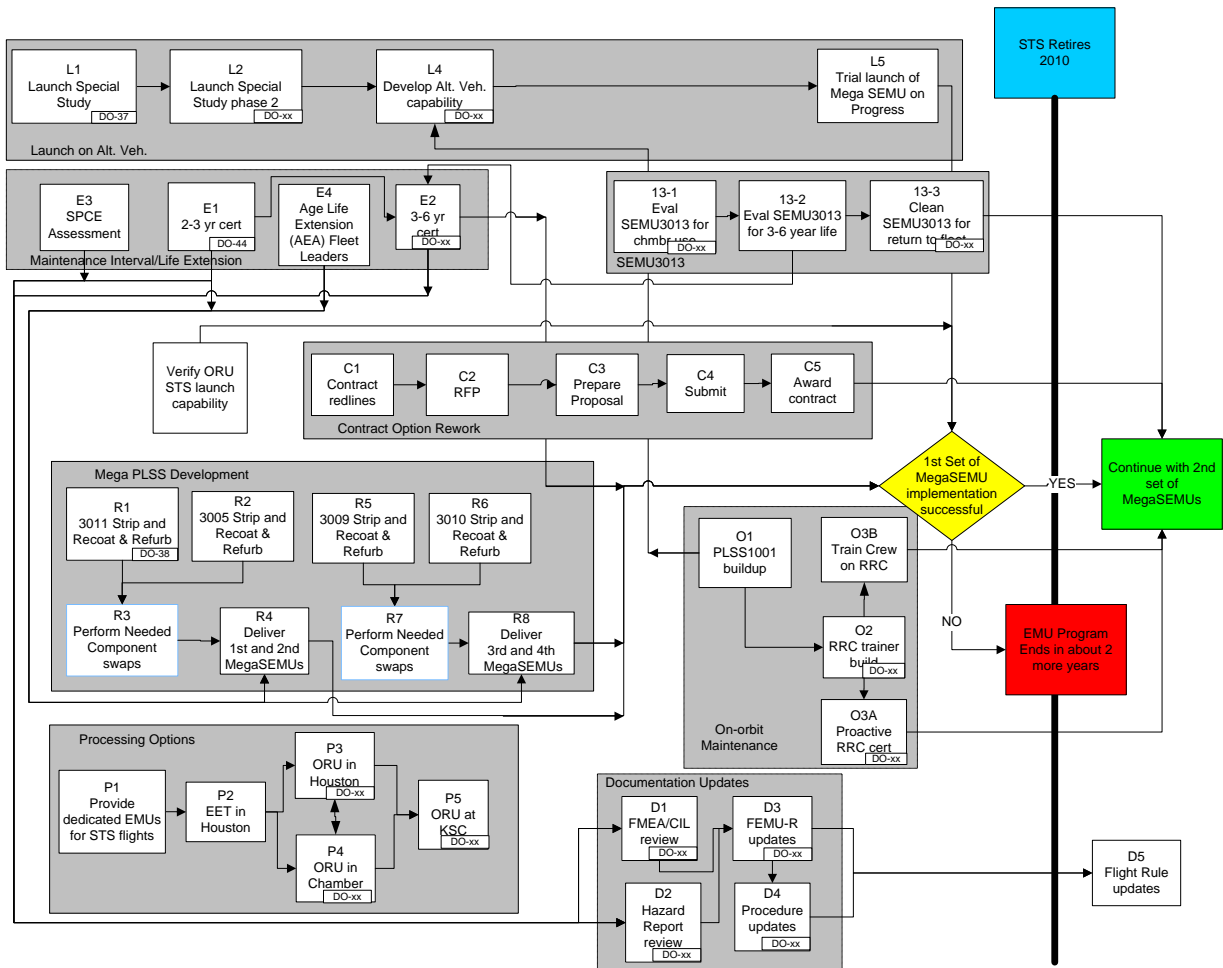
The EVA 2010 team did not limit the thought process of the subteams except by the initial groundrules and assumptions listed above. As each group put forth their concerns, the subteam with guidance from the focus team identified common issues that could potentially have a common solution. It is these coalesced issues that were selected for implementation as specific EVA 2010 projects.

