MISHAP INVESTIGATION BOARD SUMMARY OF EXTRAVEHICULAR ACTIVITY 23: LESSONS LEARNED FROM A SPACEWALK CLOSE CALL

Christopher Hansen(1), Christopher Cassidy(2)

(1) NASA-Johnson Space Center, 2101 NASA Parkway, Houston, TX USA, Email: c.p.hansen@nasa.gov
(2) NASA-Johnson Space Center, 2101 NASA Parkway, Houston, TX USA, Email: christopher.j.cassidy@nasa.gov

ABSTRACT

The Space Station program convened a Mishap Investigation Board (MIB) to investigate a High Visibility Close Call which occurred during US Extravehicular Activity (EVA) 23 on July 16, 2013. The MIB established the specific cause for the potentially catastrophic water leakage inside the Extravehicular Mobility Unit (EMU), which was a clog inside the EMU Fan Pump Separator, caused by inorganic material that led to water spilling into the vent loop. Additionally, the MIB identified Root Causes as any of the multiple factors (events or conditions, that are organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome. Root causes are ones that if eliminated or significantly modified, would have prevented the undesired outcome. Trouble-shooting also identified a catastrophic failure mode previously unknown to the ISS program. The lessons learned resulted in 49 separate recommendations to the ISS Program to correct these issues that led to this incident and prevent future such mishaps. Many of these recommendations were being implemented before the report was complete, and all of them are being specifically addressed by the ISS Program. Additional insights from NASA astronaut and EVA 23 spacewalker Christopher Cassidy are included to provide additional insight to the incident and the resulting lessons learned.

1. INTRODUCTION

On July 16, 2013, Christopher Cassidy (EV1) and European Space Agency (ESA) astronaut Luca Parmitano (EV2) exited the International Space Station US Airlock to begin U.S. Extravehicular Activity 23 (US EVA 23). Roughly 44 minutes into EVA 23, Parmitano reported water inside his helmet on the back of his head. The EVA ground team and the crew members were unable to identify the water’s source. As Parmitano continued to work, the amount of water in his helmet increased and eventually migrated from the back of his head onto his face. EVA 23 was terminated early and the crew safely ingressed the airlock. A nominal rate was used to re-pressurize the airlock followed by an expedited suit removal. The water quantity introduced into his helmet was later determined to be almost 1.4 liters. During the post-EVA debrief, Parmitano reported that he had impaired visibility and breathing, with water covering his eyes, nose, and ears. In addition, he had audio communication issues because of the water. When returning to the airlock, Parmitano had to rely on manual feel of his safety tether’s cable for pathway directions.

The event was classified as a High Visibility Close Call and a Mishap Investigation Board (MIB) was created. A related concern occurred during a post-EVA 23 suit dry-out procedure. A vacuum cleaner was used and unexpectedly suctioned O₂ from the suit’s secondary high pressure oxygen tank, causing a potentially hazardous mix of electricity and pure O₂, which could have ignited flammable materials in and around the vacuum cleaner, although fortunately no incident of this nature occurred. This paper will discuss the mishap, the results from the subsequent investigation, and lessons to be learned from the event.

The Mishap Investigation Board was commissioned by William H. Gerstenmaier, Associate Administrator for the Human Exploration and Operations Directorate at NASA Headquarters in Washington, D.C. on July 22, 2013. The final report, reference [1], was submitted on December 20, 2013. The MIB members appointed were Chairman Chris Hansen, Dr. Sudhakar Rajulu and Mike Foreman of the Johnson Space Flight Center, Joe Pellicciotti of the Goddard Space Flight Center, and Richard Fullerton from NASA Headquarters. The MIB investigation ran concurrently with an ISS Program investigation and relied on multiple experts to complete its work.

2. BACKGROUND

The International Space Station is located in low Earth orbit about 400 km (250 mi) above the Earth’s surface. It serves as a microgravity and space environment research laboratory for the physical and natural sciences. The ISS is also a tested of spacecraft systems and equipment required for future missions to the Moon and Mars. ISS EVAs, or spacewalks, are performed outside the spacecraft to build and maintain the orbital laboratory: installing new components; re-wire systems, modules, and equipment; monitor, install, and retrieve scientific experiments. EVAs also provide critical contingency capability to assure ISS viability and crew safety.

International Association for the Advancement of Space Safety
The current ISS Extravehicular Mobility Unit (EMU) (shown in Fig. 1), a complex spacesuit that provides protection from the extreme conditions of space, is a mobile life support system with an oxygen supply, electrical power, water-cooling equipment, ventilating fan, and an in-suit drink bag. The EMU was originally developed for use on the U.S. Space Shuttle to mitigate failure scenarios in which the Shuttle payload bay doors failed to close and lock properly prior to atmospheric re-entry. An additional postulated failure scenario involved achieving “rescue” of a disabled orbiter by EV A crewmembers entering a depressurized vehicle and accessing the flight deck. This particular risk mitigation approach required that the EV A suit and the Portable Life Support System (PLSS) assembly be sized—width and depth—to pass through the Shuttle hatch openings to the flight deck. The EMU has since evolved from a suit to mitigate Shuttle failure scenarios to one capable of deploying, capturing, and repairing satellites, and enabling astronauts to assemble, repair, and maintain the ISS.

As mission objectives expanded, the once single-mission EMU certification was incrementally extended to an operational life of multiple years on the ISS. The evolution of the suit over the years resulted in a long history of issues that led to many modifications to the EMU. The Quest Joint Airlock module in the U.S. segment of the ISS maintains the habitable environment when astronauts are exiting or entering the spacecraft for EV A operations. It consists of two main parts: the equipment lock and the crew lock. The equipment lock is where the EMUs are stored and preparations for spacewalks are carried out. The crew lock is depressurized during spacewalks. Continuous flight of the ISS requires spacesuits to be left on-board for longer periods of time than the suit’s original Shuttle certification allowed.

At the beginning of the ISS Program, EMUs were delivered by the Space Shuttle; a complement of suits was left on ISS when the Shuttle Orbiter un-docked. On subsequent Shuttle missions, suits were replaced and returned to the ground for maintenance and refurbishment. Originally, the maintenance cycle for an individual suit was after each Shuttle flight. Suit requirements supported three EVAs before ground conditioning. In order to support continuous ISS operation, the period of EMU maintenance cycles was extended to one year or 25 EVAs. This maintenance period was extended to two years in 2002 and to three years in 2007. The current operational certification is 6 years. NASA’s decision to retire the Shuttle fleet in 2011 required another change to the EMU operations concept. The complement of EMUs on ISS was increased from three to four. Additional ground processing is required for the EMU hardware to meet this longer 6-year maintenance interval. This processing includes cleaning or replacing water filters along with the stripping and recoating of areas with known susceptibility to corrosion.

3. EVENTS IMMEDIATELY LEADING UP TO MISHAP

Prior to EV A 23, Cassidy had completed five EVAs, totaling 29 hours and 43 minutes. Parmitano had completed one EV A (EV A 22), which was 6 hours and 7 minutes. On May 12, 2013, ISS crewmembers conducted US EV A 21. An EV A crewmember on this EV A wore EMU 3011, the EMU that experienced the close call on EV A 23. The crewmember did not experience water in the suit during EV A 21.

On July 9, 2013, just one week prior to EV A 23, Cassidy and Parmitano conducted US EV A 22 with the same EMUs that would be worn on EV A 23. When Parmitano removed his helmet post-EV A 22, he discovered between 0.5 and 1 liter of water in the helmet. Cassidy reported that when he was face-to-face with his partner at the airlock hatch prior to ingress, there was no visible indication of water in Parmitano’s helmet. Therefore, the crew concluded that the water must have entered the helmet during re-pressurization activities. Also, during EV A 22 repress, Parmitano was looking down and leaning forward. It was concluded that he likely had pressed on the drink bag (shown in Fig. 2) with his chest and could have pinched the bite valve open with his chin, releasing water into his helmet. The ground team accepted the crew’s drink bag leak suggestion and the presence of excessive water in the helmet was not investigated further. The crew cleaned up the residual water, and the ground team sent up procedure changes for EMU stowage to help the equipment dry out. The ground team instructed the crew to use a new drink bag for the upcoming EV A 23. There was no discussion of water in the helmet during EV A 23 pre-briefs which were held on July 11 and July 15.
4. EVENTS AT THE TIME OF THE MISHAP