For example, from the logistics concerns, came the need to procure, refurbish, and life extend hardware that was not originally on the initial Assured EMU Availability (AEA) plan. To maximize the ground maintenance activity to best serve the goal of maximized on-orbit life, more component swaps had to occur at the EVA hardware processor. To ease this congestion, the LSS team suggested a relatively quick extension of the maintenance interval from 2 to 3 years. This was the first step to increasing our maintenance interval to 6 years, while at the same time helping the logistics effort ease hardware flow.

So, the EVA 2010 projects stemming from the LSS team review were the new hardware procurements and refurbishments to support the first MEGA EMUs to get ISS to 2016. Those MEGA EMUs needed to be maintained on-orbit so we need to ease crew interface with the LSS components by determining what could be removed and replaced on-orbit (RRUs). Even with the development of an on-orbit maintenance technique, there needed to be some assurance that the hardware will last for the necessary duration. This led to the task of extending the maintenance interval. And lastly, none of this will serve the program without a means of supplying the hardware to the ISS, thus the need for method of launching MEGA EMUs on alternate vehicles.

It is this process of identifying historical behavior of EVA hardware and using that information to leverage the differences between performing EVA on ISS with and without Shuttle support that allowed the EVA 2010 focus team to determine which projects were paramount in implementing before the end of the Shuttle era. This process is being applied to all EVA related hardware by all the affected subteams.

After several months of discussion with the subteams, EVA community management, and the ISS program, the focus team provided the recommendation that EMU EVA capability, being based on ground turnaround processing and refurbishment utilizing Shuttle as the transfer vehicle, must switch to a longer-term solution of on-orbit maintenance and disposable mentality. To track the individual projects identified by the subteams as necessary to achieve the switch to this new philosophy, the flow diagram in Figure 2.0 was created. The projects were grouped into achieving a capability of launching on alternate vehicles, extending the maintenance interval of hardware to create long-duration MEGA EMUs, the actual transformation of the initial MEGA EMUs, enhancement of on-orbit maintenance activities, enhancements in processing techniques, and documentation updates.



**Figure 2.0. EVA2010 Initial Master Plan**

Projects discussed later in the EVA 2010 implementation section can be seen on the flow diagram in Figure 2.0. As the EVA 2010 effort continued over the past few years, new projects not originally captured on the flow diagram in Figure 2.0 have emerged. All new projects not originally on the master plan are natural extensions of other projects or were identified through EVA 2010 project team review of new requirements.

## V. EVA 2010 Project Implementation

The EVA 2010 Project was established to ensure that the EMU operational life on ISS could be extended as long as possible. Additionally critical items in helping to obtain and maintain that extended life would be of utmost importance.

Besides the EMU itself and the hardware to launch the critical components, the EVA 2010 Project included the removal and replacement of components on orbit and the development and certification of EVA tools to perform on-orbit maintenance and repair of the EMU. Also, the need to supply water for the EMU cooling system and the logistical resupply of components needed to be assessed. Additionally

the EMU component resupply was evaluated to ensure that proper sizes and number of components was adequate and available to support the ISS without the Space Shuttle. This effort resulted in the development of a new EVA hardware logistical plan

As such critical hardware items were identified as candidates for extension of their on-orbit life certification, and as new hardware builds to support EVA capability without the Shuttle. Individual projects were initiated to ensure that the hardware was ready for post-Shuttle operations. Described in more detail below, these projects are the MEGA EMU/6yr Maintenance Interval Certification Extension, the Alternate Launch Fixture, the On-Orbit Remove & Replacement Unit, the On-Orbit Diagnostic Kit, EVA Tool Certification Extension, the PGT Torque Analyzer Kit (TAK), and use of water from the Water Processor Assembly (WPA) in the EMU.

#### **A. MEGA EMU/6 yr Maintenance Interval Certification Extension**

Over the years, the EMU Maintenance interval has lengthened. When EMUs were first operated, the maintenance was performed after every Shuttle flight. Then, as the experience was gained with the hardware, the EMU maintenance interval was gradually lengthened. In the year 2000, the EMU maintenance interval was lengthened from after every Shuttle flight to 369 days. In 2002, the EMU maintenance interval was lengthened from 369 days to every 2 years. In 2007, the interval became approximately every 3 years.<sup>4</sup> The EMU engineering team had sufficient data on hand to easily increase the interval from 2 years to 3 years. Moving from 2 to 3 years was the first of two steps on the way to 6 years. Traditionally the EVA community prefers to take smaller steps when evaluating life extensions of EMU hardware.