On July 16, roughly 38 minutes into US EVA 23, Parmitano (wearing EMU 3011) had a “CO, Sensor Bad” alarm in his suit. At 44 minutes, he reported feeling water inside his helmet on the back of his neck and head. Less than 10 minutes later, he reported an increase of water behind his head. Neither the ground team nor the flight team were able to identify the water source. Cassidy visually confirmed the pooling water. The amount of water continued to increase. At 23 minutes after the first report of water, the Mission Control Team called an EVA termination, directing Parmitano to translate back to and ingress the airlock. An EVA termination allows for a crewmember with an EMU issue to return to the safety of the airlock while the other crewmember safes the worksite, followed by a nominal and orderly re-pressurization of the airlock. During his translation to the Airlock, the water behind Parmitano’s head began to migrate onto his face. During this maneuver, he experienced intermittent communication difficulties with the ground. Next, Cassidy ingresed into the airlock which was then re-pressurized (at the nominal rate). The suit removal for Parmitano (shown in Fig. 3) was expedited. Video downlink confirmed significant water covering the helmet interior when the helmet was removed. Parmitano’s Liquid Cooling and Ventilation Garment (LCVG) was relatively dry, however his communications cap and helmet interior were completely soaked with water.

During a post-EVA debrief, Parmitano reported having impaired visibility and breathing with water covering his eyes, nose, and ears during his translation to the Airlock. In addition, he mentioned having audio communication issues due to water in his communication cap. At the same time, the sun also had just set, making the environment very dark. The combination of the presence of water inside the helmet and darkness due to the loss of sunlight so significantly reduced visibility that Parmitano was forced to rely on the manual feel of the safety tether cable for pathway direction for the return to the airlock.

5. A VIEW FROM INSIDE – THOUGHTS FROM ASTRONAUT CHRISTOPHER CASSIDY

When one is about to do, or just starts doing, something that they have been looking forward to for a long time there is always a certain level of excitement and happy emotions involved. For astronauts, EVA is exactly that. It comes with many months of pre-flight training, and weeks of in-flight preparation of the plan, the suits, and the hardware. Even the act of getting out the door is a multi-hour process. So when it finally happens, and I find myself looking through my visor, between my toes at the pressure increasing, I was finally able to maneuver to the safety of the airlock while the other crewmember safes the worksite, followed by a nominal and orderly re-pressurization of the airlock. During his translation to the Airlock, the water behind Parmitano’s head began to migrate onto his face. During this maneuver, he experienced intermittent communication difficulties with the ground. Next, Cassidy ingresed into the airlock which was then re-pressurized (at the nominal rate). The suit removal for Parmitano (shown in Fig. 3) was expedited. Video downlink confirmed significant water covering the helmet interior when the helmet was removed. Parmitano’s Liquid Cooling and Ventilation Garment (LCVG) was relatively dry, however his communications cap and helmet interior were completely soaked with water.

During a post-EVA debrief, Parmitano reported having impaired visibility and breathing with water covering his eyes, nose, and ears during his translation to the Airlock. In addition, he mentioned having audio communication issues due to water in his communication cap. At the same time, the sun also had just set, making the environment very dark. The combination of the presence of water inside the helmet and darkness due to the loss of sunlight so significantly reduced visibility that Parmitano was forced to rely on the manual feel of the safety tether cable for pathway direction for the return to the airlock.
6. EVENTS FOLLOWING THE MISHAP — INCLUDING IDENTIFYING A NEW HAZARD

Initial troubleshooting of the incident began the day after the EVA. The crew inspected the drink bag and determined that no visible cuts, holes or other damage existed. The crew then filled the drink bag and applied pressure. No leaks were noted. EMU water recharge was performed nominally and 3.84 lbm (1.75 Liters) of water went into the suit. This correlated with the crew report of 1 to 1.5 L of water in the helmet post-EVA in addition to what would nominally be expended by the suit during a 1 hour and 40 minute EVA. After water recharge, the crew executed water leak troubleshooting steps: The PLSS fan was turned on with the Secondary Oxygen Pack (SOP) Check Out Fixture (SCOF) installed to cover the Vent port and O₂ Actuator in IV setting for approximately 14 minutes. The installed SCOF is shown in Fig. 4.