As part of the EVA 2010 Project, a special study was initiated in 2008 to evaluate the feasibility of keeping the EMUs on orbit for longer than their then-current maintenance interval (certification of 3 years).<sup>6</sup> The study reviewed the following: overall performance of the EMU components; performance and condition of the three EMUs exposed to long durations on-orbit following the Columbia accident; sensor and instrument data to determine aging trends; Failure Investigation Anomaly Reports (FIARs) from 1992 to 2007 to make sure that closure rationale would not be violated with the 6-year extension interval; and the Discrepancy Report database to identify any trends or occurrences of age-related hardware issues. This study included testing and analysis along with the review of historical data for each life support and Space Suit Assembly (SSA) components with a special emphasis on limited life.

The overall findings indicated that the Short EMU (Hard Upper Torso (HUT) with upper arms, Portable Life Support System (PLSS), Secondary Oxygen Pack (SOP), and Display and Control Module (DCM) attached) along with the majority of its sub-components could perform nominally for a 6-year interval without ground maintenance. This 6-year maintenance interval items includes the following:

- PLSS – Portable Life Support System,
- SOP - Secondary Oxygen Supply,
- DCM - Display and Control Module,
- SCOF – SOP Checkout Fixture,
- BTA – Bends Treatment Adaptor,
- Helmet and Combination Purge Valve, and
- EVVA – Extravehicular Visor Assembly.

One exception to the 6-year maintenance interval was the Hard Upper Torso (HUT) Water Line Vent Tube (WLVTA) which would retain a 3-year maintenance interval. This component would become an On-orbit Replaceable Unit (ORU). Additionally, the SOP ability to sustain sufficient gas levels for documented rescue scenarios is only certified for 2 years. However, community agreement has been reached that will allow the use of the SOP for up to 6 years as long as the gas pressure checks on the oxygen remains favorable.

Some of the rationale used to extend EMUs to a 6-year maintenance interval included that the SSA hardware life and maintenance supported a 6-year interval without any special ground processing. Most of the SSA components had an 8 to 10 year service life already. They did not require periodic maintenance per se, only inspections every 4 years. From a historical review of the inspections, it was determined that none of the findings were age-related, concluding that an 8-year maintenance interval was sufficient for these components. The following items met the criteria for an 8-year maintenance interval.

- EMU Helmet and
- Helmet and Extravehicular Visor Assembly (EVVA)

In order to qualify the EMU hardware to meet the longer 6-year maintenance interval on-orbit in the ISS, the hardware would be required to go through additional ground processing. Therefore, this extended duration EMU would then be processed as a “MEGA EMU”. The MEGA EMU stands for Maximized EVA Ground Activity units and the term “MEGA” would then be referred to as the class of EMUs that would be targeted for a 6-year maintenance interval for on-orbit operation in preparation for Space Shuttle retirement.<sup>2,4</sup> These 6-year MEGA EMUs would receive special ground processing that would support their certification to 6 years. This processing would include cleaning or replacing water filters along with the stripping and recoating of hardware with areas of known corrosion (the water tank walls, aluminum horn, and sublimator flange) to restore them to the best possible condition right before a launch (Shuttle or alternate vehicle). MEGA units are essentially the same configuration as the non-MEGA units except for in addition to the steps above, all component birth dates are aligned to maximize their on-orbit life. The MEGA EMUs will retain the 25-EVA capability as well.

The EMUs targeted for ground operations such as EMUs used for altitude chamber runs and astronaut crew training would still be at a 3-year certification. Additionally, for the last several flights of the Shuttle there are certain EMUs (referred to as up/down units) used as minimal stay units. These EMU units would continue with the 3-year maintenance interval as ground units or minimal-stay units (non-MEGAs) until they are eventually processed as MEGA units for launch on either the last several flights of the Shuttle or alternate vehicles.

The logistical plan is to have 4 MEGAs on orbit when the Shuttle retires. Future MEGAs will be launched on alternate vehicles as required.