No off-nominal conditions were noted and inspection of the suit revealed no visible water. When the SCOF was removed per procedure, the crew reported hearing a “sucking” sound and the fan stopped operating. The crew was directed to turn off the suit fan and move the O₂ Actuator to OFF. The crew then turned the suit fan back ON and again set the O₂ Actuator to IV. The fan briefly began spinning and then shut down almost immediately, with the crew reporting a water “sucking” or “gurgling” sound. Subsequent inspection revealed water in the METOX canister (CO₂ scrubber) outlet and suit inlet ports. The crew additionally reported seeing droplets of water in the neck vent port (called T2). While the crew was awaiting further direction from the ground, the Infrared (IR) CO₂ transducer in the suit began to show an increase in its reading and eventually went off-scale high, most likely due to moisture in the vent loop near the CO₂ transducer.

After the fan in the EMU water separator pump was...
flooded, the ground team developed a procedure for drying out EMU 3011’s Vent Loop using a wet/dry vacuum at the crew’s next available opportunity. After the crew executed the EMU 3011 vent loop wet/dry vacuum and dry-out activity, the EVA officer in Mission Control noticed a nearly 500 psi reduction in SOP pressure had occurred during a Loss of Signal (LOS), a time period where there is no telemetry available between the ground and ISS. Pressure in the SOP dropped from an initial value of 5580 psi to 5081 psi. The crew reported the SOP pressure gauge read ~5200 psi which matched the telemetry data within the allowable +/- 490 psi range for the gauge.

On July 26, during EMU 3011 troubleshooting, it was noticed that the SOP pressure reading had increased to 5271 psi; the increase being due to the warming of the bottle contents after the expansion cooling experienced during the inadvertent flow initiation. The use of a wet/dry vacuum during this troubleshooting procedure was an off-nominal operation. The EMU team did not fully appreciate that the SOP would engage and flow with the EMU O₂ Actuator in the OFF position. The transmitted procedure was not fully validated on the ground, and once implemented aboard ISS, caused an unsafe condition that exposed the crew and ISS to a potential fire hazard during inadvertent activation of the EMU SOP. A mechanical design review that was conducted after this incident indicated that the vacuum force was enough to partially open the SOP regulator valve. The vacuum produced by the vacuum cleaner in the vent loop provided enough delta-Pressure to cause the bellows of the SOP regulator to overcome the spring force designed to keep the regulator closed. When this occurred, it created a potentially hazardous mix of electricity and pure O₂, which could have ignited flammable materials in and around the vacuum cleaner.

During discussions of the post-EVA 23 SOP issue, interviewees indicated that there was at least a perceived pressure to perform the dry out procedure at the next available crew opportunity rather than take the time to perform a proper procedure verification on the ground using high-fidelity flight hardware. Only a fit check of the wet/dry vacuum on a non-functional Class-3 EMU was performed. Several further troubleshooting steps were performed on orbit, including an unmanned run of the EMU at ambient, shown in Fig. 5, removal and inspection of an internal valve and filter shown in Fig. 6, and removal and inspection of a gas trap, shown in Fig. 7.