## **B. Launching on International Partner Vehicles**

The capability to launch hardware to the ISS post-Shuttle retirement will, at least initially, fall to the ISS International partners. From the proven Soyuz & Progress vehicles provided by the Russian Space

Agency to the relatively new JAXA H-II Transfer Vehicle (HTV) and the European Space Agency's Automated Transfer Vehicle (ATV), these vehicles will allow for continued EVA activity on the ISS. Although the EVA 2010 project is currently investigating the requirements for launching on commercial vehicles (e.g. Cargo Resupply Service (CRS)) this paper does not address the possibility of such capability for EVA related hardware. EVA 2010 project plan implementation was set in motion before CRS was available.

Early-on in the EVA2010 project, the decision was made by the ISS Program Office to use the JAXA HTV as the prime vehicle for launching EVA hardware, especially the EMU PLSS/SOP launch fixture. The EVA2010 team initiated contact with representatives of JAXA and held a series of technical interface meetings in order to understand the launch environment of HTV. It was quickly realized that, given the stowage limitations of the HTV and the logistics requirements of the EMU, that major components of the spacesuit would have to be launched individually on the HTV and assembled on-orbit by the ISS crew and that the PLSS/SOP would have somehow be isolated from the vibration and loads environment for the JAXA H-II launch vehicle.

This was a dramatic shift in operational philosophy from Space Shuttle program where the PLSS/SOP & DCM are launched fully integrated into the EMU HUT. The crew would have to assemble the units on-orbit and perform some version of the checkout tasks currently done on the ground by trained technicians. Crew training for ISS Expedition crews would have to be enhanced, long-standing procedures modified, and high-fidelity mockups built to accommodate this shift in operational philosophy.

While the majority of EMU and EVA ancillary hardware would be launched in bags as soft-stowed, it was determined that a special fixture would have to be built for the PLSS/SOP in order to isolate it from the launch environment. This launch fixture would have to ensure that the vibration and acceleration loads on the PLSS/SOP did not exceed 12.4 g's.

The design ultimately selected was frame within which the PLSS/SOP could be mounted, with 4 isolators located at the four corners of the frame (Figure 3.0). This launch fixture could then be mounted on one of the eight racks located in the HTV pressurized compartment. This design utilizes the same interfaces as the airlock adapter plate (AAP) currently used in the Shuttle.



**Figure 3.0. HTV Alternate Launch Fixture**

### C. On-Orbit Remove & Replacement

After Space Shuttle retirement, pre-staged MEGA EMUs (prior to Space Shuttle retirement) and MEGA EMU components such as the PLSS are considered as disposable units. Therefore, all maintenance on the MEGA EMUs, whether planned or “off-nominal” will have to be performed on-orbit.

The desire to keep EMUs on orbit for long durations creates the potential need to remove and replace certain EMU components. Removable Replaceable Units (RRU) are components that are not already designed for on-orbit removal and replacement. Components already designed for on-orbit maintenance are known as ORUs. The PLSS, DCM, HUT, and SOP are all considered as ORU components. The incorporation of ORUs allows crew members to resize EMU suit components and perform routine (nominal maintenance) change out of components and items with specially designed interfaces. The RRU concept would be limited to crew members working only on low pressure oxygen and water circuits. Maintenance of high pressure oxygen circuit interfaces already have been redesigned and certified for ORU application. The general concept of RRU is to allow crewmembers with approved procedures, in an off-nominal situation, to perform on-orbit replacement of components. Once an off-nominal situation occurs (a single or multiple component failure), a failure investigation team would be activated to isolate the failure using a fault tree/fault logic diagnostics and testing similar to the roadmap for an RRU event as follows:<sup>7</sup>

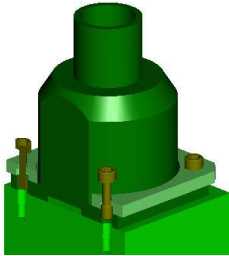
- Gather EMU performance data and generate a fault tree
- Review documented material for overall philosophy and approach
- Research the diagnostic tools available aboard ISS'
- Gather cognizant support personnel and come to consensus on the best course of action
- If the diagnosis indicates that component replacement is appropriate, it supports the crew in making the replacement
- Assess appropriate tests to be conducted to validate the component replacement
- Prepare the appropriate paperwork to return the repaired EMU to active EVA-support status.

An example of an RRU event was the replacement of a Fan/Pump/Separator (Item 123) in 2004 after an on-orbit failure occurred. The team worked to develop procedures that allowed the crew to install a new unit. Cooling to the EMU was subsequently restored thus demonstrating that an RRU concept can be successful.

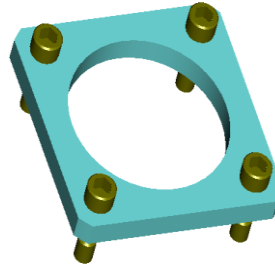
Although this RRU change out event was successful, the handling of small components during the change out of the Fan/Pump/Separator presented a challenge which emphasized the importance of incorporating, by design, hardware that captures small components whenever possible to prevent foreign-objects & debris (FOD) from floating into the EMU and other ISS systems. Only the components with small fasteners and washers that are a FOD risk, or components prone to more difficult to changeout, were considered for this retrofitable design while all other hardware remained in the current configuration for RRU or ORU change out.

The design of the RRU yoke plates and captive fasteners (Figure 4.0 and 4.1 ) would allow crew members to change out components in the EMU and be able to manage extremely small fasteners and washers during the process. ORU components typically incorporate captive fasteners as part of their design.

The current plan is to soft stow all RRU items on alternate launch vehicles. Also, there are no current plan to install the RRU yoke and captive fastener assemblies in MEGA units prior to launch on an alternate launch vehicle. The requirement indicates that the PLSS shall be capable of launch on the Shuttle or HTV with the RRU fasteners at any location.<sup>8</sup>



**Figure 4.0 Captive Screw in Yoke**



**Figure 4.1 Yoke with fasteners**

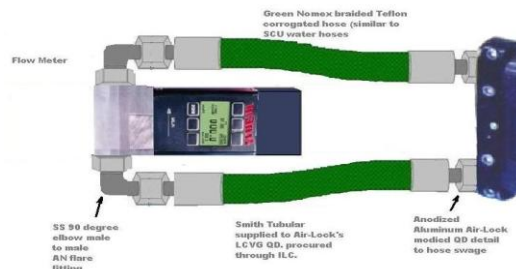
**D. Diagnostic Tool Capability**

As part of the EVA 2010 Project, diagnostic tooling is under development. This tooling is being designed to use with the MEGA EMU for diagnostics monitoring the health of the EMU and to facilitate the return to service after an RRU event. The diagnostic tooling includes hardware to monitor the health of the EMU transport loop flow, sublimator flange leak detection, vent loop leak detection fixture, and Electronic Caution and Warning System (ECWS) cabling to update the software, and the retrieve diagnostic and trending data, while on ISS.<sup>7</sup>

EMU Transport Water Loop Flow Meter<sup>8</sup>

This flowmeter as shown in Fig. 5.0 is being designed to measure the transport water flow at the Water Line Vent Tube Assembly (WLVTA) interface. The meter will verify that the water fan/pump/separator is operating properly. It also checks for filter clogging of the gas trap, umbilical and DCM multiple connector. Mechanical flowmeters were evaluated that could work in the microgravity environment, however these exhibited too high of a delta pressure so electronic sensors need to be assessed.

Two specific electronic sensors were tested and tubing for the sensor was also assessed. The flowmeter is planned to be launched to ISS on HTV, Shuttle or Soyuz vehicles in a soft stowed configuration without regard to orientation with no plans to return.

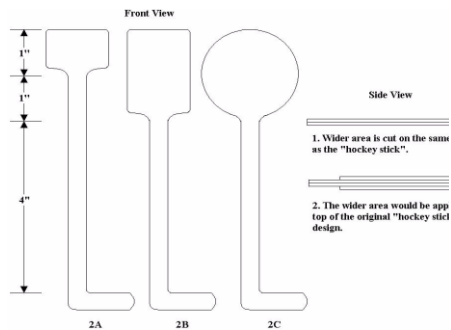


**Figure 5.0 EMU Transport Flow Meter**

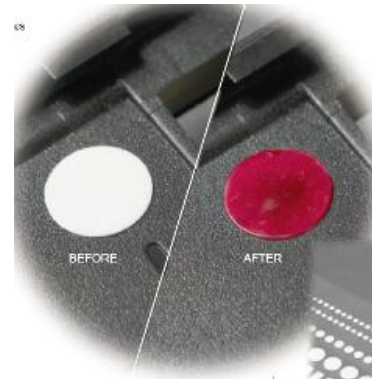
## Sublimator Flange Leakage Detection Devices<sup>9,10,11</sup>