### 7. CAUSES OF THE MISHAP

The top-level Fault Tree is shown in Fig. 8. The causes for this mishap evolved from (1) inorganic materials causing blockage of the drum holes in the EMU water separator resulting in water spilling into the vent loop; (2) the NASA team’s lack of knowledge regarding this particular failure mode; and (3) misdiagnosis of this suit failure when it initially occurred on EVA 22. The source of the inorganic materials blocking the water separator drum holes had not been experienced during an EVA before and was still undergoing investigation at the time this paper was written. The results of this investigation will ultimately lead to resolution of this issue; however, since the investigation into the source of the debris is expected to continue for many months, the
MIB did not have the required data to determine the root causes of the contamination source, which must ultimately be determined to prevent future mishaps. Because the hardware investigation must continue, the MIB report was divided into two unique areas of focus. First, the report focuses on the hardware failure investigation and understanding of the hardware involved, work completed to date, preliminary results, and future work needed to determine root causes. Second, the report focuses on real-time operation activities that can be improved to help the ground control teams and crew quickly recognize and react rapidly to emergencies of this type. Since this failure had not been seen previously or anticipated, the NASA team did not know or understand that an event like this could occur. Without this awareness, the team’s response to the failure took longer than it typically should have. The team applied what they did know to the symptoms they saw during EVA 23. Several possible causes were discussed in real-time between the flight control team and the crew members. Ultimately, the team came to the correct conclusion that the water in Parmitano’s helmet was more serious than anything that could be explained by previous experience and the EVA was terminated. In addition, the lack of understanding of this failure mode, along with several other reasons discussed in the report, caused the team to misdiagnose the failure when it initially occurred at the end of EVA 22. Had the issue been discussed in more detail at the end of that EVA, the team likely would have realized that the water experienced in the helmet was “out of family” and needed to be investigated further before pressing ahead to EVA 23. That investigation most likely would have discovered this failure mode and EVA 23 would have been postponed while the issue was resolved, thus preventing this mishap. The MIB strongly believed that both spacewalkers and the flight control team performed well given what they knew at the time of this mishap. Parmitano’s calm demeanor in the face of his helmet filling with water possibly saved his life. The flight control team quickly discussed and sorted through multiple possible explanations for the water in the helmet. The ISS Program also assembled an investigation team which responded to this failure with a level of concern and applied resources that demonstrated its awareness of both the seriousness of this event and the importance of fully understanding and correcting the deficiencies that allowed it to happen. Many of the recommendations in the report had already been implemented prior to release of the report as a result of the involved organizations’ proactive response.

8. ROOT CAUSES OF THE MISHAP

A Root Cause is one of multiple factors (events or conditions, that are organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated or modified, would have prevented the undesired outcome. Typically, multiple root causes contribute to an undesired outcome. Additional root causes to the hardware failure will be identified as the investigation of the inorganic materials found in the Fan/Pump/Separator continues. The MIB identified the following five Root Causes:

1) Program emphasis was to maximize crew time on orbit for utilization.

The ISS Program must place a strong emphasis on performing utilization (science) with the ISS; it is in fact the very reason ISS exists. However, the strong emphasis on utilization was leading team members to feel that requesting on-orbit time for anything non-science related was likely to be denied and therefore tended to assume their next course of action could not include on-orbit crew time. The danger with that thought process is that lower level team members were in effect making risk decisions for the Program, without necessarily having a Program wide viewpoint or understanding the risk trades actually being made at a Program level.

2) ISS Community perception was that drink bags leak.

The MIB could not identify a clear reason why the EVA
The community at large had the perception that the EVA drink bags leaked, other than a history of leakage with earlier designs. When presented with the suggestion that the crew member’s drink bag leaked out the large amount of water that was found in the helmet after EVA 22, no one in the EVA community challenged this determination and investigated further. Had that conclusion been challenged, the issue would likely have been discovered prior to EVA 23 and the mishap would have been avoided.

3) Flight Control Team’s perception of the anomaly report process as being resource intensive made them reluctant to invoke it.

Based on interviews and MIB investigation, it was clear that several ground team members were concerned that if the assumed drink bag anomaly experienced at the end of EVA 22 were to be investigated further, it would likely lead to a long, intensive process that would interfere with necessary work needed to prepare for the upcoming EVA 23, and that this issue would likely not uncover anything significant enough to justify the resources which would have to be spent.

4) No knowledge of the physics of water behavior in zero-g to water coming from the PLSS vent loop.

The MIB learned that while there is a significant amount of knowledge about the way water behaves in zero-gravity, the ground teams did not properly understand how the physics of water behavior inside the complex environment of the EMU helmet would manifest itself. The teams believed that if significant water entered the helmet through the vent loop that it would cling to the inner surface of the helmet rather than clinging to the crew member’s head. They also believed that if a significant amount of water entered the vent loop, the Fan/Pump/Separator would likely stall, as it had in 1-G when significant water entered the vent loop. Therefore, the significant hazard it presented was not anticipated.

5) The occurrence of minor amounts of water in the helmet was normalized.