The Sublimator cools the vent and water loops of the PLSS by sublimating feedwater to vacuum. The Sublimator flange interfaces with the PLSS valve module. Through the o-ring grooves of the cooling and condensate water ports there exists a possibility of corrosion-induced water leakage. Although the Sublimator flange has experienced corrosion, to date no leakage has ever occurred due to corrosion. If water is detected, continued use of the PLSS would have to be assessed. Even replacing the Sublimator on-orbit would be a possibility as an RRU. The Sublimator Flange is shown in Figure 8.0.

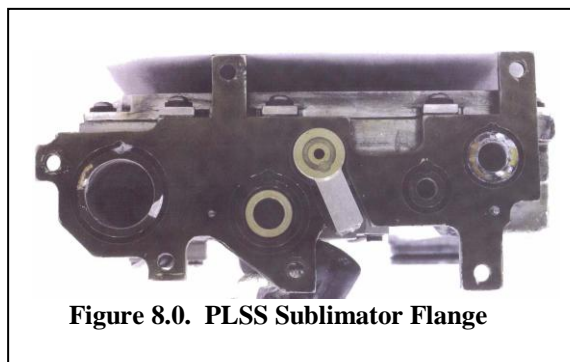
In advance of not using the PLSS, or changing out a sublimator, a way of confirming the detection of a water leakage was needed. It was concluded that visual inspection along with the use of water sensitive tape (known as water indicating test strips) could be used to detect water leakage at the Sublimator flange and other areas that cannot be seen. Visual inspection would be performed first. Since water can be difficult to see on the metal surfaces, the tape can be used as a secondary indicator. The tape as shown in Figure 6.0 is shaped similar to a hockey stick and can be hand held and run along the perimeter of the Sublimator flange. The tape is very sensitive to water and creates a very distinct appearance after its exposure to water. It turns from white to a blood red (Figure 7.0) making it very obvious of the presence of water.



**Figure 6.0 Water Indicating Test Strips**

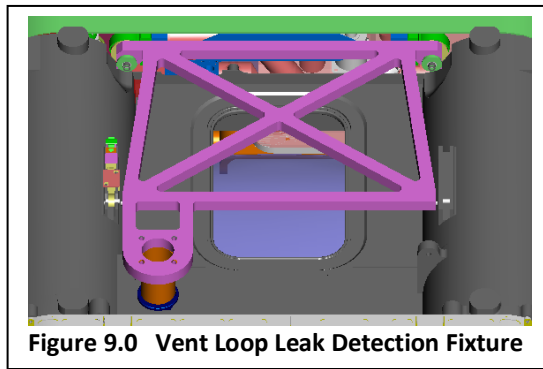


**Figure 7.0 Before and After Water Detection**



**Figure 8.0. PLSS Sublimator Flange**





**Figure 9.0 Vent Loop Leak Detection Fixture**

### Vent Loop Leak Detection Fixture

The purpose of the vent loop detection fixture is to bypass the SSA which will reduce the volume of the vent flow. This reduction in vent loop internal volume will assist in increasing the sensitivity of a pressure decay test. A hose connecting the T11 port in the HUT with the fitting on the valve module at the METOX outlet accomplishes this reduced internal volume. The pressure decay test could be used to detect the leakage range currently allowed for the PLSS. A concept of the vent loop detection fixture is shown in Figure 9.0.

### Diagnostic Cable (RS-485)

A RS-485 cable will be enhanced to provide bi-directional communication between laptop and ECWS using existing PC Software. This cable will allow the messages from anomalies stored in the ECWS to be transferred and to be looked at on orbit. This software is used regularly for ground processing. The laptop will contain crew operating instructions.