Through interviews with ground personnel and review of data from previous EMU performance, it was clear that some water entering the helmet was considered normal by the ground teams. Despite the fact that water carryover into the helmet presented a known hazard of creating eye irritation due to its interaction with anti-fog agents, and also presented a potential fogging hazard, the ground teams grew to accept this as normal EMU behavior. Since these smaller amounts of water carryover had never caused a significant close call, it was perceived to not be a hazardous condition. When water began entering Parmitano’s helmet, the ground team discussed anti-fog/eye irritation concerns and visibility concerns; however, a more hazardous condition was not expected because the presence of water in the helmet had been normalized.

9. SUMMARY OF RECOMMENDATIONS

The Mishap Investigation Board made 49 recommendations to the ISS Program to correct the issues that led to this mishap, or correct issues discovered that could lead to future mishaps. All of the recommendations will not be discussed in this paper, however, the recommendations fall into general categories that are worthy of discussion.

Program Management structure: The EVA management office evolved over the years to be a separate organization which developed its own language, processes and risk management philosophies. However, the ISS Program was very dependent on EVA to maintain the safety and operation of the ISS. The separation between the offices led to risk decisions being made by each organization without full insight of the implications of those risks to the other organization.

Safety documentation: The ISS program and EVA activities had been extremely successful historically. This led to an almost unconscious belief that the safety documentation that explained hazards and dictated their control was no longer important. By failing to continually review and update these documents, the opportunity to identify a hidden potential hazard was missed.

Hardware upgrades: The EMU has been in operation successfully for over 30 years. Yet when issues arose, like CO₂ sensors failing and anti-fog material irritating the eyes of astronauts, they were often just accepted as the price of doing business. This led to a form of complacency and normalization of deviance. Hardware upgrades to combat smaller issues must continually be investigated and improvements traded in systems with significant hazards.

Flight Rules and Procedures: It was recognized early on in the investigation that the flight rules and procedures for recognizing and dealing with the hazard of water entering the helmet must be made very clear, be implemented, and be rigorously trained into the flight control teams and the astronauts themselves.

Tracking water quality: Years of operation of the ISS have identified that water quality in such complex systems is dynamic and continually changing. Systems that are
sensitive to water quality (equipment and humans!) depend on a good understanding of the water quality to which they are being subjected. Processes need to be put in place to track water quality to the level required for systems that are sensitive to it.

10. LESSONS LEARNED

In the history of human space flight, the hardest lessons learned have often come at the expense of the health and lives of our people. In this mishap, the opportunity to learn serious lessons about how to improve the safety of our astronauts was provided without the high cost of human lives. It would be a tragedy not to take that opportunity to learn from our mistakes.

It must be noted that the failure investigation into the hardware failure is ongoing. That investigation is already uncovering many more lessons learned that should be studied and acted upon, along with those identified in this investigation. For this investigation, there are several key lessons learned that must be remembered.

A preoccupation with failure is critical for maintaining a highly reliable organization. Human nature pushes people into looking for patterns and categorizing information to save energy. However, when successful organizations who deal with complex and hazardous environments begin assuming that they understand everything perfectly, simply because they have been successful in the past, they become subject to complacency, and the cost is failure.

Speak up: Often after tragedies we find individuals being overtly pressured by managers and higher authorities to accept risk with which they are not comfortable. This issue can exist; however, an equally dangerous behavior that is far more subtle was discovered in this mishap. Dr. David Aiken stated it concisely: “People in groups tend to agree on courses of action which, as individuals, they know are stupid.” Group think must be actively fought against with constant public questioning, diversity of thought, and the promotion of a culture that accepts such behavior as healthy.

A failure of imagination: The Apollo 1 fire was referred to by Frank Borman as a failure of imagination. They couldn’t imagine a ground test could be hazardous. In this mishap, many very smart individuals couldn’t imagine water in this situation could be so hazardous.

Anyone, in any organization (safety, engineering, operations, flight crew, etc.) could have had an impact on preventing this mishap. A simple question at the right time could have prevented it. Organizations must find ways to make every individual on their teams understand that they are as responsible for the safety of others as anyone else and that they have the ability to personally save lives.

11. REFERENCES