In addition to the 4 diagnostic tools being developed as itemized above, there are several tools that may be needed that currently reside on ISS already. One is the Electrical Multi-meter. The tool is already on ISS to support ISS maintenance and is used to perform electrical bond checks from Class S high pressure O<sub>2</sub>. Another diagnostic tool is the Velocical. It measures the vent loop gas flow. It is useful in fan/pump/separator checkout, vent flow sensor accuracies, METOX blockage, and purge valve flows. The Velocical is already on ISS to support ISS maintenance.

### **E. Use of ISS WPA water for the EMU**

An investigation was undertaken as part of the EVA 2010 Project to identify if trace contaminants would be an issue for the EMU if the ISS Water Processor Assembly (WPA) water was used instead of resupplying water. If this was successful then the need to resupply water for the EMU cooling system would go away or be reduced. The WPA was developed by Hamilton Sundstrand Space Systems International, Inc., Windsor Locks, Conn., and Marshall Space Flight Center (MSFC) and was recently installed on ISS. Although some problems have been encountered with the unit, WPA is the first major hardware delivery of the ISS Regenerative Environmental Control Life Support System in 2008. It supports a 7-member crew providing up to 35 gallons of water a day. If EMU could potentially use the WPA as the source for water coolant, then the need to provide a resupply of water for EMU use will be eliminated. To ensure that the water could meet EMU expectations, the WPA water was returned from the ISS and was tested in a mini-sublimator accomplishing 350 hours testing (50-EVA) equivalent without issue.

Some pre-testing was performed with MSFC generated WPA water. The evaluation of WPA materials determined that the multifiltration (MF) bed IRA-67 resin aqueous extract failed mini-sublimator testing. However, with Darco 20:40 charcoal, the results indicated successful scrubbing of the MSFC-generated WPA water and the IRA-67 aqueous extract. Due to the life of the MF bed when the tested water was collected (~ 10-months), there still existed some risk of using the WPA water with the EMU sublimator (fresh MF bed concern). Several options were assessed by the EVA 2010 Project team and presented to the EVA Panel and Control Boards and it was decided that additional testing with WPA water directly from ISS after a “fresh” MF bed changeover had occurred. At the writing of this paper, the second set of WPA water had not been obtained. The team is in hopeful anticipation that the results will be favorable which would save a tremendous amount of upmass on high quality water that the EMU needs to operate properly.

#### **F. EVA Tool Certification Extension**

As stated earlier in describing the EVA 2010 project strategy development, the focus team placed the majority of their time on addressing EMU and its support equipment. The issues surrounding EVA Tools and Crew Aids (ETCA) were based on cycle and age life, as well as calibration. Many EVA tools are limited in their use because of the number of times an EVA crewmember can actuate the mechanical interfaces before the tool is no longer functional or provides erroneous feedback. In some cases the harsh extravehicular environment causes material degradation due to exposure to atomic oxygen or ultraviolet light. Normally these issues are not critical to the safety of the crewmember or the vehicle. It is because of this lower criticality that the EVA 2010 focus team chose not to concentrate on addressing ETCAs in the early phase of the EVA 2010 project. So far the ETCA community has reviewed and obtained approval of the list of EVA tools and equipment that will be used on ISS post Shuttle retirement. Just like the EMU, EVA tools had on-orbit life limits in the 2 year range. Using manufacturer and historical data, analysis has been completed on a majority of the soft good materials used on ETCAs. The results of the analysis have shown that instead of 2 years, the materials should sustain their characteristics and provide their certified capabilities for at least 5 years. These results allow for on orbit use of EVA tools up to 2015 and possibly beyond. To continue use of these life extended tools more work must be performed. The current alternative plan is to launch replacement tools, as required.

The other major issue for ETCA was calibration. In particular the Pistol Grip Tool (PGT) has calibration of less than 2 years. That calibration was traditionally performed on the ground in a calibration laboratory. Each time the tool returned from orbit on the shuttle, it was checked for calibration and the processed again for flight. The PGT is the work-horse tool for ISS assembly and ORU changeout tasks. If the PGT is not properly calibrated, the feedback given to the crew on its torque application will become suspect. So, as part of the EVA 2010 project, the PGT torque analyzer Kit (TAK) was developed. This tool is equipped with a load sensor that interfaces with the PGT drive shaft. With the TAK properly mounted to vehicle structure, the PGT calibration can be measured and compared to its original ground settings. This will allow the ground engineers and ISS crew to know if any particular PGT is drifting in its calibration. Procedures and training can then be adjusted to compensate for the drift, thus providing appropriate torque application in whatever EVA task it is used.

## **G. Logistics & Stowage**

A carefully integrated and coordinated logistics and stowage plan is critical to maintaining EVA capability on-board the ISS. Without sufficient hardware to support ISS crewmembers, EVA capability could be severely affected or even lost until replacement hardware could be launched. Under the “Shuttle” model EVA hardware was routinely rotated back to the ground.

The Shuttle provided a cargo capability of almost 8818lbs, equivalent to almost 2 ½ Russian Progress resupply vehicles. Additionally the Shuttle could return 8818lbs of hardware, allowing for hardware to be returned on a routine basis. Additionally, as hardware experienced failures, or showed anomalous behavior, the EVA Logistics Team could plan for the return and replacement of the hardware on the next Shuttle flight. This 8818lbs capability allowed for sizable amounts of EVA hardware to be rotated on each Shuttle flight (for example, over 500lbs of EVA hardware on STS-132 in May 2010). And the location of the Shuttle launch site at Kennedy Space Center allowed for flexibility in shipping the hardware for launch.

With the retirement of the Space Shuttle, the model is undergoing a radical change. Limited cargo capability on International Partner launch vehicles, shipping hardware to overseas launch sites requiring advanced, and no return capability of hardware back to the ground.

### MEGA Component Alignment

One significant part of a MEGA EMU designation is that all of the LSS component birth dates are aligned to provide sufficient age life to meet that particular units planned use on ISS. This can be achieved by installing a newly procured part, a recently refurbished part, or extending the life of the part already installed. The LSS team and the processing team developed a matrix showing every component by serial number and age life that tracked in which EMU it was installed and where the component needed to be next. This matrix (nick named the “horse blanket” for its myriad of colors in a patchwork layout) is how the EVA 2010 team was able to ensure the first four MEGA EMUs received the appropriate hardware with the appropriate age life. These first four MEGA EMUs have been delivered to ISS and are being used for EVAs. The EVA 2010 team continues its logistics efforts by procuring hardware and performing life extensions and refurbishments on the components slated for the next four MEGA EMUS in accordance with the “horse blanket”.

### EVA Tools & Crew Aids

The ETCA team also had to manage its limited inventory to perform life extension efforts and refurbishments, all the while supporting the ongoing Space Shuttle Flights and ISS assembly EVAs. Although ETCA refurbishments and life extensions are usually not as extensive as those of EMU hardware, there hundreds of tools that must always be ready to support ISS & Shuttle missions. The challenge for all EVA hardware was to pull it from the fleet while minimizing the impacts to on-going mission requirements.

## **VI. Conclusion**

The upcoming retirement of the Space Shuttle will pose a significant challenge to EVA hardware and systems on-board the ISS. The EVA hardware currently used to assemble and maintain the ISS was designed assuming that it would be returned to Earth on the Space Shuttle for processing, repair, or refurbishment then re-launched. With the retirement of the Space Shuttle, a new concept of operations had to be developed that enable EVA hardware (EMU, Airlock Systems, EVA tools, and associated support hardware and consumables) to perform 8 EVAs per year on the ISS EVAs until 2015, and possibly beyond to 2020. Shortly after the decision to retire the Space Shuttle was announced, the EVA 2010 Project was jointly initiated by NASA and the One EVA contractor team. Individual projects were initiated to extend the operating life and certification of EVA hardware, to secure the capability to launch EVA hardware safely on alternate launch vehicles, to protect for EMU hardware operability on-orbit, and to determine a source of high water purity to support recharge of the EMU.

EVA operations on-board the ISS without the Space Shuttle will be a paradigm shift in safely operating EVA hardware on orbit. Without the ability to return the hardware for repair and refurbishment, it will become disposable. Under the old paradigm trained technicians on the ground would service the hardware, while under the new paradigm the ISS crews will be trained to perform these tasks under the direction of the Mission Control Center in Houston.

This shift in operational philosophy, from one that depended on ground resources and frequent Shuttle flights returning the hardware to one where the hardware is never returned and the crew assumes a greater role in maintaining the hardware, will more likely be the scenario that will occur in future NASA missions beyond Low-Earth Orbit.

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### **Footnotes**

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